Earth Energy Budget

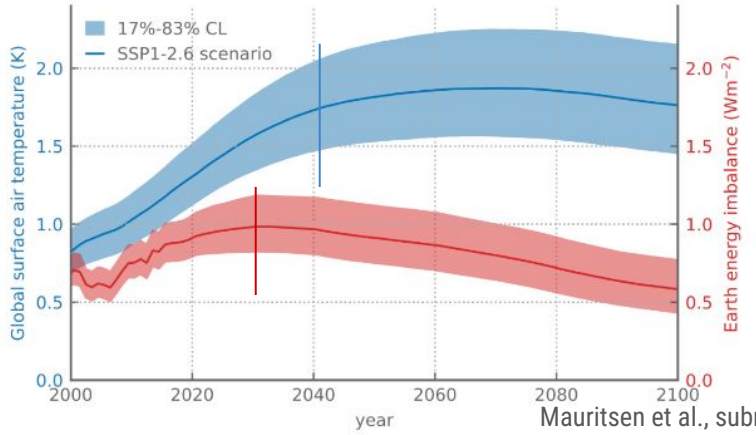
Ryan Kramer

Q2: Concerning NOAA's key mission element of understanding, predicting, and projecting changes in the Earth System, how can GFDL drive further advances in these areas, including extremes and environmental hazards, through scientific innovation based on observations, theory, and modeling? Where are the strengths, gaps, and new frontiers?

Towards Routine Evaluation of Earth's Energy Budget to Explain Observed and Future Climate Changes

Radiation Budget is the first signal of an impending change in Earth's climate, providing a powerful framework for climate detection, climate attribution, and evaluation of mitigation techniques.

Through *seven activities* described here, GFDL is building an infrastructure that uses observations and climate models to routinely track and interpret past, present and future energy budget changes

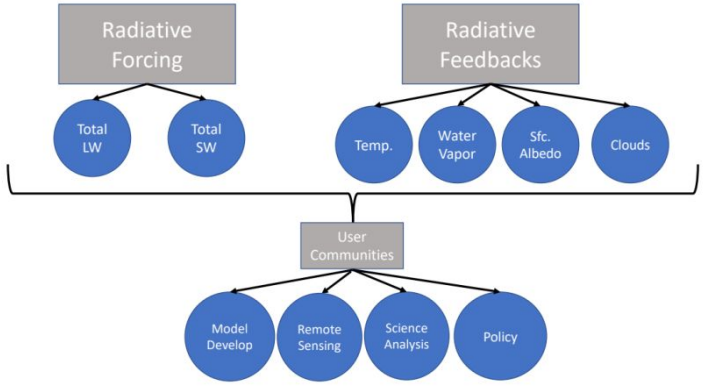


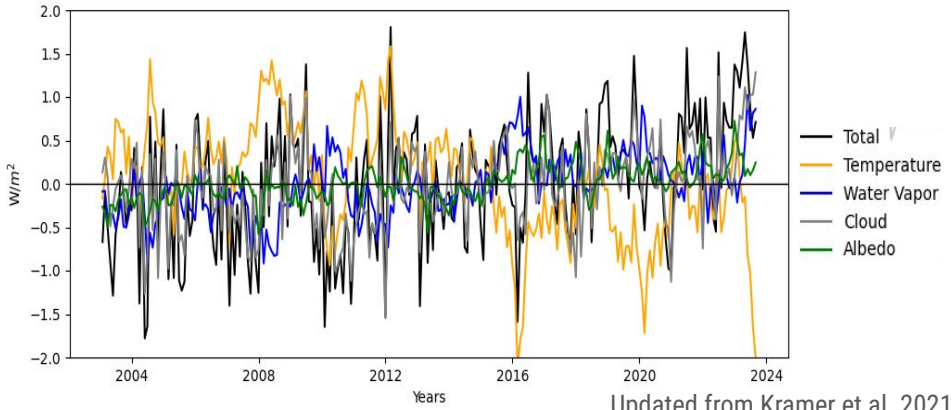
Mauritsen et al., submitted

Energy imbalance (red) responds to emission reductions (roughly beginning at vertical lines) well before surface temperature (blue), providing a means of faster policy evaluation.

