Jet Propulsion Laboratory
California Institute of Technology

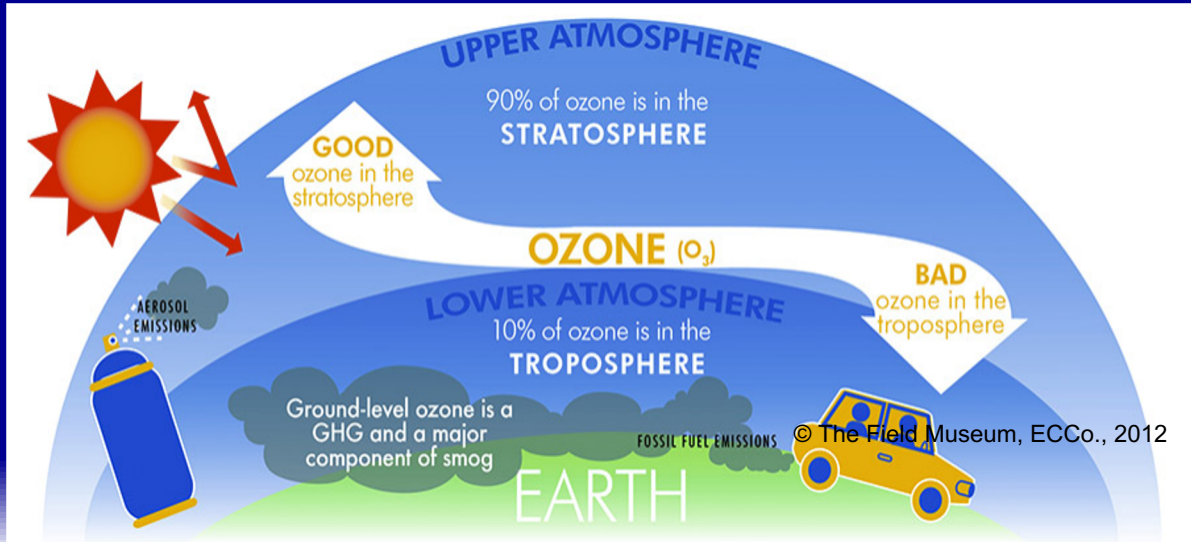
The Chemistry Climate Model Initiative (CCMI) Science Workshop 2019

ccmi
chemistry-climate model initiative

Attribution of the ozone band radiative flux bias in Chemistry-Climate Model Initiative (CCMI) models from satellites

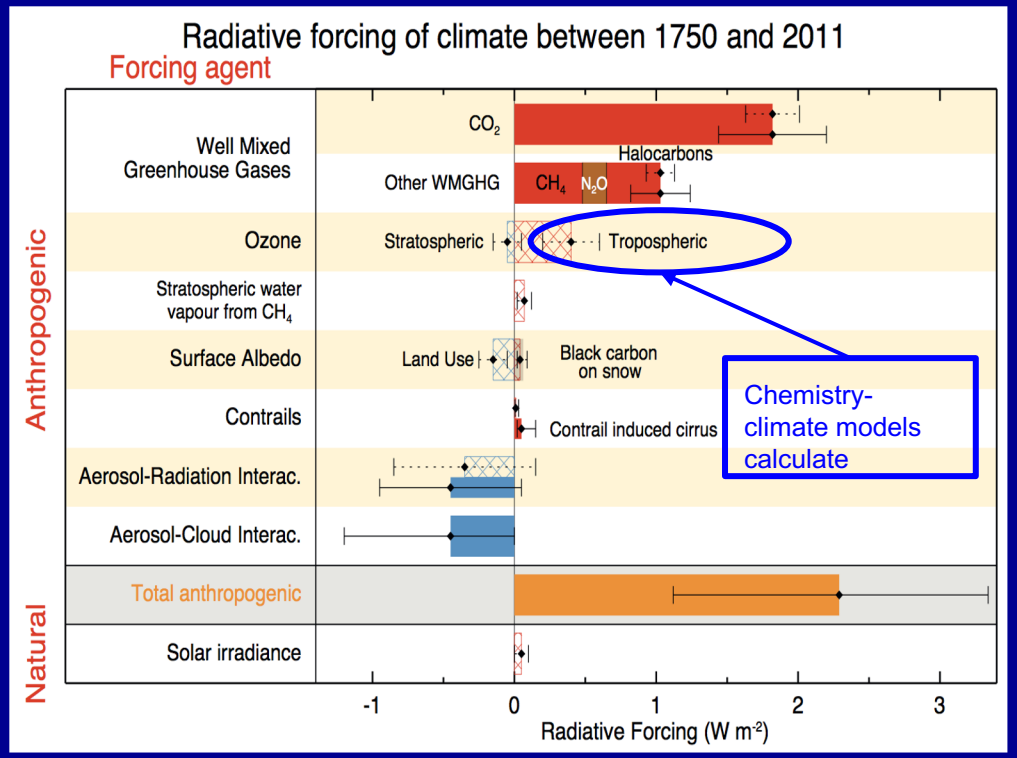
Le Kuai[1,2], Kevin W. Bowman[1], Helen Worden[3], Kazuyuki Miyazaki[1,5], Andrew Conley[3], Jean-François Lamarque[3], Fabien Paulot[3], David Paynter[6], Luke Oman[7], Sarah Strode[7], Eugene Rozanov[8,9], Andrea Stenke[9], Laura Revell[9, 10], David Plummer[11], Makoto Deushi[12], Kiyotaka Shibata[12], Patrick Jöckel[13], Markus Kunze[14], Susan Kulawik[4]

1. Jet Propulsion Laboratory, California Institute of Technology, USA;
2. University of California, Los Angeles, USA;
3. National Center for Atmospheric Research, USA;
4. Bay Area Environmental Research Institute, USA;
5. Japan Agency for Marine-Earth Science and Technology 6. NOAA, Geophysical Fluid Dynamics Laboratory, USA;
7. USRA, NASA Goddard Space Flight Center, USA;
8. Physikalisch-Meteorologisches Observatorium Davos– World Radiation Center (PMOD/WRC), Davos, Switzerland;
9. Institute for Atmospheric and Climate Science, ETH Zürich (ETHZ), Zürich, Switzerland;
10. Bodeker Scientific, Christchurch, New Zealand;
11. Environment Canada, Canada;
12. Meteorological Research Institute, Japan;
13. German Aerospace Center (DLR), Germany;
14. Freie Universität Berlin, Berlin, Germany

