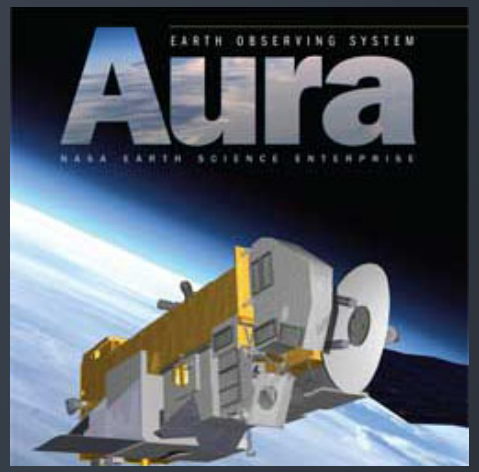
Jet Propulsion Laboratory
California Institute of Technology

Aura Science Team Meeting



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

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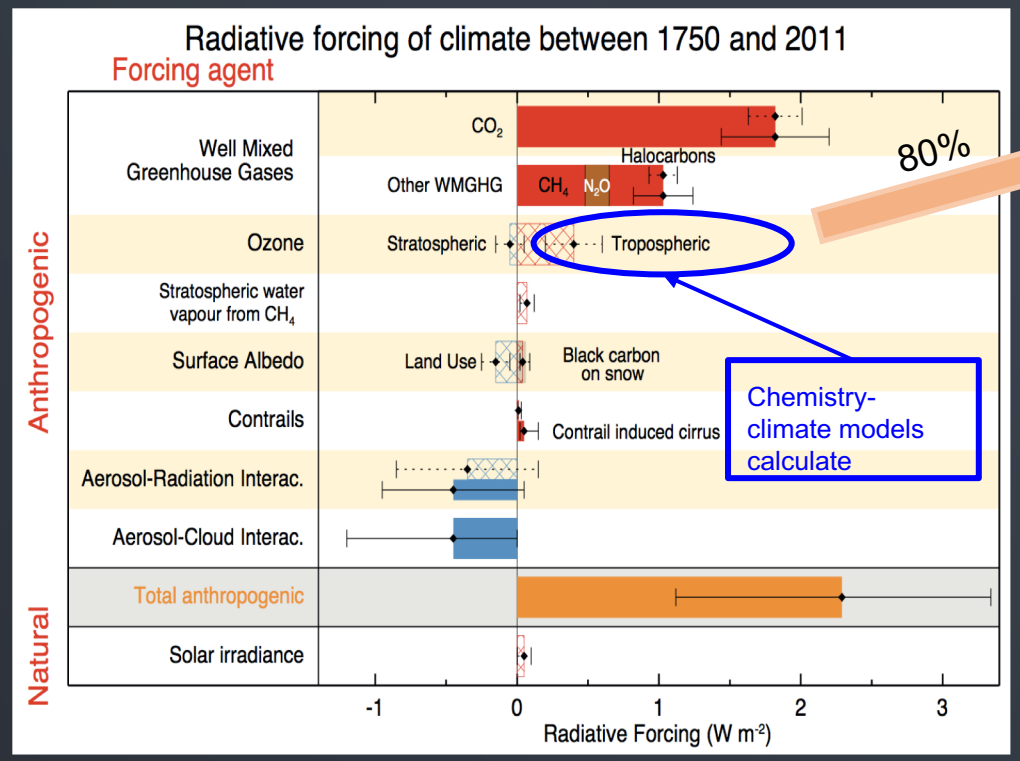
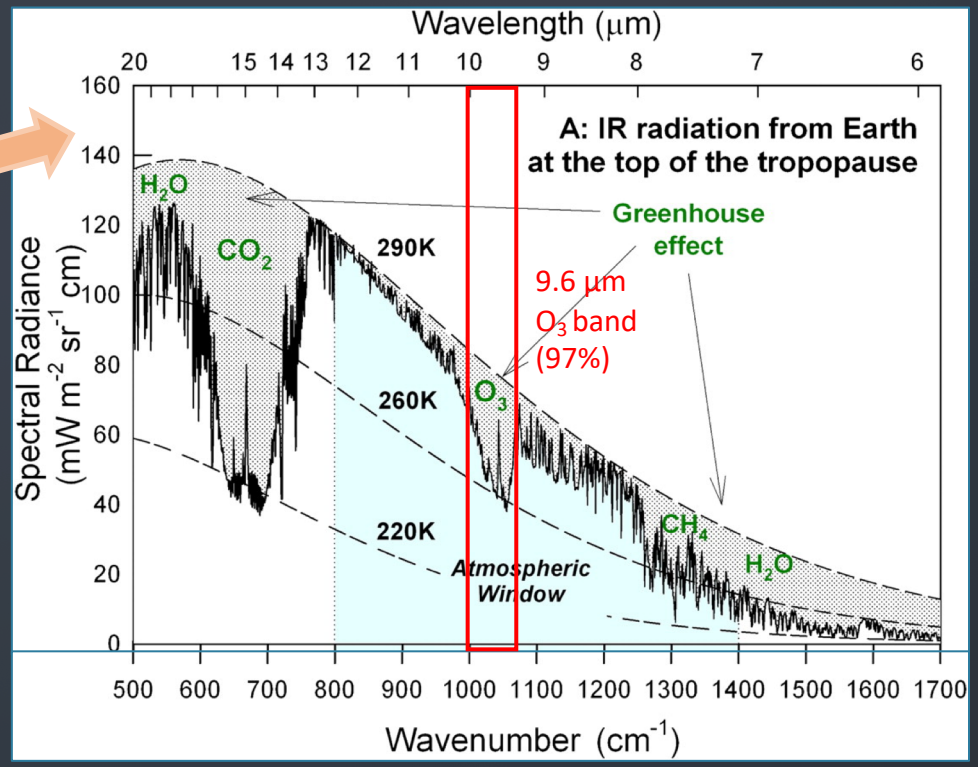
14. Freie Universität Berlin, Berlin, Germany

