Radiation Model in Climate and Forecast

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SMR4067 – Trieste 5-16 May 2025

ICTP The Abdus Salam International Centre for Theoretical Physics

IAEA International Atomic Energy Agency

United Nations Educational, Scientific and Cultural Organization

Earth Budget

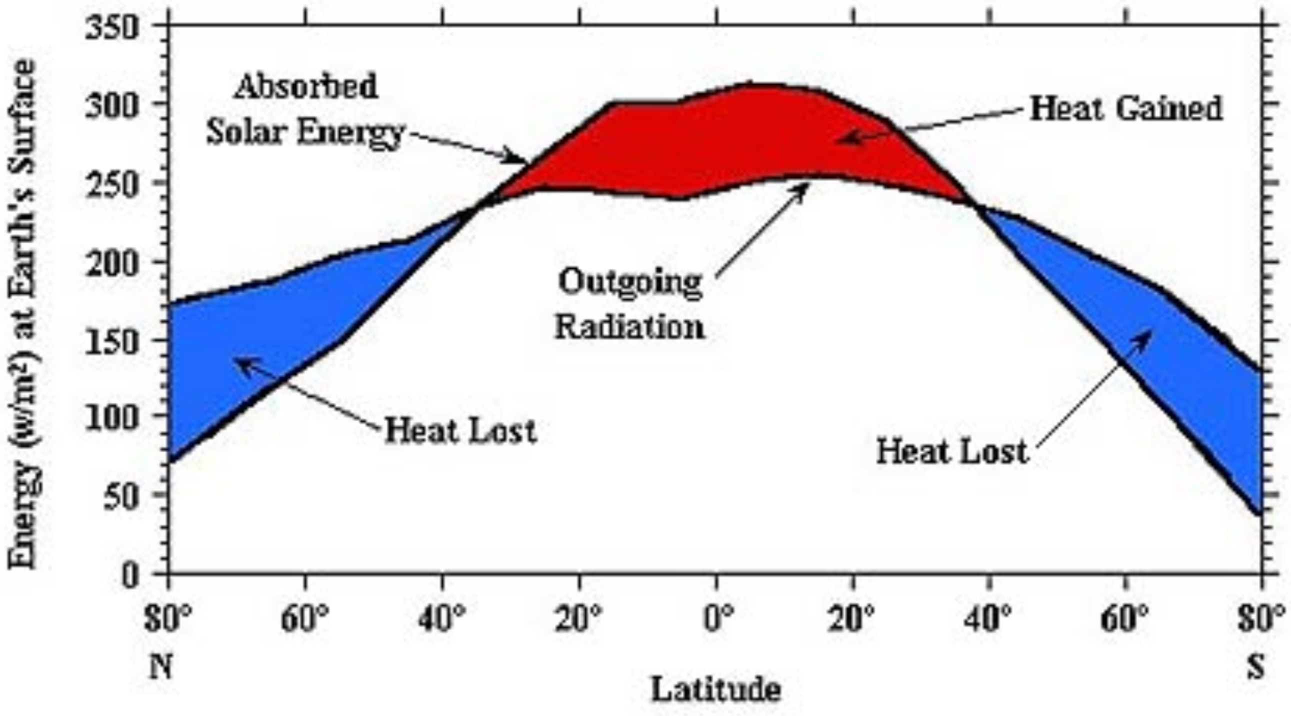
- Objects lose/gain energy by the emission/absorption of electromagnetic radiation.
- The main frequencies of the radiation emitted depends on the temperature of the body in question.
- The earth’s surface and gases/clouds in the atmosphere can scatter or absorb radiation.
- Absorption occurs at specific frequencies or wavelengths of radiation.

Different wavelenght

- The earth-atmosphere system receives incident radiation from the sun at wavelengths of 0.2 to 4 μm. Some of this radiation is absorbed or reflected back to space by the atmosphere, while the rest is absorbed or reflected back to space by the earth's surface.
- The net solar radiation absorbed by the earth-atmosphere system must be balanced by the outgoing thermal infra-red radiation that this system emits at longer wavelengths of 4 to 500 μm.

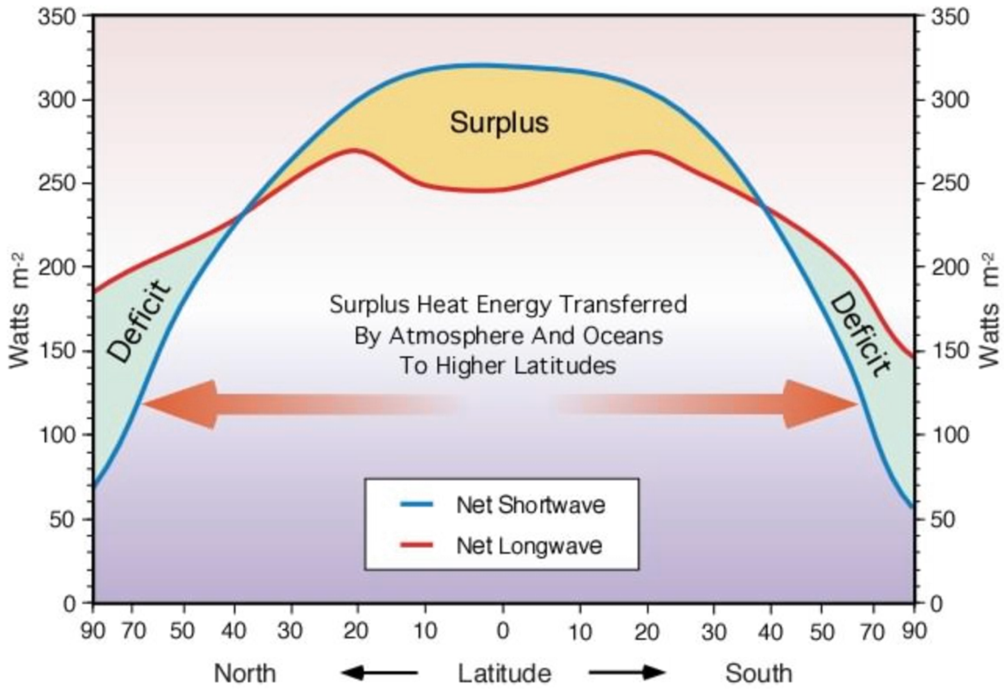
Anisotropy

- The solar radiation is not equally distributed over the globe, with the tropics receiving more incoming solar energy than the poles. The energy lost to space through infra-red emission does not locally balance the solar radiation