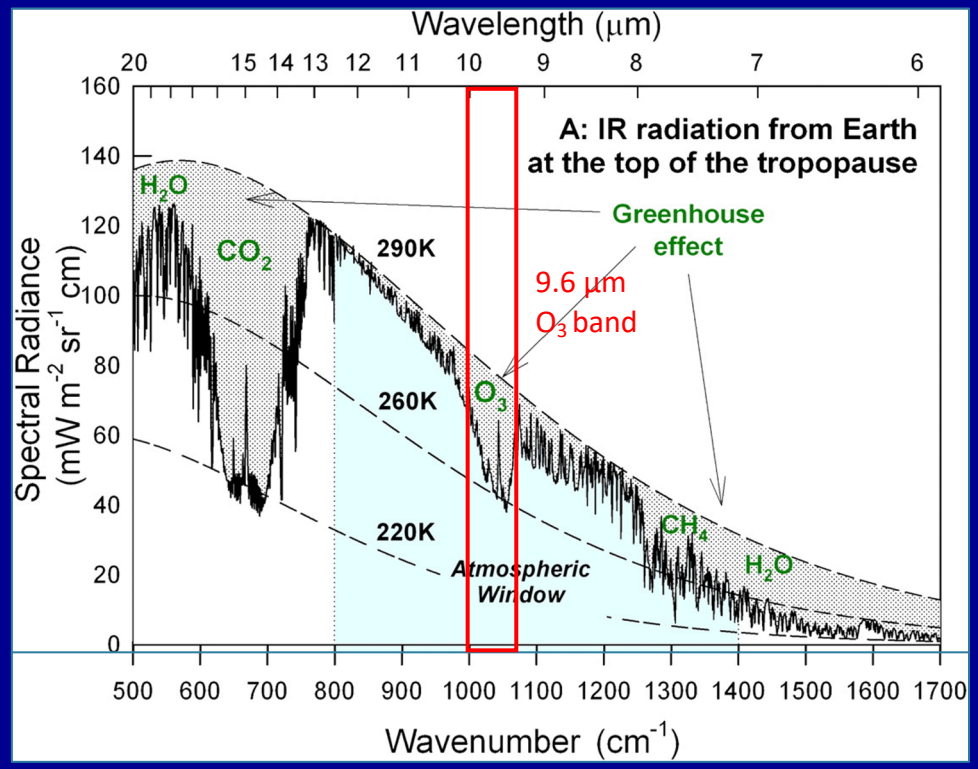


© The Field Museum, ECCo., 2012

Tropospheric O_3 Radiative Forcing & 9.6 µm O_3 band



IPCC AR5, 2013

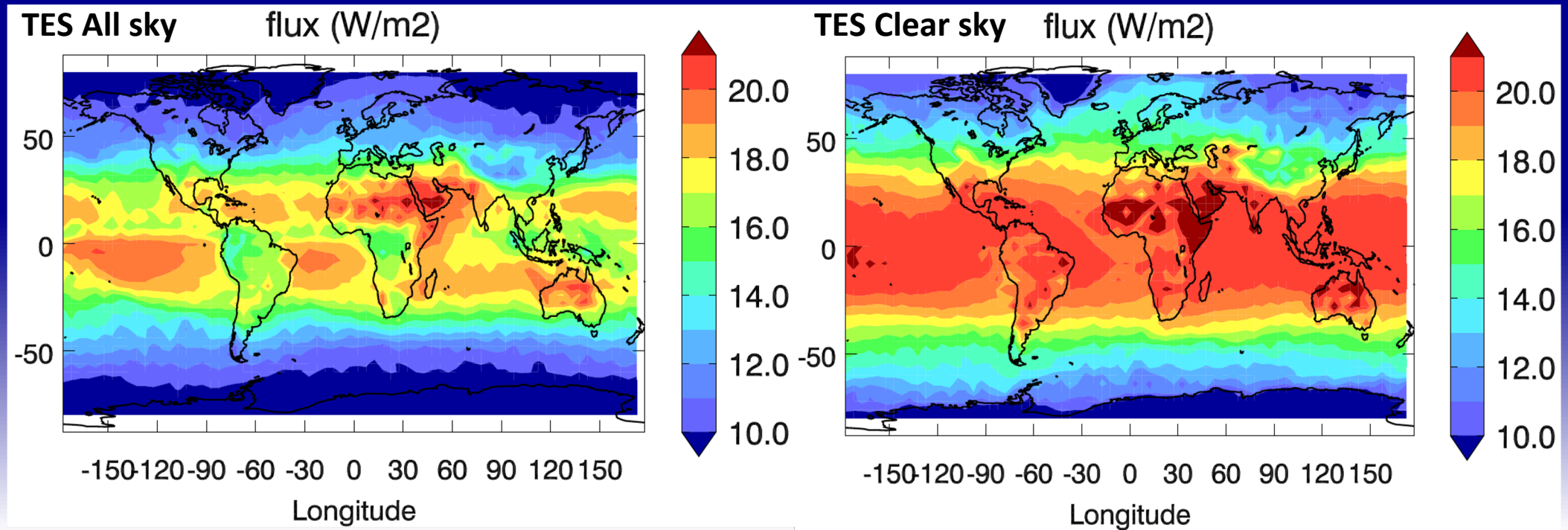


Wallington T J et al. PNAS 2010;107:E178-E179

- Tropospheric ozone (O_3) is a GHG.
- Increases in tropospheric O_3 from pre-industrial to present day add radiative forcing (RF) to the climate.
- The chemical-climate model estimated radiative forcing (RF) range widely from +0.2 to +0.6 Wm^{-2}.
- ~80% of tropospheric O_3 RF is in longwave (rest is shortwave).
- 97% of the O_3 longwave absorption is in the 9.6 µm band [Rothman et al., 1987].

Motivations:

- TES, IASI, AIRS, CrIS and models provides 9.6-µm O_3 band flux and flux sensitivity (e.g. IRK)
- O_3 GHG effect is more unevenly distributed than long-lived GHG gases
- How do modeled TOA fluxes compare to the observations?
- Biases in model O_3, water vapor, and temperature are sources of uncertainties in O_3 RF.
- Benchmarking present day ozone band flux is the first step to understand model divergence in ozone RF.



Flux and IRK (Instantaneous Radiative Kernel)

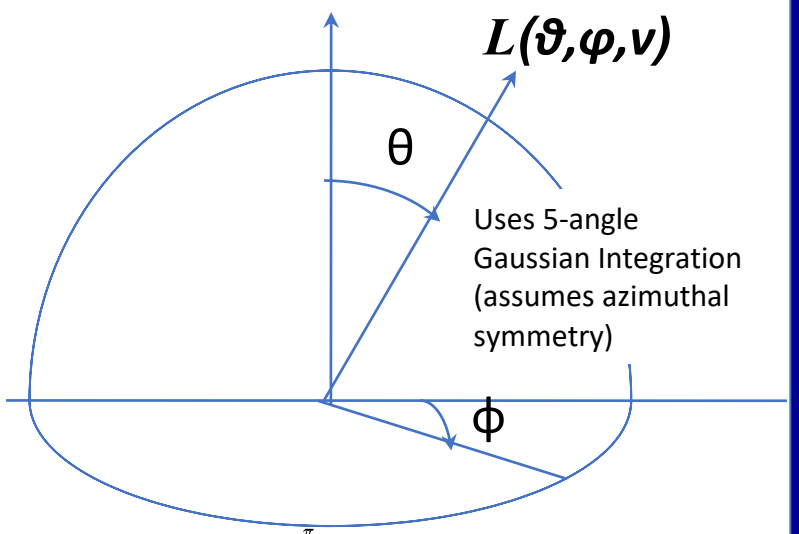
TES:

Worden et al., 2011

IASI:

Doniki et al., ACP, 2015

- Ozone Band TOA Flux (W/m^2)
- IRK (e.g. $W/m^2/ppb$)
- Tropospheric O_3 longwave radiative effect (LWRE, W/m^2)

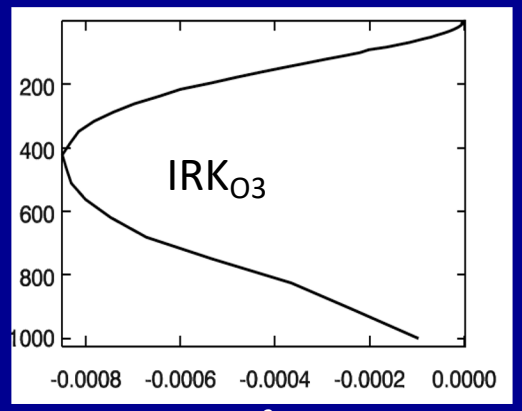


$$F_{TOA} = \int dv \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L_v(\theta)\cos\theta\sin\theta\, d\theta\, d\phi$$

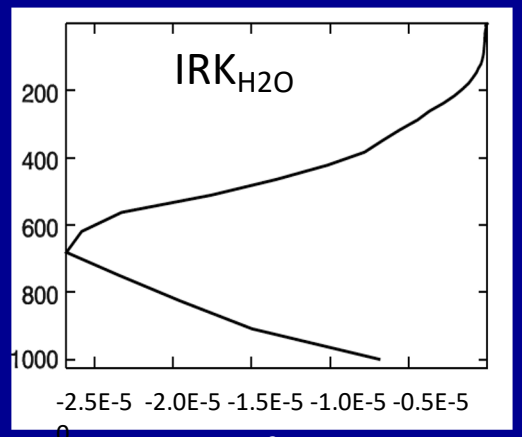
$$IRK = \frac{\partial F_{TOA}}{\partial q_l}$$

q_l (z): O_3, H_2O, T_a, *etc.*

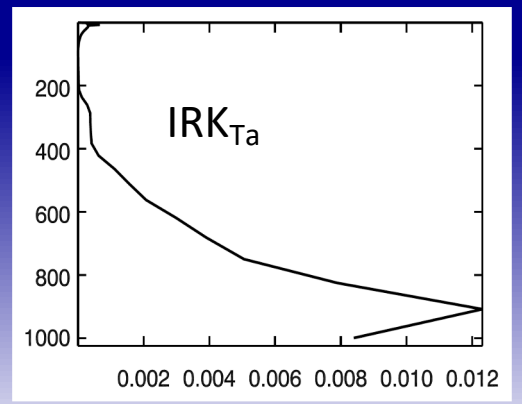
$$LWRE = \Delta F_{TOA} = \sum_{l=surface}^{tropopause} \left(\frac{\partial F_{TOA}}{\partial q_l}\right) q_l$$



$W/m^2/ppb$



$W/m^2/ppm$



$W/m^2//K$

The history of the studies used Instantaneous Radiative Kernel (IRK)

TES:

