Confirming a Critical Foundation of Global Warming:

Direct Observational Evidence from Space of the Effect of CO_2 Growth on Infrared Spectral Radiances

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Launch of the NASA Aqua Satellite

4 May 2002

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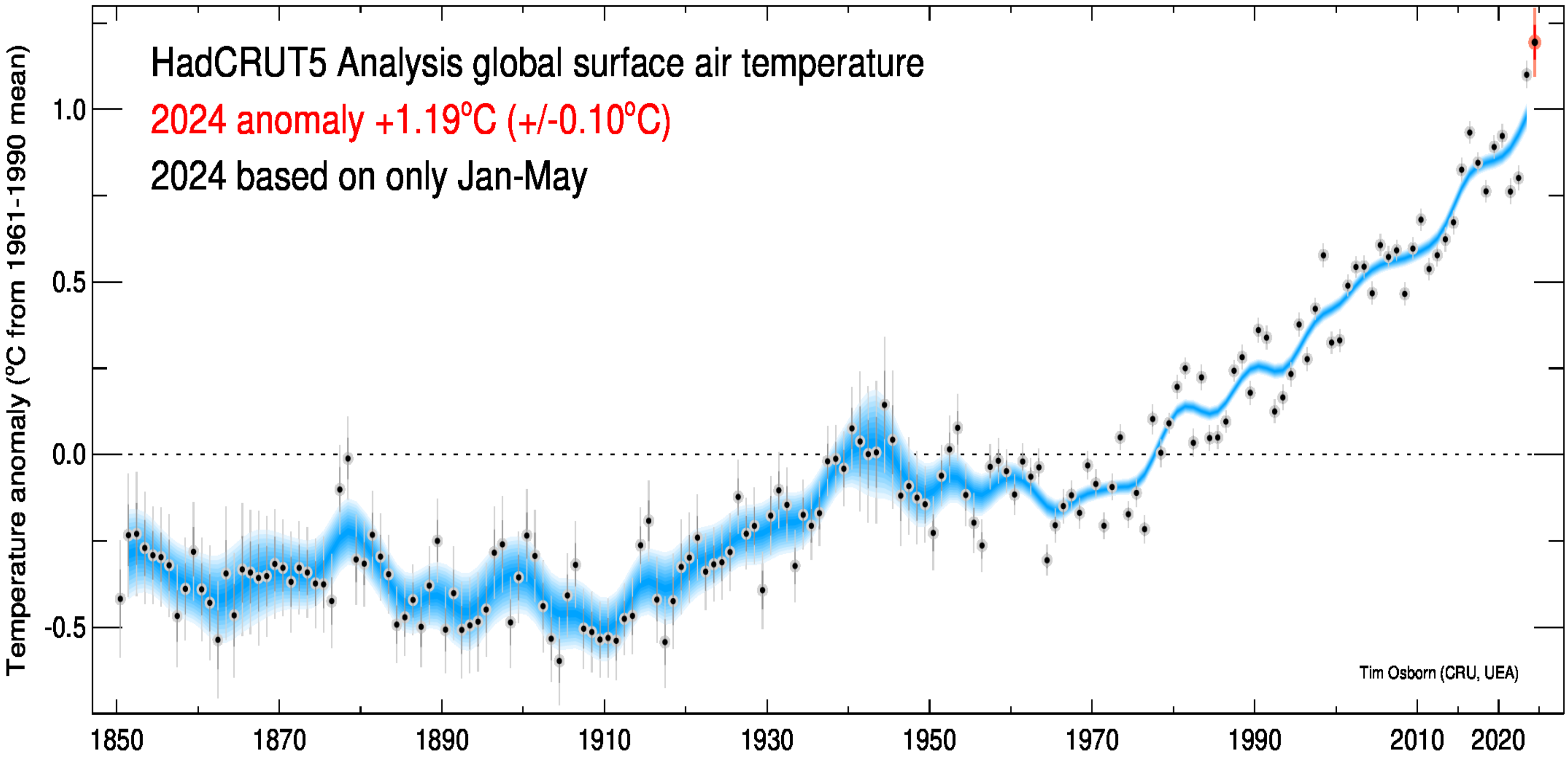
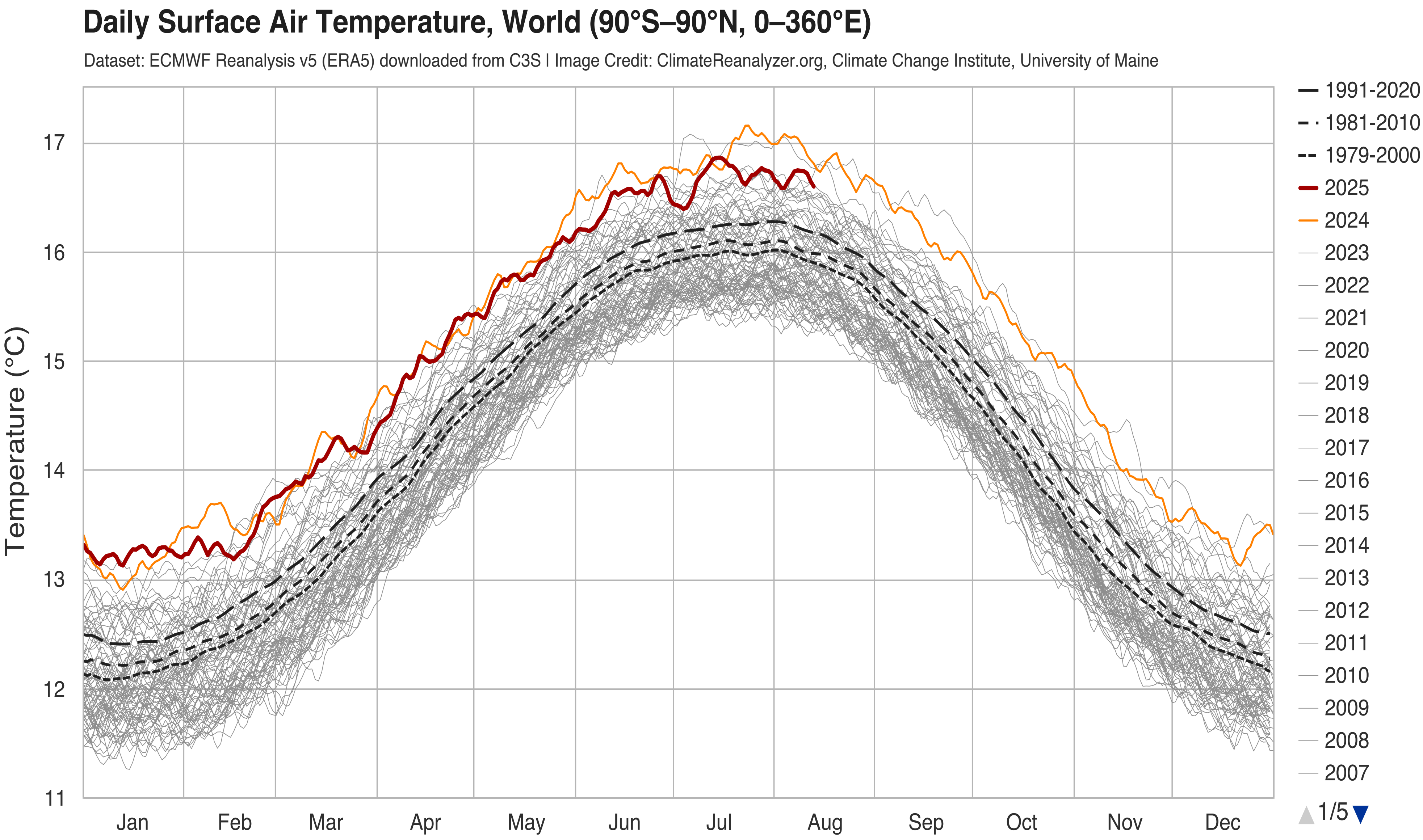
Global surface temperature over the last 170 years: Global Warming



Significant increase in global mean surface temperature in last 50 years

2023, 2024 and 2025: Global warming appears to be accelerating



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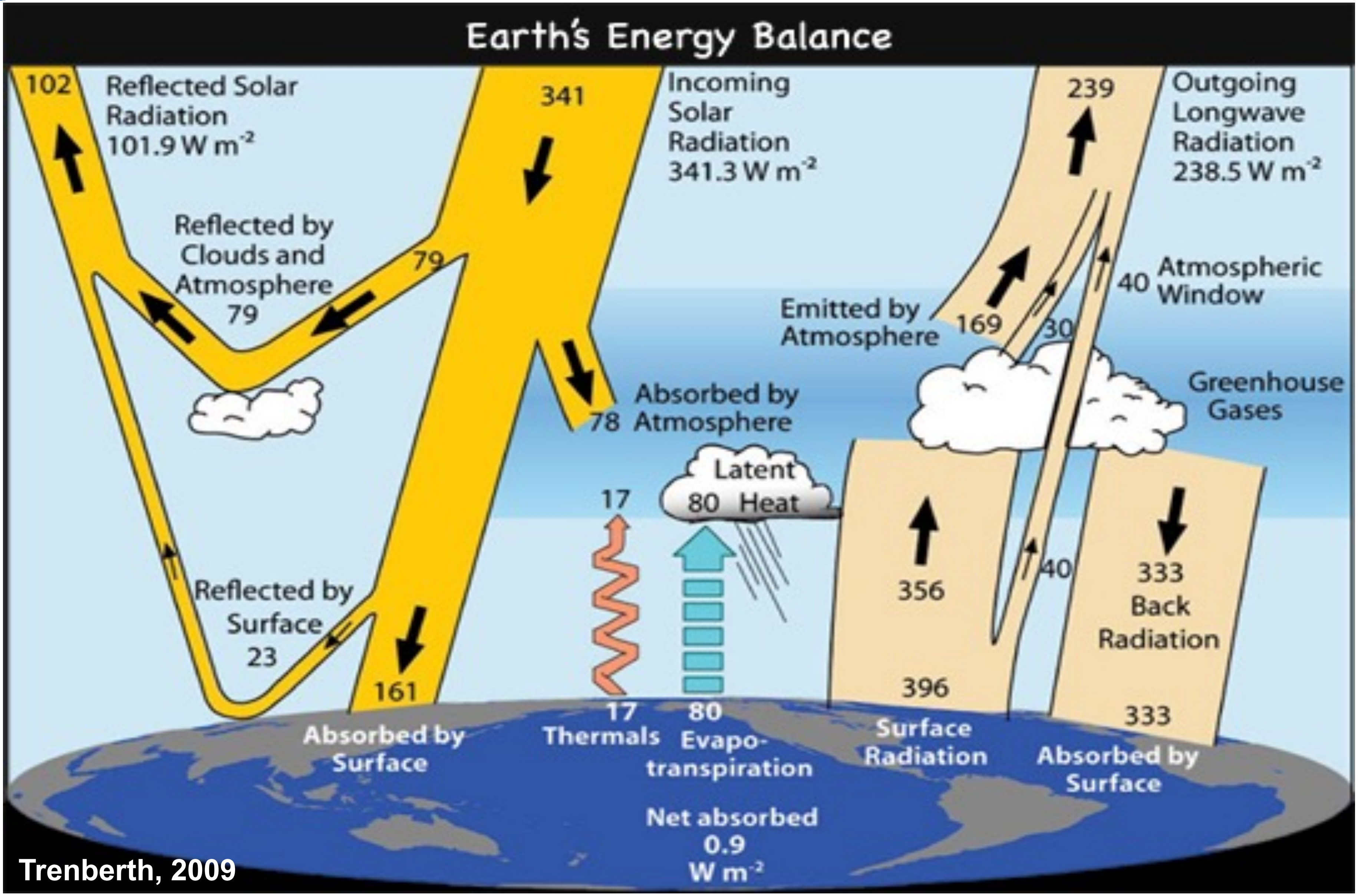
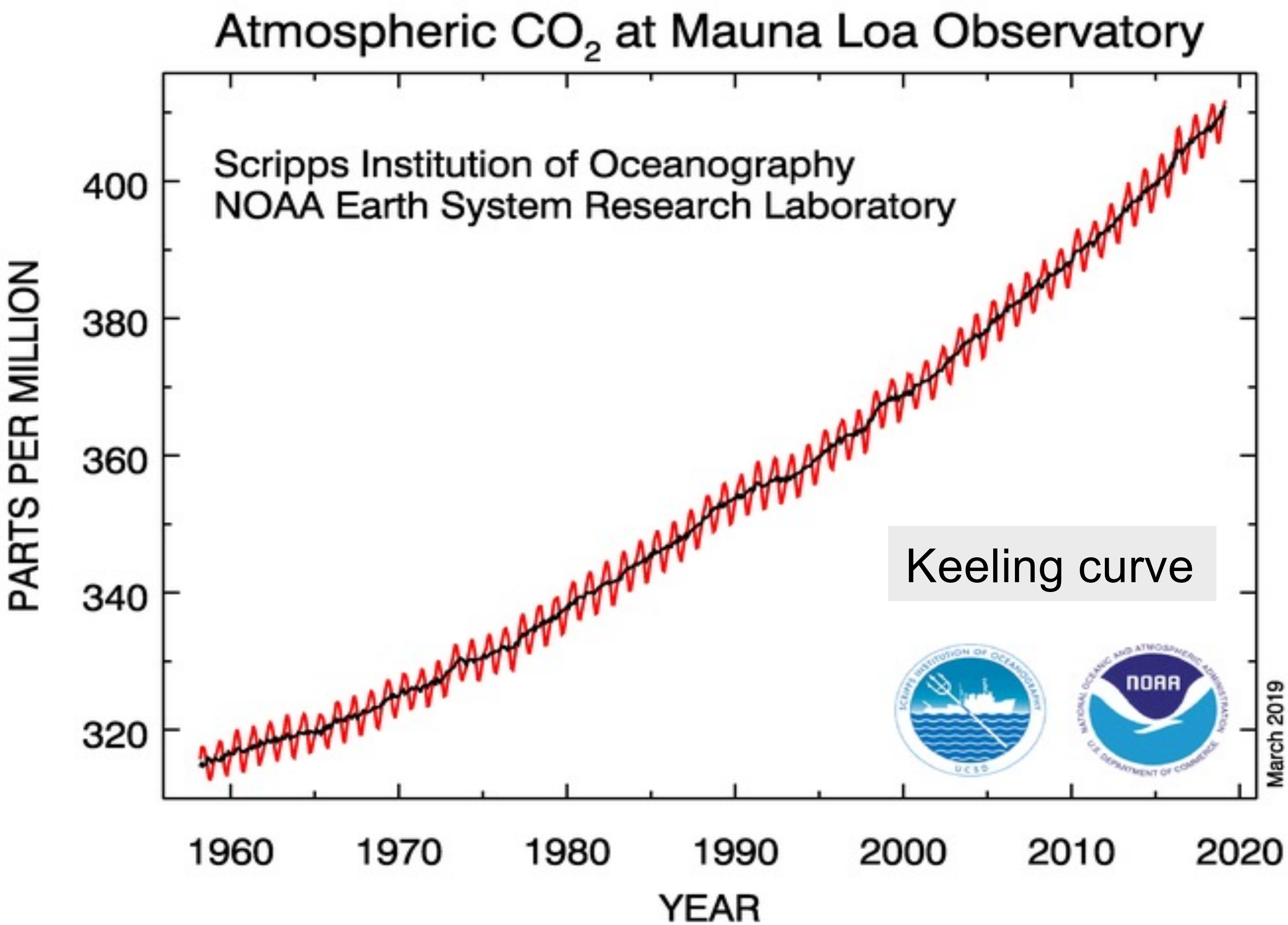
Top of Atmosphere (TOA) Radiation Balance