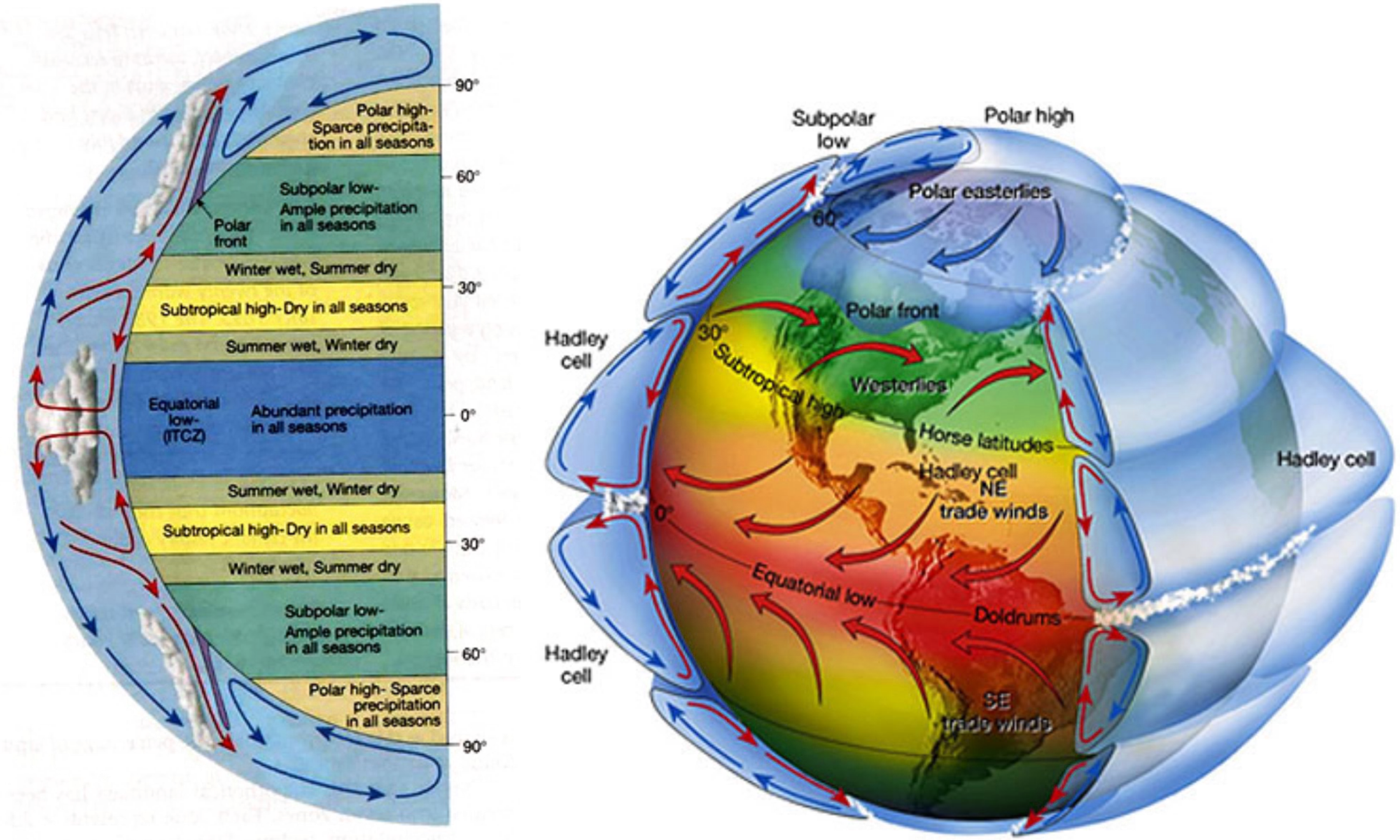


Energy transfer

- The energy is redistributed by large-scale dynamical motions driven by the imbalance of heating



Global circulation



Stefan Boltzman Law

- The Stefan–Boltzmann law, also known as Stefan's law, describes the intensity of the thermal radiation emitted by matter in terms of that matter's temperature. It is named for Josef Stefan, who empirically derived the relationship, and Ludwig Boltzmann who derived the law theoretically. For an ideal absorber/emitter or black body, the Stefan–Boltzmann law states that the total energy radiated per unit surface area per unit timeis directly proportional to the fourth power of the black body's temperature, T:

$$E = \frac{2\pi^5 k^4}{15h^3c^2}T^4 = \sigma T^4$$

- σ is called the Stefan–Boltzmann constant. It's value is $5.67037442 \times 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$

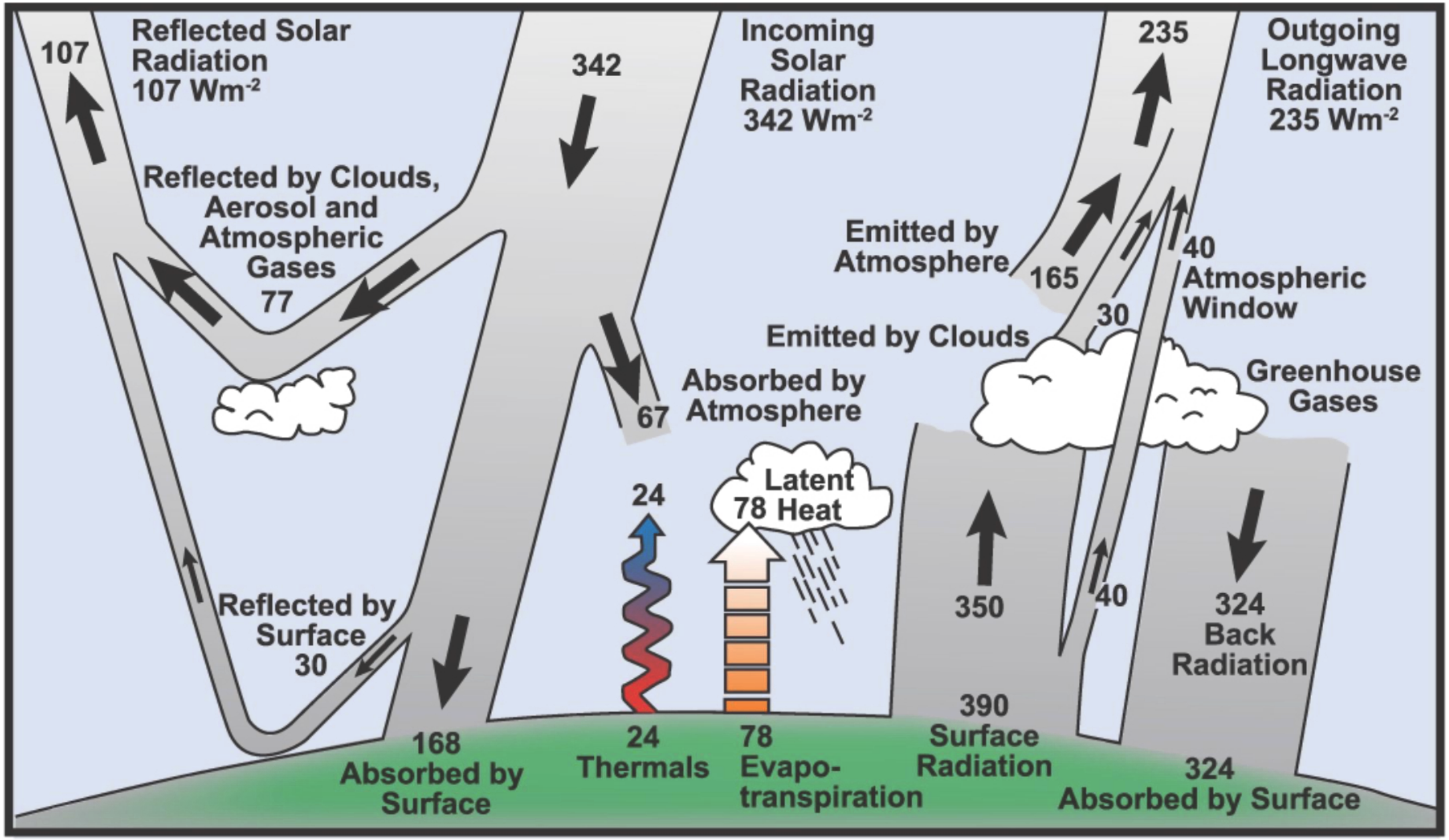
Solar constant S_0

- The average irradiance at the top of the earth's atmosphere, is known as the Solar Constant. Measurements from satellites show that $S_0 \simeq 1370$ W m^{-2} . The value varies by ≈ 1 W m^{-2} over a solar cycle that has an average length of 11 years.
- The energy intercepted by the earth is $S_0 \pi r_e^2$ so that the average incident solar radiation on the earth's surface is

$$E_e = \frac{S_0 \pi r_e^2}{4 \pi r_e^2} = \frac{S_0}{4}$$

or 340 W m^{-2}

Global radiative process



Planetary albedo α_p

- Proportion of the incoming solar radiation is scattered back to space by clouds, atmospheric gases and the planet's surface. We thus introduce the parameter α_p as the planetary albedo.
- It is defined as the ratio between the reflected solar irradiance (at top of atmosphere) and the incident solar irradiance
- Observations from Satellites put the earth albedo at $\alpha_p \simeq 0.3$.
- It is affected by surface properties and locations of clouds. The "whiter" (reflective) the irradiated body, the higher the albedo.