Worden et al., 2011

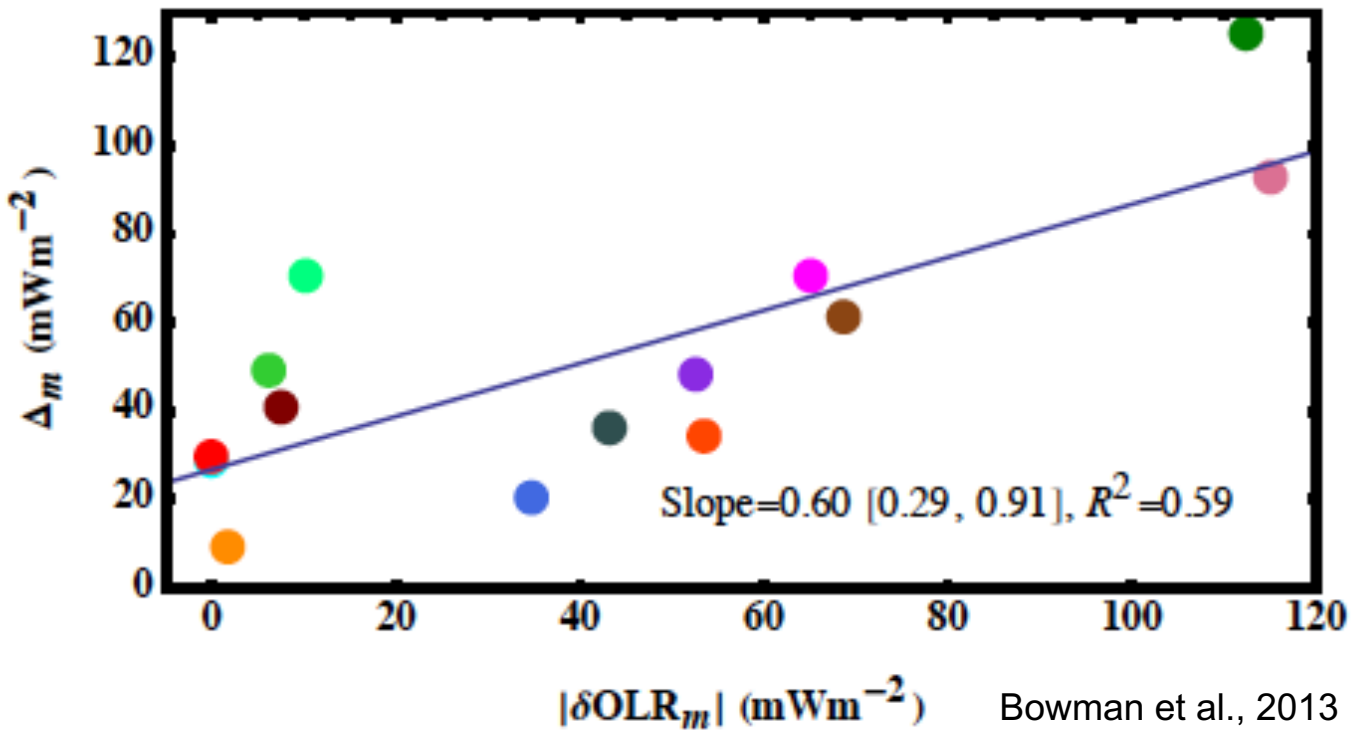
Aghedo et al., 2011

Bowman et al., 2013

Kuai et al., 2017

IASI:

Doniki et al., ACP, 2015

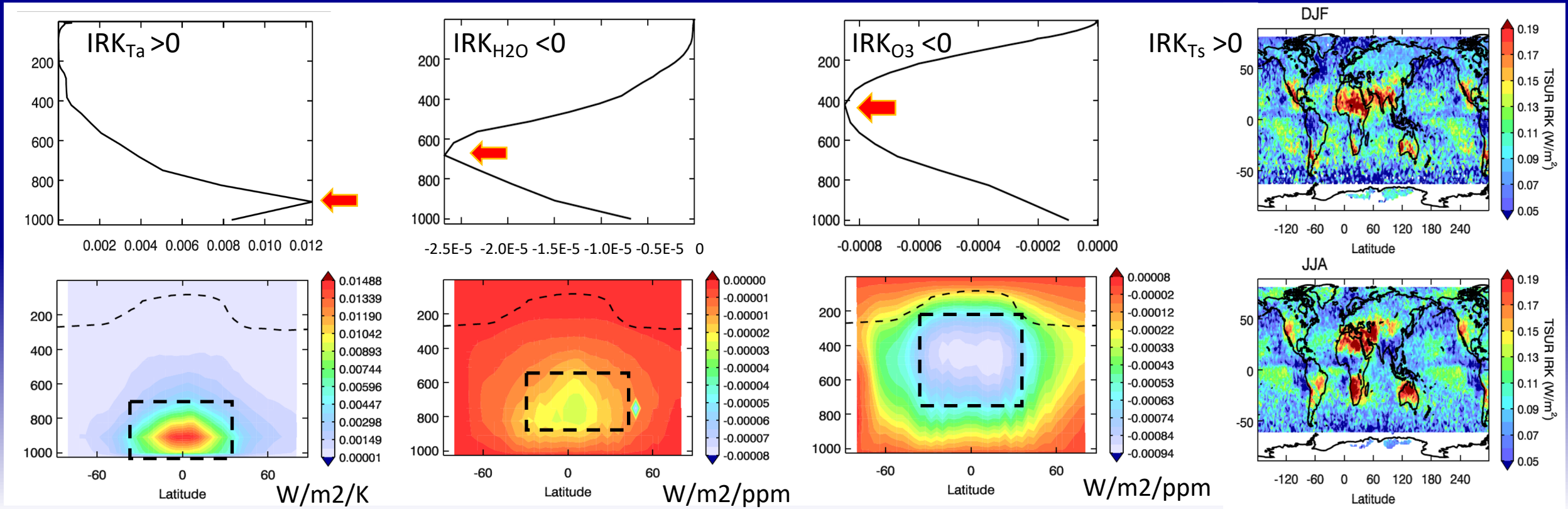


Bowman et al., 2013

Global patterns (Clear Sky) For O_3, H_2O, and T IRKs

- The bias at the regions with large IRKs would contribute more errors to the flux than other places.
- All kernels are large at low latitudes and decrease to high latitude.

- The TOA flux is most sensitive to
  - tropical lower troposphere for temperature (~900 hPa) & water vapor (~700 hPa)
  - Tropical mid-tropospheric O_3 (~400 hPa)



A FUNDAMENTAL EQUATION:

Instantaneous Radiative Kernel (IRK): $\frac{\partial F_{TOA}}{\partial q}$ e.g. $\frac{\partial F_{TOA}}{\partial O_3}$

TOA Flux bias

$$\Delta F_{TOA} = \frac{\partial F_{TOA}}{\partial O_3}\Delta O_3 + \frac{\partial F_{TOA}}{\partial T_{sur}}\Delta T_{sur} + \frac{\partial F_{TOA}}{\partial T_{atm}}\Delta T_{atm} + \frac{\partial F_{TOA}}{\partial H_2O}\Delta H_2O + r_s$$

9.6 µm band flux change | O_3 | Surface temperature | Atmos. temperature | Water vapor | residual

Model bias

Chemistry-Climate Model Initiative (CCMI) models & reanalysis

		Model	CCMI runs		
1	CCCma	CMAM	refC1	r1i1p1	v1
2	ETH-PMOD	SOCOL3	refC1	r1i1p1	v1
3	GSFC	GEOSCCM	refC1	r1i1p1	v1
4	MESSy	EMAC-L47MA	refC1	r1i1p1	v1
5	MESSy	EMAC-L90MA	refC1	r1i1p1	v1
6	MRI	MRI-ESM1r1	refC1	r1i1p1	v1
7	GFDL/NOAA	AM3	-	-	-
8	NCAR	CESM	-	-	-
	Reanalysis	ERA-Interim TCR-1	-	-	-

refC1:

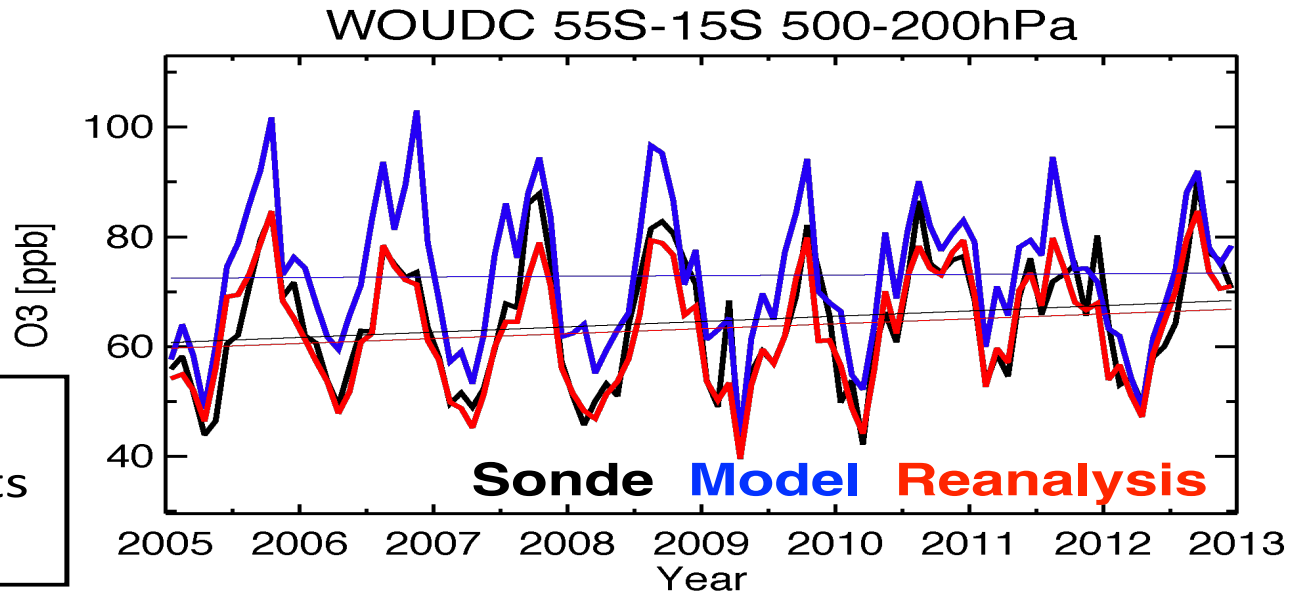
- uses state-of-knowledge historic forcing
- observed sea surface conditions
- the models simulate the recent past (1960–2010).
- The models are free-running

