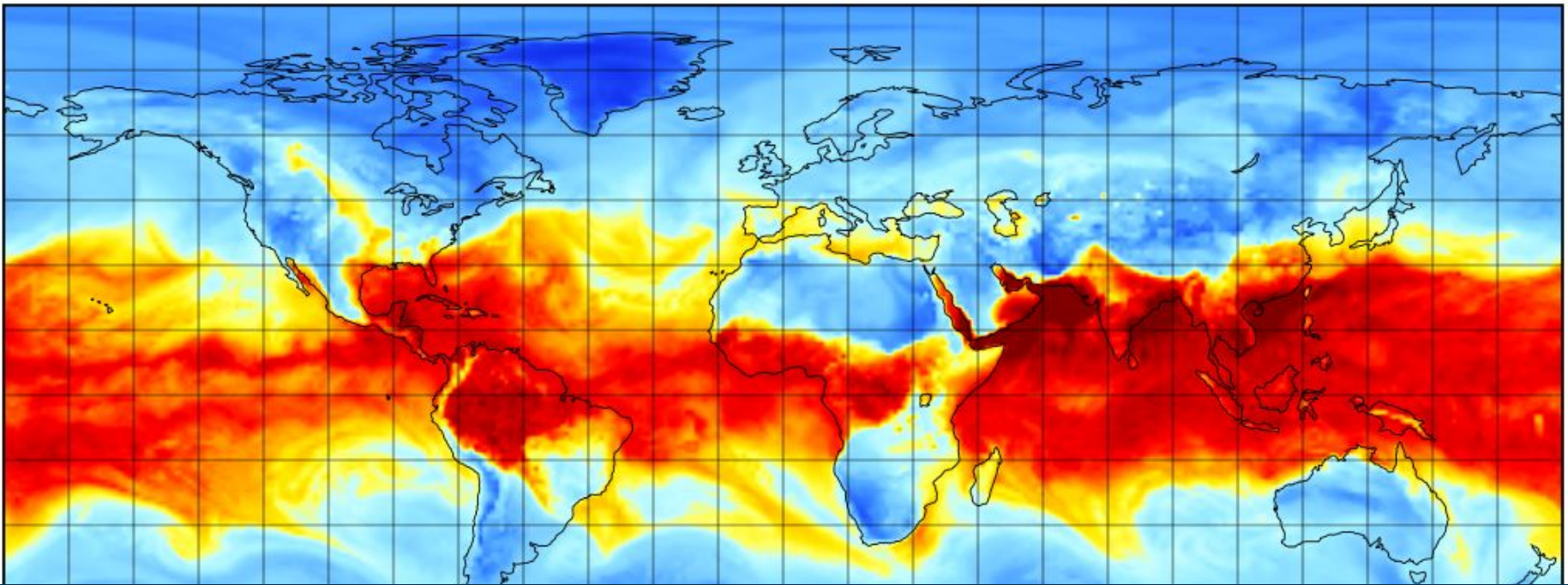




WATER IN THE ATMOSPHERE AND THE ROLE FOR CLIMATE

Part 5: Water and climate feedback

WS 25/26 | CHRISTIAN ROLF

TOPICS

1. Introduction into units and definitions
2. Water vapor and the relevance for the atmosphere
3. Cloud formation (water and ice clouds)
4. Water cycle
- 5. Water and climate feedback**
6. Measurement of water in the atmosphere

SUBTOPICS

5. Water and climate feedback (I)

General radiation processes

- **Basic laws for radiation (Planck and Boltzmann)**
- Earth Radiation balance
- Gaseous absorption of water vapor
(Line broadening, water vapor continuum)
- Absorption spectra of the atmosphere
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 - Greenhouse effect
 - Simple Energy Balance Model
- Global energy flows
- Radiative forcing
- Cloud radiative forcing

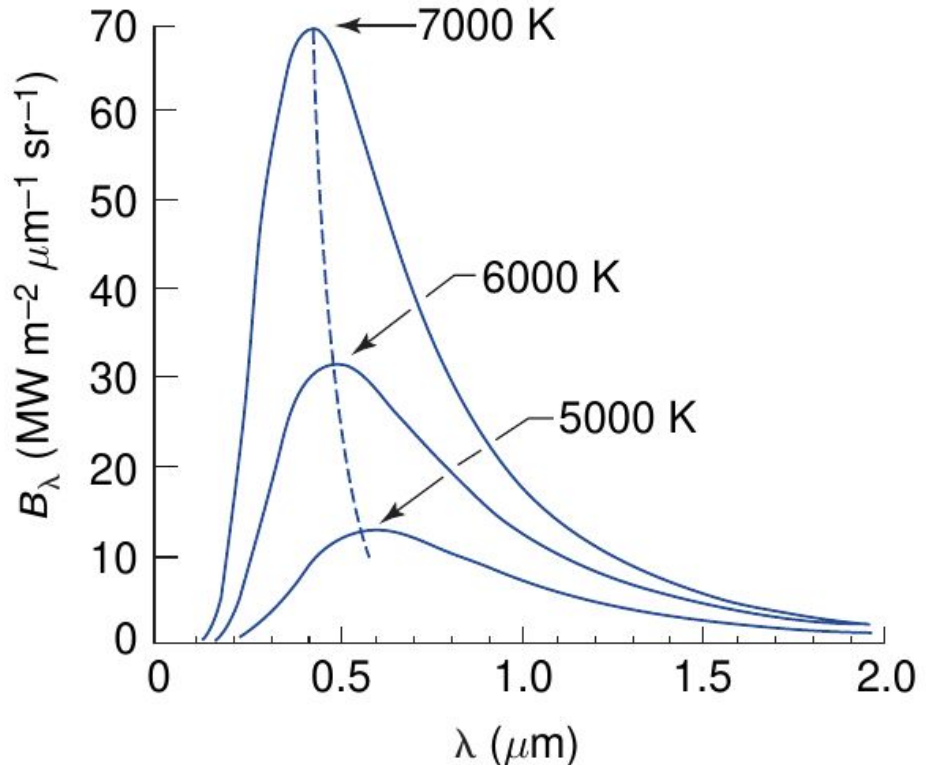
RADIATION - REMINDER

Wallace & Hobbs

Planck Function – Black body

$$B_{\lambda}(T) = \frac{c_1 \lambda^{-5}}{\pi (e^{c_2/\lambda T} - 1)}$$

With $c_1 = 3.74 \times 10^{16} \text{ W m}^2$
 $c_2 = 1.45 \times 10^2 \text{ m K}.$



Stefan Boltzmann law

$$B(T) = \int_0^{\infty} B_{\lambda}(T) d\lambda = \sigma \frac{T_e^4}{\pi}$$

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

Integral over the Planck function
(all wavelengths)

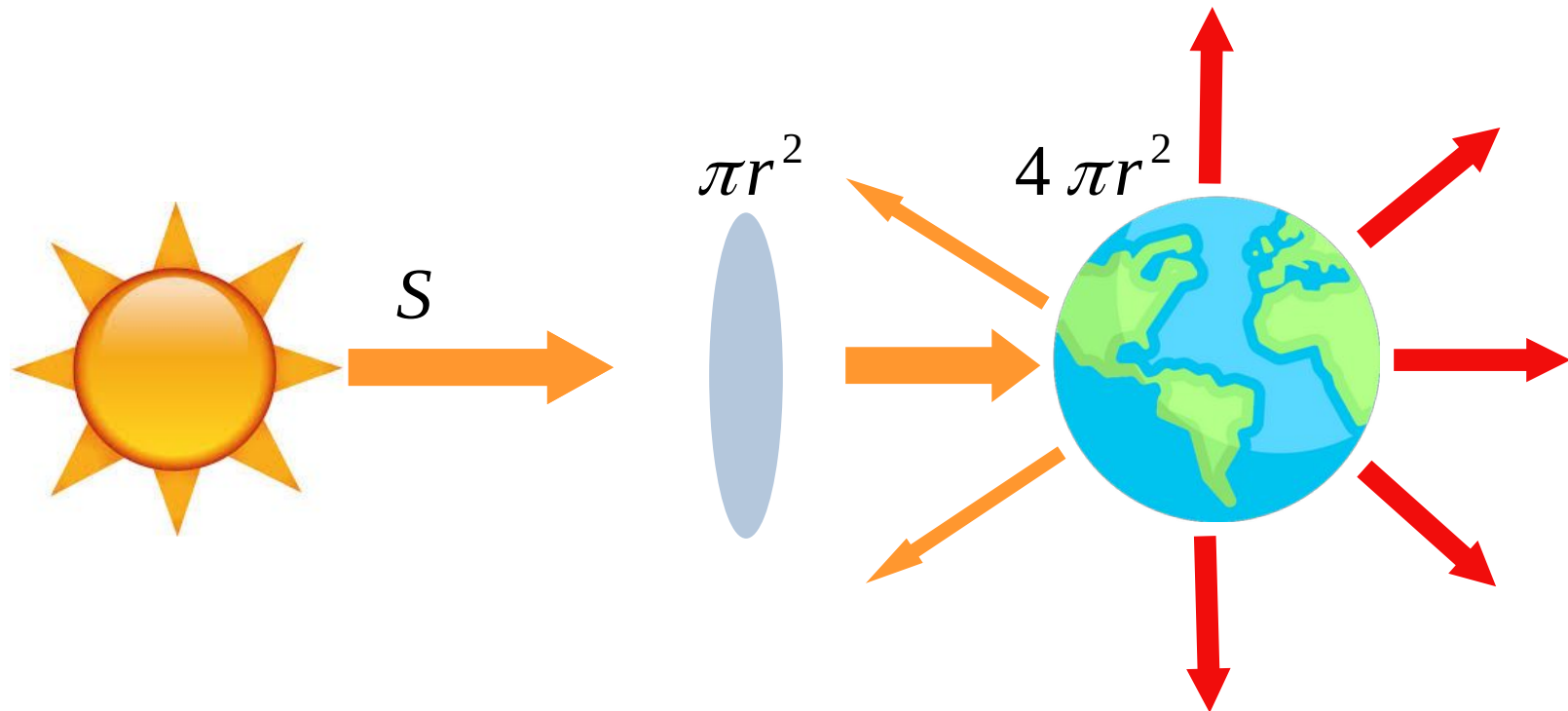
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EARTH'S RADIATION BALANCE



Incomming Solar or shortwave radiation

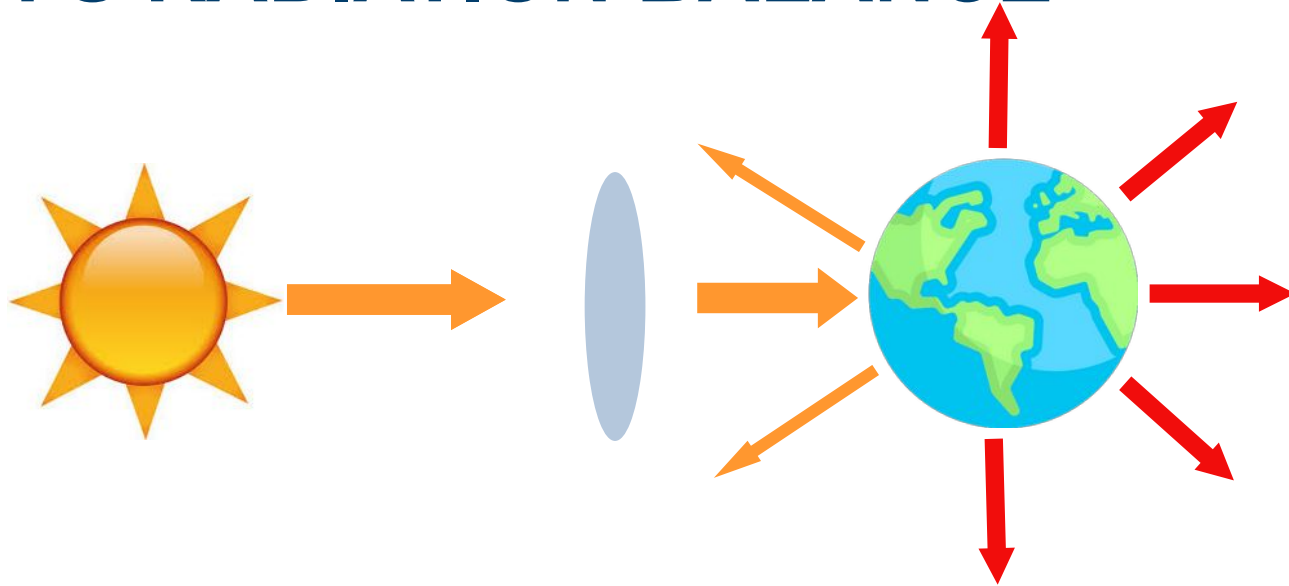
Thermal/Infrared or Outgoing Longwave Radiation (OLR)

$$E_i = S (1 - \alpha) \pi r^2$$

$$E_o = \sigma T_e^4 4 \pi r^2$$

α = albedo of the Earth

EARTH'S RADIATION BALANCE



There is a balance between the absorbed sunlight and the thermal/longwave cooling of the planet:

$$E_i = S(1 - \alpha) \pi r^2 = \sigma T_e^4 4 \pi r^2 = E_o$$

$$T_e = \sqrt[4]{\frac{S}{4\sigma}(1 - \alpha)} = 254.82 \text{ K} = -18.33^\circ \text{C}$$

with

$$S \sim 1366 \text{ Wm}^{-2}$$

$$\alpha \sim 0.3$$

$$\text{OLR} \sim 239 \text{ Wm}^{-2}$$

$$\sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$$

Why is the Earth's average temperature $\sim +15^\circ\text{C}$?

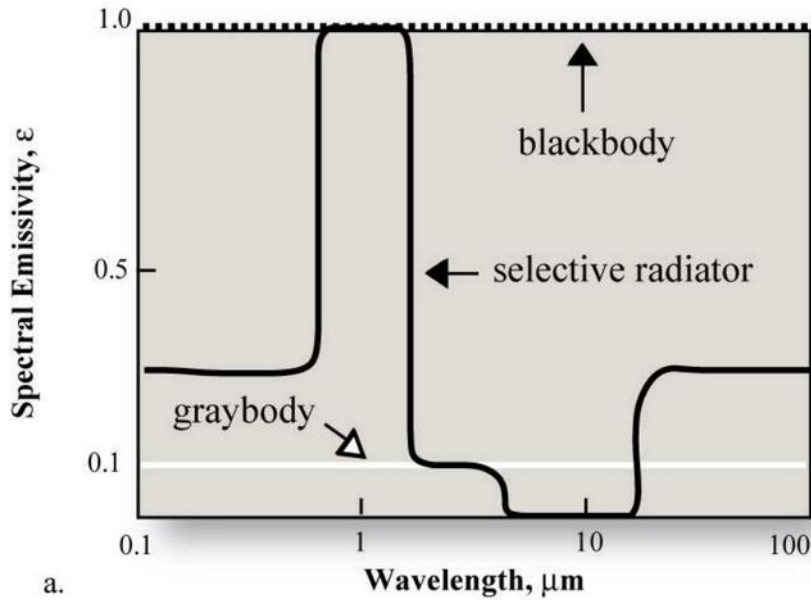
SUBTOPICS

5. Water and climate feedback (I)

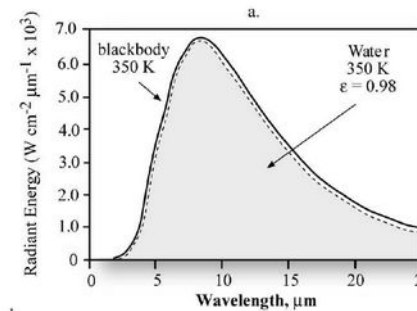
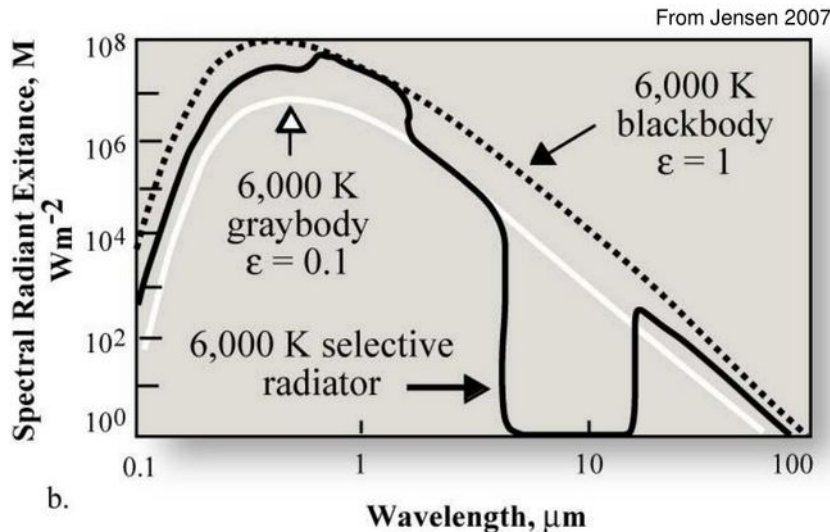
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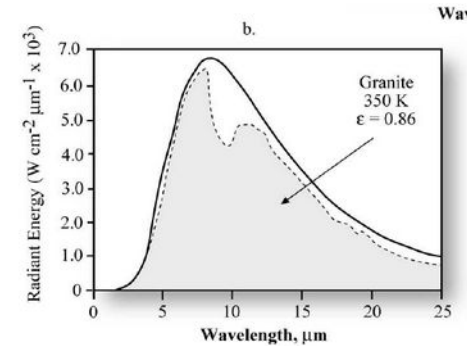
NON BLACK-BODY RADIATION



All selectively radiating bodies have emissivity ranging from 0 to <1 that fluctuate depending upon the wavelengths of energy being considered. A gray body outputs a constant emissivity that is less than one at all wavelengths.



From Jensen 2007



GASEOUS ABSORPTION

The interaction of radiation with matter is related to 4 phenomenon

- **Absorption; Emission; Diffusion/Scattering (Gas, particles); Reflection**

In the longwave, considering the atmospheric gases only

- **Absorption**

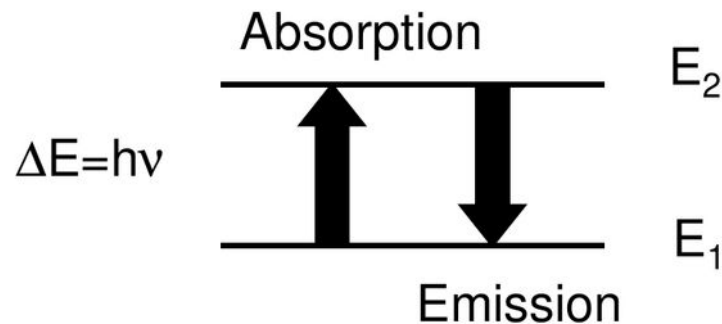
- **Emission** $dI_{\lambda} = \sigma_{\lambda} (B_{\lambda}(T) - I_{\lambda}) ds$

- Note that gases are not black bodies and do not have a continuous spectrum of absorption/emission. These are selective radiators described by molecular spectroscopy.
- The absorption coefficient σ_{λ} summarizes the governing laws.

ν is the frequency

λ is the wave length $\lambda = c/\nu$

κ is the wave number $\kappa = 1/\lambda$



GASEOUS ABSORPTION

- A molecule can only absorb a photon if its energy corresponds to the difference between two allowed states of the molecule.
- **Smallest difference:** translational/rotational energy
- **Largest difference:** electronic processes

$$E_{gesamt} = E_{trans} + E_{rot} + E_{vibr} + E_{elektr}$$

small $\leftarrow \Delta E \rightarrow$ large

- Allowed states determine frequencies that are effectively absorbed and emitted by the atmosphere.
- Photons with energy $\neq$ permitted difference pass through the atmosphere without being absorbed.

GASEOUS ABSORPTION

Translational energy:

- Movement of molecules or atoms in space
- *Not quantized*
- In the atmosphere generally « vibrational energy
- However: Energy transfer through collisions of molecules is important for absorption behavior!
- Equally important: Doppler effect due to molecular motion!

Rotational energy:

- Rotation of objects in space
- *Quantized* (in contrast to the “macroscopic” gyroscope)
- Rotational energy conversion corresponds to photons with wavelengths $< 1\text{ cm}$

Vibrational energy:

- Molecules: stable due to balance between attraction and repulsion
- Energy can be stored in vibrations around this equilibrium state
- *Quantized*
- Photon wavelengths $< 20\text{ }\mu\text{m}$
- 3-atom molecules (e.g., CO_2): 2 stretching modes, 1 bending mode

GASEOUS ABSORPTION

Other possible processes:

Photodissociation:

- Wavelengths $< 1 \mu\text{m}$:
 O_2 bei $\lambda < 200 \text{ nm}$; O_3 bei $200 \text{ nm} < \lambda < 300 \text{ nm}$

Electronic excitation:

- Excitation of electrons in the outer shell by photons with sufficient energy

Photoionization:

- $\lambda < 100 \text{ nm}$, removal of electrons from the outer shell, resulting in ionization
($\rightarrow$ ionosphere)

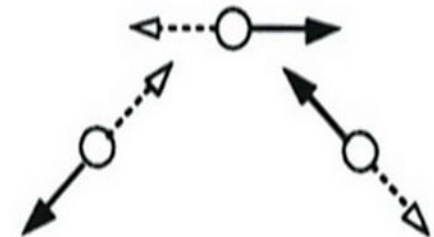
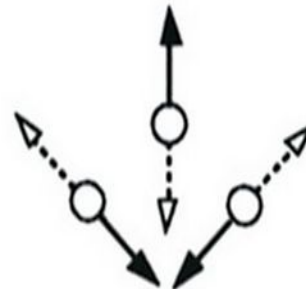
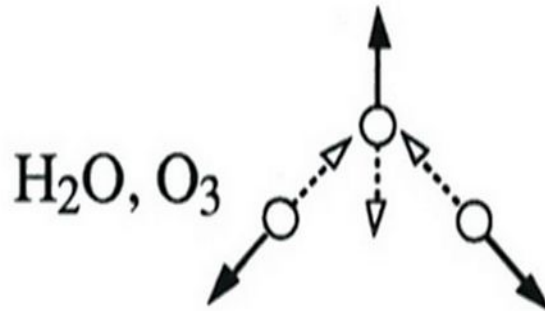
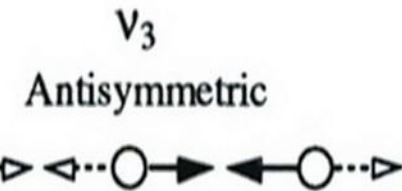
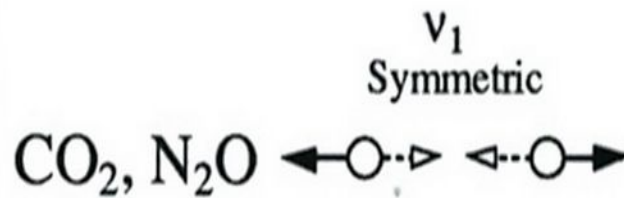
ABSORPTION + EMISSION BY ATM. GASES

Diatomic Structures

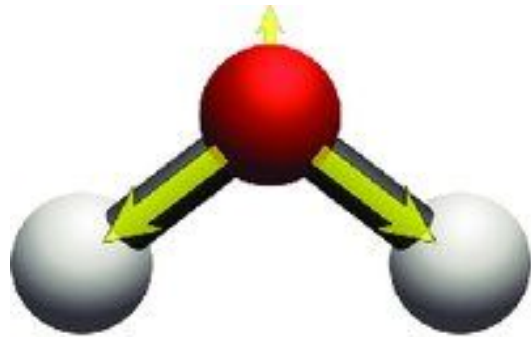
N_2, O_2, CO



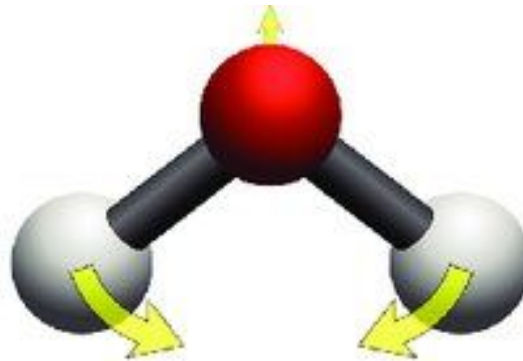
Triatomic Structures



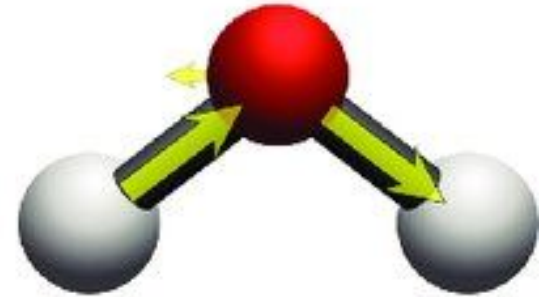
VIBRATION MODE OF THE H₂O MOLECULE



Symmetric stretch
 $\nu_1 \approx 3250 \text{ cm}^{-1}$



Symmetric bend
 $\nu_2 \approx 1600 \text{ cm}^{-1}$



Asymmetric stretch
 $\nu_3 \approx 3450 \text{ cm}^{-1}$

Durickovic, 2016

- H₂O is an asymmetric molecule that creates during vibration a permanent dipole moment. O₂ or N₂ molecules do not possess this property.
- More **complex absorption spectrum** due to transitions between different levels and the movements of **rotation** and **vibration** of the atoms composing the molecules
- Yield to many transitions and hence many absorption lines all over the spectrum.