Balance between absorbed solar radiation and outgoing LW radiation

Why is the global surface temperature increasing?



Steady and significant increase in carbon dioxide concentration

Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity

SYUKURO MANABE AND RICHARD T. WETHERALD

Geophysical Fluid Dynamics Laboratory, ESSA, Washington, D. C.

(Manuscript received 2 November 1966)

Radiative-convective single column model of the Earth's atmosphere

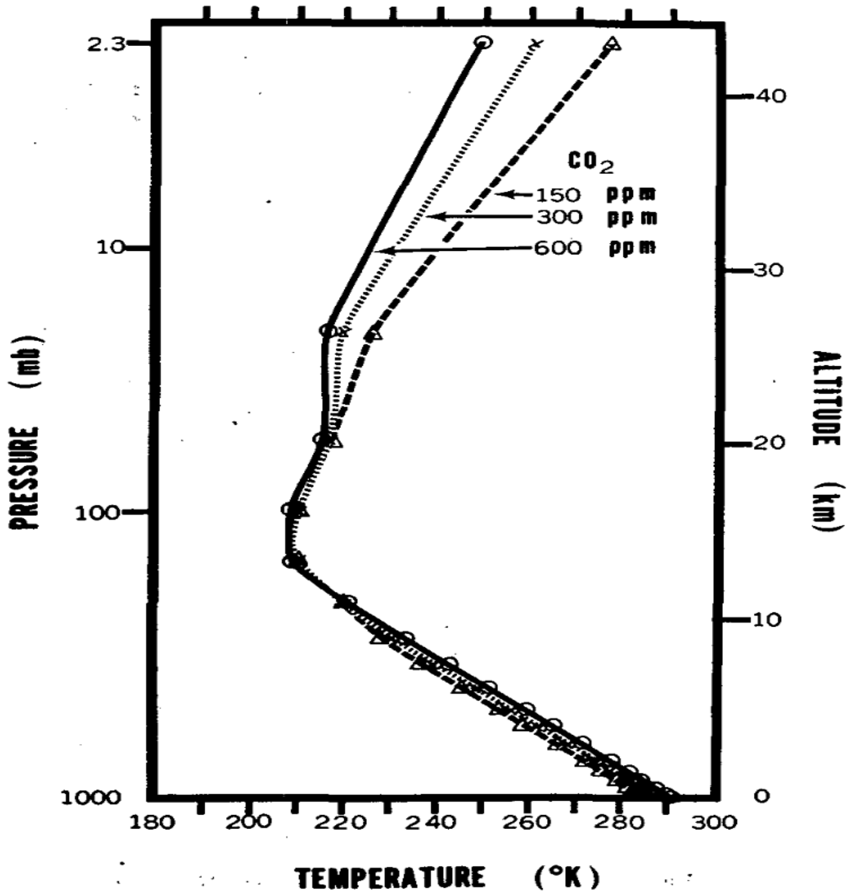


TABLE 5. Change of equilibrium temperature of the earth's surface corresponding to various changes of CO_2 content of the atmosphere.

Change of CO_2 content (ppm)	Fixed absolute humidity		Fixed relative humidity	
	Average cloudiness	Clear	Average cloudiness	Clear
300 → 150	−1.25	−1.30	−2.28	−2.80
300 → 600	+1.33	+1.36	+2.36	2.92

Doubling CO_2 leads to surface warming of ~ 2.3 K (with fixed RH)

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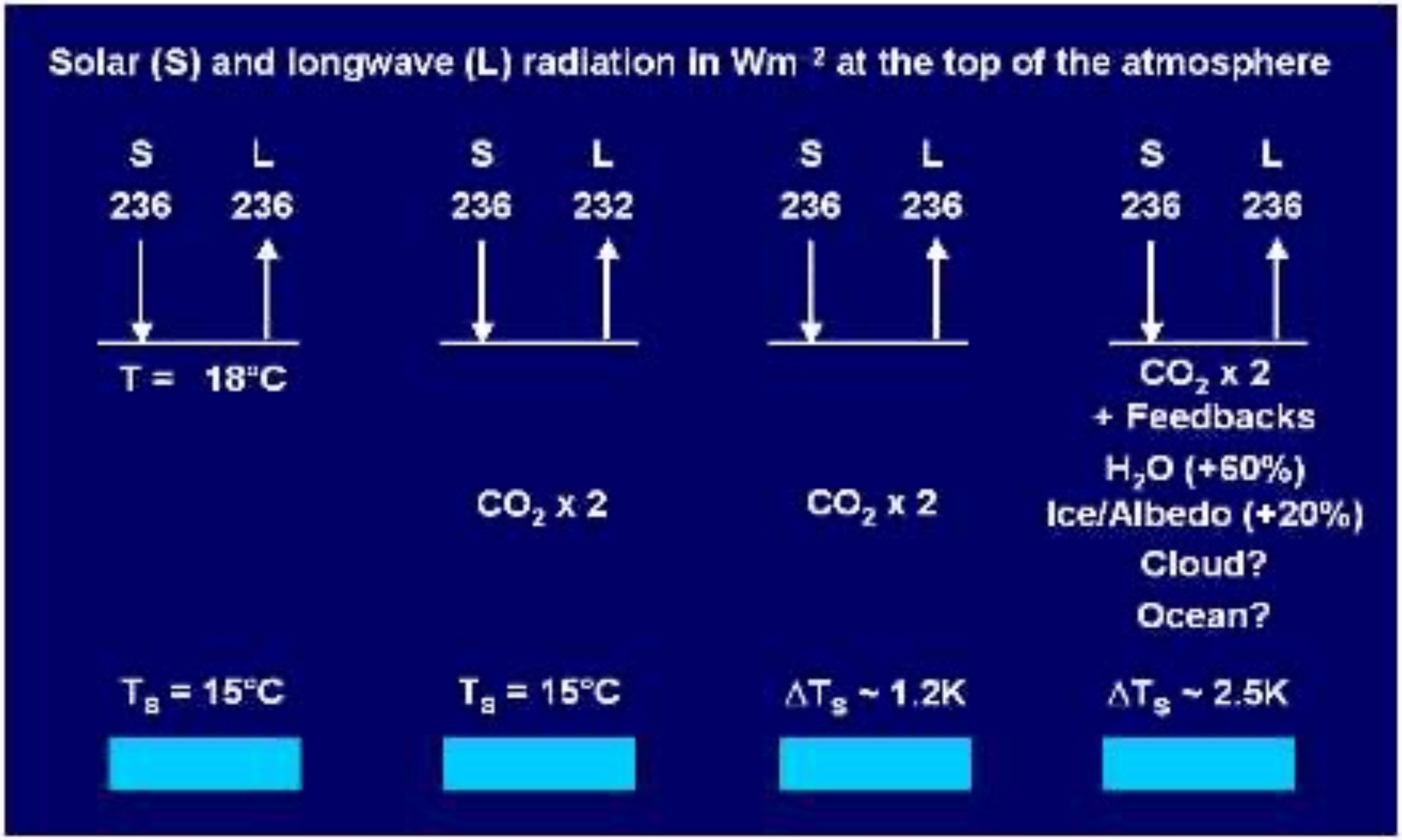
Top of Atmosphere (TOA) radiation balance and global warming: a simplified view



Houghton, 1991, 1997

Changes in TOA longwave fluxes following doubling CO_2

Energy balance is restored with increase of surface temperature

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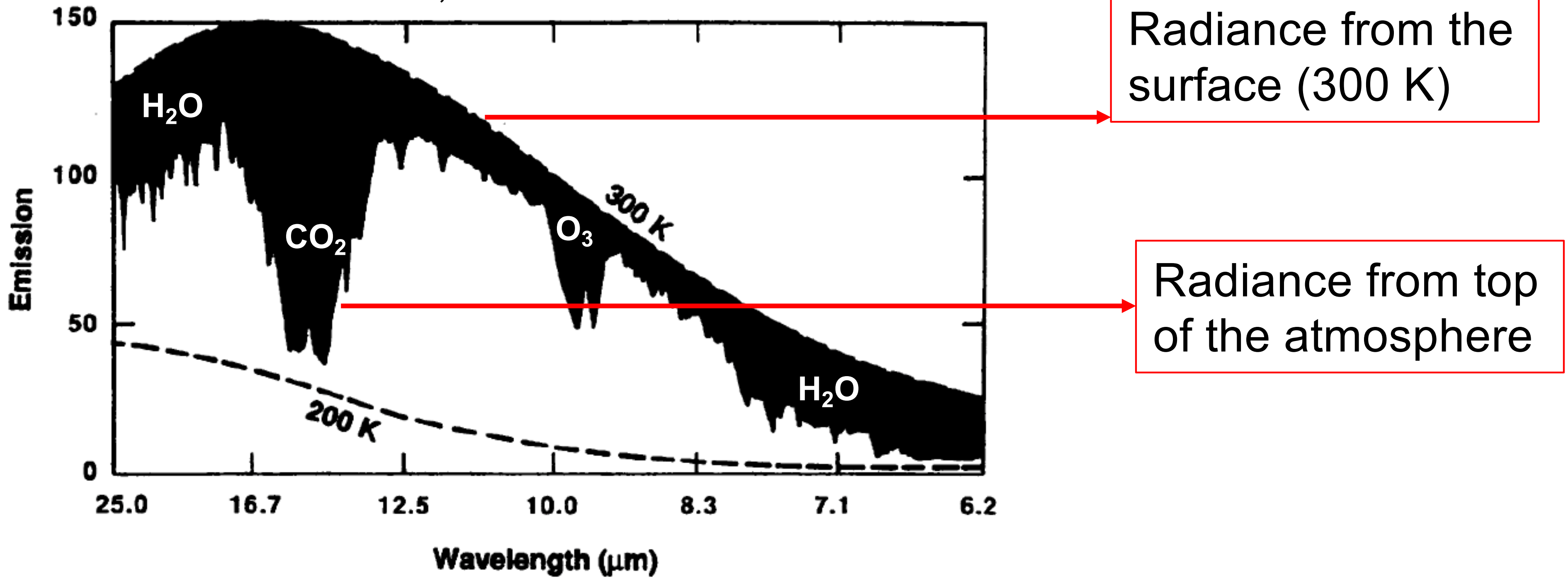
But how can we demonstrate that it is CO_2 that is causing the changes in outgoing LW radiation?

