Elevating the Decomposition of Energy Budget Changes as a Tool for Climate Monitoring

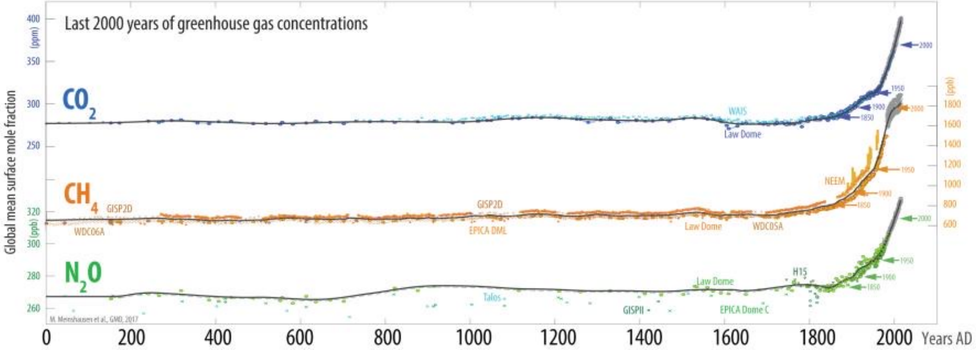
Ryan Kramer

NOAA/Geophysical Fluid Dynamics Laboratory

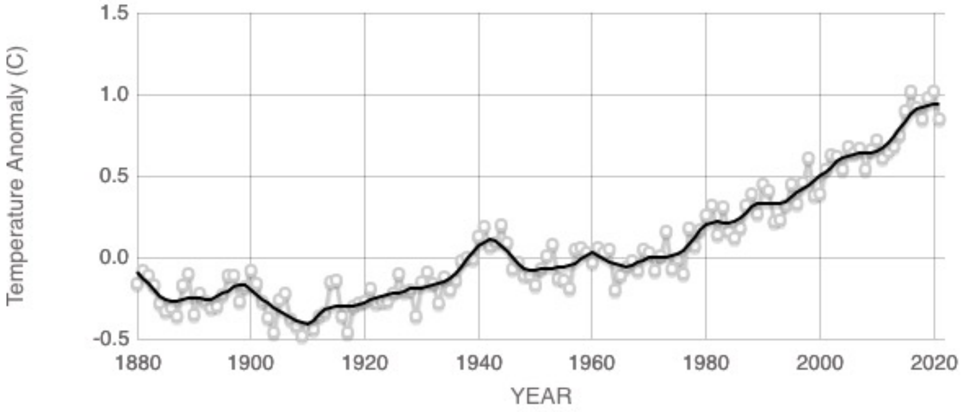
Fall CERES Science Team Meeting – Oct. 18, 2023

Collaborators: Lazaros Oreopoulos, Haozhe He, Brian Soden, David Paynter, Jing Feng, Ray Menzel, Gunnar Myhre, Keith Shine, Chris Smith, Daeho Jin, Nadir Jeevangee, Dongmin Lee and others!

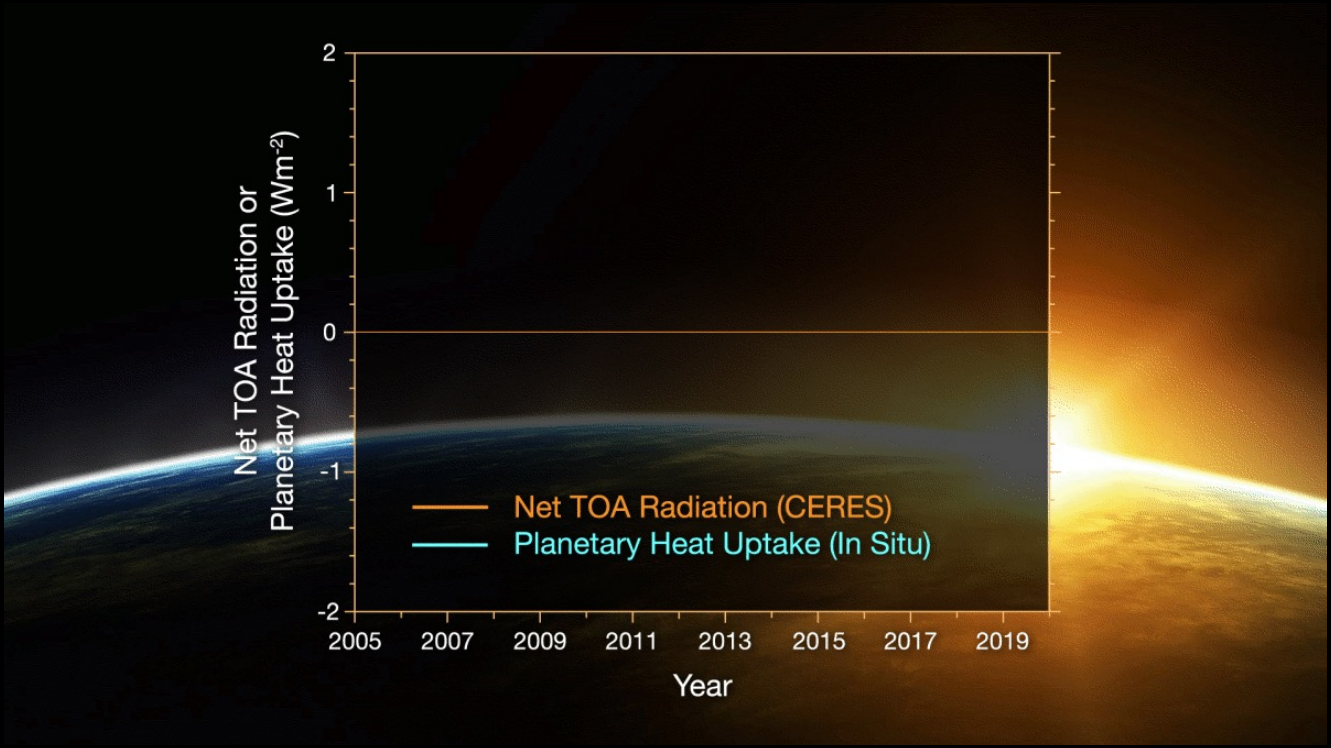
Measuring Climate Change



Meinhausen et al. (2017)



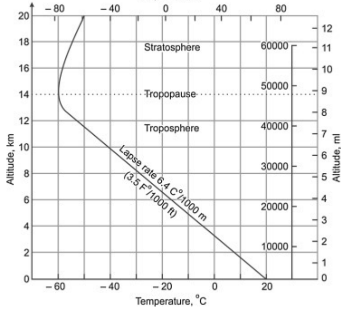
Source: climate.nasa.gov

Net TOA Radiation or Planetary Heat Uptake (Wm^{-2})
2
1
0
-1
-2
Net TOA Radiation (CERES)
Planetary Heat Uptake (In Situ)
2005
2007
2009
2011
2013
2015
2017
2019
Year

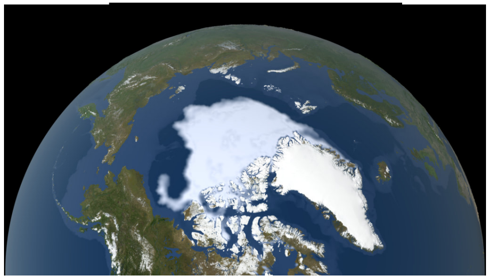
Energy Balance Equation

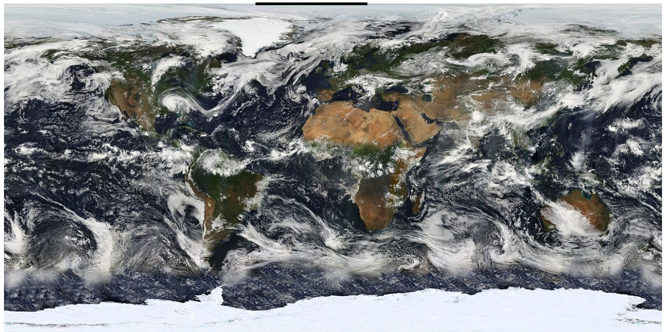
$$\underbrace{\Delta N}_{\textbf{Total Radiative Imbalance}} = \underbrace{\Delta F}_{\textbf{Radiative Forcing}} + \underbrace{\lambda \Delta T_s}_{\textbf{Radiative Feedbacks}}$$

Variable	Source
Temperature(T)	AIRS Version 6 L3
Water Vapor (q)	
TOA	CERES EBAF Ed4.1 TOA and Surface Products
Surface Albedo (a)	
Cloud Radiative Effects (C)	


Temperature


Water Vapor


Surface Albedo


Cloud

Energy Balance Equation

$$\underbrace{\Delta N =}_{\textbf{Total Radiative Imbalance}} \quad \underbrace{\text{IRF} +}_{\textbf{Radiative Forcing}} \quad \underbrace{\text{ADJ} + \text{FB}}_{\textbf{Radiative Feedbacks}}$$

Variable	Source
Temperature(T)	AIRS Version 6 L3
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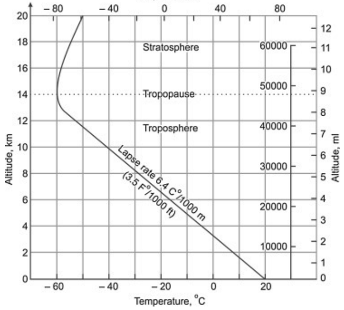
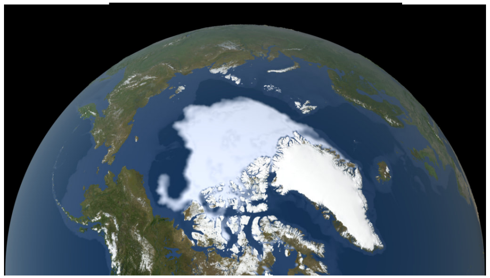
Temperature

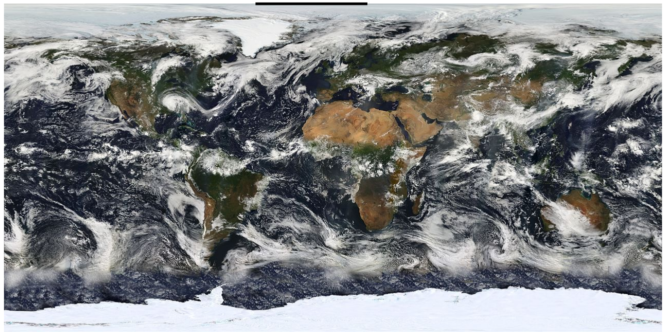


Water Vapor

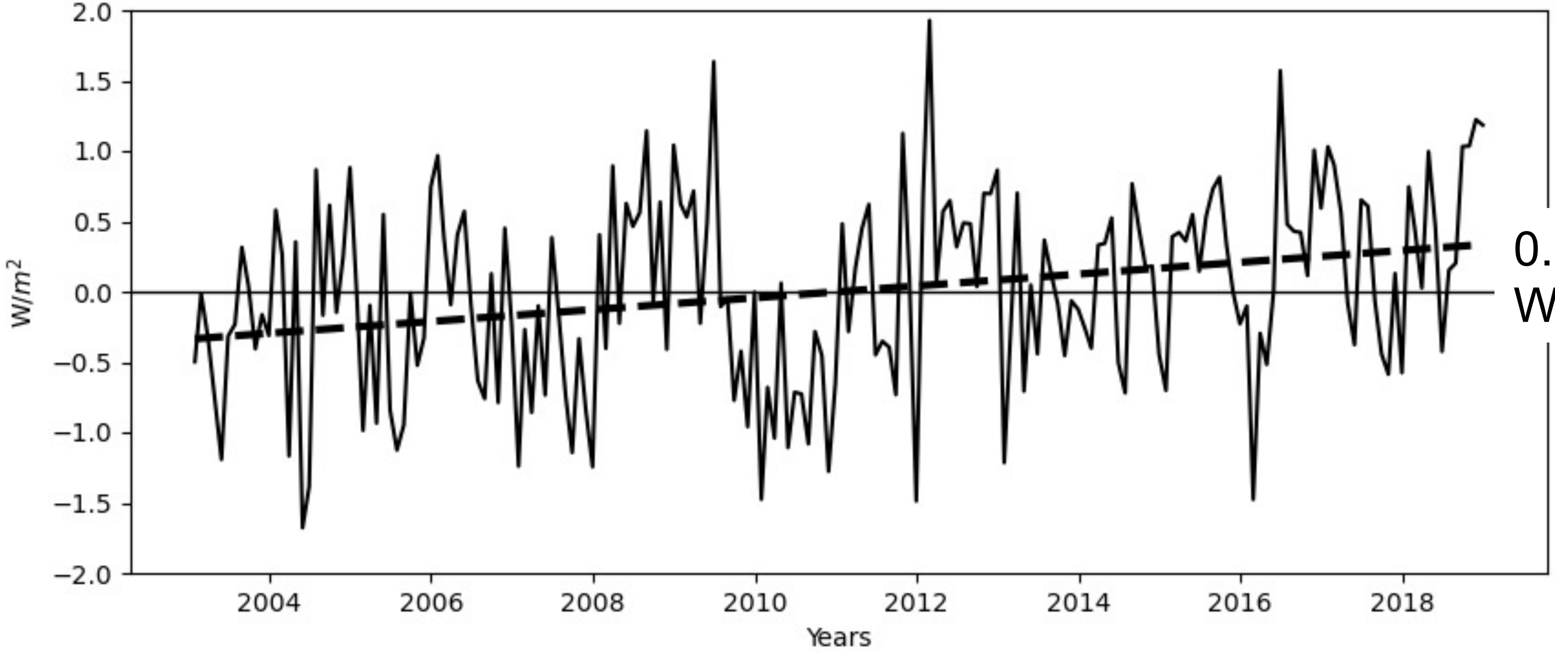
Surface Albedo



Cloud



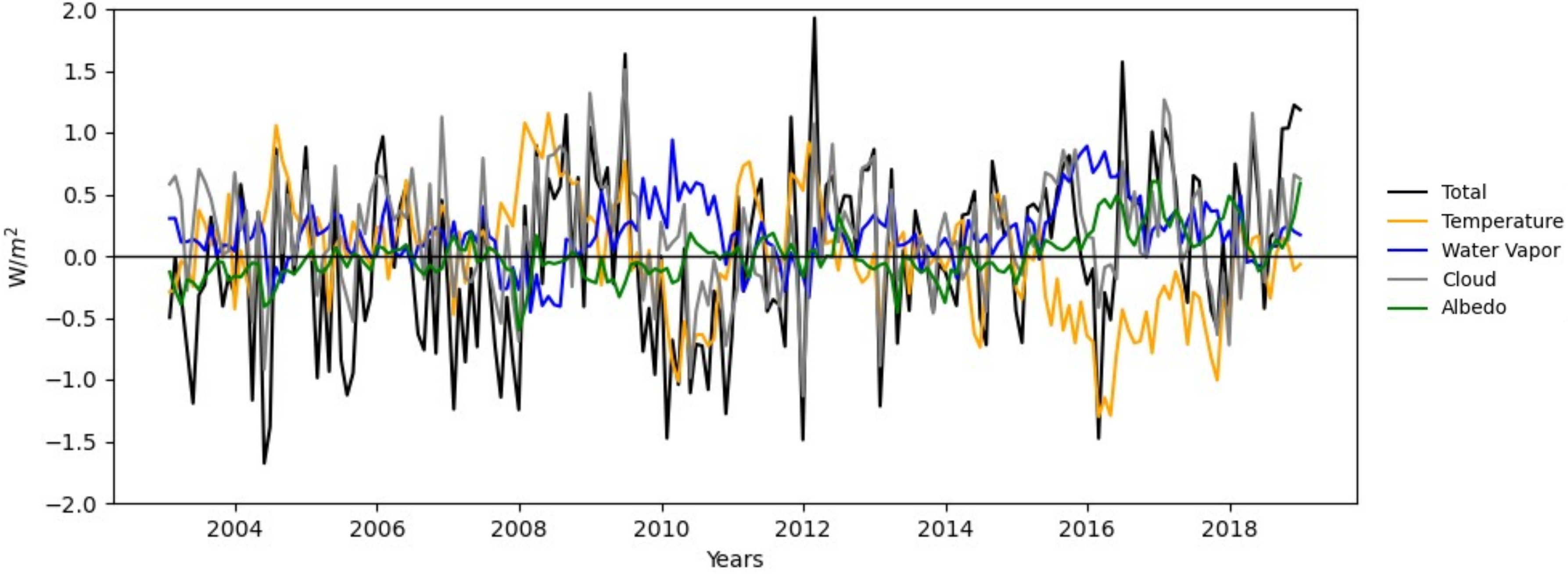
Top-of-Atmosphere CERES Net Radiative Flux Anomalies



