Why Observing the Climate State Matters for Diagnosing Carbon Dioxide Radiative Forcing

Ryan Kramer[1,2], Dongmin Lee[1,2], Lazaros Oreopoulos[2], Robert Pincus[3], Nayeong Cho[1,2]

[1]GESTAR-II, University of Maryland-Baltimore County, Baltimore, MD USA
[2]Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, MD USA
[3]Lamont Doherty Earth Observatory, Columbia, Palisades, NY USA

Introduction

The instantaneous radiative forcing (hereafter just "radiative forcing") is the initial radiative flux perturbation directly due to a change in atmospheric composition. All anthropogenic climate change is a response to the radiative forcing. When defined at the top-of-atmosphere (TOA), the radiative forcing constrains surface temperature changes. When defined for surface flux perturbations, the radiative forcing constrains hydrological cycle changes.

Often underappreciated, the radiative forcing is sensitive to the underlying climate state that the radiation propagates through. Here we explore the implications of that sensitivity for radiative forcing for a uniform change in CO_2 concentration.

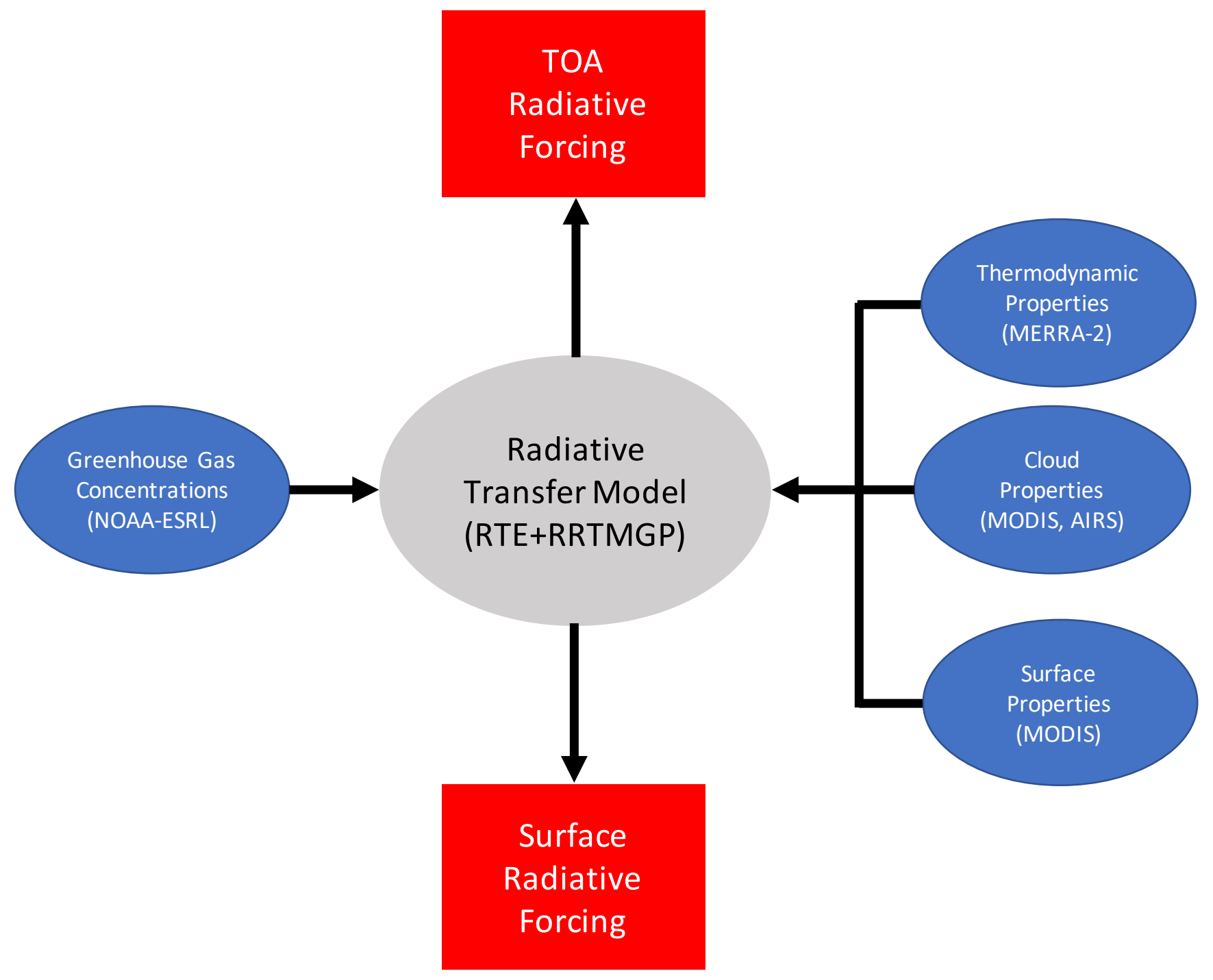
Contact ryan.j.kramer@nasa.gov

Methods

Changes in net atmospheric radiation are comprised of radiative forcing (F) and multiple climate feedback responses (λ_x):

$$\Delta R_{atm} = F + \sum \lambda_x$$

The goal of this project is to calculate globally resolved radiative forcing for perturbations of CO2 and other greenhouse gases from realistic, observed climate conditions using a well-vetted radiative transfer model.



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

Figure 1. We will use satellite observations to initialize a radiative transfer model and estimate the all-sky radiative forcing from greenhouse gases.

Importantly, this includes initializing the calculations with clouds observed from satellites.

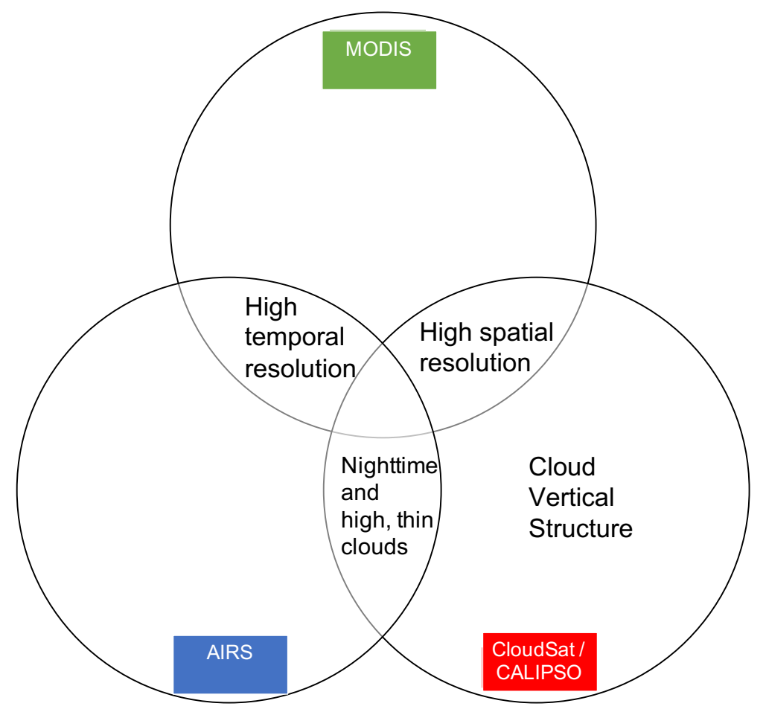


Figure 2. Venn diagram showing relevant unique and shared characteristics of cloud observations from MODIS, AIRS and CloudSat/CALIPSO.