1) Building a Satellite Climate Data Record for Decomposing Total Radiation Budget Changes

- Co-Leading a 5-yr NOAA-NASA collaboration to develop a multi-satellite climate data record (CDR) of observed radiative forcing and radiative feedbacks
  - GFDL collaboration with UMBC, NASA GSFC, NASA JPL, University of Miami, University of Michigan via a NASA MEASURES grant
- Allows for routine observational attribution of recent Earth Energy Imbalance changes



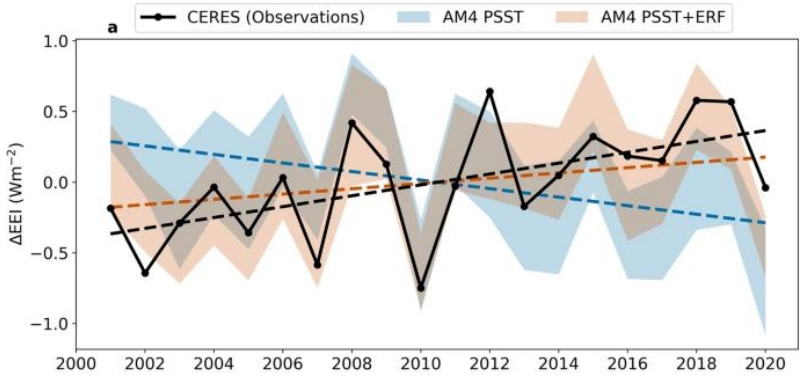


Updated from Kramer et al. 2021

Top: Schematic of CDRs being produced
Bottom: Total, net radiation from CERES and time series of individual radiative feedback contributions

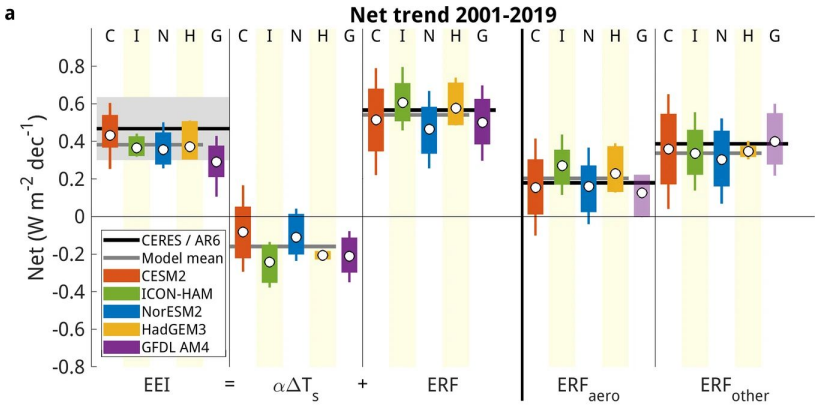
2) Attribution of Observed Radiation Budget Changes using GFDL Climate Model Ensembles

Ensembles from GFDL AM4 are used to dissect the relative contribution of radiative forcings and feedbacks to total energy budget change, and to interpret the role of anthropogenic effects, with a specificity not possible using observations alone



Raghuraman et al. 2021

CERES-observed energy imbalance timeseries (black) and GFDL AM4 simulations with (orange) and without (blue) anthropogenic forcing