0.38 +/- 0.2 W/m^2/dec

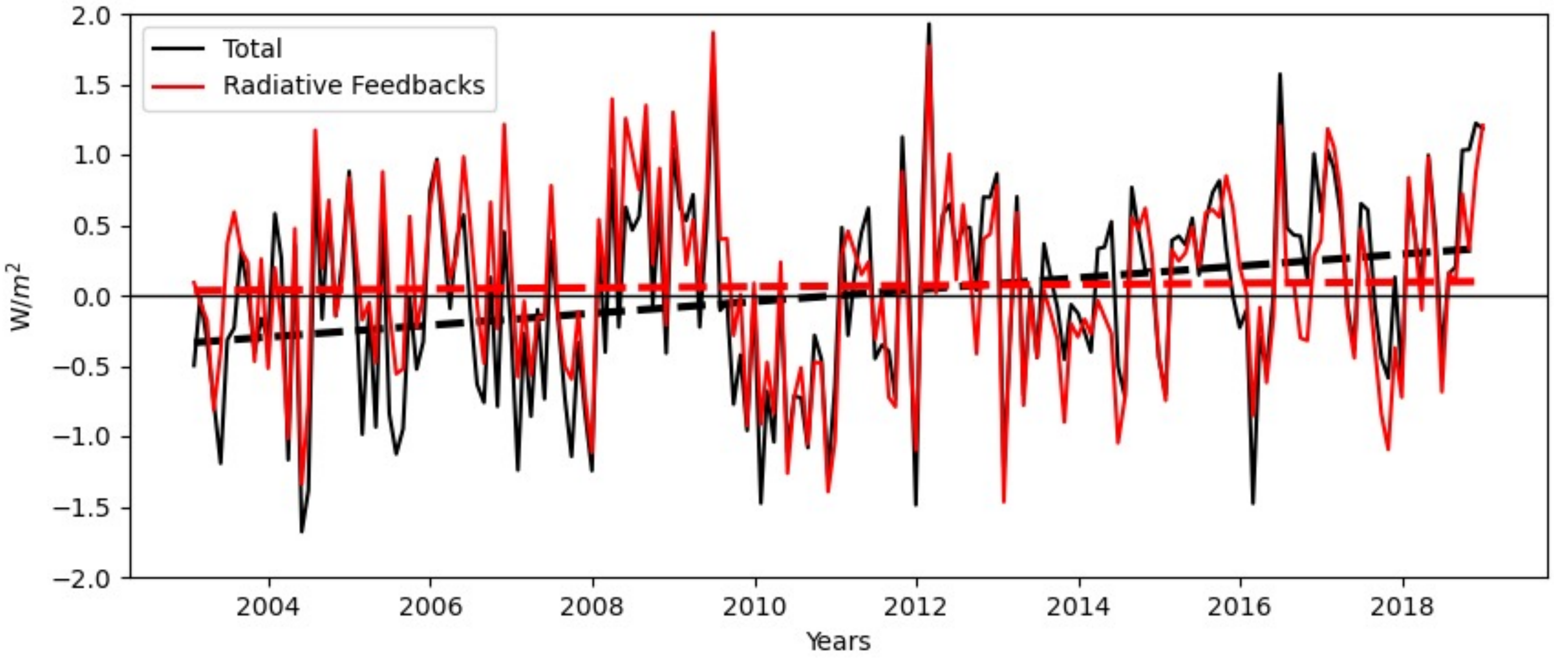
Longwave (LW) + Shortwave (SW)

Top-of-Atmosphere CERES Net Radiative Flux Anomalies



Longwave (LW) + Shortwave (SW)

Top-of-Atmosphere
CERES Net Radiative Flux Anomalies



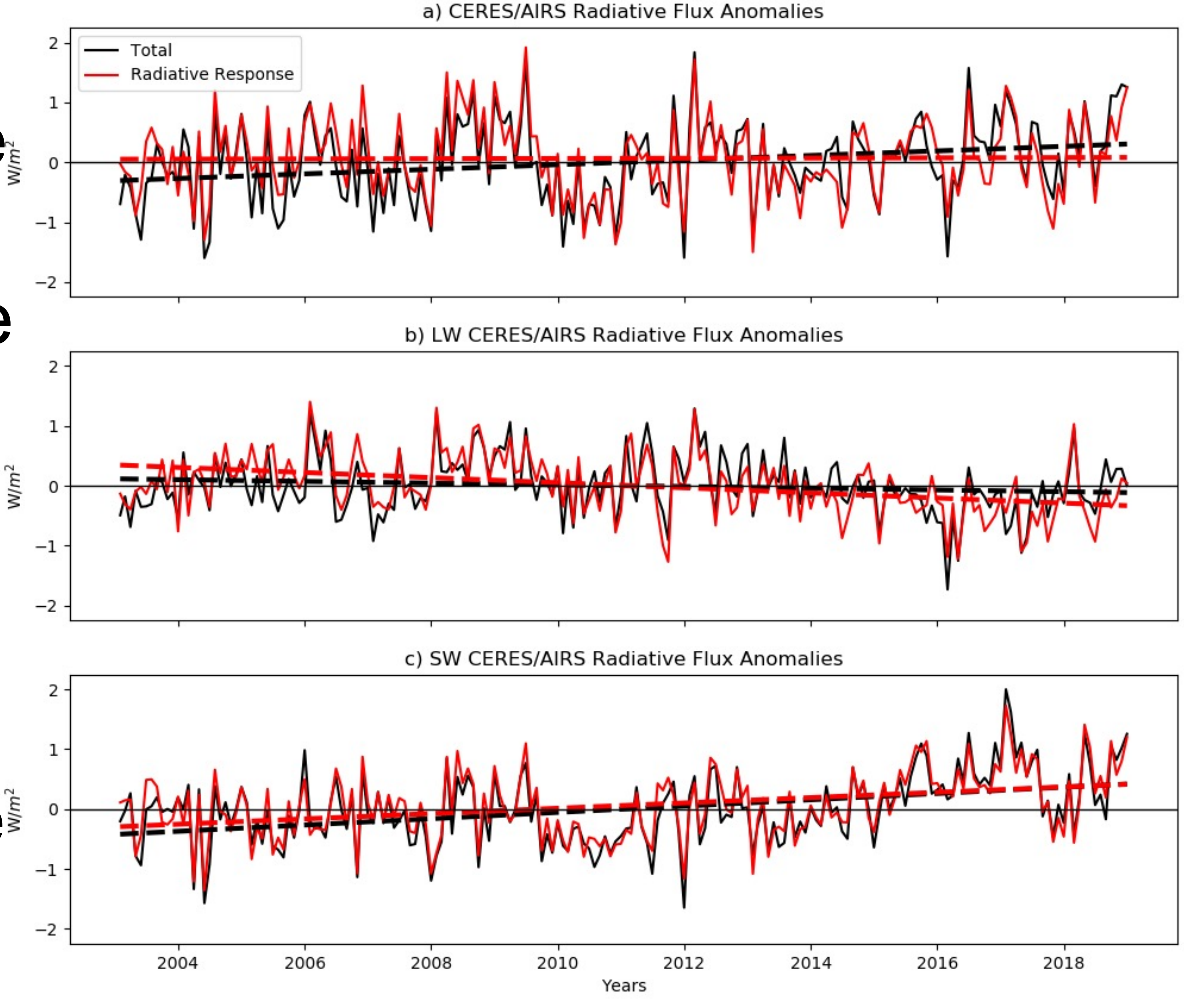
0.02 +/- 0.2 W/m^2/dec

Longwave (LW) + Shortwave (SW)

Longwave
+
Shortwave

Longwave

Shortwave



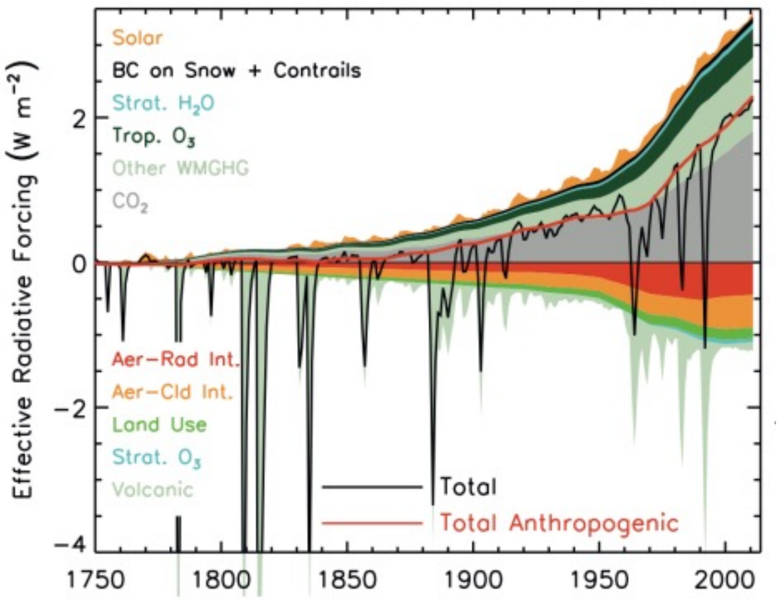
0.02 +/- 0.2 W/m²/dec

-0.42 +/- 0.3 W/m²/dec

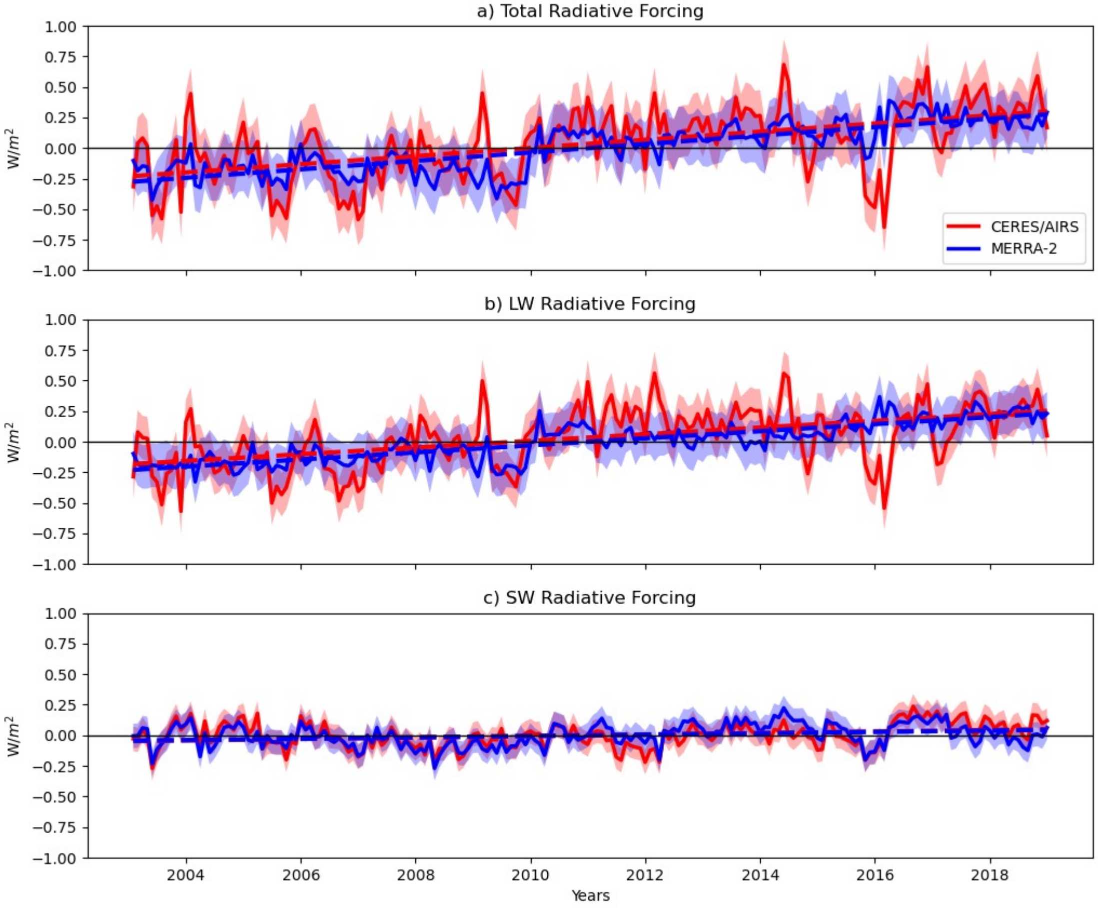
0.44 +/- 0.3 W/m²/dec

Energy Balance Equation

$$\underbrace{\Delta N}_{\textbf{Total Radiative Imbalance}} = \underbrace{\Delta F}_{\textbf{Radiative Forcing}} + \underbrace{\lambda \Delta T_s}_{\textbf{Radiative Feedbacks}}$$



Observed Radiative Forcing



Longwave
+
Shortwave

0.33 +/- 0.07 W/m^2/dec

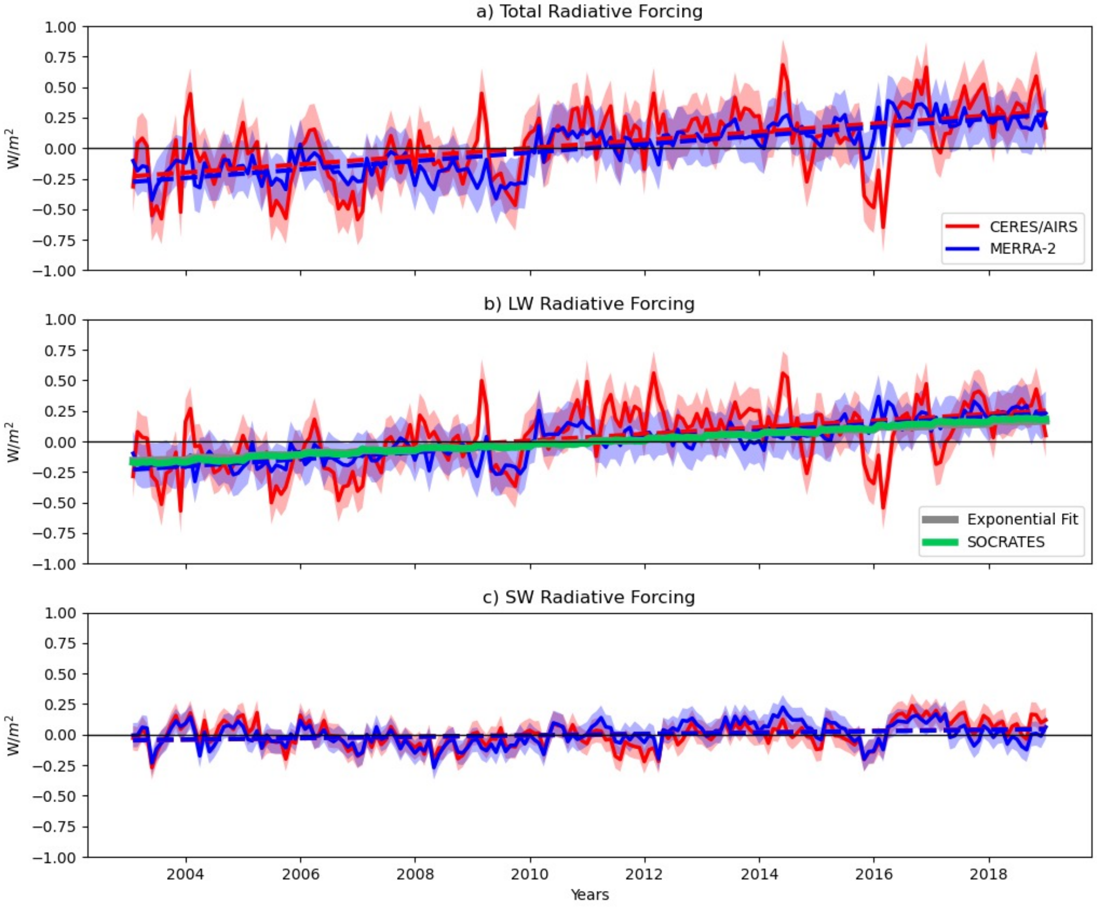
Longwave

0.27 +/- 0.06 W/m^2/dec

Shortwave

0.06 +/- 0.003 W/m^2/dec

Observed Radiative Forcing



Longwave
+
Shortwave

0.33 +/- 0.07 W/m²/dec

Longwave

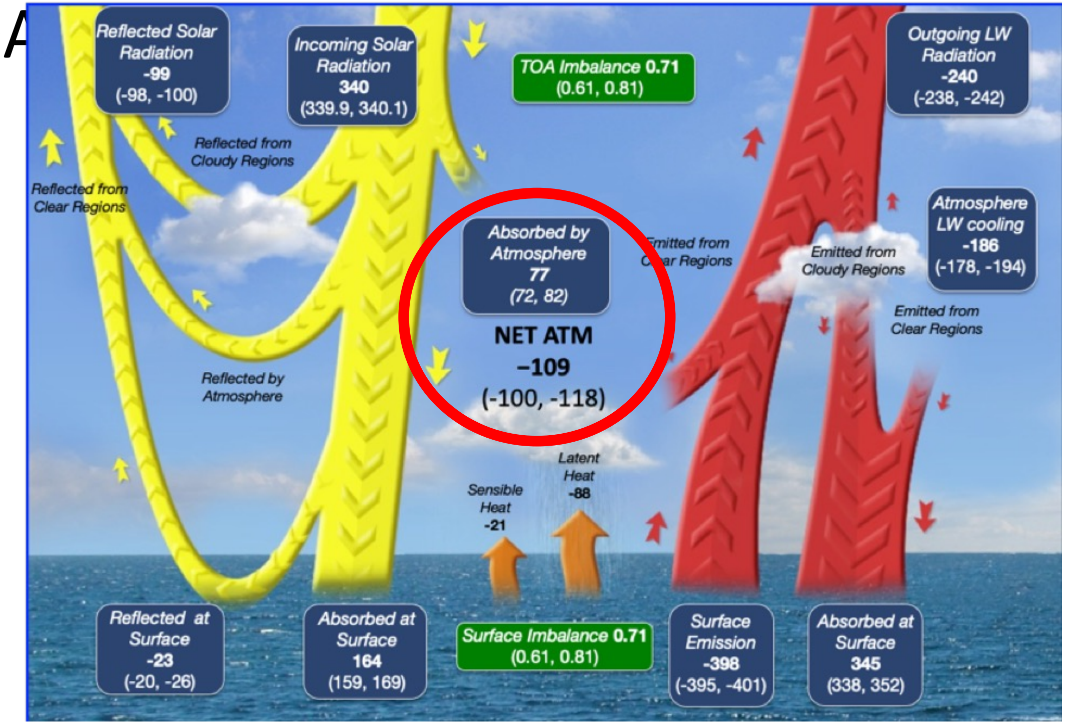
0.27 +/- 0.06 W/m²/dec

Shortwave

0.06 +/- 0.003 W/m²/dec

Atmospheric Energy Budget and Precipitation

Top-of-Atmos. (TOA



ATM = TOA - SFC

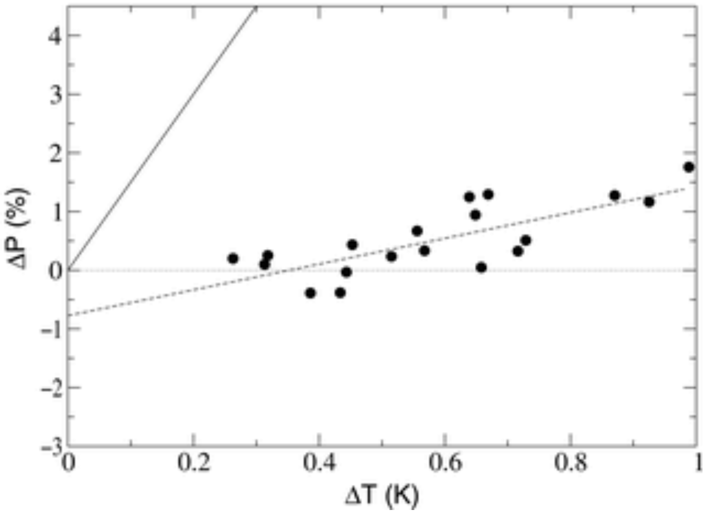
SFC

CERES/NASA LarC

$$-R_{ATM} = LP + SH$$

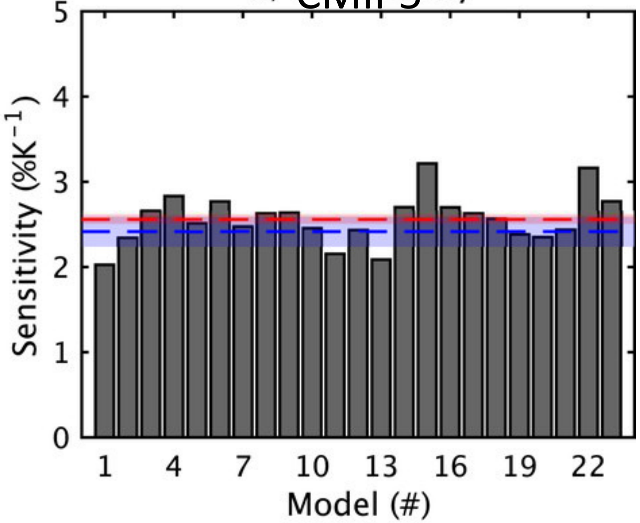
Robust Precipitation Increase with Warming