Observation-Based Estimate of Radiative Forcing for 4xCO_2 Concentrations

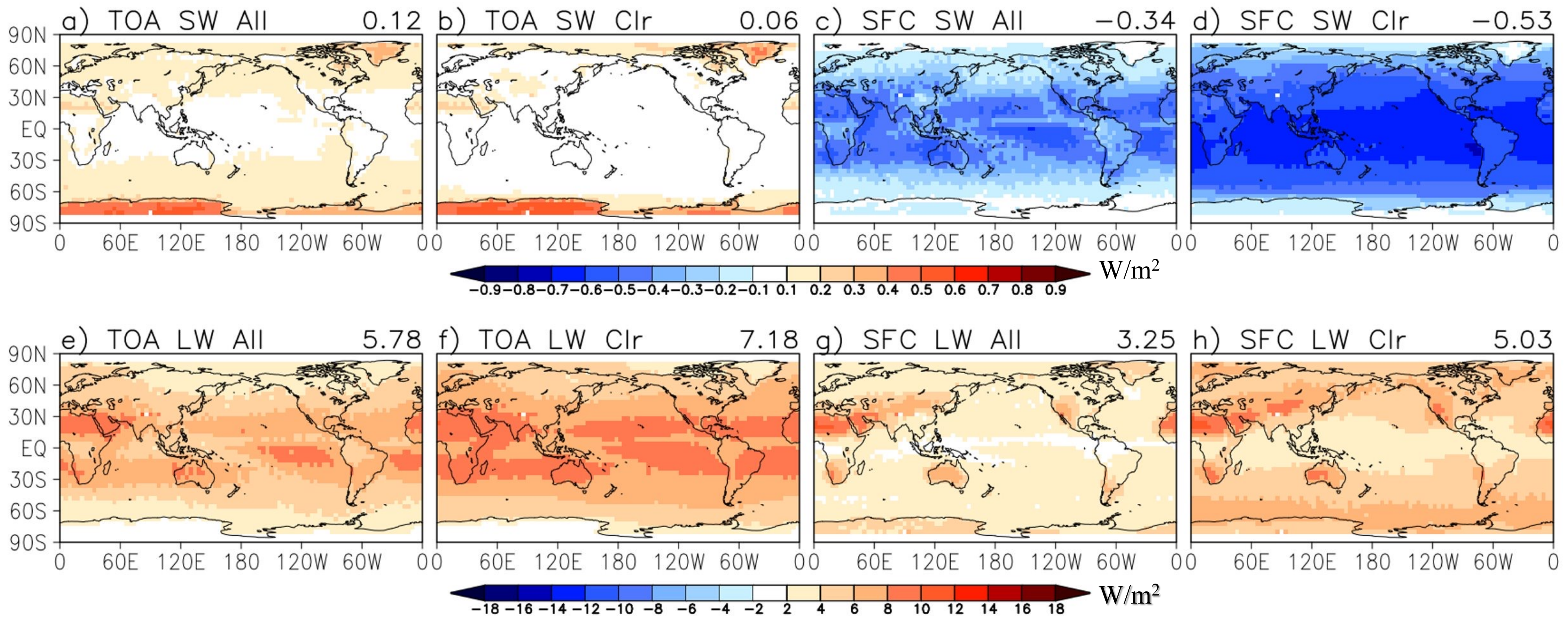


Figure 3. Shortwave (SW) (top) and longwave (LW) (bottom) instantaneous radiative forcing for 4xCO2 concentrations from pre-industrial levels. Shown for top-of-atmosphere (TOA) and surface (SFC) radiative flux perturbations under all-sky ("All") and clear-sky ("Clr") conditions. Global-mean values shown at top-right of each panel. Computed using RRTMG initialized with cloud information from CloudSat constrained by MODIS and all other state variables from ECMWF reanalysis.