From Ramanathan, 1988



LW spectra measured by the IRIS instrument (Hamel et al, 1972) over tropical Pacific Ocean (clear-sky)

Earth's LW spectra is modulated by CO_2, water vapor, ozone, clouds, …

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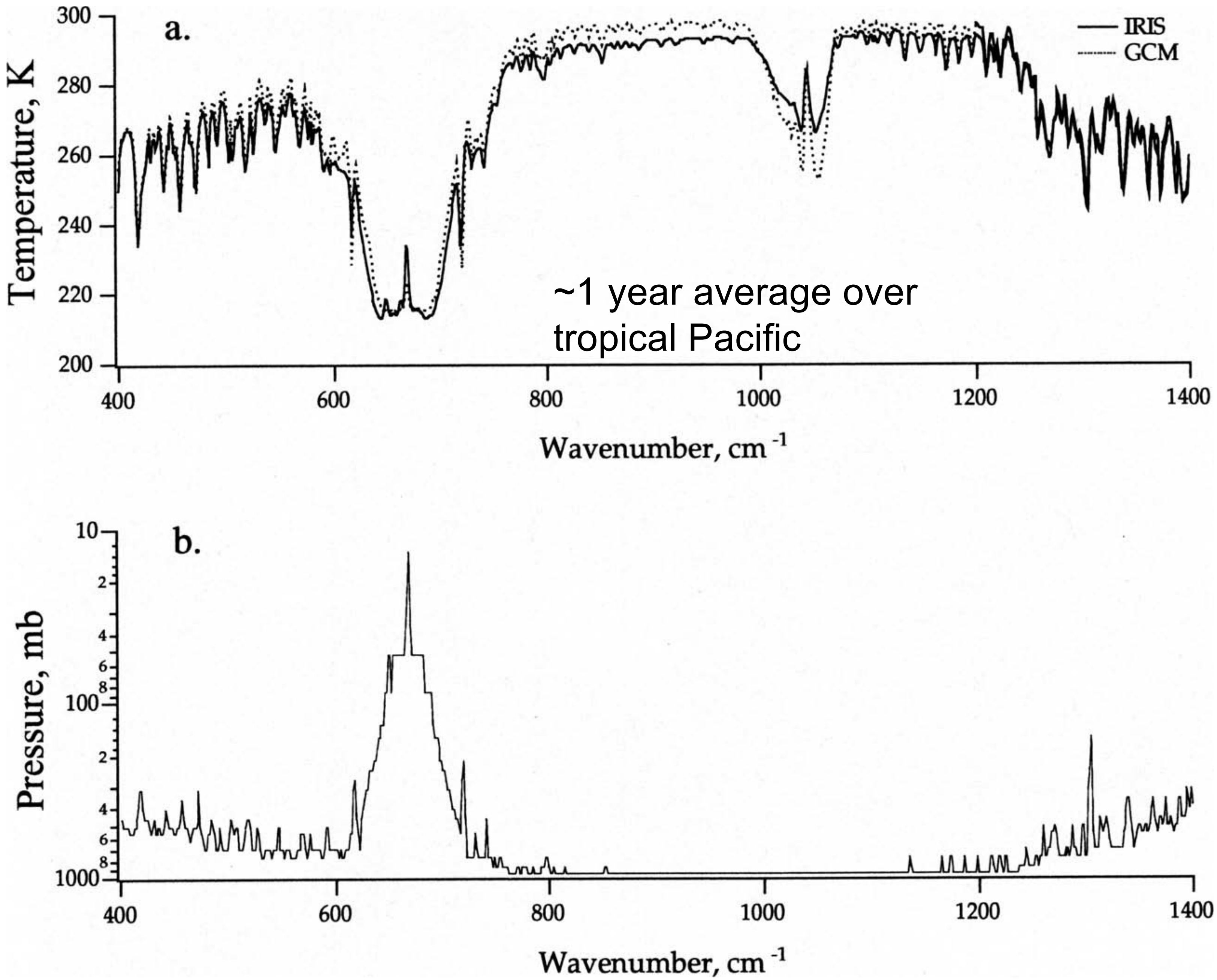
Earth's atmosphere emits from different heights at different wavenumbers

Pressure level of maximum emission to space



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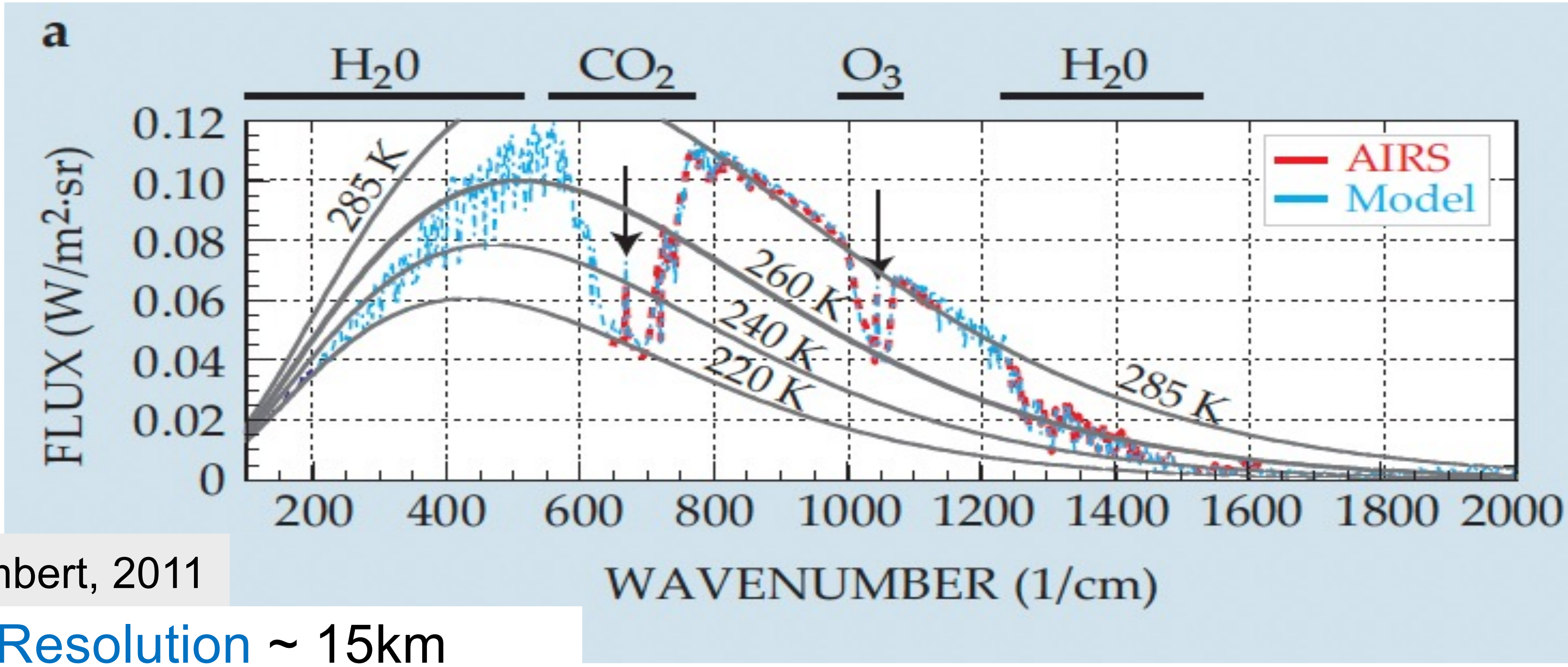
Atmospheric Infrared Sounder (AIRS)



Pierrehumbert, 2011

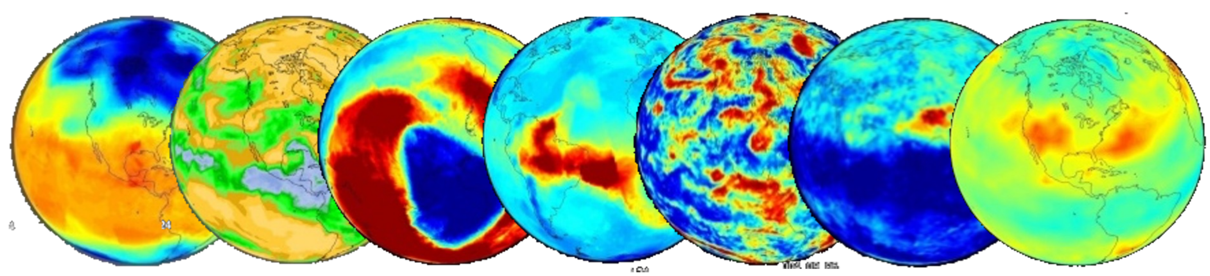
Spatial Resolution ~ 15km

Spectral properties

- 2378 Channels
- 3.74-15.4 µm

Radiometric properties

- Accuracy < 0.2 K
- Stability < 0.002 K/year



Temperature · Water Vapor · Ozone · Carbon Monoxide · Clouds · Methane · Carbon Dioxide

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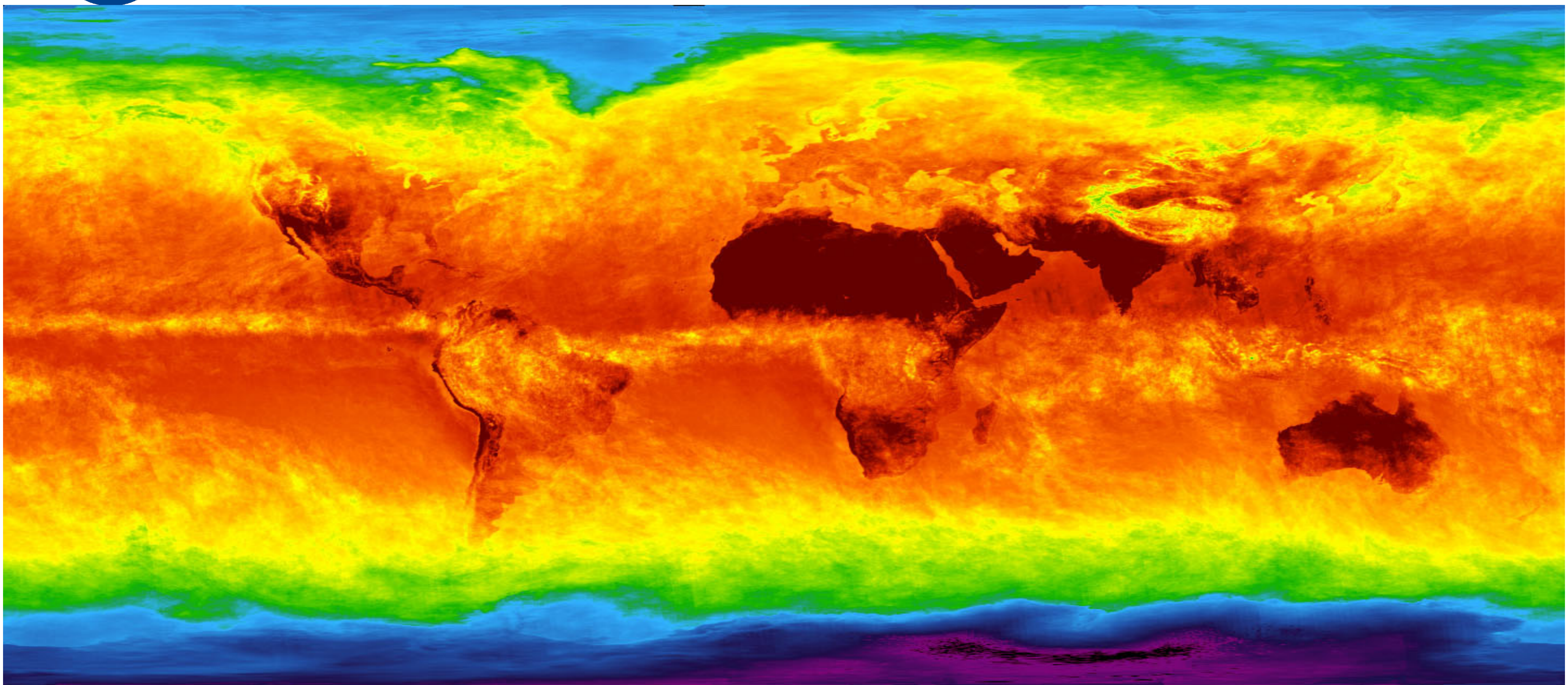
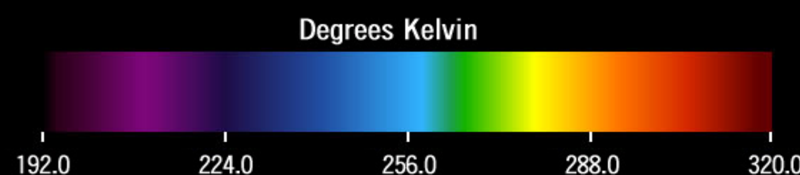
Infrared View of Earth's Climate