LINE BROADENING

Natural

- Heisenberg uncertainty principle: the time and level of energy are not known simultaneously perfectly $\Delta E \sim h/\Delta t$ which turns into $\Delta \nu = \Delta E/h$
- Small compared to others

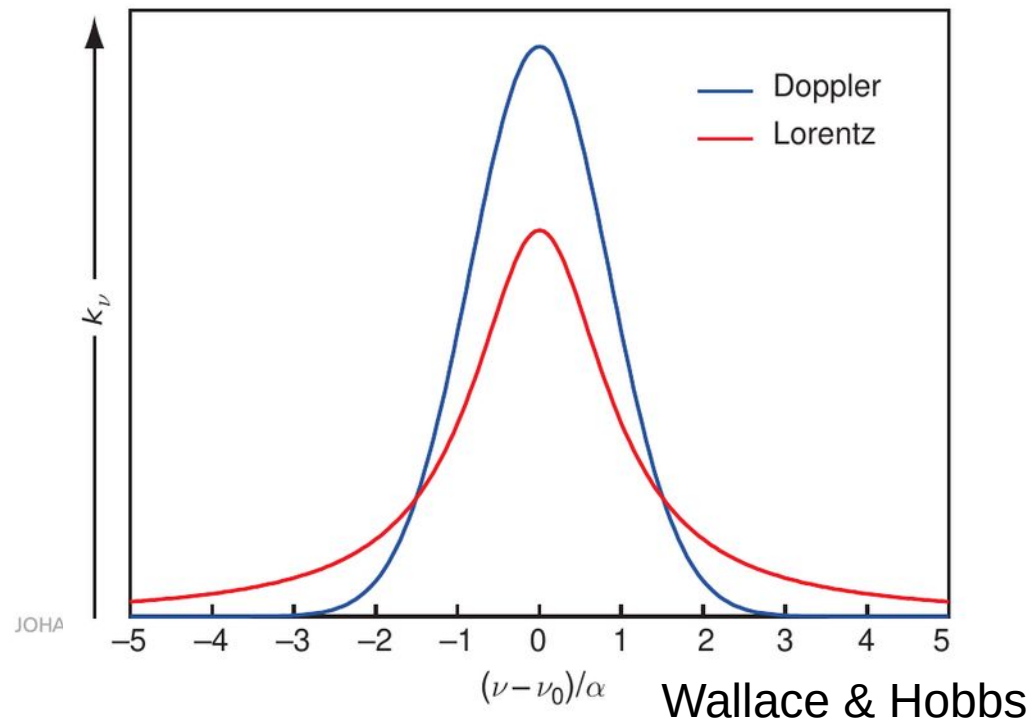
Collision broadening (Lorentz)

- In the infrared, collision makes the molecule state jumps from one to another
- pressure effect
- Collisions broaden spectroscopic linewidths by shortening the lifetime of the excited states

Doppler Broadening (Gaussian)

- Due to molecular thermal motions
- Temperature effect
- Gaussian shape

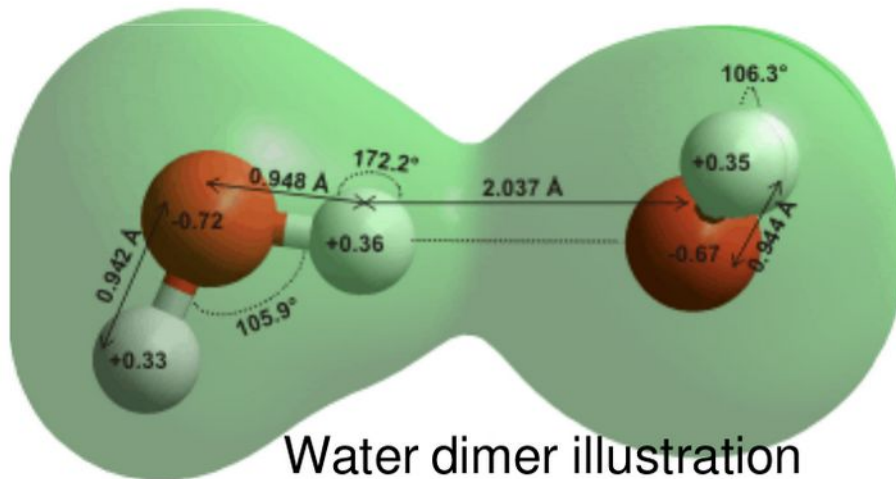
Voigt Profile = Collision + Doppler



THE WATER VAPOR CONTINUUM

Absorption due to a water vapor continuum in the atmospheric window (e.g. 8-14 microns)

- Sum effects of the far wings (Voigt profiles) of active absorbers on the edges of the windows
- Isolated water clusters formed by collisions of two molecules
- Foreign-continuum, due to interaction of water vapour with other molecules



Isolated water clusters. Typically, in the atmosphere there is about one water dimer for every thousand free water Molecules.

(Shine, JMS, 2016)

SUBTOPICS

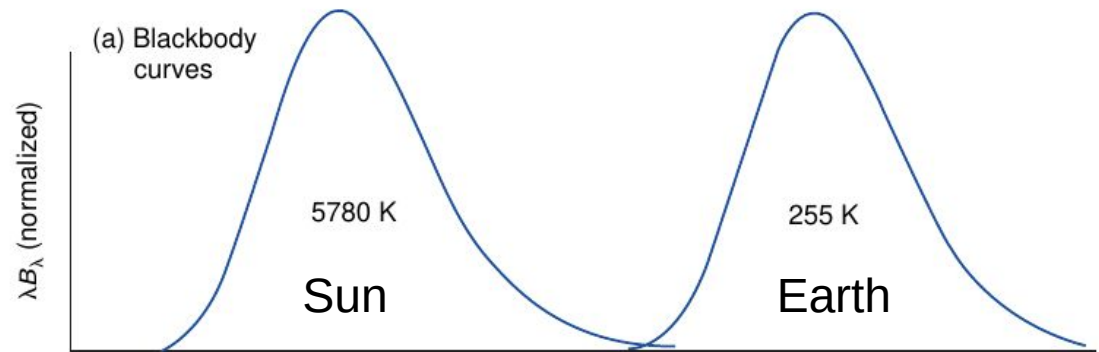
5. Water and climate feedback (I)

General radiation processes

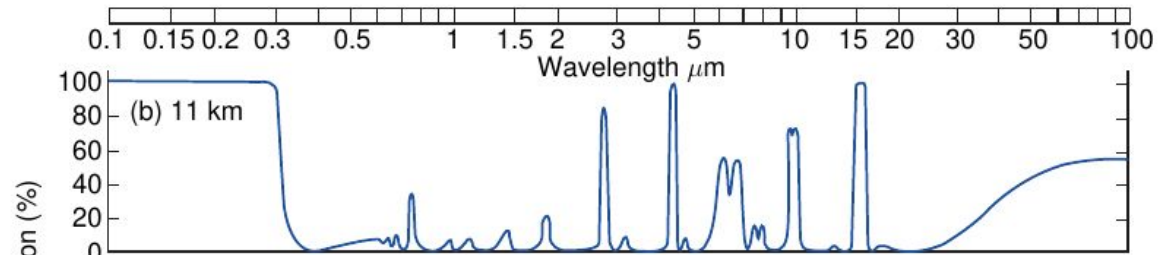
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ABSORPTION OF MOLECULES

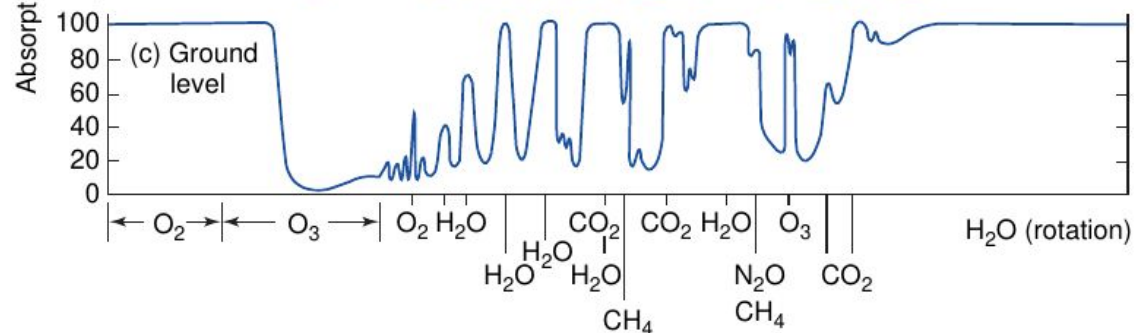
(a) **Blackbody spectra** representative of the sun (left) and the Earth (right). The intensity scales for the two curves have been scaled to make the areas under the two curves the same;



(b) **Spectrum of monochromatic absorptivity** of the part of the atmosphere that lies above the **11-km level**;

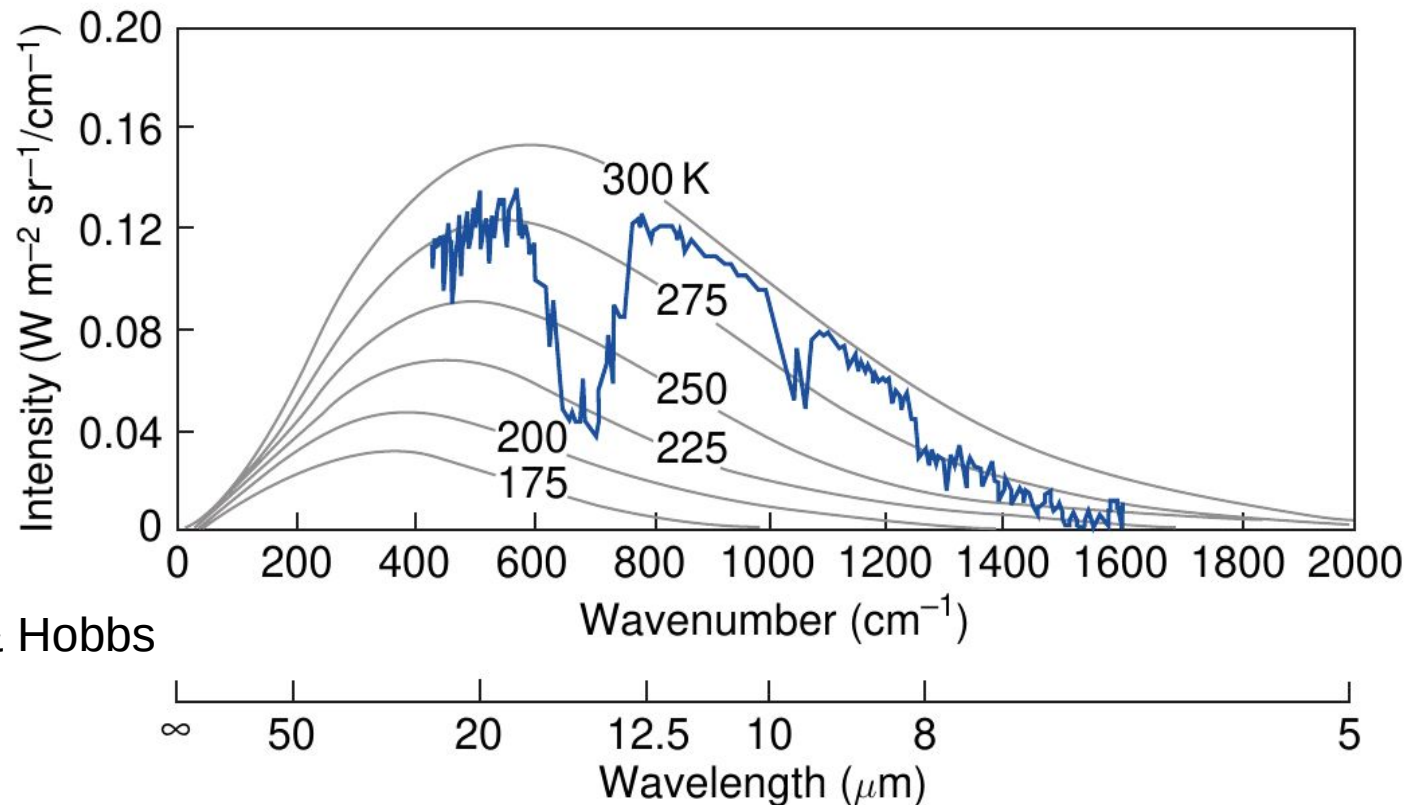


(c) **Spectrum of monochromatic absorptivity** of the **entire** atmosphere.



Wallace & Hobbs

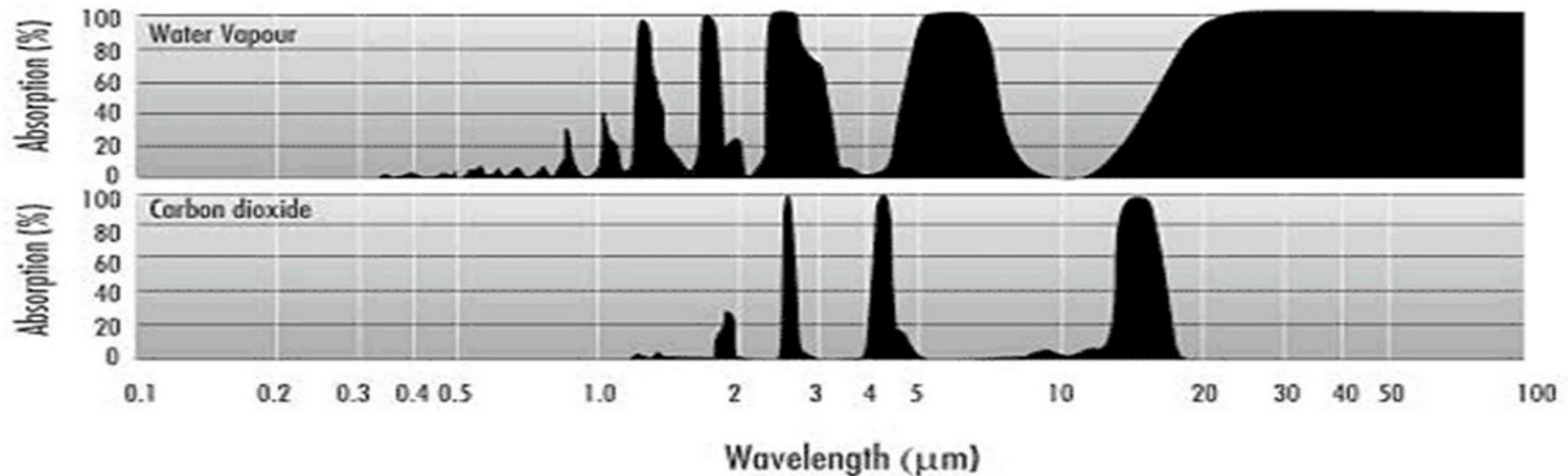
ATMOSPHERIC SPECTRUM OF LONGWAVE RAD.



Wallace & Hobbs

- The physical structure of molecules determines which wavelengths of electromagnetic radiation may be absorbed/emitted e.g. through vibration, rotation, spin, electron transitions, etc.
- Radiation absorbed by molecules is re-emitted at the local temperature, in all directions

WATER VAPOR ABSORPTION OF SPECTRUM



Al-Ghussain , 2018

- The water molecule is particularly versatile in its absorption/emission properties
- **Second most important greenhouse** gas often not explicitly named per molecule, H_2O is less effective than CO_2 but much more abundant concentrations vary strongly in space and time
- relatively **small anthropogenic influence**

REMINDER: IR RADIATION TRANSPORT

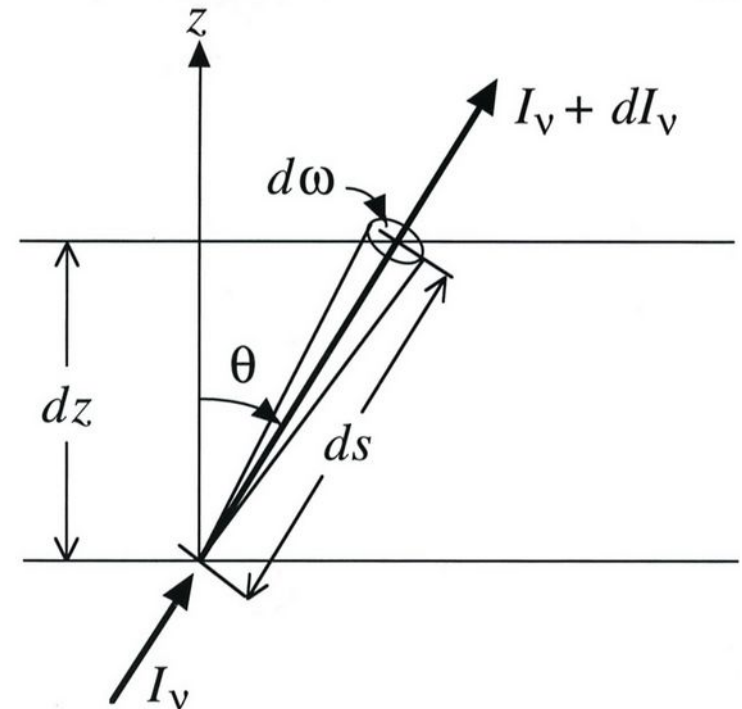
Change in radiation intensity I_ν along path ds through:

- Emission (B)
- Absorption (τ)

$$\cos \theta \frac{dI_\nu}{d\tau_\nu} = B_\nu - I_\nu$$

Schwarzschild Equation

$$F_\nu^\uparrow(z) = \int_{\Omega_+} I_\nu \cos \theta d\Omega$$
$$F_\nu^\downarrow(z) = - \int_{\Omega_-} I_\nu \cos \theta d\Omega$$



Net radiation flux integrated over all ν :

$$F_{net} = F^\uparrow - F^\downarrow$$

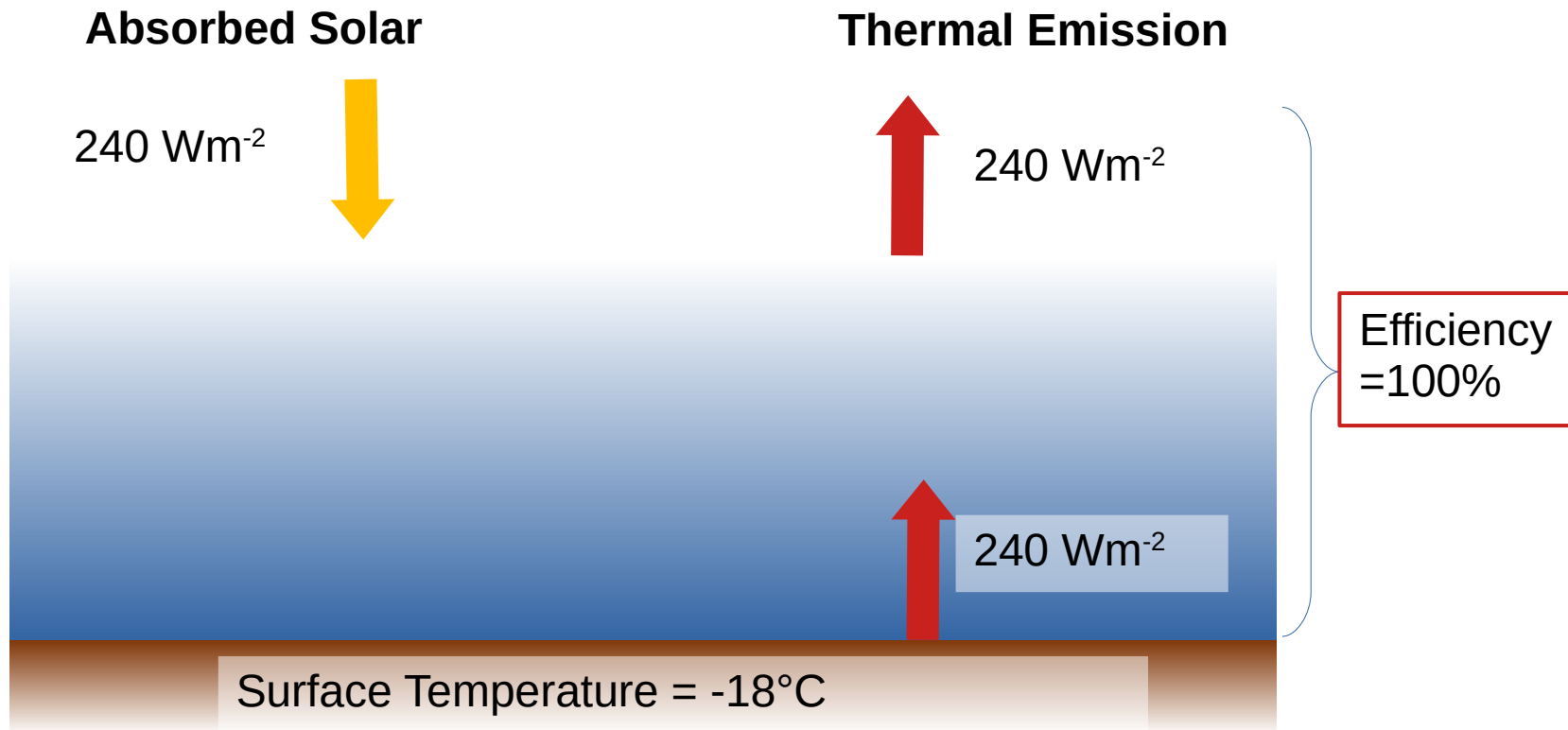
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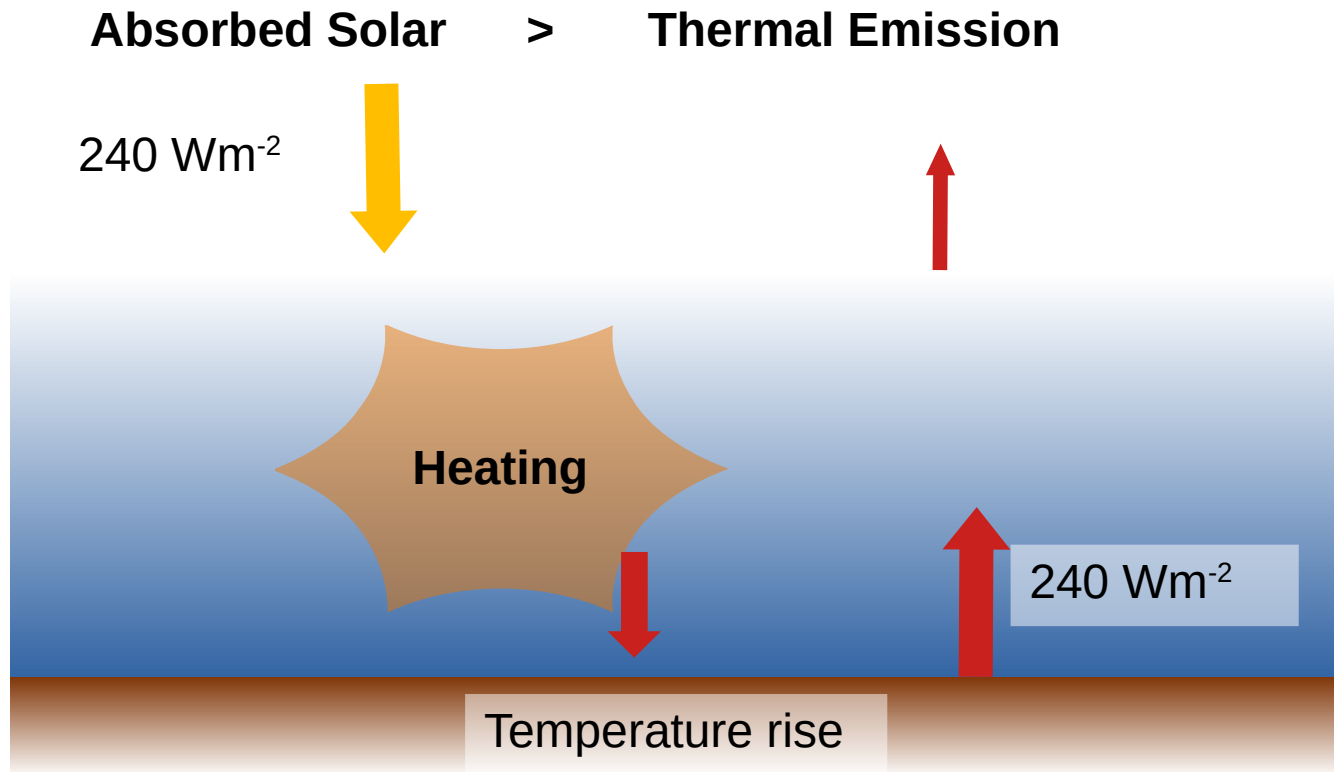
EARTH'S GLOBAL AVERAGE ENERGY BALANCE: NO ATMOSPHERE



$$S_0 \sim 1366 \text{ Wm}^{-2}$$
$$\alpha \sim 0.3$$

$$\frac{S_0}{4}(1 - \alpha) = \sigma T_e^4$$

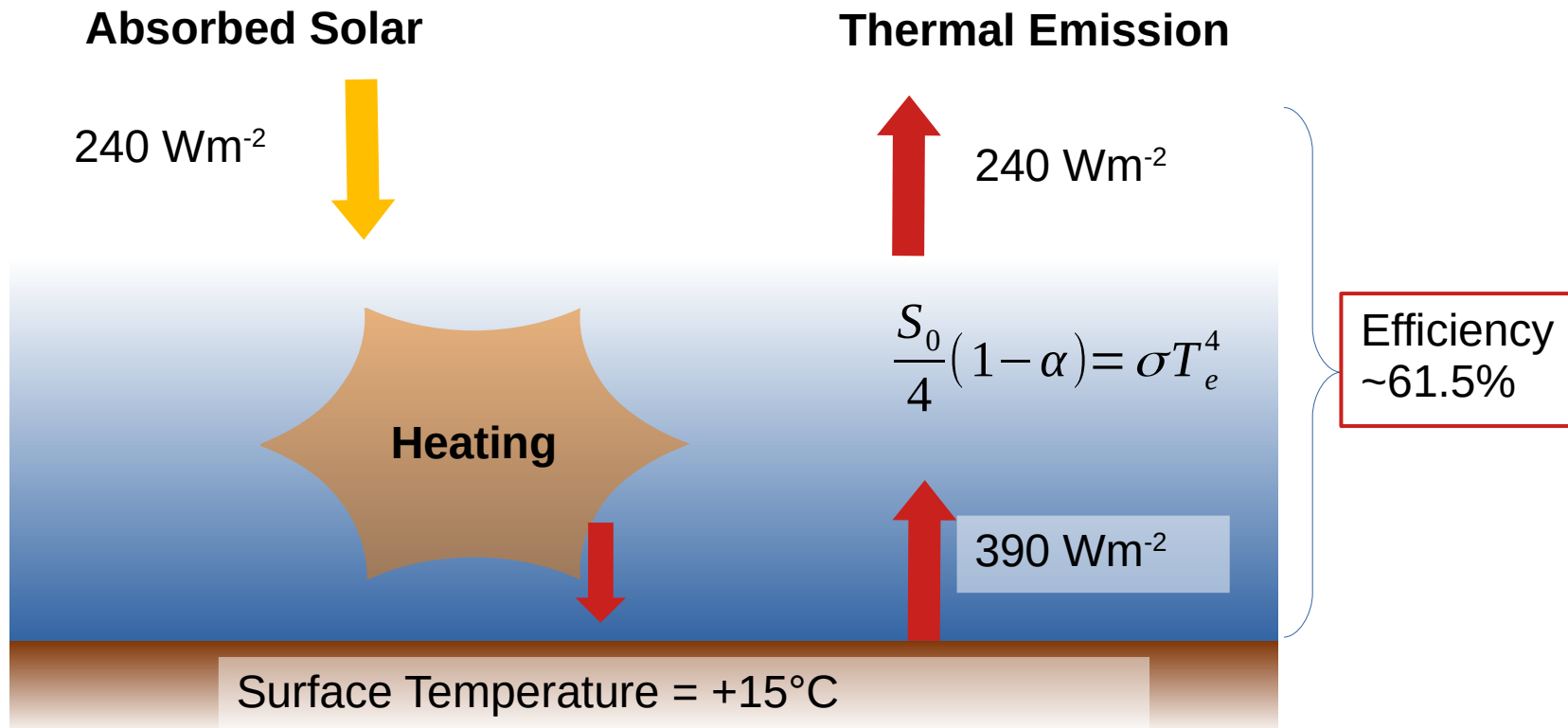
EARTH'S GLOBAL AVERAGE ENERGY BALANCE: ADD ATMOSPHERE



$$S_0 \sim 1366 \text{ Wm}^{-2}$$
$$\alpha \sim 0.3$$

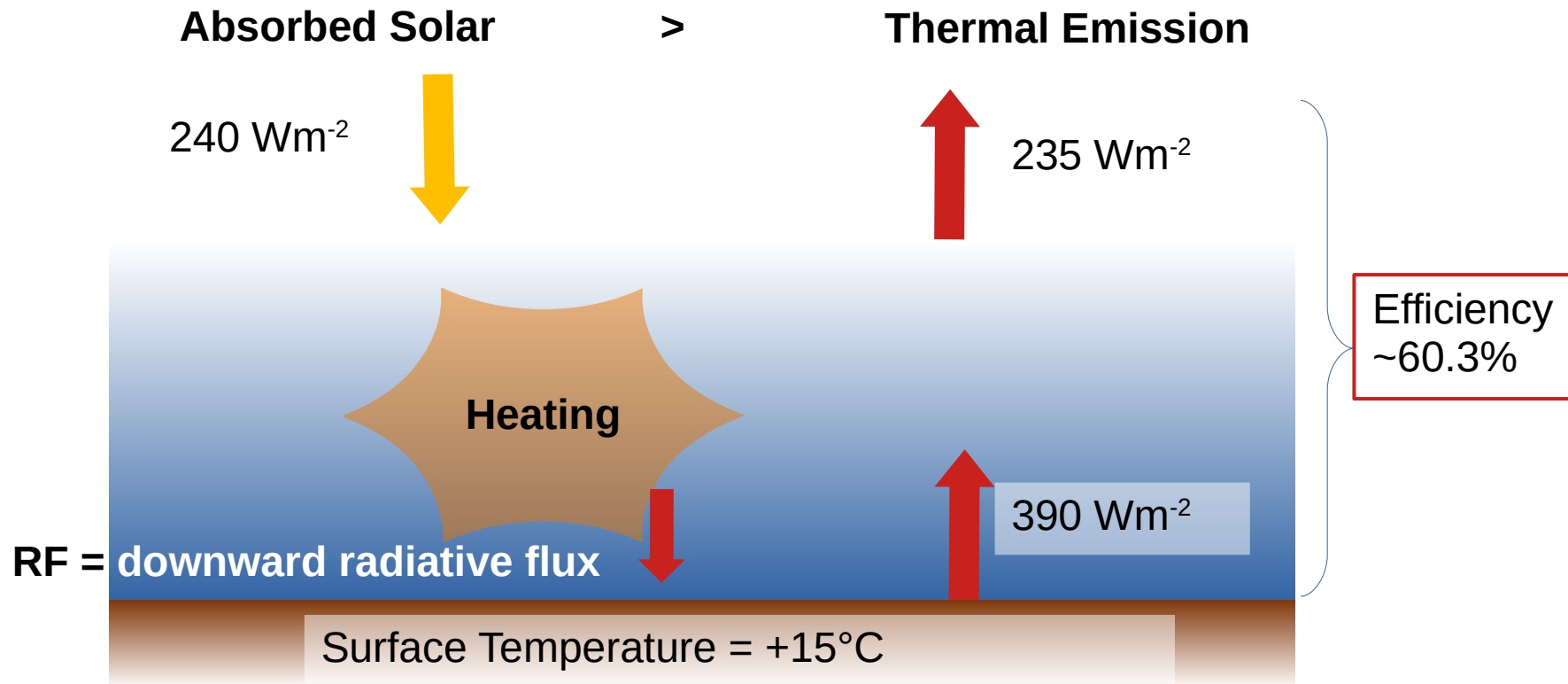
$$\frac{S_0}{4}(1 - \alpha) \neq \sigma T_e^4$$

