https://doi.org/10.5194/egusphere-2026-1013
Preprint. Discussion started: 27 May 2026

Technical Note: On the Experimental Confirmation from Space of the Spectral Signature of CO_2 Growth

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Abstract. We present conclusive experimental confirmation from space that the observed impact of CO_2 growth on longwave spectral radiances follows theory, both in the troposphere and stratosphere, and that these results are independent of CO_2 uncertainties. We refine the methodology used in a previous study on the direct measurement of the impact of increased atmospheric CO_2 on the spectra of Earth's longwave radiation by addressing three critical issues and as such provide a definitive experimental confirmation from space of the impact of CO_2 growth on longwave spectral radiances. In our study, we (i) use temperature profiles retrieved from microwave radiances for our analogue methodology, clearly illustrating the independence of our approach from any role that the longwave spectral radiances may play in the retrieval of the analogue temperature profiles; (ii) show that the effect of the uncertainties due to CO_2 spatial and temporal variability when estimating theoretical spectral radiances is small (often imperceptible) and has no meaningful impact on the interpretation of the results; (iii) show that the CO_2 growth spectral signature in the stratosphere can be captured by using a slight variant of the method that allows to conclusively detect the more challenging stratospheric signature. By addressing these three critical issues, refining our methodology and extending the initial study, our current results conclusively confirm a critical theoretical foundation of the science of global warming.

1 Introduction

The fact that the increase of atmospheric greenhouse gases such as CO_2 can lead to global warming by changing the longwave (LW) radiative fluxes of energy at the top of the atmosphere has been known for more than a century and has been the focus of remarkably important research over the last few decades (e.g., Plass, 1956; Manabe and Wetherald, 1967, 1975; Hansen et al., 1984; Ramanathan, 1988; Held and Soden, 2006; Archer and Pierrehumbert, 2011; Ramaswamy et al., 2018). The spectroscopic details of the impact of CO_2 growth on the longwave spectra have been investigated in detail and are well understood from the theoretical and laboratory perspectives (e.g., Kiehl, 1983; Mlynczak et al., 2016; Brindley and Bantges, 2016).

However, direct measurements from space of the effects of CO_2 growth on the LW spectra have been challenging to obtain because of i) the sparsity of spectrally resolved observations of LW radiances before the 21st century; ii) the lack of long term and stable LW spectral observations from space, and iii) the challenge of disentangling the effects of CO_2, temperature, and water vapor on the spectral radiances. While 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; Feldman et al., 2015; Brindley and Bantges, 2016; Strow and DeSouza-Machado, 2020; Whitburn et al., 2021; De Longueville et al., 2021; Huang et al., 2022; Raghuraman et al., 2023), direct measurements from space of the effects of CO_2 alone have not been presented until very recently.

In Teixeira et al. (2024), hereafter T24, a novel methodology was proposed to isolate the effects of CO_2 (from temperature and water vapor) on the measured LW spectra, leading to a direct and more precise comparison between theory and observations. T24 provide the experimental confirmation from space that the direct effects of CO_2 growth (independent from temperature and water vapor changes) on the Earth's outgoing LW spectra follow theoretical estimates.

The new methodology proposed by T24 is based on an algorithm that searches for atmospheric profiles of temperature and water vapor that are as similar as possible (referred to as analogues) but have CO_2 concentrations that are significantly different. Measuring from space the spectral radiances that correspond to these analogues allows for the detection of the unique impact of CO_2 growth on the radiances with enough precision and accuracy in critical spectral regions. T24 present positive results that show close agreement between theory and observations from space of the spectral impact of CO_2 growth in the 680-780 cm^{-1} spectral region where this impact is most significant.

In the present study, we refine the T24 methodology by performing three critical sensitivity experiments that further confirm and improve the robustness of the new methodology. In particular, we i) estimate the uncertainty on the theoretical spectral radiances due to the spatial and temporal variability of CO_2 and the impact that these uncertainties have on the comparison between theory and observations; ii) utilize analogues based on MW-only retrievals to eliminate any possible indirect influence of the LW spectra on the analogue temperature retrieved profiles; and iii) develop a variant of the analogue sampling that allows for the methodology to capture the weaker stratospheric signal more precisely.

