Global trends in Earth's spectrally resolved outgoing longwave radiation

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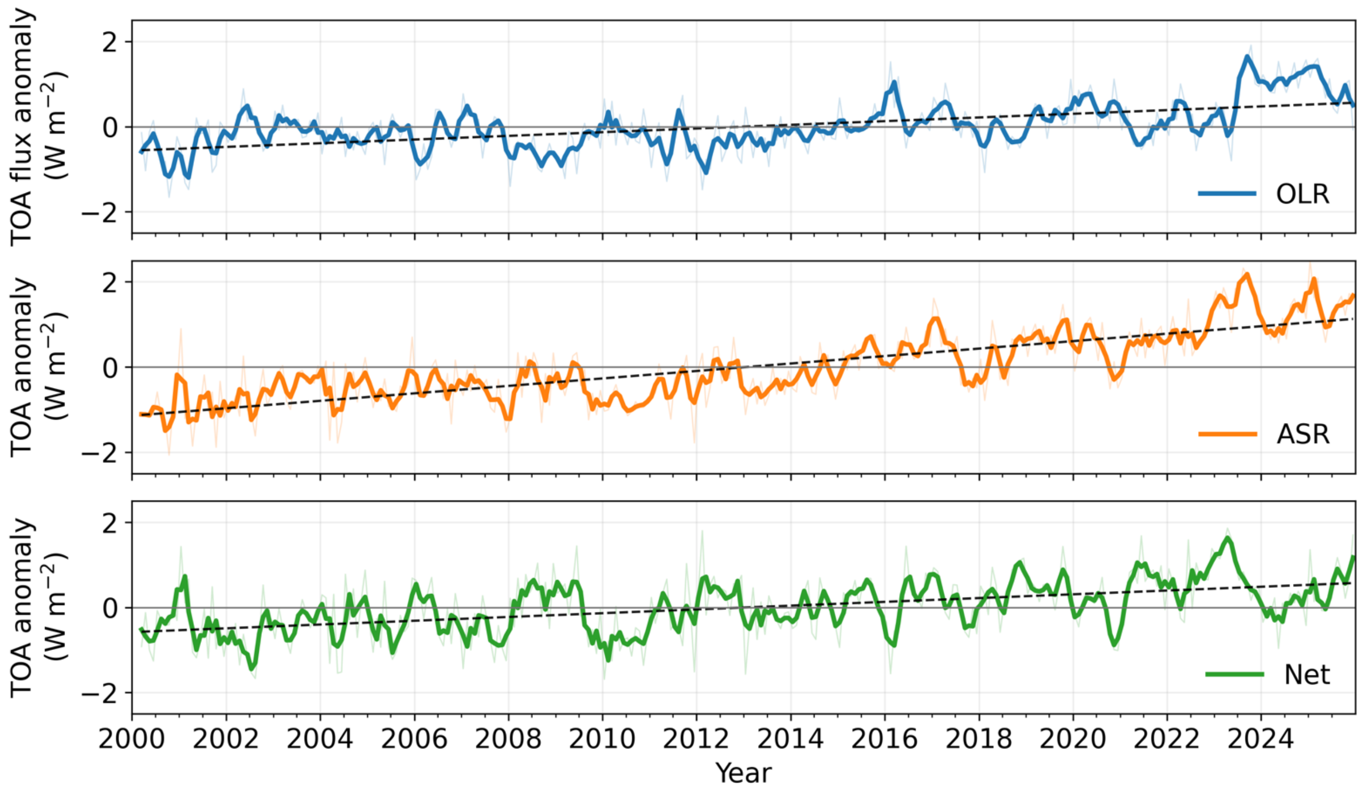
2nd GEWEX Earth's Energy Imbalance Assessment Workshop
Pasadena, CA

Components of Earth’s radiation budget



OLR increasing

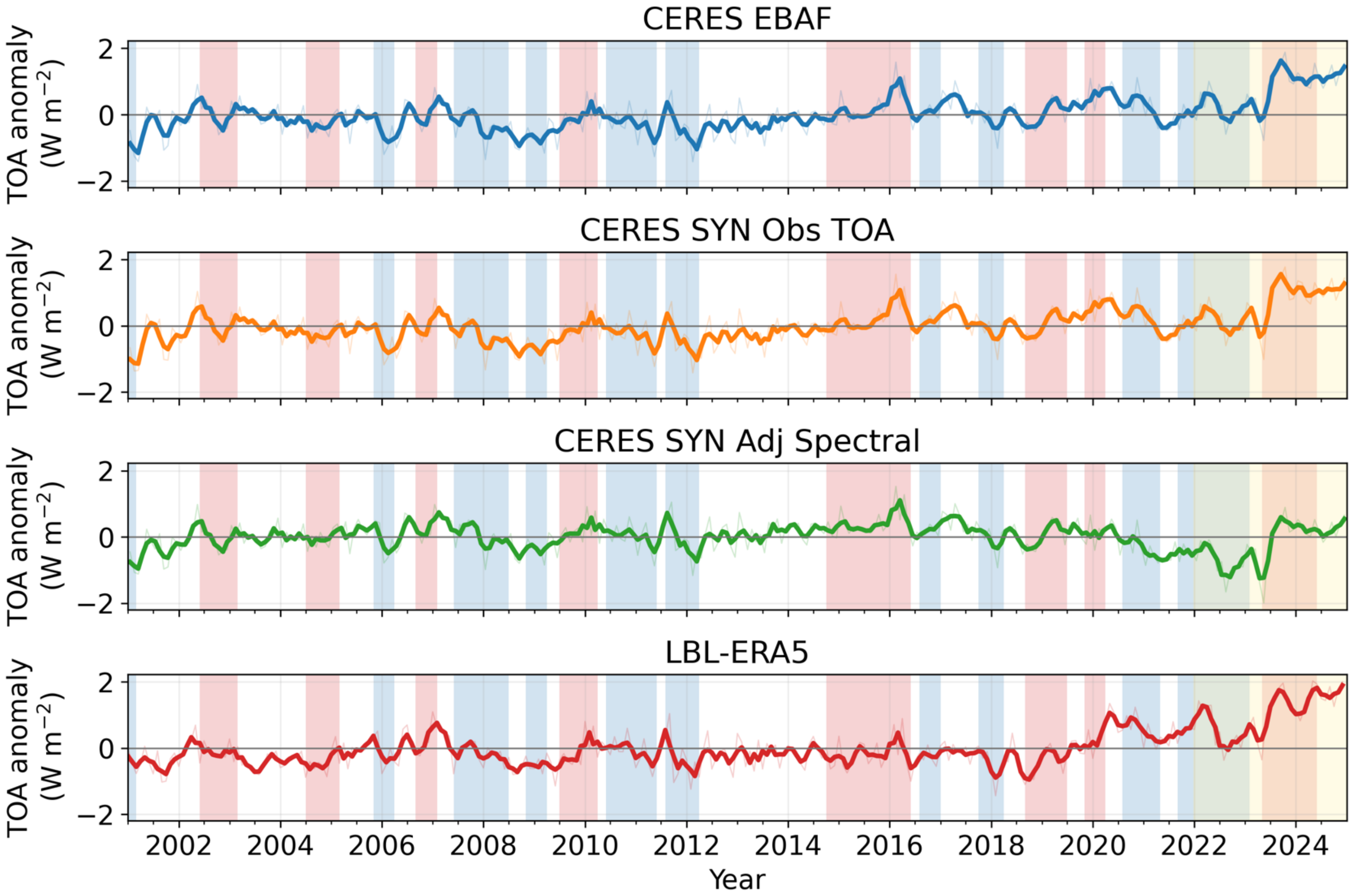
ASR increasing most

$$EEI = ASR - OLR$$

- Outgoing longwave radiation (OLR) is Earth’s cooling term in the EEI equation
- Increasing greenhouse gases (GHGs) should **decrease OLR** due to enhanced absorption
- However, competing effect is increasing temperatures which also **increases OLR**

Broadband context: recent OLR increase across datasets

- Global mean OLR anomalies show a late-record increase



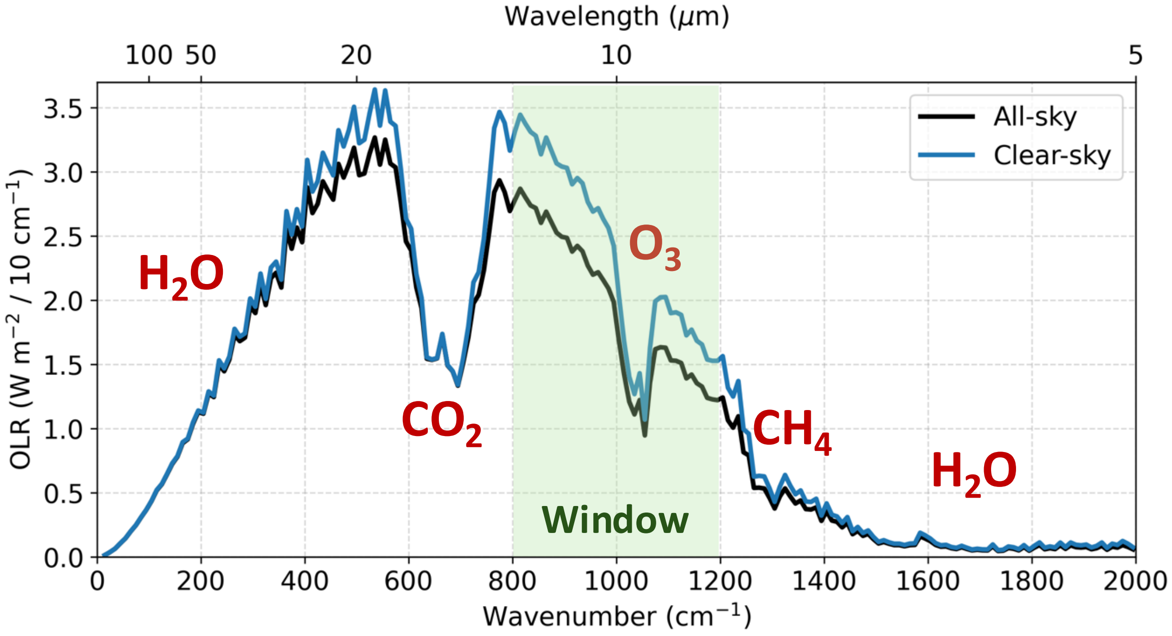
Large increase in OLR in 2023–24 apparent in all datasets