Kuai, L., et al., 2019.: Attribution of Chemistry-Climate Model Initiative (CCMI) ozone radiative flux bias from satellites, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-231, in review, 2019.

Tropospheric O_3 Radiative Forcing & 9.6 µm O_3 band



IPCC AR5, 2013

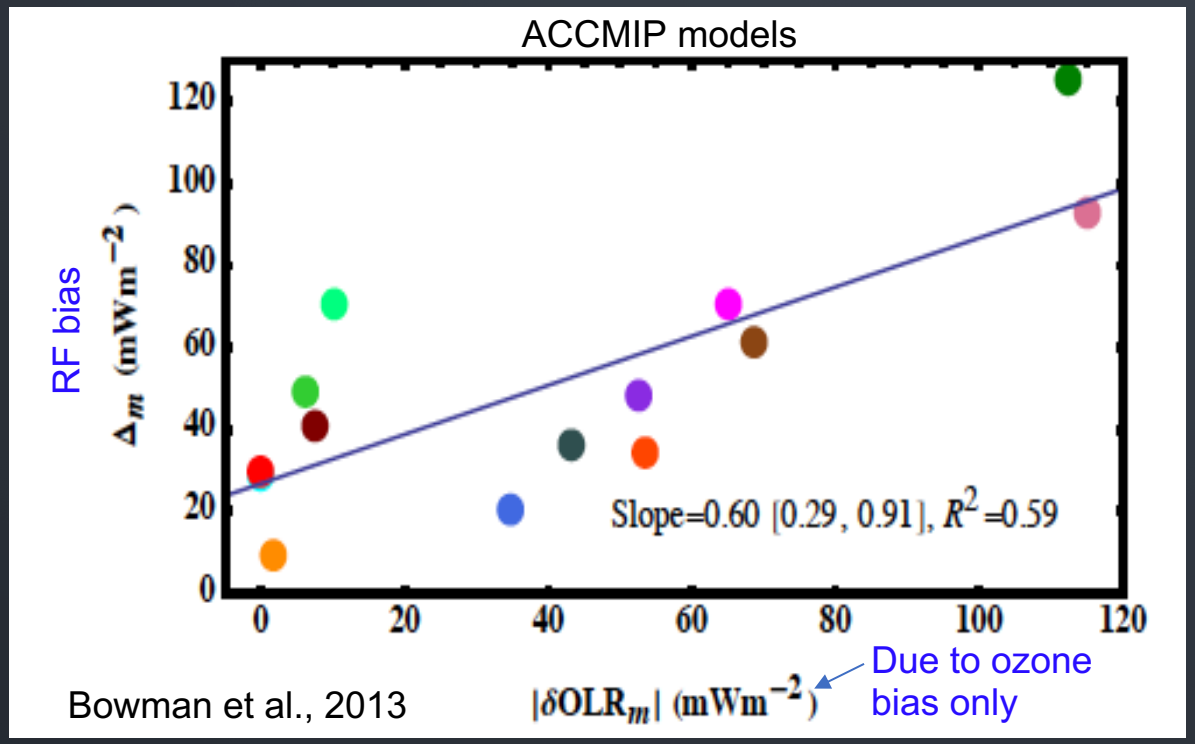


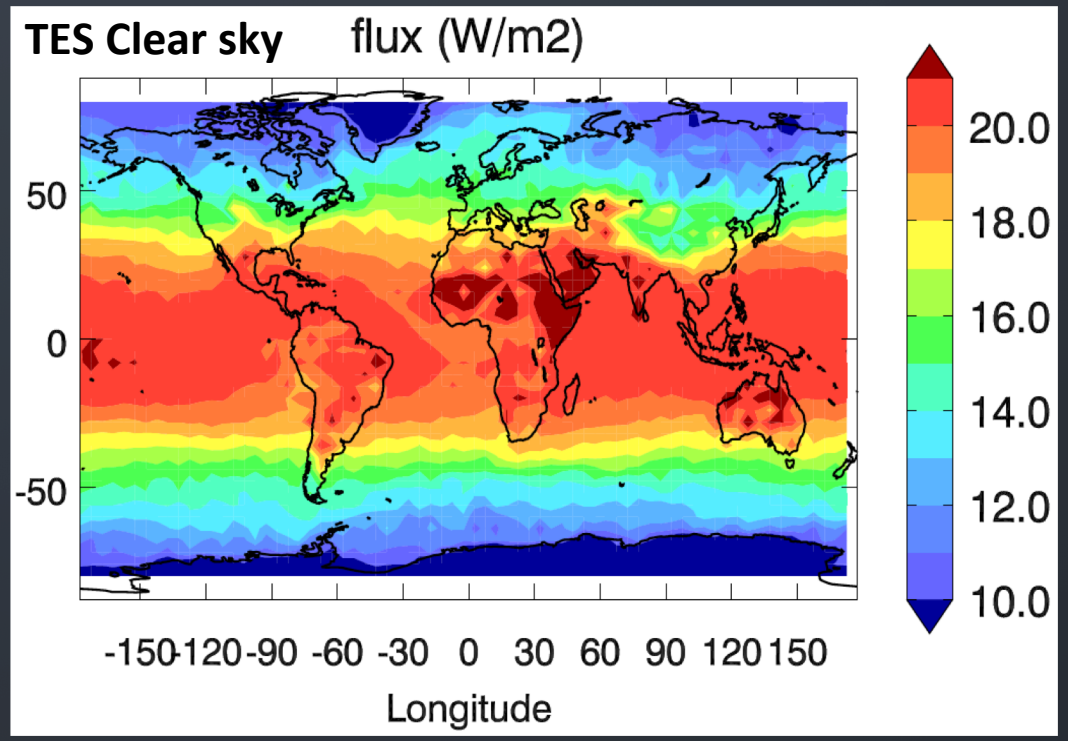
Wallington T J et al. PNAS 2010;107:E178-E179

- Tropospheric ozone (O_3) is the third GHG with large uncertainty of its radiative forcing (RF: +0.2 to +0.6 Wm^{-2}).
- ~80% of tropospheric O_3 RF is in longwave (rest is in shortwave).
- 97% of the O_3 longwave absorption is in the 9.6 µm band [Rothman et al., 1987].

Motivations:

- Tropospheric O_3 GHG effect is more unevenly distributed than long-lived GHG gases
- Model biases in ozone, water vapor, and temperature are the sources of uncertainties in 9.6 µm O_3 band radiative flux and RF.
- Investigate the relationship between the 9.6-µm flux bias and ozone RF in CCMI models.
- Quantify and attribute the 9.6-µm flux bias to ozone, water vapor, and temperature.





