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Direct observational evidence from space of the effect of CO_2 increase on LW spectral radiances

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Measuring CO_2 Effects 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

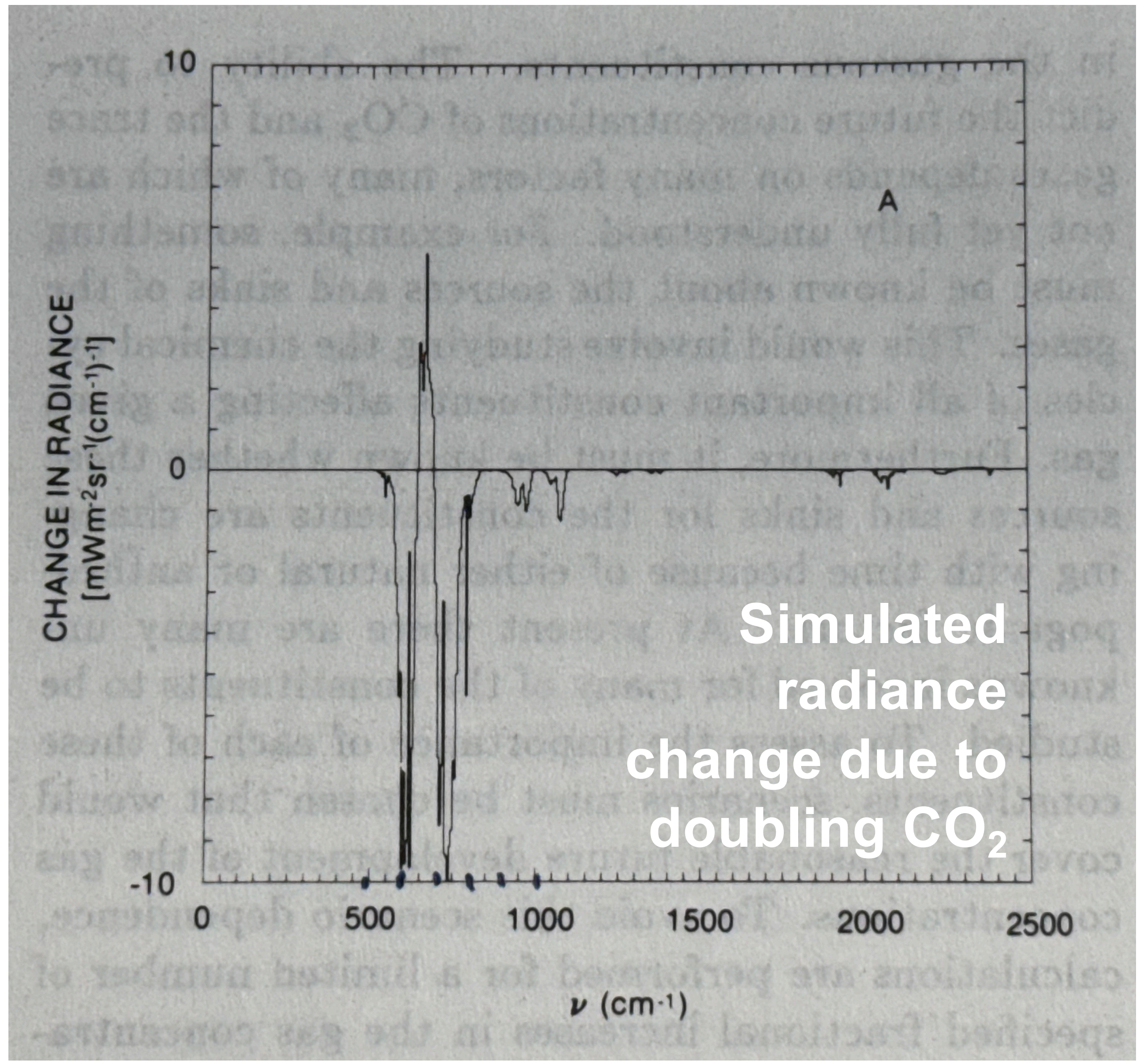
- Measurements of the spectral effects of the combined changes in CO_2, temperature, water vapor and other gases have been published (e.g., Harries et al., 2001; Brindley and Bantges, 2016; Strow and DeSouza-Machado, 2020; Whitburn et al., 2021; Huang et al., 2022; Raghuraman et al., 2023)