AIRS was launched onboard Aqua satellite, 4 May 2002



AIRS is working well and could continue to collect data for years

AIRS Average Brightness Temperature for month of April 2003

Data from AIRS Surface Channel 2616 cm^{-1}

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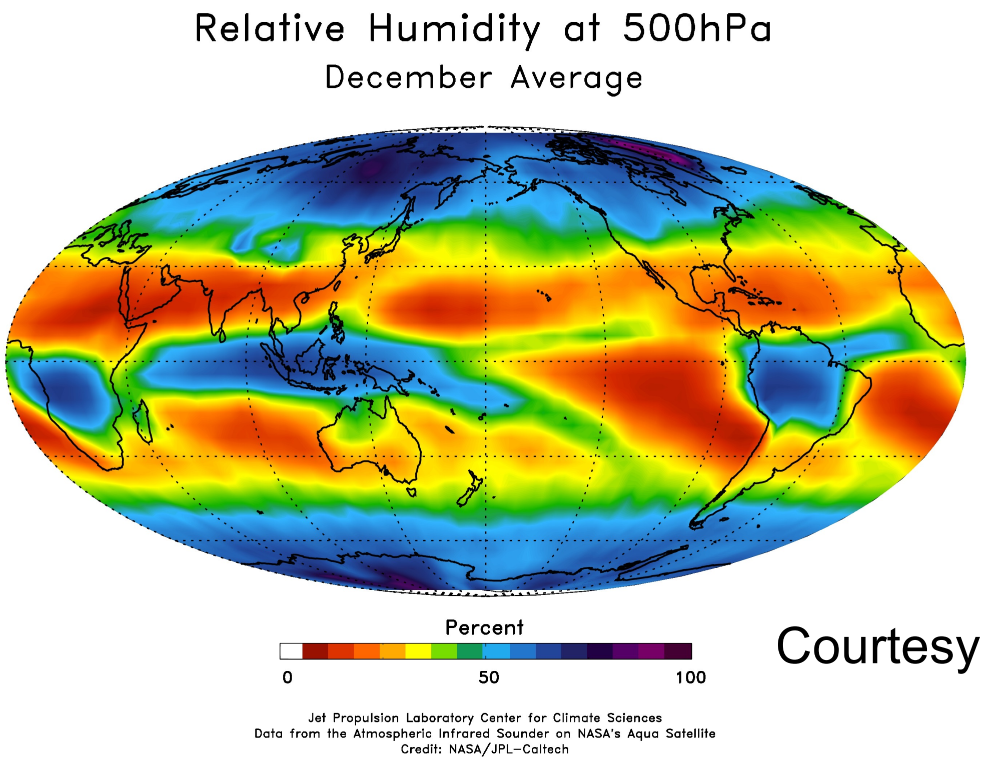
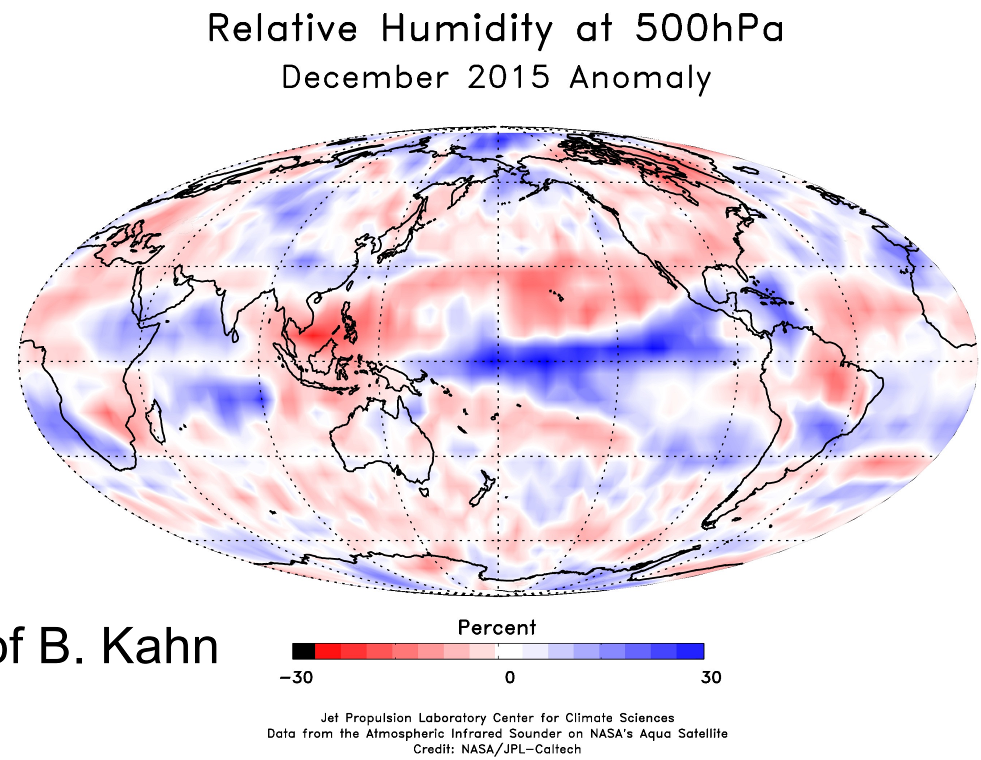
First Observations of 3D Structure of Global Atmospheric Thermodynamics

AIRS probes into the vertical structure of the atmosphere: e.g., Significant ENSO changes in mid-tropospheric relative humidity



Courtesy of B. Kahn



Long records allow to study several ENSO events and to better understand the impacts of - and what controls - ENSO

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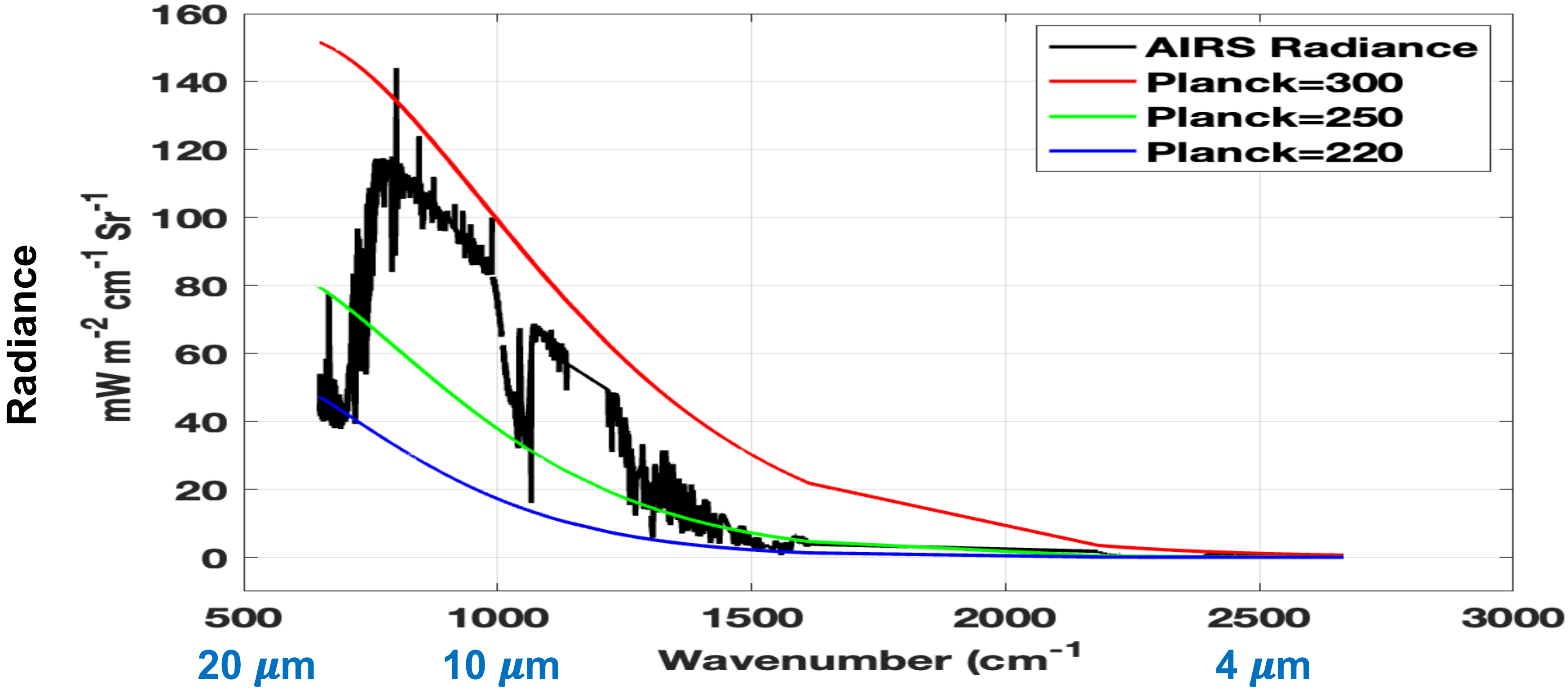
Wealth of climate physics information contained in the AIRS spectra



How do we optimally exploit the wealth of information about the physics of climate change contained in the AIRS spectra?

Great work has been performed over the last 20 years using AIRS spectral observations: e.g., Huang et al. 2007, 2008; Strow and DeSouza-Machado, 2020; Huang et al., 2022; Raghuraman et al., 2023.

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Going back to the root cause of global warming…
Can we measure the direct effect of CO_2 growth on LW spectra from space?

- Measurements from space of the direct effects of increased CO_2 on the LW spectra have been **notoriously difficult** to obtain because:
  1) **Sparsity** of high spectral resolution observations of longwave radiances before the early 21st century
  2) Absence of **long term** (many years) and stable radiance records
  3) Challenge of **disentangling** the effects of CO_2, temperature, and water vapor on the spectral radiances

- Measurements of the spectral effects of the combined changes in CO_2, temperature, water vapor and other gases have been published (e.g., Harries et al., 2001; Brindley and Bantges, 2016; Strow and DeSouza-Machado, 2020; Whitburn et al., 2021; Huang et al., 2022; Raghuraman et al., 2023)

- Effects of CO_2 alone have not been observed directly

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Going back to the root cause of global warming…

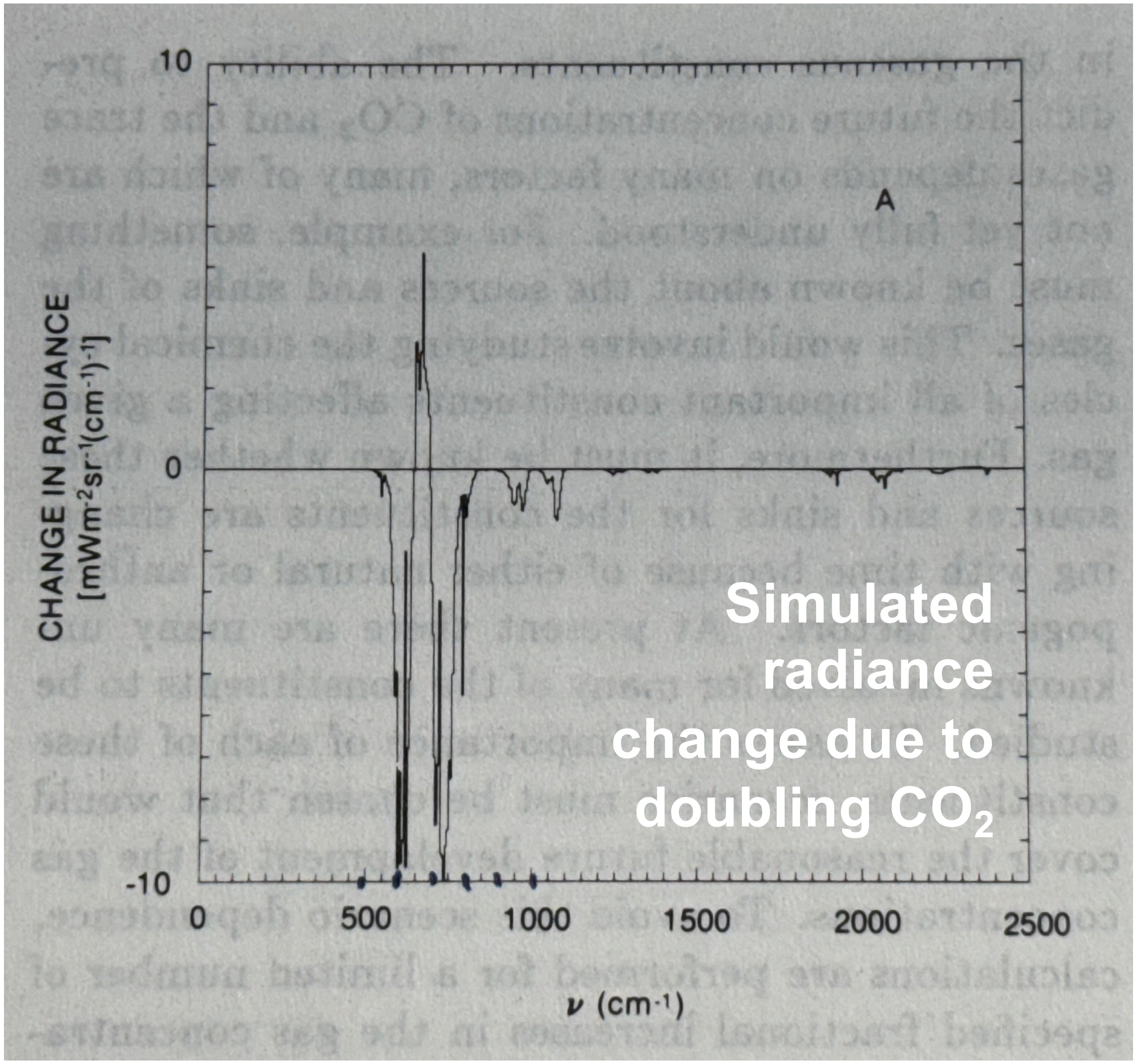
What is the precise impact of CO_2 growth on LW spectral radiances?