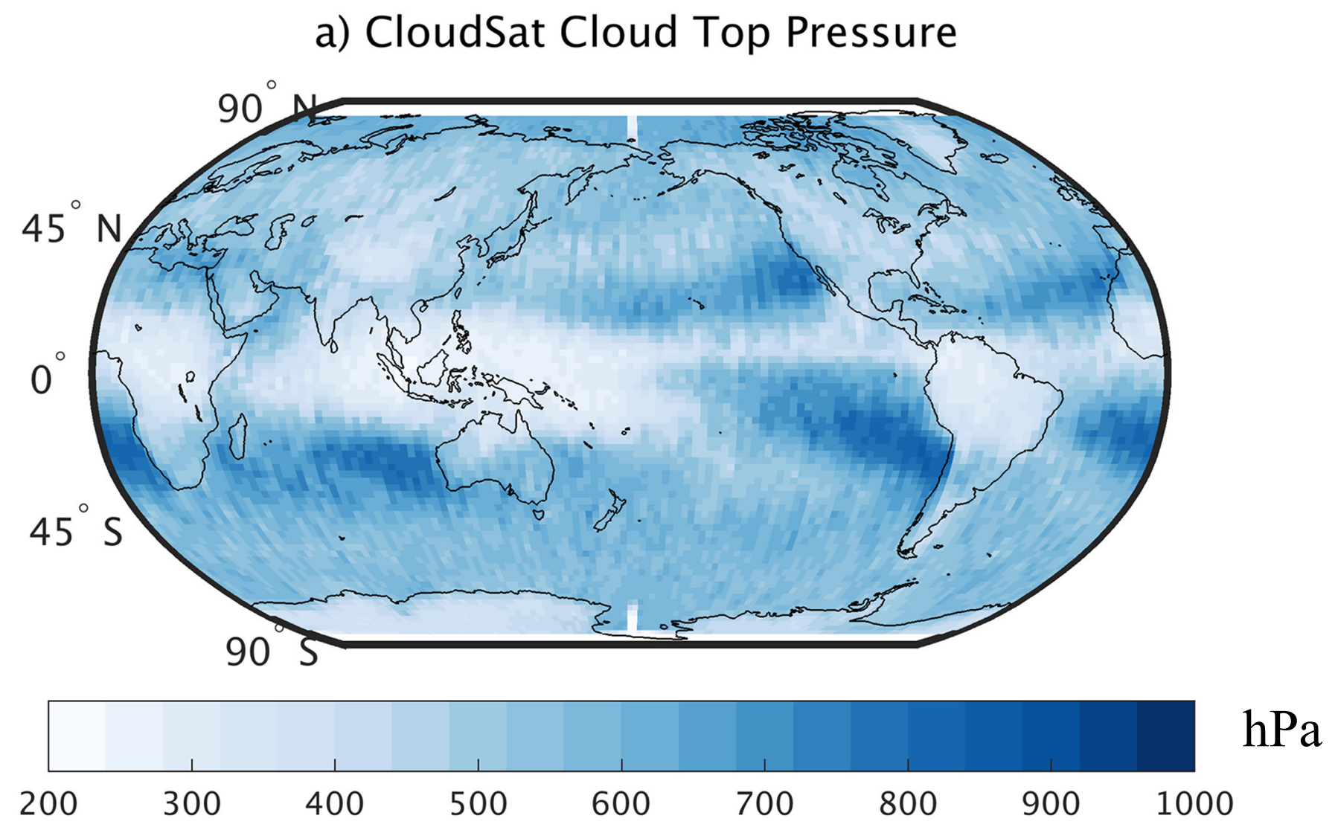


Figure 4. Observed cloud top pressure from CloudSat (Kramer et al. 2019)

Despite a uniform quadrupling of CO_2 concentration, the radiative forcing has a distinct spatial pattern dictated by the climate state's temperature, water vapor, cloud and surface albedo distribution