- Effects of CO_2 alone have been difficult to observe directly

Theoretical/Modeling Studies of the CO_2 Impact on Radiances: Kiehl (1983)

Kiehl (1983):

1) Discussed the possibility of using spectrally resolved satellite measurements of LW radiation to detect and characterize the impact of climate change on LW spectra
2) Simulated the changes in clear-sky spectra due to increases in CO_2 and temperature



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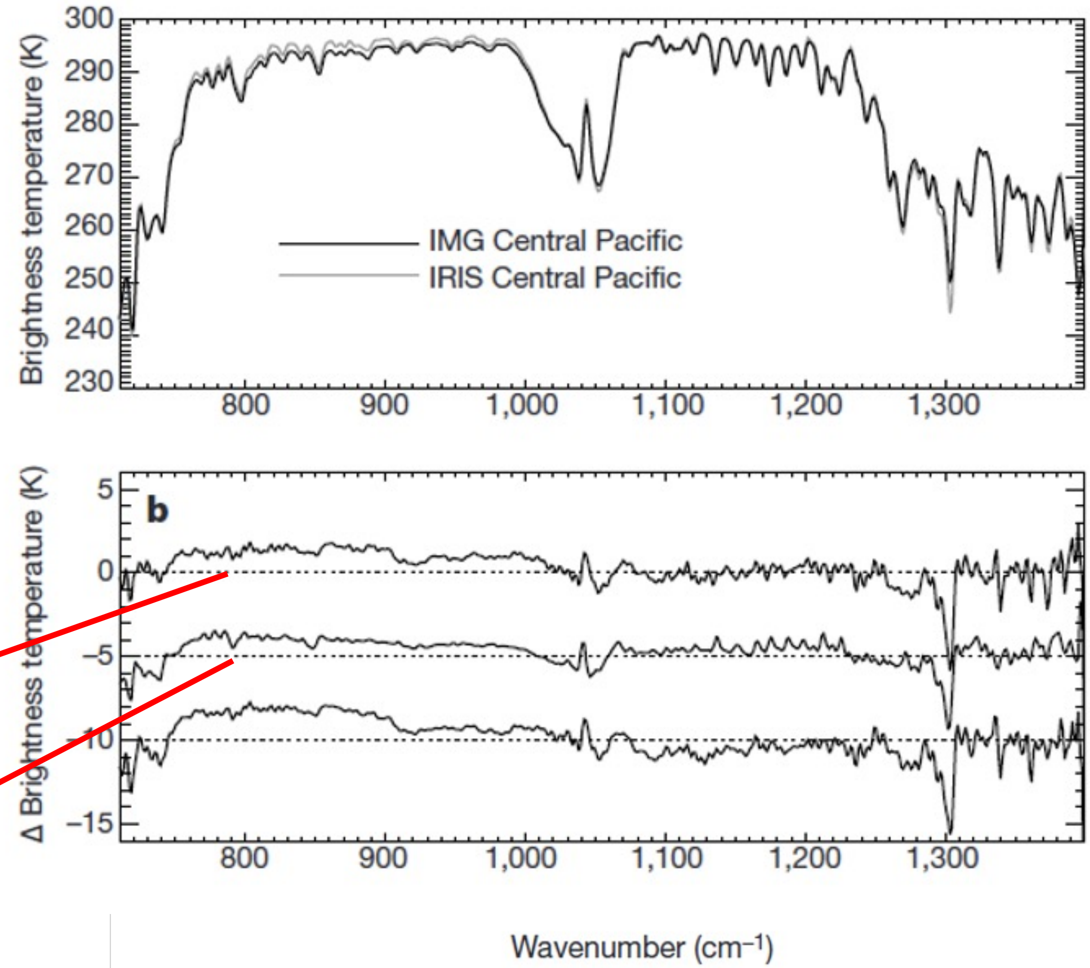
Pioneering Observational Study: Harries et al. (2001)