EARTH'S GLOBAL AVERAGE ENERGY BALANCE: PRESENT DAY



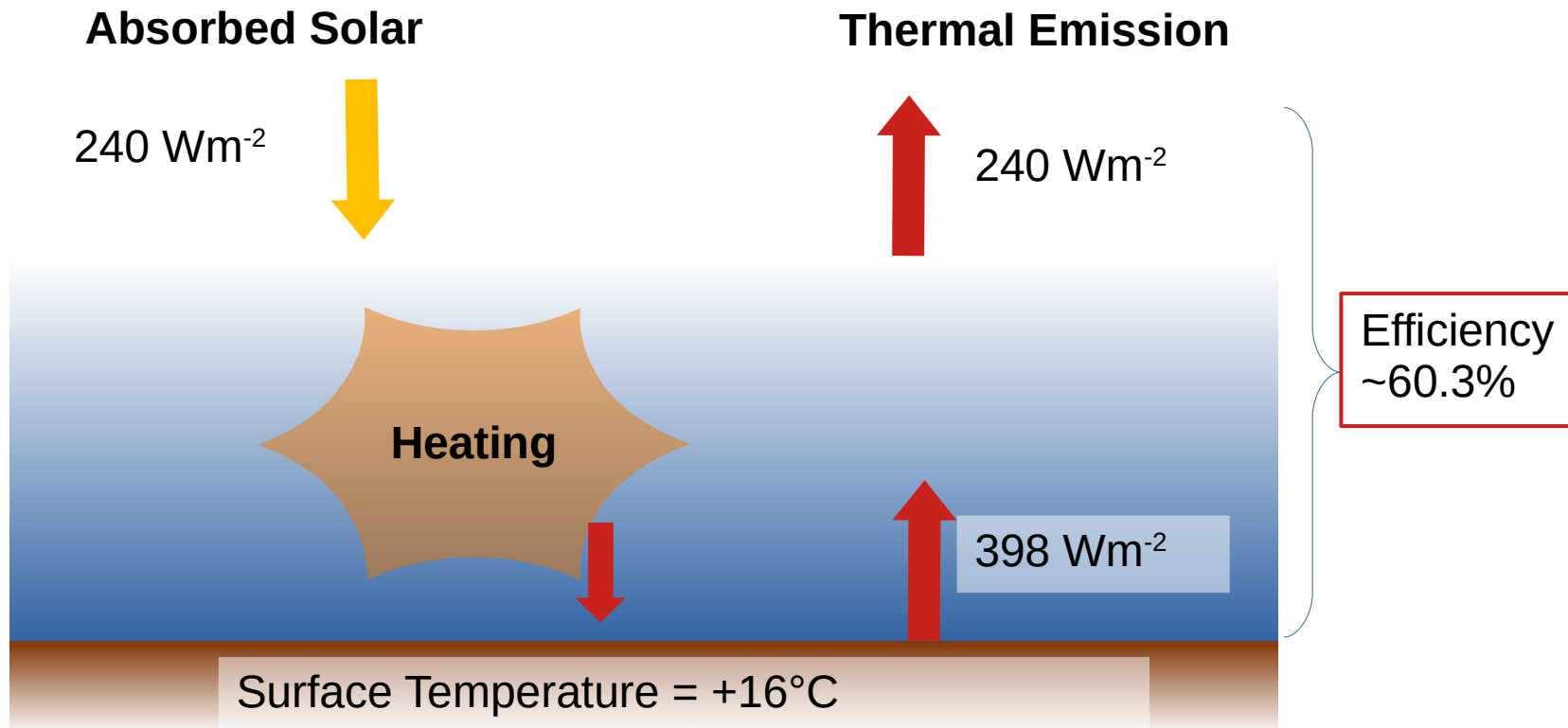
Radiating Efficiency, or the inverse of the Greenhouse Effect, is strongly determined by water vapour absorption across the electromagnetic spectrum.

NOW INTRODUCE AN ADDITIONAL RADIATIVE FORCING (RF, E.G. 2XCO₂)



Radiating Efficiency, or the inverse of the Greenhouse Effect, is strongly determined by water vapour absorption across the electromagnetic spectrum.

NEW GLOBAL TEMPERATURE



The **2xCO₂** increased temperature by about **1°C** but this is without considering the response of the system including, crucially, feedbacks involving water vapor.

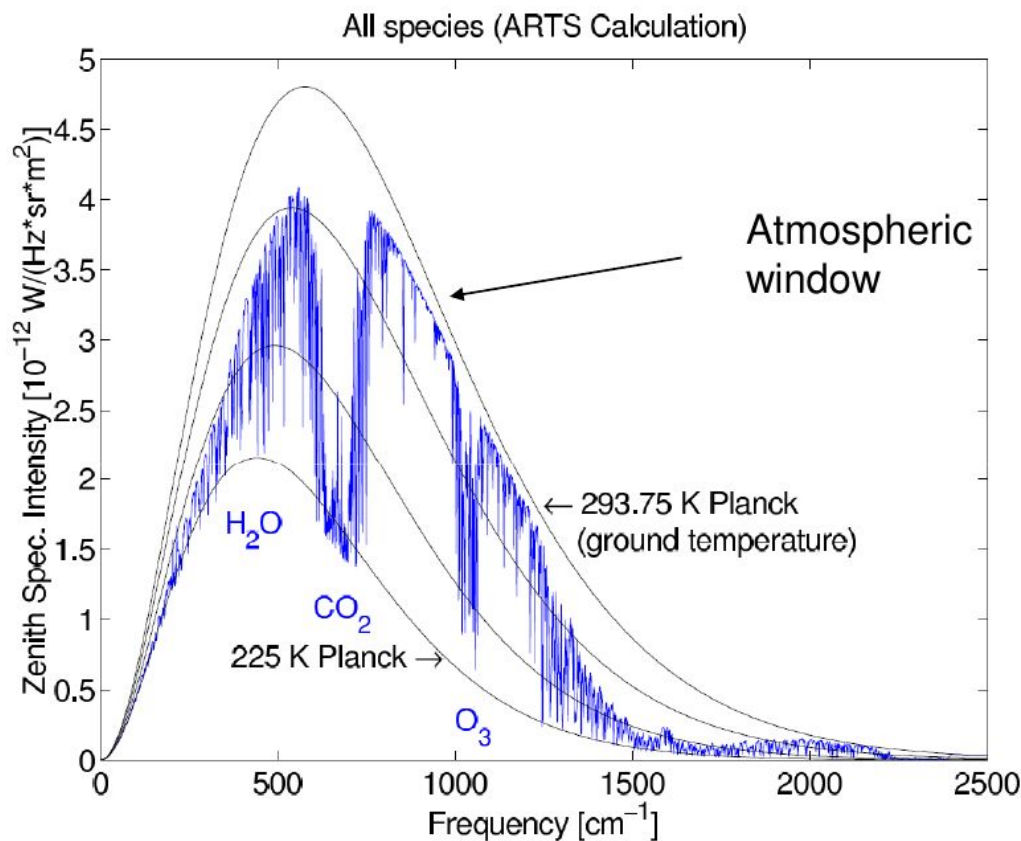
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THE GREENHOUSE EFFECT



- Greenhouse gases effectively reduce the efficiency of Earth's ability to cool through thermal radiative emission to space
- To balance the absorbed solar radiation, Earth's temperature has to be sufficient to combat this radiating inefficiency to generate the necessary outgoing longwave radiation

Simple model to simulate Greenhouse effect:
<http://climatemodels.uchicago.edu/modtran/>

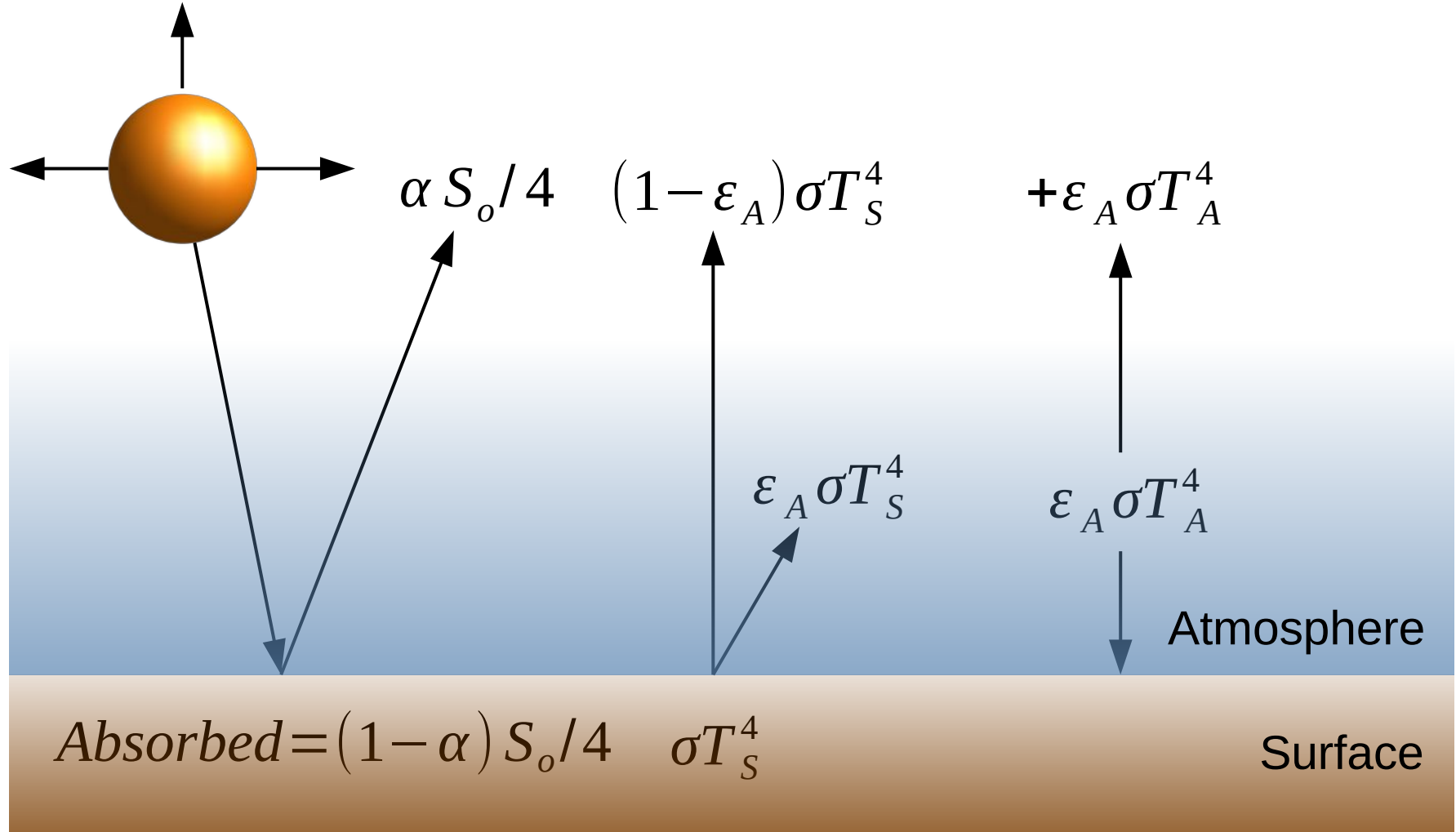
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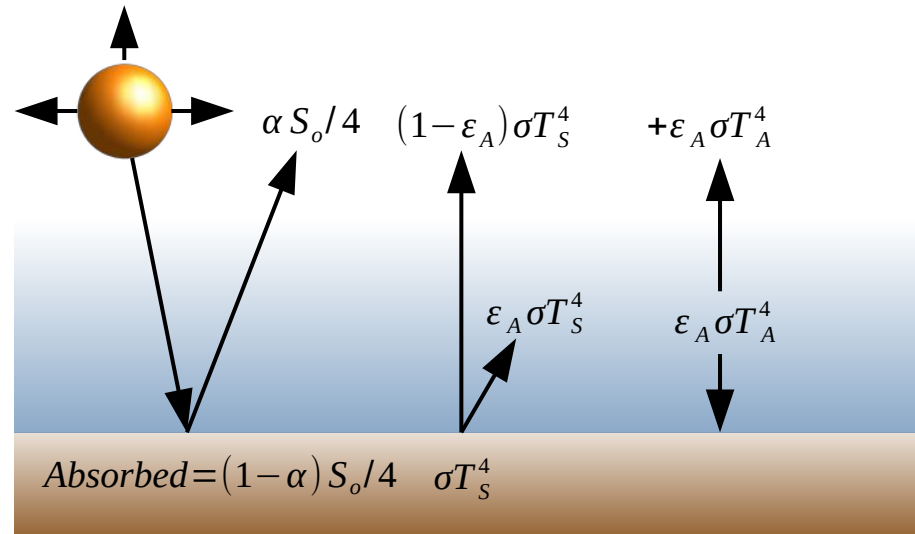
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SIMPLE ENERGY BALANCE MODEL



$$S_o = 1366 \text{ W m}^{-2}; \alpha = 0.3; \epsilon_A = 0.8; \sigma = 5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$$

SIMPLE ENERGY BALANCE MODEL



If $\sigma T_{eff}^4 = (1-\alpha)S_o/4$ then $T_{eff} \approx 255 K$

Consider equilibrium of the atmosphere and then of the surface;

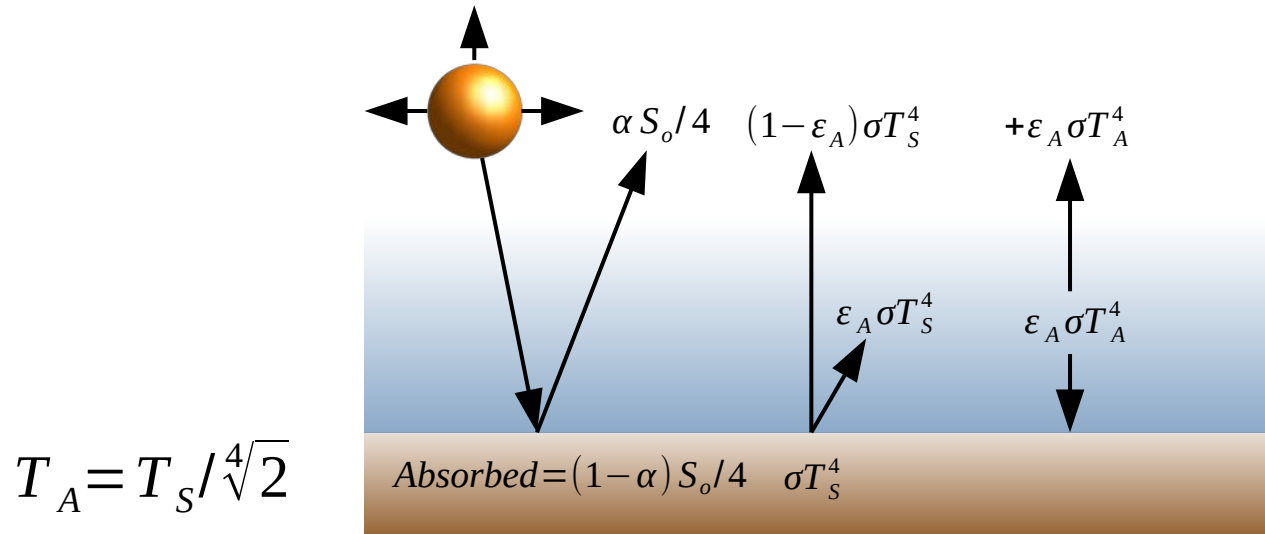
$$\epsilon_A \sigma T_S^4 = 2 \epsilon_A \sigma T_A^4$$

(2)

$$(1-\alpha)S_o/4 + \epsilon_A \sigma T_A^4 = \sigma T_S^4$$

$$\sigma T_S^4 = ((1-\alpha)S_o/4)/(1-\epsilon_A/2) \quad \text{and} \quad T_A = T_S/\sqrt[4]{2}$$

SIMPLE ENERGY BALANCE MODEL



Note that T_s is larger than T_{eff} , because of the additional downward thermal emission from the atmosphere. So, the greenhouse effect ensures that the surface is warmer with an atmosphere than without.

Secondly, the atmosphere is colder than the surface and slightly colder than T_{eff} .

If we assume that $\alpha = 0.3$ and $\epsilon_A = 0.8$ then we find that;

$$T_s = 289 \text{ K}$$

$$T_A = 243 \text{ K}$$

Which are reasonable values for the global mean surface and atmospheric temperatures.

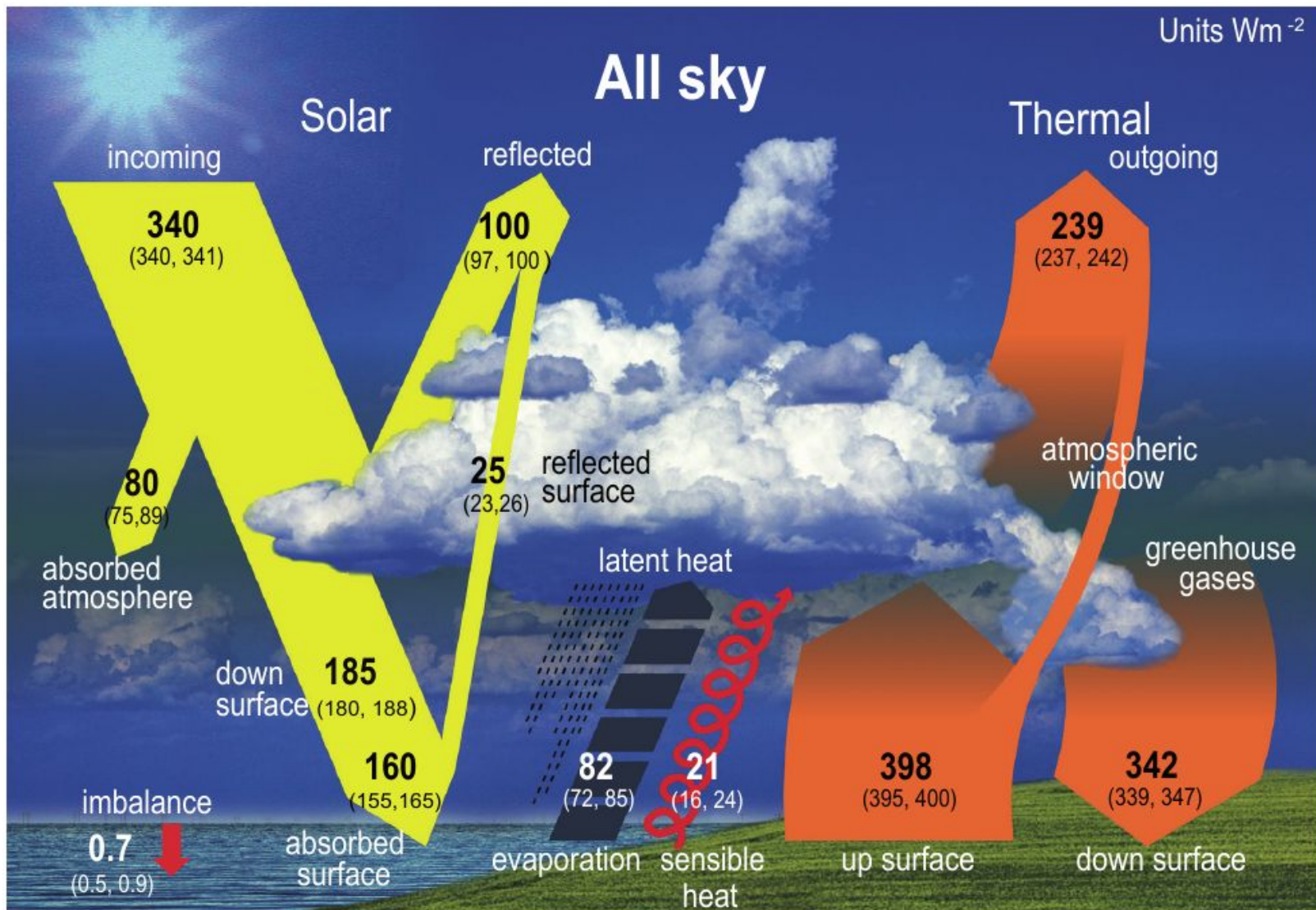
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GLOBAL ENERGY FLOWS

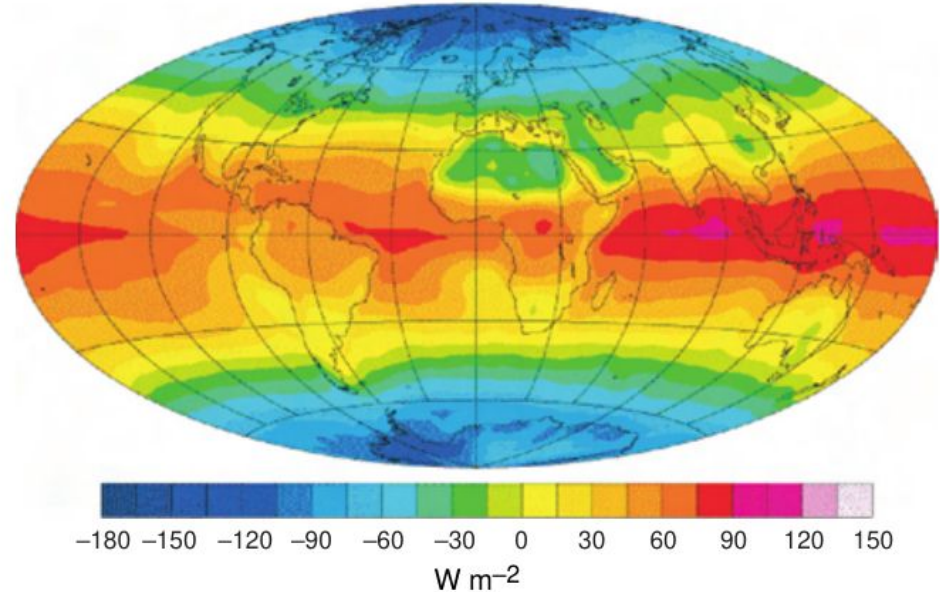
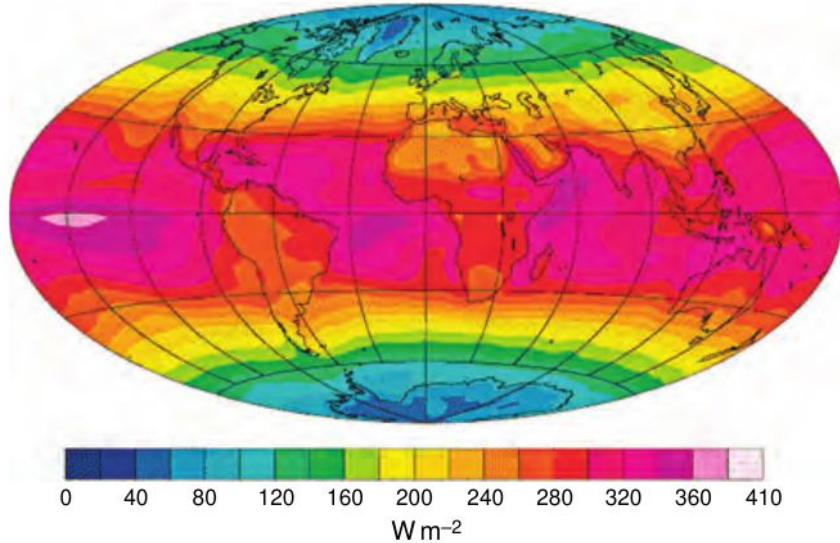


IPCC 21, All values in W/m^2 +
uncertainty ranges (5-95%)

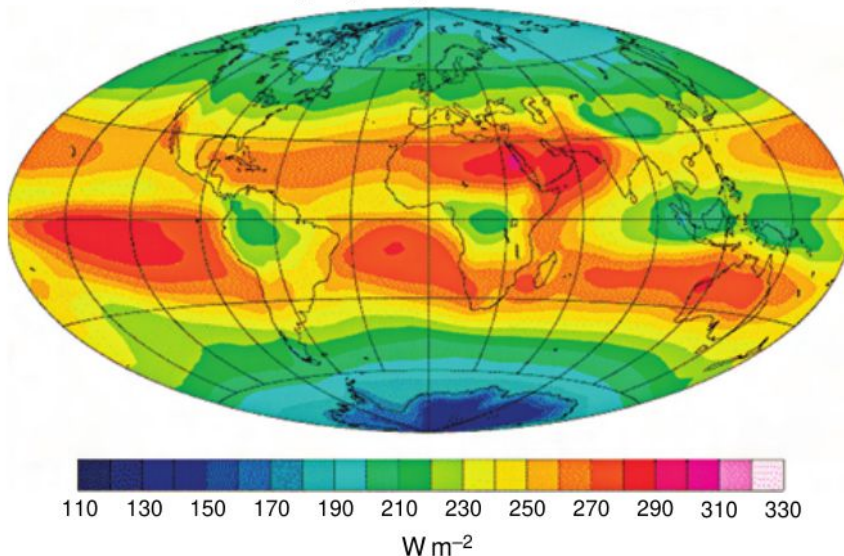
RADIATION BALANCE AT THE TOA

Net Radiation Wallace & Hobbs

Absorbed Solar Radiation



Outgoing Longwave Radiation



Global distribution of the net imbalance between the annual-mean net incoming solar radiation and the outgoing longwave radiation. Positive values indicate a downward flux. [NASA Earth Radiation Budget Exp.]