Cloud-Influenced Pattern of Radiative Forcing May Drive Circulation Changes

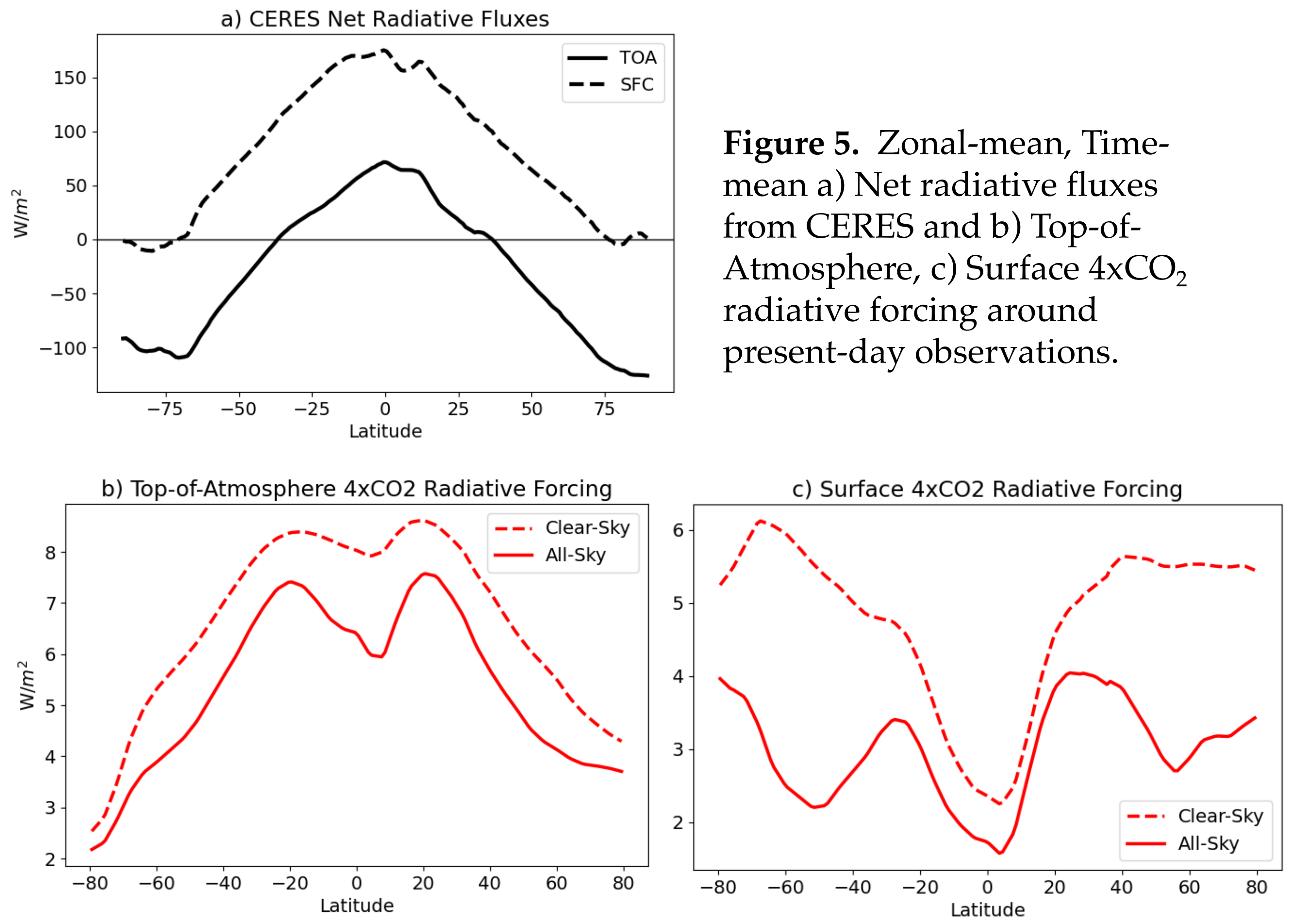


Figure 5. Zonal-mean, Time-mean a) Net radiative fluxes from CERES and b) Top-of-Atmosphere, c) Surface 4xCO_2 radiative forcing around present-day observations.