- Model inter-comparison exercises
- ACCMIP follow up
- Coordinate model comparison and evaluation
- Associate modeling activities
- In support of the upcoming IPCC
- ERA-Interim: physical variable
- TCR-1: O3

Tropospheric Chemistry Reanalysis (TCR-1)

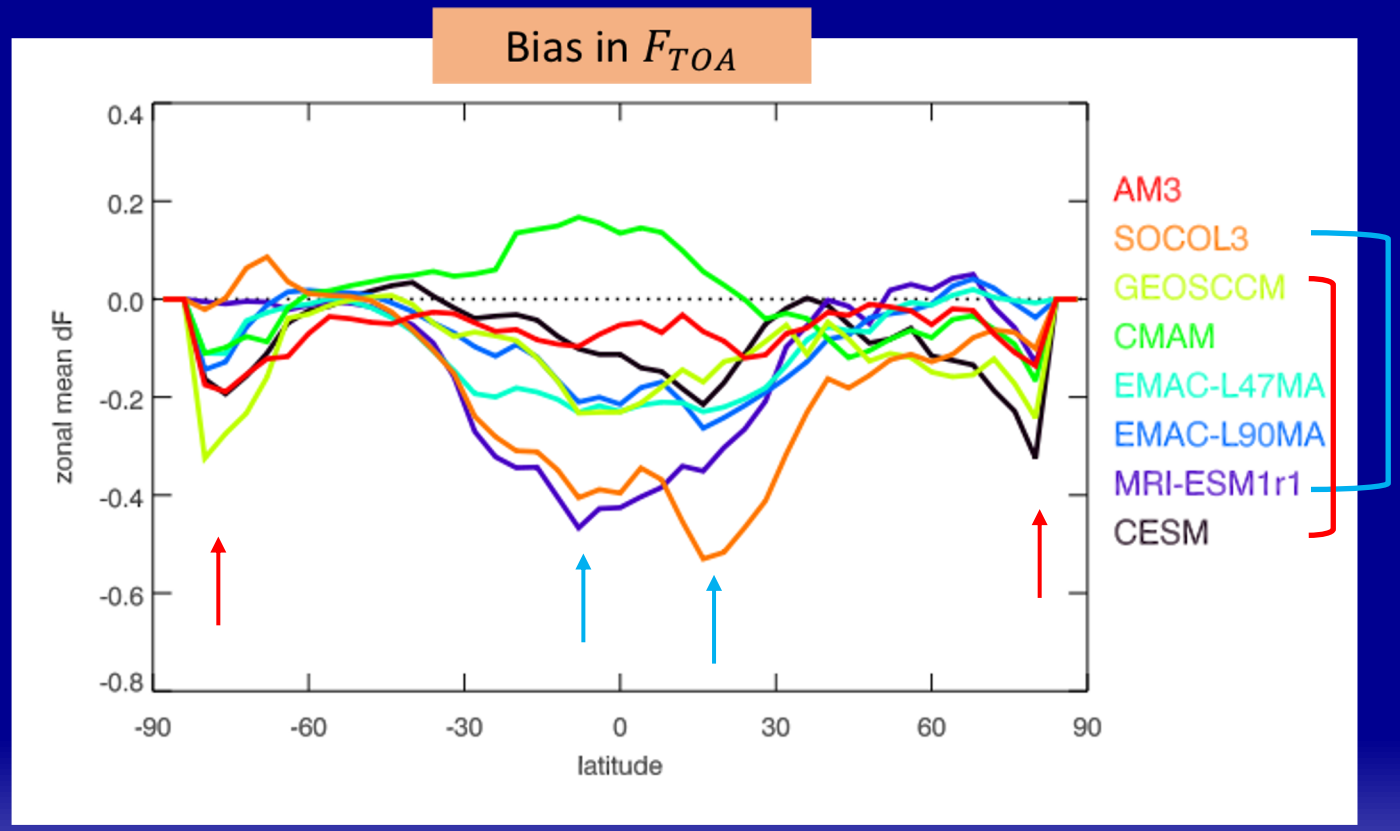
Assimilation scheme	Ensemble Kalman filter, 32 members
Forecast model	MIROC-Chem, 92 species & 262 reactions
State vector	NOx & CO emissions, lightning NOx, 35 chemical species
Assimilated data	OMI, SCIAMACHY, GOME-2 NO_2 (DOMINO2), TES O_3 (v6), MOPITT CO (v7 NIR), MLS O_3,HNO_3 (v4.2)
A priori emissions	EDGAR v4.2, GFED v3.1, GEIA
Period	2005-2017
Resolution	Horizontal: 2.8°, Vertical: 32 layers to 4 hPa

Multi-constituent, multi-satellite data assimilation provides comprehensive constraints on the entire tropospheric profile of ozone.



$$\Delta F_{TOA} = \sum_i \Delta F_{TOA}^{var_i}$$

Total Toa Flux Bias:
Significantly Different Between Models



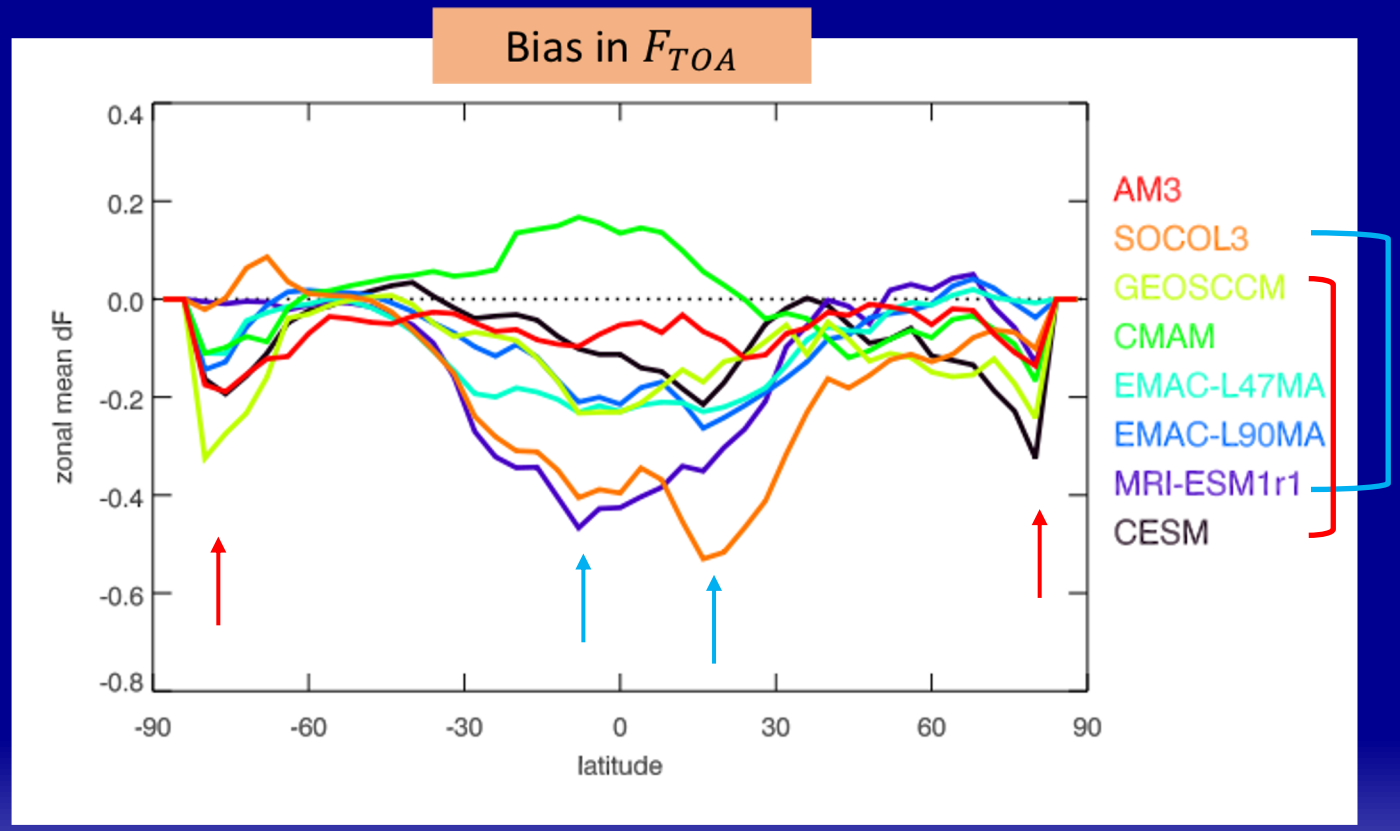
- Major biases in tropics and subtropics for most models.
  - Tropics: large negative bias except CMAM (positive bias).
  - SOCOL3 and MRI-EMS1r1 both have the largest negative biases (-0.4 to -0.6 W/m^2) between ±30°.
- Secondary peaks at polar regions, e.g. GEOSCCM and CESM

Implications:

- Model's atmospheres are more opaque than reanalysis atmosphere at 9.6 micron ozone band
- On average of 0.2 W/m^2 less emitted to the TOA.
- A opaque atmosphere will have a weaker IRK than transparent atmosphere.