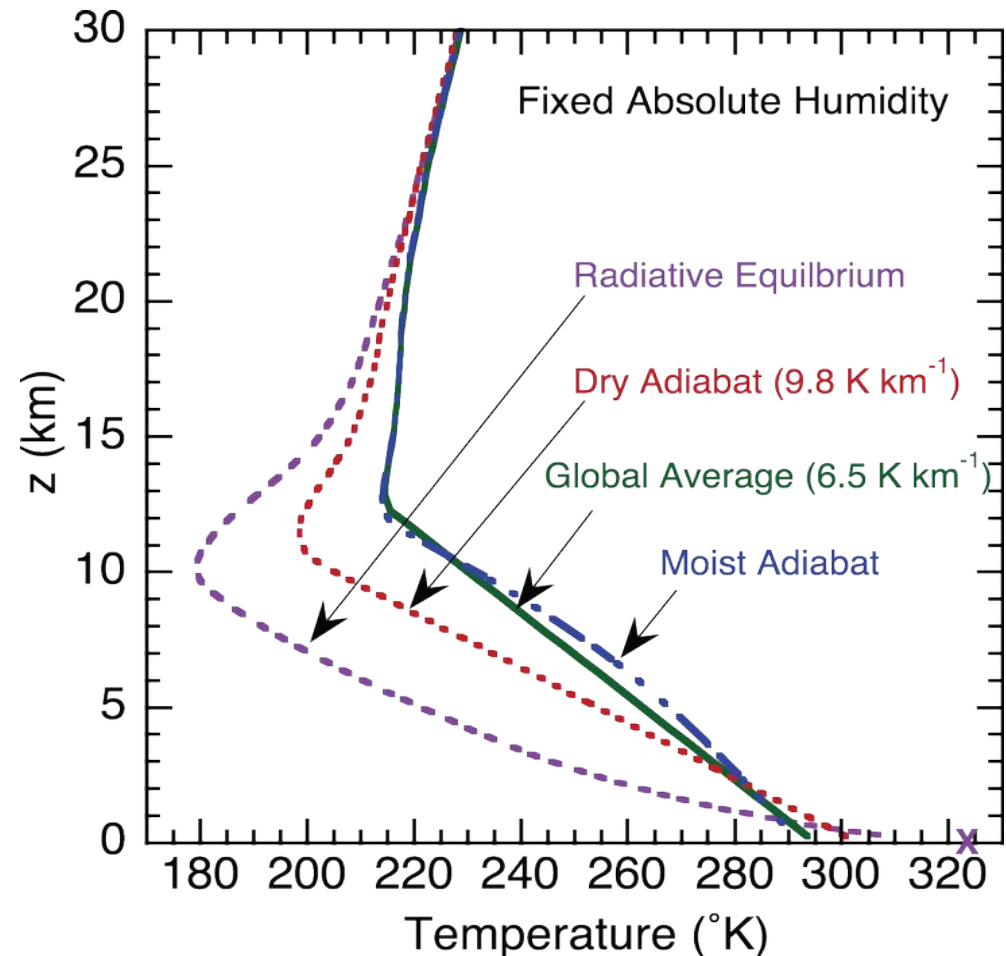
Tropics and monsoon regions reveals a strong greenhouse effect: clouds and water vapor.

RADIATIVE-CONVECTIVE EQUILIBRIUM

If we assume that only radiative processes are operating, the equilibrium surface temperature is very high, tropospheric temperatures very low and the profile is strongly superadiabatic (**rad. eq**).

In reality, convection removes heat from the surface, warms the atmosphere and adjusts the lapse-rate towards that observed (**glob avg.**).

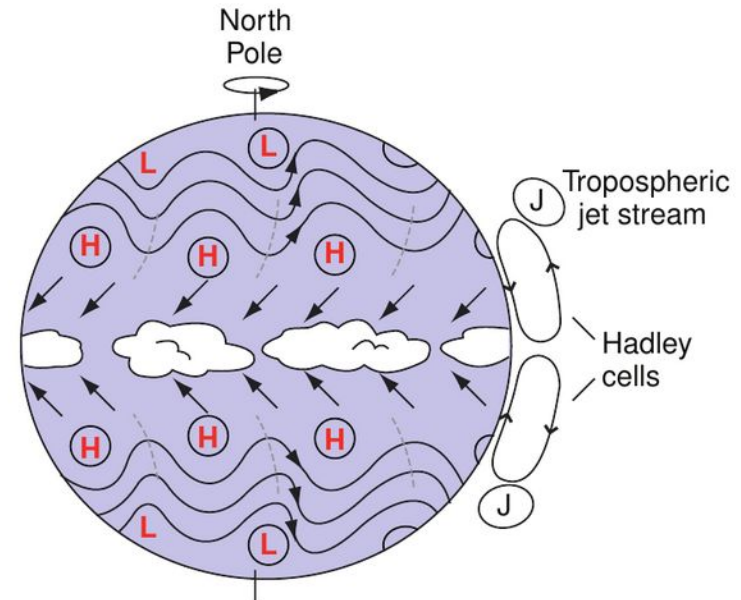
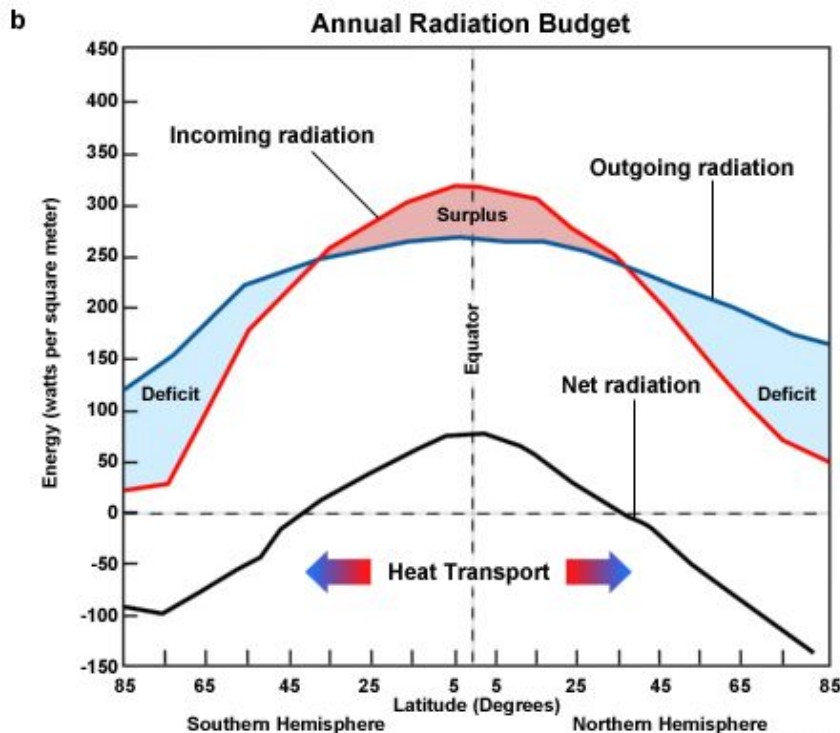
Manabe and Wetherald, JAS, 1967



GLOBAL ENERGY FLOWS

Radiative-convective equilibrium is not the whole story, because the Earth is a sphere that is heated non-uniformly.

Radiative imbalances between the surface and the atmosphere, and between the tropics and polar regions, together with the planet's rotation, drive convection and the general circulations of the atmosphere and oceans.



Wallace & Hobbs

SUBTOPICS

5. Water and climate feedback (I)

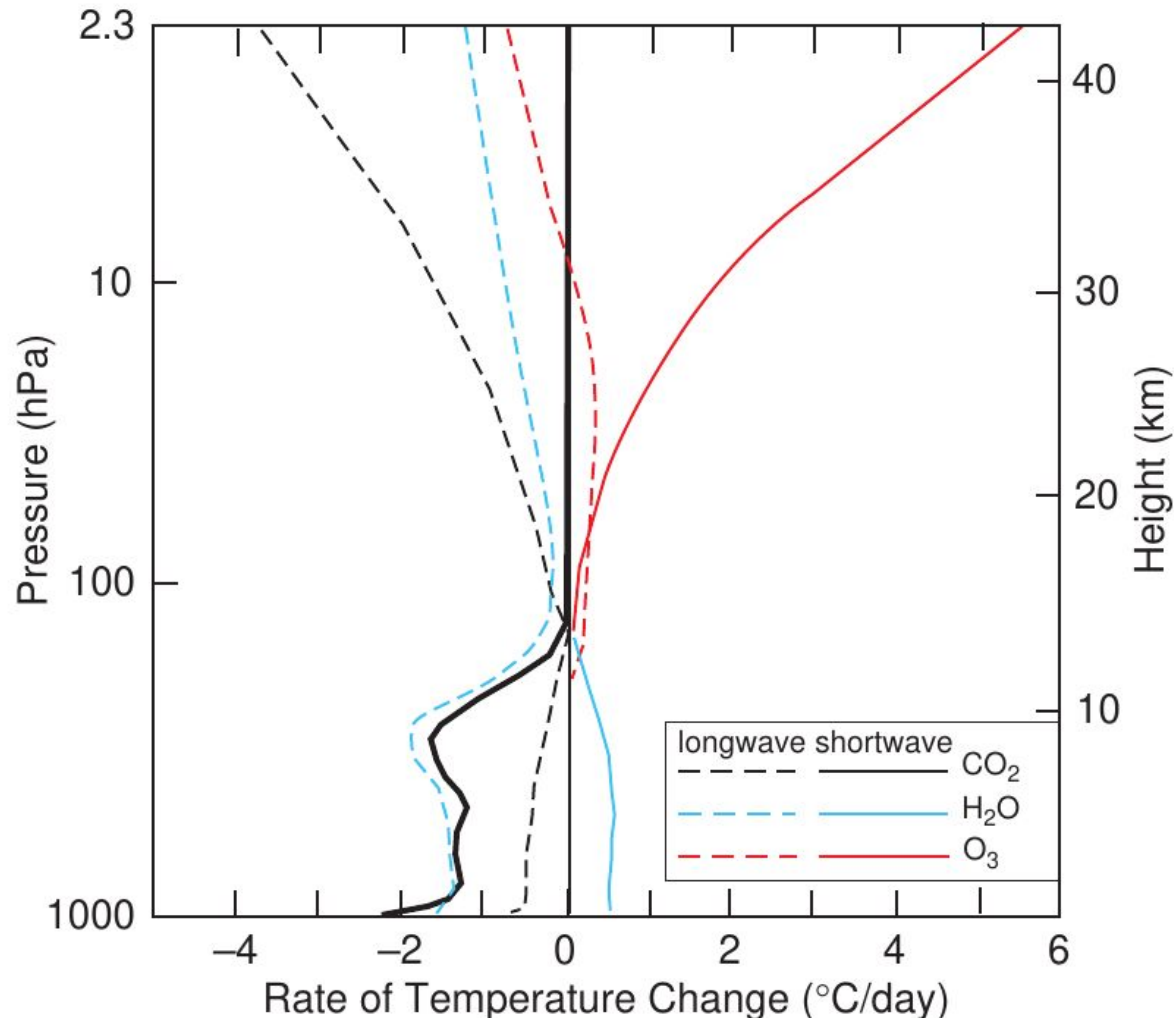
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LOCAL VERTICAL RADIATIVE FORCING

Vertical profiles of the time rate of change of temperature due to the absorption of solar radiation (solid curves) and the transfer of infrared radiation (dashed curves) by **water vapor** (blue), **carbon dioxide** (black), and **ozone** (red). The heavy black solid curve represents the combined effects of the three gases.

Troposphere cools radiatively. H_2O plays a central role in it. This cooling destabilizes the troposphere hence lead to **convective adjustment**.

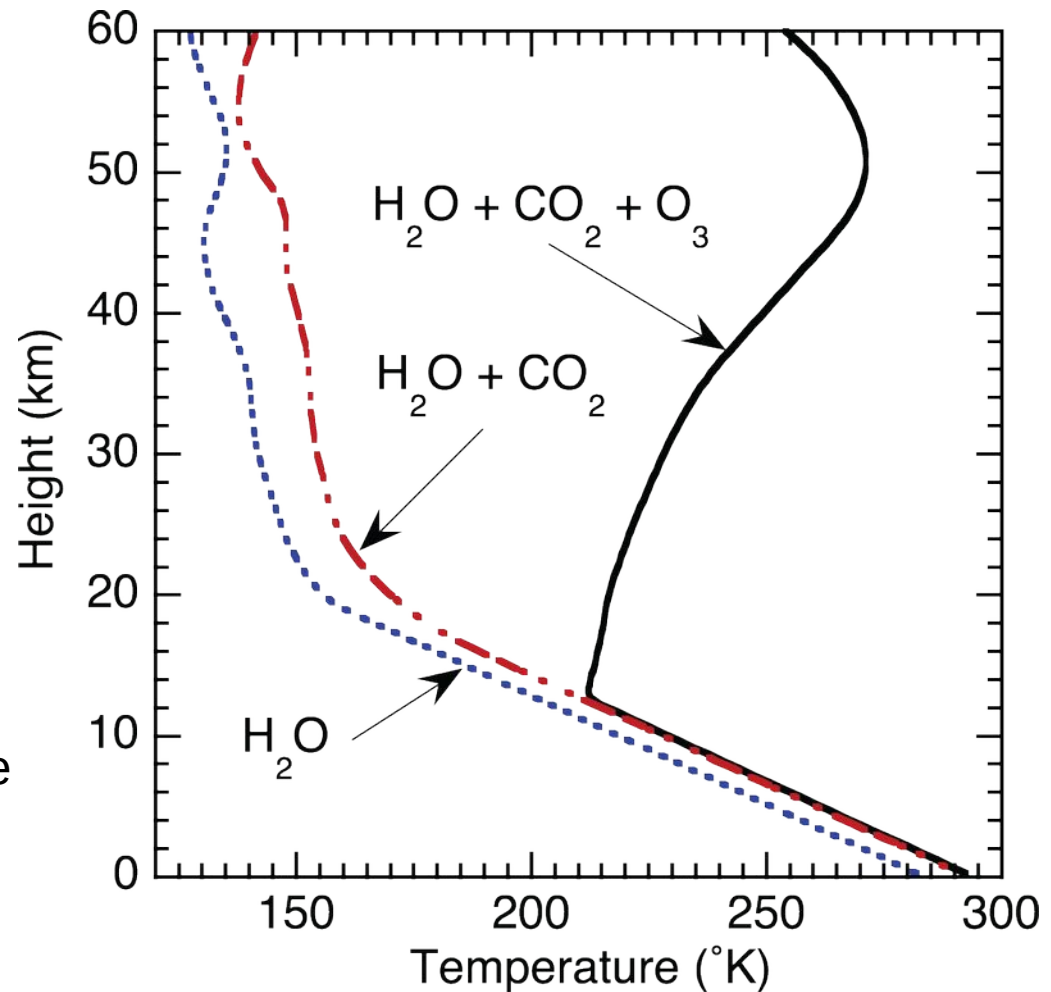


Adapted from S. Manabe
and R. F. Strickler,
J. Atmos. Sci., 21, p. 373 (1964).

RELATIVE CONTRIBUTION FROM VARIOUS ABSORBERS (STRATOSPHERE)

- All profiles show clear sky radiative convective equilibrium
- **H₂O only:**
realistic troposphere, Stratosphere not present
- **H₂O + CO₂:**
T increase of approx. 10 K everywhere
- **H₂O + CO₂ + O₃:**
Sharp tropopause and T increase in the stratosphere due to absorption of solar radiation

(Manabe and Wetherald, JAS, 1967)

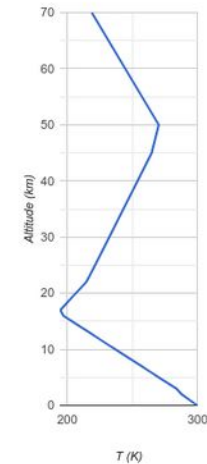
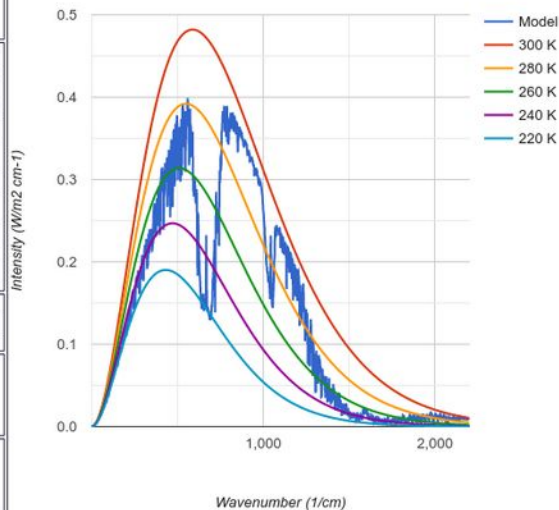


RADIATIVE TRANSFER MODEL SIMULATIONS

Clear sky!

MODTRAN Infrared Light in the Atmosphere

Model Input	
CO ₂ (ppm)	400
CH ₄ (ppm)	1.7
Trop. Ozone (ppb)	28
Strat. Ozone scale	1
Water Vapor Scale	1
Freon Scale	1
Temperature Offset, C	0
Locality	Tropical Atmosphere
	No Clouds or Rain
Altitude (km)	70
	Looking down
Save This Run to Background	
Show Raw Model Output	
Model Output	
Upward IR Heat Flux 298.52 W/m²	
Ground Temperature 299.7 K	
Spectrum expanded 5-11-17, changing the IR out value.	



<http://climatemodels.uchicago.edu/modtran/>

SUBTOPICS

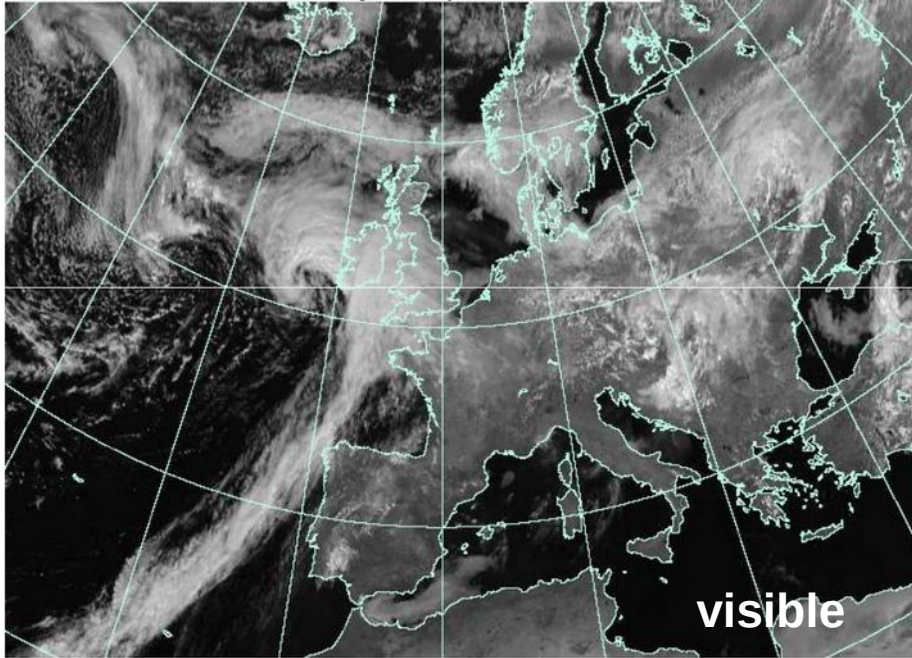
5. Water and climate feedback (I)

General radiation processes

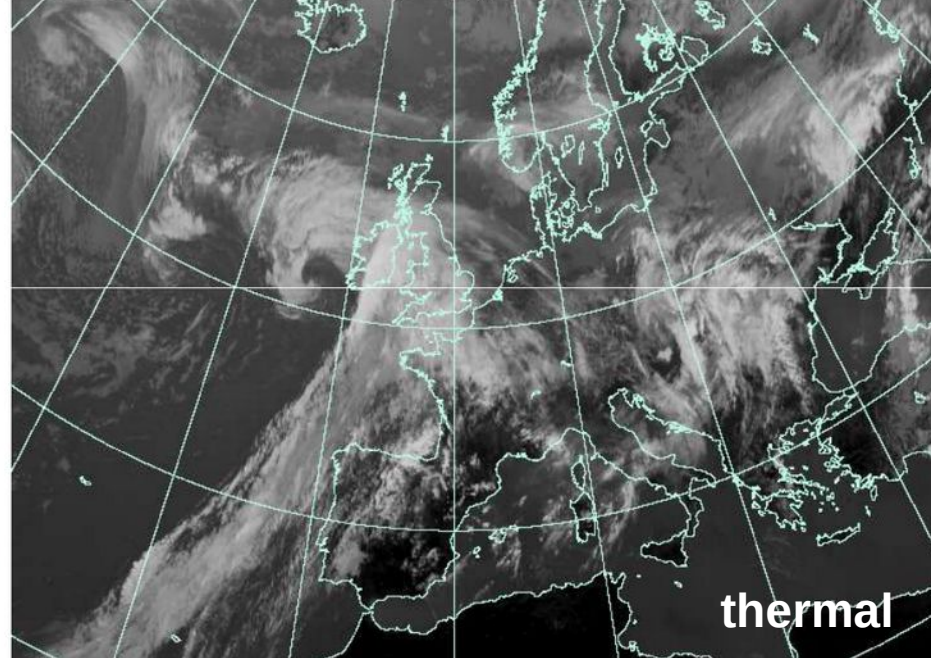
- Basic laws for radiation (Planck and Boltzmann)
- Earth Radiation balance
- Gaseous absorption of water vapor
(Line broadening, water vapor continuum)
- Absorption spectra of the atmosphere
- Earth Radiation balance with atmosphere
 - Greenhouse effect
 - Simple Energy Balance Model
- Global energy flows
- Radiative forcing
- **Cloud radiative forcing**

CLOUD EFFECT – RADIATIVE IMPACT

EVEH31 MSG 0.8 micron Visible Image 17 May 2006 1200 UTC

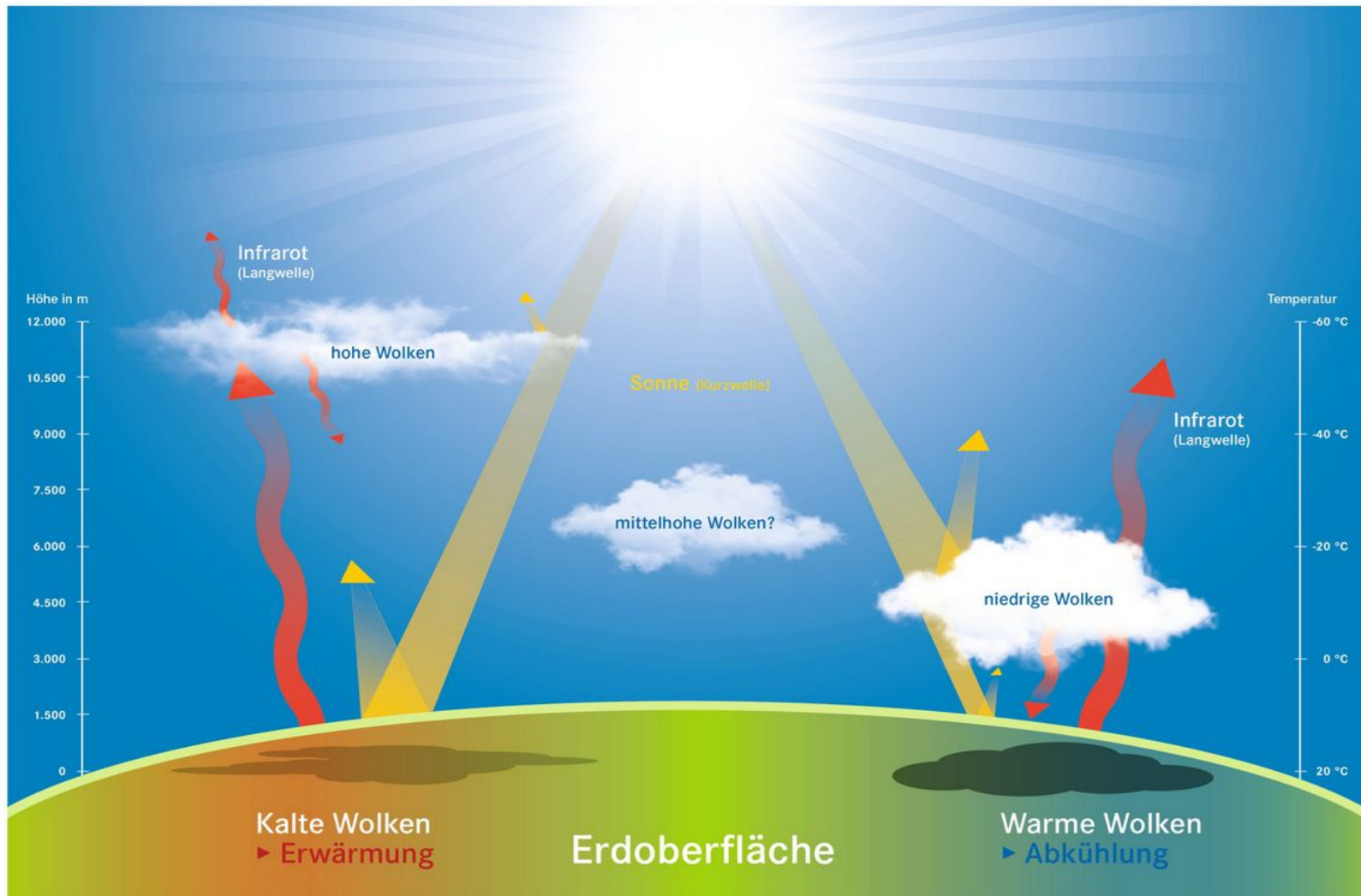


EIEH51 MSG 10.8 micron Infrared Image 17 May 2006 1200 UTC



- Most of the water in the atmosphere is invisible vapor (Clouds are only a small fraction)
- Clouds exhibit strong interaction with longwave and shortwave radiation (emission, absorption, scattering)
- Many types of cloud feedbacks are plausible!