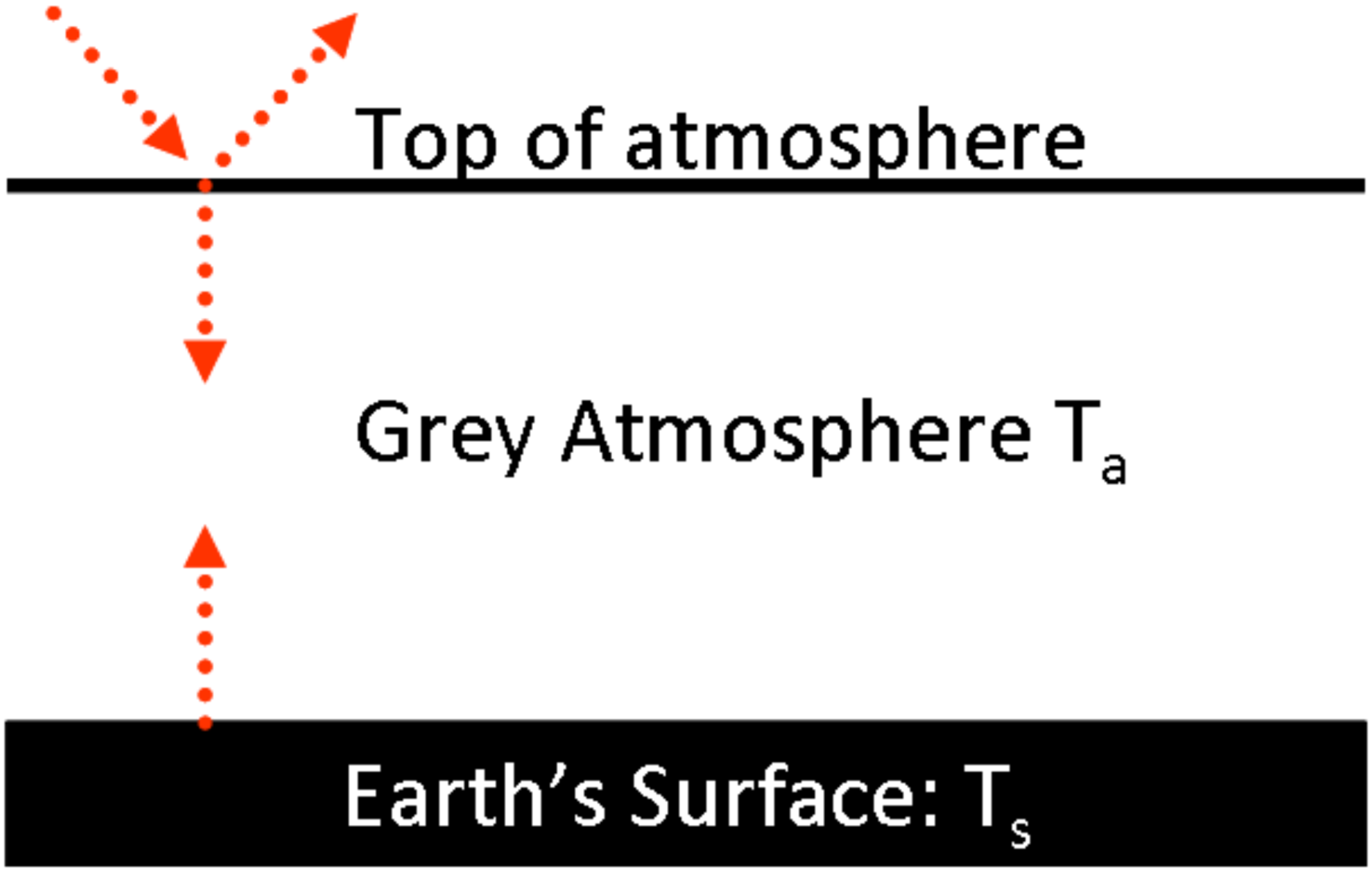
Emissivity

- The emissivity of the surface of a material is its effectiveness in emitting energy as radiation. The emissivity of a surface depends on its chemical composition and geometrical structure. Quantitatively, it is the ratio of the thermal radiation from a surface with the radiation from an ideal black surface at the same temperature as given by the Stefan–Boltzmann law. The ratio varies from 0 to 1

Simple slab model of the atmosphere

- Model the atmosphere as a single slab: outgoing radiation at the top of the atmosphere is balanced by the net incoming absorbed solar radiation. This model contains basic elements of natural and anthropogenic climate variability.
- We make the following simplifying assumptions:
  - The earth surface is a black body.
  - The atmosphere does not absorb solar radiation.
  - Atmosphere can be represented as a grey body.

Schematic



Equations

- Top of atmosphere

$$\frac{S_0}{4}(1-\alpha_p) = \sigma T_s^4(1-\epsilon) + \epsilon\sigma T_a^4$$

- Atmosphere

$$\epsilon\sigma T_s^4 = 2\epsilon\sigma T_a^4$$

- Surface

$$\epsilon\sigma T_a^4 + \frac{S_0}{4}(1-\alpha_p) = \sigma T_s^4$$

Solution

- From the atmosphere equations, we have a relationship between atmospheric temperature and surface temperature

$$T_a = \frac{T_s}{\sqrt[4]{2}}$$

- Replacing this in any of the other two equations we have

$$T_s = \sqrt[4]{\frac{S_0(1-\alpha_p)}{2\sigma(2-\epsilon)}}$$

The “Greenhouse effect”

- A reasonable value for the emissivity is = 0.78, which results in T s = 288K. Thus we can see that introducing an atmosphere that can absorb in the thermal IR causes a surface warming. This is known as the “greenhouse effect”.
- Changes to the parameter values would lead to a disequilibrium.
- Changes to the solar constant S_0 due to sunspot activity or changes in the earth’s orbital parameters.
- Changes in the planetary albedo α_p , due to changing ice cover, land cover and vegetation, properties of clouds or the atmospheric composition.
- Changes to the atmospheric infra-red emissivity ε_{ir} , due to changes in the atmosphere composition of radiatively active gases (water vapour, CO_2, methane, Ozone, etc).