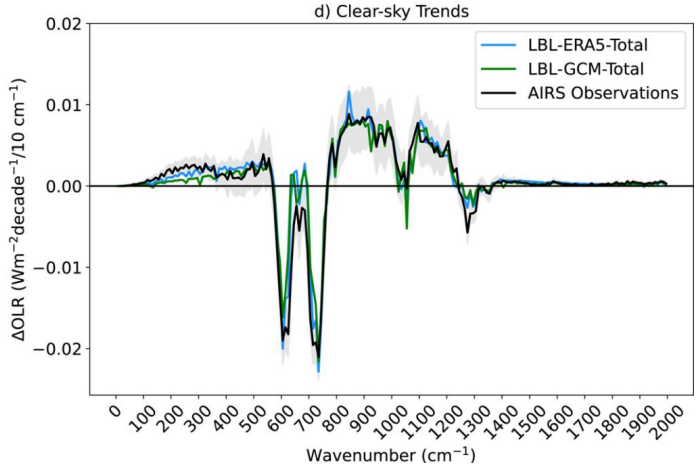


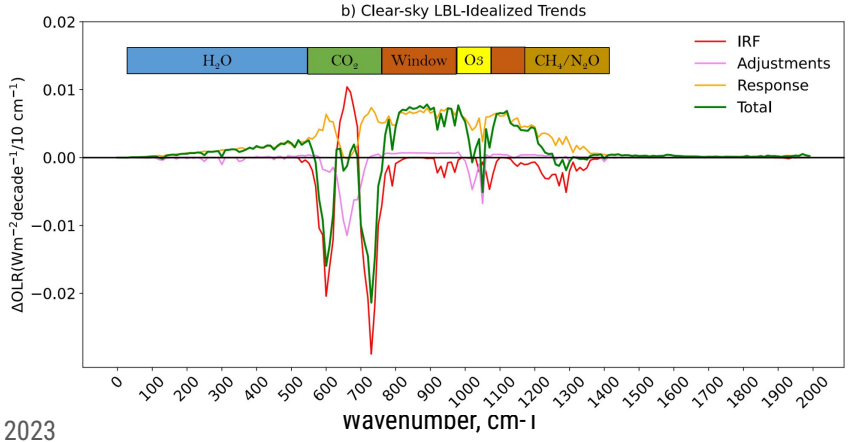
Hodnebrog et al. 2024

Decomposing net CERES trends into contributions from feedbacks and forcing. Whiskers represent spread from ensemble members.

3) Pinpointing Drivers of Observed Radiation Budget Changes Through Spectral Analysis

GFDL AM4 + Reanalysis + Line-by-Line radiation scheme is being used to spectrally evaluate which individual atmospheric constituents are contributing to energy budget changes and how





Raghuraman et al. 2023

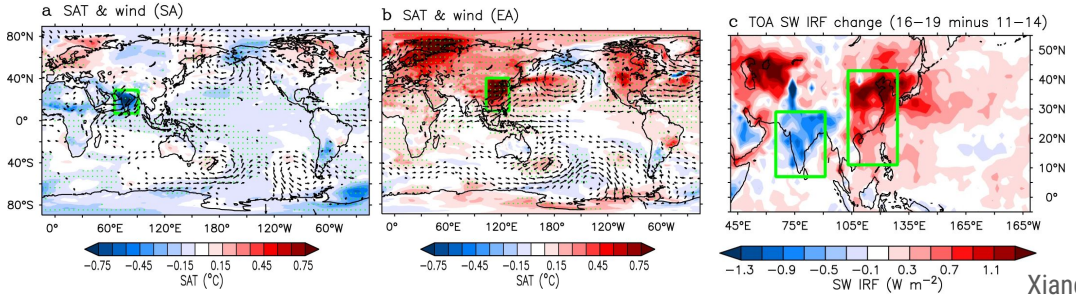
AM4 (Green) able to reproduce spectral LW trends from ERA5 (Blue) and direct AIRS observations (black)

Decomposing LW spectral trends into radiative response and forcing components using AM4 simulations scaled to AIRS-observed trends