↓

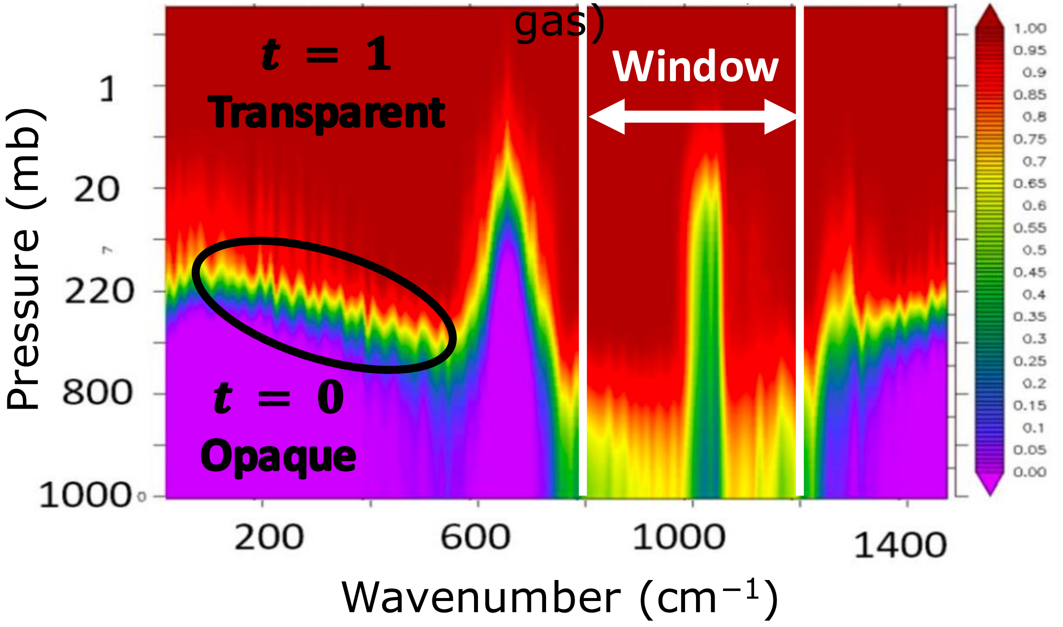
Coincident with 2023–24 El Niño and record warmth

The spectral dimension provides the full picture

- Broadband OLR hides spectral fingerprints of temperature, clouds, and greenhouse gases
- **H_2O, CO_2, O_3, CH_4 and N_2O** leave distinct absorption band signatures
- This spectral structure motivates **studying OLR beyond broadband,** especially since warming is due to anthropogenic GHG increases

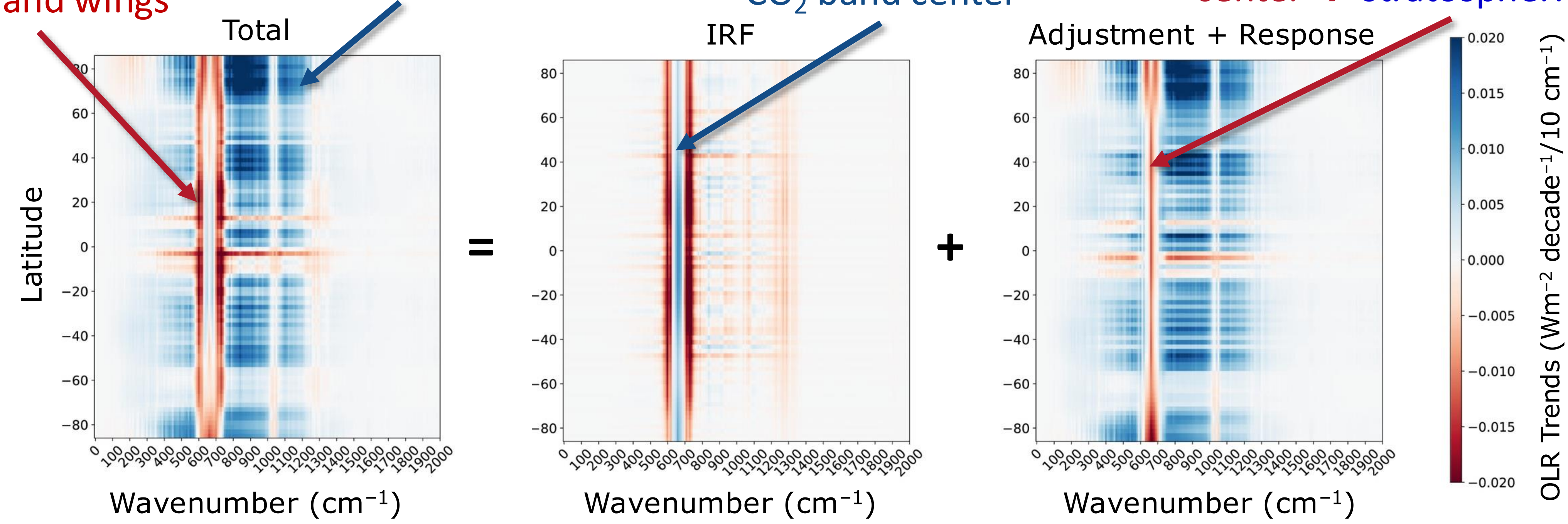


Global mean transmittance, t, from TOA to pressure level (All gas)



Spectral decomposition allows for attribution

- Raghuraman et al. (2023) used spectral OLR to show vastly different trends across the spectrum over the observational record
- Decomposition of total trends in instantaneous radiative forcing (IRF) and adjustment + response allowed for deeper understanding of observed trends



Decreasing OLR in CO_2 band wings

Increasing OLR

Increasing OLR in CO_2 band center

Decreasing OLR in CO_2 band center → stratospheric cooling

Leveraging the full spectrum to understand OLR trends

OLR is a major component of ERB. Anthropogenic changes in GHGs have changed OLR.

OLR is inherently a **spectral quantity**. GHGs have strong absorption fingerprints across the spectrum.

What are the global and spatial trends in Earth’s outgoing infrared spectrum? Can LBL–ERA5 reproduce the observed AIRS spectral signal over 2003–2021?

What spectral regions account for the recent OLR rise?

Observational datasets

CERES:

- **CERES SYN1deg Obs. TOA:** Measured window band fluxes (830–1250 cm^{-1})
- **CERES SYN1deg Adj. Spectral:** Computed all-sky fluxes in 5 bands:

Bands	Wavenumbers (cm^{-1})	Dominant absorber/feature
LW 12	0 – 280	Rotational H_2O band
LW 10–11	280 – 540	Rotational H_2O band
LW 8–9	540 – 800	CO_2 band
LW 5–7	800 – 1250	Atmospheric window
LW 1–4	1250 – 2200	CH_4, N_2O, H_2O

AIRS:

- **AIRS L3 spectral OLR:** Monthly gridded spectral fluxes from 10–2000 cm^{-1} at 10 cm^{-1} intervals covering period **2003–2021**

Line-by-line radiative transfer model

- We used Geophysical Fluid Dynamics Laboratory (GFDL) line-by-line (LBL) radiative transfer model (GFDL-GRTCODE)
- Inputs are **ERA5 monthly-mean** surface and atmospheric profiles (water vapor, surface and atmospheric temperature, surface albedo, clouds, O_3) and observed well-mixed greenhouse gas (CO_2, CH_4, N_2O, and CFCs) during **2001–2024**
- We sum together the following 5 bands for LBL-ERA5 and AIRS:

Band range (cm^{-1})	Dominant absorber/feature
50 – 2000	Total broadband
160 – 560	Rotational H_2O band
560 – 630, 700 – 800	CO_2 band wings
800 – 990, 1070 – 1200	Window
830 – 1250	Window (CERES-comparable)

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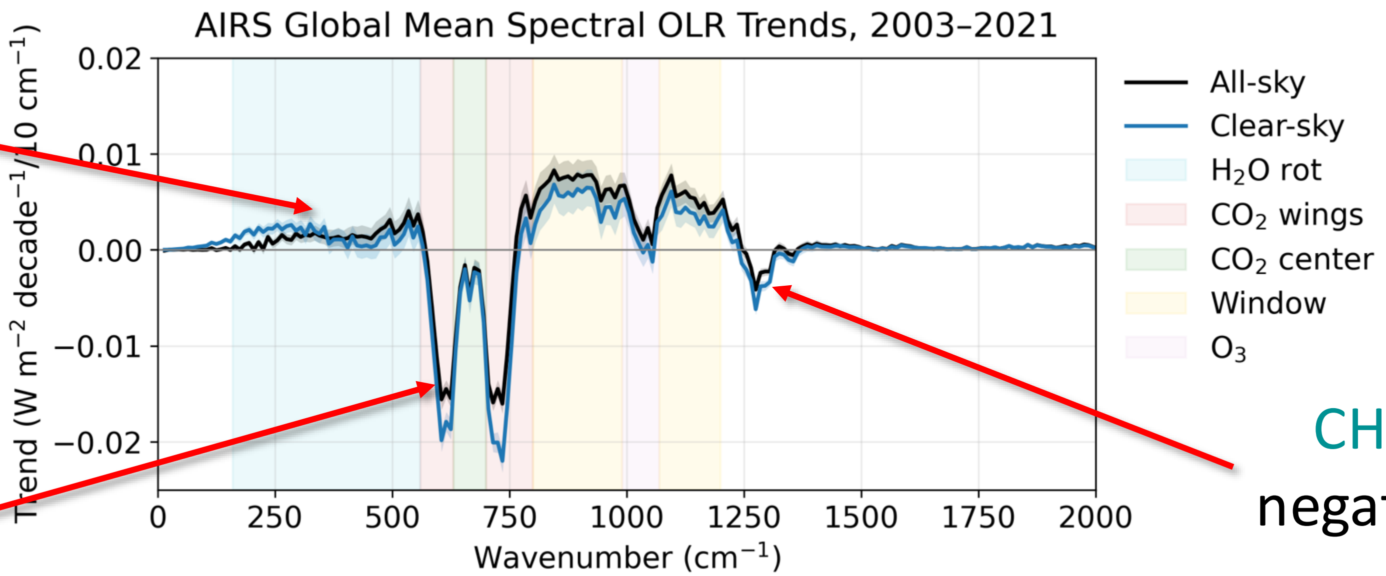
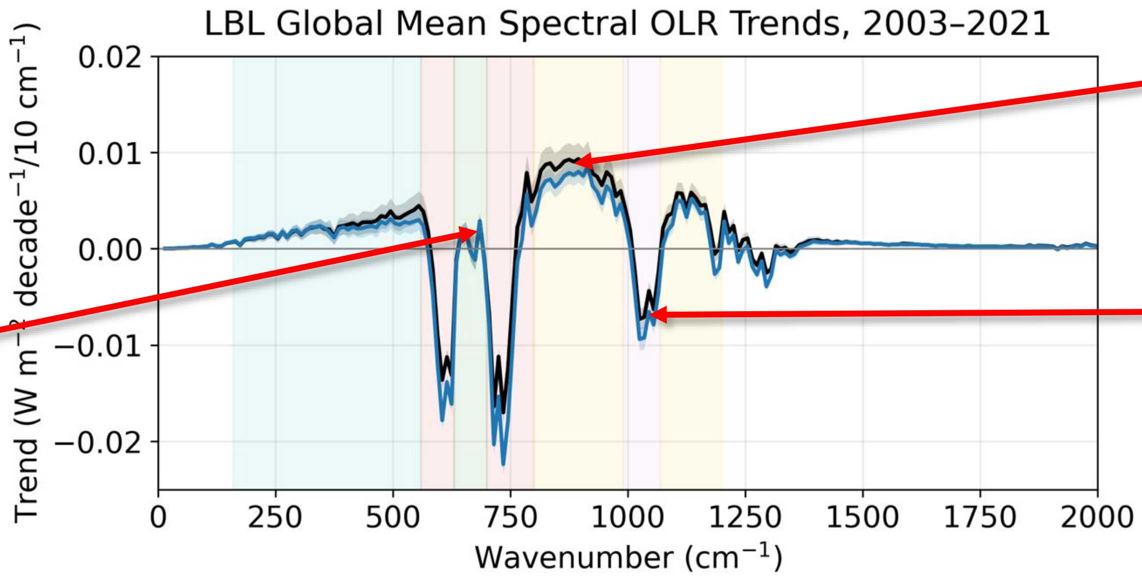
Line-by-line simulations can reproduce AIRS global trends