Simulation Studies

Kiehl (1983):

1) Simulated the impact of CO_2 growth on clear-sky spectra

2) Suggested hyper-spectral LW satellite instruments to detect from space the impact of CO_2 growth



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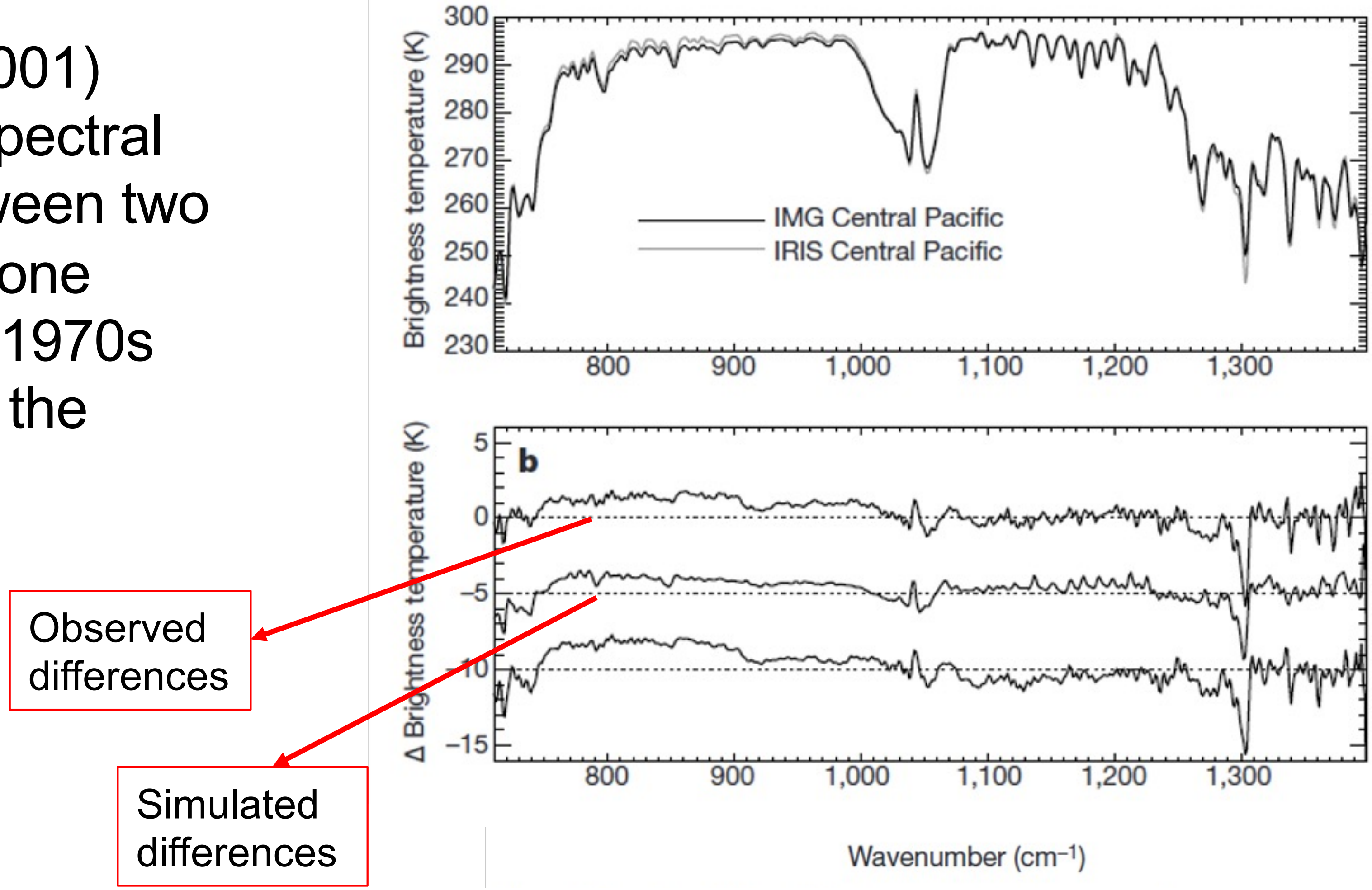
Pioneering Observational Study: Harries et al. (2001)

Harries et al. (2001) calculated the spectral differences between two IR instruments, one launched in the 1970s and the other in the 1990s



Harries et al. (2001) are able to discern and assign, using model simulations, some of the spectral differences to changes in greenhouse gases such as CO_2 BUT does not observe CO_2 growth impact directly

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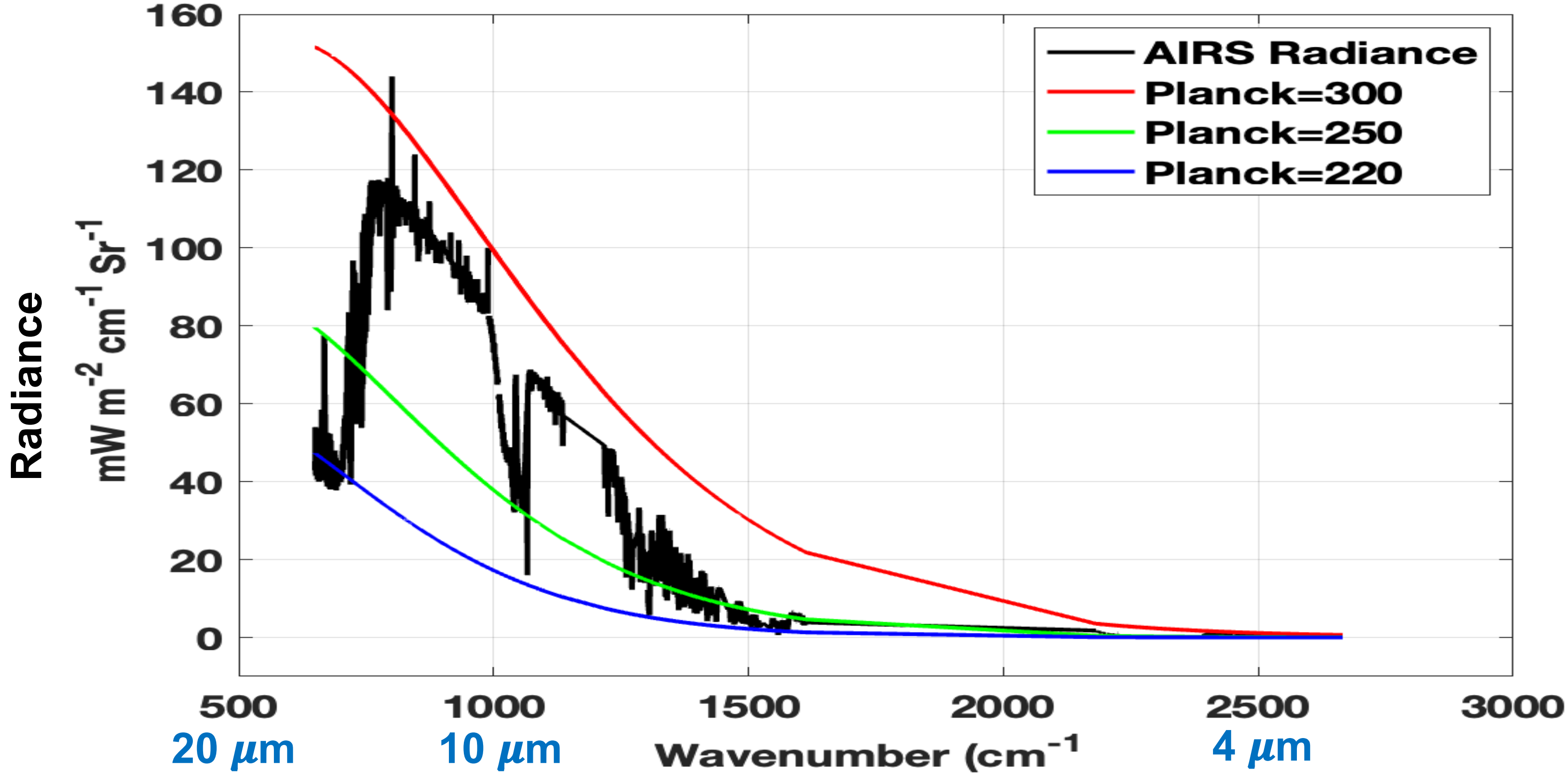
Going back to the root cause of global warming…

Can we measure from space the direct effect of CO_2 growth on LW spectra?



AIRS has a **long** and **stable** radiance record

But how can we disentangle the effects of CO_2 from temperature and water vapor on the spectral radiances?

AIRS Radiance Trends and Stability

Recent key studies (Strow & DeSouza-Machado 2020, Huang et al. 2022, Raghuraman et al. 2023):

i) Investigate AIRS radiance trends in detail

ii) Establish the remarkable stability of the AIRS radiance record (2.10^{-3} K/year)

iii) Discuss the role of temperature, water vapor, CO_2, and other gases in framing the nature of the AIRS radiances.

But these studies use modelling to isolate these effects

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New Methodology: Temperature and Water Vapor Analogues

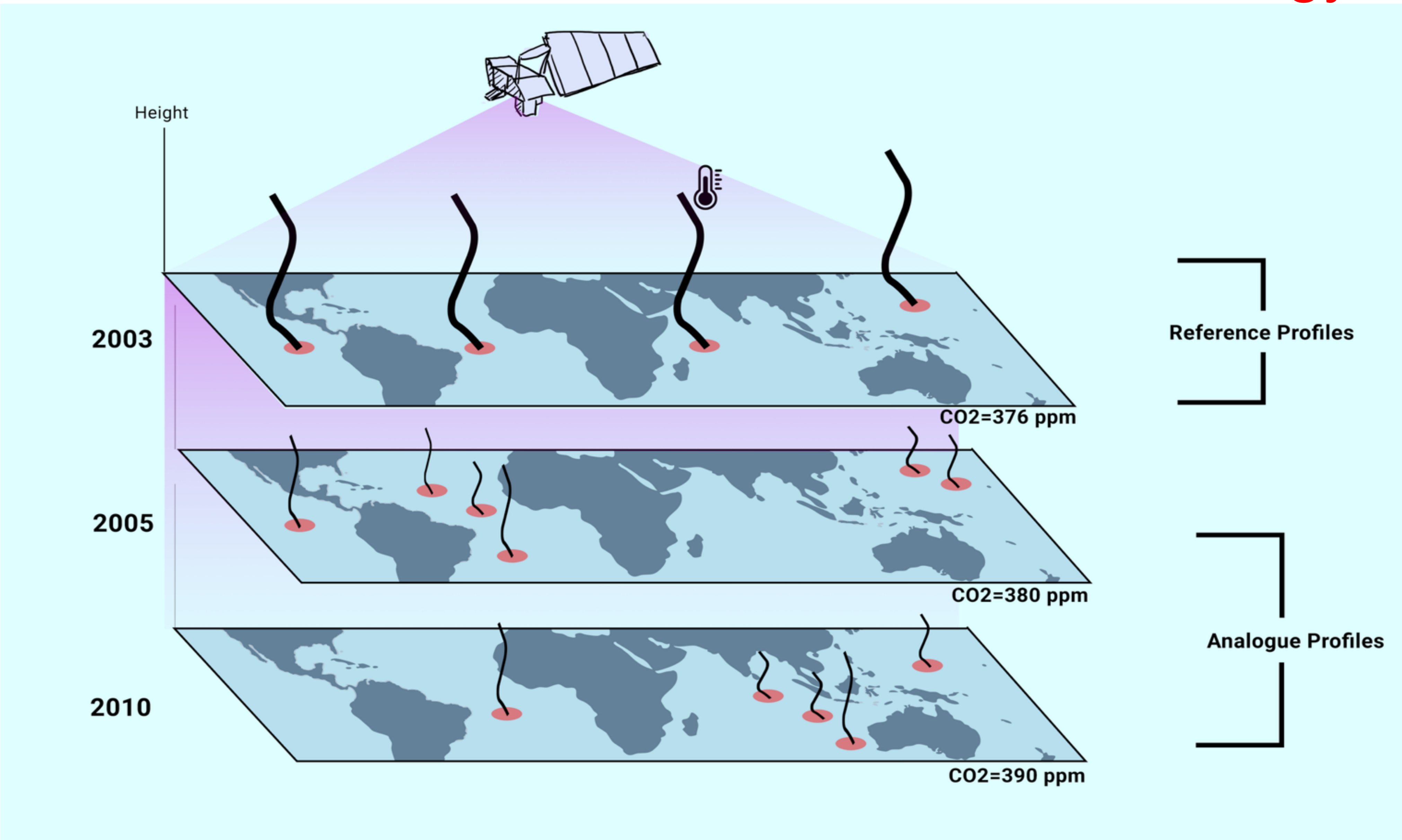
- New methodology for a more direct measurement of the effect of CO_2 increase on longwave spectral radiances

- **Objectives**:
  - To isolate the effects of CO_2 from temperature and water vapor
  - To provide a direct and more precise comparison with theory

- **Approach**: **search for atmospheric profiles of temperature and water vapor that are as similar as possible** (‘analogues’) to a set of reference profiles, but have different CO_2 concentrations

- Measuring from space the spectral radiances of these analogues allows to detect the impact of CO_2 in key spectral regions.