2 Observational Data

The spectral LW radiances are measured by the Atmospheric Infrared Sounder (AIRS), the temperature profiles are retrieved from AMSU (Advanced Microwave Sounding Unit) microwave (MW) radiances using the MW-only retrieval of Rosencranz (2001), and the water vapor profiles are from retrievals that include data from the AIRS/AMSU suite of instruments on Aqua (e.g., Aumann et al., 2003; Chahine et al., 2006) as well as other datasets (see appendix). The theoretical spectral radiances are calculated using different values of CO_2 over time, as measured by the National Oceanic and Atmospheric Administration (NOAA) at Mauna Loa (e.g., Thoning et al., 1989). Data from Carbon Tracker (Jacobson et al., 2023) are used to estimate the theoretical uncertainties due to the spatial variability of CO_2 and NOAA observations from Mauna Loa are used to estimate uncertainties due to the temporal variability of CO_2.

3 Results

As in T24, we use a set of 1000 randomly selected temperature and water vapor reference profiles over ocean from July 2003, within a sea surface temperature (SST) range of 298 K to 302 K. For each of these 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 $\mathrm{gkg^{-1}}$ for water vapor at any vertical level (with respect to the corresponding reference profiles). The search spans the period from 2003 to 2012 but only includes June-July-August (JJA) of each year. The reference and analogue profiles are over the tropical and subtropical oceans (30 S to 30 N), with cloud cover less than 10 % and the analogue SST differences are also within 1.4 K. As illustrated in the figure 1 schematic, by selecting radiances that correspond to analogue profiles at different years, and as such with significantly different CO_2 concentrations, we can detect the impact of CO_2 growth (independently of temperature and water vapor) and produce a direct observation of the impact of CO_2 growth on LW spectral radiances.