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



Observed differences

Simulated differences

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

AIRS Radiance Trends and Stability

- Recent key studies (Strow & DeSouza-Machado 2020, Huang et al. 2022):
  i) Investigate in detail the AIRS radiance trends
  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.

- These studies use modelling and re-analysis to isolate these effects

Methodology: T and q 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 close to each other as possible** ('analogues'), 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.

T and q Reference and Analogue Profiles

Reference profiles: 1000 AIRS temperature and water vapor profiles from July 2003 are randomly selected, obeying the following constraints: i) over the tropical/subtropical oceans [30 S to 30 N], ii) cloud cover less than 10% and iii) within an SST range of 298 K to 302 K.

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 cover less than 10 %)
- Analogue SST differences are also within 1.4 K.
- For each of these analogue profile locations/times, the corresponding cloud-cleared AIRS spectral radiances are selected

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Observed CO_2 Radiance Differences

To estimate the impact of CO_2 increase on the observed spectral radiances:

- Differences between the radiances observed at the location/time of each analogue and the radiances observed at the location/time of the corresponding reference profile are calculated
- These differences (in different years 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 the theoretical radiances are estimated at nadir

Key assumption: annual mean spectral radiance differences corresponding to each reference state are (to first order) not sensitive to the reference state itself for these selected reference profiles.

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Theoretical CO_2 Radiance Differences

The observed radiance differences are compared with theoretical estimates of the radiance impact of CO_2.

To estimate theoretical radiance differences:

1) Spectral radiances corresponding to the reference temperature and water vapor profiles are simulated with different values of CO_2 concentration that reflect its mean increase from 2003 to 2012 as measured in Mauna Loa
2) kCARTA forward model (Strow et al., 1998; DeSouza-Machado et al., 2020) is used to simulate the spectral radiances and is convolved with the AIRS spectral response functions to get theoretical AIRS radiances

