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
Energy Balance Equation

\[ \Delta N = \Delta F + \lambda \Delta T_s \]

Total Radiative Imbalance  Radiative Forcing  Radiative Feedbacks

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (T)</td>
<td>AIRS Version 6 L3</td>
</tr>
<tr>
<td>Water Vapor (q)</td>
<td>TOA</td>
</tr>
<tr>
<td>Surface Albedo (a)</td>
<td>CERES EBAF Ed4.1 TOA and Surface Products</td>
</tr>
<tr>
<td>Cloud Radiative Effects (C)</td>
<td></td>
</tr>
</tbody>
</table>

Temperature  Water Vapor  Surface Albedo  Cloud
Energy Balance Equation

\[ \Delta N = \text{IRF} + \text{ADJ} + \text{FB} \]

**Variables**

- **Total Radiative Imbalance**
- **Radiative Forcing**
- **Radiative Feedbacks**

**Sources**

<table>
<thead>
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<tr>
<td>Cloud Radiative Effects (C)</td>
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</tbody>
</table>
Top-of-Atmosphere CERES Net Radiative Flux Anomalies

Longwave (LW) + Shortwave (SW)

0.38 +/- 0.2 W/m²/dec
Top-of-Atmosphere CERES Net Radiative Flux Anomalies

Longwave (LW) + Shortwave (SW)
Top-of-Atmosphere CERES Net Radiative Flux Anomalies

Longwave (LW) + Shortwave (SW)

0.02 +/- 0.2 W/m²/dec
Longwave + Shortwave

0.02 +/- 0.2 W/m²/dec

Longwave

-0.42 +/- 0.3 W/m²/dec

Shortwave

0.44 +/- 0.3 W/m²/dec
Energy Balance Equation

\[ \Delta N = \Delta F + \lambda \Delta T_s \]

Total Radiative Imbalance | Radiative Forcing | Radiative Feedbacks
Observed Radiative Forcing

Longwave + Shortwave

Longwave

Shortwave

\[ 0.33 \pm 0.07 \text{ W/m}^2/\text{dec} \]

\[ 0.27 \pm 0.06 \text{ W/m}^2/\text{dec} \]

\[ 0.06 \pm 0.003 \text{ W/m}^2/\text{dec} \]
Observed Radiative Forcing

Longwave + Shortwave

Longwave

Shortwave

0.33 +/- 0.07 W/m²/dec

0.27 +/- 0.06 W/m²/dec

0.06 +/- 0.003 W/m²/dec
Atmospheric Energy Budget and Precipitation Top-of-Atmos. (TOA)

\[ \text{ATM} = \text{TOA} - \text{SFC} \]

\[ -R_{\text{ATM}} = \text{LP} + \text{SH} \]

CERES/NASA LarC
Robust Precipitation Increase with Warming

Held and Soden (2006)

Kramer et al. (2019)
Weak Global Radiative Cooling Trend

\[ \Delta R_{\text{atm}} \text{ (CERES)} \]
\[ \Delta P \text{ (GPCP)} \]
\[ \Delta SH \text{ (MERRA-2)} \]

\[ \Delta R_{\text{atm}} \text{ vs. } \Delta P: r = 0.76 \]
Atmospheric Radiative Change Decomposition

Net Atmospheric Radiative Anomalies

- Total
- Radiative Feedbacks
- Radiative Forcing

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

b) P Sensitivity

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<tr>
<th>Model (#)</th>
<th>1</th>
<th>4</th>
<th>7</th>
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<td>Sensitivity (%K$^{-1}$)</td>
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<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
<td>4.0</td>
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</tbody>
</table>

Increased CO$_2$

Reduced Precipitation (P)

Reduced longwave radiative cooling ($4Q$)

Instantaneous
Local Trends in Shortwave Radiative Forcing

Red = Radiative Heating and Blue = Radiative Cooling

Kramer et al. (2021)
Local Trends in Shortwave Radiative Forcing

Red = Radiative Heating  and  Blue = Radiative Cooling

Kramer et al. (2021)
Local Trends in Shortwave Radiative Forcing

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

Kramer et al. (2021)
Monitoring and Identifying the Anthropogenic Influence on Climate

NASA: Vital Signs of the Planet

Understanding our planet to benefit humankind.