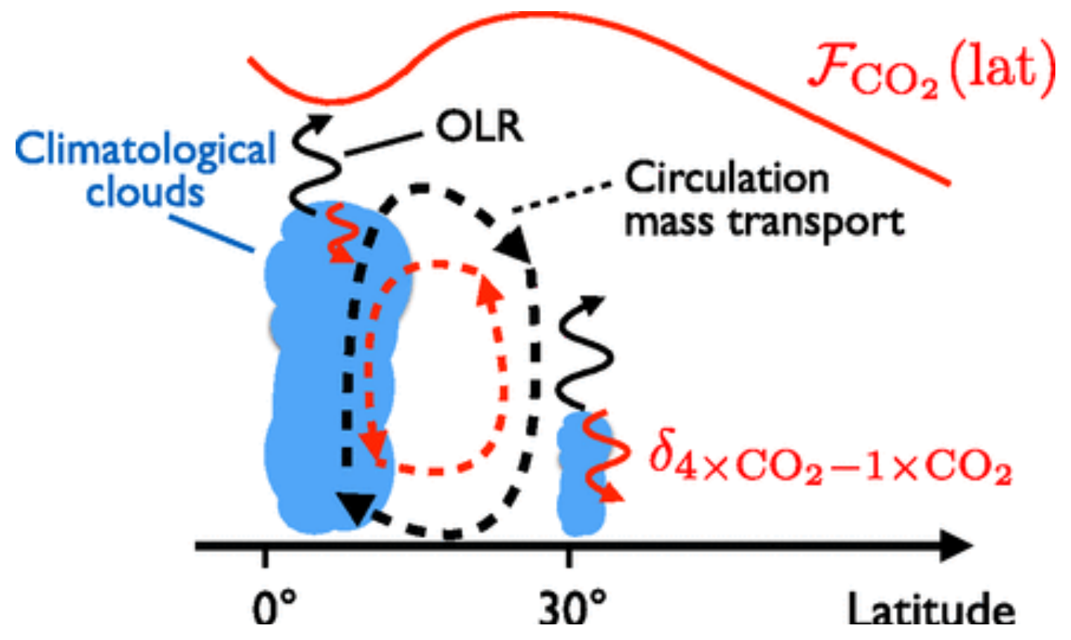


Figure 6. From Merlis (2015). Schematic showing pattern of CO_2 radiative forcing caused by cloud masking and its connection to mass transport.

Clouds and water vapor mask CO_2 radiative forcing in the deep tropics more than at higher latitudes. This may act to weaken tropical overturning circulation.

Model Spread from Climate State

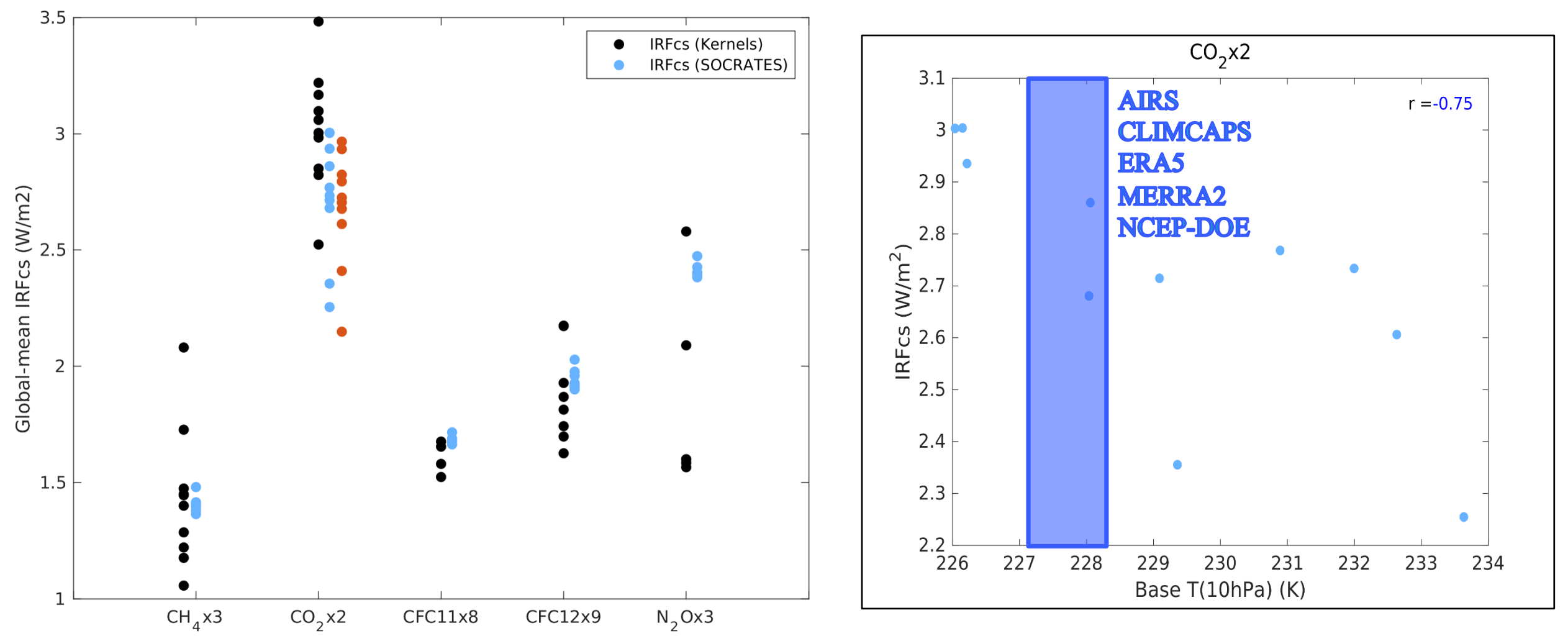


Figure 7. LEFT: Clear-sky radiative forcing for various greenhouse gases computed using radiative kernels vs. offline calculations. Orange points are additional offline double calls where model-mean water vapor profiles were used for all calculations.