The Planetary Science Journal, 5:67 (10pp), 2024 March https://doi.org/10.3847/PSJ/ad226d

Fermi Resonance and the Quantum Mechanical Basis of Global Warming

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Received 2023 July 14; revised 2024 January 16; accepted 2024 January 17; published 2024 March 11

Abstract

Although the scientific principles of anthropogenic climate change are well-established, existing calculations of the warming effect of carbon dioxide rely on spectral absorption databases, which obscures the physical foundations of the climate problem. Here, we show how CO_2 radiative forcing can be expressed via a first-principles description of the molecule's key vibrational-rotational transitions. Our analysis elucidates the dependence of carbon dioxide's effectiveness as a greenhouse gas on the Fermi resonance between the symmetric stretch mode ν_1 and bending mode ν_2. It is remarkable that an apparently accidental quantum resonance in an otherwise ordinary three-atom molecule has had such a large impact on our planet's climate over geologic time, and will also help determine its future warming due to human activity. In addition to providing a simple explanation of CO_2 radiative forcing on Earth, our results may have implications for understanding radiation and climate on other planets.

Unified Astronomy Thesaurus concepts: Earth atmosphere (437); Greenhouse effect (2314); Planetary atmospheres (1244); Planetary climates (2184)

1. Introduction

Carbon dioxide is an essential greenhouse gas on all rocky planets in the solar system with significant atmospheres (Venus, Earth, and Mars). On Earth, the carbonate-silicate cycle regulates atmospheric CO_2 on geological timescales, but the last 150 yr has seen a rapid rise in concentrations from approximately 280 ppmv to 415 ppmv (Tziperman 2022), due to burning of fossil fuels by humans and land use changes (Friedlingstein et al. 2022). Earth's global-mean surface temperature has risen by approximately 1 K during this same period, with most of the warming a direct result of this CO_2 increase. CO_2 affects surface temperature because it is a greenhouse gas: It absorbs more effectively at thermal infrared frequencies than the near-infrared and visible frequencies where solar radiation peaks. As a result, increasing levels of atmospheric CO_2 shifts the emission of thermal radiation to space to higher-altitude regions of the atmosphere, where air is less dense and colder. This colder air releases less thermal radiation, so increasing CO_2 decreases total emission to space for fixed surface and atmospheric temperatures. The magnitude of this decrease is defined as the radiative forcing of CO_2.

Atmospheric mixing is fast compared to the rate of CO_2 emission and removal, so to a first approximation the CO_2 concentration is uniform in Earth's lower atmosphere. The stratosphere-adjusted radiative forcing due to an increase in the atmospheric CO_2 molar concentration from x_0 to x is typically expressed as[4]

$$\Delta F \approx +\alpha \ln[x/x_0], \quad (1)$$

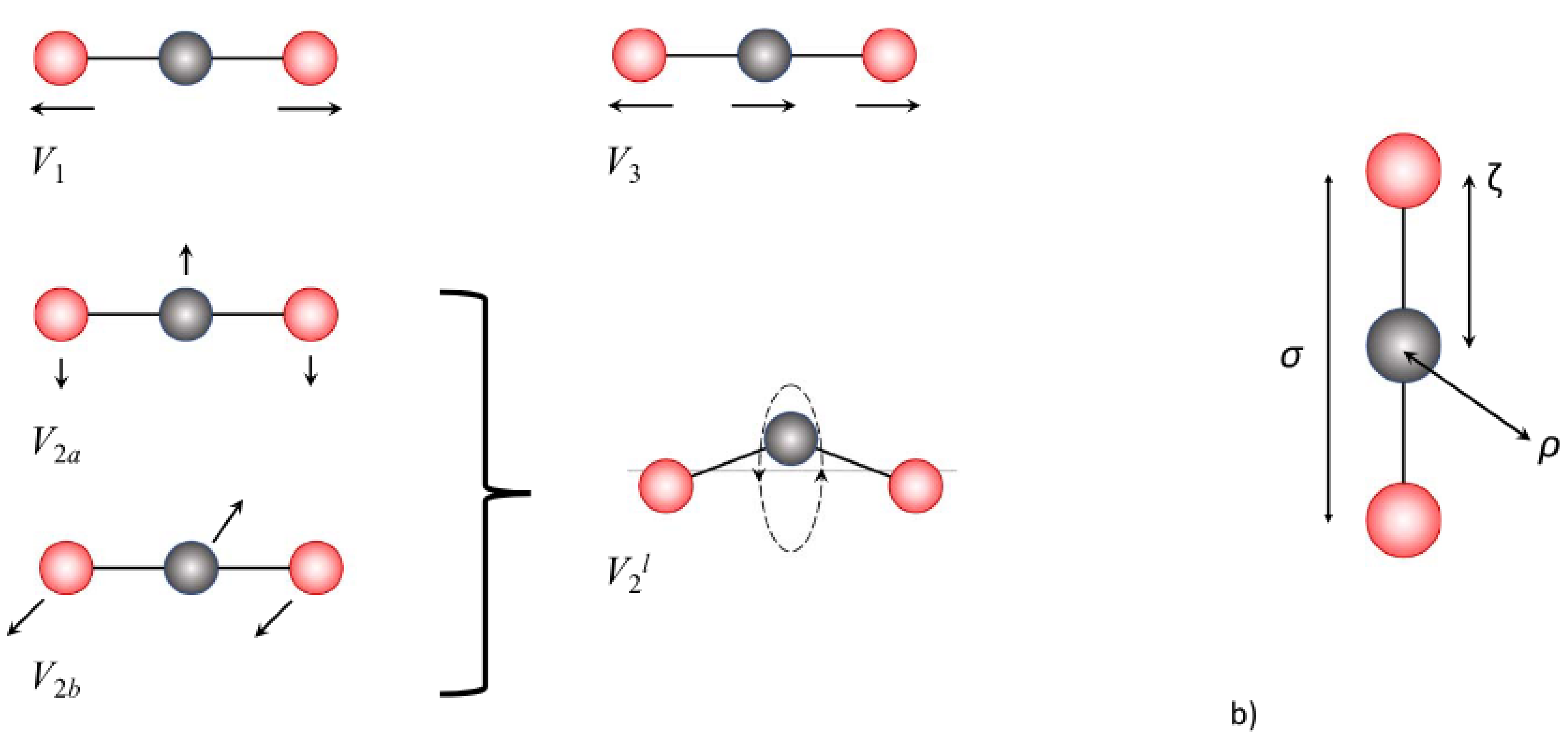
where α is defined as the CO_2 radiative forcing parameter. Global-mean calculations from detailed radiative transfer codes using tabulated spectroscopic data yield $\alpha \approx 5.35$ W m^{-2} (Myhre et al. 1998), with an estimated accuracy of around 10%. Once the atmosphere and ocean have thermally equilibrated, this radiative forcing gives rise to a surface-temperature change of magnitude

$$\Delta T_s \approx +\lambda^{-1}\Delta F, \quad (2)$$

where the parameter λ is the climate feedback parameter, with units of W m^{-2} K^{-1}. Based on data from a range of observational and modeling sources, the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR6) stated that ΔT_s for a doubling of CO_2 is "very likely" (i.e., with greater than 90% probability) in the range 2 to 5 K, with a best estimate of 3 K (Masson-Delmotte et al. 2021). Since the radiative forcing for CO_2 doubling $\Delta F_{2\times} = 5.35 \ln(2) = 3.71$ W m^{-2}, this indicates a value of between 0.74 and 1.85 W m^{-2} K^{-1} for λ.