CLOUD EFFECT – RADIATIVE IMPACT

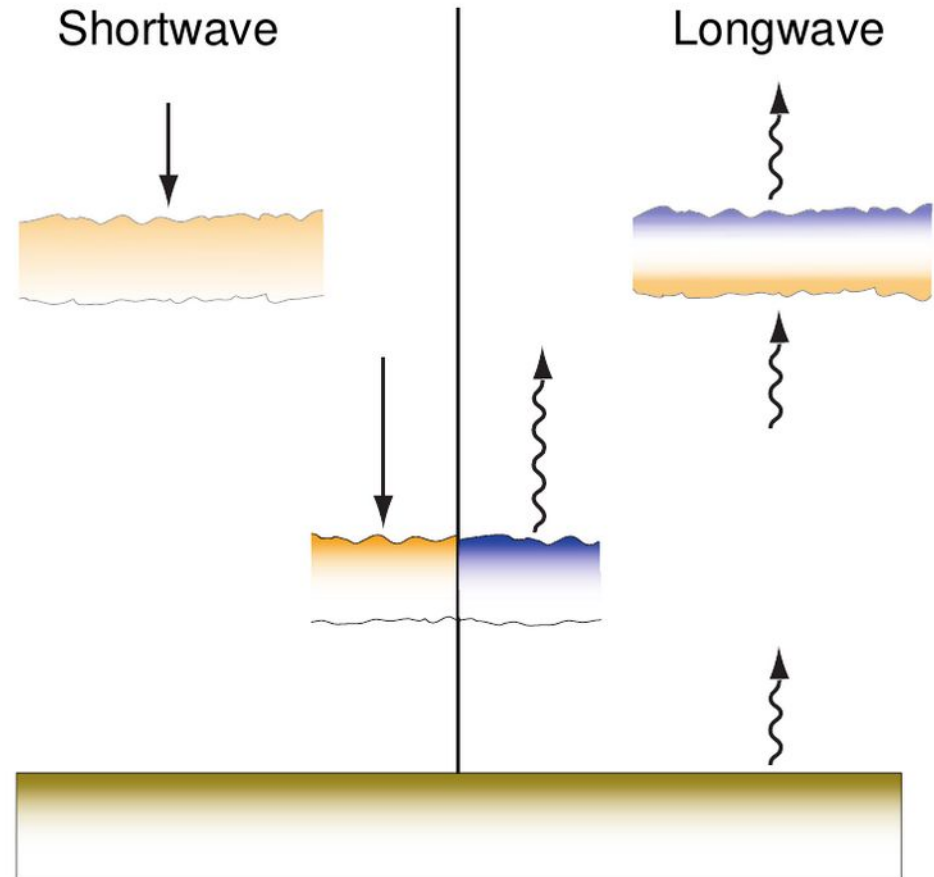


CLOUD RADIATIVE FORCING

Schematic of vertical profiles of heating in cloud layers at various heights in the atmosphere as indicated.

Orange shading indicates **warming** and **blue** shading indicates **cooling**.

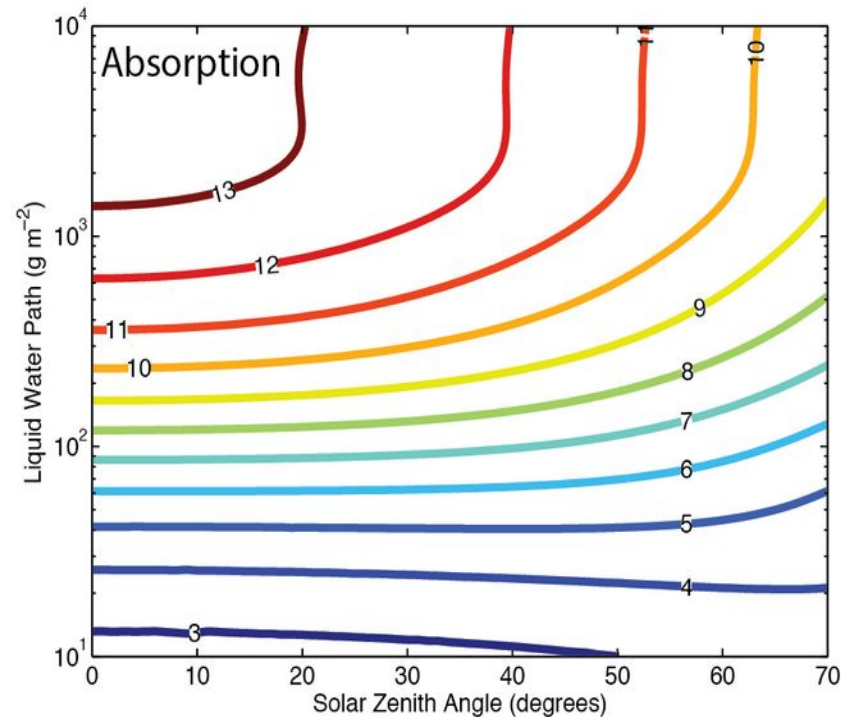
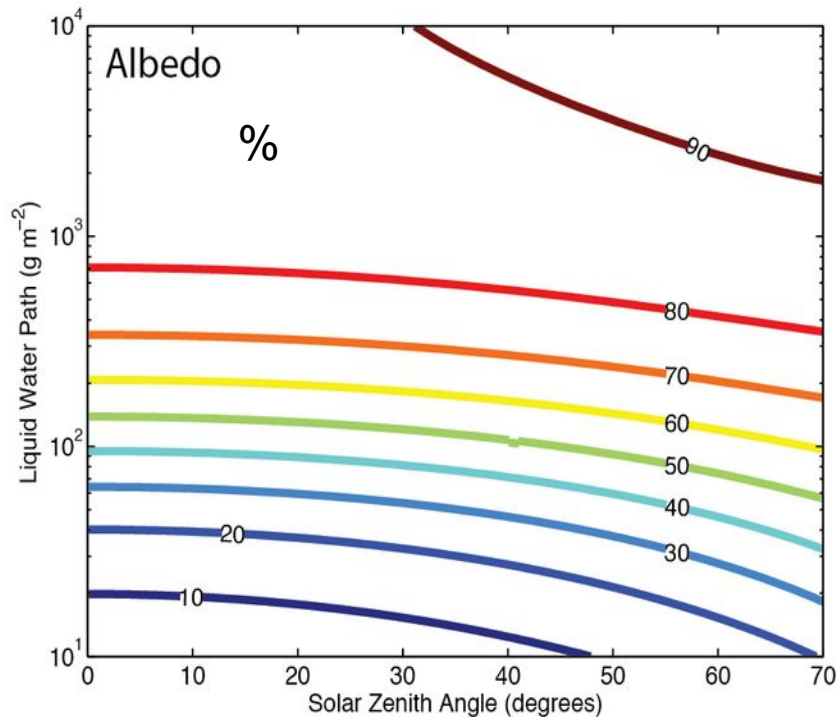
Effects of shortwave radiation are represented on the left, and effects of longwave radiation on the right.



Wallace & Hobbs

CLOUD RADIATIVE FORCING

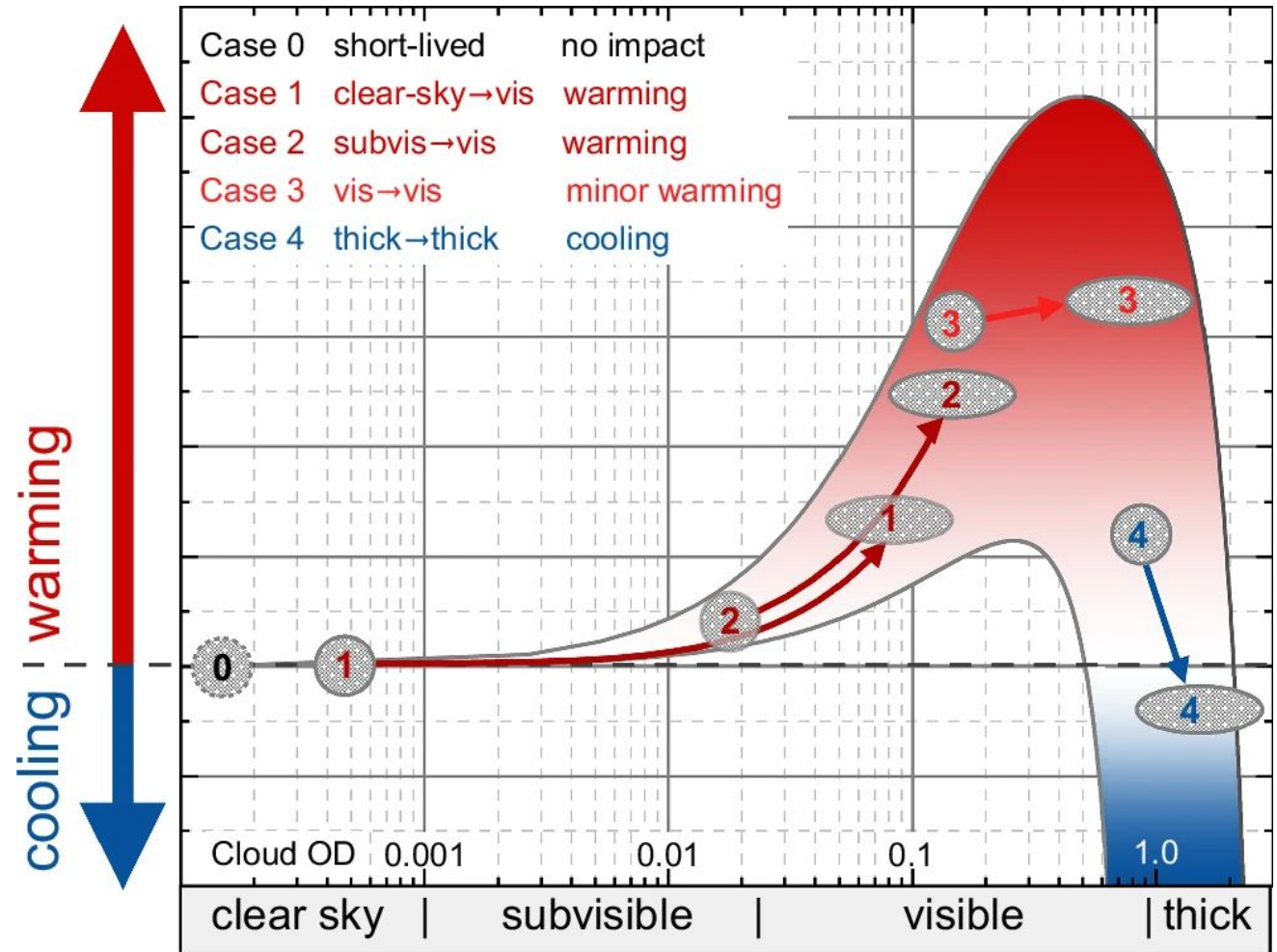
- Dependence on albedo and absorption of total water and zenith angle



- Sun at zenith: Albedo and absorption increase with water content.
- Sun lower above the horizon: Increase in albedo stronger, increase in absorption weaker. Reason: Flatter incident radiation remains in the cloud for a shorter time, reducing the chance of being absorbed.

ICE CLOUD RADIATIVE FORCING

Ice clouds can also have a warming effect when they are high up in the atmosphere at cold temperatures and have a thin optical thickness.



Petzold et al. 2025

SUBTOPICS

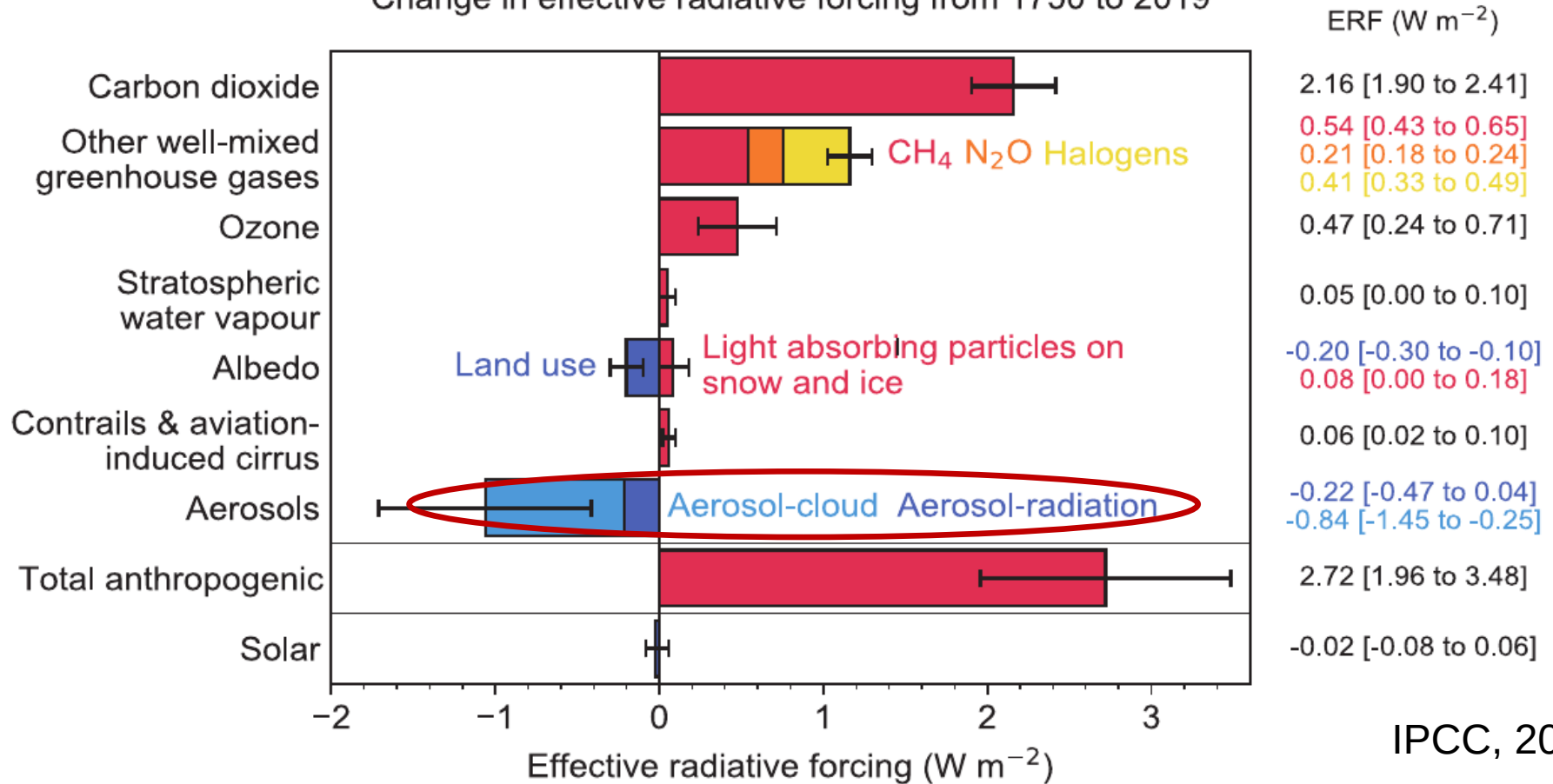
5. Water and climate feedback (II)

Climate feedbacks with focus on water feedback

- **Climate feedbacks (direct and indirect effects)**
- Climate sensitivity and relation to climate feedbacks
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RADIATIVE FORCING

Change in effective radiative forcing from 1750 to 2019



All cloud types and many indirect effects included:

- ❖ But **clouds are still the largest uncertainty** in climate prediction
- ❖ Ice cloud are particularly poor represented

CLIMATE FEEDBACKS

- **Direct effects** are associated with a release of Greenhouse gases and instantaneous change of radiative forcing (RF). **Indirect effects** are the result of such a heating and add an additional RF (feedback).
- These feedback processes can amplify (**positive feedback**) or damp (**negative feedback**) an initial perturbation:
 - **Radiative feedback** (Stefan-Boltzmann)
If Temperature increases then the loss of energy through radiation increases : **very strong negative feedback**
 - **Ice albedo feedback**
If Temperature increases then the ice cover decreases hence the absorbed solar incoming radiation and the temperature increases:
Positive feedback
 - **Cloud feedback**
If Temperature increases and induced more clouds, more albedo then temperature decreases. But the greenhouse effect of clouds temperature increases: **slightly positive (most unclear)**

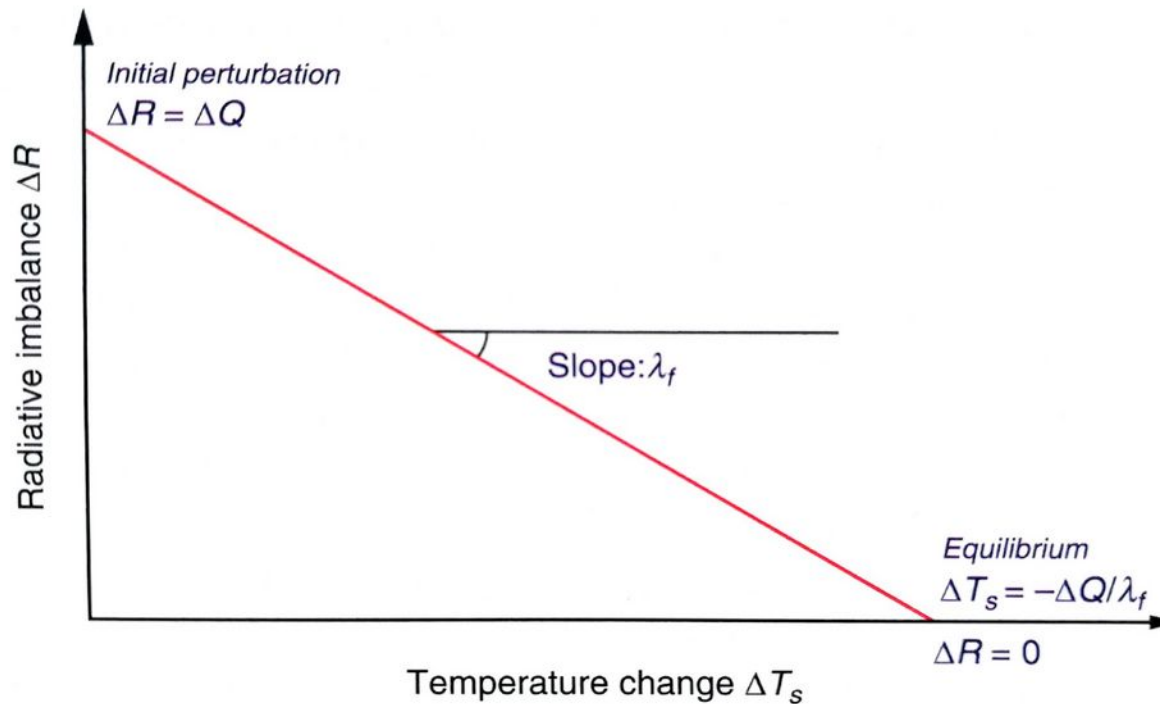
SUBTOPICS

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CLIMATE SENSITIVITY



Goosse, CSDM

$$\Delta R = \Delta Q + \lambda_f \Delta T_s$$

λ_f : climate feedback parameter

ΔQ : Radiative forcing

$$\Delta T_s = \frac{-1}{\lambda_f} \Delta Q$$

$\Delta R = 0$ in new equilibrium

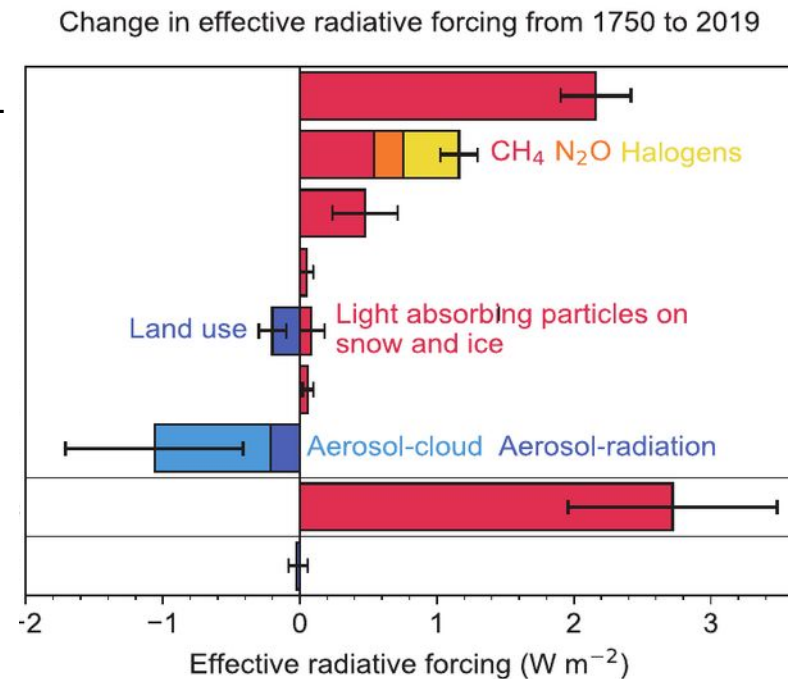
CLIMATE SENSITIVITY

- Total anthropogenic forcing (in 2019 relative to 1750, IPCC 2021) is 2.7 Wm^{-2} . The increase of the globally averaged Earth's surface temperature from IPCC 2021 is $\Delta T = 1.1 \text{ K}$ (2019).

However, we are still far away from the equilibrium. Thus, the corresponding

$\lambda = - (2.7 \text{ Wm}^{-2} / 1.1 \text{ K}) = -0.41 \text{ W m}^{-2} \text{ K}^{-1}$
describes much more the so-called **transient climate sensitivity**
(including all feedbacks).

$$\Delta T_s = -\frac{1}{\lambda_f} \Delta Q$$



CLIMATE FEEDBACK (1)

CLIMATE FEEDBACK (2)

CLIMATE FEEDBACK (2)

CLIMATE FEEDBACK (3)

Water Feedbacks	g_T^n
water	0.6
ice-albedo	0.1
clouds	0,5....-0.1

$-1 < g_T < 0$: negative feedback

$1 > g_T > 0$: positive feedback

$g_T \sim 1$: runaway greenhouse effect

SUBTOPICS

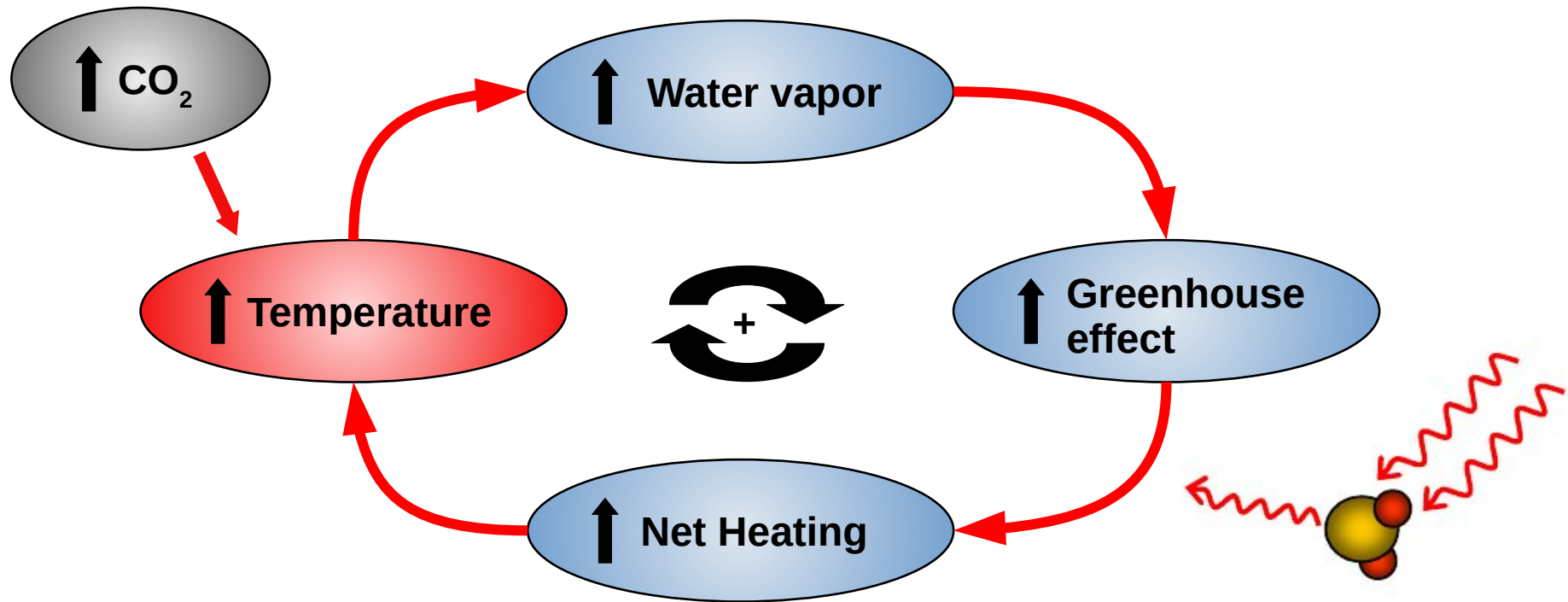
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Climate feedbacks with focus on water feedback

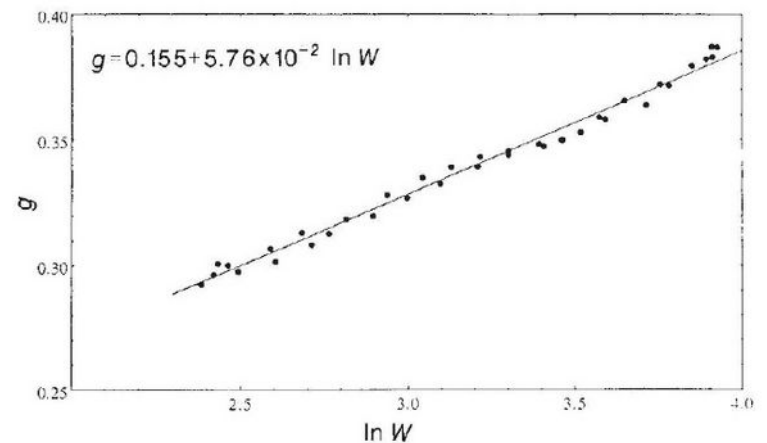
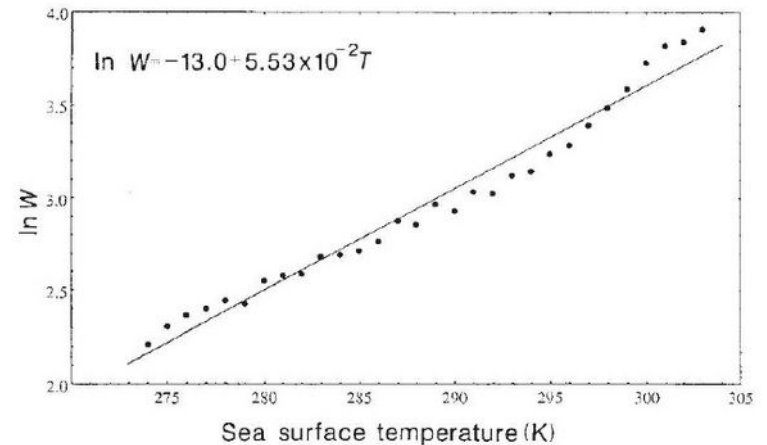
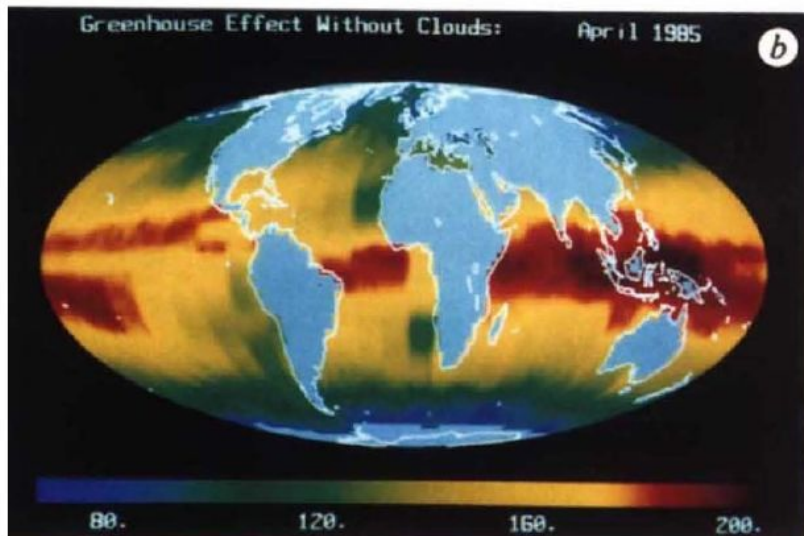
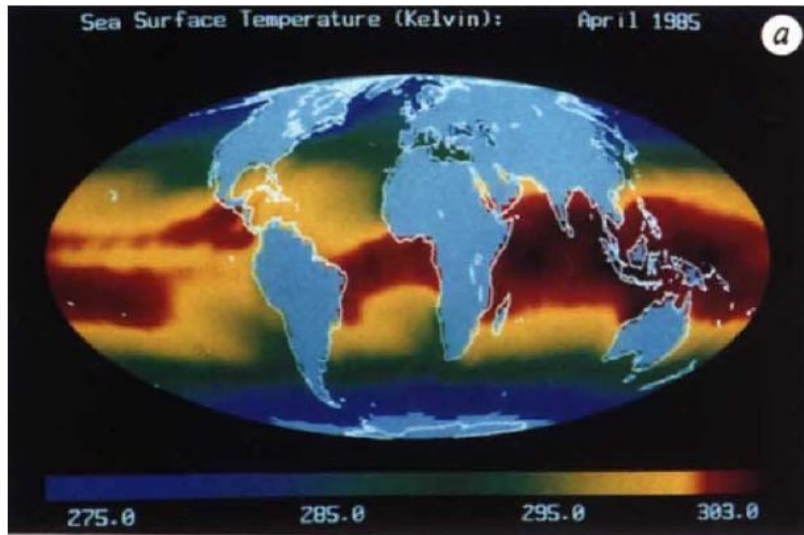
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WATER VAPOR FEEDBACK

- Increase in CO_2 reduced radiative cooling
- Increased Temperature to balance radiative forcing
- The **water vapor** radiative feedback is the **most important feedback** in the Earth climate system and doubles the climate sensitivity.