Analogue Methodology



Analogue radiances isolate CO_2 impact from T and q

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T and q reference and analogue profiles

Reference profiles:

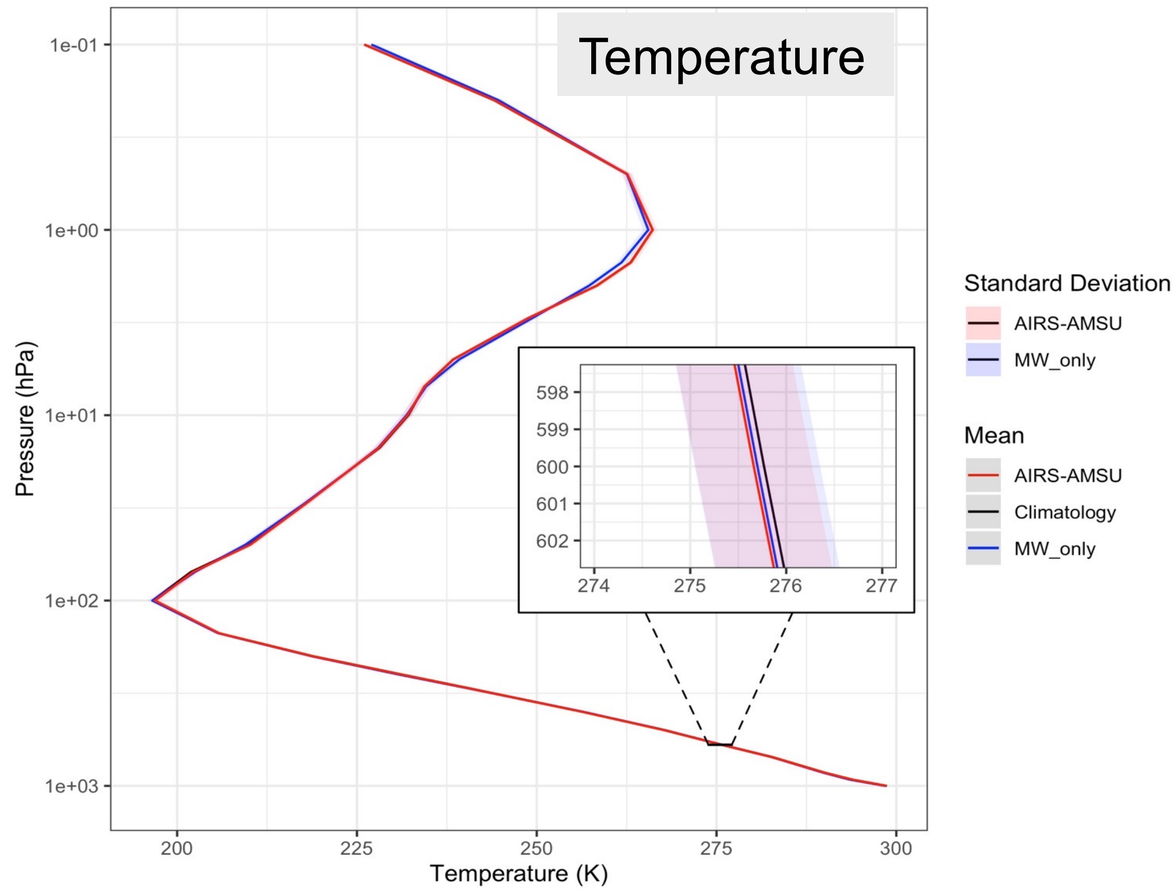
1000 temperature and water vapor profiles from July 2003 are randomly selected

Constrained to:

i) Tropical-subtropical oceans [30S to 30 N]

ii) Cloud cover < 10%

iii) 298 K < SST < 302 K



Profiles can be from retrievals or reanalysis: in this study we use IR/MW (AIRS/AMSU) with NN prior and MW-only retrievals

- Mean T reference profiles for AIRS/AMSU (red) and MW-only (blue) retrievals, and mean climatology AIRS/AMSU profile (black).
- Profiles of standard deviations of all analogue differences (vs reference profiles) from AIRS/AMSU (red shading) and MW-only (blue shading) analogues.

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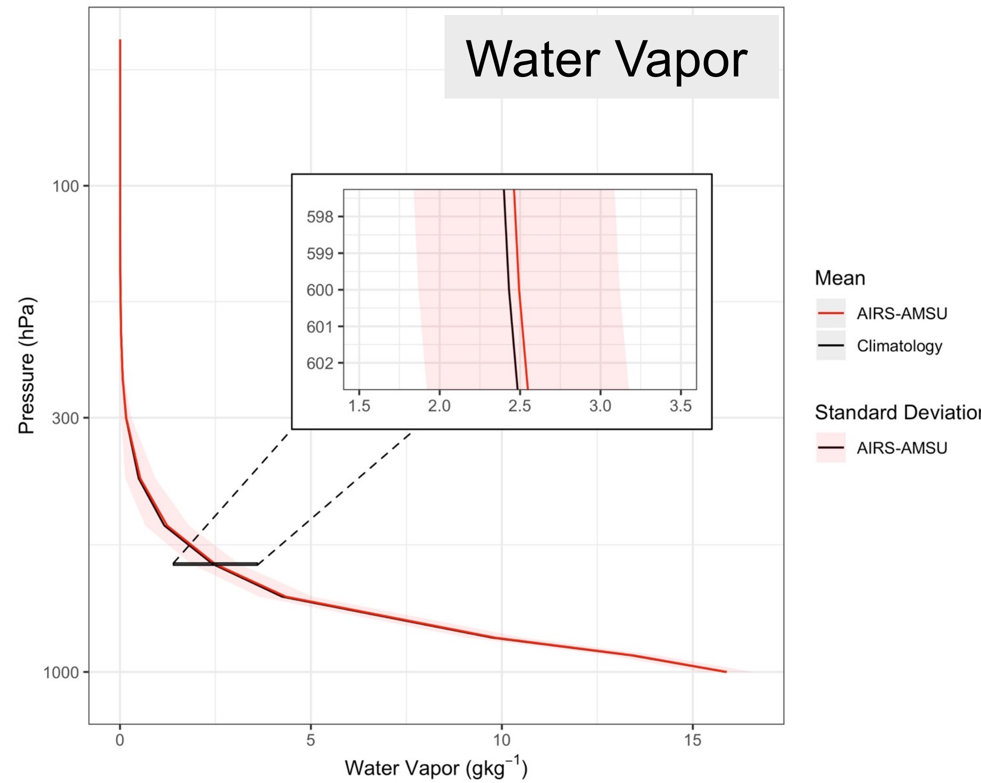
T and q reference and analogue profiles

Analogue profiles:

- For each of the 1000 reference profiles a search is performed to find analogue profiles that are within absolute value thresholds of 1.4 K for temperature and 1.4 gkg^{-1} for water vapor at any vertical level
- Period: JJA 2003 to 2012.
- Analogue profiles are also over the tropical/subtropical oceans, in (almost) clear sky (cloud < 10 %)
- Analogue SST differences < 1.4 K.

Simulation studies show that the results are not sensitive to the thresholds (as long as there are enough analogues)



- Mean water vapor (gkg^{-1}) reference profiles for the AIRS/AMSU (red) and the mean climatology AIRS/AMSU profile (black)
- Profile of standard deviations of all analogue differences (vs reference profiles) from AIRS/AMSU (red shading) analogues

Observed CO_2 Radiance Differences

- Cloud-cleared AIRS radiances are used; these contain IR radiances for each AIRS channel that would have been observed within each MW (AMSU) footprint if there were no clouds in the field of view.

- Differences between radiances observed at location/time of each analogue and radiances observed at location/time of corresponding reference profile are calculated.

- These differences (from 2003 to 2012) are aggregated to provide an estimate of the annual mean difference.

- Observations correspond to scan-angles between -5^o and 5^o from nadir and theoretical radiances are estimated at nadir

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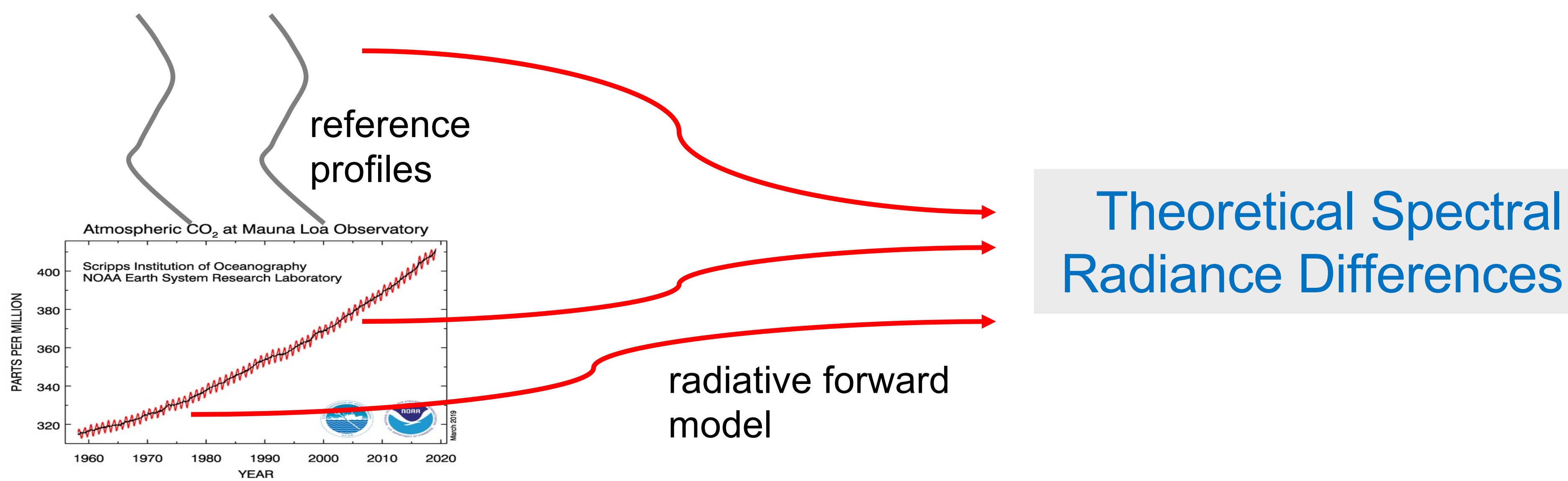
Theoretical CO_2 Radiance Differences

To estimate theoretical radiance differences:

1) Spectral radiances corresponding to 1000 reference temperature and water vapor profiles are simulated with different values of CO_2 (2003-2012) measured in Mauna Loa.

2) kCARTA forward model (Strow et al., 1998; DeSouza-Machado et al., 2020) is used to simulate the theoretical spectral radiances.



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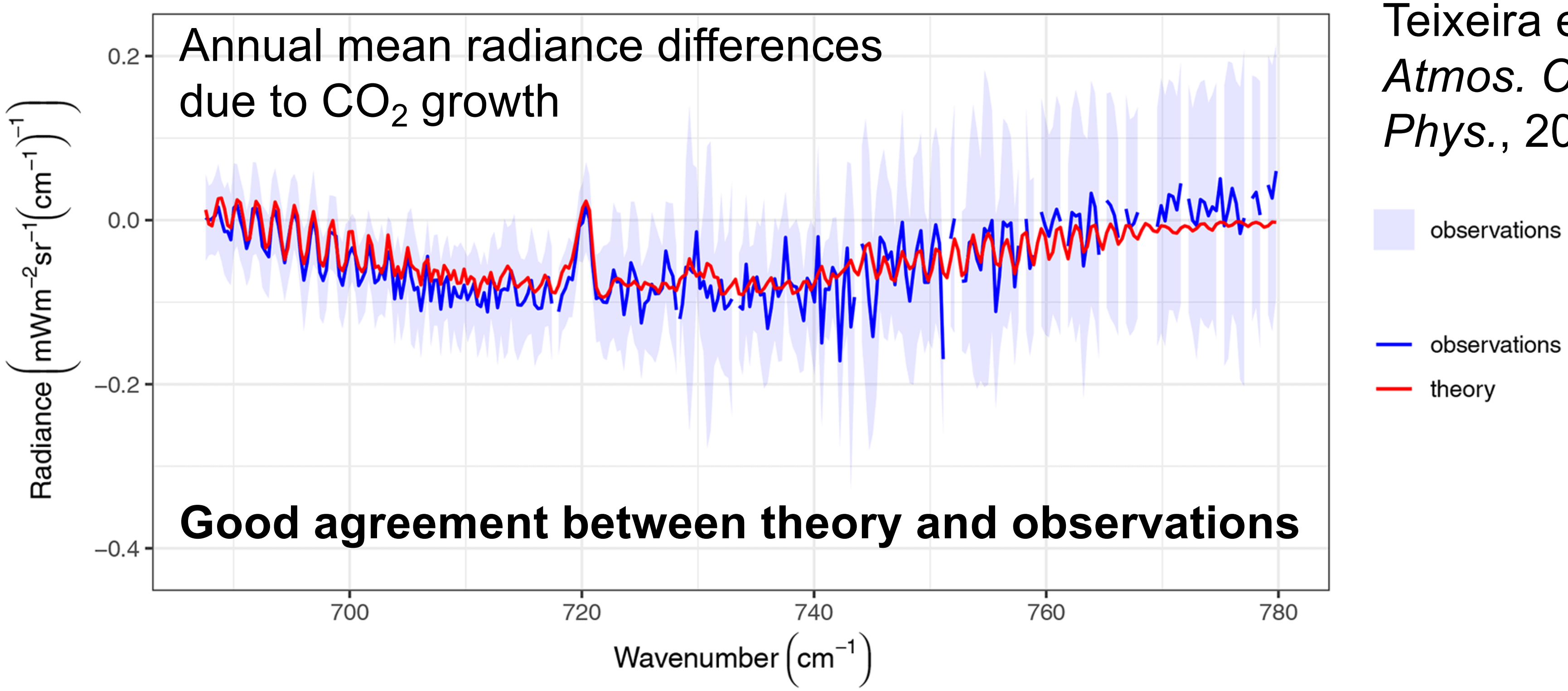
Experimental Evidence from Space of Direct Effect of CO_2 Growth on LW Spectral Radiances