H_2O rotational band: positive trends

CO_2 wings: largest negative trend

CO_2 band center: neutral or slightly negative trend





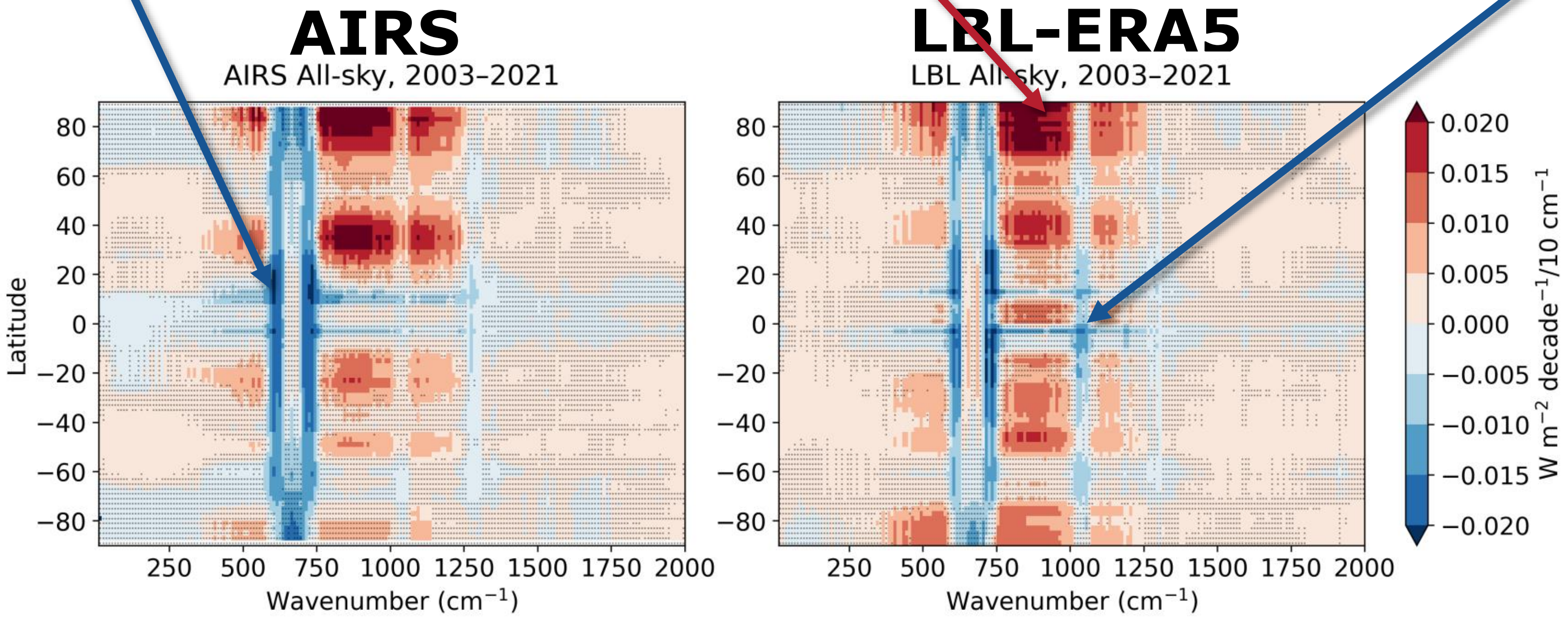
CH_4: small negative trend

Window: largest positive trend

(!) O_3 band: large discrepancy between AIRS and LBL-ERA5

Zonal trends shed light on hemispheric differences

- There are large variations in zonal and spectral trends



Negative trends in CO_2 band wings, largest in tropics

Warming-induced response in window, largest 20–50°N and 70–90°N

Negative trends in O_3 band largest in tropics

Note: stippling indicates where trends are ***not*** *significant.*

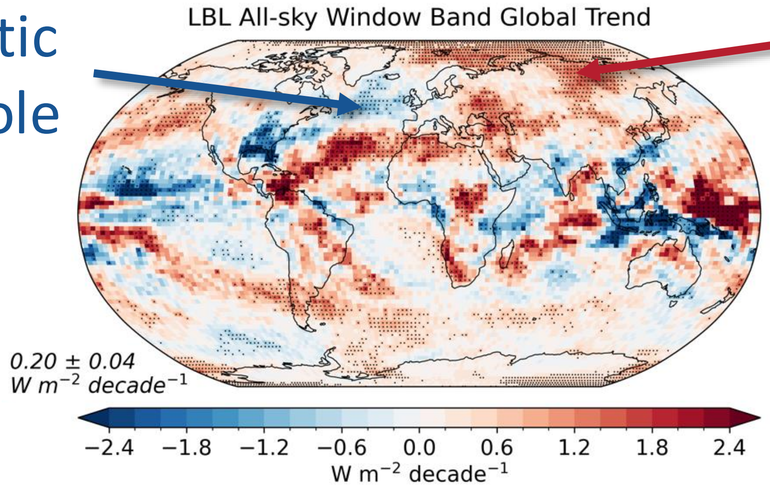
Global and regional trends are highly heterogeneous

All-sky

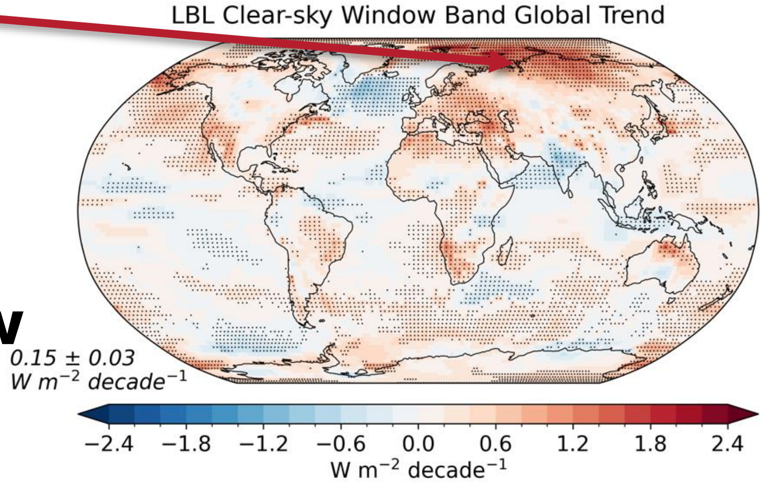
Arctic warming

Clear-sky

North Atlantic Warming Hole

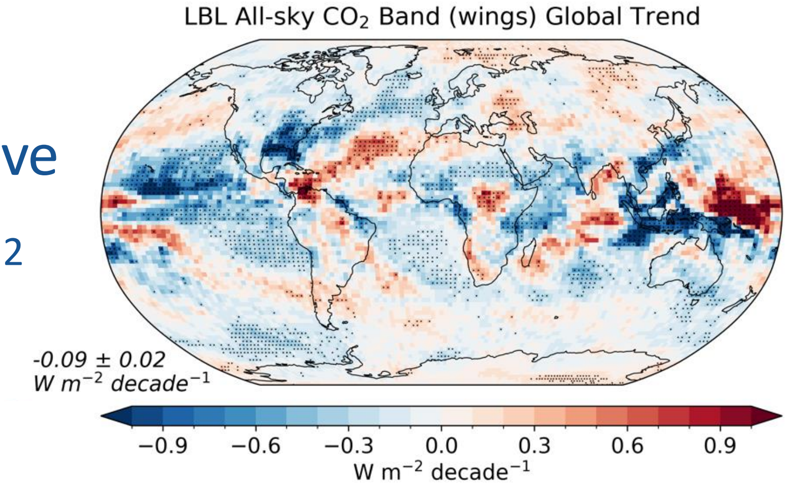

LBL All-sky Window Band Global Trend

LBL-ERA5 window

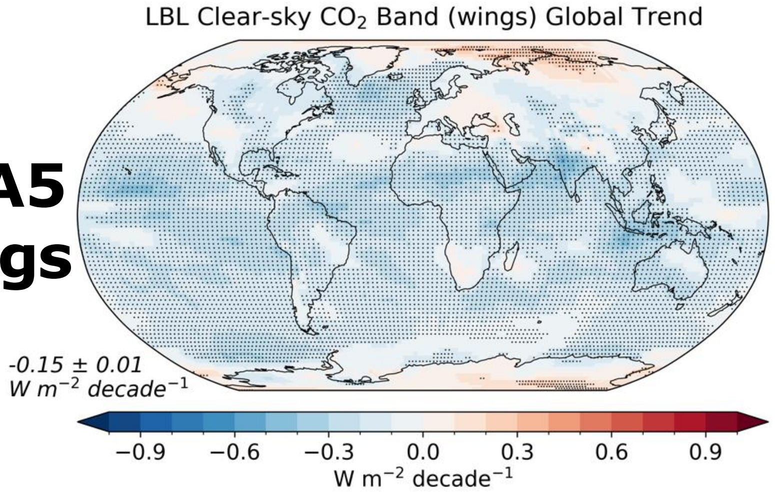

LBL Clear-sky Window Band Global Trend

Cloud changes **increase** overall OLR trends in both spectral regions

Mostly negative trends in CO_2 band wings


LBL All-sky CO_2 Band (wings) Global Trend

LBL-ERA5 CO_2 wings


LBL Clear-sky CO_2 Band (wings) Global Trend

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Spatial agreement with CERES window measurements