Uncertainty Simulation Study I

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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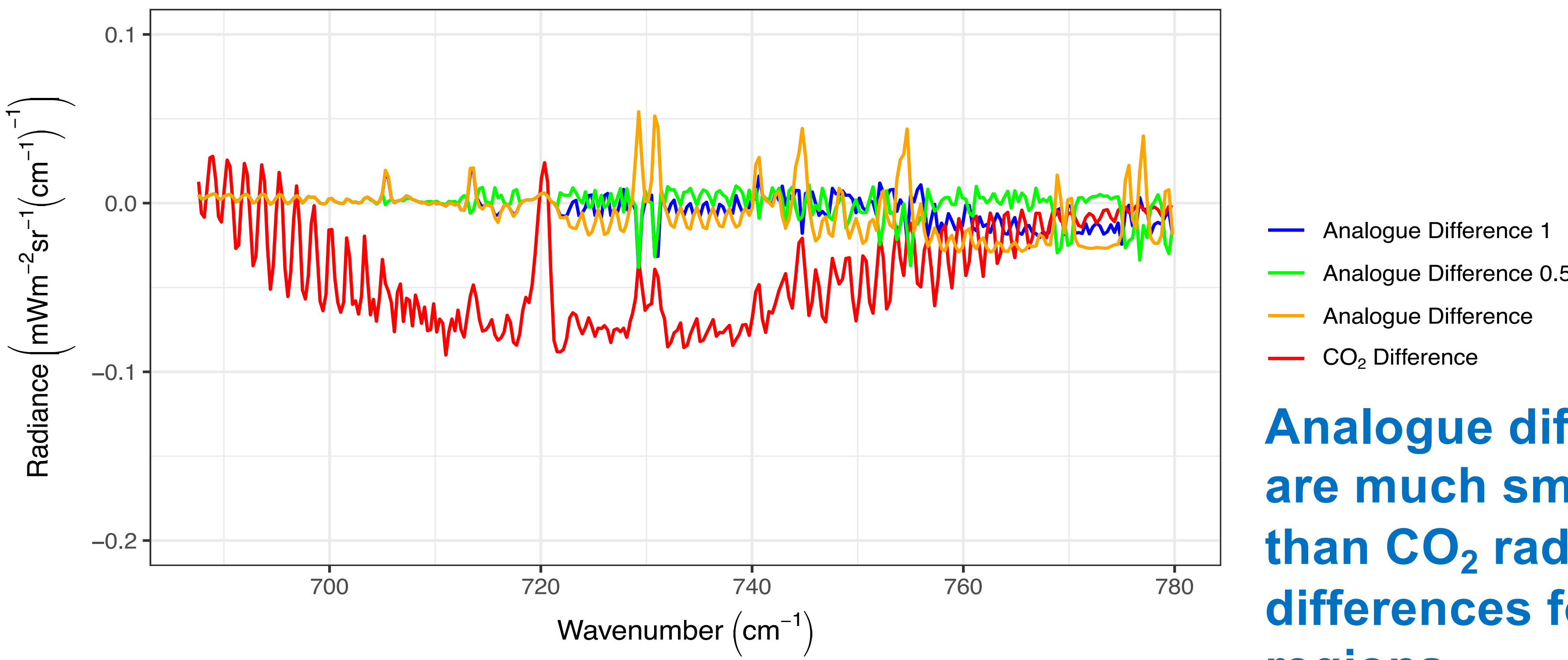
Uncertainty Simulation Study II

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

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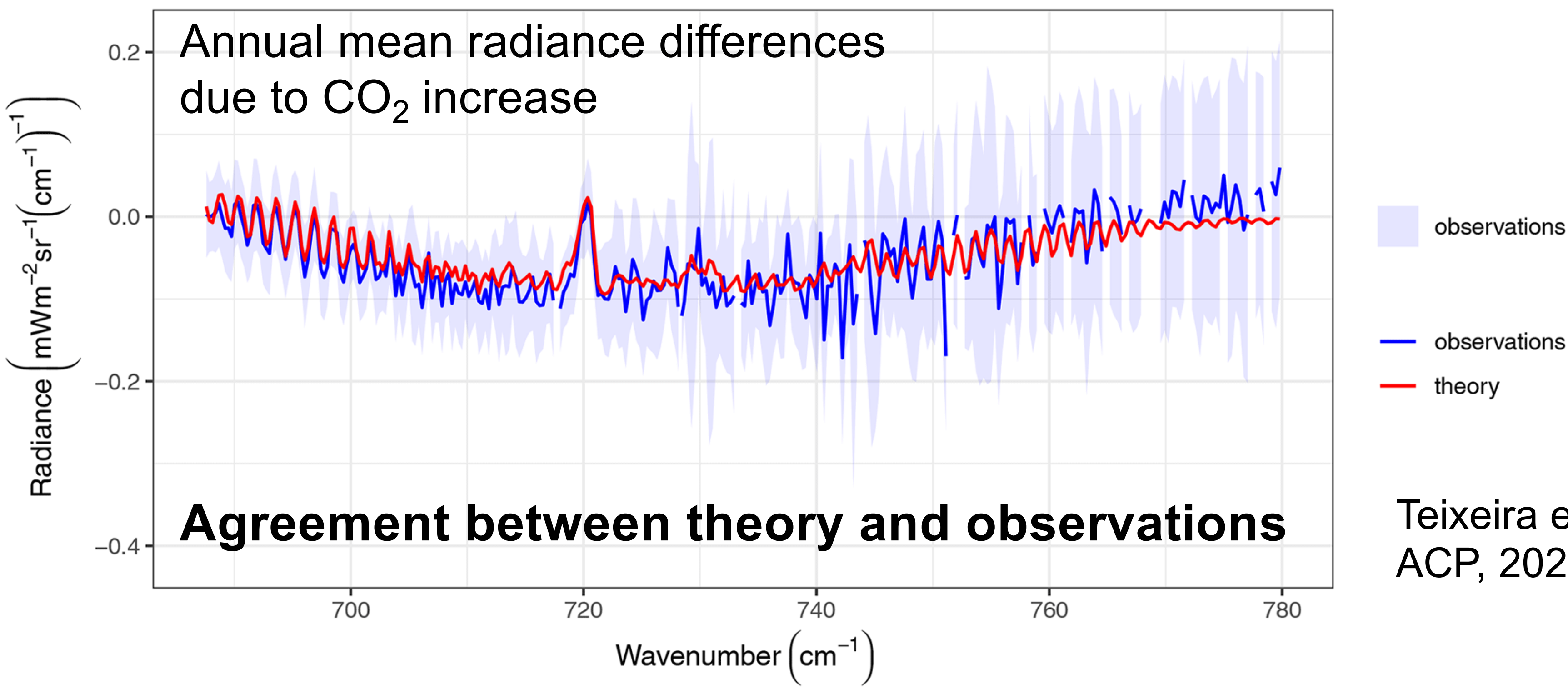
Direct observational evidence from space of the effect of CO_2 increase on LW spectral radiances