TOA FLUX BIAS:
Significantly different between models

$$\Delta F_{TOA} = \sum_i \Delta F_{TOA}^{var_i}$$



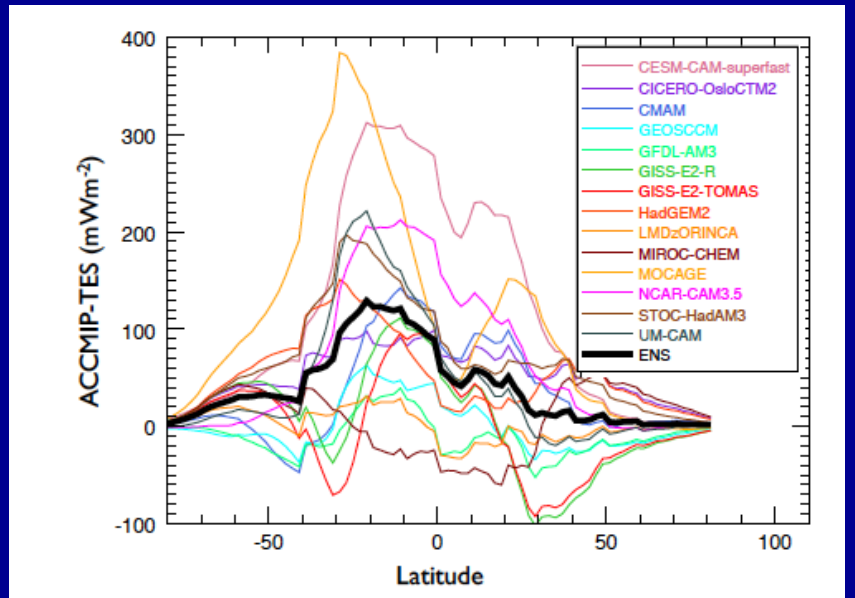
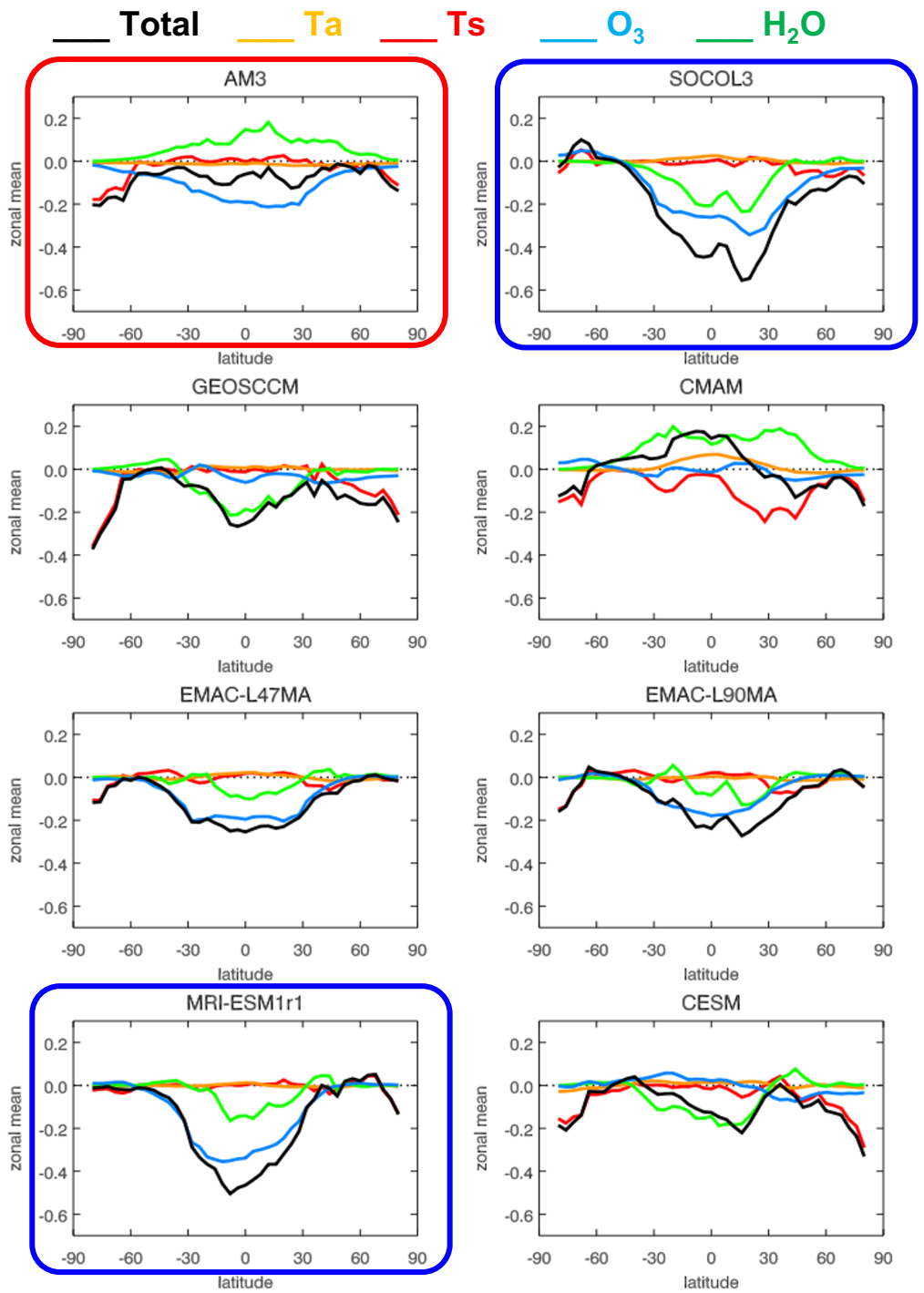


Fig. 5. Zonal δOLR_m^j between ACCMIP and TES from 2005-2010, limited to 80° S–80° N, and is based on a TES diagnosed chemical tropopause ($q = 150$ ppb). The "ENS" refers to the ACCMIP ensemble average, $\overline{\delta OLR}_j$. Positive values indicate model ozone is biased low relative to TES ozone and consequently the model OLR is biased high relative to TES OLR.

Bowman et al., 2013

4 components
Current CCMI project

Only Ozone component
Past ACCMIP project



Flux bias attribution:

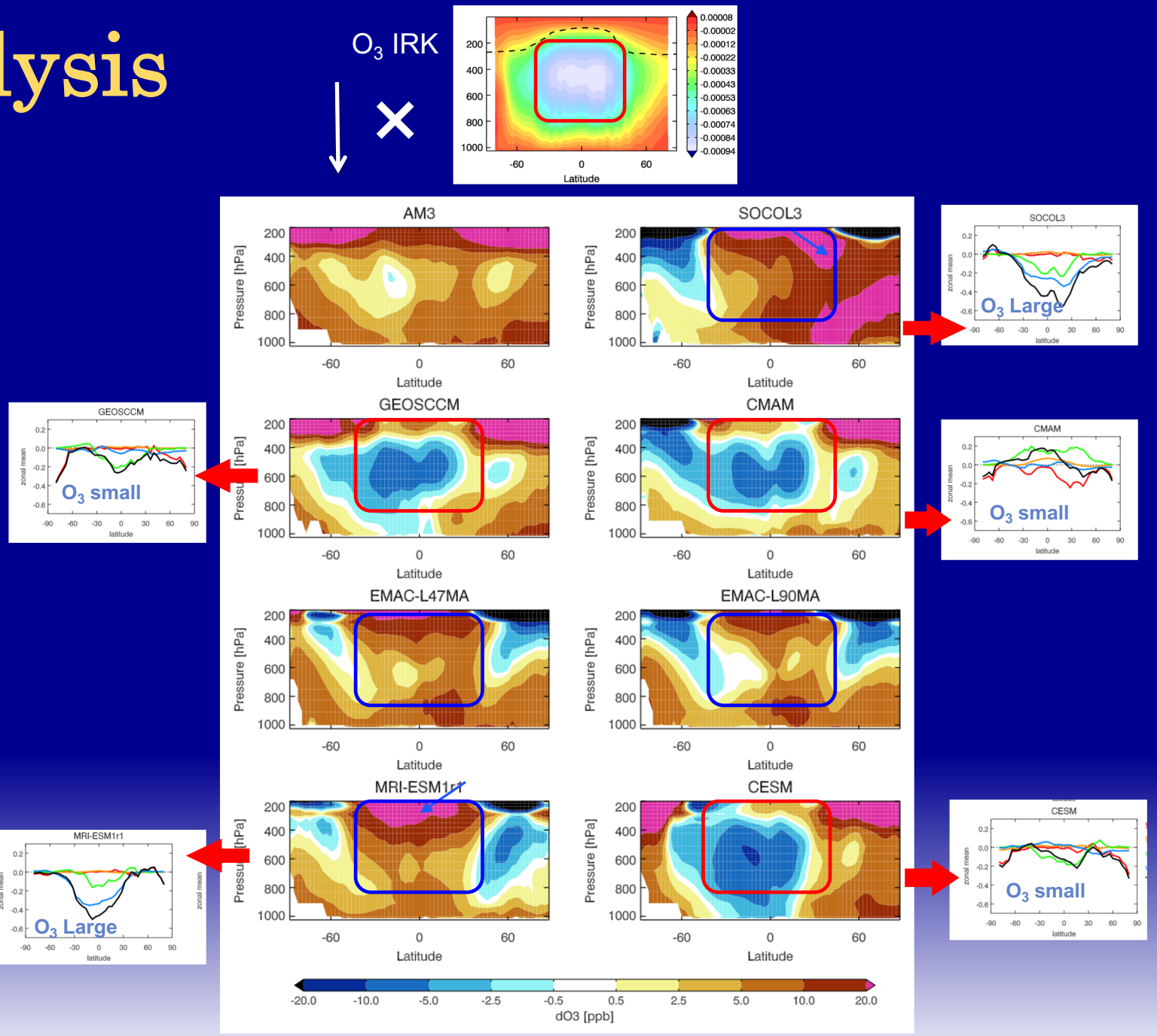
Color means bias :