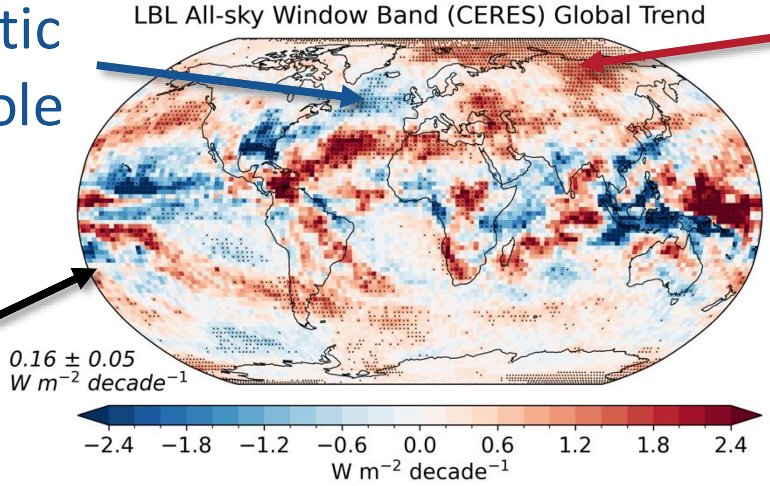
All-sky

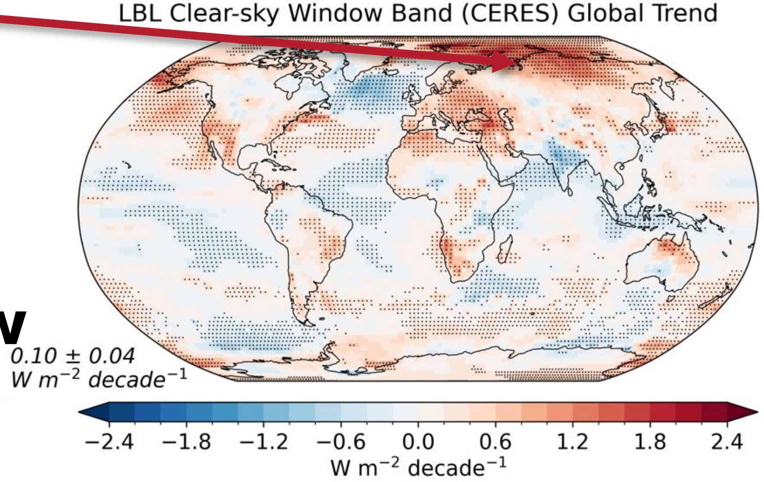
Arctic warming

Clear-sky

North Atlantic Warming Hole

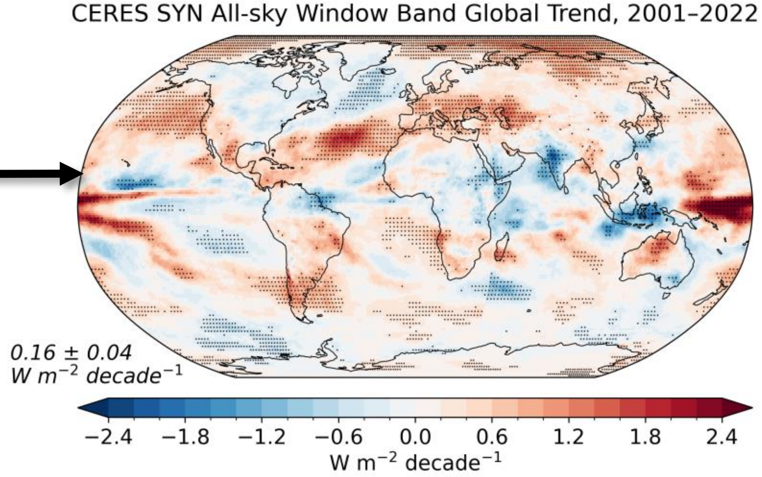
LBL-ERA5 window

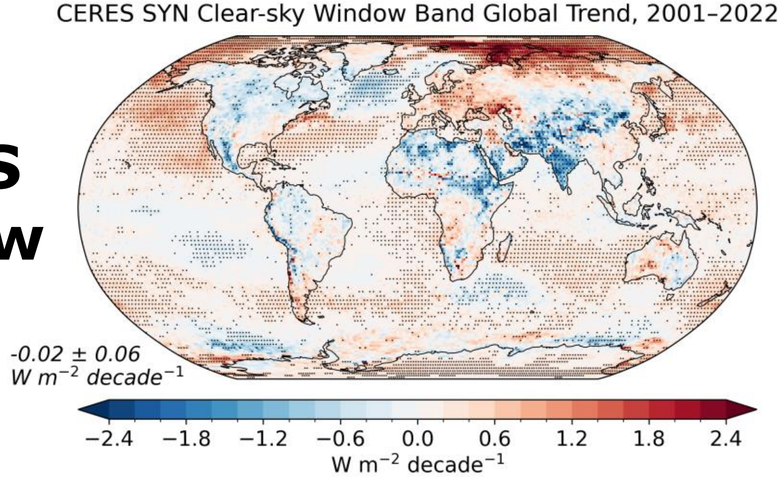

LBL All-sky Window Band (CERES) Global Trend


LBL Clear-sky Window Band (CERES) Global Trend

Larger magnitude positive and negative trends in LBL-ERA5 than CERES

CERES window


CERES SYN All-sky Window Band Global Trend, 2001–2022


CERES SYN Clear-sky Window Band Global Trend, 2001–2022

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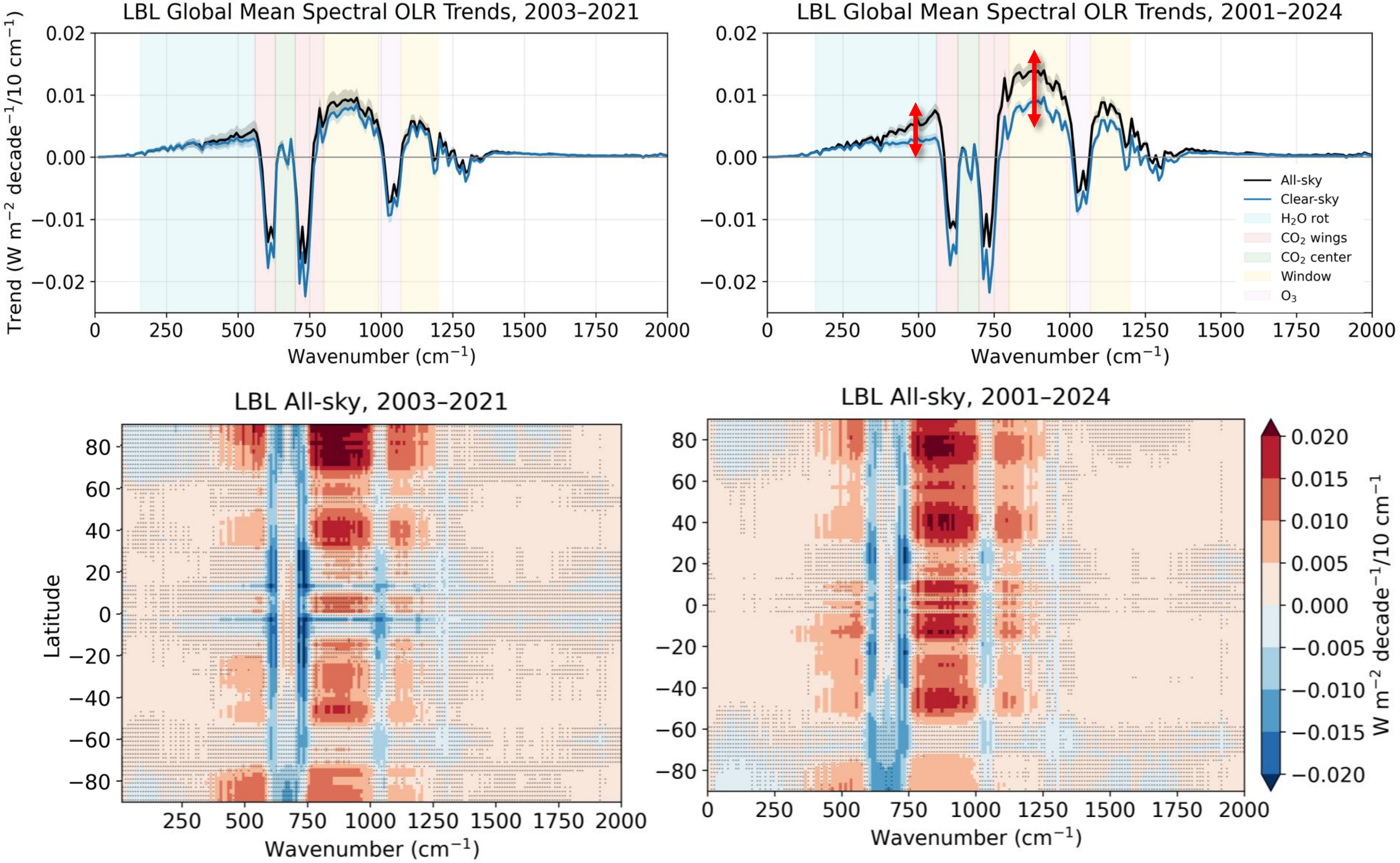
Late-record years reshape trend patterns

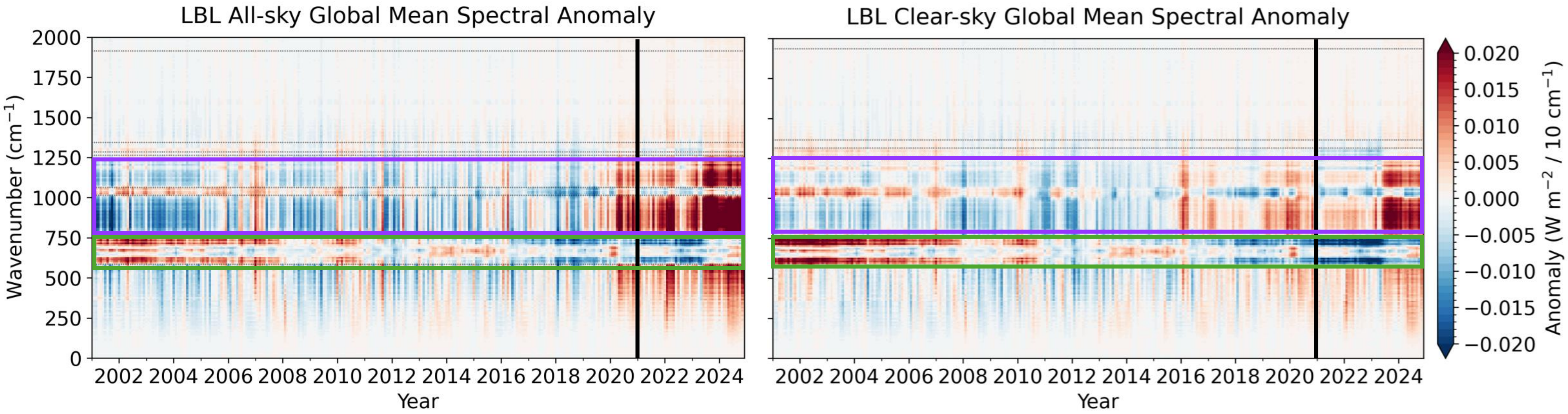
2003–2021 **2001–2024**



- Larger all-sky vs clear-sky divergence in 2001–2024
- Weaker hemispheric polarity when late-record years are included