- **Goal: to experimentally confirm that the direct effects of CO_2 increase on the Earth's outgoing longwave spectra follow theoretical estimates**
- **Methodology**: search is performed to find observed profiles of temperature and water vapor that are as close as possible to each other in terms of their values (analogues)
- **Results**: AIRS spectral radiances corresponding to these analogue profiles show impact of increased CO_2 on the spectra (isolated from temperature and water vapor)



Teixeira et al., ACP, 2024

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

CO_2 Impact on LW Spectral Radiances: Results I

- **Theoretical annual mean differences** and associated standard deviations are **calculated based on the 1000 reference profiles**

- Theoretical standard deviations are not shown because they would be almost imperceptible in the figure

- This lack of theoretical sensitivity to the reference states supports the key assumption mentioned above

- **Cloud-cleared AIRS radiances** contain IR radiances for each AIRS channel that would have been observed within each (AMSU) footprint if there were no clouds in the Field of View

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CO_2 Impact on LW Spectral Radiances: Results II

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

- To remove outliers and to select analogues that are as close as possible to the reference states, analogues that have absolute radiance differences, as compared to the reference states, that are larger than 0.5 $mWm^{-2}sr^{-1}(cm^{-1})^{-1}$ are filtered out

- Results with scan-angles between -10^o and 10^o, and with outlier filter values of 1 $mWm^{-2}sr^{-1}(cm^{-1})^{-1}$, show no meaningful differences

- Lack of accurate knowledge of CO_2 for each specific reference and analogues leads to uncertainties in theoretical radiances