- **Methodology**: search is performed to find observed profiles of temperature and water vapor that are as similar as possible (analogues)
- **Results**: AIRS spectral radiances corresponding to these analogue profiles show impact of CO_2 growth on LW spectra



Teixeira et al., *Atmos. Chem. Phys.*, 2024

Spectral signature of CO_2 growth directly observed from space

(isolated from temperature and water vapor changes)

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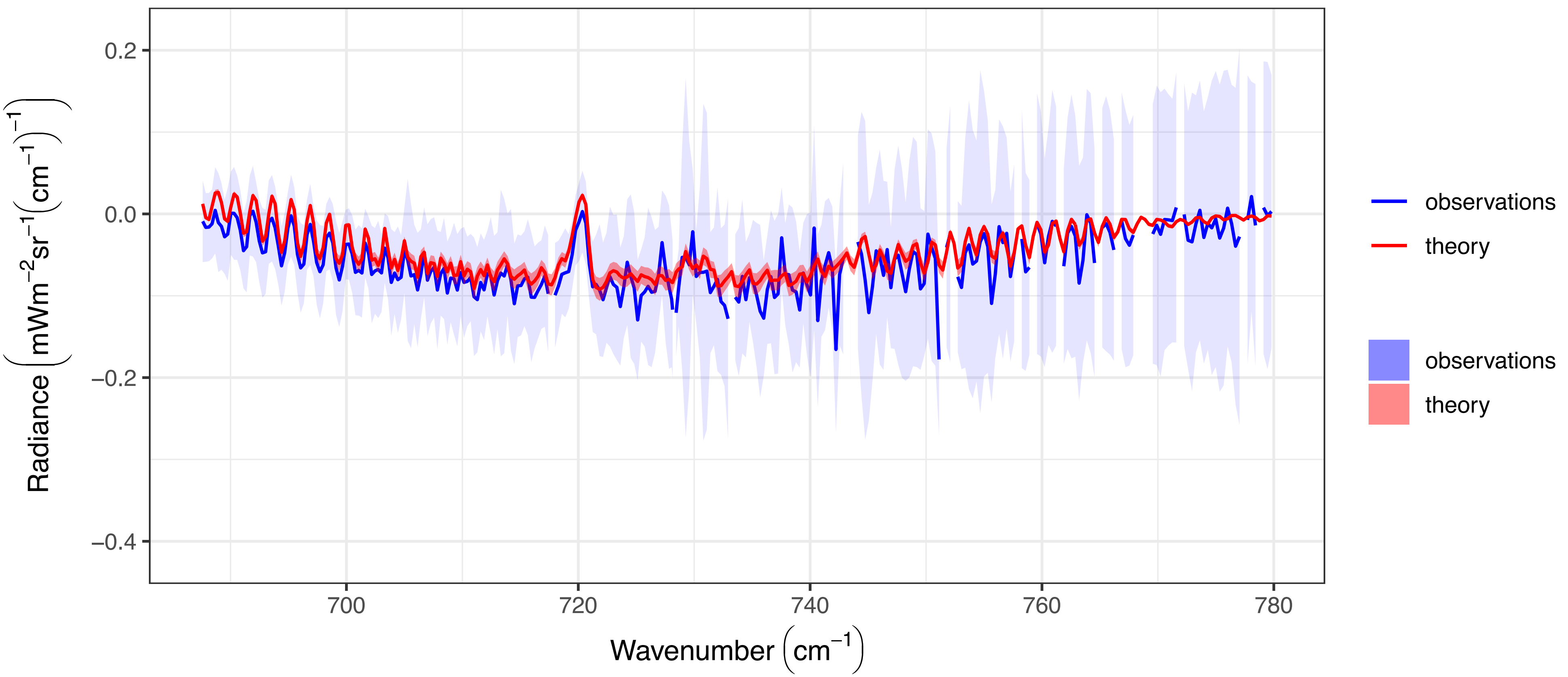
The role of MW-only analogues and CO_2 uncertainties



- CO_2 spatial/temporal variability is used to estimate impact of CO_2 uncertainty in theoretical radiances: small but relevant in some areas
- MW-only T analogues are used to exclude any influence from IR in retrievals: No meaningful differences

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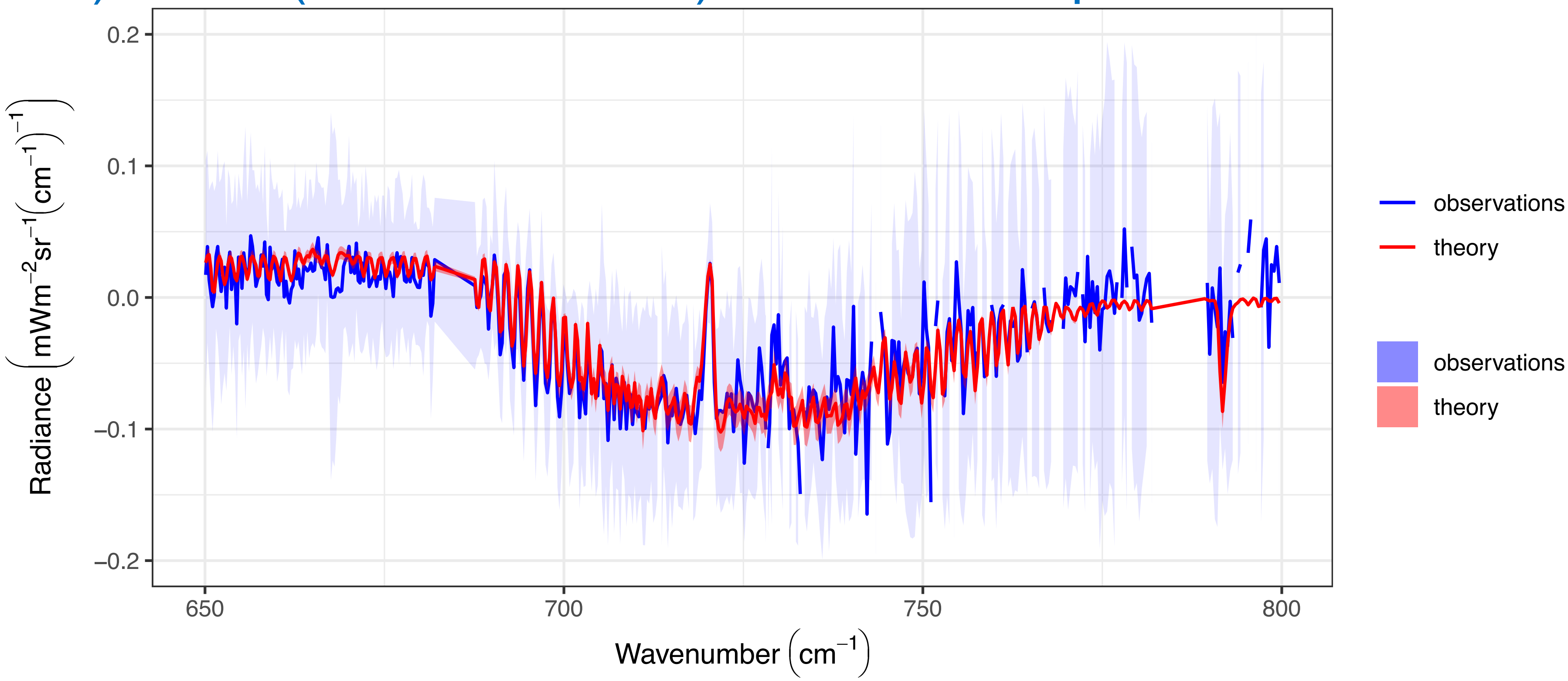
The stratosphere and the impact of temperature trends

Stratospheric T trends (e.g., Ramaswamy et al. 2001, DeSouza-Machado et al. 2025) require a new variant of the method:
Select 1000 analogues with T smallest differences (wrt to the reference profiles) above (and 1000 below) zero in stratosphere



Variant of the method captures the (smaller) theoretical signal in the stratosphere as well as the troposphere

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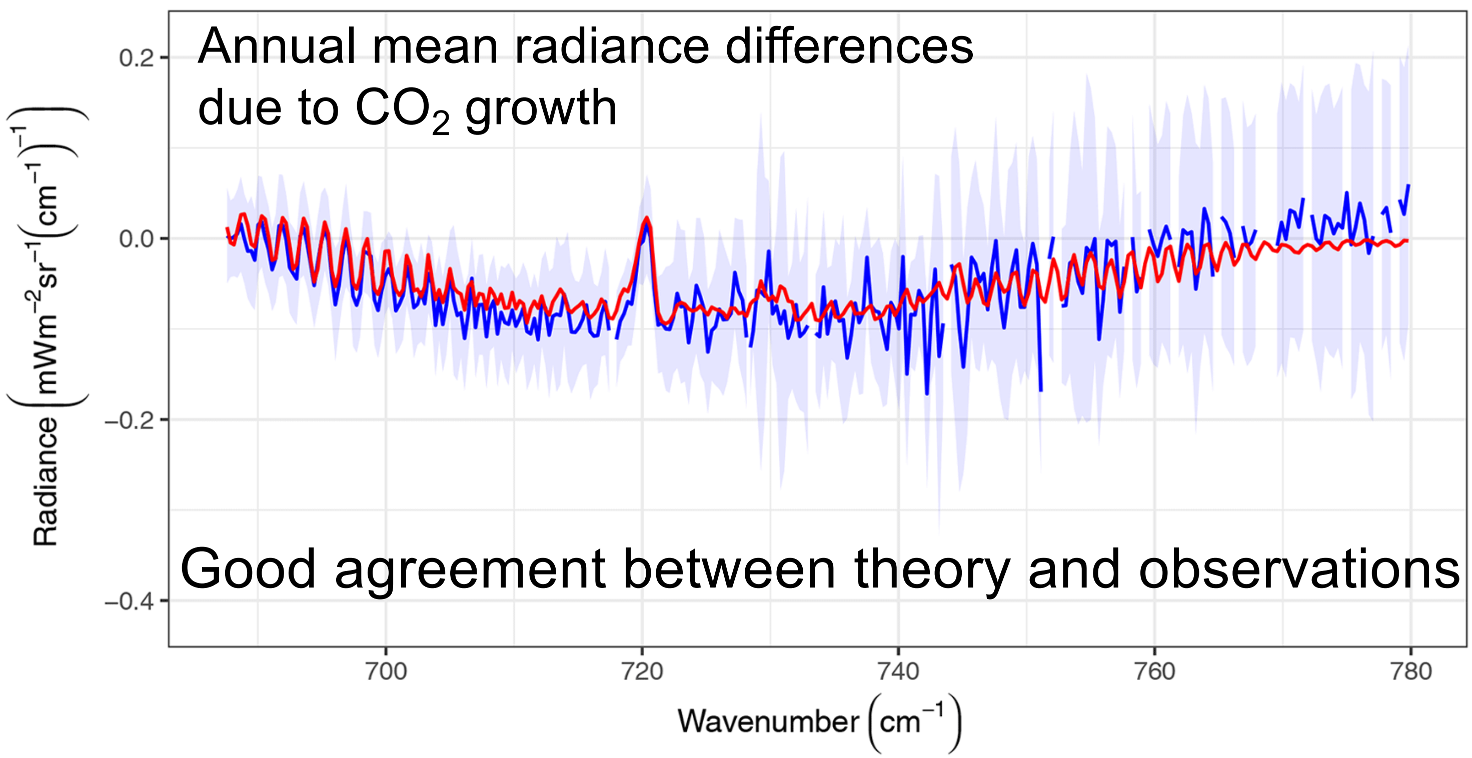
Confirming a critical theoretical foundation of global warming

Goal: to experimentally confirm that the direct effects of CO_2 growth on the Earth's outgoing LW spectra follow theory