Given the clear correspondence between observations and the results of sophisticated climate models, the scientific basis of climate change is indisputable. In addition, many comprehensive descriptions of the physics of climate and global warming, including the specifics of the radiative effects of CO_2 doubling, already exist (Pierrehumbert 2011; Wilson & Gea-Banacloche 2012; Zhong & Haigh 2013; Mlynczak et al. 2016; Dufresne et al. 2020; Jeevanjee et al. 2021; Romps et al. 2022; Tziperman 2022; Shine & Perry 2023). Despite this, it is currently still not possible to derive Equation (1) directly starting from fundamental properties of the CO_2 molecule. This is an important objective, because analytic methods are a powerful tool to increase understanding and elucidate the results of numerical simulations. Here, we build on previous efforts and show how this can be achieved, via a synthesis of molecular spectroscopy and climate physics. Our analysis here focuses on Earth's present-day climate, but potential applications to other planets in the solar system and exoplanets are discussed in Section 6.

[4] This differs slightly from the effective radiative forcing definition now used by the IPCC (Masson-Delmotte et al. 2021), although the difference is not important for our purposes. See also discussion in Section 5.



Schematic of the three vibrational modes of carbon dioxide. The two degenerate bending modes superimpose to produce a motion where each atom rotates around the major axis of the molecule, which is represented via the quantum number l. (b) Mass-weighted coordinate system used to express the three fundamental modes of CO 2 as simple harmonic oscillations

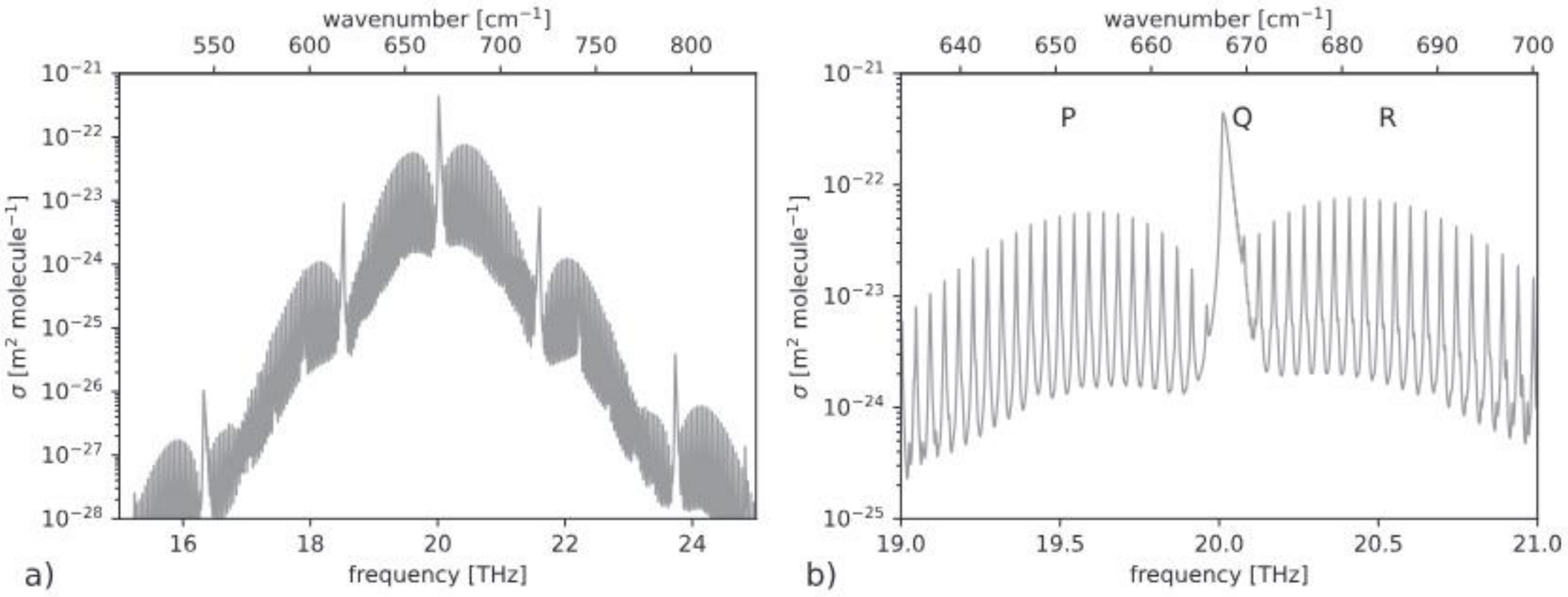
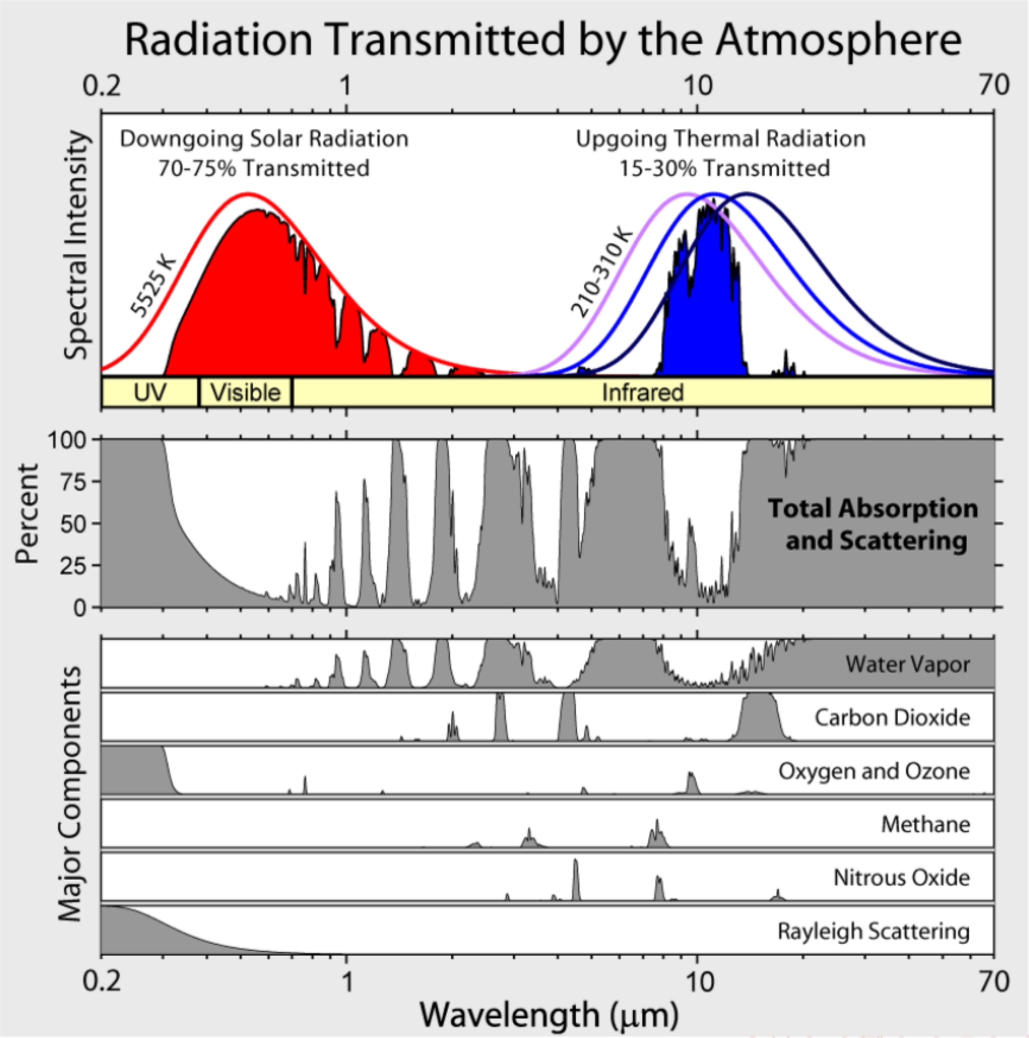


Figure 2. High-accuracy absorption spectrum of CO_2 in the region of the ν_2 band, in cross-section units of meters squared per molecule of CO_2, at pressure p_s and temperature T_s (see Table 1). (a) shows the band over a wide frequency range, while (b) zooms in on the central fundamental band, with P, Q, and R branches labeled (see Section 3). Both plots were produced using the HITRAN2020 database, with line truncation at the standard value of 25 cm^{-1}(0.75 THz) (Gordon et al. 2022).