CMIP3



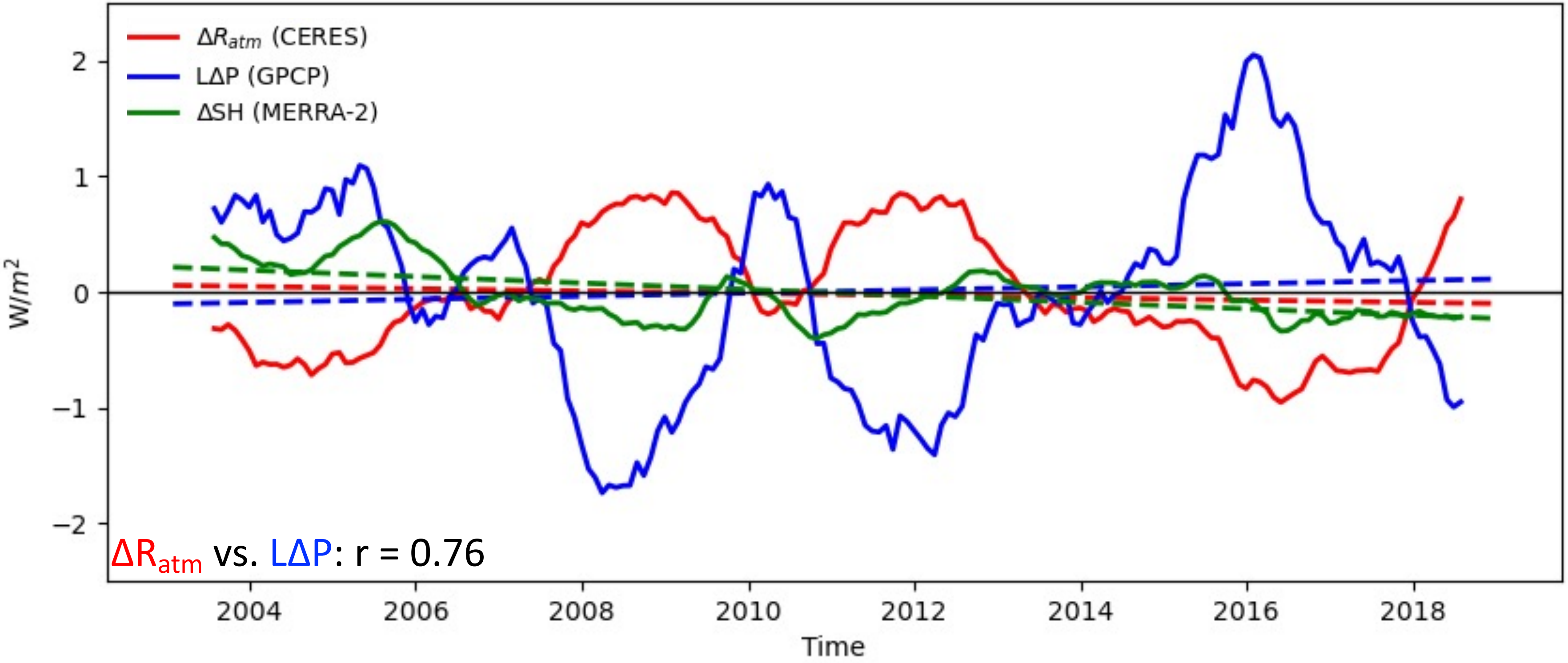
Held and Soden (2006)

CMIP5



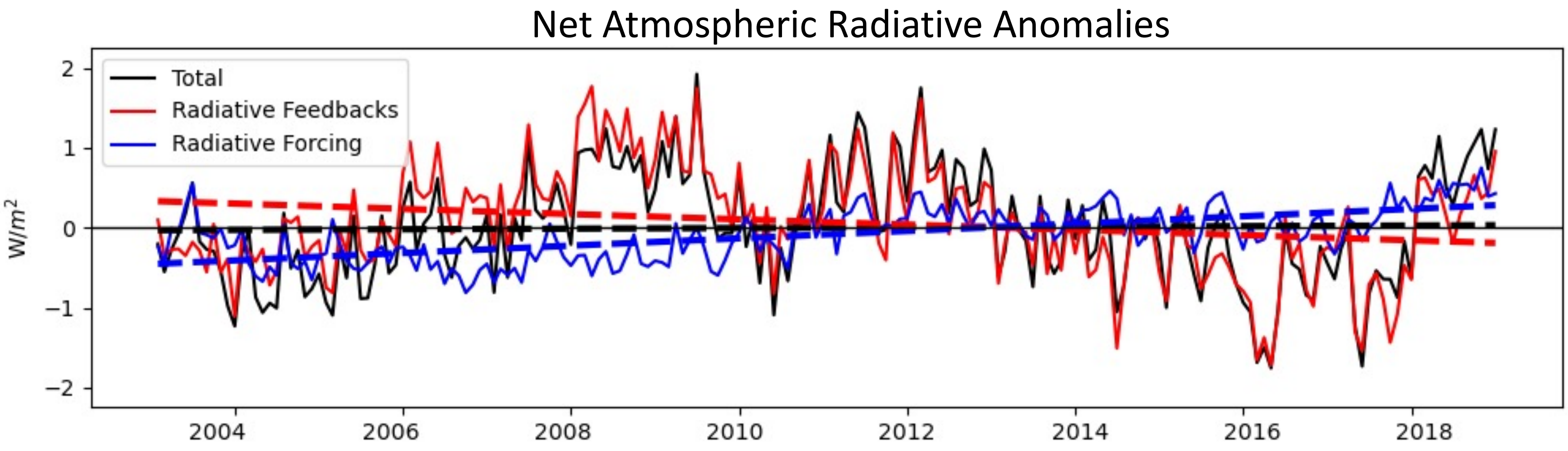
Kramer et al. (2019)

Weak Global Radiative Cooling Trend



ΔR_{atm} vs. LΔP: r = 0.76

Atmospheric Radiative Change Decomposition



Positive

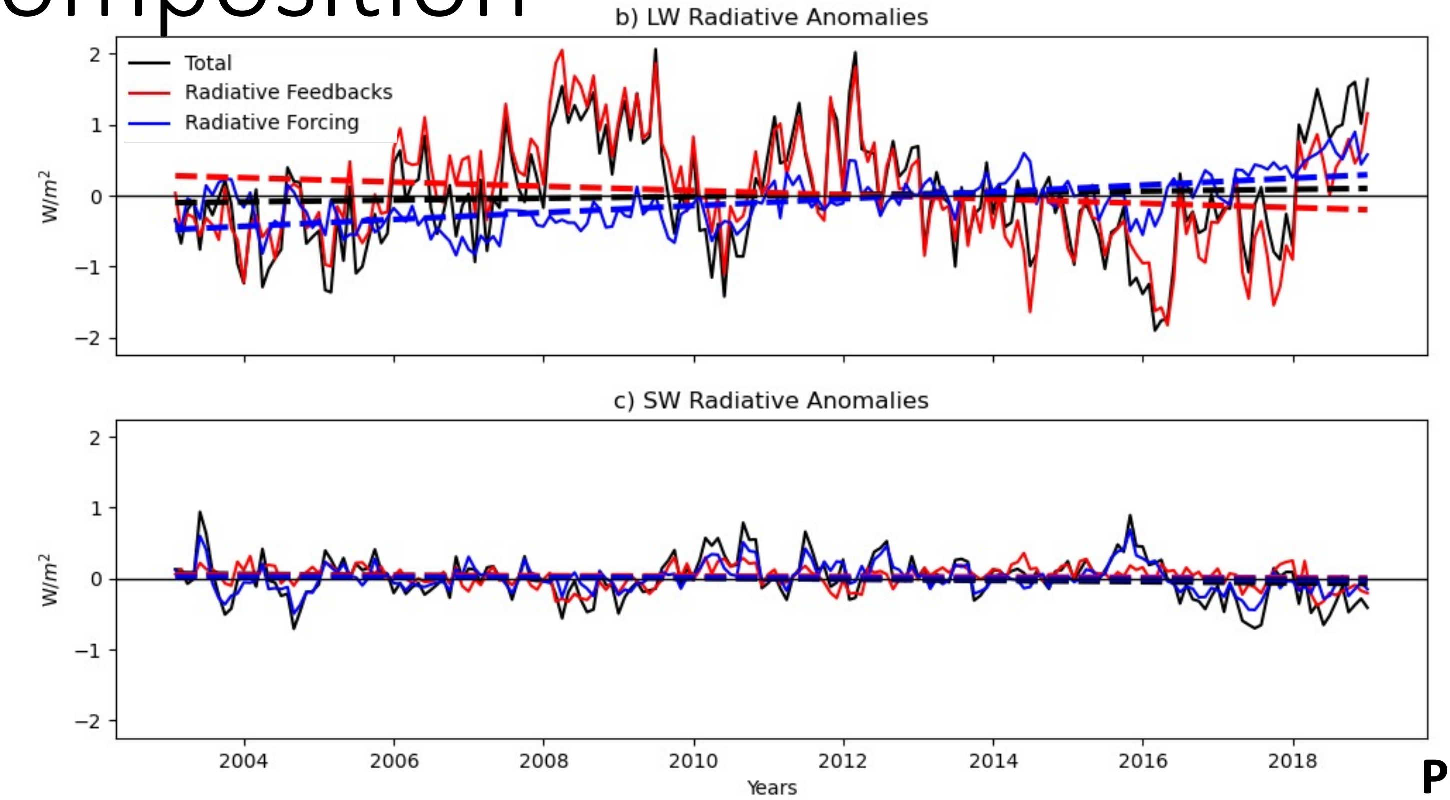
=

Radiative Heating

Atmospheric Radiative Change Decomposition

Longwave

Shortwave



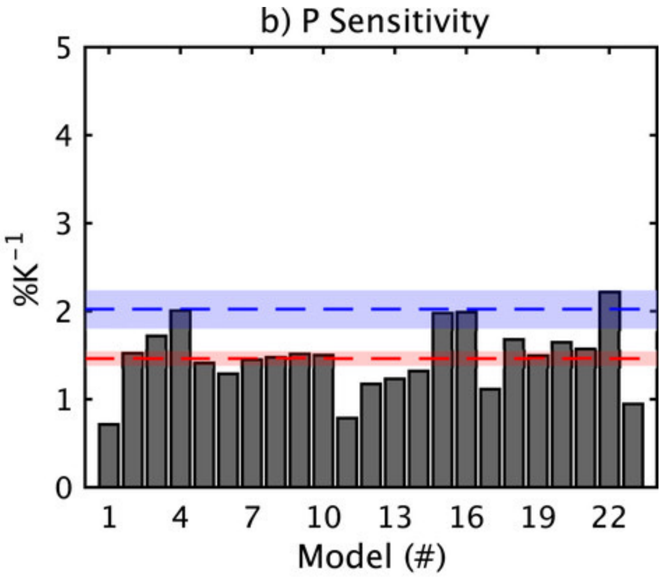
Positive

=

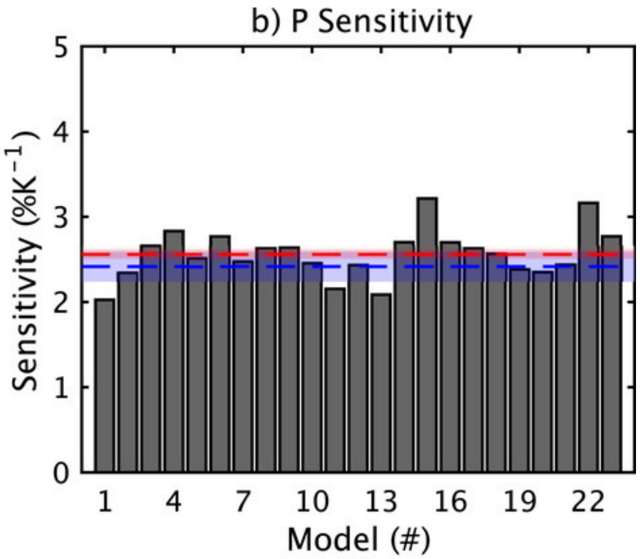
Radiative Heating

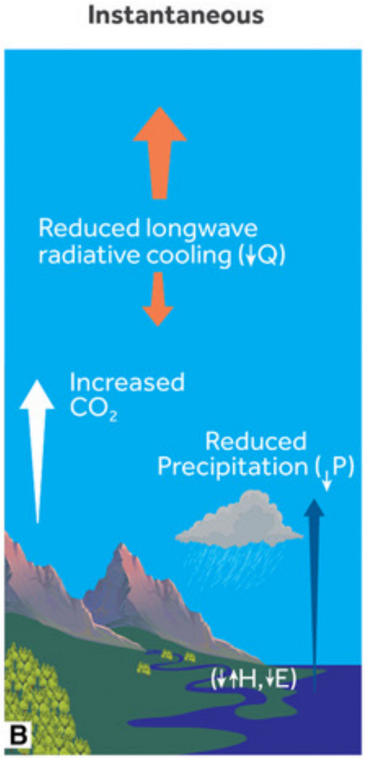
Competing Role of Forcings and Feedbacks