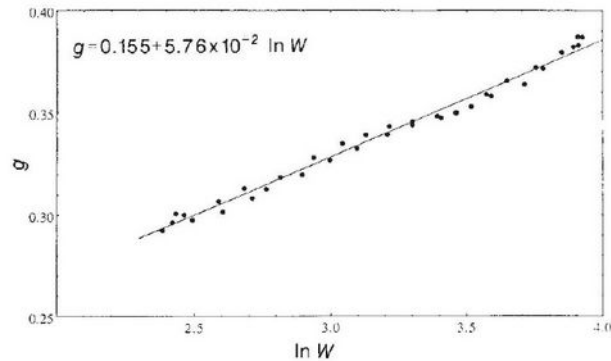


OBSERVATIONAL EVIDENCE FOR THE WATER VAPOR FEEDBACK



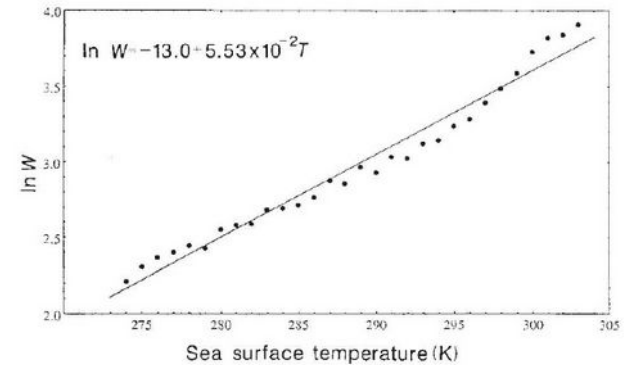
Raval & Ramanathan, Nature, 1989

ESTIMATING WATER VAPOR FEEDBACK



Slope $\sim 0,0576 \ln W^{-1}$

$$\lambda_{WV}^{norm} = \frac{\partial R}{\partial x_{WV}} \frac{\partial x_{WV}}{\partial T_S}$$



Slope $\sim 0,0553 \ln W \text{ K}^{-1}$

$$\lambda_{WV}^{norm} = 3.2 \cdot 10^{-3} \text{ K}^{-1} \quad T_S = 294 \text{ K}$$

$$\lambda_{WV} = \lambda_{WV}^{norm} \sigma T_S^4 = 1.35 \text{ Wm}^{-2} \text{ K}^{-1}$$

$$\lambda_{BB} = -4 \sigma T^3 = -3.2 \text{ Wm}^{-2} \text{ K}^{-1}$$

$$\begin{aligned} \lambda_{WV} + \lambda_{BB} &\sim 1.35 - 3.2 \\ &= -1.85 \text{ Wm}^{-2} \text{ K}^{-1} \end{aligned}$$

2XCO₂ RESPONSE + WATER VAPOR FEEDBACK

$$\Delta Q = \lambda \Delta T_s$$

$$3.7 = -(-3.2 + 1.35) \Delta T_s$$

$$\Delta T_s = 2 \text{ K}$$

So **water vapor feedback** approximately **doubles the feedback temperature** response to doubling of CO₂.

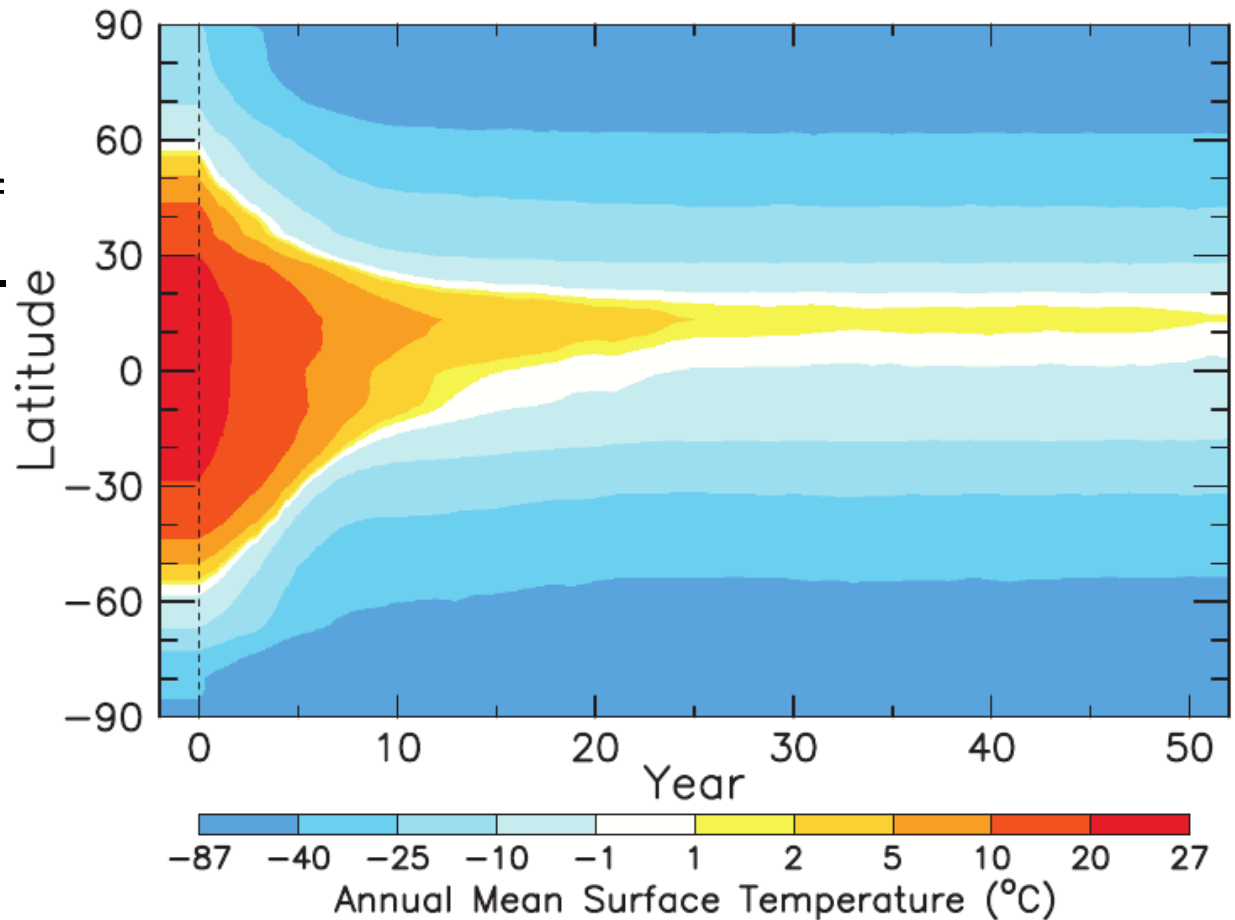
Including feedbacks from temperature lapse rate (negative), ice albedo (positive) and clouds (positive), models produce a best estimate **$\Delta T \sim 3 \text{ K}$**

INVERSE WATER VAPOR FEEDBACK

Zonally averaged annual mean surface temperature change after the zeroing out of noncondensing GHGs.

Cooling of the Earth due to whole water vapor freezes out of the atmosphere.

Snowball Earth, i.e. this final state is comparable with the the Earth about 700 MY ago.



Lacis et al., Science, 2010

SUBTOPICS

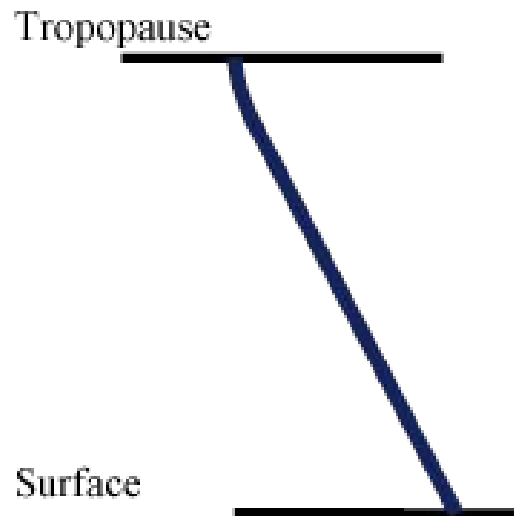
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Climate feedbacks with focus on water feedback

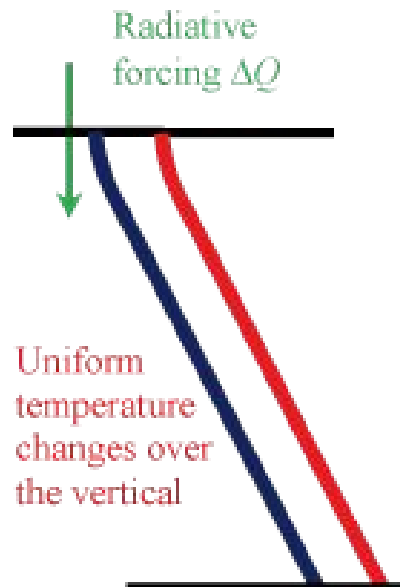
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LAPSE RATE FEEDBACK

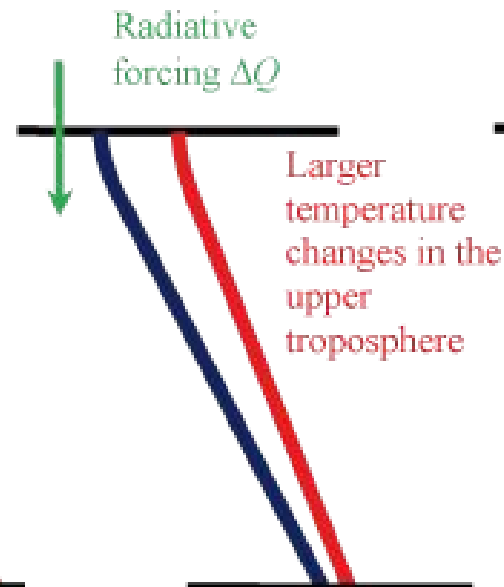
Unperturbed
profile



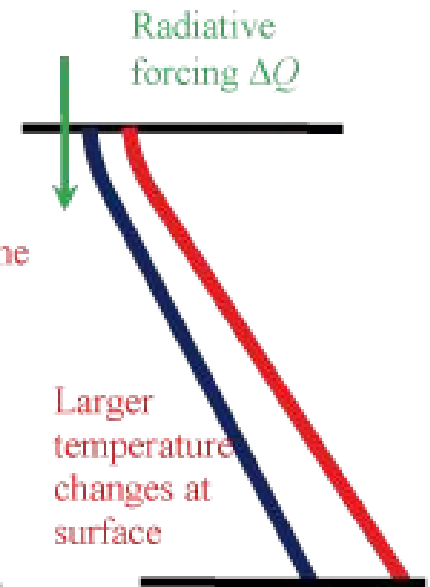
No lapse rate
feedback



Negative lapse
rate feedback

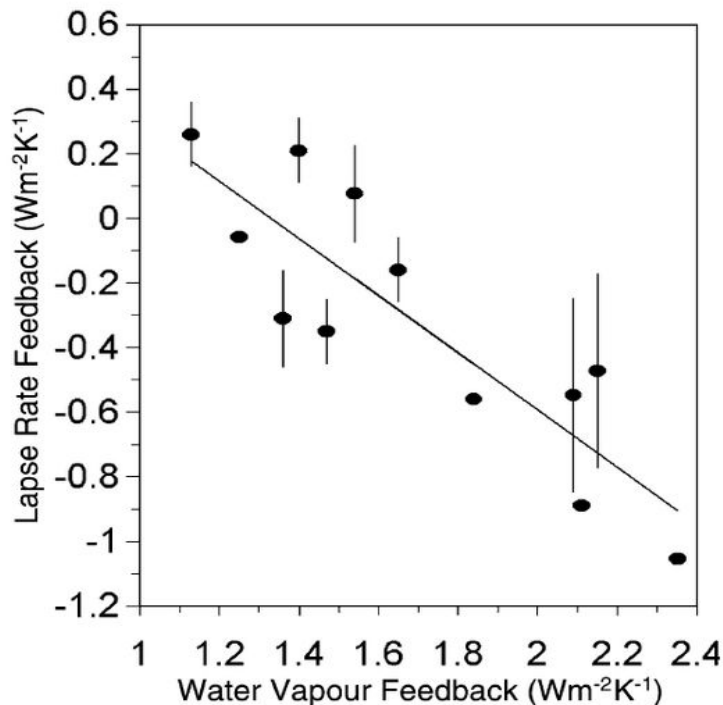
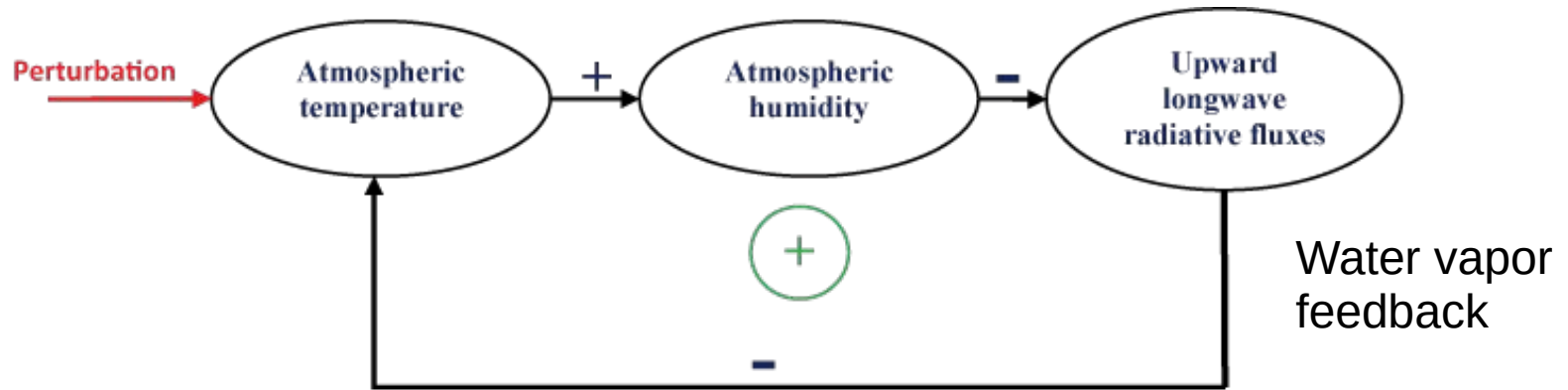


Positive lapse
rate feedback



Goosse, CSDM

WATER VAPOR / T-LAPSE RATE Γ



- Compensation between water vapor and temperature lapse rate feedback in models.

$$\lambda_{WV} + \lambda_{\Gamma} + \lambda_{BB} \quad \lambda_{\Gamma} = -0.6 \text{ Wm}^{-2} \text{ K}^{-1} \text{ (tropics)}$$

Lapse Rate feedback and water vapor feedback are generally negatively correlated. Thus, lapse rate feedback is negative.

Colman, Climate Dynamics, 2003

SUBTOPICS

5. Water and climate feedback (II)

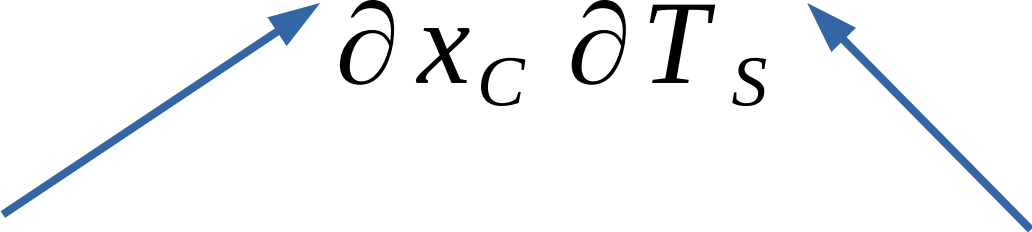
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CLOUD FEEDBACKS

- Partial pressure of H₂O increases exponentially with temperature
→ **positive feedback**
- Cloud formation depends on H₂O concentration
 - high cirrus clouds warm → **positive feedback**
 - low clouds cool → **negative feedback**
- Low level cloud feedback: Calculated from differences between cloudy-sky and clear-sky radiative fluxes to space (Ramanathan et al. 1989)
 - thermal effect **warms** planet by $\sim 30 \text{ Wm}^{-2}$
 - Solar shading **cools** planet by $\sim 50 \text{ Wm}^{-2}$
 - Net cooling of $\sim 20 \text{ Wm}^{-2}$ ($\sim 10\%$ of clear-sky greenhouse effect)

CLOUD FEEDBACK: A MORE COMPLEX PROBLEM

$$\frac{\partial R}{\partial x_C} \frac{\partial x_C}{\partial T_S}$$


Depends on:

- Type of cloud
- Height of cloud
- Time of day/year
- Surface characteristics

Non-trivial relationship between cloud and temperature

Response of cloud to
warming is highly uncertain

CLOUD RESPONSES TO WARMING

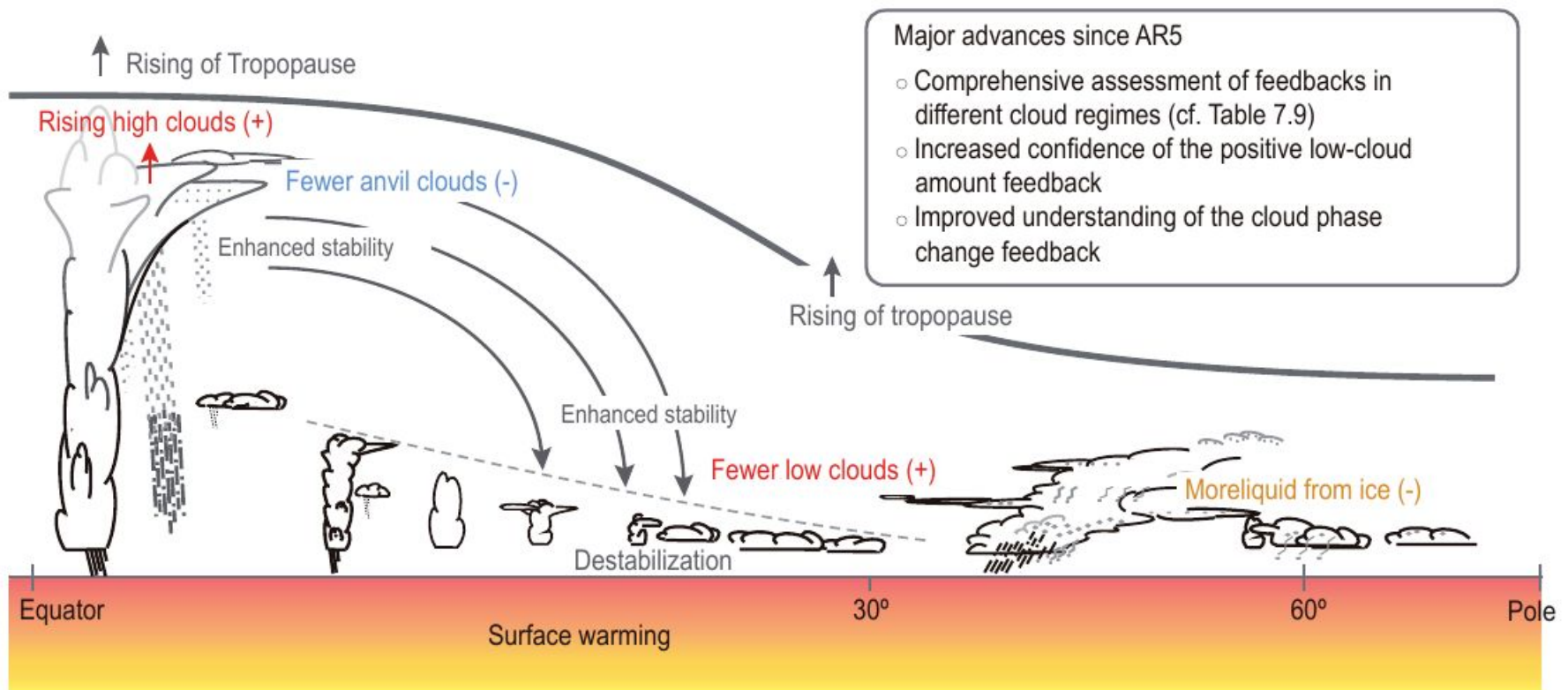


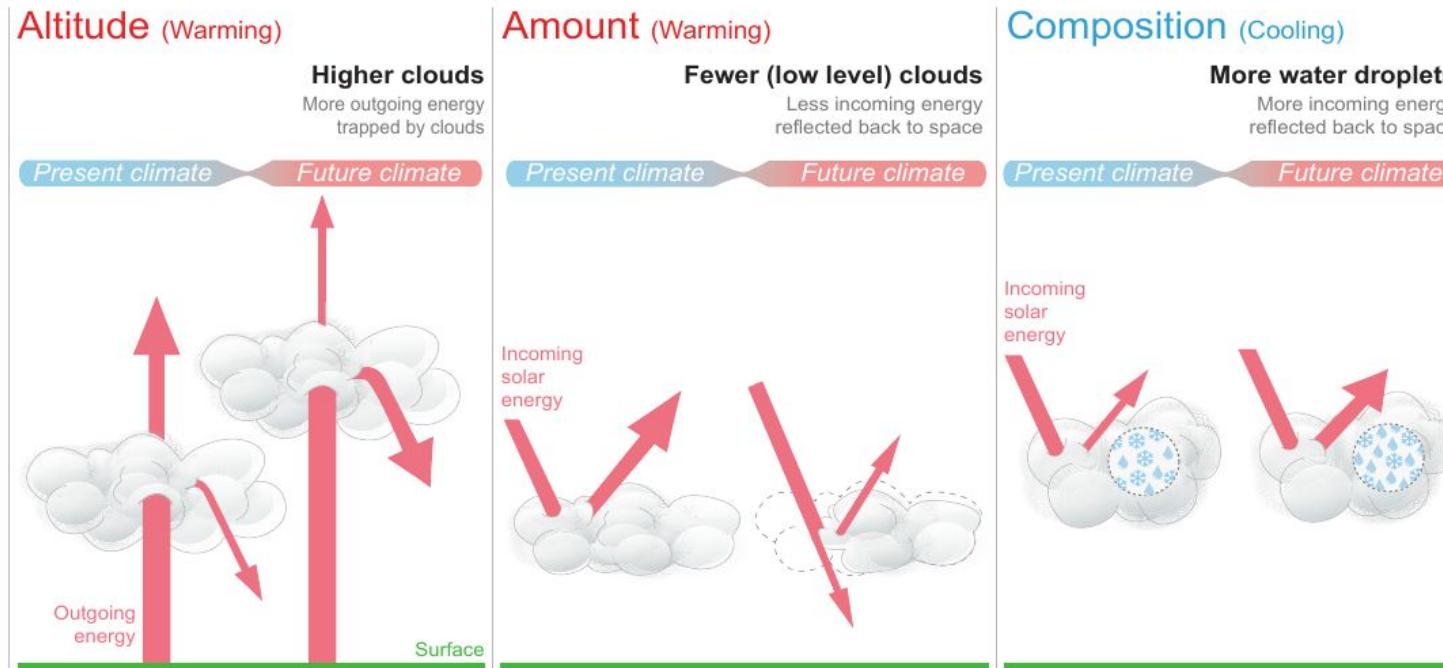
Figure 7.9 | Schematic cross section of diverse cloud responses to surface warming from the tropics to polar regions. Thick solid and dashed curves indicate the tropopause and the subropical inversion layer in the current climate, respectively. Thin grey text and arrows represent robust responses in the thermodynamic structure to greenhouse warming, of relevance to cloud changes. Text and arrows in red, orange and green show the major cloud responses assessed with *high*, *medium* and *low confidence*, respectively, and the sign of their feedbacks to the surface warming is indicated in the parenthesis. Major advances since AR5 are listed in the box. Figure adapted from Boucher et al. (2013).

IPCC, 2021

CLOUD RESPONSES TO CLIMATE CHANGE

FAQ 7.2: What is the role of clouds in a warming climate?

Clouds affect and are affected by climate change. Overall, scientists expect clouds to **amplify future warming**.



IPCC, 2021

Interactions between clouds and the climate today and in a warmer future.

Global warming is expected to alter the altitude (left) and the amount (centre) of clouds, which will amplify warming. On the other hand, cloud composition will change (right), offsetting some of the warming. Overall clouds are expected to amplify future warming.