Global Stocktake
## GHG Monitoring Satellite Missions

<table>
<thead>
<tr>
<th>Satellite, Instrument</th>
<th>Agency/Origin</th>
<th>CO₂</th>
<th>CH₄</th>
<th>Public</th>
<th>Private</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
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<tr>
<td>GOSAT TANSO-FTS</td>
<td>JAXA-NIES-MOE/Japan</td>
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<td>OCO-2</td>
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*CO₂ + CH₄, CO₂ Only, CH₄ Only, Extended Mission, Planned, Phased Deployment*
NASA-MEASURES:
A Multi-Instrument Record for Radiative Forcing and Feedback Responses for Climate Monitoring and Global Change Studies
2023-2028

Ryan Kramer
Co-l’s: Lazaros Oreopoulos, Brian Soden, Qing Yue, Xianglei Huang

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

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

From Xianglei Huang

- 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\(_2\)O from NOAA GML

- O\(_3\) from the NASA GEOS with the full chemistry version (GEOSCCM) with nudged meteorology
  - ~100km horizontal resolution, 72 vertical levels

Working-in-progress. Please do not cite.
Scientists are baffled why the oceans are warming so fast

Loeb et al. 2021

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

Raghuraman et al. 2021
Forcing Simplified Expressions Should Account for Base State

Table 1. Updated IPCC Expressions for Calculating Radiative Forcing*

<table>
<thead>
<tr>
<th>Trace Gas</th>
<th>Simplified Expression</th>
<th>Radiative Forcing, $\Delta F$ (Wm$^{-2}$)</th>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>$\Delta F = (a + c \cdot \ln(C/C_o))$ where $a = a_1 + a_2(C - C_o) + b_1(C - C_o)^2$</td>
<td>$\Delta F = CO_2$</td>
<td>$-2.48E-07$</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>$\Delta F = (a_2 + b_2 \cdot N + d_2) \cdot (\ln(M) - \ln(M_o))$</td>
<td>$\Delta F = CH_4$</td>
<td>$7.59E-04$</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>$\Delta F = (a_3 + b_3 \cdot N + c_3 \cdot M + d_3) \cdot (\ln(N) - \ln(N_o))$</td>
<td>$\Delta F = N_2O$</td>
<td>$-2.15E-03$</td>
</tr>
<tr>
<td>Other gases</td>
<td>$\Delta F = u(X - X_o)$</td>
<td>$\Delta F = Other gases$</td>
<td>$5.2488$</td>
</tr>
</tbody>
</table>
Radiative Forcing and the Underlying Climate

Huang et al. (2016)
Forcing Sensitivity to Temperature

Lapse Rate computed as $T(10\text{hPa}) - T_s$ 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

2014AER ERF \(-0.86 \text{ W/m}^2\)

2014AER ERF w/ +4K \(-0.68 \text{ W/m}^2\)

AER ERF Diff \(-0.18 \text{ W/m}^2\)

\(~ 23\% \text{ Global-Mean Difference}~\)
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

\[ \Delta F = \Delta N - \lambda \Delta T_s \]

- Radiative Forcing
- Total Radiative Imbalance
- Radiative Response
MEaSUREs Forcing: Observation Validation

\[ \Delta F = \Delta N - \lambda \Delta T_s \]

Radiative Forcing, Total Radiative Imbalance, Radiative Response
Long Term Trends Disagree

**Temperature Trends**

**Water Vapor Trends**

From Sergio DeSouza-Machado, UMBC
Constraining Models with Observations

Observational differences are as large as model spread

He et al. (2021)
Accounting for Cloud-sky vs. Clear-sky Water Vapor

IR Sounder Cloud-Cleared Retrievals

Model Grid

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

N. Smith et al. (2023)
Accounting for Cloud-sky vs. Clear-sky Water Vapor

IR Sounder Cloud-Cleared Retrievals

Model Grid

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

N. Smith et al. (2023)
Accounting for Cloud-sky vs. Clear-sky Water Vapor

\[ Q_{tot} = f Q_{sat} + (1 - f) Q_{clr} \]
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
CERES (clear region, c) Clear LW

CERES (total region, t) Clear LW

DIFF

Clear LW \[ q_{clr} – q_{tot} \]
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/m²

NEW-OLD Rclr LW
Mean = 2.2 W/m²

OLD-OBS Rclr LW
Mean = -6.4 W/m²

NEW-OBS Rclr LW
Mean = -4.1 W/m²
**The Hyperspectral Fingerprints of Climate Change**

**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