Sun and Earth Spectrum



The majority of the solar radiation at the top of atmosphere reaches the earth's surface, with the atmosphere on average absorbing around 17% of solar radiation.

Much of the radiation emitted from the surface is absorbed in the atmosphere.

Radiative forcing for GCM

- Increase in concentrations of GHG

  Change in the radiative fluxes

  - No initial condition!

- Different model, different
  - distribution of clouds, humidity, and temperature
  - errors in approximation of radiative transfer

BC Dataset for GCM

- CMIP6 Forcing Dataset Summary, 6.2.41
  - Anthropogenic SLCF, CO_2, and CH_4 Emissions
  - Open Biomass Burning Emissions
  - Land Use
  - GHG Historical Concentrations
  - Stratospheric Aerosols
  - Ozone
  - Nitrogen Deposition
  - Solar
  - Aerosol Optical Properties and Cloud Droplet Number Concentration change

  https://docs.google.com/document/d/1pU9IiJvPJwRvIgVaSDdJ4O0Jeorv_2ekEtted34K9cA

Radiative Transfer Packages

- Line by line (LBL) models
  - high fidelity
  - very fine spectral resolution
- LBL model cannot be used in a GCM for the impossible computational cost required
- (O)105 monochromatic radiation calculations needed

LBLRTM, Clough and Iacono, JGR [1995] M. J.Alvarado et al., ACP [2013]

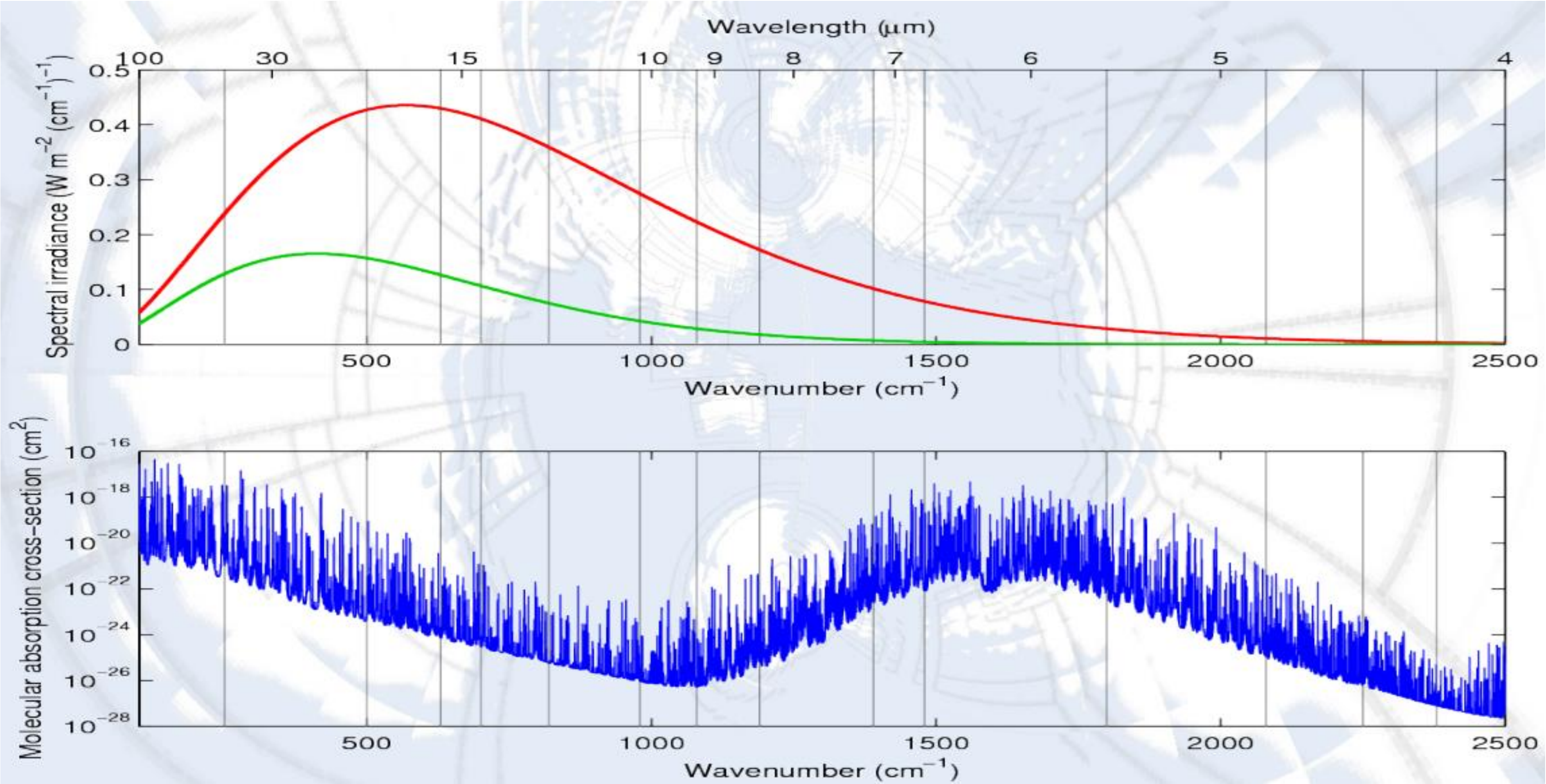
ICA (IPA) model

- Independent Column Approximation: 1D radiative transfer model
  - No net radiative transfer between vertical columns
  - Efficient and embarrassingly parallel.

$$\langle F(z)\rangle=\int S(\lambda)\left[\int\int F_{3D}(x,y,\lambda)\,dx\,dy\right]d\lambda\approx\int S(\lambda)\left[\int\int F_{1D}(x,y,\lambda)\,dx\,dy\right]d\lambda=(1-A_c)\langle F^{clr}\rangle+A_c\langle F^{cld}\rangle$$