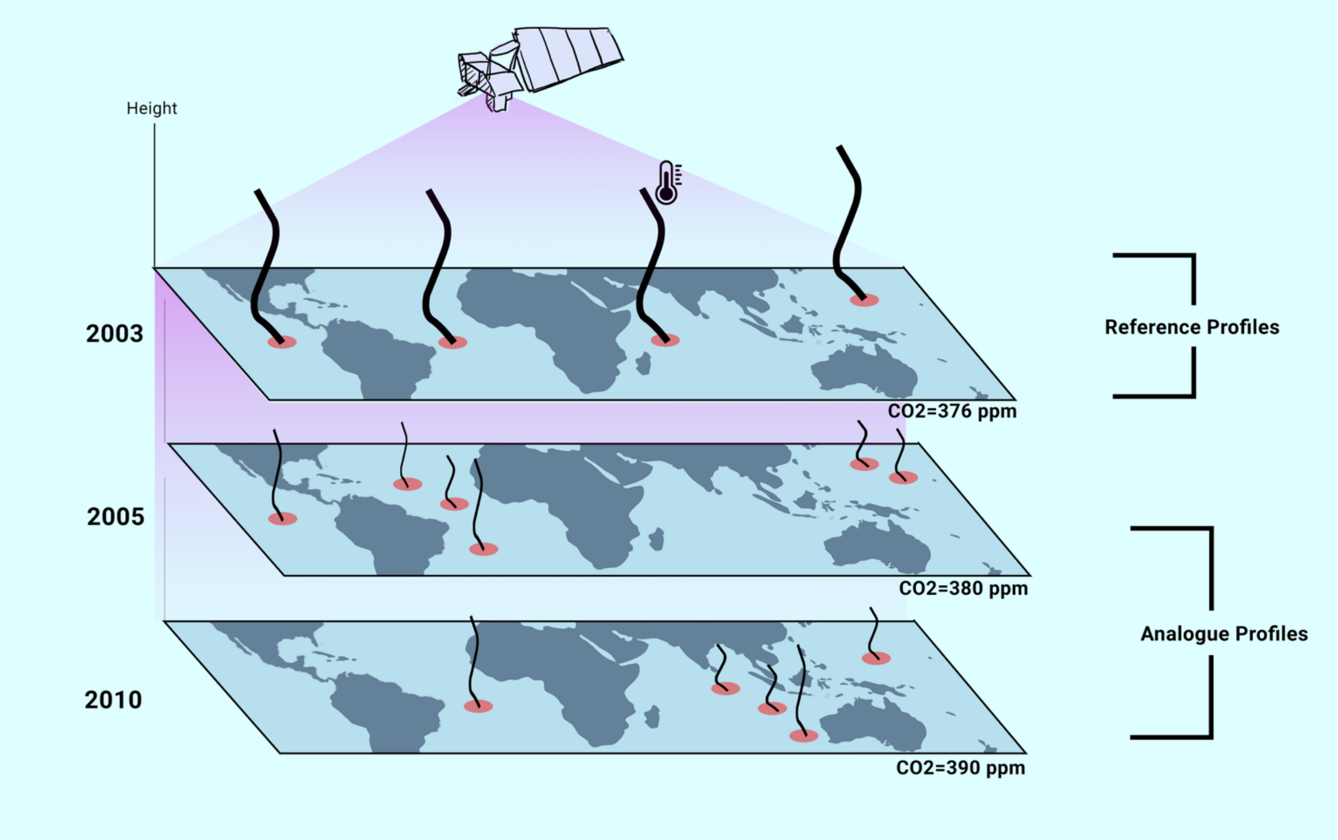

Figure 1. Schematic illustrating the analogue methodology proposed in T24 and used in the present study.

The cloud-cleared (e.g., Susskind et al., 2003) spectral radiances that are measured at the locations and times of each of the analogue profiles and corresponding reference profiles, are used to calculate the impact of CO_2 growth on the observed spectral radiances. The differences between the analogue profile radiances and the corresponding reference profile radiances are aggregated to calculate the spectral radiance impact of the annual mean increase of CO_2 and are compared with theoretical estimates.

The theoretical spectral radiance differences corresponding to the annual mean increase of CO_2 are calculated using the kCARTA forward model (Strow et al., 1998; DeSouza-Machado et al., 2020) applied to the reference temperature and water vapor profiles with different values of CO_2 (reflecting its mean increase from 2003 to 2012) as measured in Mauna Loa; convolved with the AIRS spectral response functions.

While the values at Mauna Loa are likely accurate first order estimates of the CO_2 values in other oceanic tropical and subtropical locations, the exact CO_2 concentration of each analogue is unknown. In this study we now provide an estimate of the impact of this uncertainty on the calculation of the theoretical spectral radiances. The daily values at Mauna Loa are used to estimate the variance of a distribution of CO_2 values associated with its temporal variability and the Carbon Tracker dataset is used to estimate the variance of a distribution of CO_2 values associated with its spatial variability within the tropical and subtropical atmosphere [30 S to 30 N]. These values are used to estimate the theoretical radiance uncertainty inherent to CO_2 temporal and spatial variability. Specifically, the CO_2 values that are used as input for each of the theoretical spectral radiance calculations (for each reference profile) are drawn from normal distributions that have as their mean the Mauna Loa CO_2 monthly values, and variances (due to spatial and temporal variability) estimated as described above. This approach leads to theoretical estimates of both the mean and variance of the impact of CO_2 growth on LW spectral radiances.

Figure 2 shows the annual mean spectral differences (due to CO_2 growth) for the AIRS analogue observations and theory together with their respective standard deviations. This figure is focused on the 680 to 780 cm^{-1} spectral range, which is the spectral region where the spectral signal of CO_2 growth is most significant.