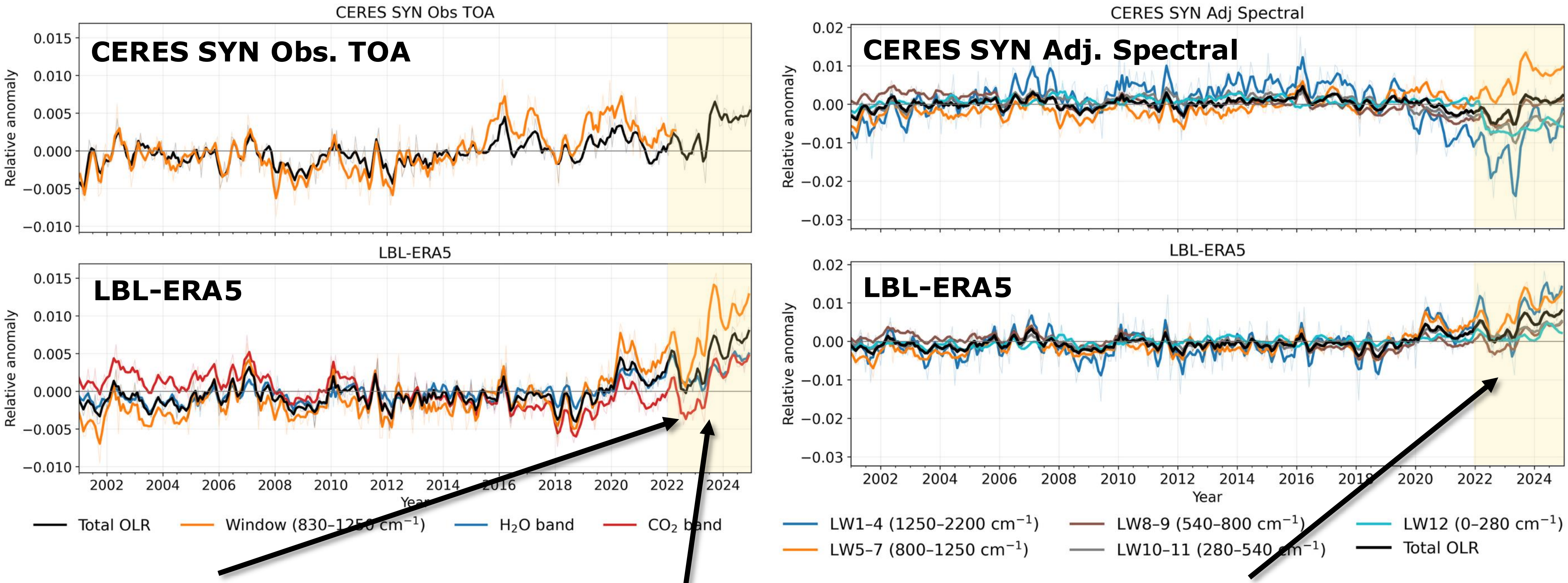
Late-record increases in OLR

- **Window:** Spectrally, the window band is largely responsible for large increases in broadband OLR in 2023–24
- **CO_2 band:** Very clear long-term negative trend in band wings, followed by reduced negative anomalies in 2023–24



*Note: stippling indicates where trends are **not** significant.*

Spectral breakdown in CERES and LBL



Late-record positive anomalies in CO_2 band wings weaken long-term negative trend

Window emission accounts for much of recent broadband OLR increase

LBL suggests MIR (1250–2200 cm^{-1}) also contributes, but CERES adjusted spectral bands show different behavior

Summary

Key takeaway: Spectral dimension provides insight that broadband OLR alone can't and allows for deeper understanding of the mechanisms driving OLR and EEI changes.

- **LBL-ERA5 broadly captures observed AIRS spectral trends**
  - Positive window and H_2O rotational band trends and negative CO_2 band wing trends
  - Supports use of line-by-line models for physically interpreting spectrum
- **Spectral and regional structure matters**
  - For example, Arctic warming is important in the window band and time-period-dependent hemispheric polarity
- **Recent OLR increases**
  - Recent OLR increases are dominated by window band emission, while MIR discrepancies highlight where further intercomparison is needed

Thoughts for future work

- **Ozone:** What are the reasons for the large discrepancy between AIRS and LBL-ERA5 in the ozone band?
- **Different instruments:** Full intercomparison between and utilization of different hyperspectral instruments (e.g. AIRS, IASI, CrIS).
- **Shortwave:** Can we use similar spectral tools to understand changes in ASR? Relevant for future missions with novel measurement capabilities (e.g. Libera split-shortwave channel).

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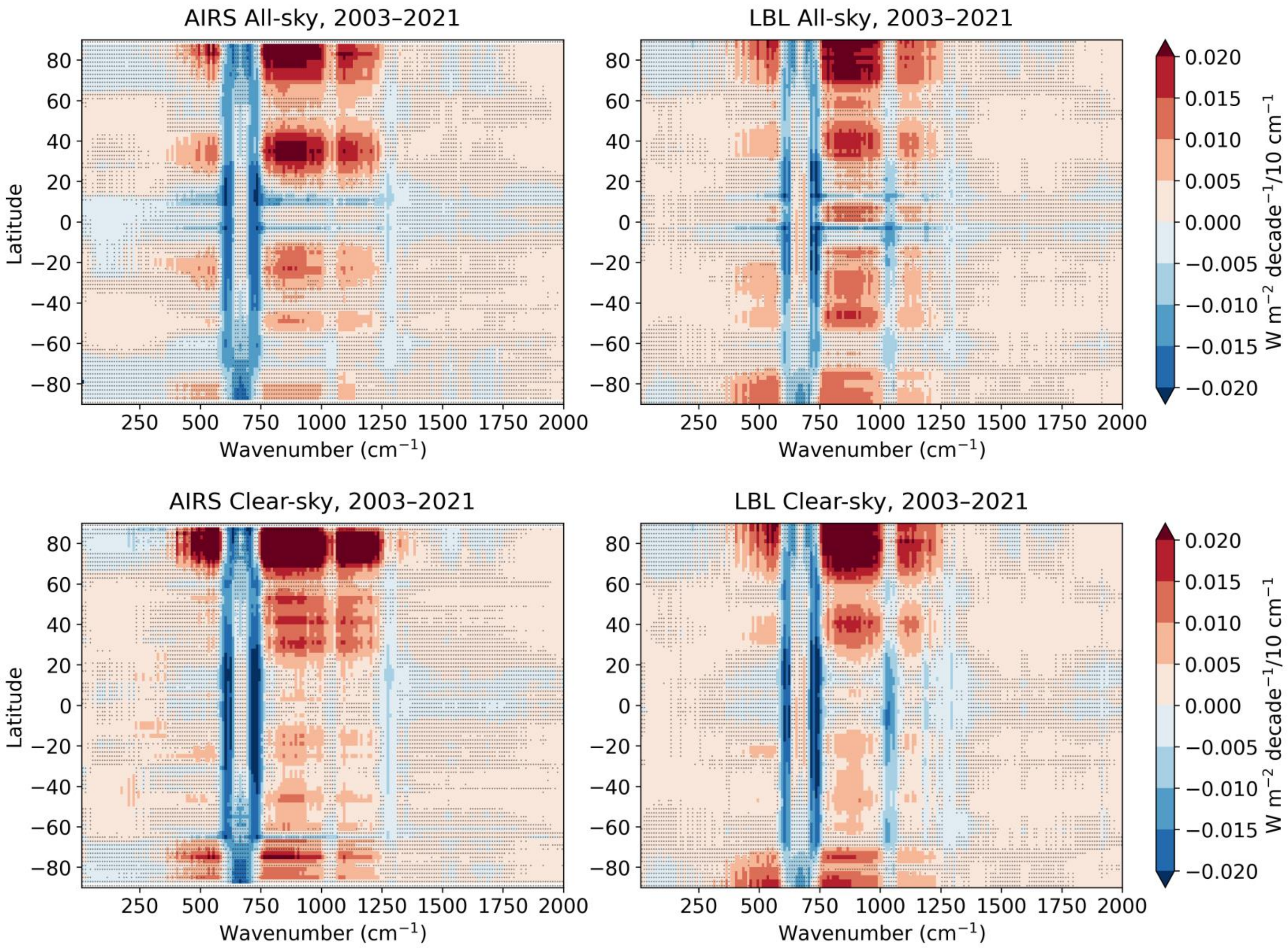
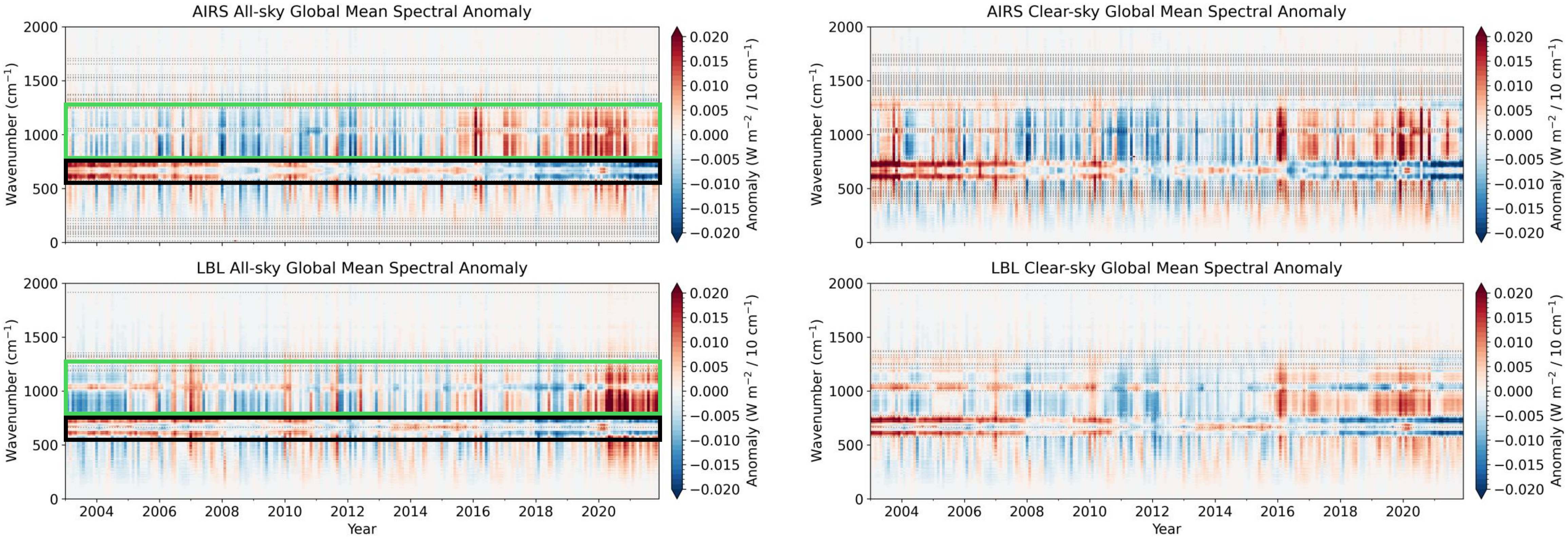
Extra slides