- large at Polar region
- large at Tropical region
- Small contribution

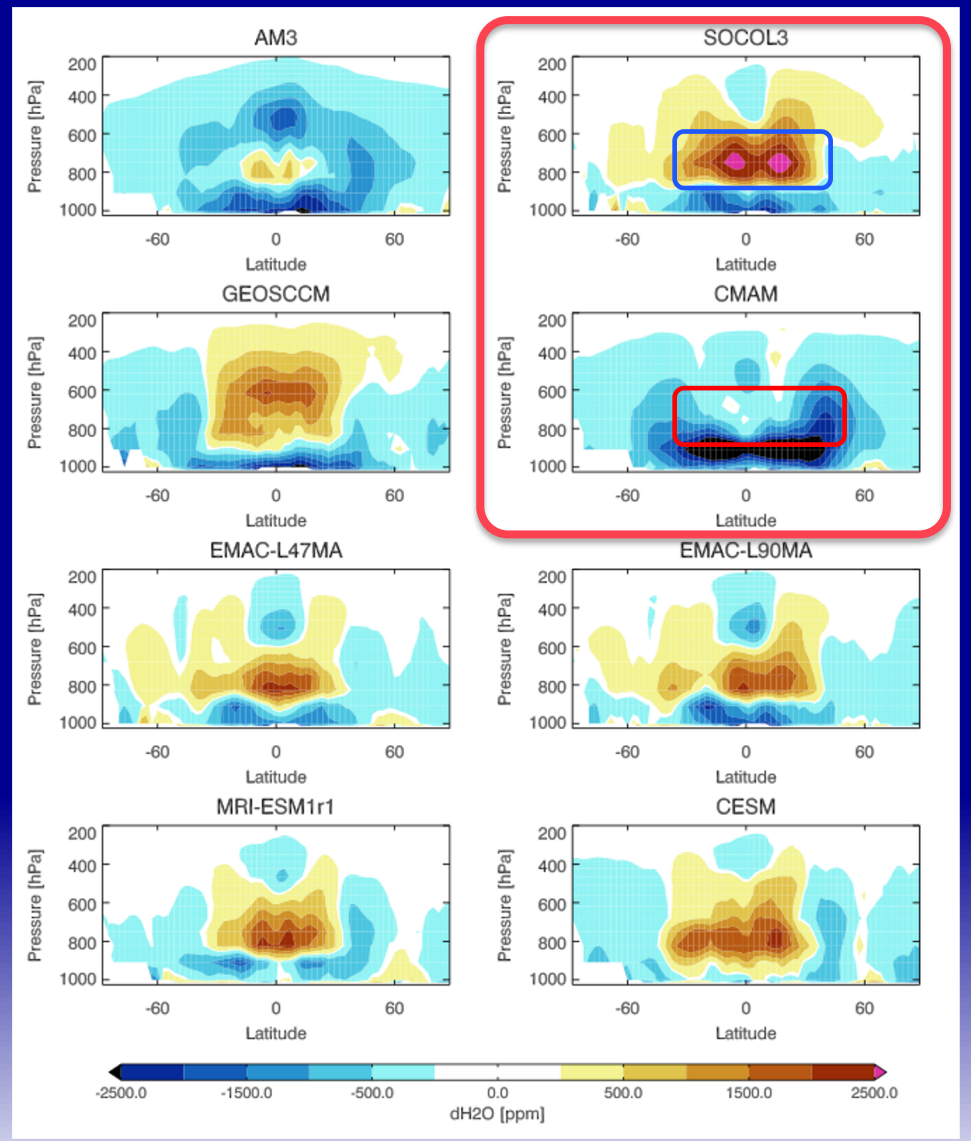
Model	Contribution rank			
	1	2	3	4
AM3	O3	H2O	Ts	Ta
SOCOL3	O3	H2O	Ts	Ta
GEOSCCM	Ts	H2O	O3	Ta
CMAM	Ts/Ts	H2O	O3	Ta
EMAC-L47MA	O3	H2O	Ts	Ta
EMAC-L90MA	O3	H2O	Ts	Ta
MRI-ESM1r1	O3	H2O	Ts	Ta
CESM	H2O	Ts	O3	Ta

O_3 bias to reanalysis

- Dominant region: 200-800 hPa, 45S – 45N
- GEOCCM, CMAM, and CESM have similar patterns
  - Low-high pattern
  - ⇒ small biases to TOA fluxes
- SOCOL3 & MRI-ESM1r1
  - large positive bias over tropical upper troposphere
  - add additional bias in tropics