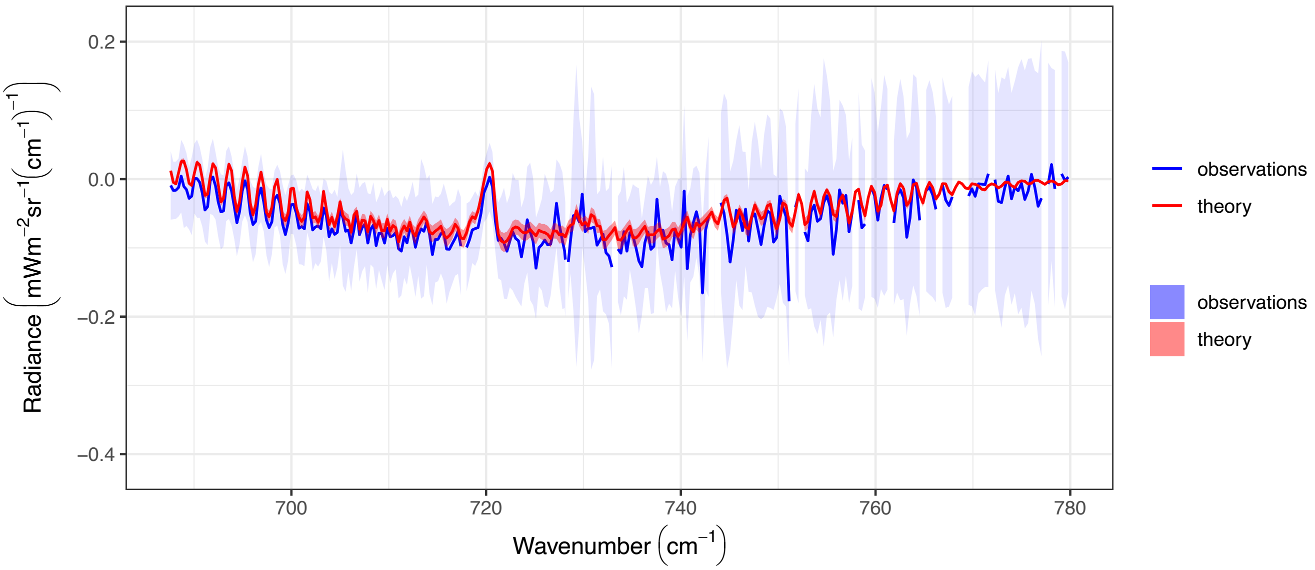

Figure 2: Annual mean radiance differences (in mWm^{-2} sr^{-1} (cm^{-1})$^{-1}$) due to CO$_2$ growth, from the AIRS observations (blue line) and from theory (red line), and standard deviations for theory (red shading) and observations (blue shading), following the methodology described and illustrating the direct impact of CO$_2$ growth on the spectral radiances during the 2003-2012 period (see text for details). Based on observations within scan angles between -10º and 10º and on MW-only temperature retrievals for the analogues, illustrating the theoretical uncertainty due to CO$_2$ temporal and spatial variability (red shading).

Figure 2 illustrates well how close the observations are to the theoretical results when using the MW-only temperature analogues (which are completely independent of the AIRS spectra) confirming the robustness of the analogue methodology. The spectral radiance uncertainty induced by the CO$_2$ spatial and temporal variability in the theoretical results is small and even undiscernible in many spectral regions. This is reassuring in two critical ways: it highlights i) the robustness of the theoretical results and as such of the close agreement between theory and observations, as well as ii) the fact that in the spectral regions where the theoretical CO$_2$ uncertainty is larger, the observations are in some of these regions close to being within the theoretical CO$_2$ uncertainty range. Uncertainties associated with the radiative transfer model and spectroscopy could be behind some of the differences between theory and observations. These issues require further study.

Stratospheric temperatures have decreased in a consistent manner during the study period (2003-2012) (e.g., Maycock et al., 2018; DeSouza-Machado et al., 2025). This fact combined with the smaller theoretical stratospheric spectral signature of CO$_2$ growth (compared to the tropospheric signature shown in figure 2) makes it more challenging to extract a clear signal using the initial analogue methodology proposed by T24. To address these issues, a variant of the approach for sampling the analogues was developed. In this variant, the analogues are sampled by selecting only the 1000 analogues that are closest to their corresponding reference profiles in terms of stratospheric temperatures with a positive (vertical mean) difference, and the 1000 closest analogues with a negative (vertical mean) difference. The subset of analogues measured within scan angles between -10º and 10º is sampled from this set of the 2000 closest analogues.

Figure 3 shows the theoretical estimates together with the observational results using this variant of the analogue methodology. In this figure, we extend the results beyond what is illustrated in figure 2 (and in T24) to also show the spectral region associated with the stratosphere (650 to 680 cm^{-1}) where the CO_2 signal is more challenging to extract. It is clear from the figure that using this new variant allows to extract from the analogue observations a CO_2 spectral signature that compares well with theory, showing the impact of CO_2 growth on spectral radiances associated with the stratosphere, even in a spectral region where the signal is smaller and much more difficult to detect than in the 'tropospheric' spectral region of 690 to 780 cm^{-1}. It is noticeable that using this variant does not affect the results in the 'tropospheric' spectral region where the signal is stronger, as can be seen by comparing with figure 2, further confirming the robustness of the general analogue approach.