4) Determining the Global Response to Local Energy Perturbations

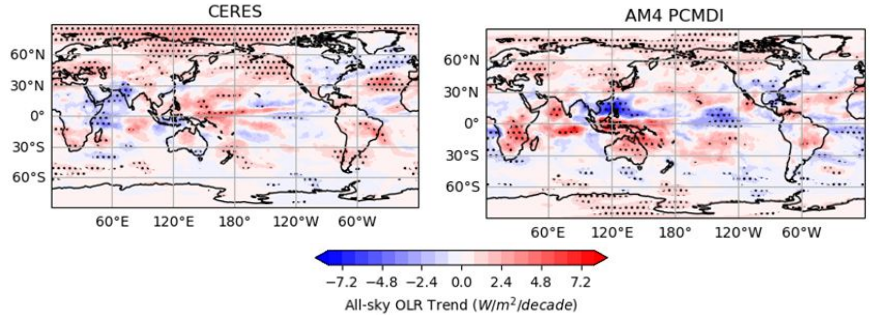
Quantifying regional radiative changes and investigating global teleconnections to local forcings, using idealized and realistic model simulations

- Includes participation in relevant CMIP activities (AerChemMIP, RFMIP, RAMIP)



Contrasting surface-air temperature and wind responses to negative South Asian (A) and positive East Asian (B) idealized aerosol forcing perturbations in GFDL AM4. Observed dipole forcing trends are also shown (C)

Xiang et al. 2023

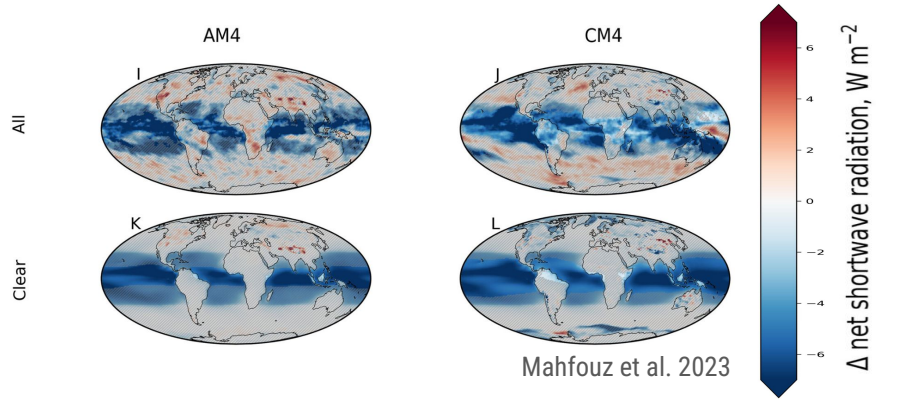


Local trends in outgoing LW radiation from CERES (left) vs. AM4 simulations (right) for model evaluation

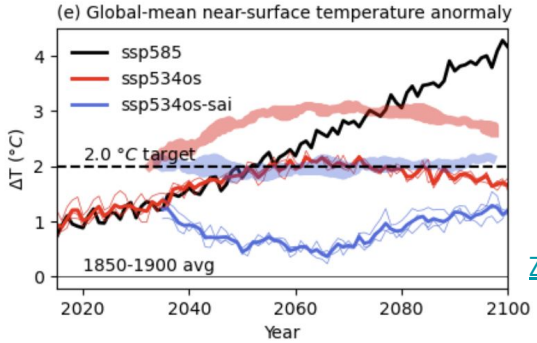
Fan et al., submitted

5) Assessing Solar Radiation Management Techniques Through an Energy Budget Perspective

- Through CPO ERB funding, GFDL is performing a variety of modeling studies using the energy budget to study potential solar radiation management (SRM) techniques and evaluate our ability to simulate their impacts
    - This work will prepare GFDL to conduct monitoring and evaluation of SRM activities in the future, if implemented