Warming + Direct CO_2 Effects

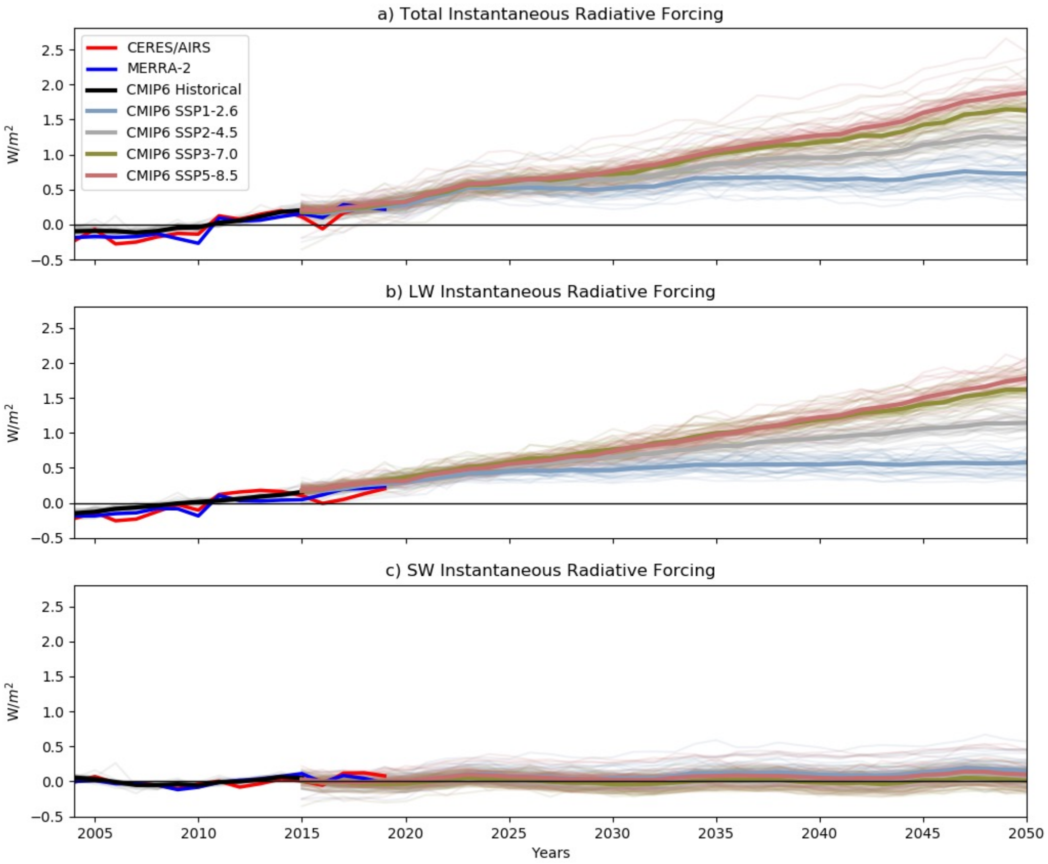


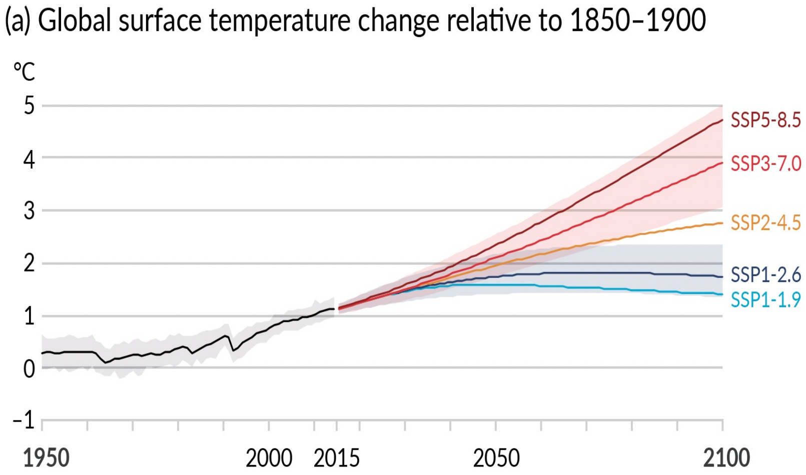
Warming Effects



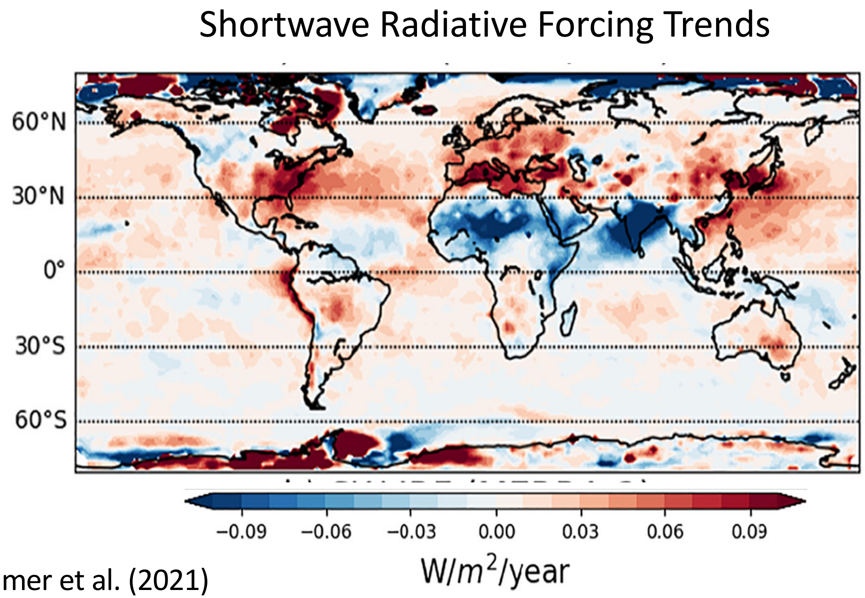


Tracking our Impact on the Climate





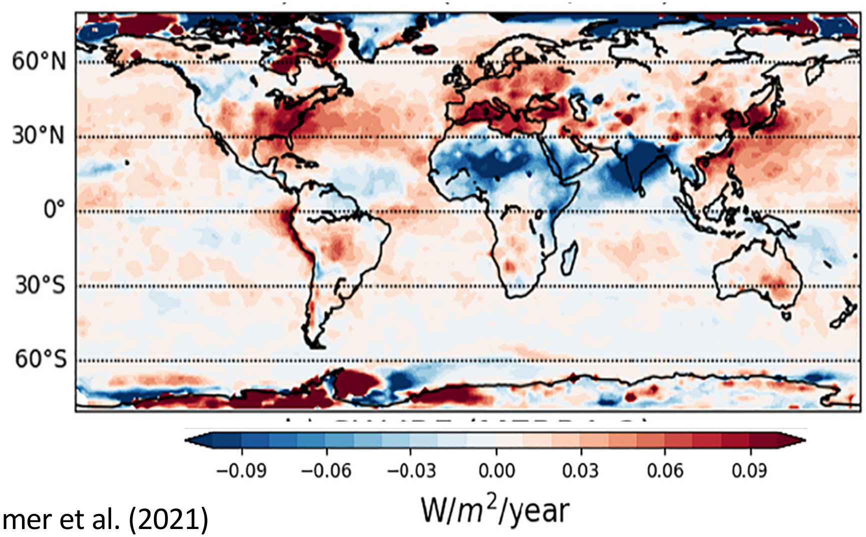
Local Trends in Shortwave Radiative Forcing

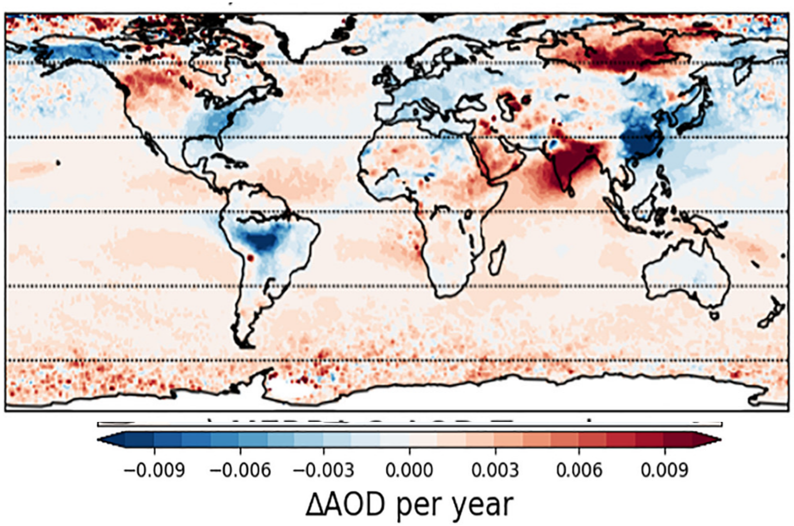


Kramer et al. (2021)

Red = Radiative Heating **and** **Blue = Radiative Cooling**

Local Trends in Shortwave Radiative Forcing

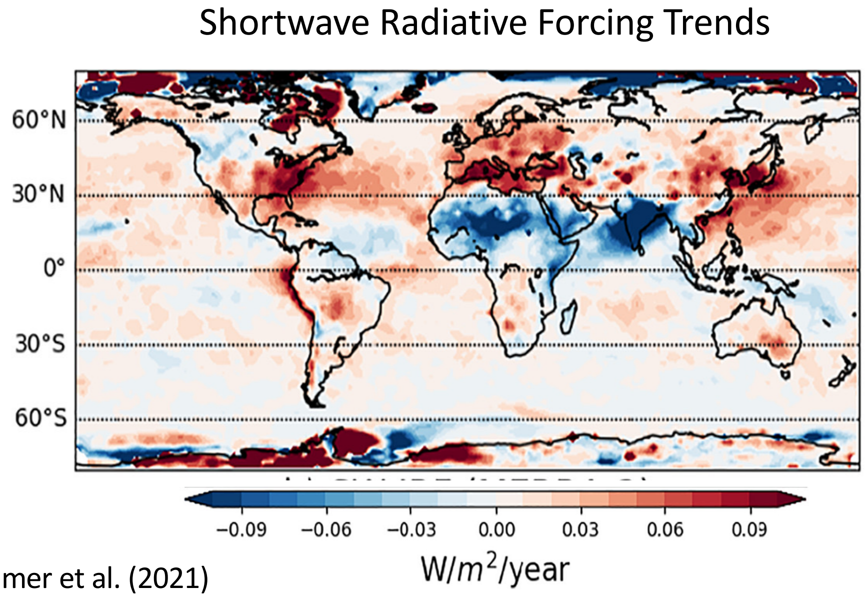

Shortwave Radiative Forcing Trends


MODIS Aerosol Optical Depth Trends

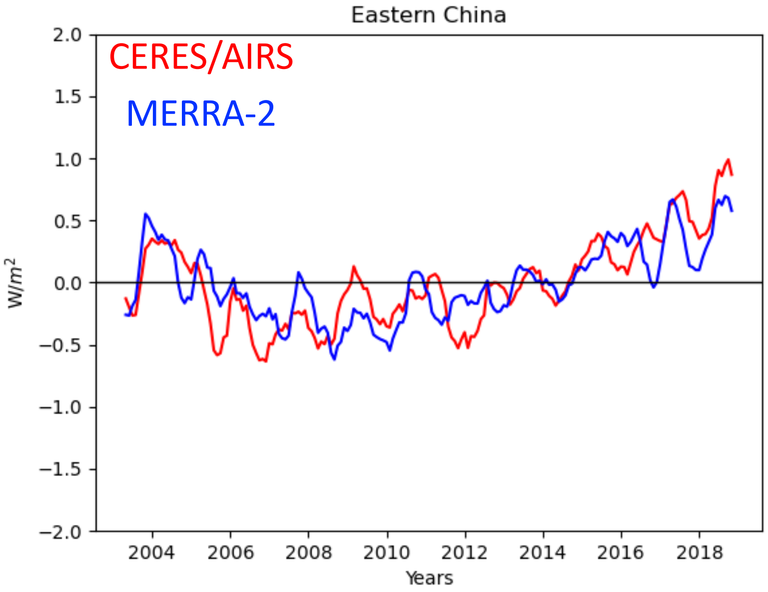
Kramer et al. (2021)

Red = Radiative Heating **and** **Blue = Radiative Cooling**

Local Trends in Shortwave Radiative Forcing


Shortwave Radiative Forcing Trends

Kramer et al. (2021)



Red = Radiative Heating **and** **Blue = Radiative Cooling**

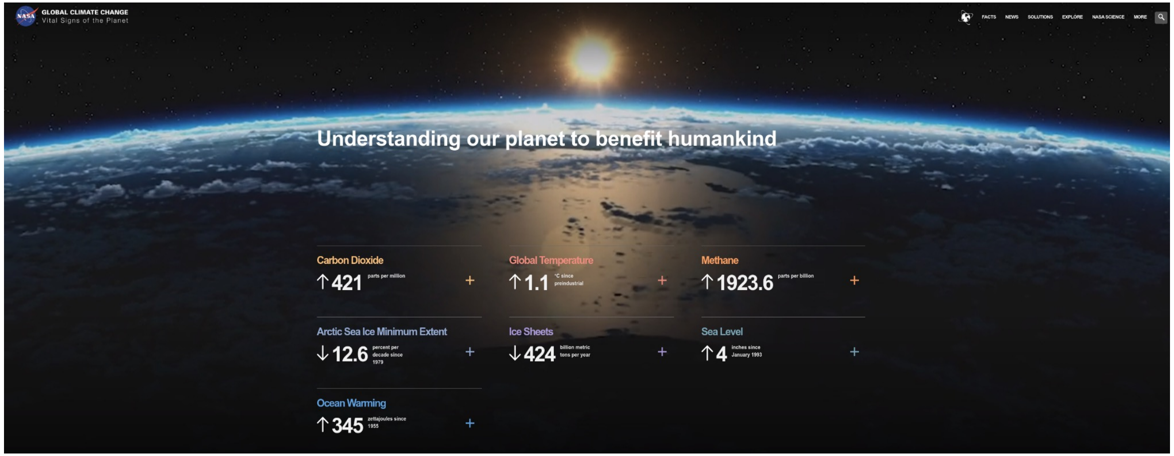
Monitoring and Identifying the Anthropogenic Influence on Climate

ipcc
INTERGOVERNMENTAL PANEL ON
climate change
WMO UNEP

United Nations
Climate Change

Global Stocktake

NASA: Vital Signs of the Planet



Understanding our planet to benefit humankind

Carbon Dioxide
↑ 421 parts per million +

Global Temperature
↑ 1.1 °C since preindustrial +

Methane
↑ 1923.6 parts per billion +

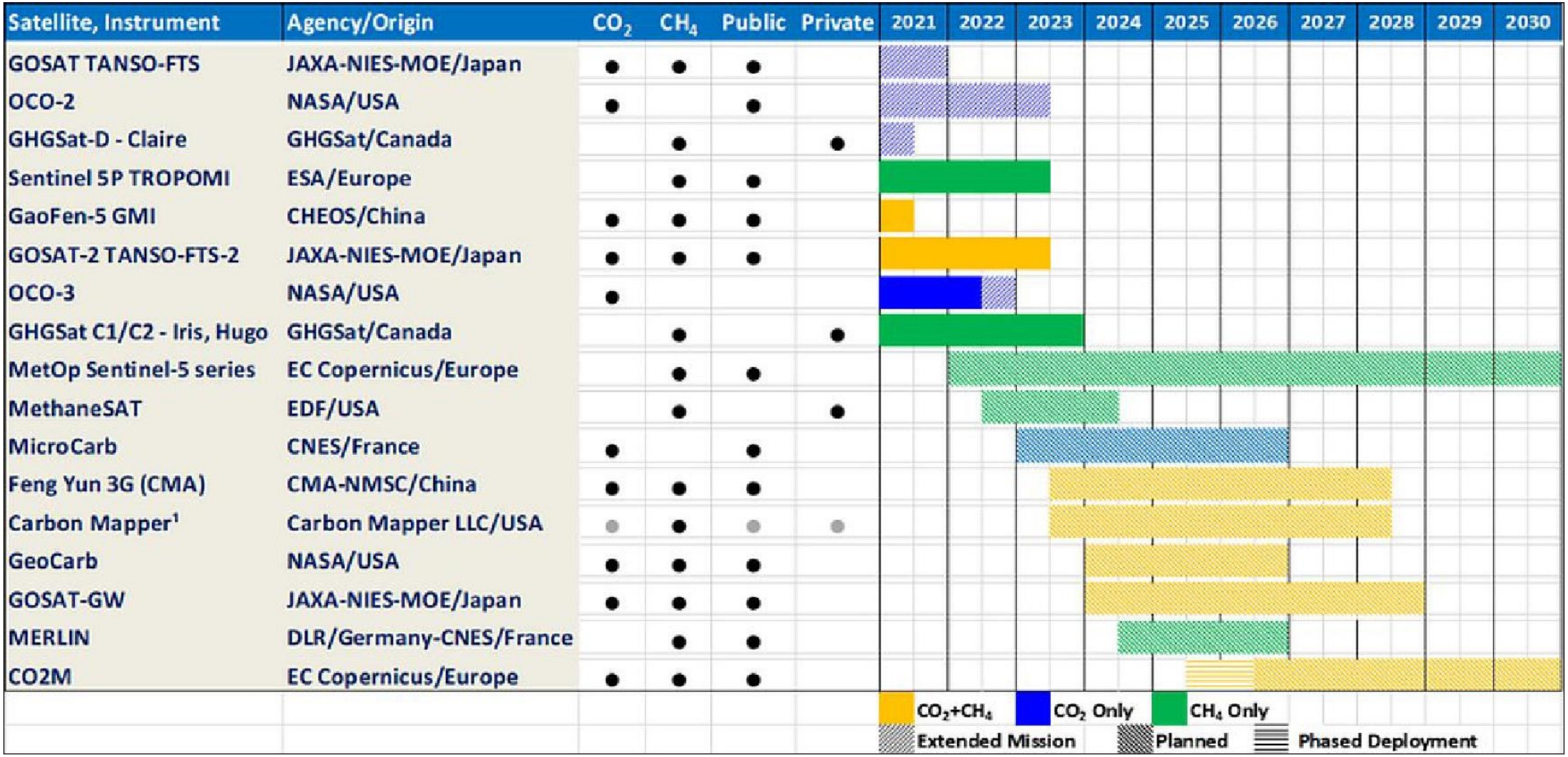
Arctic Sea Ice Minimum Extent
↓ 12.6 percent per decade since 1979 +

Ice Sheets
↓ 424 billion metric tons per year +

Sea Level
↑ 4 inches since January 1993 +

Ocean Warming
↑ 345 zettajoules since 1955 +

GHG Monitoring Satellite Missions



Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan	●	●	●		▨									
OCO-2	NASA/USA	●		●		▨	▨	▨							
GHGSat-D - Claire	GHGSat/Canada		●		●	▨									
Sentinel 5P TROPOMI	ESA/Europe		●	●		🟩	🟩	🟩							
GaoFen-5 GMI	CHEOS/China	●	●	●		🟨									
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan	●	●	●		🟨	🟨	🟨							
OCO-3	NASA/USA	●				🟦	🟦▨								
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada		●		●	🟩	🟩	🟩							
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●			🟩▦	🟩▦	🟩▦	🟩▦	🟩▦	🟩▦	🟩▦	🟩▦	🟩▦
MethaneSAT	EDF/USA		●		●		🟩▦	🟩▦	🟩▦						
MicroCarb	CNES/France	●		●				🟦▦	🟦▦	🟦▦	🟦▦				
Feng Yun 3G (CMA)	CMA-NMSC/China	●	●	●				🟨▦	🟨▦	🟨▦	🟨▦	🟨▦	🟨▦		
Carbon Mapper[1]	Carbon Mapper LLC/USA	○	●	○	○			🟨▦	🟨▦	🟨▦	🟨▦	🟨▦	🟨▦		
GeoCarb	NASA/USA	●	●	●					🟨▦	🟨▦	🟨▦				
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●					🟨▦	🟨▦	🟨▦	🟨▦	🟨▦		
MERLIN	DLR/Germany-CNES/France		●	●					🟩▦	🟩▦	🟩▦				
CO2M	EC Copernicus/Europe	●	●	●						🟨▤	🟨▤▦	🟨▦	🟨▦	🟨▦	🟨▦