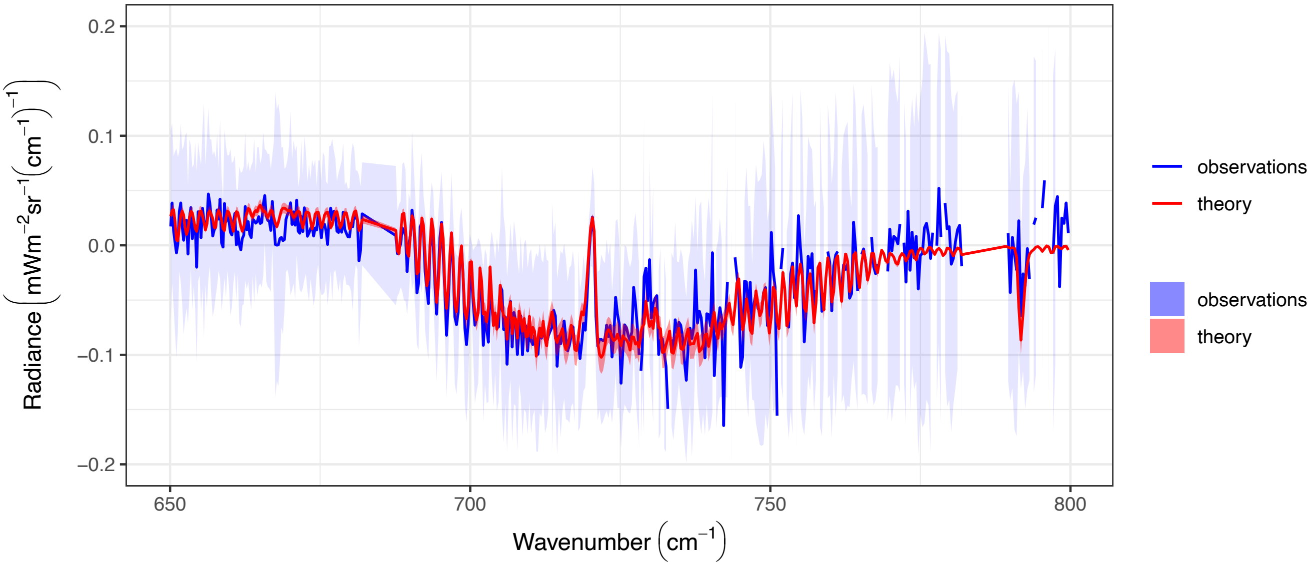

Figure 3: Annual mean radiance differences (in mWm^{-2} sr^{-1} (cm^{-1})$^{-1}$) due to CO_2 growth, from the AIRS observations (blue line) and from theory (red line), and standard deviations for the AIRS observations (blue shading) and theory (red shading), following a variant of the analogue methodology and illustrating the direct impact of CO_2 growth on spectral radiances during the 2003-2012 period (see text for details), including the 'stratospheric' spectral region. Based on observations within scan angles between -10° and 10°.

4 Conclusions

This study provides a definitive experimental confirmation from space of the impact of CO_2 growth on LW spectral radiances. By refining the initial T24 study, these new results conclusively confirm a critical theoretical foundation of the science of global warming.

We use analogue temperature profiles retrieved from MW-only radiances, unambiguously confirming the independence of our results from any role that the LW spectral radiances may play (via retrieval and/or data assimilation) in the analogue temperature profiles. The uncertainties due to CO_2 spatial and temporal variability when estimating the theoretical spectral radiances are shown to be small (often imperceptible) and have no impact on the interpretation of the results. The stratospheric spectral signature of CO_2 growth can be captured by using a slight variant of the analogue method that allows to also conclusively detect the smaller, and more challenging, signal from the stratosphere.

The analogue methodology to disentangle the impact of CO_2 growth on the observed LW spectral radiances, from the effects of temperature and water vapor, together with the long duration and remarkable stability of the AIRS radiance record, provides a direct and precise comparison with theoretical estimates of the radiance impact of CO_2 growth, confirming the theory. This methodology could be applied to experimentally confirm from space the precise role of other radiatively important components of the climate system, to measure radiative climate forcings, and given the current and planned duration of hyperspectral LW records, to directly observe critical climate feedbacks.

Appendix: Data and Methods

AIRS is a hyperspectral infrared (IR) sounder on the Aqua spacecraft (Parkinson, 2003) covering the 3.7-15.4 µm spectral regions with 2378 channels and spatial resolution of 13.5 km at nadir. AIRS was launched into a 705 km altitude orbit on May 4, 2002, and has been in routine data gathering mode essentially uninterrupted since September 2002. The 1:30 PM ascending node and orbital altitude of the Aqua spacecraft orbit have been accurately maintained (until 2022, when Aqua started to slowly drift) and daily (near) global coverage is achieved from the ascending and descending orbits. The AIRS radiometric accuracy has been discussed in several studies (e.g., Pagano et al., 2003; Tobin et al., 2006; Aumann et al., 2006), and prelaunch calibration (Pagano et al., 2003) showed an accuracy within 0.2 K for scene temperatures between 205 K and 310 K (between -0.2 and 0 K in the 15 µm spectral region).