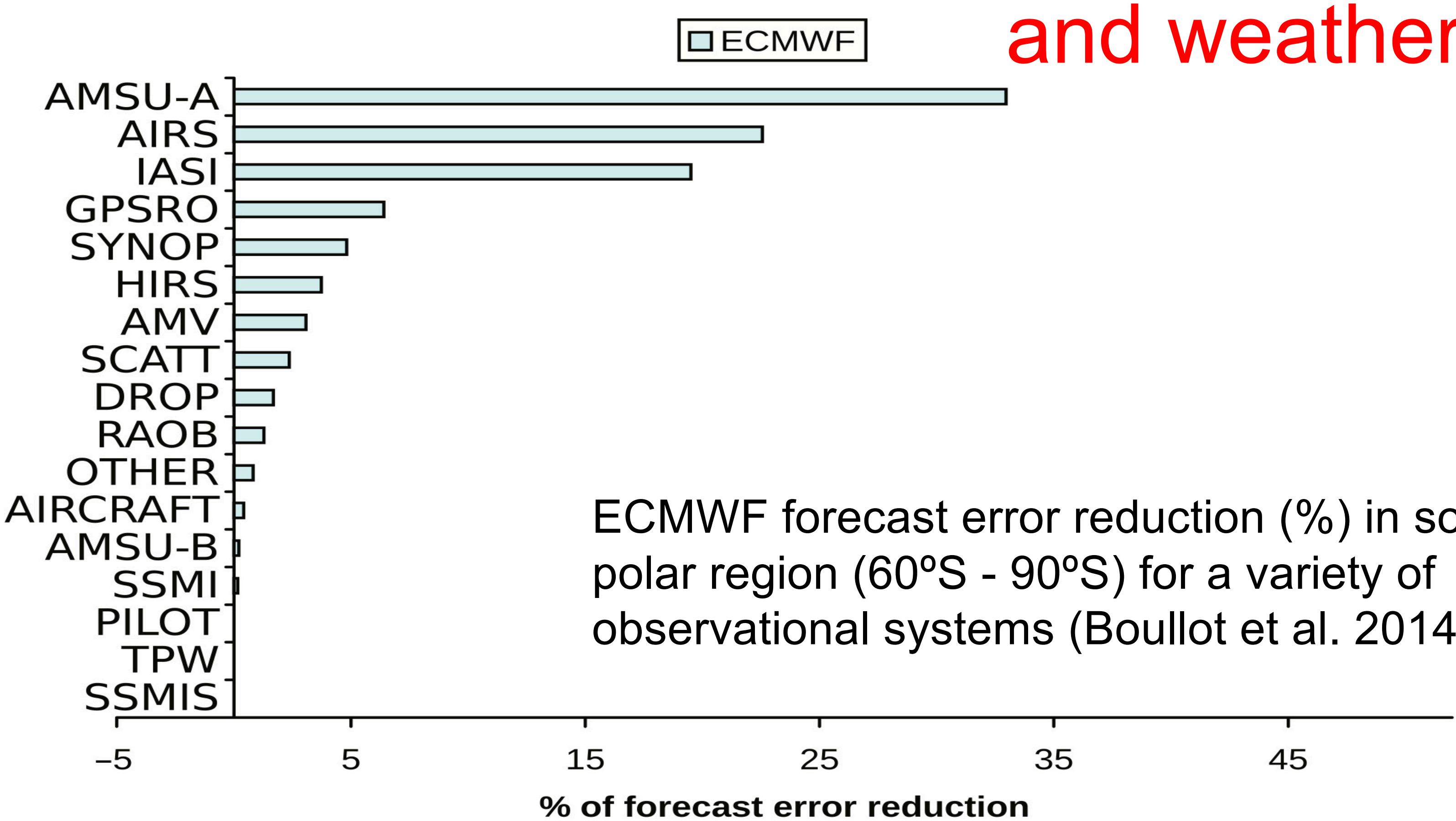
Spectral signature of CO_2 growth directly observed from space
(isolated from temperature and water vapor changes)



Teixeira et al., *Atmos. Chem. Phys.*, 2024

Results confirm a critical foundation of global warming

AIRS started as a weather mission: data assimilation and weather prediction



ECMWF forecast error reduction (%) in south polar region (60ºS - 90ºS) for a variety of observational systems (Boullot et al. 2014)

AIRS was the first hyperspectral IR instrument assimilated in NWP systems and has been critical for:

- Improving global weather forecasts over last 20 years
- Improving re-analysis products (ERA, MERRA)

AIRS is now a climate mission

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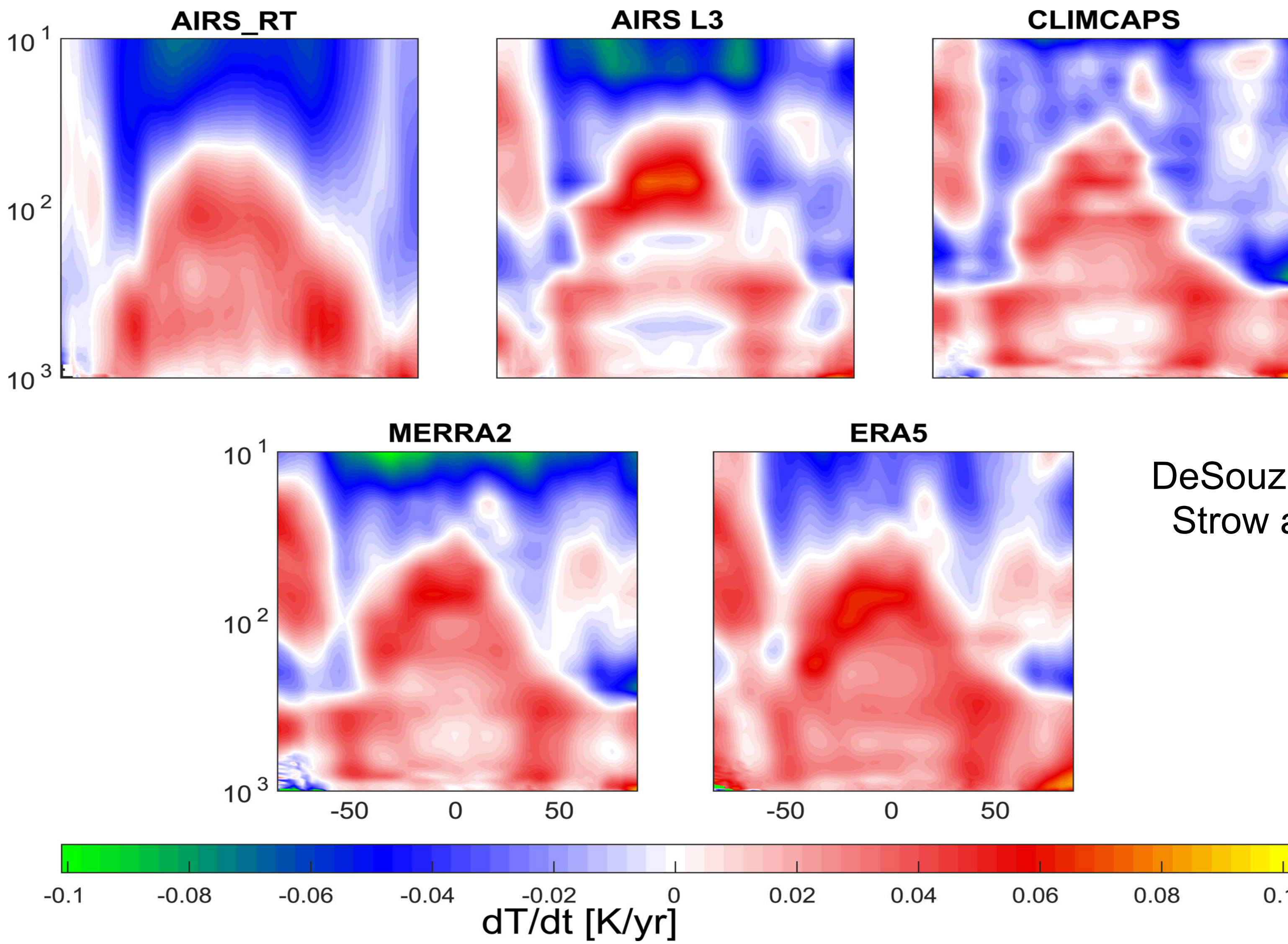

DeSouza-Machado, Strow and Kramer, 2025

Novel algorithms to directly retrieve trends show great promise

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T and q Reference and Analogue Profiles

Reference profiles: 1000 temperature and water vapor profiles from July 2003 are randomly selected: i) over the **tropical oceans** [30 S to 30 N], ii) cloud cover < 10% and iii) within SST range of 298 K to 302 K.

Analogue profiles:

- Within absolute value thresholds of 1.4 K for temperature and 1.4 gkg^{-1} for water vapor at any vertical level.
- Period: **JJA 2003 to 2012**.

Reference and analogue profiles: From AIRS/MW (which includes NN trained on ECWMF) or MW-only retrievals.

Observations correspond to **scan-angles between -5º and 5º** from nadir and theoretical radiances are estimated at nadir

Uncertainty Simulation Study

To investigate the uncertainties associated with the temperature and water vapor thresholds used to search for analogues, a preliminary theoretical study is performed:

- 1000 synthetic temperature and water vapor analogues of a reference profile are created by drawing from a normal distribution defined by zero mean and standard deviations of 0.5 K and 0.5 gkg^{-1} (*which are close to the values estimated based on the observed temperature and water vapor analogues*)
- Additional constraint that the absolute difference values at any level cannot be larger than the thresholds of 1.4 K and 1.4 $g.kg^{-1}$
- Theoretical spectral radiances are calculated for each of these 1000 synthetic analogues

These theoretical values are used to estimate the impact of the temperature and water vapor thresholds on the spectral radiances

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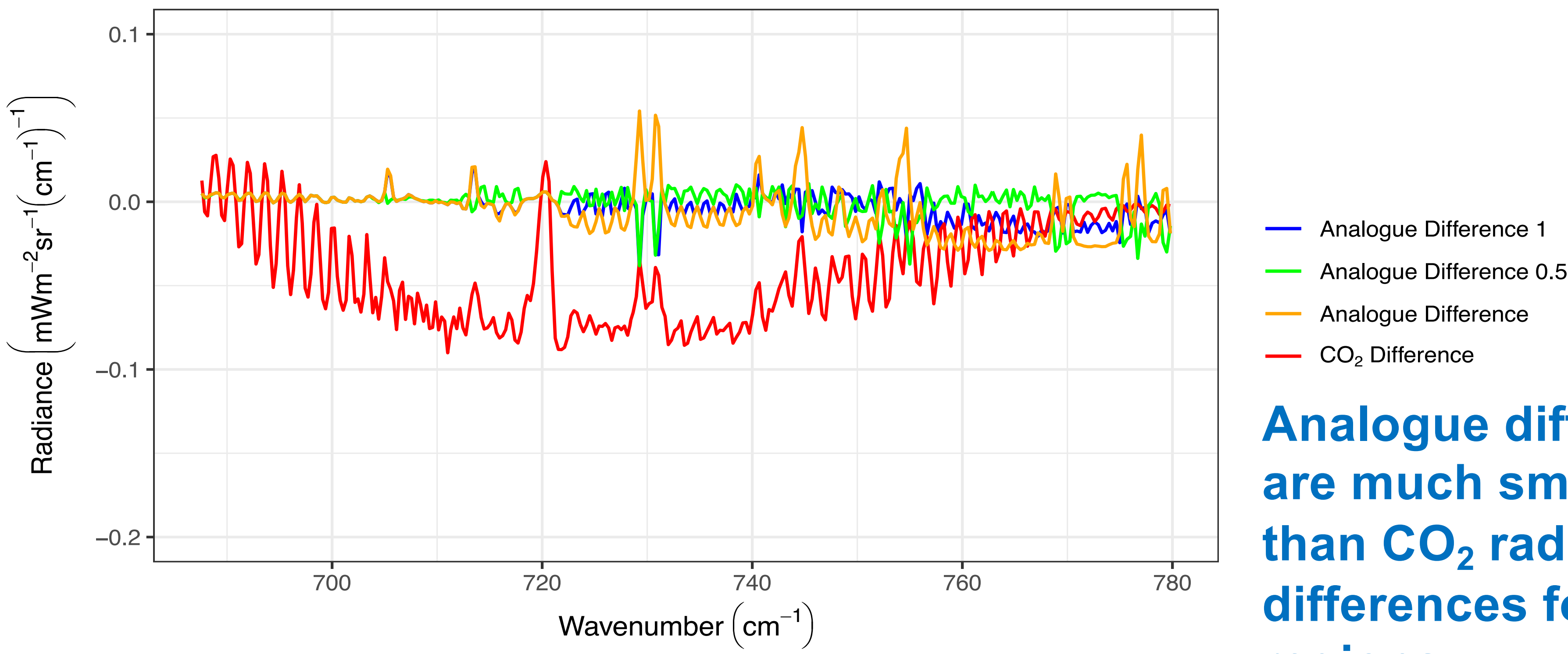
Uncertainty Simulation Study

Theoretical spectral radiance differences (in $mWm^{-2}\ sr^{-1}\ (cm^{-1})^{-1}$) due to the annual mean increase of CO_2 during the period from 2003 to 2012 (red line)

Theoretical mean radiance differences between the 1000 synthetic temperature and water vapor profiles and the reference profile:

- Orange: all 1000 synthetic radiances
- Green: Radiance difference outliers larger than 0.5 $mWm^{-2}sr^{-1}(cm^{-1})^{-1}$ are filtered out
- Blue: Radiance difference outliers larger than 1 $mWm^{-2}sr^{-1}(cm^{-1})^{-1}$ are filtered out



Analogue differences are much smaller than CO_2 radiance differences for most regions