🟨 CO_2+CH_4 🟦 CO_2 Only 🟩 CH_4 Only

▨ Extended Mission ▦ Planned ▤ Phased Deployment

ESA

NASA-MEASURES: **A Multi-Instrument Record for Radiative Forcing and Feedback Responses for Climate Monitoring and Global Change Studies**

2023-2028

Ryan Kramer

Co-I's: Lazaros Oreopoulos, Brian Soden, Qing Yue, Xianglei Huang

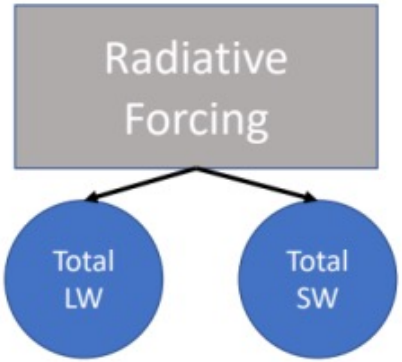
Collaborators: Sergio DeSouza-Machado, Eric Fetzer, Norman Loeb, Larrabee Strow, Tyler Thorsen, Martin Wild

UMBC

MIAMI

UNIVERSITY OF MICHIGAN

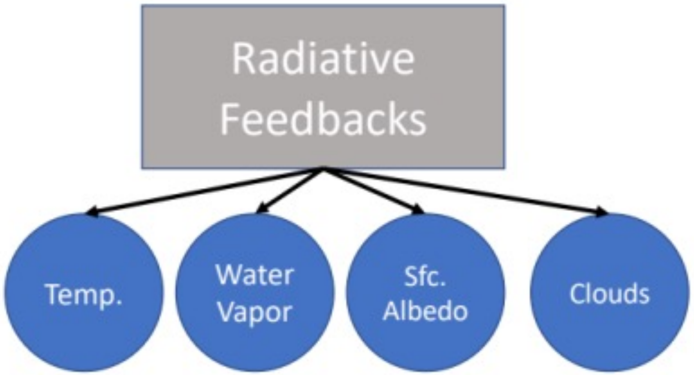
Producing and Maintaining Up-to-Date Timeseries of EEI Drivers



Radiative Forcing

Total LW

Total SW



Radiative Feedbacks

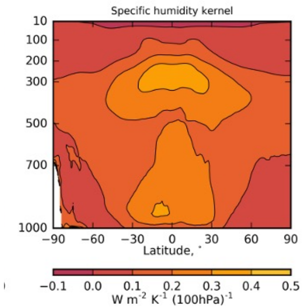
Temp.

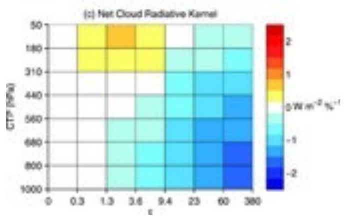
Water Vapor

Sfc. Albedo

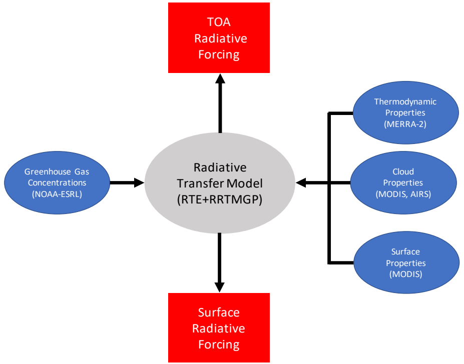
Clouds

Radiative Kernels





RT Calculations/PRP Method



TOA Radiative Forcing

Greenhouse Gas Concentrations (NOAA-ESRL)

Radiative Transfer Model (RTE+RRTMGP)

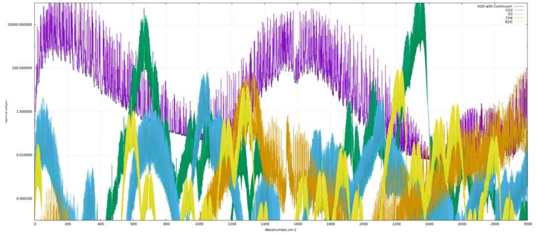
Thermodynamic Properties (MERRA-2)

Cloud Properties (MODIS, AIRS)

Surface Properties (MODIS)

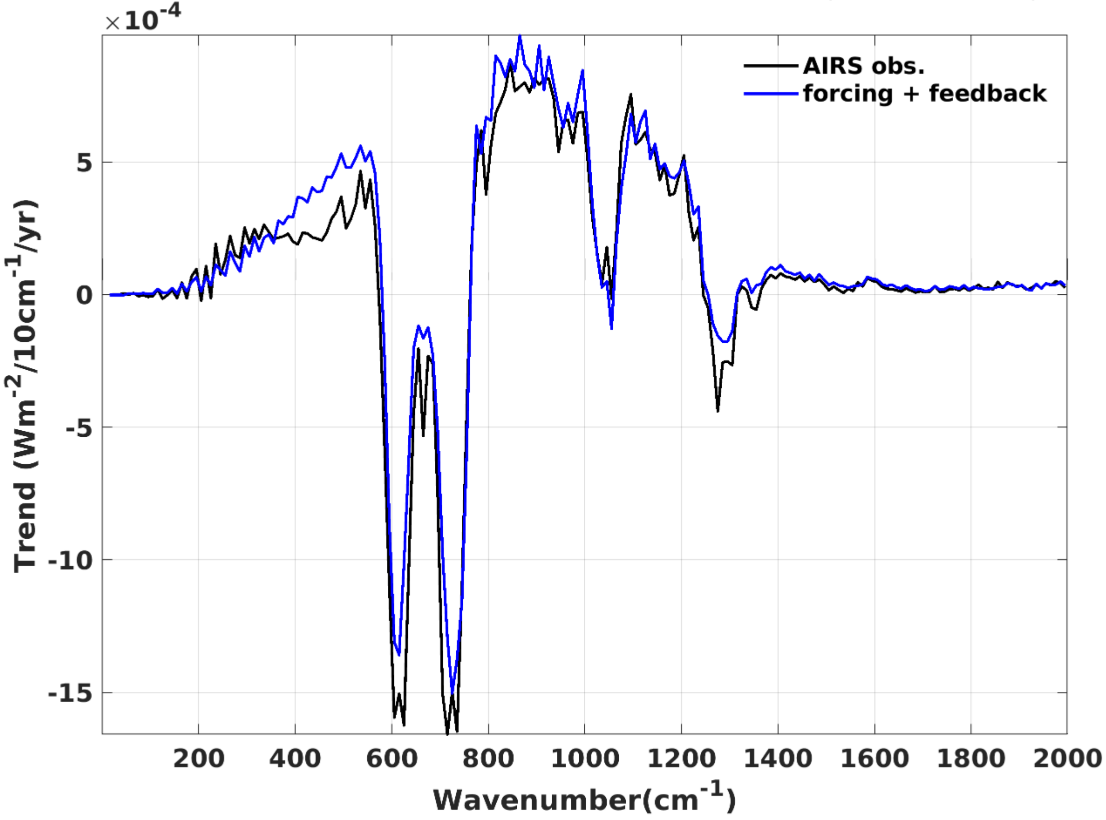
Surface Radiative Forcing

Spectral Decomposition



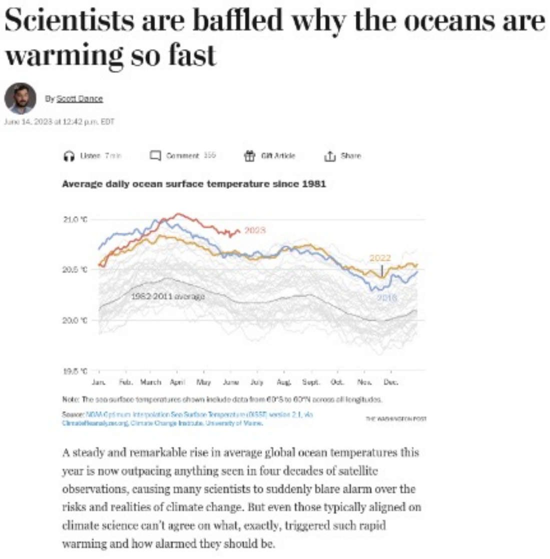
Spectral trend vs. Forcing + Feedback (2003 - 2022)

From Xianglei Huang



Working-in-progress. Please do not cite.

- AIRS L3 Spectral OLR product
  - 10cm^{-1} spectral flux derived from collocated AIRS and CERES measurements
  - Directly estimated from AIRS L1 radiances
- MODIS monthly-mean cloud state joint histograms (derived from Eric Fetzer's MEASURES project)
- ECMWF ERA5 reanalysis temperature and humidity profiles
- CO_2/CH_4/N_2O from NOAA GML
- O_3 from the NASA GEOS with the full chemistry version (GEOSCCM) with nudged meteorology
  - ~100km horizontal resolution, 72 vertical levels



Scientists are baffled why the oceans are warming so fast

By Scott Dance

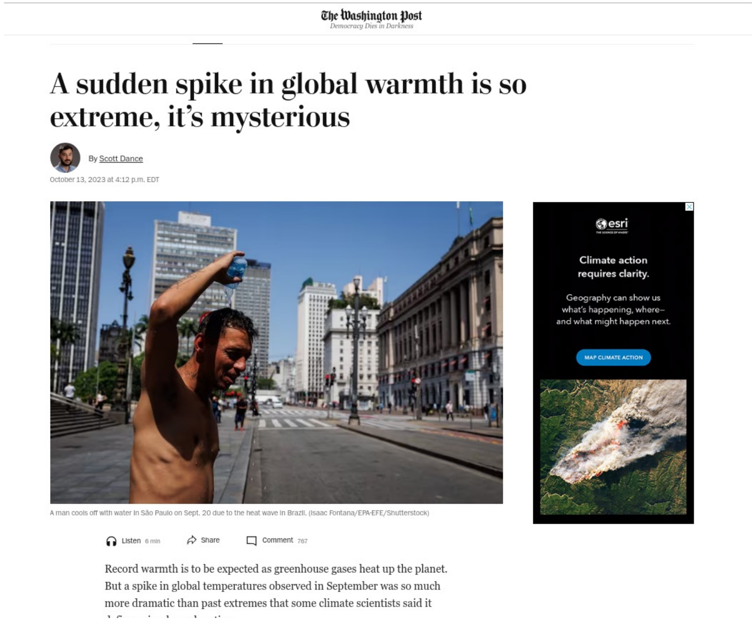
June 14, 2023 at 12:42 p.m. EDT

Average daily ocean surface temperature since 1981

Note: The sea surface temperatures shown include data from 60°S to 60°N across all longitudes.

Source: NOAA Optimum Interpolation Sea Surface Temperature (OISST) version 2.1, via ClimateReanalyzer.org, Climate Change Institute, University of Maine.

A steady and remarkable rise in average global ocean temperatures this year is now outpacing anything seen in four decades of satellite observations, causing many scientists to suddenly blare alarm over the risks and realities of climate change. But even those typically aligned on climate science can't agree on what, exactly, triggered such rapid warming and how alarmed they should be.



The Washington Post
Democracy Dies in Darkness

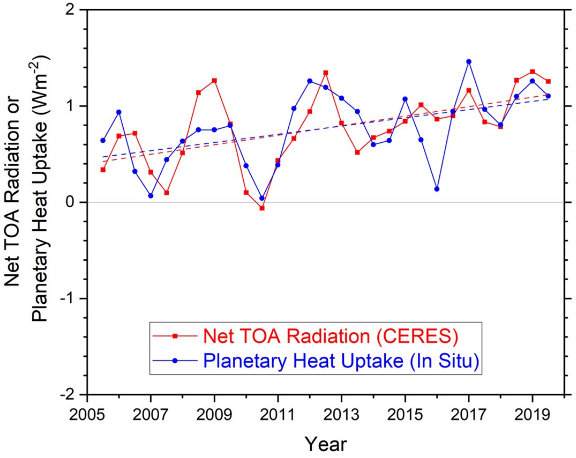
A sudden spike in global warmth is so extreme, it's mysterious

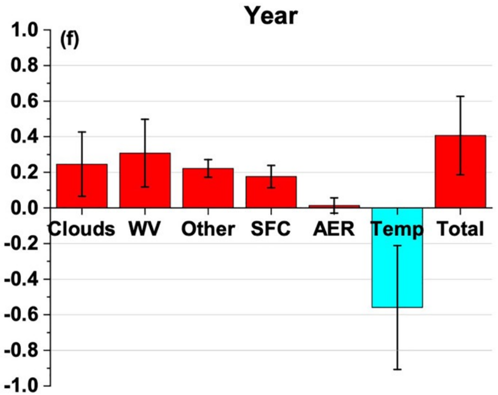
By Scott Dance

October 13, 2023 at 4:12 p.m. EDT

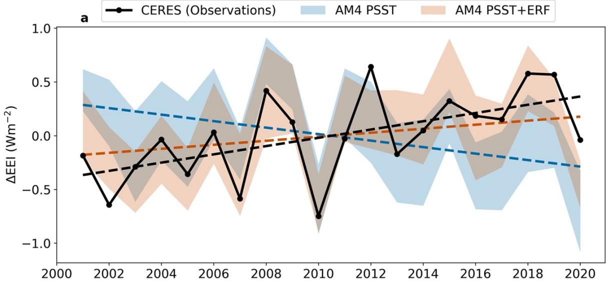
A man cools off with water in São Paulo on Sept. 20 due to the heat wave in Brazil. (Isaac Fontana/EPA-EFE/Shutterstock)

Record warmth is to be expected as greenhouse gases heat up the planet. But a spike in global temperatures observed in September was so much more dramatic than past extremes that some climate scientists said it



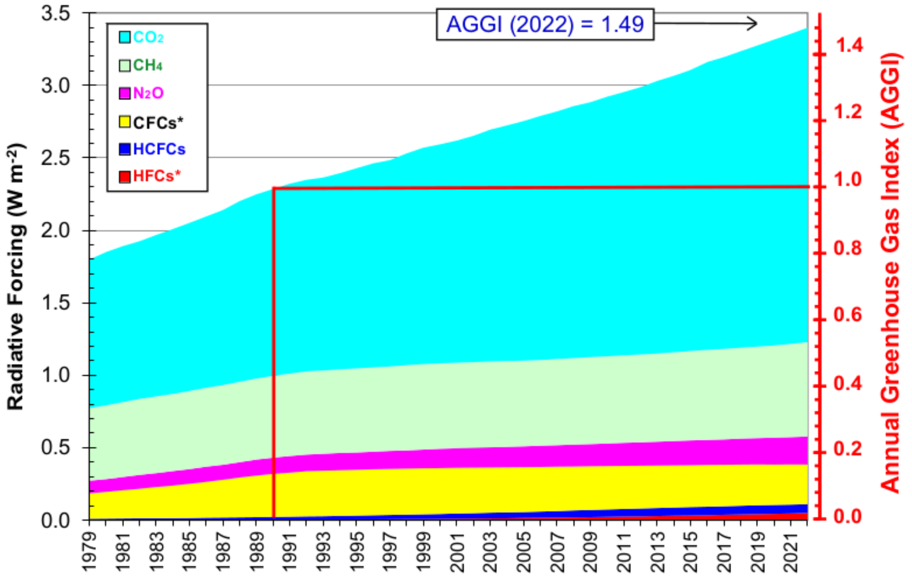


Loeb et al. 2021



Raghuraman et al. 2021

Forcing Simplified Expressions Should Account for Base State



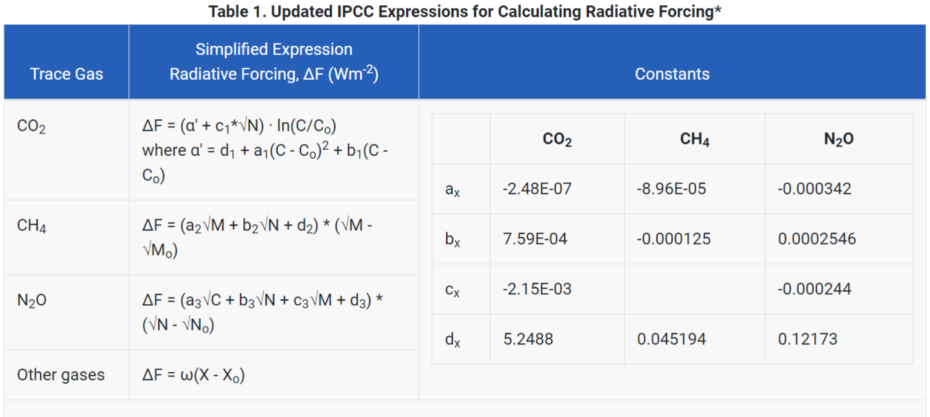
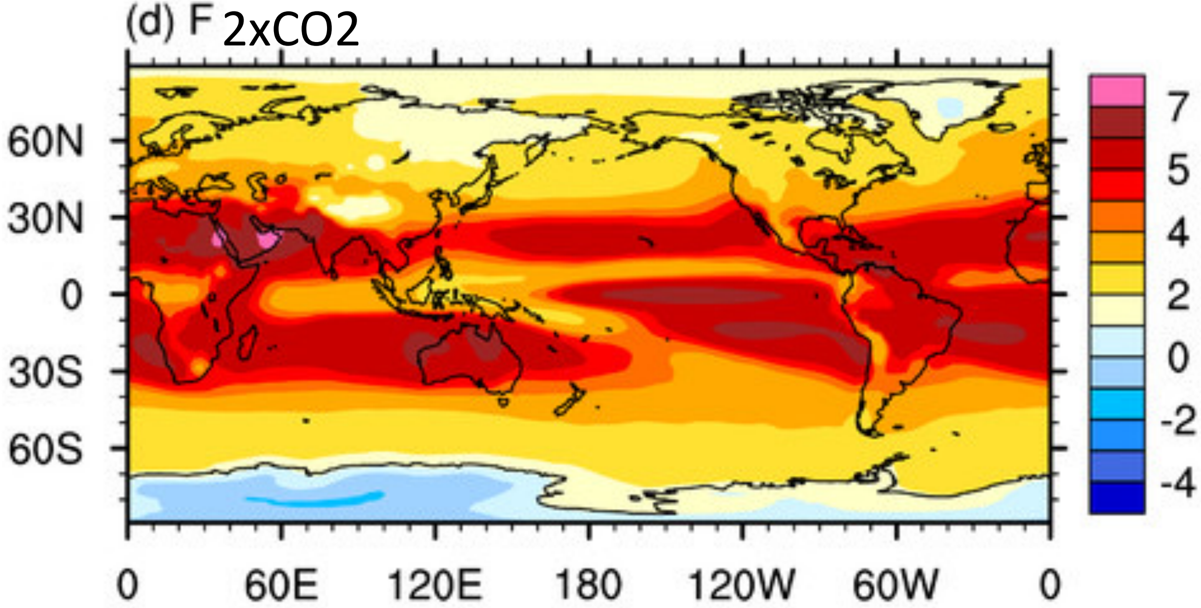