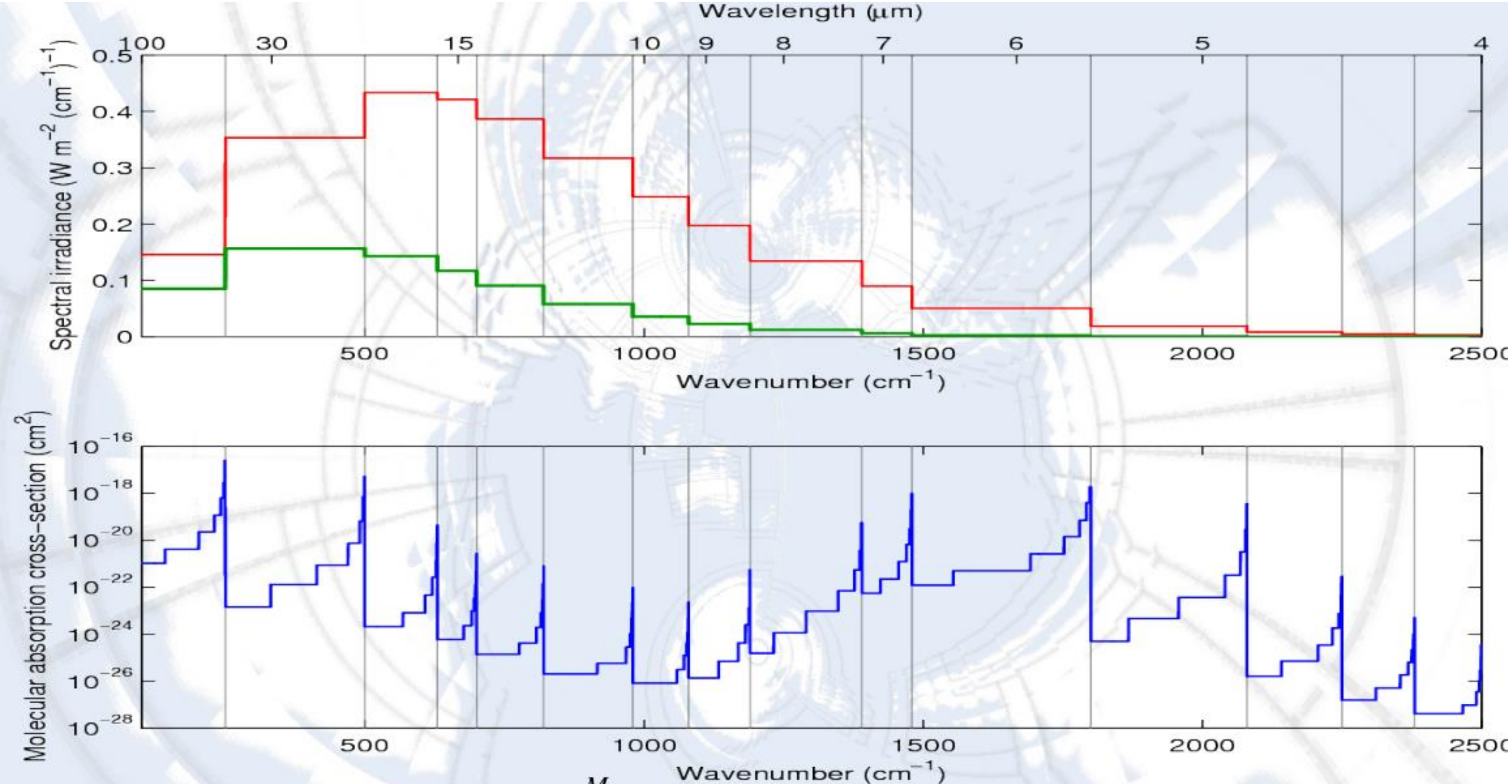
- Subgrid-scale parameterizations

Correlated k-distribution model



Lacis and Oinas, JGR [1991], Fu and Liou, JAS [1992]

Correlated k-distribution model



$$T(z) \approx \sum_{i=0}^{M} c_i \exp\left[-k(g_i)z\right]$$

RRTMG

- Absorption coefficient data for the k-distributions from LBL
- Fluxes and heating rates can be calculated over small number of “well defined” contiguous bands (16LW, 12SW) using a relatively small set of “g” points (140,112)
- LW absorbers: H_2O, CO_2, O_3, N_2O, CH_4, O_2, N_2 and halo-carbons from 100µ to 3µ
- SW sources of extinction: H_2O, CO_2, O_3, CH_4, O_2, N_2, aerosols, and Rayleigh scattering from 3µ to 0.2µ

- https://github.com/AER-RC/RRTMG_LW
- https://github.com/AER-RC/RRTMG_SW

LW integration

Spectral intervals cm^{-1}	Number of g-points	Gases included: Troposphere	Gases included: Stratosphere
10–250	8	H_2O	H_2O
250–500	14	H_2O	H_2O
500–630	16	H_2O, CO_2	H_2O, CO_2
630–700	14	H_2O, CO_2	O_3, CO_2
700–820	16	H_2O, CO_2, CCl_4	O_3, CO_2, CCl_4
820–980	8	H_2O, CFC11, CFC12	CFC11, CFC12
980–1080	12	H_2O, O_3	O_3
1080–1180	8	H_2O, CFC12, CFC22	O_3, CFC12, CFC22
1180–1390	12	H_2O, CH_4	CH_4
1390–1480	6	H_2O	H_2O
1480–1800	8	H_2O	H_2O
1800–2080	8	H_2O	
2080–2250	4	H_2O, N_2O	
2250–2380	2	CO_2	CO_2
2380–2600	2	N_2O, CO_2	
2600–3000	2	H_2O, CH_4	

Clouds, McICA

- Compute the clear and cloud part transmission separately by level
- Prescribe vertical structure using simple, fixed rules
  - Substantial horizontal variability
  - Complicated vertical structure
- Stochastic processing using Monte Carlo techniques (Mc)
  - Uncorrelated random noise produced do not affect mean circulation.
  - Cloud structure external to the solver

Pincus et al, JGR 2003, Räisänen et al., JC 2005

GCM RT Evaluation

Wild CD, [2020] - https://doi.org/10.1007/s00382-020-05282-7

- Energy balance components are often in better agreement with reference estimates
- Sortwave clear-sky budgets are almost consistently simulated by the CMIP6 models
- Inter-model spread in the representation of many of the components on the order of 10–20 W m^{-2} globally
- The inter-model spread in mean latent heat fluxes exceeds 20% (18 Wm −2)