Mahfouz et al. 2023

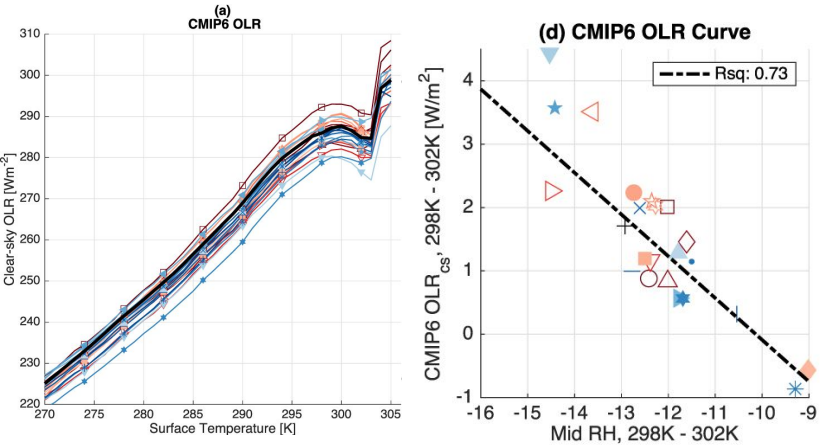


Zhang et al. 2024

Top: All-sky and Clear-sky SW radiation response to marine cloud brightening via sea-salt emissions in AM4 and CM4
Bottom: Overshoot scenario with (os-sai) and without (os) stratospheric aerosol injections. Response differs for CESM2-WACCM5 (shading) vs. GFDL ESM4.1 (line), highlighting uncertainty in the strength of SRM needed to limit warming to 2C

6) Conducting Fundamental Research of Earth's Energy Budget

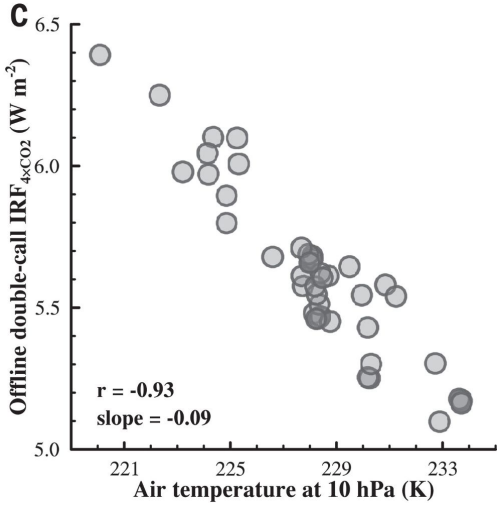
We are using observations, reanalysis, idealized model simulations and radiative transfer calculations to study the sensitivity of radiation to the underlying climate state.



Feng et al. 2023

Left: (a) Magnitude of Outgoing Longwave Radiation largely controlled by surface temperature , but (d) CMIP6 model spread (markers) is driven by mid-tropospheric RH

Right: CMIP6 model spread (gray dots) in CO_2 radiative forcing is inversely related to stratospheric temperatures via a dependency on emission height



He et al. 2023

7) Informing Future Development of Key Resources

Routine evaluation of Earth's Energy Budget changes using models and observations will require three key developments, listed below, from the lab-wide and external community. GFDL efforts to address these topics are provided in italics:

A. Continuity of the CERES-anchored satellite record of Earth's Radiation Budget
   - *GFDL scientists are engaging with NESDIS leadership and the NOAA Science Council about the need for sustained measurements of these metrics. Developing a NOAA Value Assessment of radiation budget satellite continuity.*

B. Regular extension of forcing input datasets to extend historical model simulations to present day
   - *GFDL scientists are leading the CMIP Forcing Datasets Team, engaging with CPO on future funding opportunities to support sustained extension of forcing datasets and providing regular feedback to developers on new versions of forcing datasets*

C. Updated model diagnostic tools to evaluate accuracy of simulations of the energy budget
   - *Currently developing, testing and implementing new community- and internally- developed radiation diagnostic packages, including from NOAA's Model Diagnostic Task Force*