CLOUD FEEDBACK ESTIMATES

Feedback	AR5	AR6
High-cloud altitude feedback	Positive (<i>high confidence</i>)	Positive (<i>high confidence</i>)
Tropical high-cloud amount feedback	N/A	Negative (<i>low confidence</i>)
Subtropical marine low-cloud feedback	N/A (<i>low confidence</i>)	Positive (<i>high confidence</i>)
Land cloud feedback	N/A	Positive (<i>low confidence</i>)
Mid-latitude cloud amount feedback	Positive (<i>medium confidence</i>)	Positive (<i>medium confidence</i>)
Extratropical cloud optical depth feedback	N/A	Small negative (<i>medium confidence</i>)
Arctic cloud feedback	Small positive (<i>very low confidence</i>)	Small positive (<i>low confidence</i>)
Net cloud feedback	Positive (<i>medium confidence</i>)	Positive (<i>high confidence</i>)

IPCC, 2021

Multitude of cloud feedbacks exist!

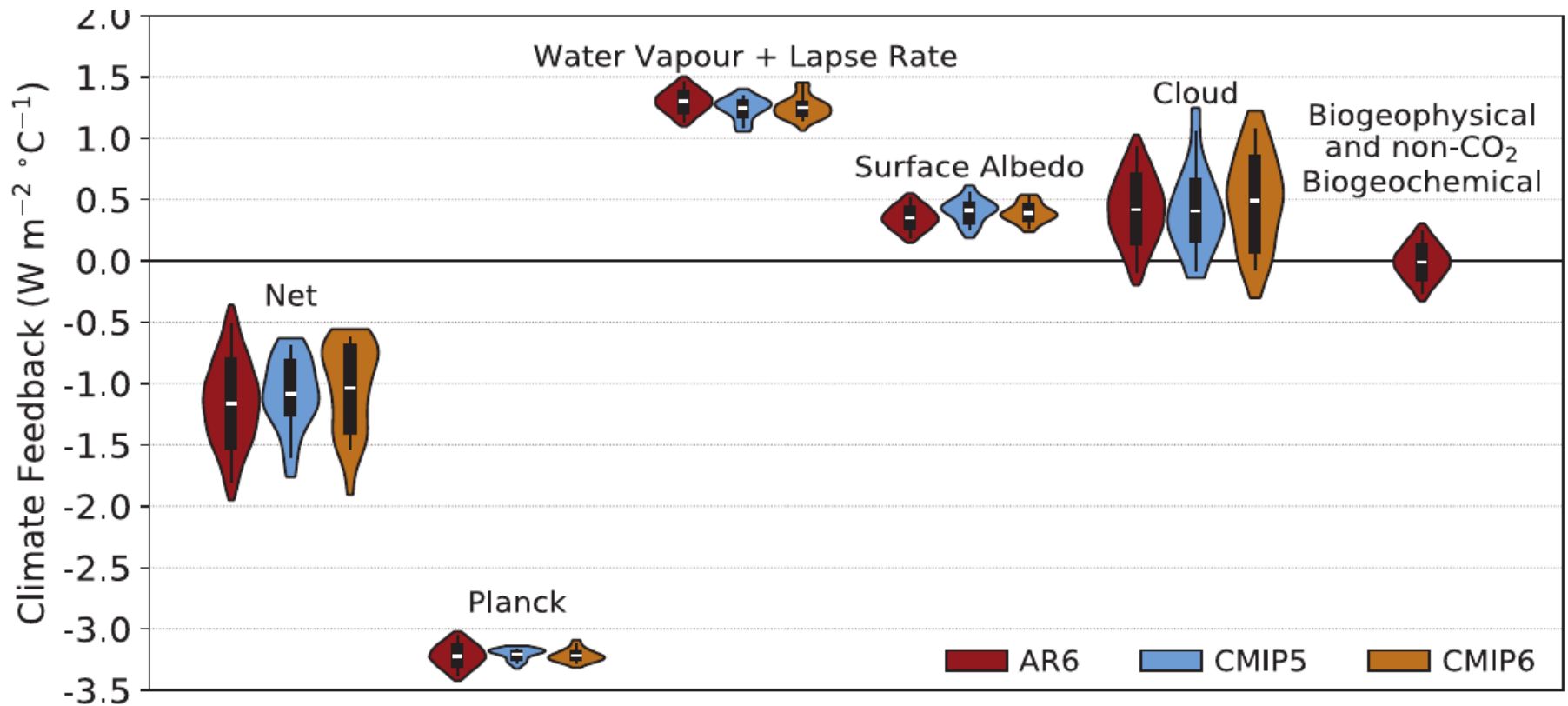
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ASSESSMENT OF CLIMATE FEEDBACKS



IPCC,
2021

Global mean climate feedbacks estimated for abrupt $4 \times \text{CO}_2$ increase simulated by different model ensembles (AR6, CMIP5 (29), CMIP6(49)).

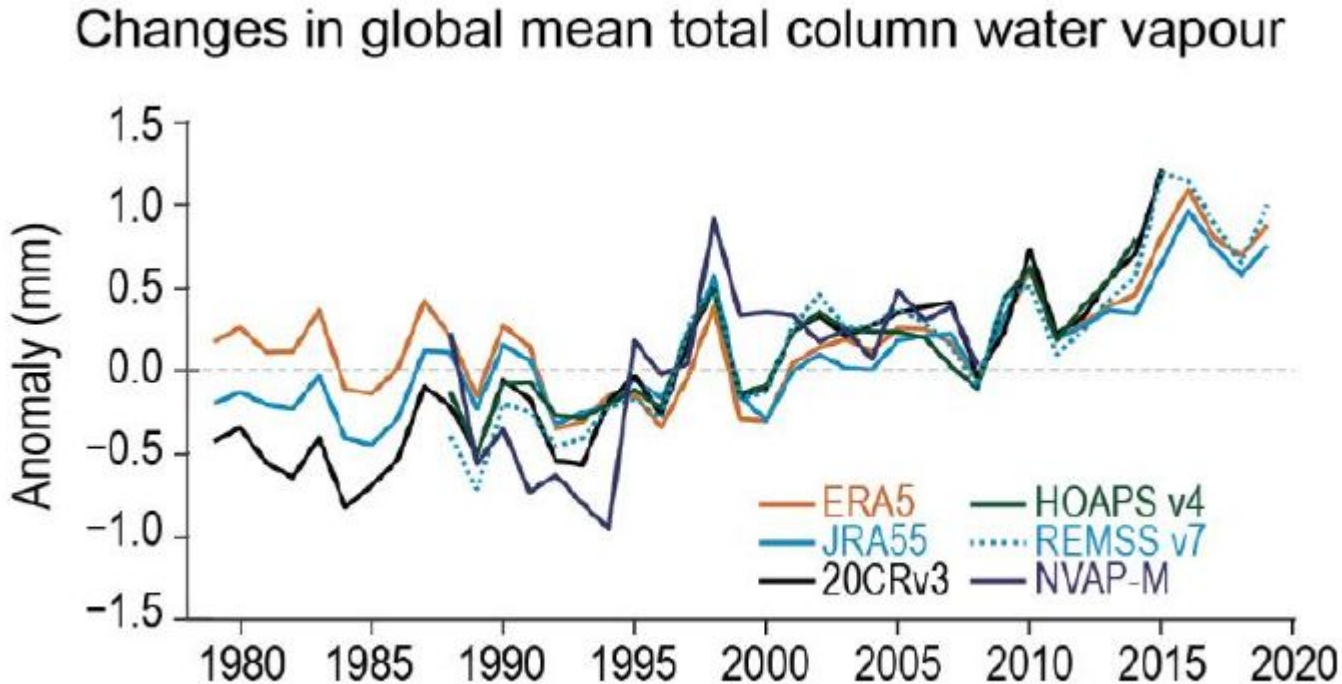
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TROPOSPHERIC WATER VAPOR TRENDS

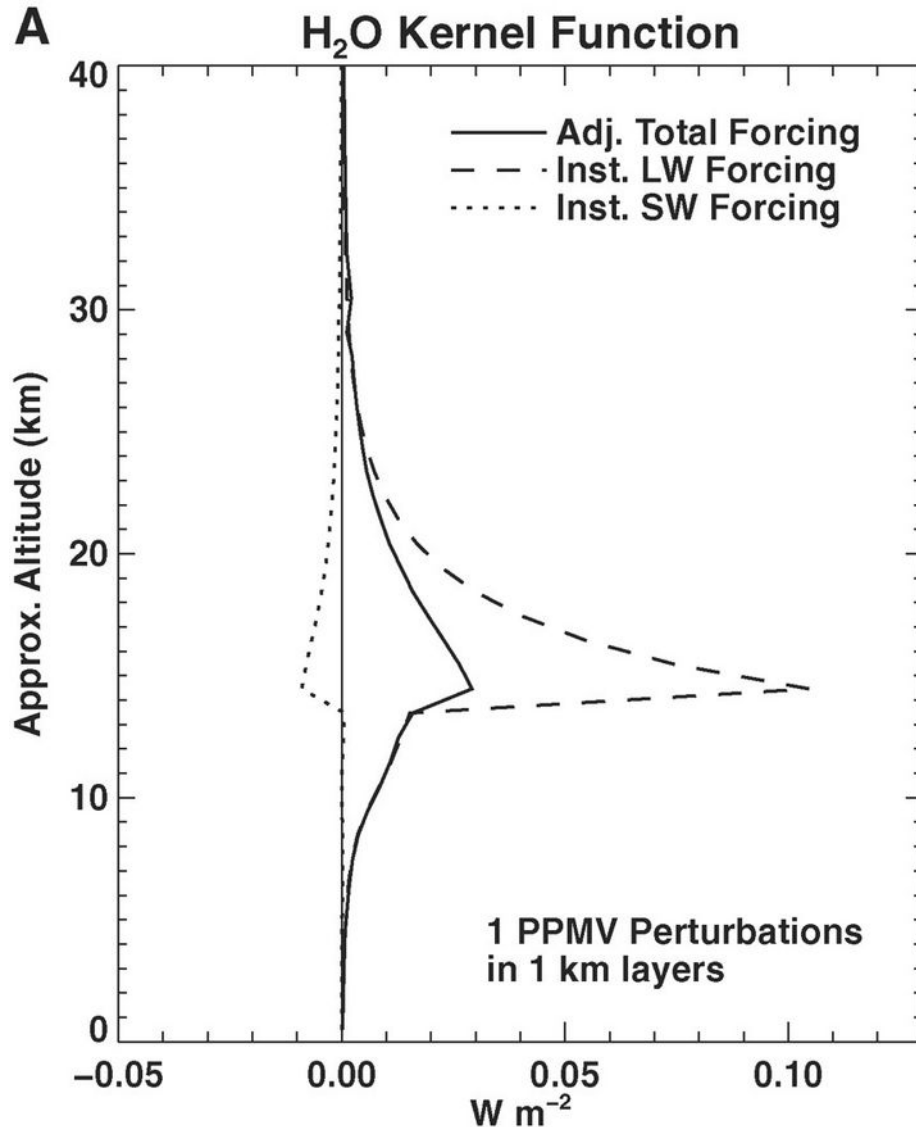


IPCC, 2021

Total column 50°S-50°N for 1988-2019 from model (CMIP5, CMIP6), satellite (RSS), and reanalysis (ERA5.1)

- Overall increase by 1-2.5 % per decade

RADIATIVE FORCING OF WATER VAPOR

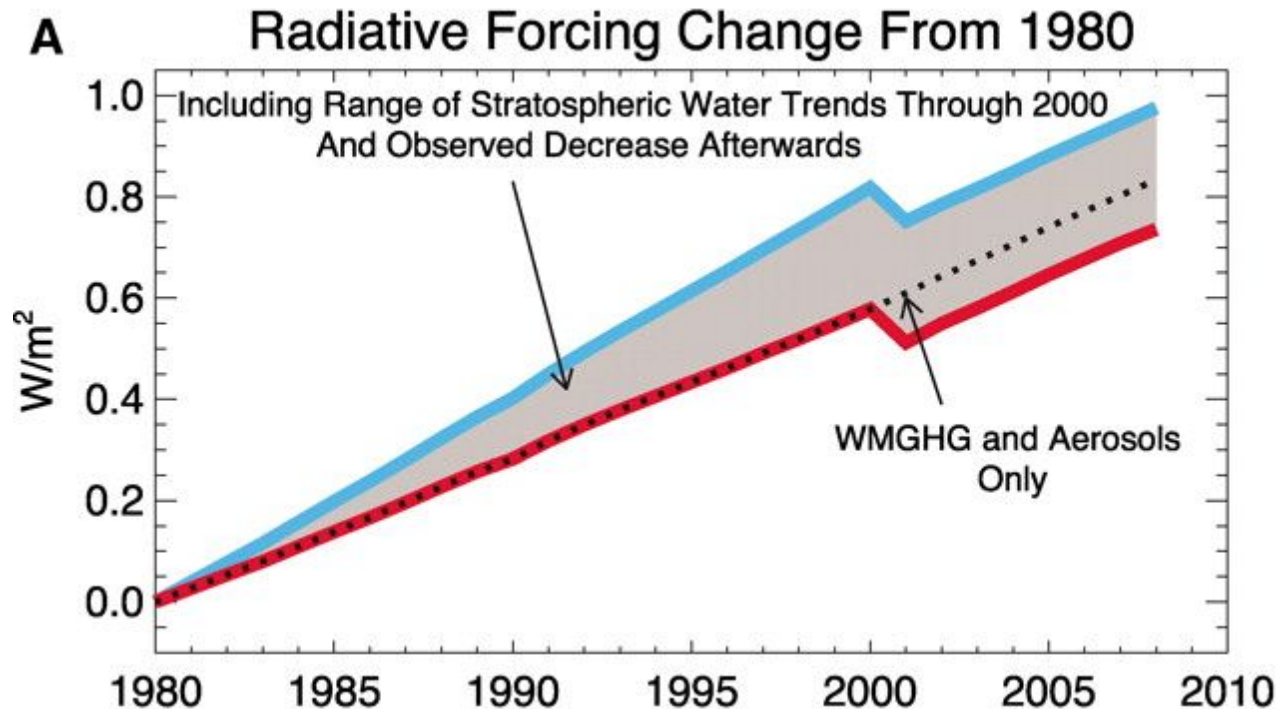


Effect of stratospheric water vapor changes on radiative forcing of surface climate based on detailed line-by-line calculations.

Instantaneous longwave (LW) and instantaneous shortwave (SW) radiative forcing, along with the adjusted net total forcing versus altitude at 35°N obtained for a uniform change of 1 ppmv in 1km layers using a line-by-line radiative transfer model;

The largest sensitivity occurs close to the tropopause.

CLIMATE IMPACT OF STRATOSPHERIC WV

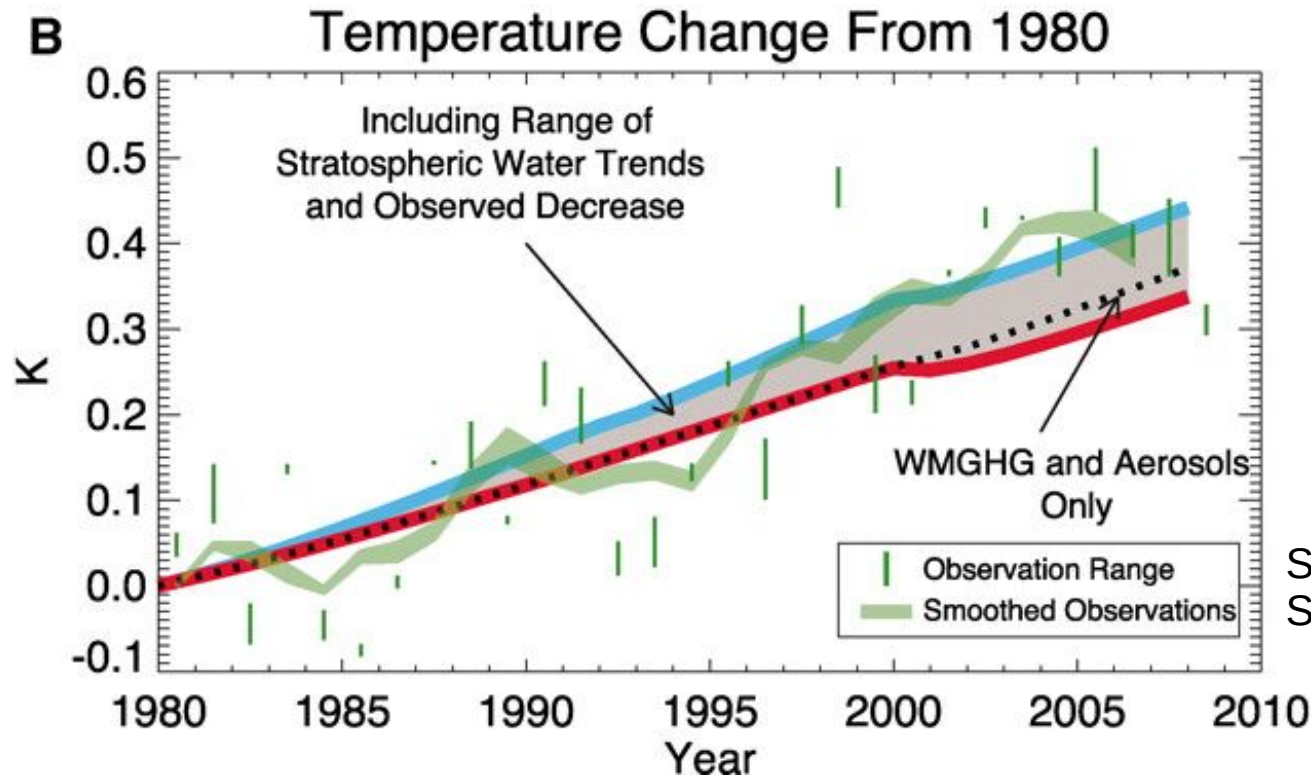


Solomon et al.,
Science, 2010

Impact of changes in stratospheric water vapor on surface climate.

(A) Time series of the changes in radiative forcing since 1980 due to well-mixed greenhouse gases (WMGHG), aerosols, and stratospheric water vapor. The shaded region shows the stratospheric water contribution calculated from an assumed range of decadal trends from 1980 to 2000 of 0 (red line) to 0.5 ppmv per decade (blue line) along with the observed decline prescribed after 2000.

CLIMATE IMPACT OF STRATOSPHERIC WV



Solomon et al.,
Science, 2010

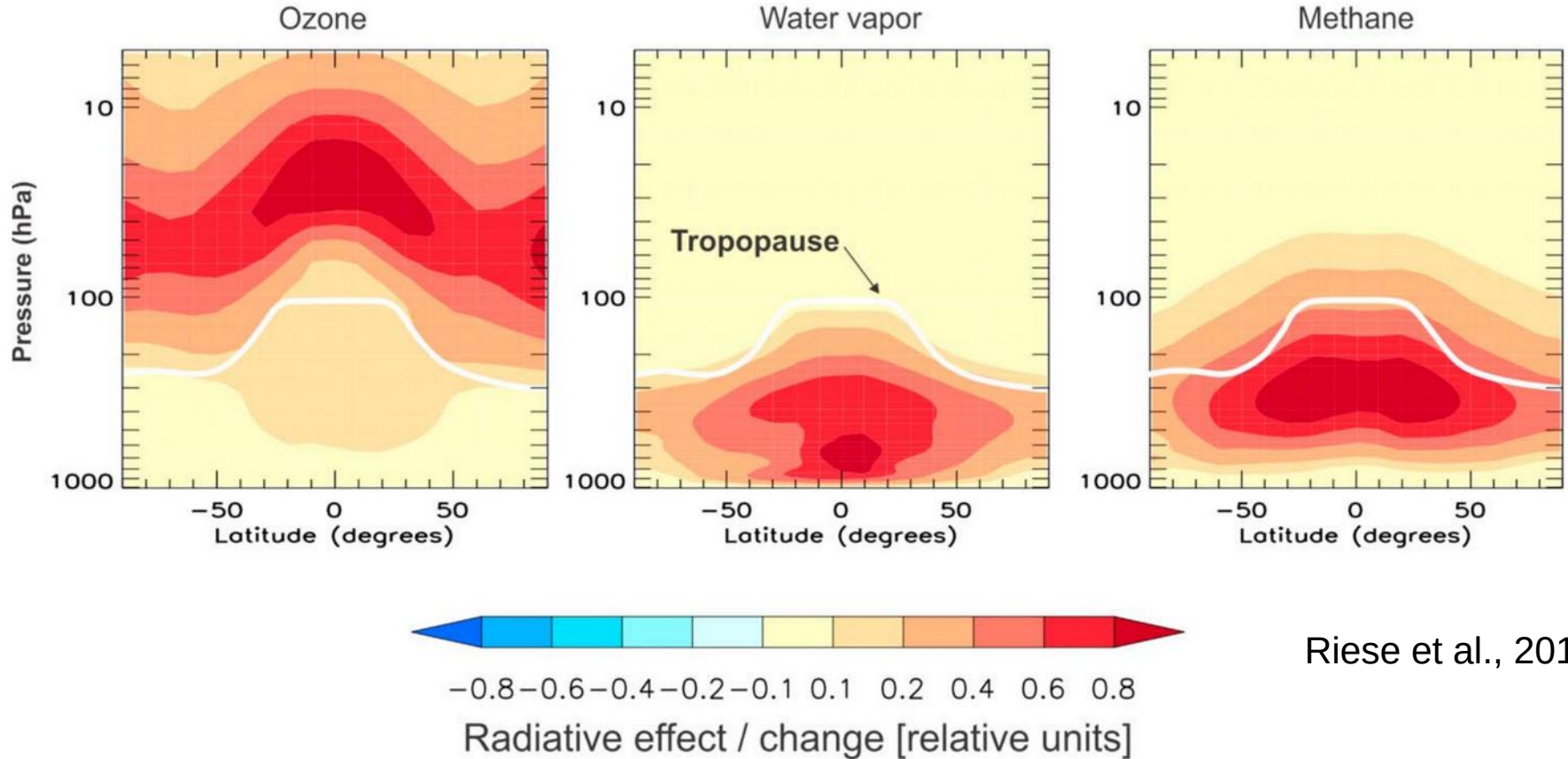
Impact of changes in stratospheric water vapor on surface climate.

(B) Measured and modeled temperature changes relative to 1980. Three different observed global temperature records were used [from the NCDC, CRU, and GISS records], with the green markers indicating the range across the three data sets in each year. The green shaded line shows the range of the 5-year running mean of the three data sets.

TRACE GAS PERTURBATION

1 % increase of the trace gas concentration along the profile.

Radiative effect / percentage change

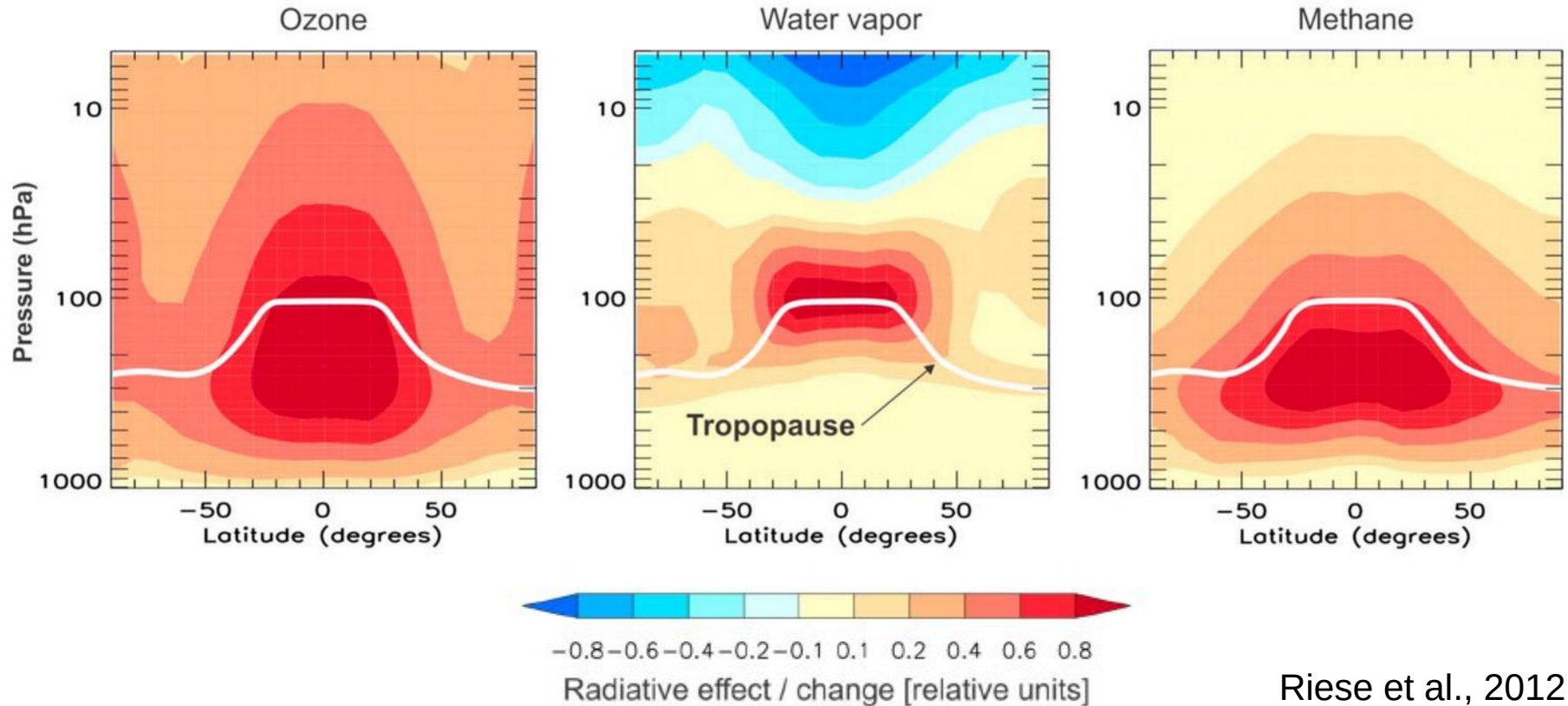


Impact and contribution to **surface temperature** changes depend on the **type** of gas, the **altitude** and **amount**.

TRACE GAS PERTURBATION

1 ppmv increase of the trace gas concentration along the profile

Radiative effect / unit mass change



Impact and contribution to **surface temperature** changes depend on the **type** of gas, the **altitude** and **amount**.