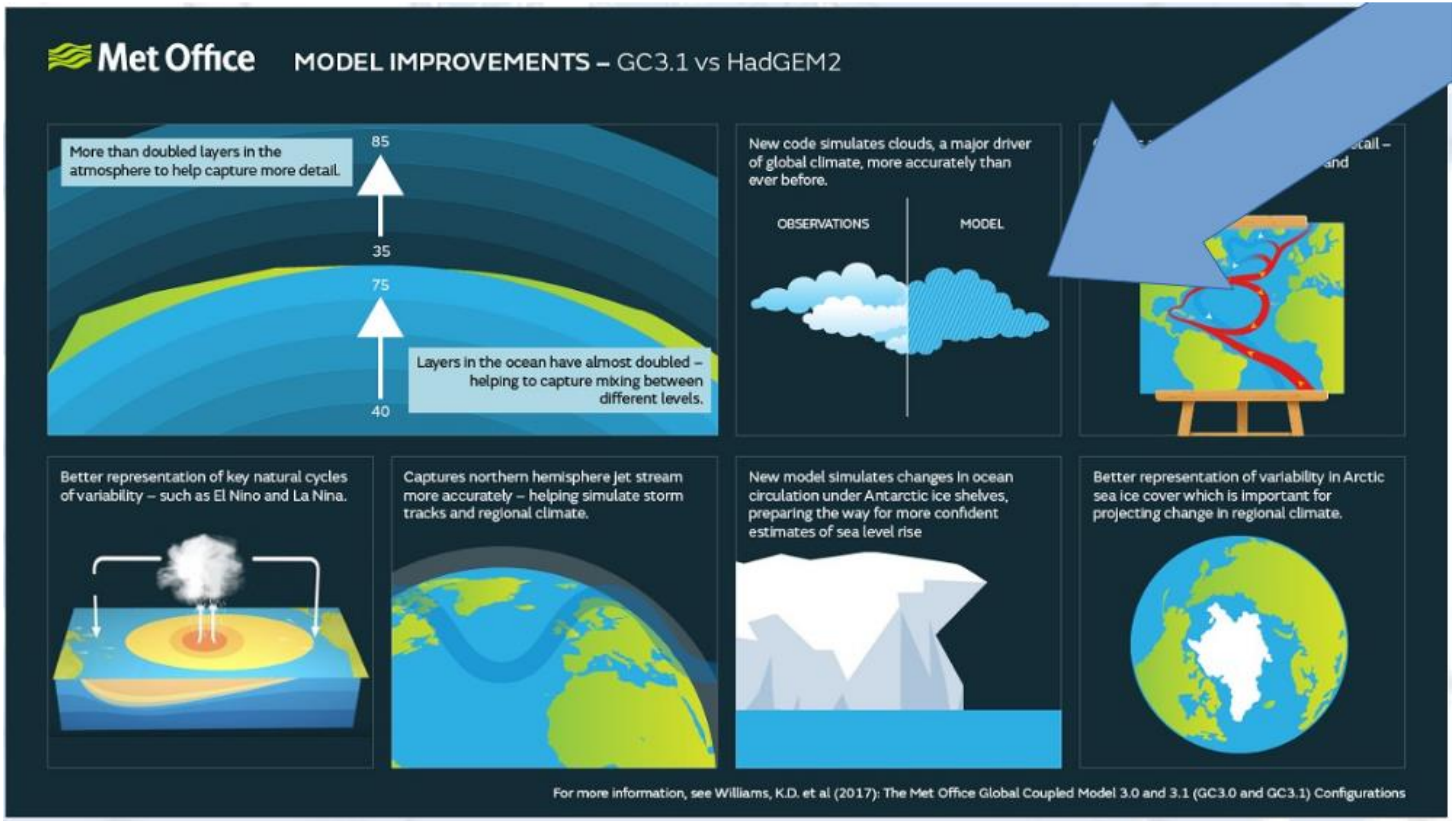
CMIP6 largely remediates overestimation in surface downward shortwave and underestimation in downward longwave radiation

The Cloud Feedback

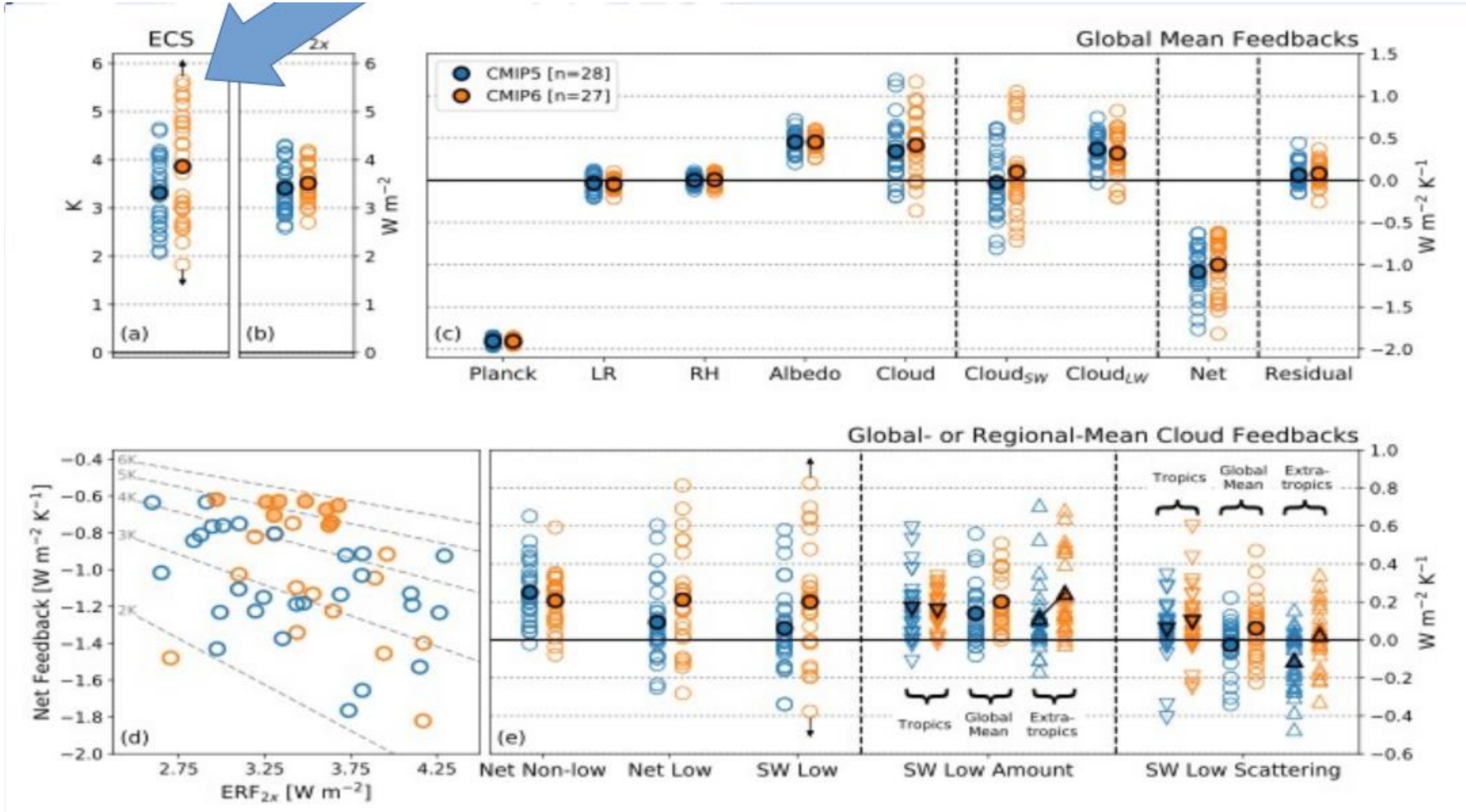
- Problem is in the cloud :(
  - rising free tropospheric clouds (LW +)
  - decreasing tropical low cloud amount (LW -)
  - increasing high-latitude low cloud optical depth (SW-)
- cloud micro-physics, turbulence, convection

Ceppi et al., (2017) WIREs Clim Change

Better models?



Better models?



Zelinka et al, [2020] GRL

Chance

Does Model Calibration Reduce Uncertainty in Climate Projections? Tett et al, [2022], JC

MODEL PARAMETER CALIBRATION WORKS!

STANDARD PROCEDURE?

Future RT improvements

Radiation codes can reproduce LBL calculations to within 1% for shortwave fluxes and fractions of a percent for longwave

- Computational cost force a large timestep.
- Accelerators for computational kernels: RTE-RRTMGp
- Neural Network solutions are not fit for GCM use: statistical assumption by using “prior” data can break for future.

  https://github.com/earth-system-radiation/rte-rrtmgp

3D Couds

Should we go 3D?

At what horizontal resolution ICA assumption breaks?

https://github.com/AlexandraLJones/MCBRaT3D

Journal of Applied Meteorology and Climatology 47, 12; 10.1175/2008JAMC1842.1

Thank you