Table 1. Updated IPCC Expressions for Calculating Radiative Forcing*

<table>
<tr><th>Trace Gas</th><th>Simplified Expression
Radiative Forcing, ΔF (Wm^{-2})</th><th>Constants</th></tr>
<tr><td>CO_2</td><td>$\Delta F = (\alpha' + c_1 * \sqrt{N}) \cdot \ln(C/C_o)$
where $\alpha' = d_1 + a_1(C - C_o)^2 + b_1(C - C_o)$</td><td rowspan="4">
<table>
<tr><th></th><th>CO_2</th><th>CH_4</th><th>N_2O</th></tr>
<tr><td>a_x</td><td>-2.48E-07</td><td>-8.96E-05</td><td>-0.000342</td></tr>
<tr><td>b_x</td><td>7.59E-04</td><td>-0.000125</td><td>0.0002546</td></tr>
<tr><td>c_x</td><td>-2.15E-03</td><td></td><td>-0.000244</td></tr>
<tr><td>d_x</td><td>5.2488</td><td>0.045194</td><td>0.12173</td></tr>
</table>
</td></tr>
<tr><td>CH_4</td><td>$\Delta F = (a_2\sqrt{M} + b_2\sqrt{N} + d_2) * (\sqrt{M} - \sqrt{M_o})$</td></tr>
<tr><td>N_2O</td><td>$\Delta F = (a_3\sqrt{C} + b_3\sqrt{N} + c_3\sqrt{M} + d_3) * (\sqrt{N} - \sqrt{N_o})$</td></tr>
<tr><td>Other gases</td><td>$\Delta F = \omega(X - X_o)$</td></tr>
</table>

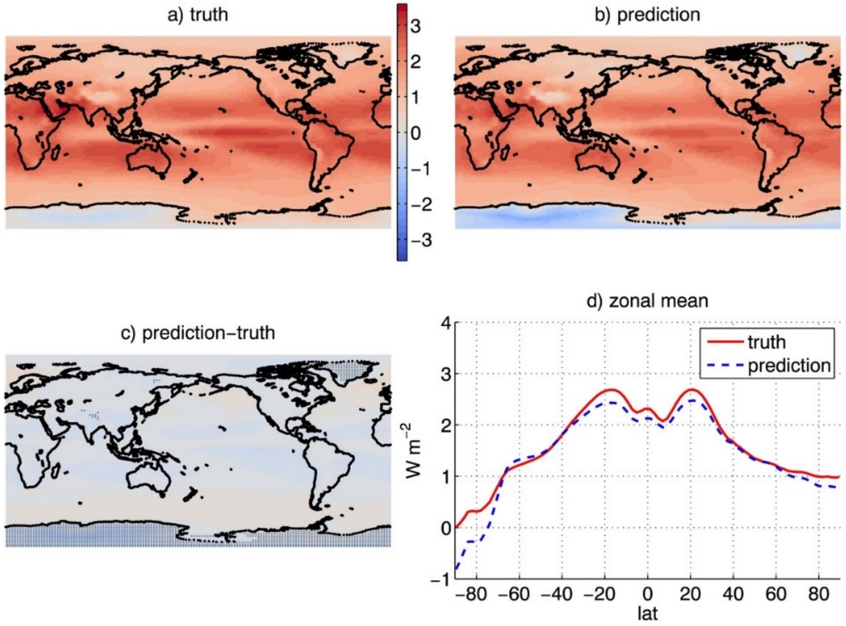
NOAA GMD

Radiative Forcing and the Underlying Climate



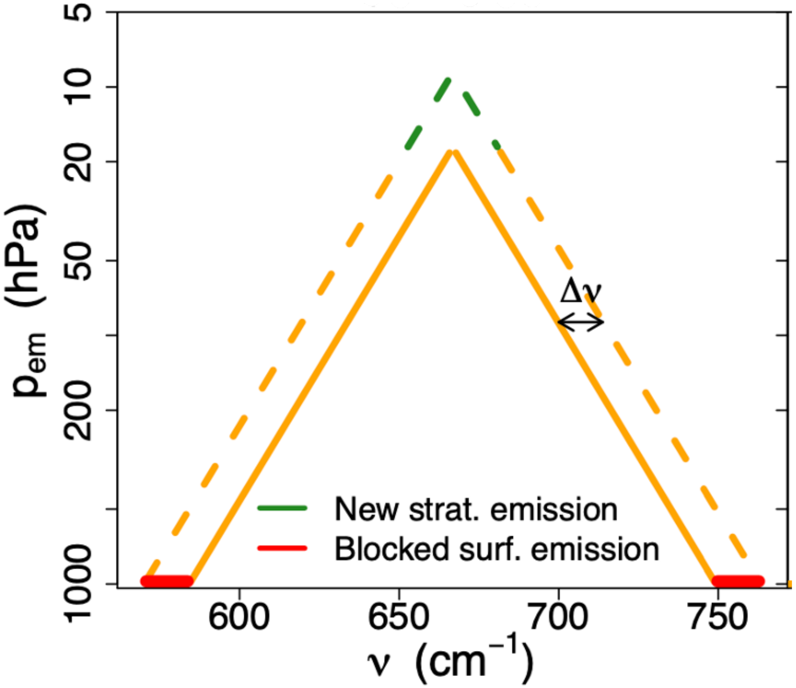
Huang et al. (2016)

Forcing Sensitivity to Temperature



Lapse Rate computed as T(10hPa) – Ts explains 93% of the forcing variance

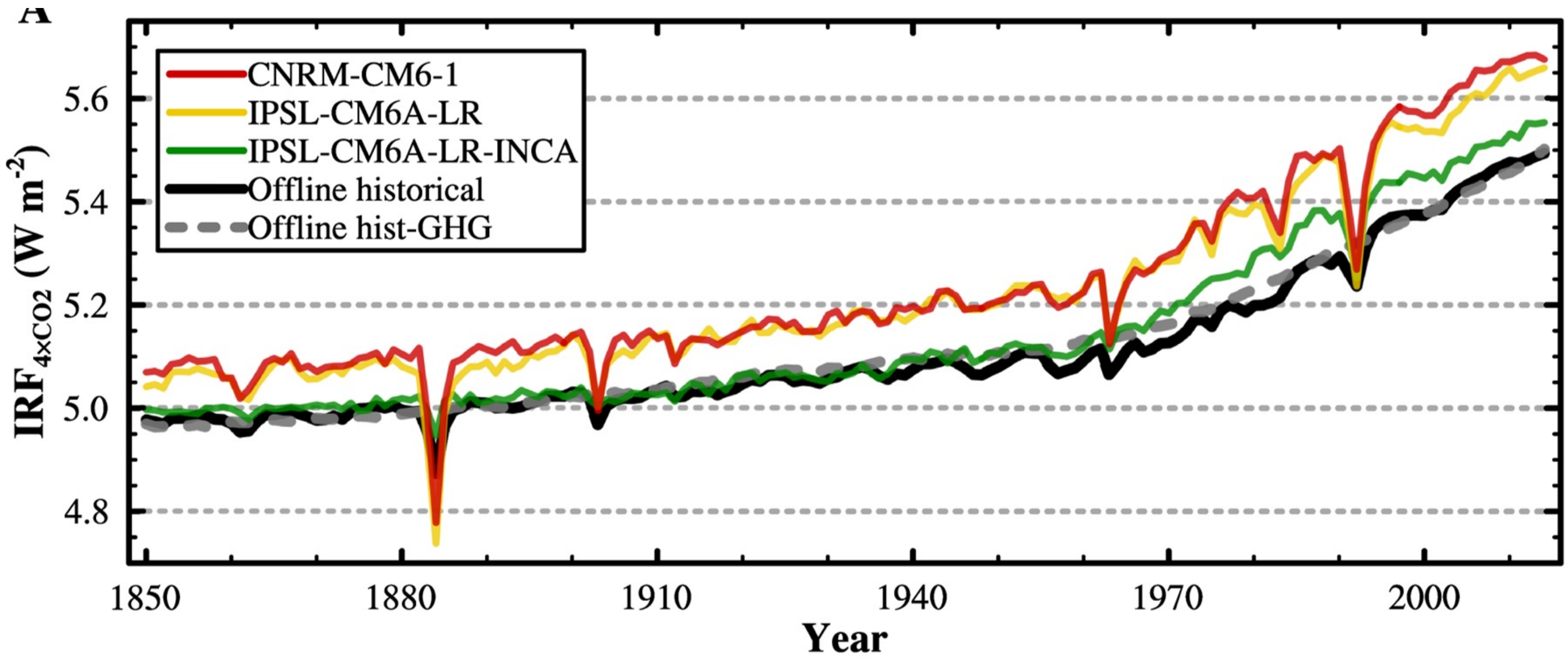
Y. Huang et al. (2016)



CO_2 forcing can be considered a swap of surface emission for stratospheric emission.

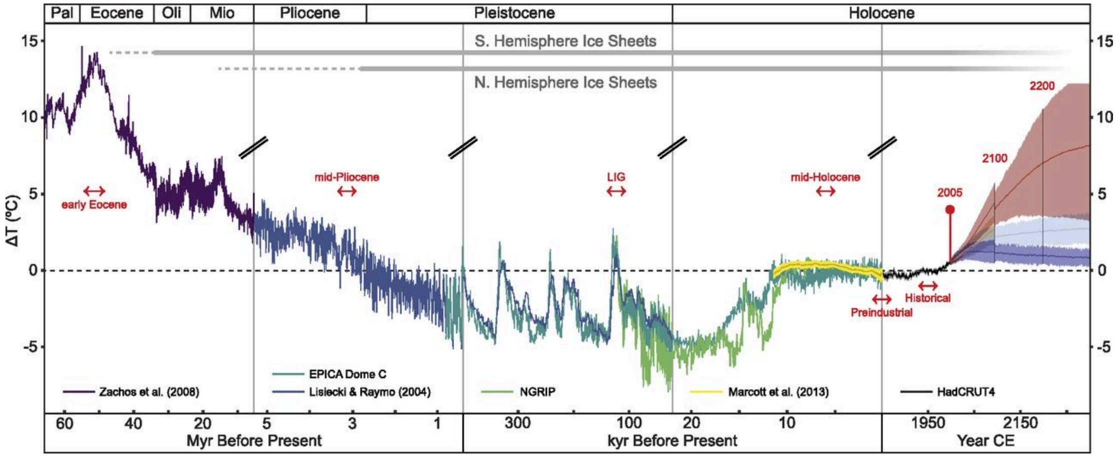
N. Jeevanjee et al. (2021)

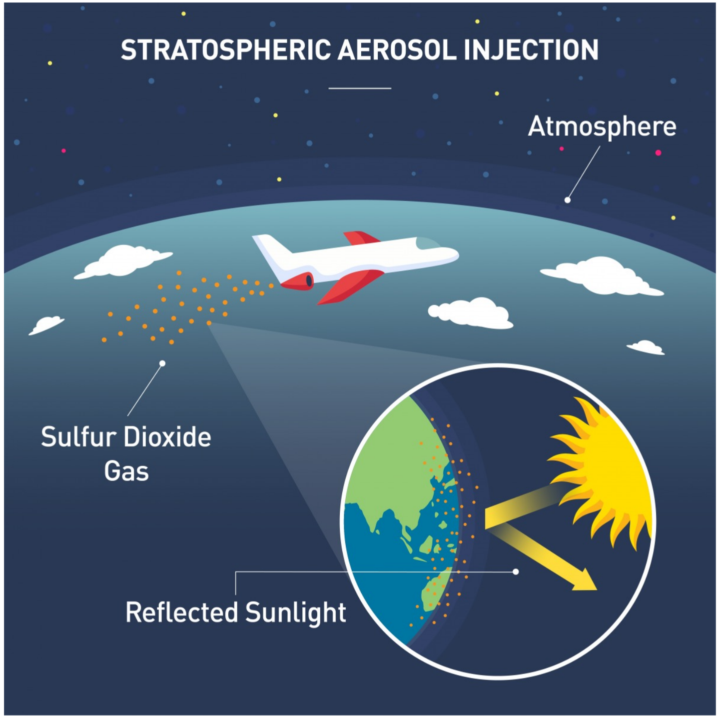
CO_2 Radiative Forcing Changes with the Base State



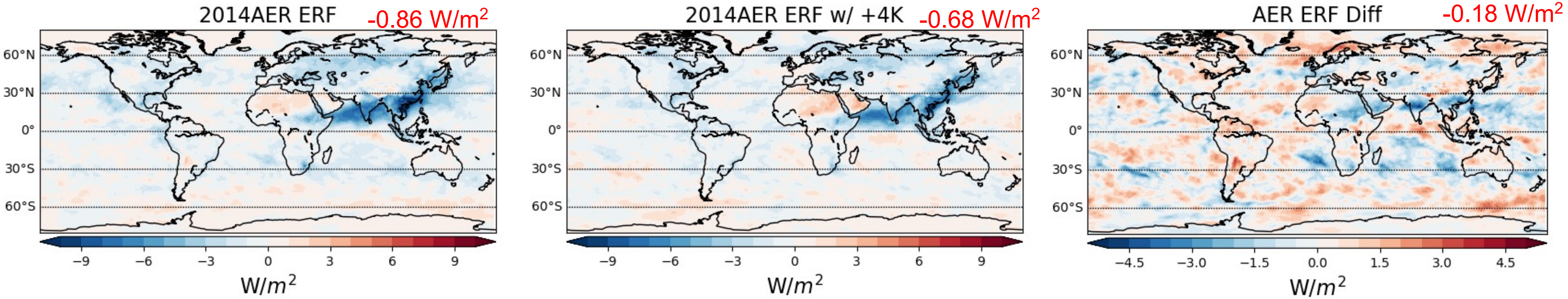
He et al., in-review

Different Radiative Forcing in Different Climates





Aerosol Forcing Dependent on Temperature



-0.86 W/m^2

-0.68 W/m^2

-0.18 W/m^2

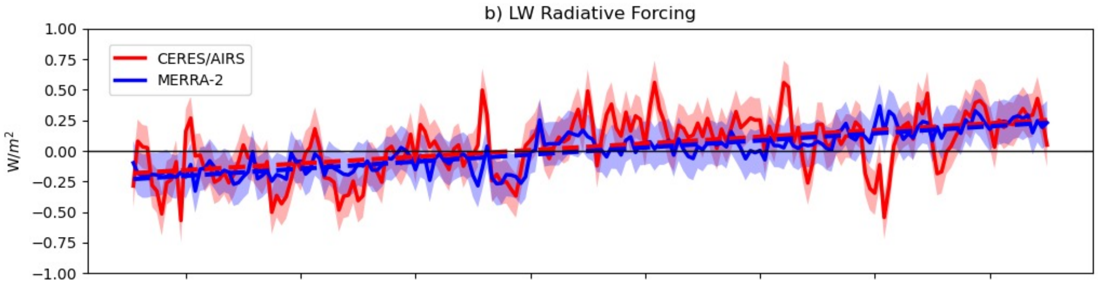
~ 23% Global-Mean Difference

A Testbed for Continuity

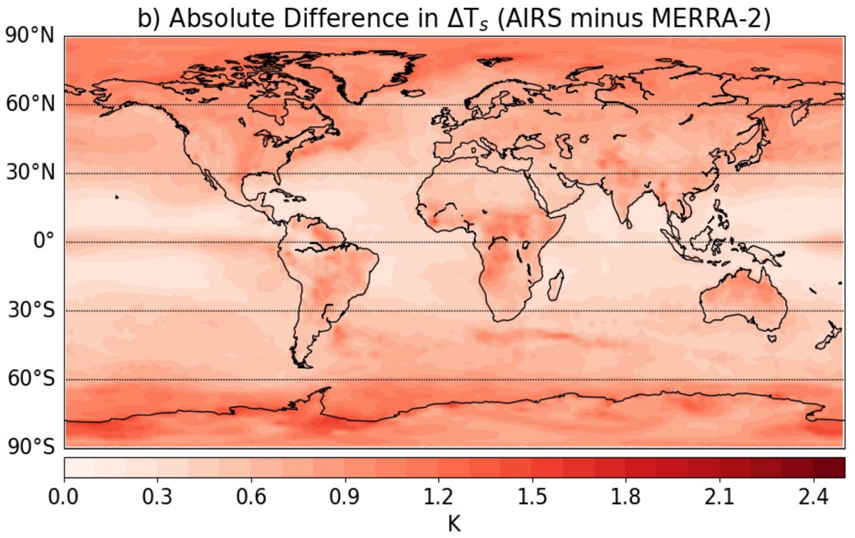
Broadband Radiation	CERES →	Libera	
Temp/WV	AIRS →	IASI →	CrIS
Clouds (Passive)	MODIS →	VIIRS	
Clouds (Active)	CloudSat/ CALIPSO →	EarthCARE →	AOS