SUBTOPICS

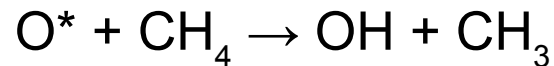
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IMPACT OF METHANE (CH₄) INCREASE

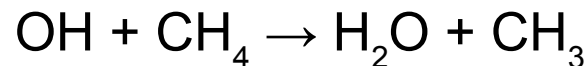
- change in CH₄ could induce change in OH concentration



→ negative feedback

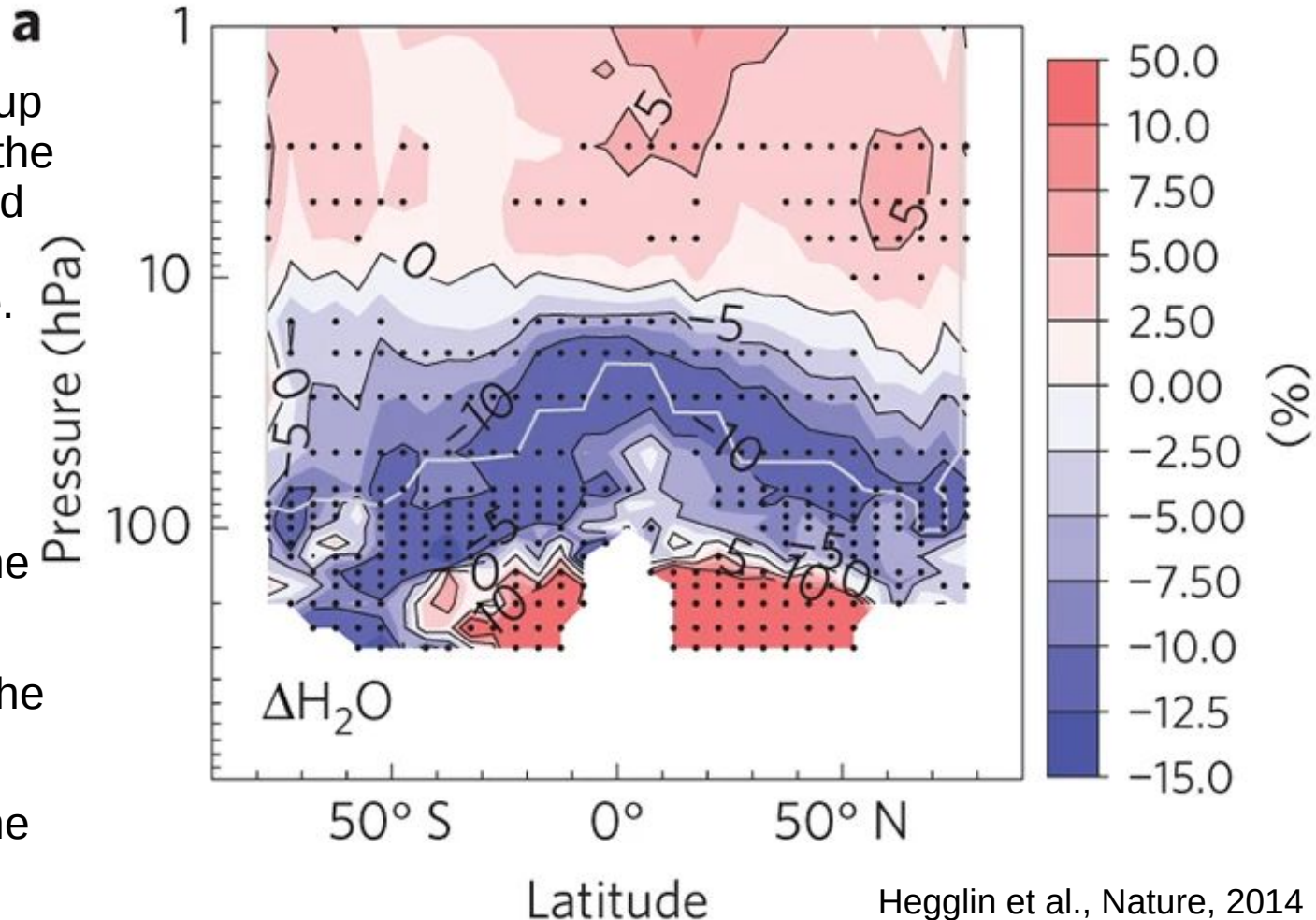
(possible reason for observed reduction in trend)

- increase in stratospheric H₂O:



→ positive feedback

WATER VAPOR TRENDS IN UTLS AND ST.



Hegglin et al., Nature, 2014

Percentage changes up to 2010 derived from the merged satellite record since 1986/1988 above/below grey line. Dots indicate 95%-significance level.

Observation show:

- **Positive trend** in the upper troposphere
- **Negative trend** in the lower stratosphere
- **Positive trend** in the upper stratosphere

WATER VAPOR TRENDS IN UTLS AND ST.

Contribution to a
from tropospheric
methane increases.

Stratospheric water
and methane
depend on the **entry
value [e]** at the
tropical tropopause.

Potential water:

$$H_2O = H_{2O[e]} + 2\alpha CH_{4[e]}$$

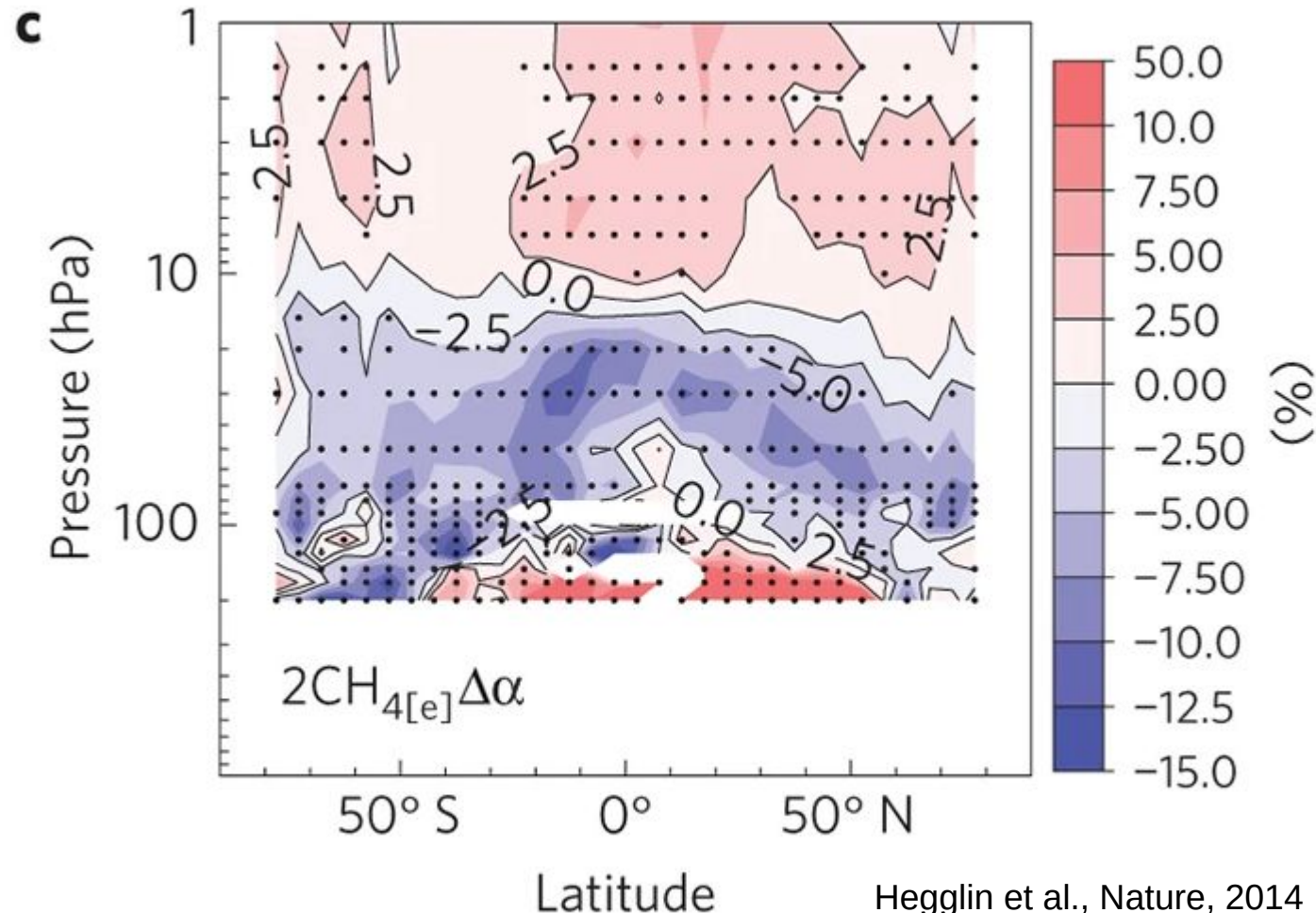
**Methan
concentration:**

$$CH_4 = (1 - \alpha)CH_{4[e]}$$

**Change of
potential water:**

$$\Delta H_2O = \Delta H_{2O[e]} + 2\alpha \Delta CH_{4[e]} + 2CH_{4[e]} \Delta \alpha$$

Change in the Brewer dobson circulation



Hegglin et al., Nature, 2014

SUBTOPICS

5. Water and climate feedback (II)

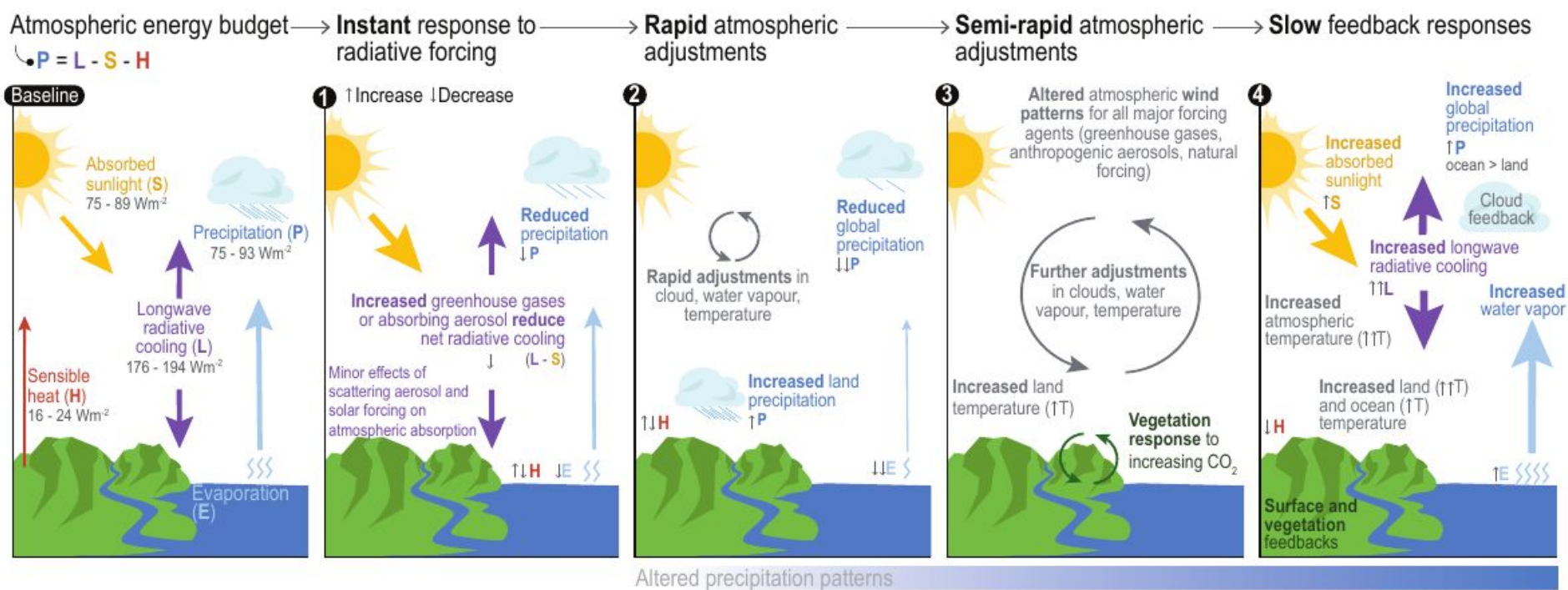
Climate feedbacks with focus on water feedback

- Climate feedbacks (direct and indirect effects)
- Climate sensitivity and relation to climate feedbacks
 - Water vapor feedback
 - Lapse rate feedback
 - Cloud feedbacks
 - Assessment of climate feedbacks
- Water vapor trends (troposphere, stratosphere) and their impact
- Methane increase impacts on water vapor
- **Climate projections of the water cycle (IPCC 2021)**

CLIMATE PROJECTIONS OF THE WATER CYCLE (IPCC 2021)

Interactive atlas of climate projections:
<https://interactive-atlas.ipcc.ch/>

RESPONSES OF PRECIPITATION TO RADIATIVE FORCING CHANGES



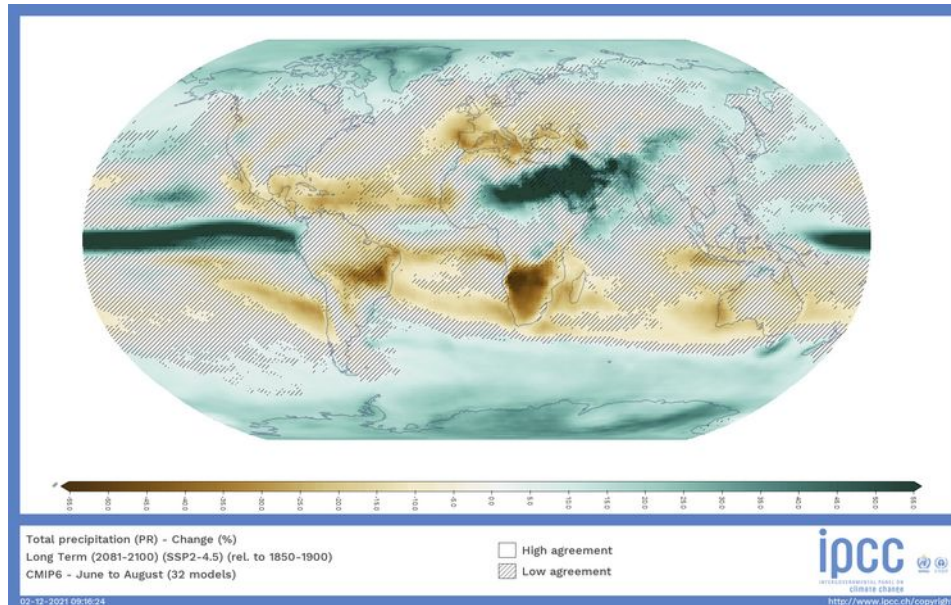
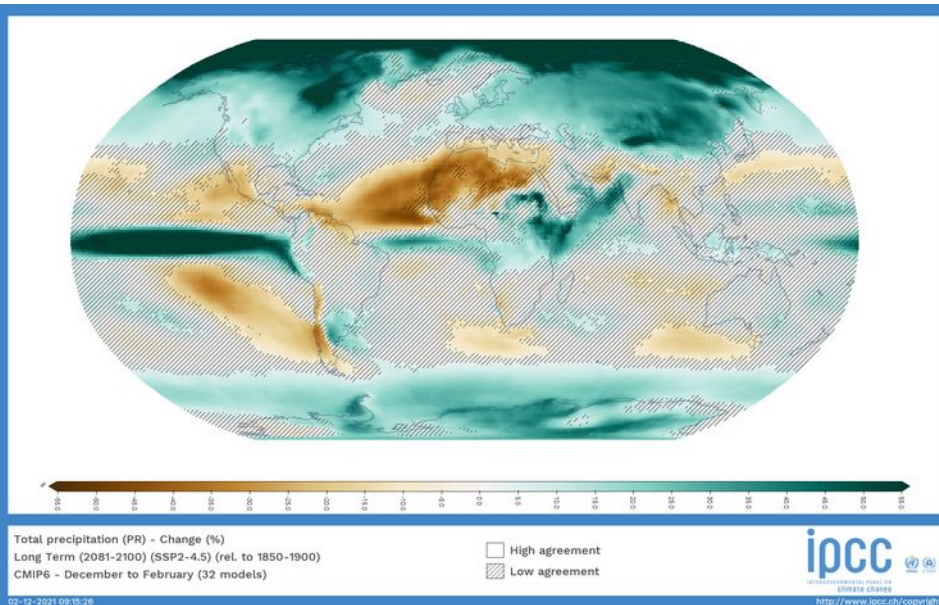
- (1) Fast rapid atmospheric adjustment, (2) Slower adjustment involving land surface and vegetation (3) Slow precipitation response to global mean surface air temp. (4) hydrological sensitivity η and the slow total precipitation response

IPCC, 2021

PRECIPITATION CHANGES IN A FUTURE CLIMATE

DJF

JJA



SSP2-4.5: Changes 2081-2100 vs. 1850-1900

- Precipitation increase mainly over land
- In general, moist regions are getting moister and dry regions are getting dryer

Taken from
<https://interactive-atlas.ipcc.ch/>

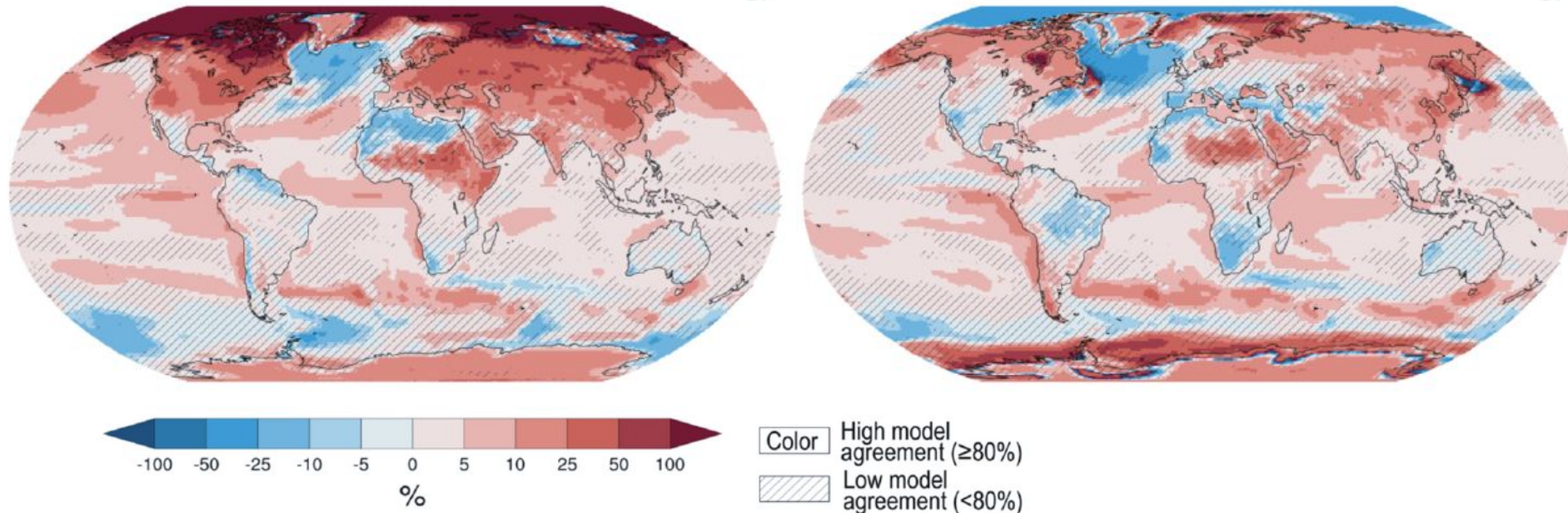
EVAPORATION CHANGES IN A FUTURE CLIMATE

(c) SSP2-4.5 DJF

37

(d) SSP2-4.5 JJA

37

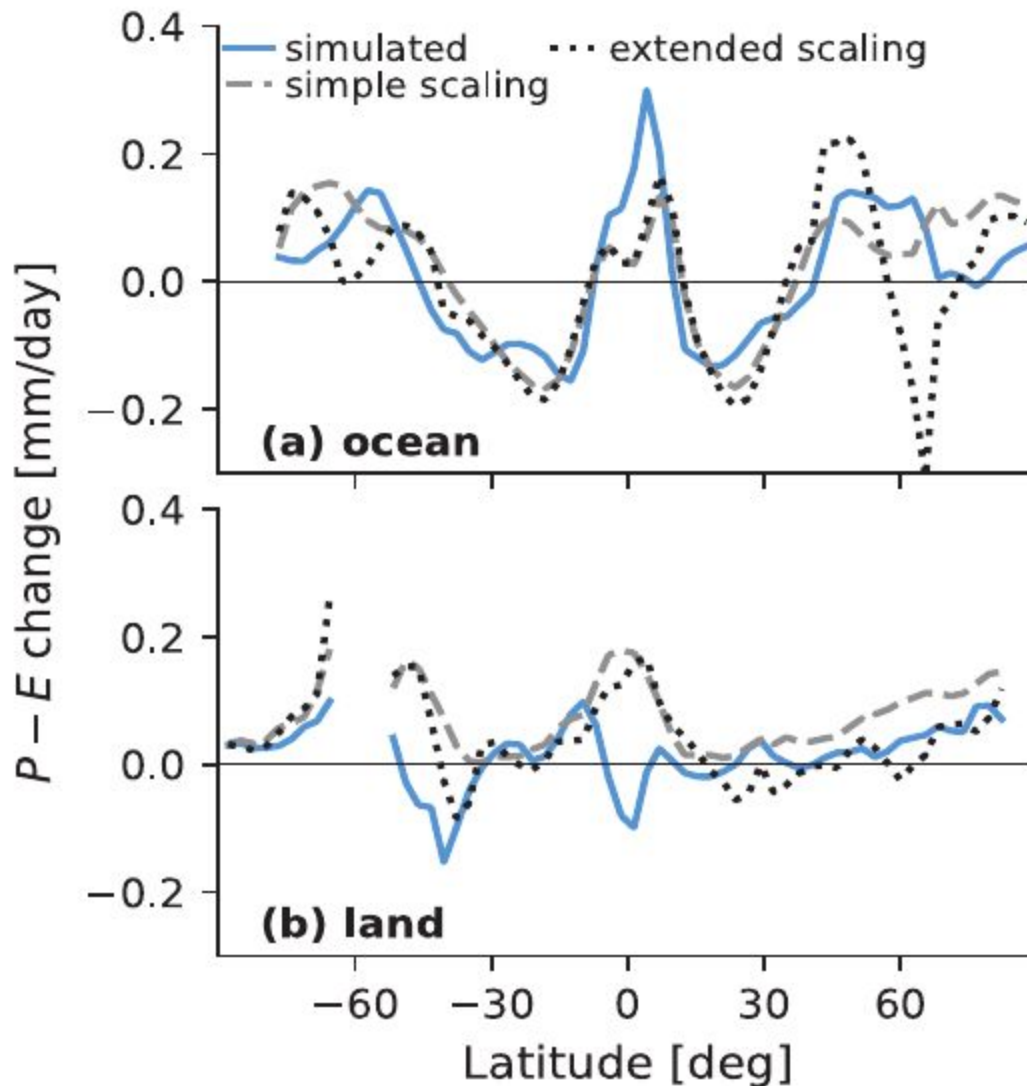


SSP2-4.5: Changes 2081-2100 vs. 1995-2014

IPCC, 2021

- Evaporation changes are coupled to precipitation changes – but not everywhere (poles, some ocean regions)
- Increase in evaporation over most land areas with exception of moisture limited regions
- Increase in global mean evaporation over most oceanic areas

EXPECTED ZONAL MEAN P-E CHANGES

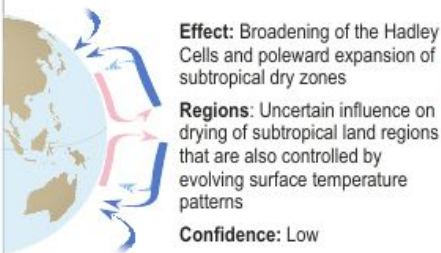


Zonally-averaged annual mean changes in precipitation minus evaporation (P-E) over **(a) ocean** and **(b) land** between 1995-2014 and 2081-2100 (SSP2-4.5) CMIP6 simulations.

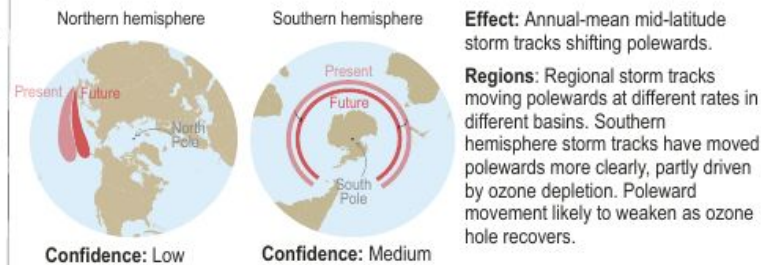
- Tropical ocean is wetter
- Sub-tropics are dryer
- Mid-latitudes are wetter
- High latitudes are also wetter

IPCC, 2021

Poleward expansion of Hadley Cells

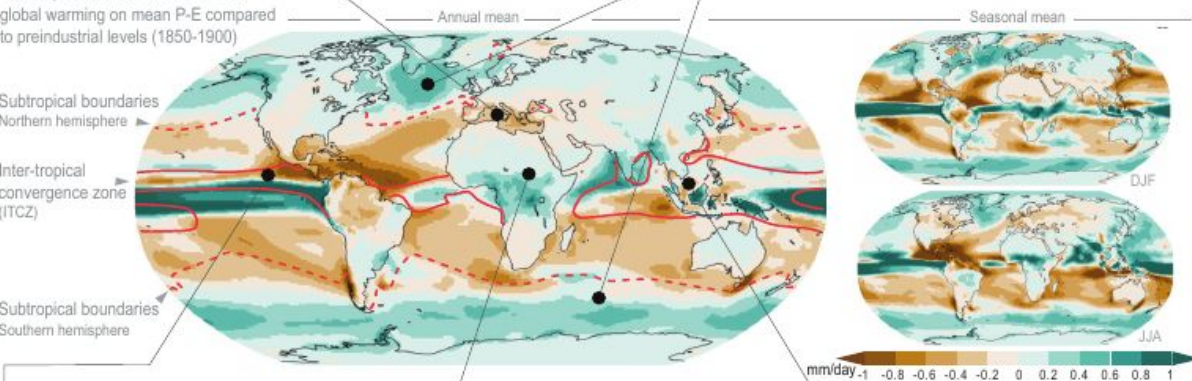


Poleward migration of storm tracks

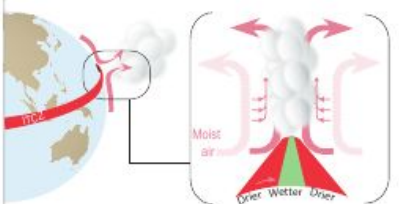


LARGE SCALE CIRCULATION PROJECTED CHANGES AND THEIR EFFECT ON THE GLOBAL WATER CYCLE

The maps show the effect of 3°C of global warming on mean P-E compared to preindustrial levels (1850-1900)



Narrowing/strengthening of ITCZ core



Effect: Drying tendency on edges of the ITCZ; moistening tendency in the core, where the wet gets wetter response is expected to be amplified.

Regions: Impacts on individual regions only beginning to be investigated.

Confidence: Medium

Regional shifts in ITCZ

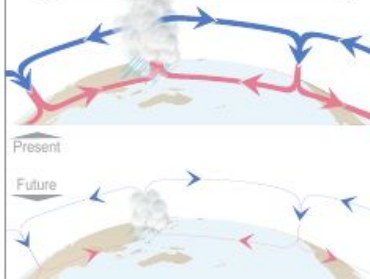


Effect: Shifts in location of wettest tropical regions, increases or decreases in precipitation amount

Regions: Southward shift 1950-1970s over west Africa due to aerosol cooling of northern hemisphere, recovery since driven mainly by GHGs. Signals of regional shifts emerging.

Confidence: Low

Weaker Walker circulation

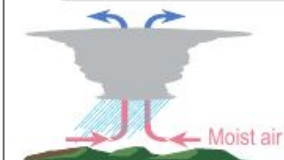


Effect: Reduces thermodynamic strengthening of monsoons and the increasing contrasts between wet and dry regimes

Regions: Maritime Continent

Confidence: Medium

Thermodynamic increases in moisture transport into weather systems



Effect: Thermodynamic strengthening of contrasts between wet and dry events regionally despite shifts in circulation patterns. Increases in convergence of moisture into mid-latitude weather systems, tropical cyclones, and monsoons; increases precipitation.

Regions: Global

Confidence: High

IPCC, 2021