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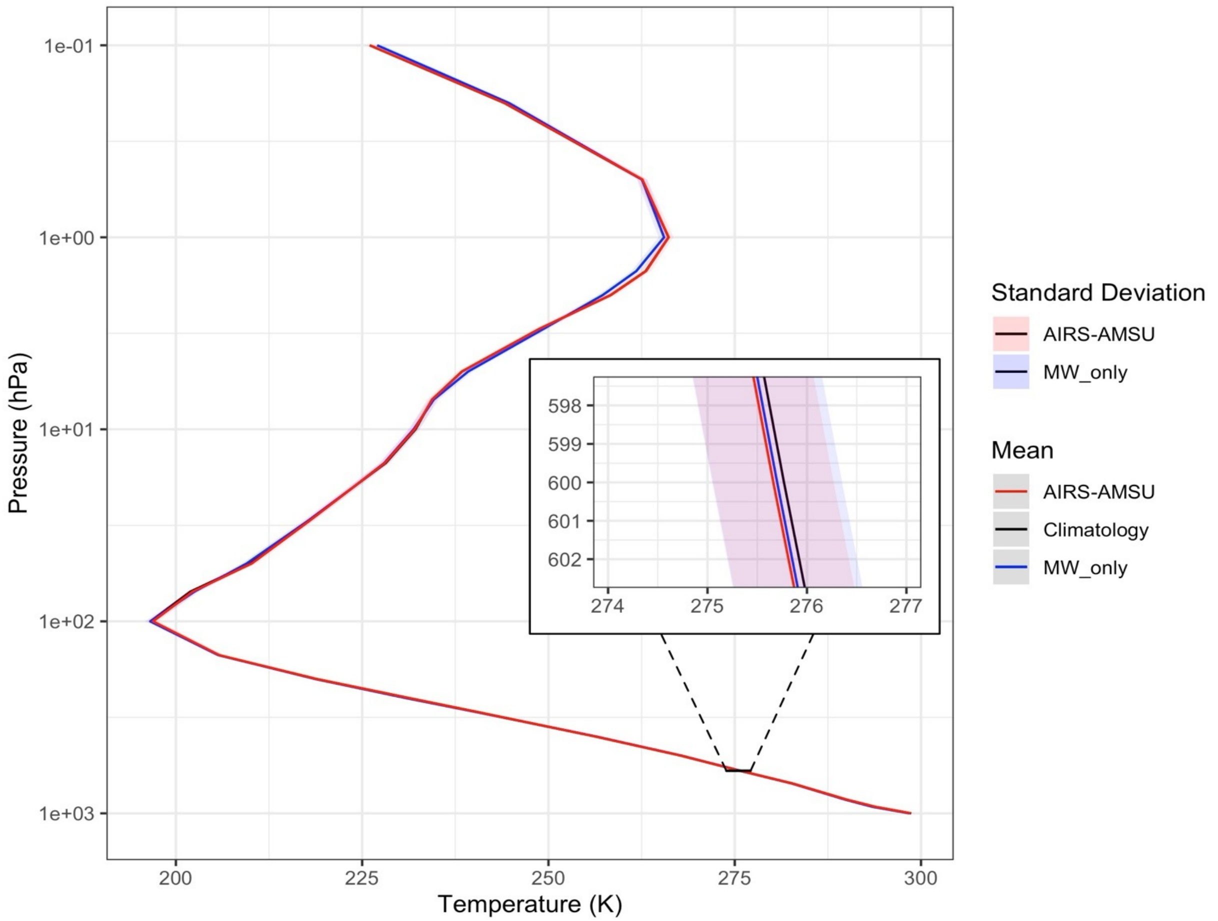
Temperature Profiles



- Mean temperature reference profiles for AIRS/AMSU (red line) and MW-only (blue line) retrievals, and mean climatology AIRS/AMSU profile (black line) for this regime.
- Profiles of standard deviations of all the analogue differences (versus the reference profiles) from both AIRS/AMSU (red shading) and MW-only (blue shading) analogues.