Recently, Strow and DeSouza-Machado (2020) confirmed that the stability of the AIRS instrument for about 400 channels is within 2.10^{-3} $Kyear^{-1}$ in brightness temperature, which is about one order of magnitude smaller than the climate temporal signal in brightness temperature for the spectral region that is investigated in this study. According to Huang et al. (2022), the trend due to the AIRS instrument spectral shift is also within 2.10^{-3} $Kyear^{-1}$. AIRS radiances are routinely assimilated in global weather prediction systems and are used to retrieve vertical profiles of atmospheric temperature and water vapor, cloud and surface variables, and other atmospheric constituents (e.g., Susskind et al., 2003; Smith and Barnet, 2020; Kahn et al., 2014; Irion et al., 2018).

The Advanced Microwave Sounding Unit (AMSU) on Aqua is a 15-channel microwave (MW) instrument with 12 temperature sounding channels in the 50-58 GHz oxygen absorption band, that are used to produce the MW-only retrieved temperature profiles used in this paper (Rosencranz, 2001) and are also part of the AIRS/AMSU retrieval.

In this study, as mentioned above, the reference and analogue temperature profiles are retrieved solely from AMSU radiances (MW-only retrievals). The reference and analogue water vapor profiles are from the AIRS/AMSU retrieval products that are based on AIRS and AMSU, as well as on a neural network retrieval first-guess (Milstein and Blackwell, 2016) that uses the European Centre for Medium-range Weather Forecasts (ECMWF) analyses as the training dataset. As such, the water vapor profiles depend on AIRS and AMSU data, and on the ECMWF data-assimilation system as well as on a variety of observational datasets that are assimilated by ECMWF (e.g., radiosondes, Global Navigation Satellite System (GNSS) Radio Occultation (RO), and other infrared (IR) and MW sounders) via a neural network retrieval algorithm. Specifically, version 6 of the AIRS/AMSU retrieval products is used. The standard pressure levels for the retrieved temperature and water vapor profiles are described in: https://docserver.gesdisc.eosdis.nasa.gov/public/project/AIRS/V7_L2_Standard_Pressure_Levels.pdf.

The main reason why AMSU and AIRS temperature and water vapor profiles are used in our implementation of the analogue methodology is their direct collocation with the AIRS radiance spectra, which are used to estimate the spectral radiance differences discussed in this paper. Since these retrieved profiles are only used to find reference profiles and their analogues, other temperature and water vapor profile datasets, such as from hyperspectral IR instruments like the Infrared Atmospheric Sounding Interferometer (IASI) or the Cross-track Infrared Sounder (CrIS), from other MW sounder retrievals, or from analysis and re-analysis products, could be used as well to implement the analogue methodology.

The sensitivity of the methodology to the specific temperature and water vapor thresholds was analysed in T24 and was shown not to have an impact in the interpretation of the results. In our current study, only spectra measured within scan-angles between -10º and 10º from nadir are discussed, to simplify the methodology implementation and to circumvent the influence of different viewing angles on the overall results (e.g., Huang et al., 2022). For consistency, the theoretical radiances are calculated at nadir.

Analogues that have absolute radiance differences larger than 0.5 mWm^{-2}sr^{-1}(cm^{-1})$^{-1}$ are filtered out in order to remove outliers and to select analogues that are as close as possible to the reference states. No meaningful differences are seen in the results obtained with scan-angles between -5º and 5º, and/or with outlier filter values of 1 mWm^{-2}sr^{-1}(cm^{-1})$^{-1}$.

Code availability: The kCARTA model is available at (SRCv1.18 was used): https://github.com/sergio66/kcarta_gen.

Data availability: The AIRS/AMSU version 6 and AMSU MW-only L2 standard products are used for the temperature and water vapor profiles: https://doi.org/10.5067/Aqua/AIRS/DATA201 (AIRS Science Team and Teixeira, 2013). For AIRS L1B infrared radiances (version 5): https://doi.org/10.5067/YZEXEVN4JGGJ (AIRS Project, 2007).

Author contributions: JT developed the methodology, performed the analysis, and wrote the manuscript. RCW and HTT implemented the methodology and contributed to the analysis and the manuscript.

Competing interests: The authors declare that they have no conflict of interest.

Financial support: The research described in this manuscript was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

Acknowledgements: The authors would like to thank everyone who has been involved in creating the AIRS radiance record. Exciting conversations over the years with several colleagues, including L. Strow, C. Barnet, H. Aumann, S. DeSouza-Machado and X. Huang, and the advice from J.V.C. Teixeira on technical aspects, are gratefully acknowledged.

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