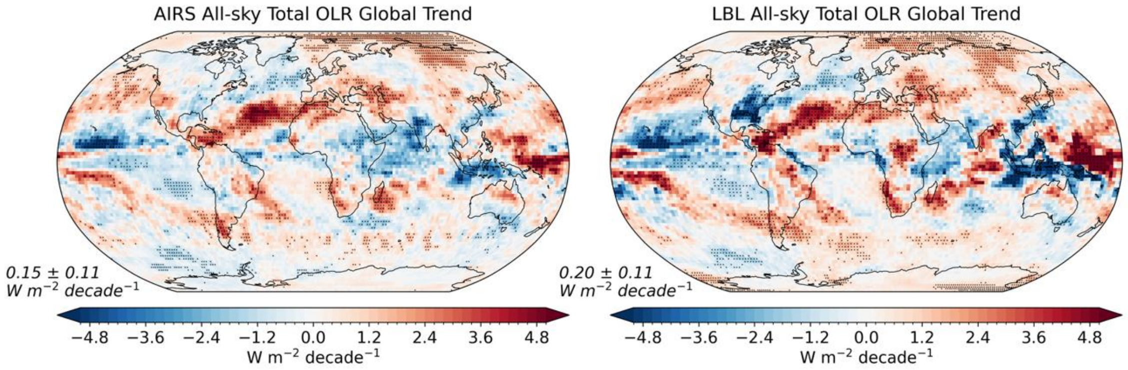
Zonal mean trends (All-sky vs clear-sky)

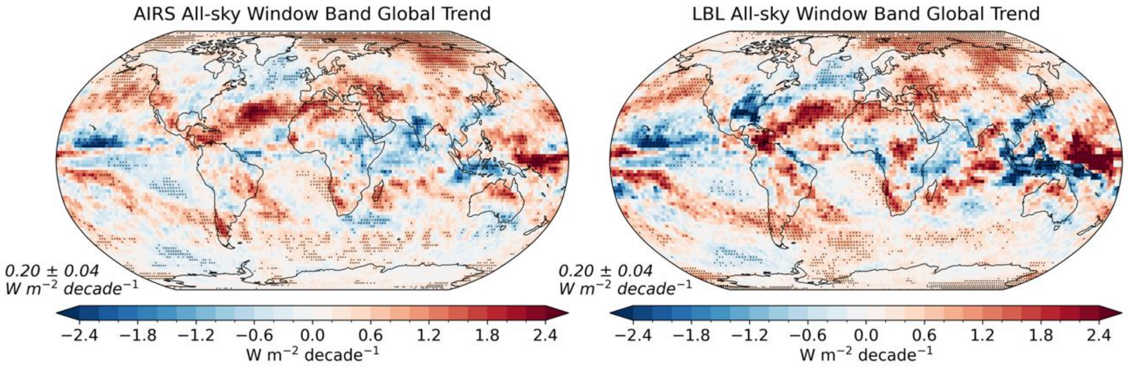


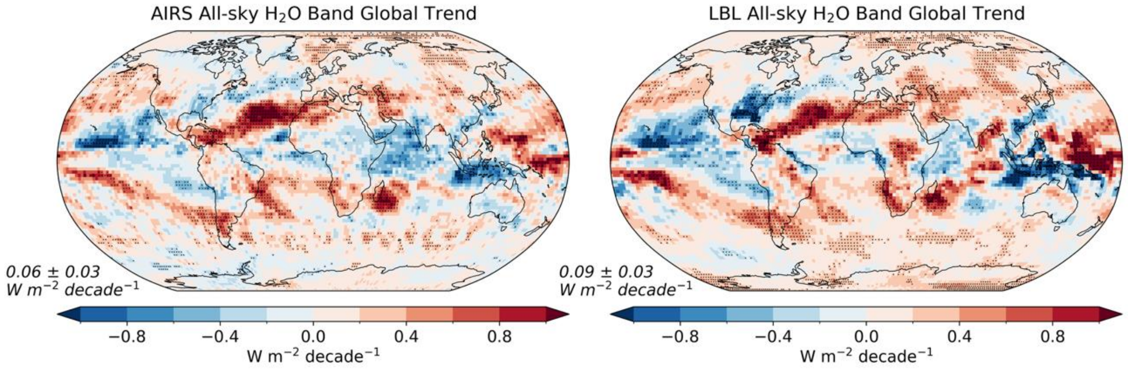
2003–2021 global mean spectral time series

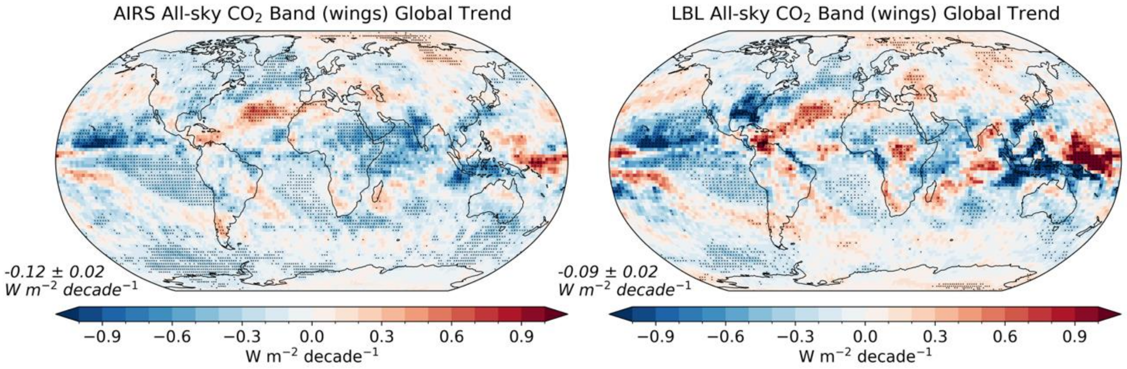


All-sky trends (AIRS vs LBL 2003–2021)