Observed Radiative Forcing

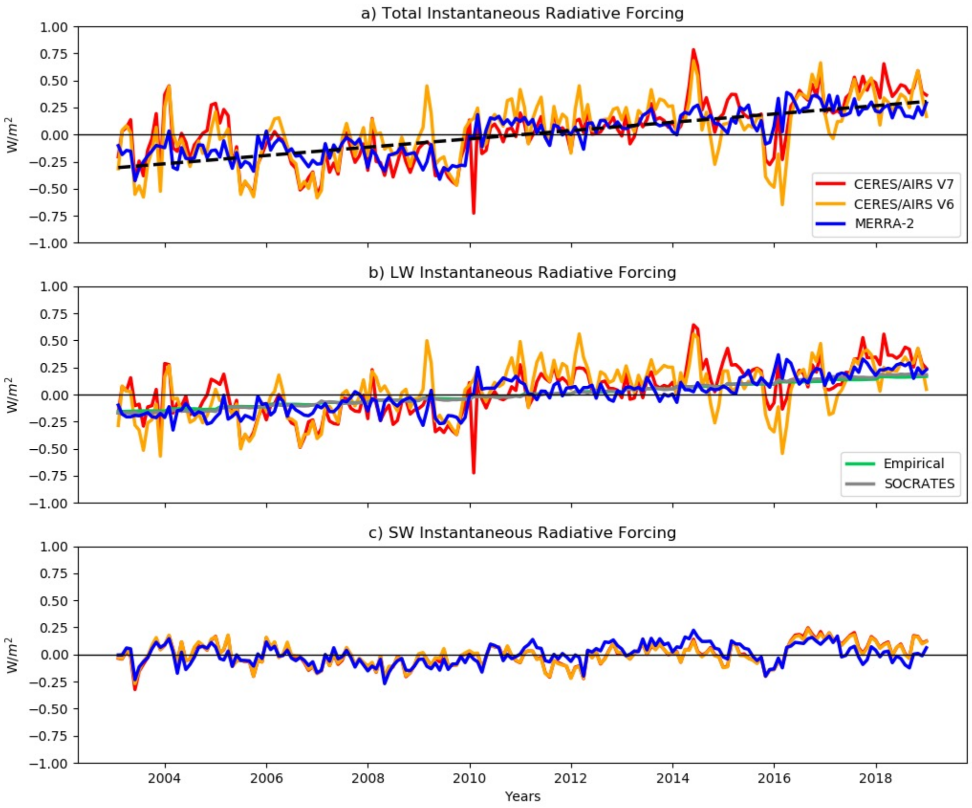
Longwave



$$\underbrace{\Delta F}_{\text{Radiative Forcing}} = \underbrace{\Delta N}_{\text{Total Radiative Imbalance}} - \underbrace{\lambda \Delta T_s}_{\text{Radiative Response}}$$



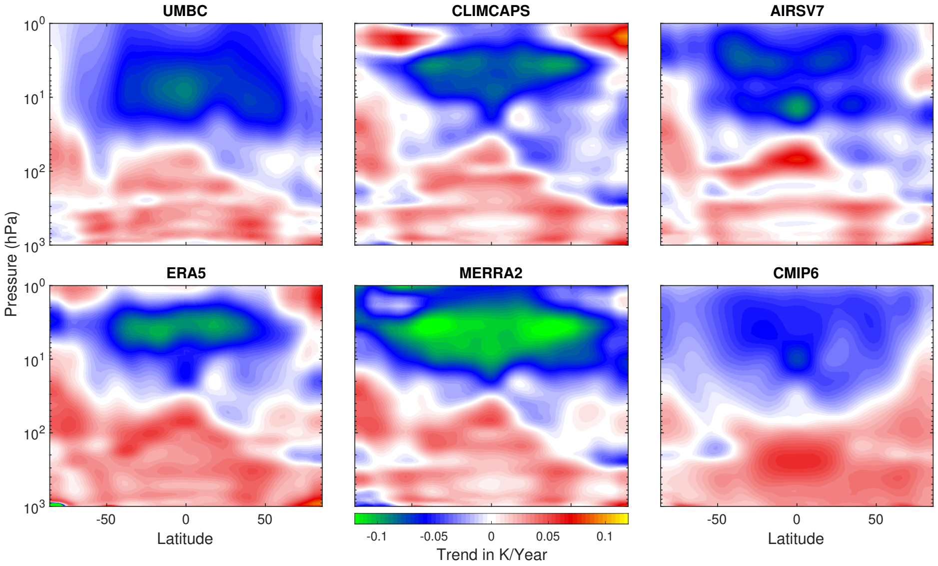
MEaSUREs Forcing: Observation Validation



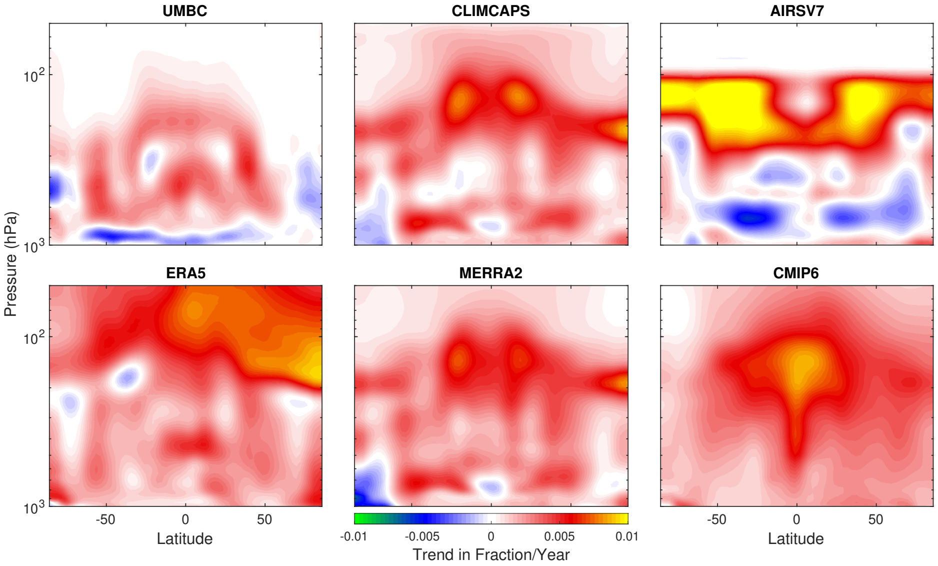
$$\underbrace{\Delta F}_{\text{Radiative Forcing}} = \underbrace{\Delta N}_{\text{Total Radiative Imbalance}} - \underbrace{\lambda \Delta T_s}_{\text{Radiative Response}}$$

Long Term Trends Disagree

Temperature Trends

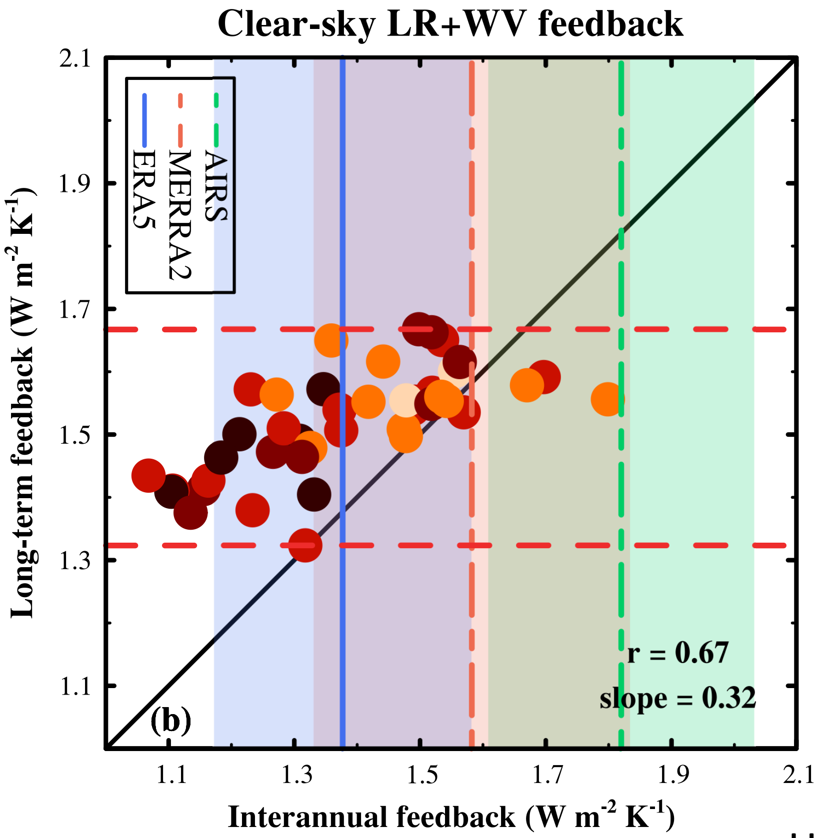


Water Vapor Trends



From Sergio DeSouza-Machado, UMBC

Constraining Models with Observations

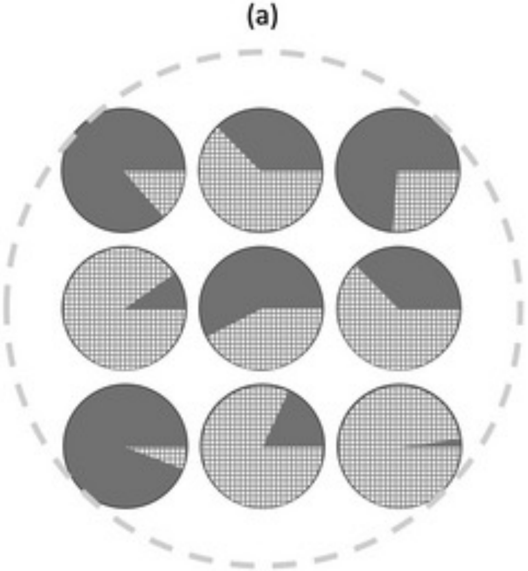


He et al. (2021)

Observational differences are as large as model spread

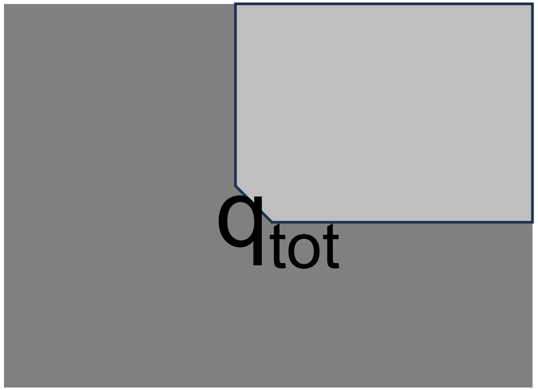
Accounting for Cloud-sky vs. Clear-sky Water Vapor

IR Sounder Cloud-Cleared Retrievals



N. Smith et al. (2023)

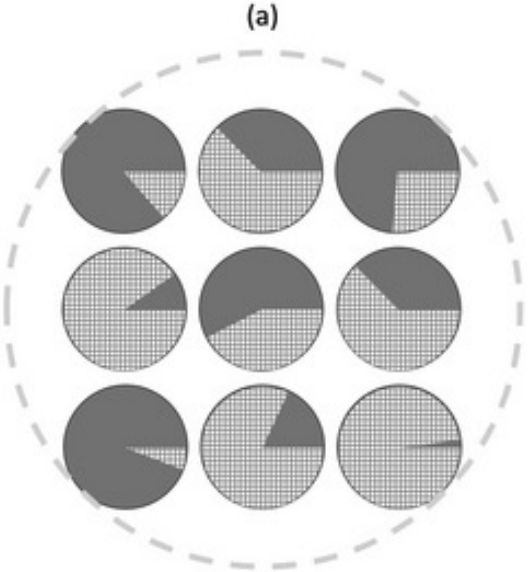
Model Grid



Grid-Mean T,q, Cloud Fraction (f)

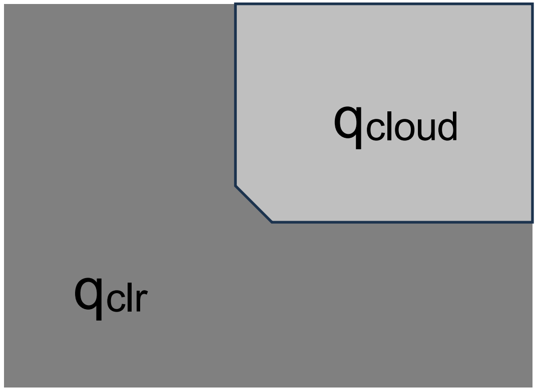
Accounting for Cloud-sky vs. Clear-sky Water Vapor

IR Sounder Cloud-Cleared Retrievals



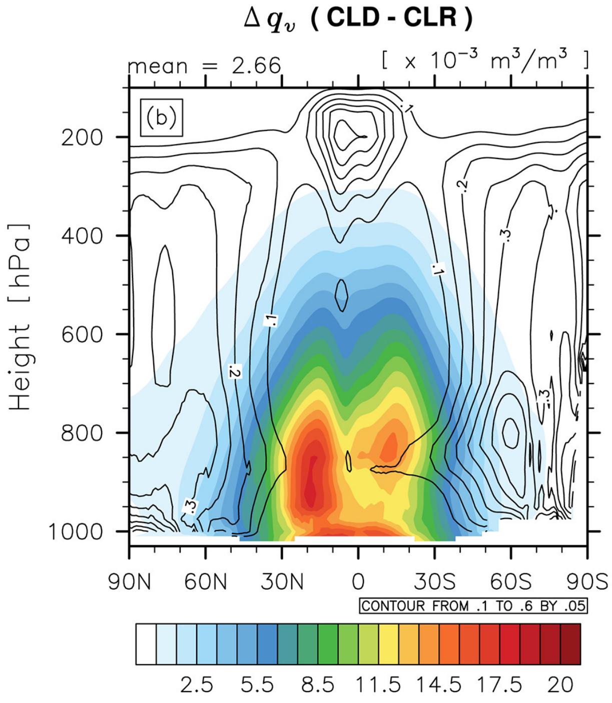
N. Smith et al. (2023)

Model Grid



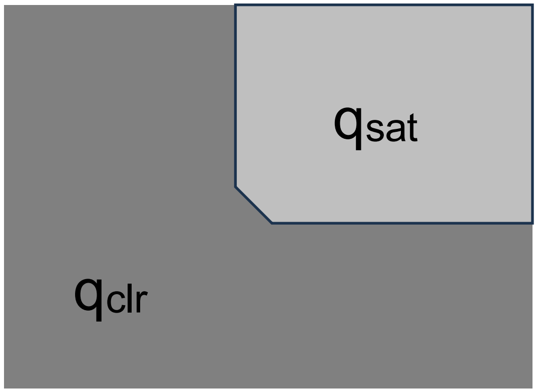
Grid-Mean T,q, Cloud Fraction (f)

Accounting for Cloud-sky vs. Clear-sky Water Vapor



Δq_v (CLD - CLR)

Model Grid

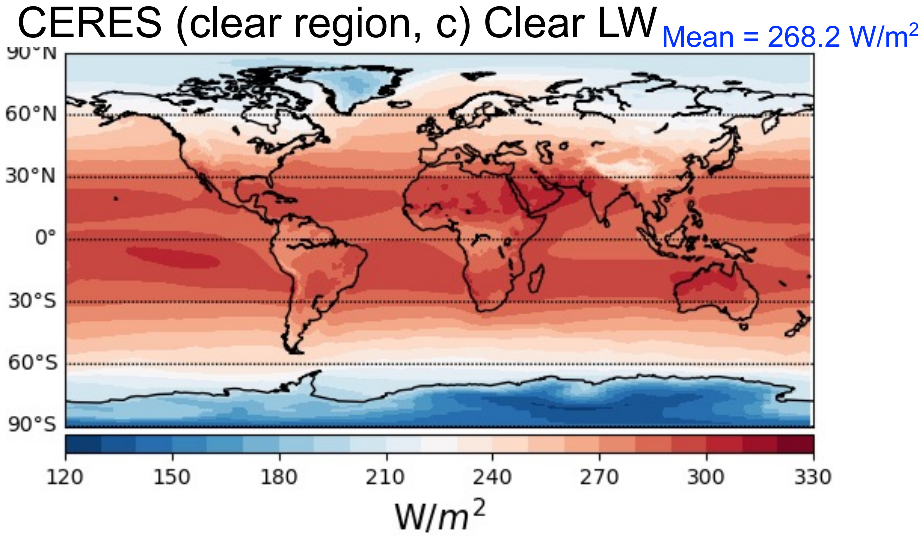


Grid-Mean T,q, Cloud Fraction (f)