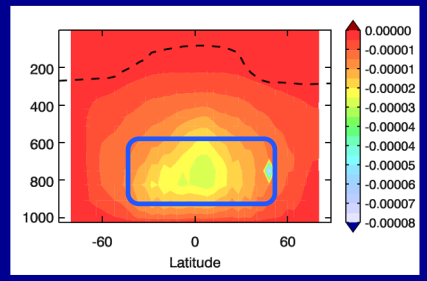


H_2O bias to reanalysis

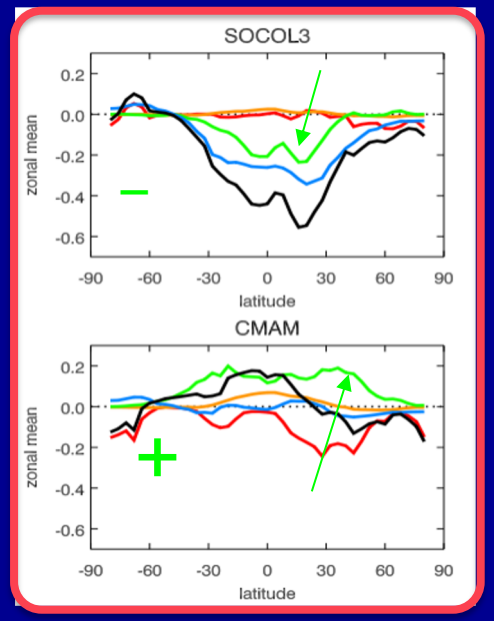


×

H_2O IRK

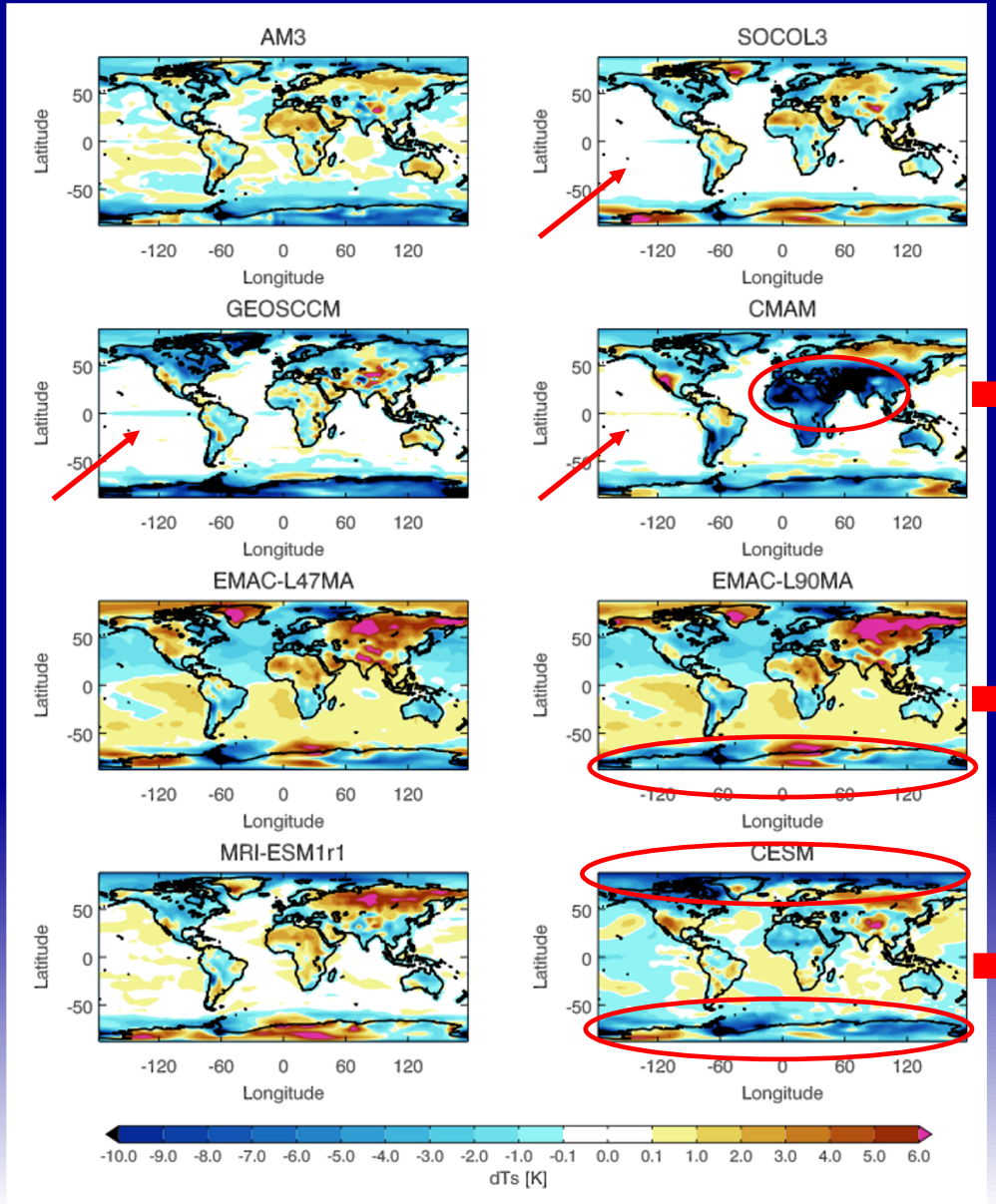


=

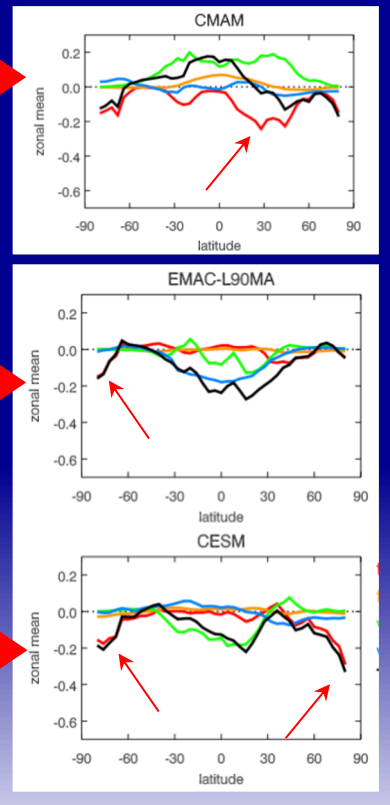


- Dominant region:
  - 900 - 600 hPa, 30S – 30N
  - tropical and lower/middle troposphere region ⇒ Large TOA flux bias
- SOCOL3:
  - strongest positive bias
  - tropical 800~600 hPa
  - ⇒ negative TOA flux bias
- CMAM:
  - strongest negative bias
  - ⇒ positive TOA flux bias

Ts bias to reanalysis

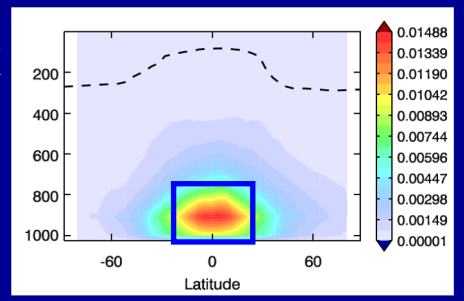


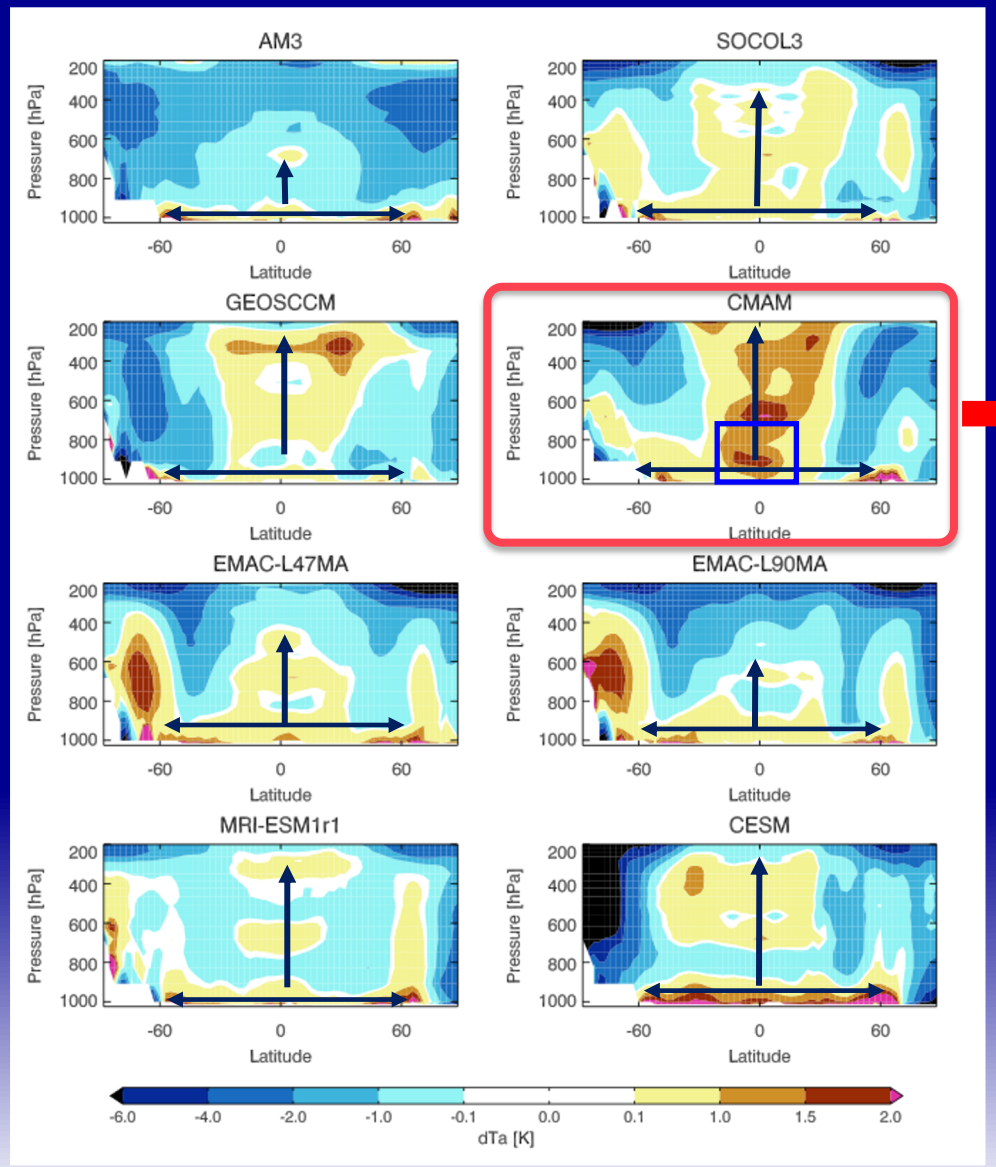
× IRK

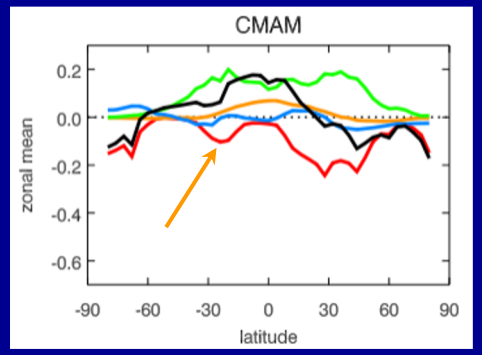


- Localized bias ⇒ cancellation
- SOCOL3, GEOSCCM, CMAM:
  - Small differences in global SST
  - Except polar sea.
- Large differences over land, e.g.
  - CMAM at Middle East and N. Africa, ⇒ flux bias
- AM3, GEOSCCM, CMAM, two EMAC, CESM:
  - Zonally constantly underestimate at polar region ⇒ flux bias

Ta bias to reanalysis







- Symmetric about equator
- Lower troposphere
  - all model overestimate Ta.
- CMAM:
  - overestimate Ta
  - tropics entire troposphere
  - strong at lower troposphere
  - ⇒ flux bias in tropics
- Not contribute much to flux bias in other models

Conclusions

- We expanded IRK for O_3 to H_2O, Ta, and Ts.
- We for the first time used chemical reanalysis data for the model bias
- We demonstrate a method to benchmark the model TOA fluxes with the 9.6-μm O_3 band satellite observations
  - Where and which variables in the model bias ➔ flux bias
  - Most model atmosphere: more opaque than reanalysis atmosphere
  - AM3 has the smallest flux bias but right for wrong reason.
  - SOCOL3 and MRI-ESM1r1 have large potential to improve their fluxes.
  - Both ozone and water vapor contribute more biases to fluxes than temperature

Outlooking:

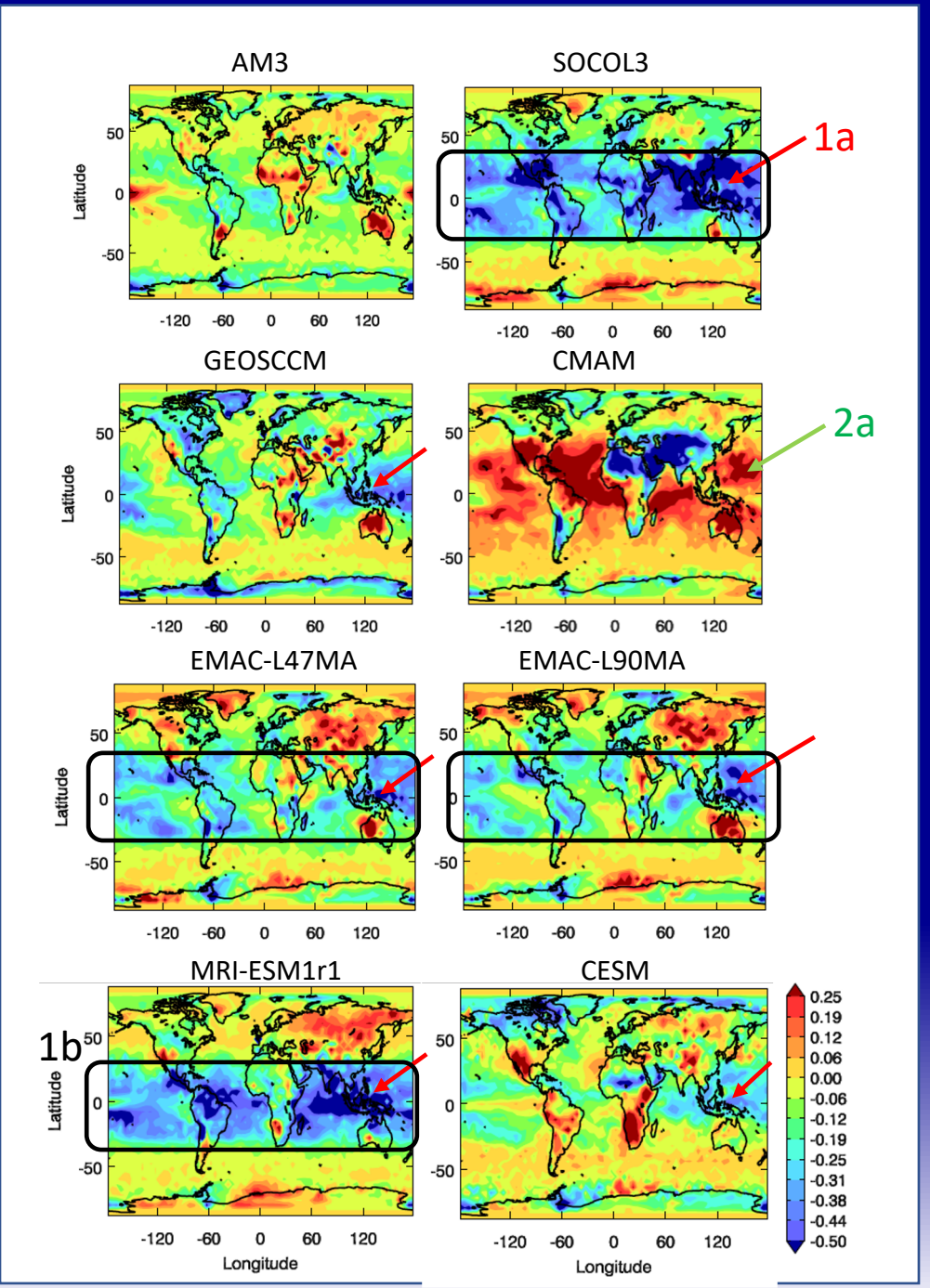
- Adding AIRS/CrIS IRK products will extend the analysis to decadal scales.
- The similar study could be applied to any other GHG, i.e. CO_2 and CH_4.

Acknowledgement

IGAC/SPARC Chemistry-Climate Model Initiative COMMITTEE

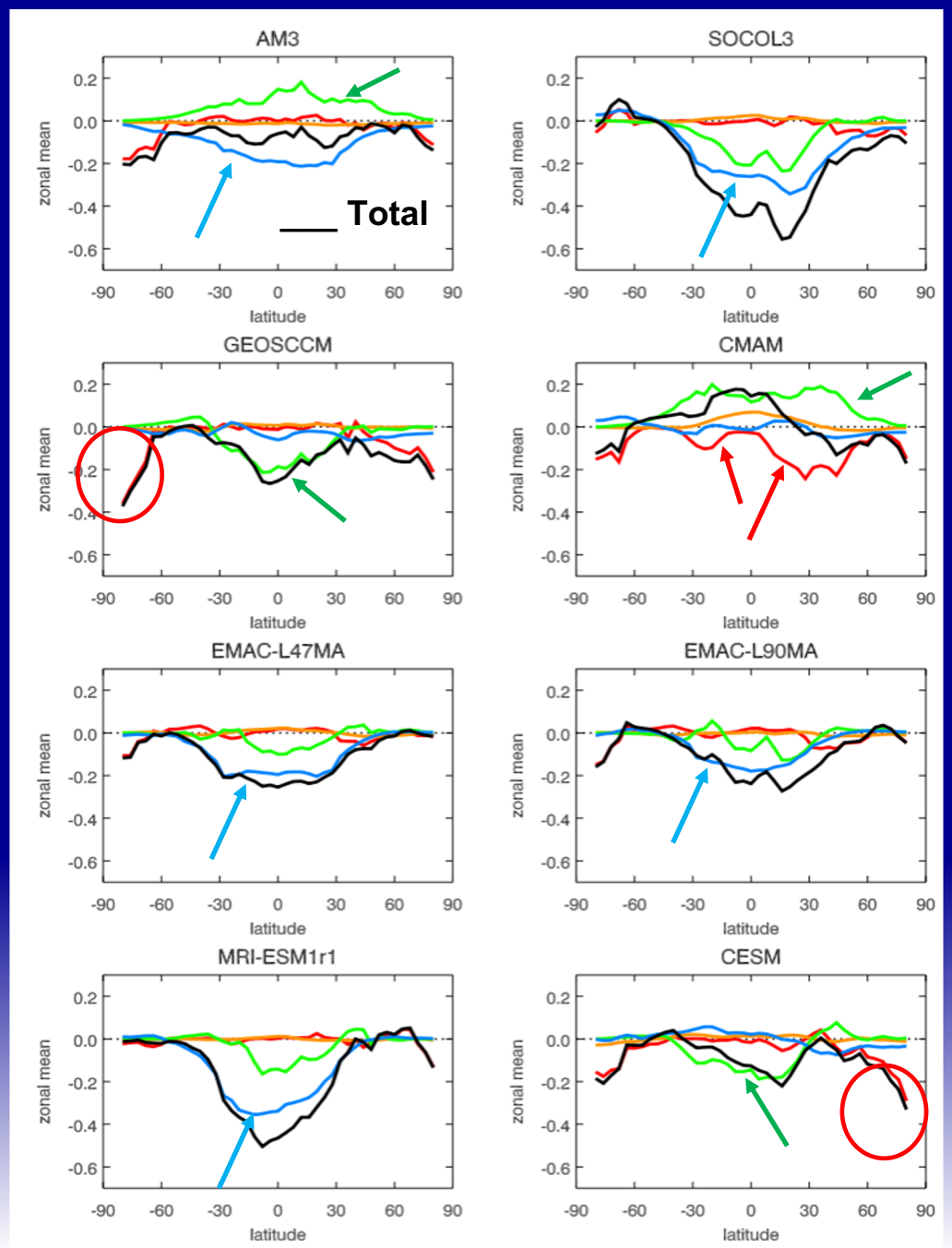
Funded by NASA ROSES AuraST

Thank you!



Spatial distribution of F_{TOA} BIAS: Expand To A Global View

1. Significant diversity in the spatial patterns in flux bias
2. SOCOL3, 2 EMAC, and MRI-ESM1r1 biased low at:
   a. the Indonesia warm pool region
   b. subtropical ocean
   c. ⇒ tropical negative biases in zonal flux
3. CMAM
   a. strong overestimates (-0.25 W/m2) over ocean
   b. ⇒ tropical positive biases in zonal flux
   c. N. Africa, Middle East and Asia biased low.
   d. ⇒ less overestimate than SH subtropics



Flux bias attribution:

- Ta: Generally small contributions for most models.

- Ts: commonly small contributions except
  - CMAM (large negative bias (-0.2 to -0.3 W/m2) in both subtropics) and polar region
  - Polar bias ⇒ flux bias: GEOSCCM, CESM (-0.3 W/m2).

- O_3 contributes to low latitudes
  - Strong and dominant in SOCOL3 and MRI-ESM1r1 at (-0.2 to -0.4 W/m2);
  - moderate in AM3 and both EMAC runs (-0.2 W/m2);
  - weaker in GEOSCCM, CMAM, and CESM.

- H_2O contribution mainly in low latitudes as O_3
  - Moderate in magnitude (~0.2 W/m^2) compare to O_3
  - AM3: biased high and balanced by biased low from O_3
  - AM3 has right answers for the wrong reasons.
  - CMAM: also bias high and partly balanced by biased low from Ts over both subtropics but not tropics.
  - Dominant sources for total bias in GEOSCCM and CESM