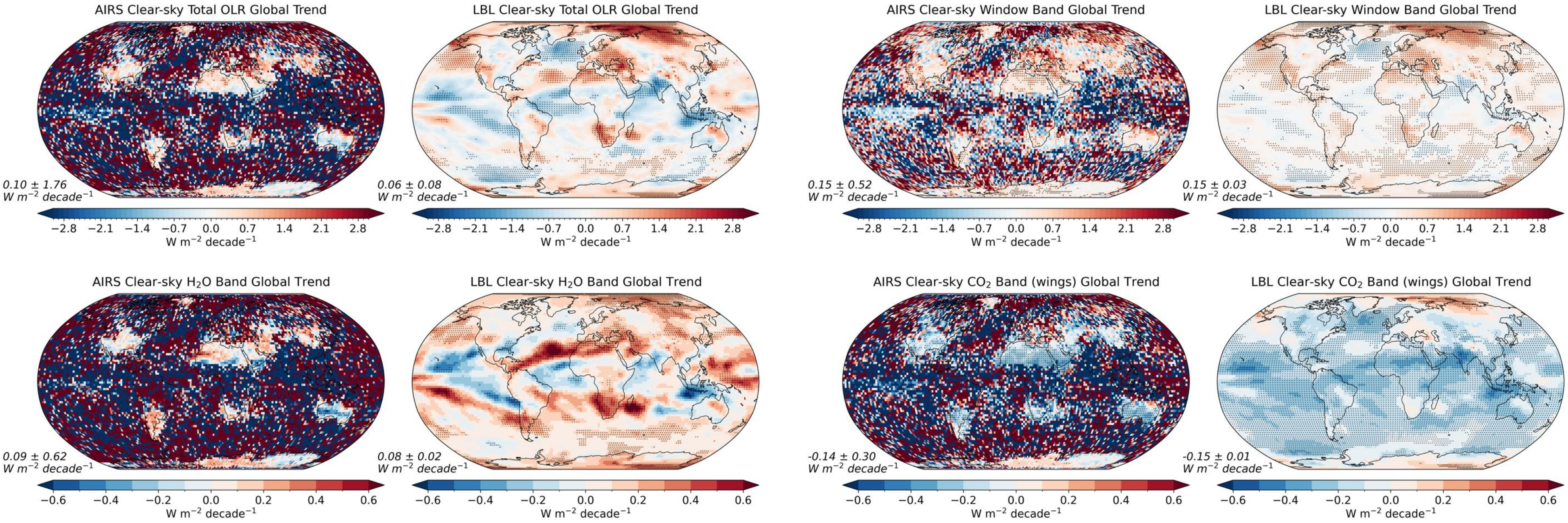




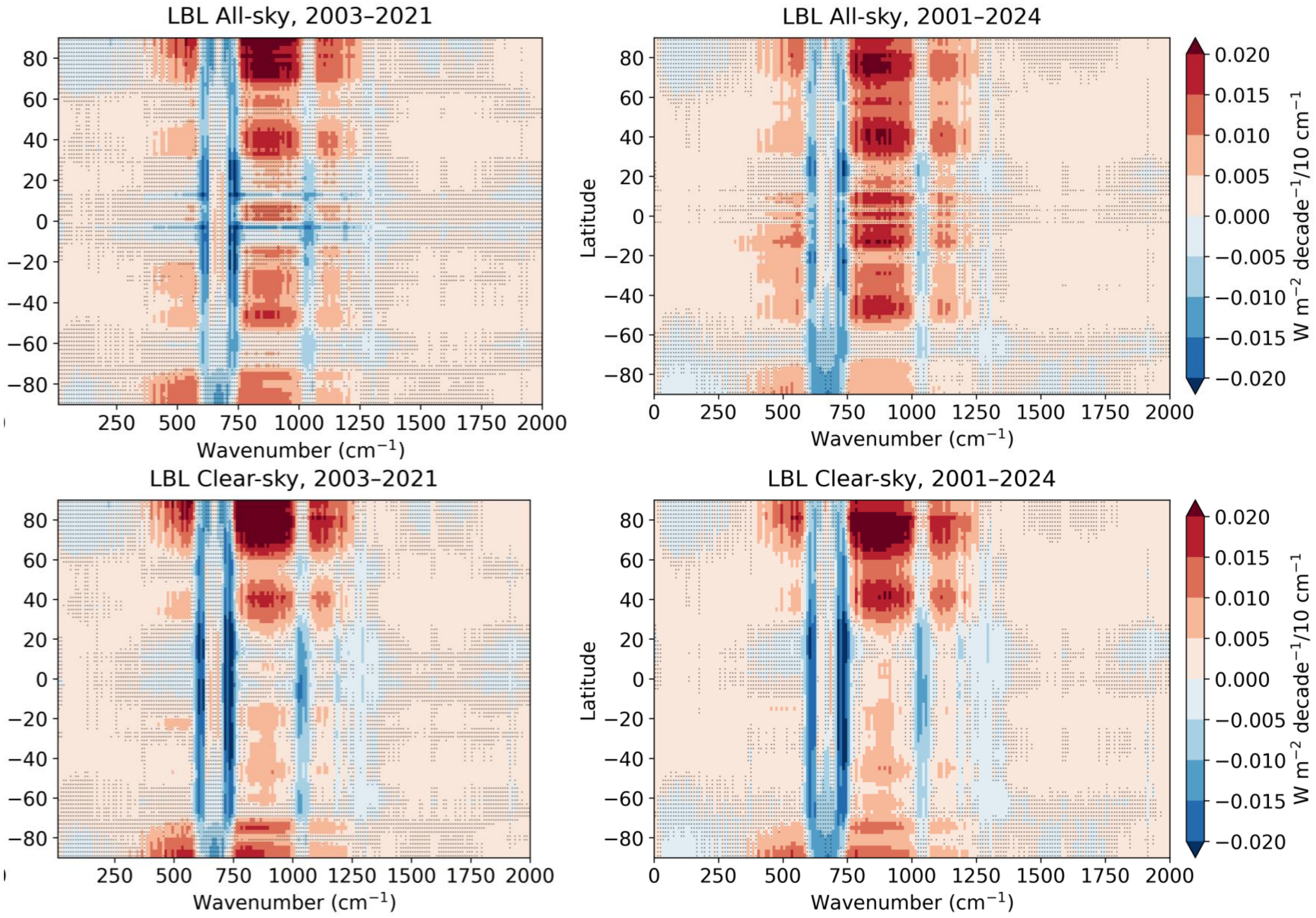




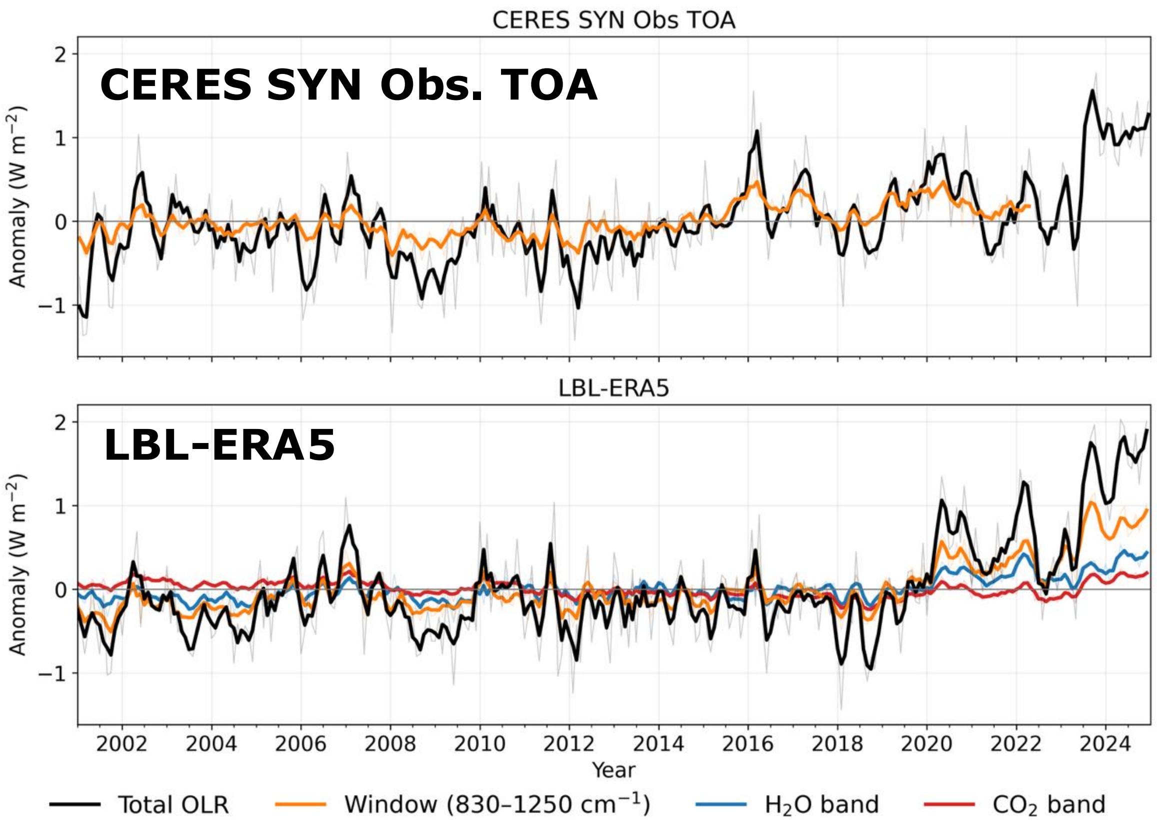
Clear-sky trends (AIRS vs LBL 2003–2021)

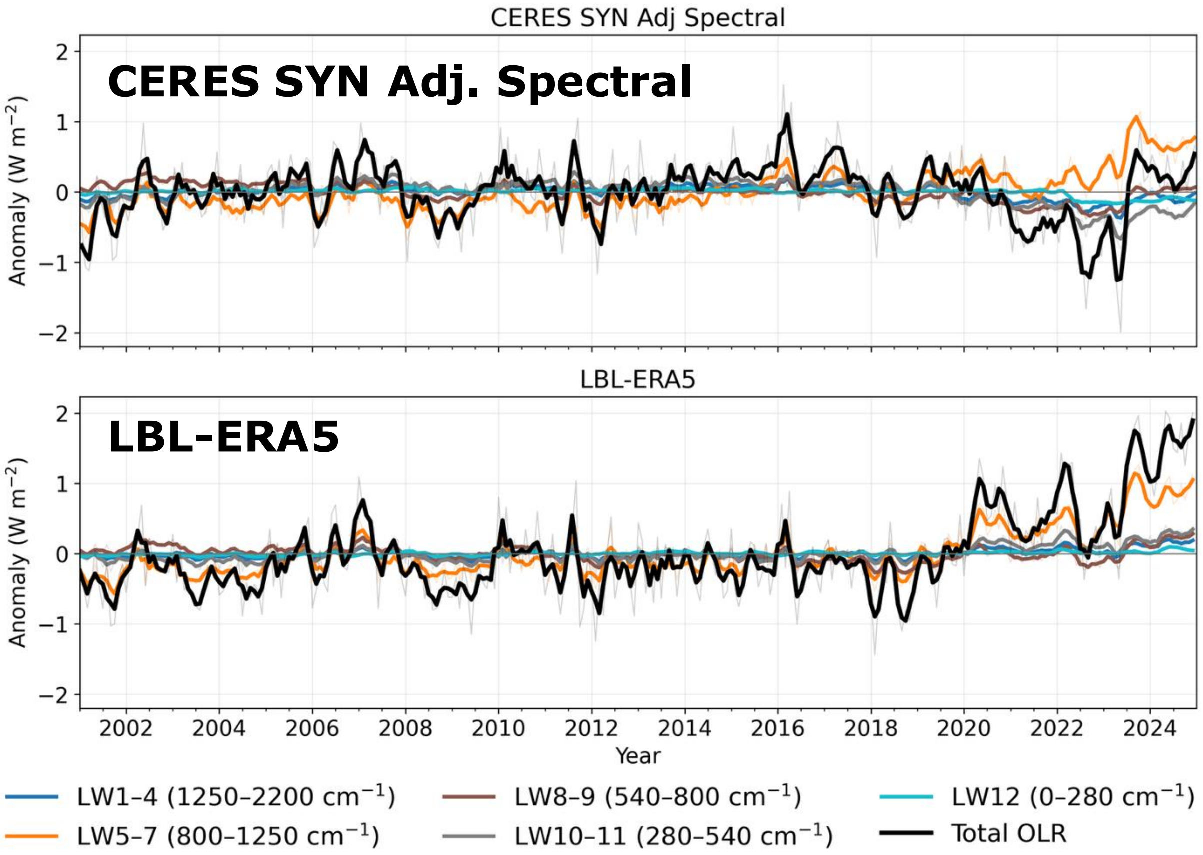


Comparison of 2003–2021 to 2001–2024



Spectral breakdown in CERES vs LBL (non-relative)





- LBL-ERA5 window matches CERES window in global mean
- Late-record positive anomalies in CO_2 band responsible for reducing overall negative trends

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CERES observational data

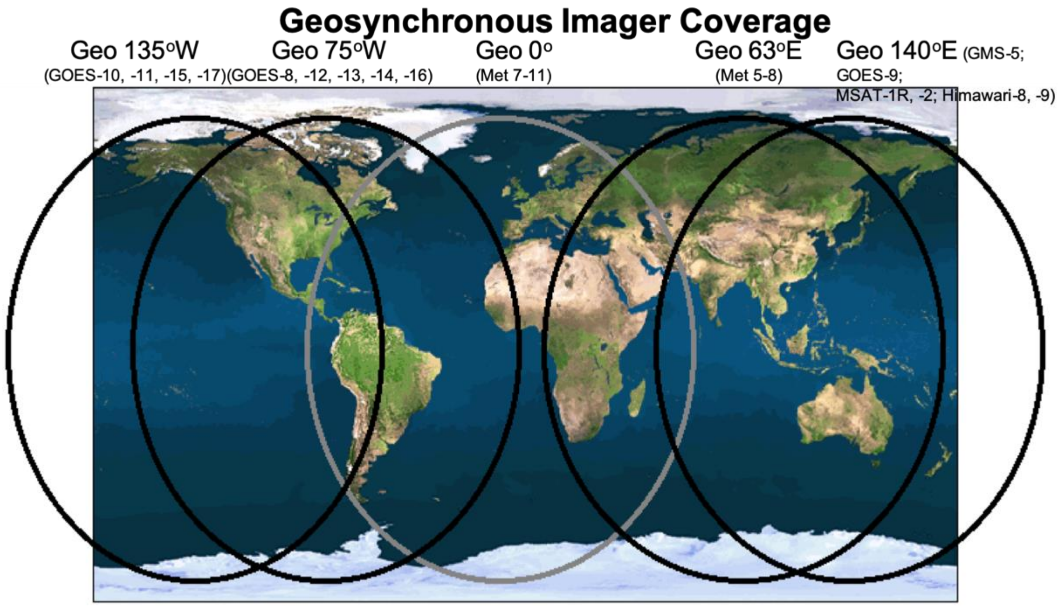
(1) CERES instruments on sun-synchronous satellites

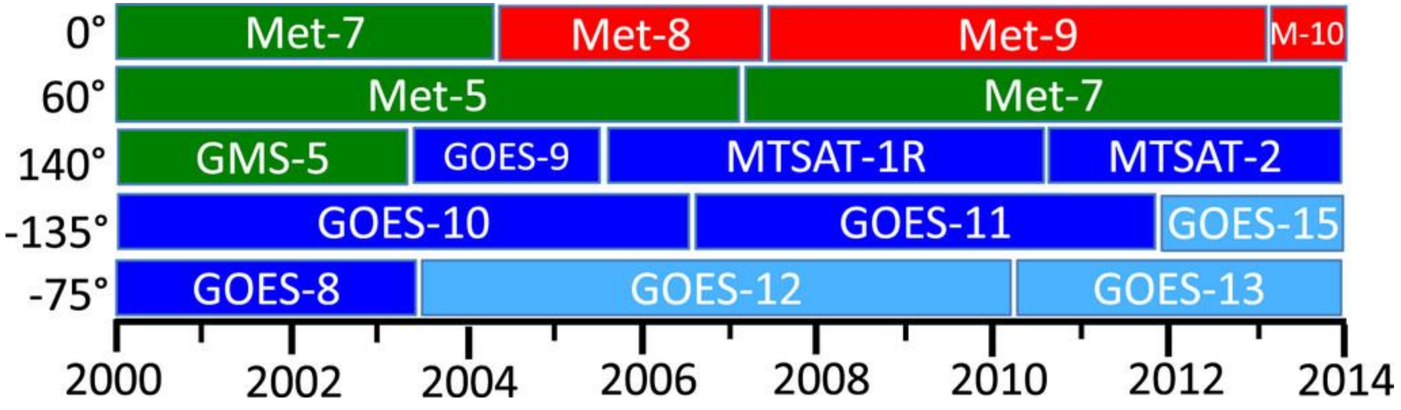
- CERES instruments fly on Terra and Aqua satellites in sun-synchronous orbits with local equator crossing times (LECT) of 10:30 and 13:30 local time → 2 observations per location per day
- Measure broadband radiances in three channels:
  - Shortwave (SW; between 0.3 and 5 µm)
  - Total (TOT; between 0.3 and 200 µm)
  - Window (WN; between 8 and 12 µm)
- Longwave isn't directly measured: LW = TOT – SW