RIGHT: Scatter of 2xCO2 radiative forcing versus 10hPa climatological temperature. Blue shading is range of observed global-mean temperatures at 10hPa from a variety of sources (text)

Uniquely for CO_2 radiative forcing, inter-model spread is largely due to differences in base state stratospheric temperatures across GCMs rather than radiative transfer model diversity.

CO_2 Radiative Forcing is Not a Constant

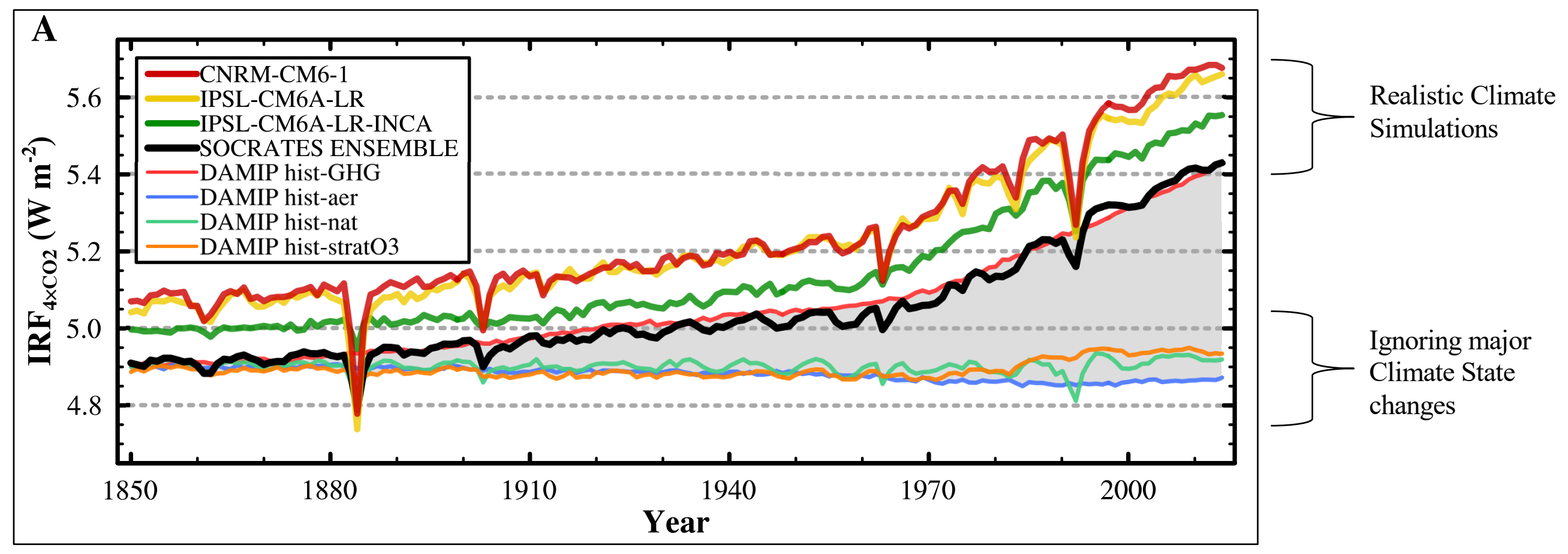


Figure 8. From He et al., submitted. Clear-sky, longwave 4xCO2 radiative forcing computed at each timestep of multiple CMIP6 historical simulations where the climate state responds to, or ignores, historical forcings.

Due to its sensitivity to the climate state, as the climate state changes so does the magnitude of CO_2 radiative forcing. It increases as the stratosphere cools and the surface warms.

CONCLUSION: Over time, CO_2 becomes a more "potent" greenhouse gas. Long-term observations of the climate state are necessary to monitor this effect.

This work is supported by NASA ROSES Science of Terra, Aqua and Suomi-NPP grant 80NSSC21K1968