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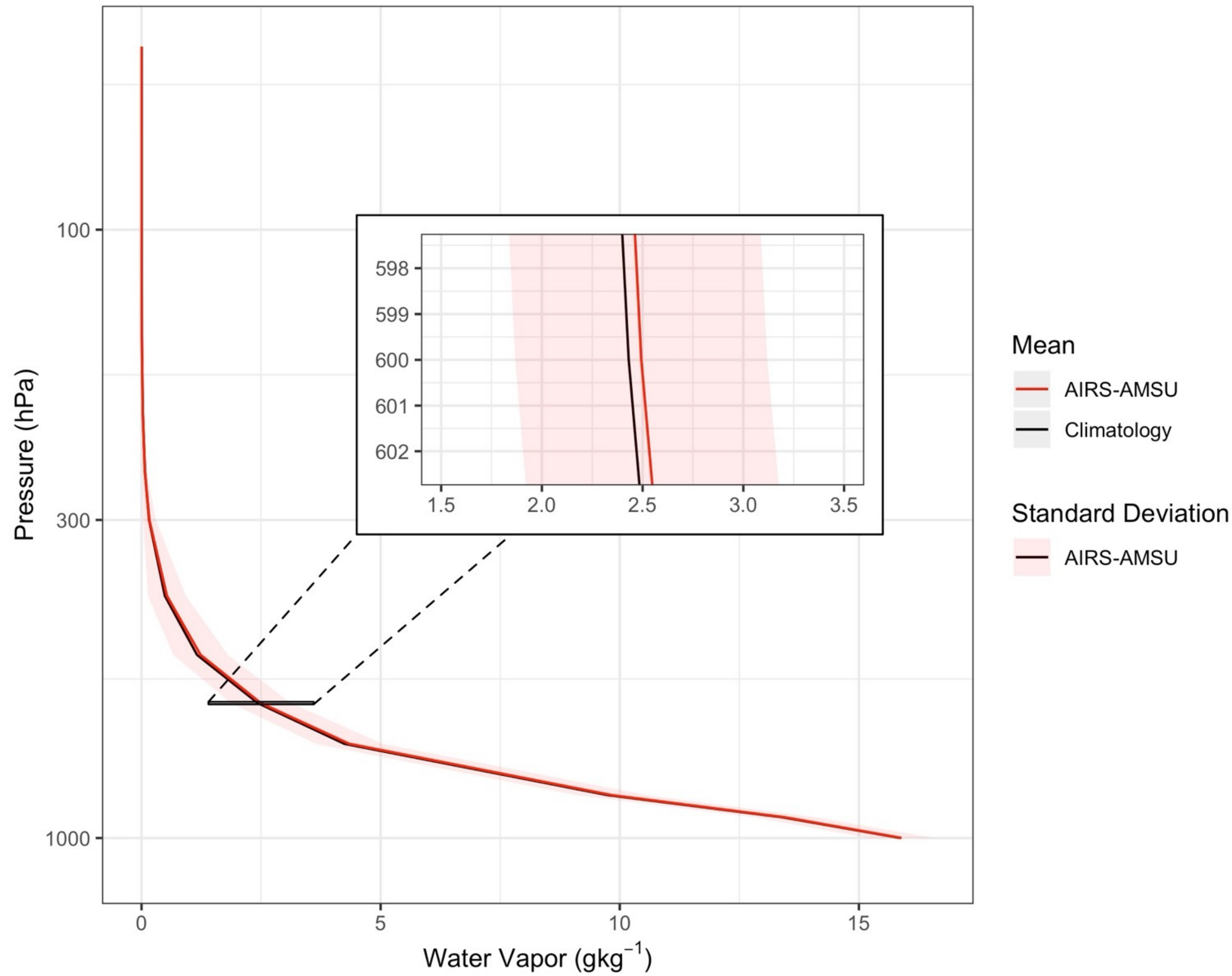
Water Vapor Profiles



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

Summary I

- **Direct measurement** of the impact of increased atmospheric CO_2 on the spectra of Earth's LW radiation obtained from space

- **New methodology** disentangles the impact of CO_2 on the observed LW radiances, from the effects of temperature and water vapor

- New approach provides a **direct and more precise comparison** with theoretical estimates of the radiance impact of CO_2

- New **observations compare well with theoretical estimates** of the direct CO_2 radiative impact on LW spectra.

Summary II

- New method can undoubtedly be refined, and its uncertainties better characterized and understood to establish its accuracy and precision

- This study represents the first attempt to **establish a more precise experimental confirmation from space** of the direct effects of CO_2 on LW spectral radiances

- Results (solely based on observations) confirm that the effects of the recent atmospheric CO_2 increase on LW spectral radiances follow theoretical estimates

Results confirm a critical foundation of the science of global warming