CERES observational data

(2) Geostationary satellite (GEO) imagers

- To resolve the diurnal cycle at each location, a constellation of GEO imagers are employed
- Coverage between 60°S and 60°N





CERES observational data

- Raw data (Level 0) is acquired from CERES instruments on Terra and Aqua satellites and from geostationary (GEO) satellite image products.
- Raw CERES Level 0 data is processed into instantaneous filtered Level 1B radiances using updated gains and spectral response functions, which are then converted into unfiltered radiances and estimated instantaneous TOA fluxes (Level 2) using empirical Angular Distribution Models (ADMs).
- Cloud properties are derived from both MODIS data on Terra and Aqua using CERES working group Ed4A retrievals and from GEO imager data using algorithms designed to minimize differences from MODIS, including multiple-channel algorithms for newer GEOs and a two-channel algorithm for first-generation GEOs.
- GEO radiances are cross-calibrated with MODIS to ensure consistency, involving adjusting GEO visible radiances with Aqua-MODIS Collection 6 band 1 using Spectral Band Adjustment Factors (SBAF) and adjusting GEO infrared (IR) brightness temperatures to Aqua MODIS-equivalent BTs using monthly linear regressions of coincident data.
- Calibrated GEO narrowband radiances are converted to broadband TOA fluxes, using empirical models and angular geometry for Shortwave (SW) fluxes and the Radiance-Based Approach (RBA) that uses adjusted GEO IR and Water Vapor channel radiances directly to convert to Longwave (LW) fluxes.
- CERES footprint fluxes, MODIS cloud properties, and GEO pixel-level data are spatially averaged and gridded onto a 1° equal-angle grid, processed on a nested grid and then replicated to form the final complete 360x180 grid covering the GEO domain between 60°S and 60°N.
- The gridded broadband GEO TOA fluxes are normalized with CERES fluxes using a regional normalization technique by linearly regressing instantaneously matched CERES and GEO fluxes within moving 5°x5° regions of the same surface type monthly to remove biases.
- The normalized 1-hourly GEO fluxes and CERES observed fluxes are combined into 1-hourly datasets, with CERES fluxes taking precedence over GEO fluxes when both are available in a region, and linear interpolation is used only to fill remaining data gaps.
- Surface and in-atmosphere fluxes (computed fluxes) are calculated hourly using the Langley Fu-Liou radiative transfer model with inputs including MODIS and GEO-derived cloud properties, GEOS-5.4.1 atmospheric profiles, surface properties, and aerosol optical thicknesses.
- The final SYN1deg-1Hour product is generated, containing the 1-hourly observed TOA fluxes, computed TOA, surface, and in-atmosphere fluxes, and associated retrieved properties.

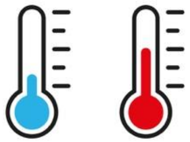
Langley Fu-Liou RTM

Inputs

- Cloud properties derived from MODIS and geostationary satellites (GEO). These cloud properties include fraction, optical depth, top height, phase, and particle size. The DQS specifies how optical thickness variability is treated using linear and logarithmic means. Cloud properties are kept separately for four cloud types.
- Atmospheric profiles for temperature, humidity (specific humidity), and ozone from the GEOS-5.4.1 Data Assimilation System. Six-hourly profiles are used for surface computations.
- Skin temperatures from GEOS-5.4.1, used at three-hourly resolution.
- Surface albedo and emissivity, with sources varying by surface type (ocean, land, snow/ice).
- Aerosol optical thicknesses derived from the MATCH aerosol transport model which assimilates MODIS data.
- Incoming solar daily irradiance from the SORCE TSI V-15 dataset.

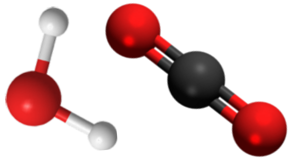
What controls outgoing longwave radiation?

- OLR is controlled by a variety of factors:



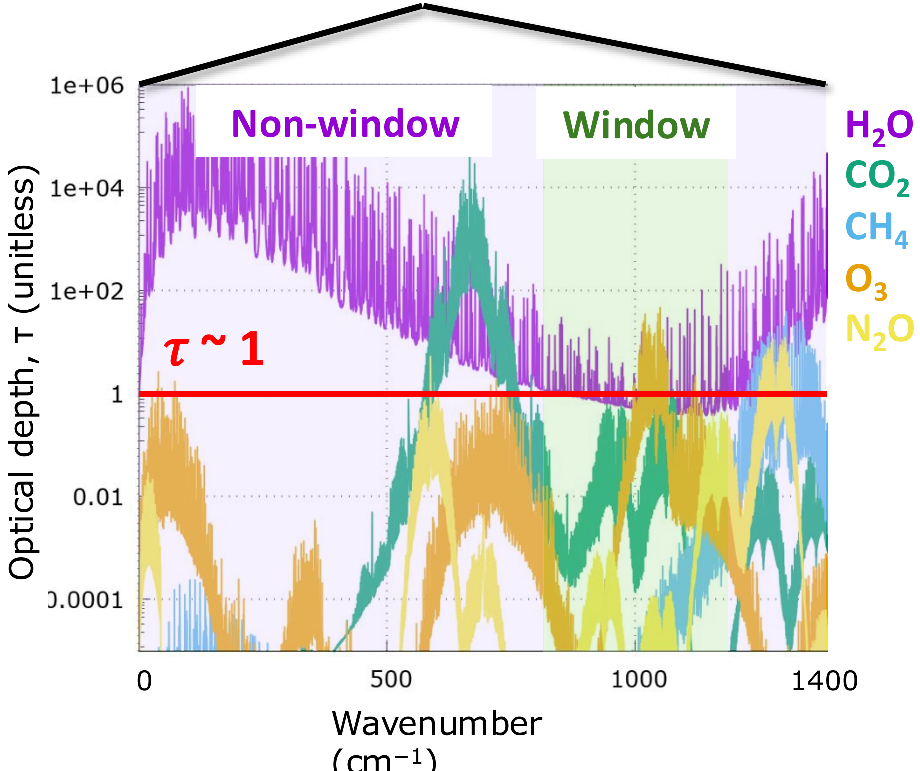
Surface/atmospheric temperature

Clouds



Atmospheric composition

- OLR is heavily modulated by atmospheric constituents that absorb and re-emit longwave radiation.
- **Window band:** atmosphere is mostly transparent
- **Non-window bands:** atmosphere is more strongly absorbing



The spectral nature of OLR

The spectral radiance at TOA is defined as:

$$I^{\uparrow}(\infty) = \underbrace{I^{\uparrow}(0)\,t(0,\infty)}_{\text{(1) Surface}} + \underbrace{\int_0^{\infty} B(z)\frac{\mathrm{d}t(z,\infty)}{\mathrm{d}z}\,\mathrm{d}z}_{\text{(2) Atmosphere}}$$

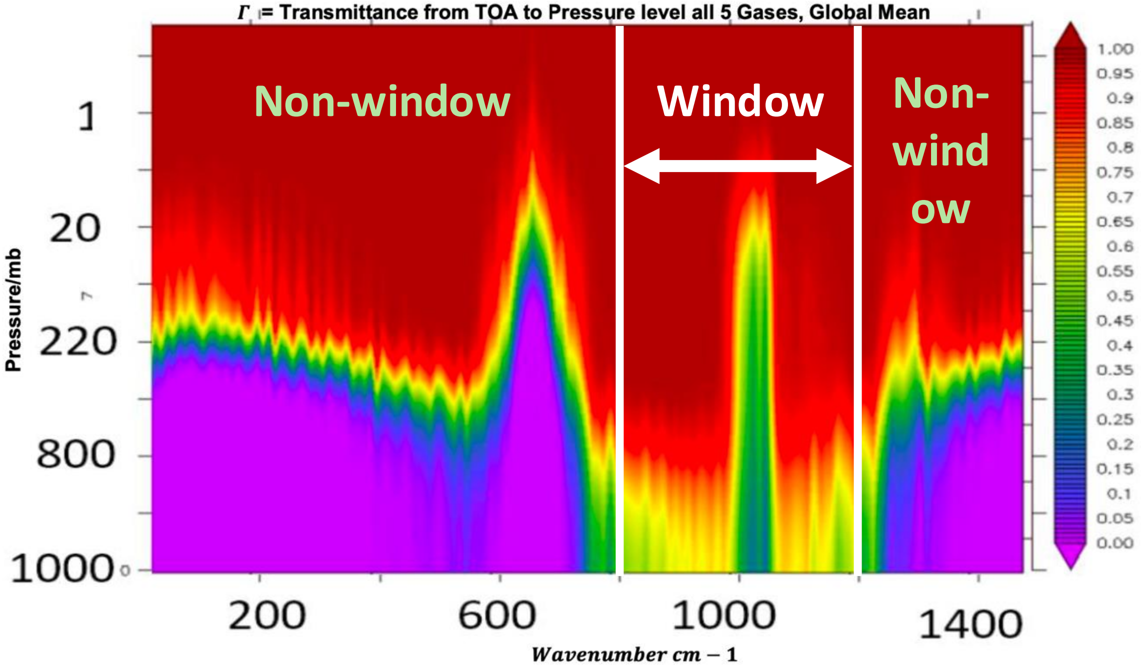
(1) Radiation from surface that makes it through the entire atmosphere

(2) Radiation due to absorption/emission from each atmospheric level

Transmittance: $t = e^{-\tau}$

Window band: atmosphere is mostly transparent

Non-window band: atmosphere is more strongly absorbing



↑ **t = 1**
Transparent

↓ **t = 0**
Opaque

Definitions of the window band

The window and non-window bands are defined slightly differently

Band	CERES (cm^{-1})	AM4 (cm^{-1})
Window	833–1250	800–1200
Non-window	50–833, 1250–2000	0–800, 1200–1400

To account for this, we instead convert fluxes to **brightness temperature**, which is the temperature associated with an intensity if it was emitted by a perfect blackbody

$h =$ Planck's constant
$c =$ speed of light
$k =$ Boltzmann constant
$\tilde{\nu} =$ wavenumber
$T =$ temperature
$I_{\tilde{\nu}} =$ spectral radiance/intensity

Planck function

$$B_{\tilde{\nu}}(T) = 2hc^3\tilde{\nu}^3 \frac{1}{e^{hc\tilde{\nu}/kT} - 1}$$

Brightness temperature

$$T_B(\tilde{\nu}) = B^{-1}(I_{\tilde{\nu}}) = \frac{\frac{hc}{k}\tilde{\nu}}{\ln\left(\frac{2hc^3\tilde{\nu}^3}{I_{\tilde{\nu}}} + 1\right)}$$