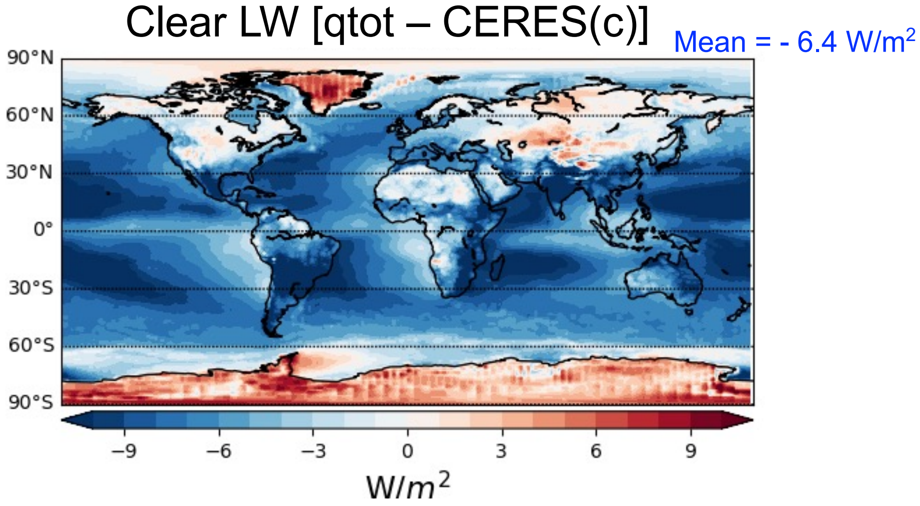
$$Q_{\text{tot}} = fQ_{sat} + (1 - f)Q_{clr}$$

Kim et al. 2020 JAMES

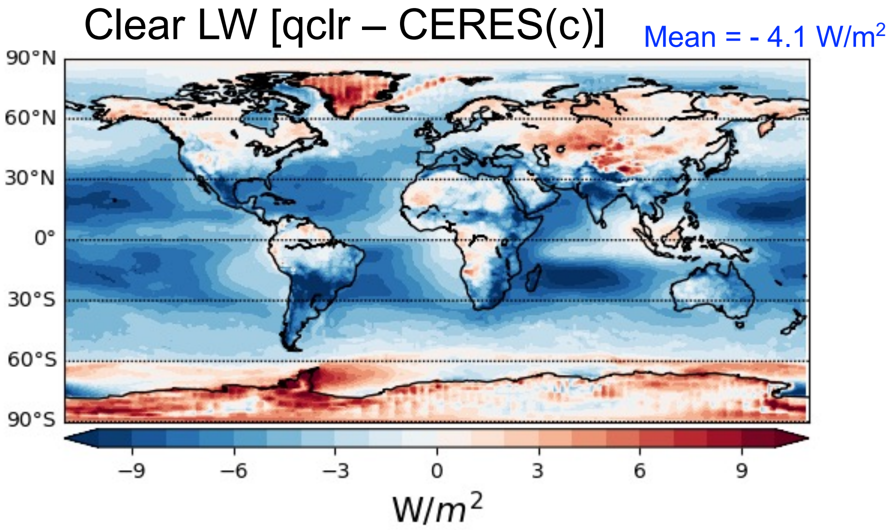
GFDL-AM5 (LW Clear-Sky) for 2010-2014


CERES (clear region, c) Clear LW

Mean = 268.2 W/m²


Clear LW [qtot – CERES(c)]

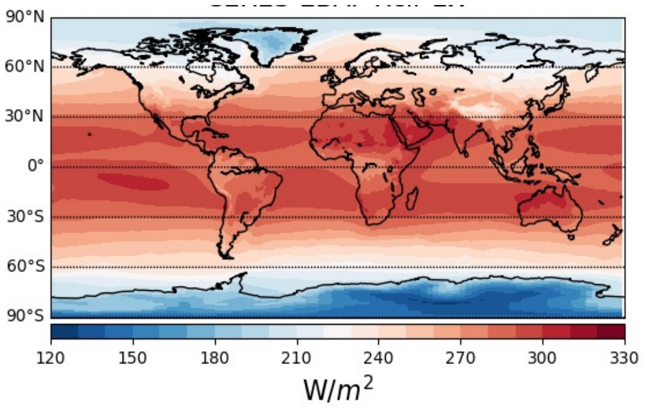
Mean = - 6.4 W/m²


Clear LW [qclr – CERES(c)]

Mean = - 4.1 W/m²

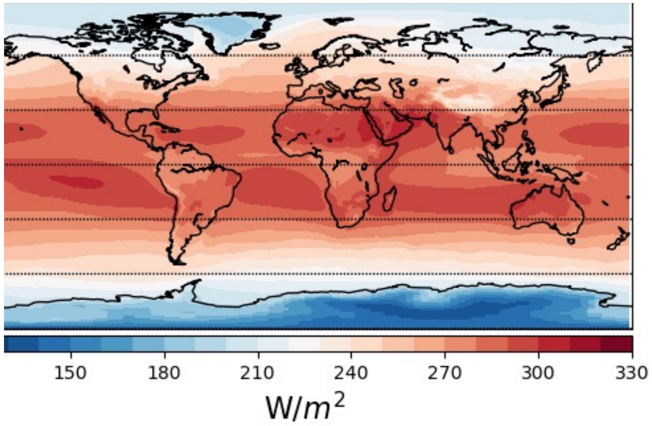
Mean = 268.19 W/m^2

CERES (clear region, c) Clear LW



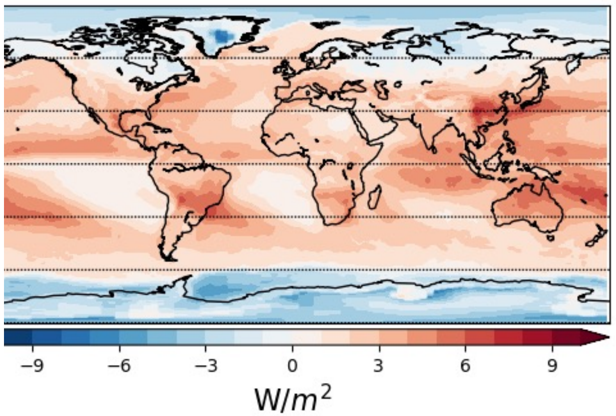
Mean = 266.13 W/m^2

CERES (total region, t) Clear LW



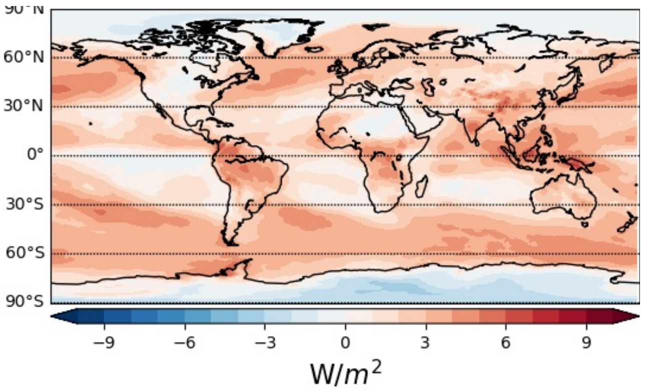
DIFF

Mean = 2.1 W/m^2



Clear LW [qclr – qtot]

Mean = 2.2 W/m^2



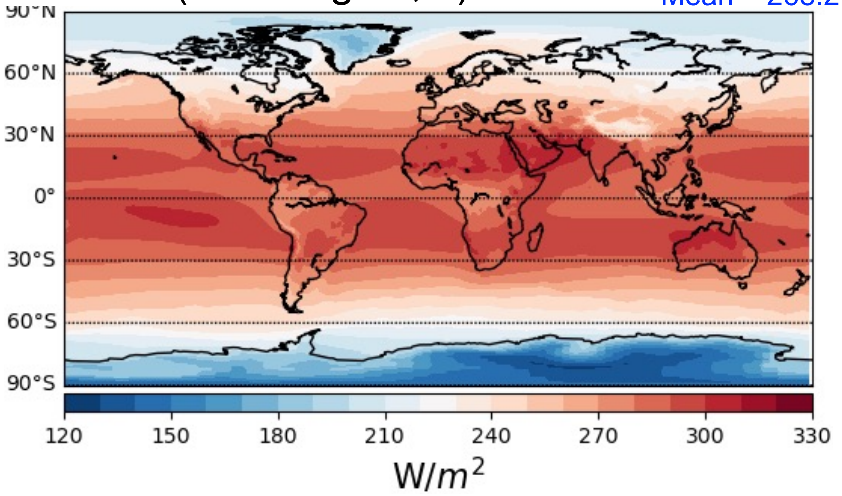
Conclusions

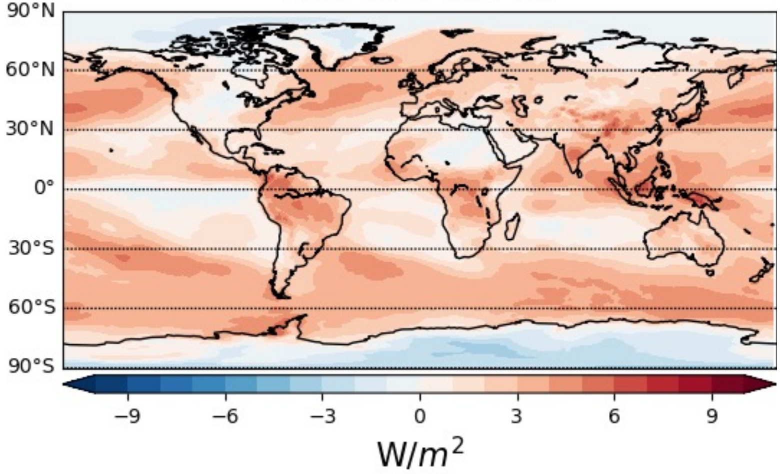
- Considerable growth in Earth's radiative energy imbalance being driven by human activity
  - Satellite observable increase in radiative forcing, largely driven by GHG concentrations
  - Strong regional trends in SW radiative forcing driven influenced by government actions to reduce aerosol emissions

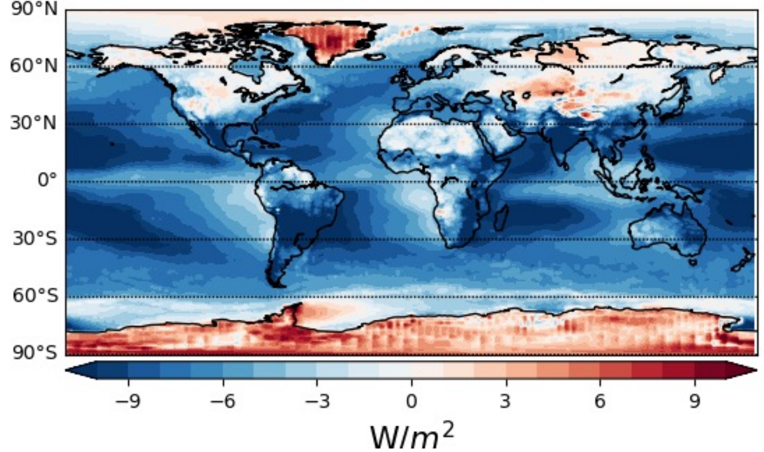
- Lack of global-mean precipitation trend also influenced by human activity
  - Atmospheric radiative heating from rising GHG concentrations counteracts radiative cooling from surface warming-induced radiative feedbacks

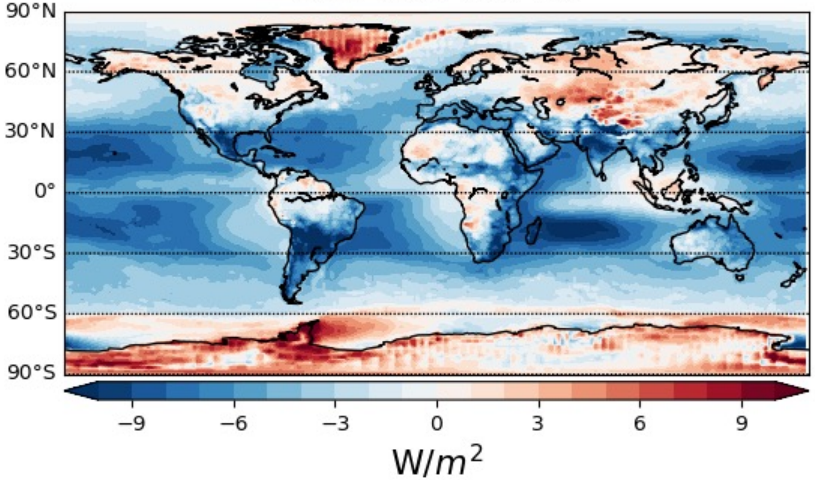
- Many applications for tracking individual drivers of EEI "operationally"

GFDL-AM5 (LW Clear-Sky) for 2010-2014


CERES (clear region, c) Clear LW Mean = 268.2 W/m^2

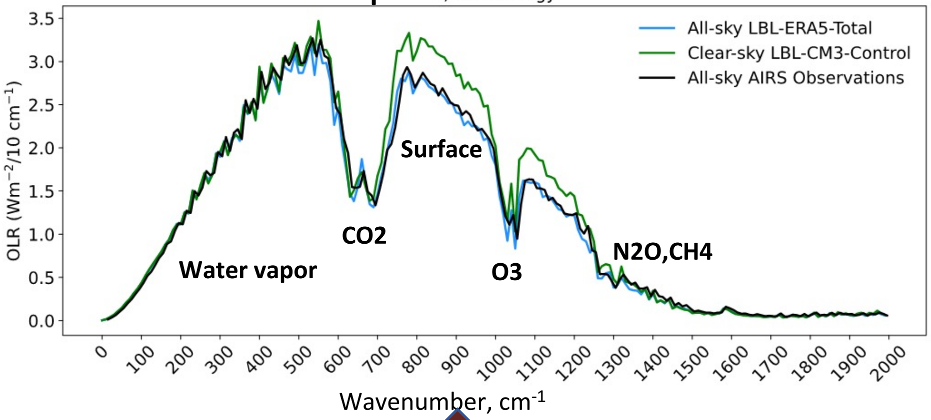

NEW-OLD Rclr LW Mean = 2.2 W/m^2


OLD-OBS Rclr LW Mean = - 6.4 W/m^2


NEW-OBS Rclr LW Mean = - 4.1 W/m^2

The Hyperspectral Fingerprints of Climate Change

Thermal ERB Spectra Observed and Simulated

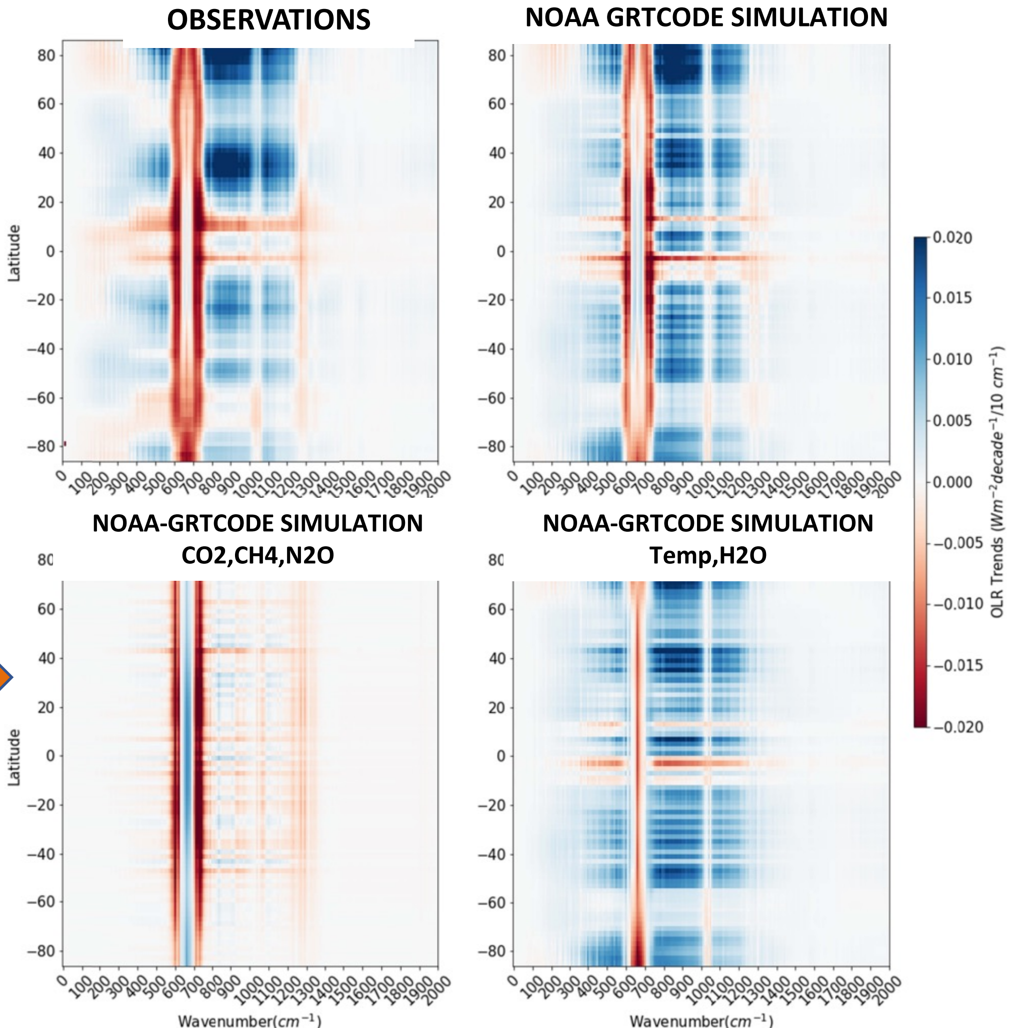


ABOVE: With NOAA GML values for CO2,CH4,N2O concentrations and reanalysis data we can predict the thermal ERB spectra (Blue) using **NOAA-GRTCODE**. This agrees well with AIRS instrument measured spectra (Black).

RIGHT: We can reproduce the zonal mean trends over the 2003-2021 period (top rows right) and break the signal due to CO2,CH4,N2O change (bottom left) and temperature/H2O(bottom right).

Raghuraman et al., summited GRL

Zonal Mean Trends in the Thermal ERB Spectra 2003-2021


OBSERVATIONS

NOAA GRTCODE SIMULATION

NOAA-GRTCODE SIMULATION CO2,CH4,N2O

NOAA-GRTCODE SIMULATION Temp,H2O