Ozone Instantaneous Radiative Kernel (IRK) & Ozone band TOA flux

TES:

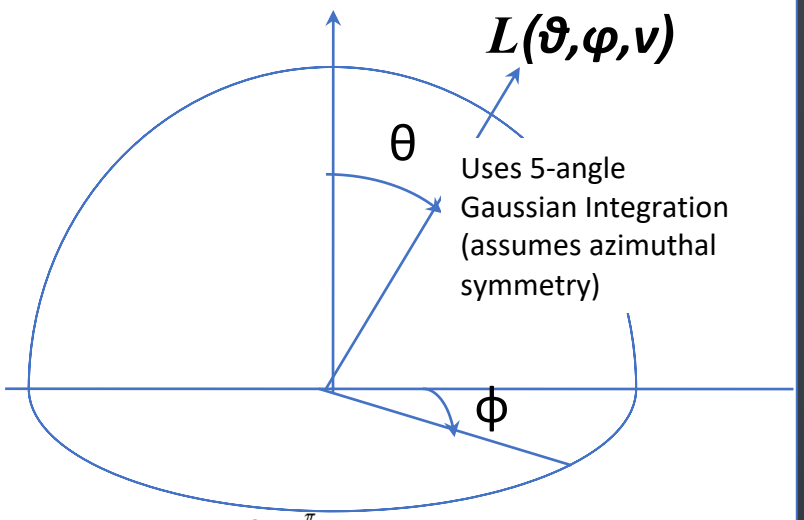
Worden et al., 2011

Kuai et al., 2017

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)

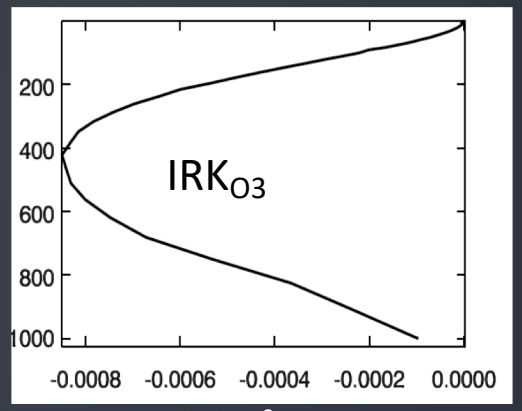


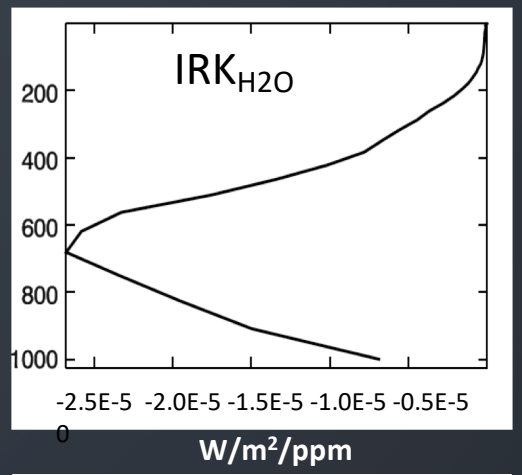
$$F_{TOA} = \int d\nu \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L_\nu(\theta) \cos\theta \sin\theta \, d\theta \, d\phi$$

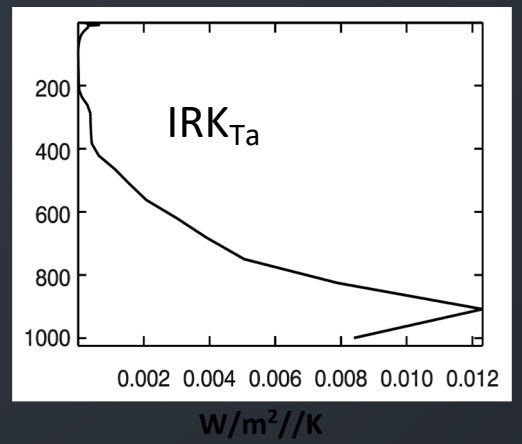
$$IRK = \frac{\partial F_{TOA}}{\partial q_l}$$

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

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







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

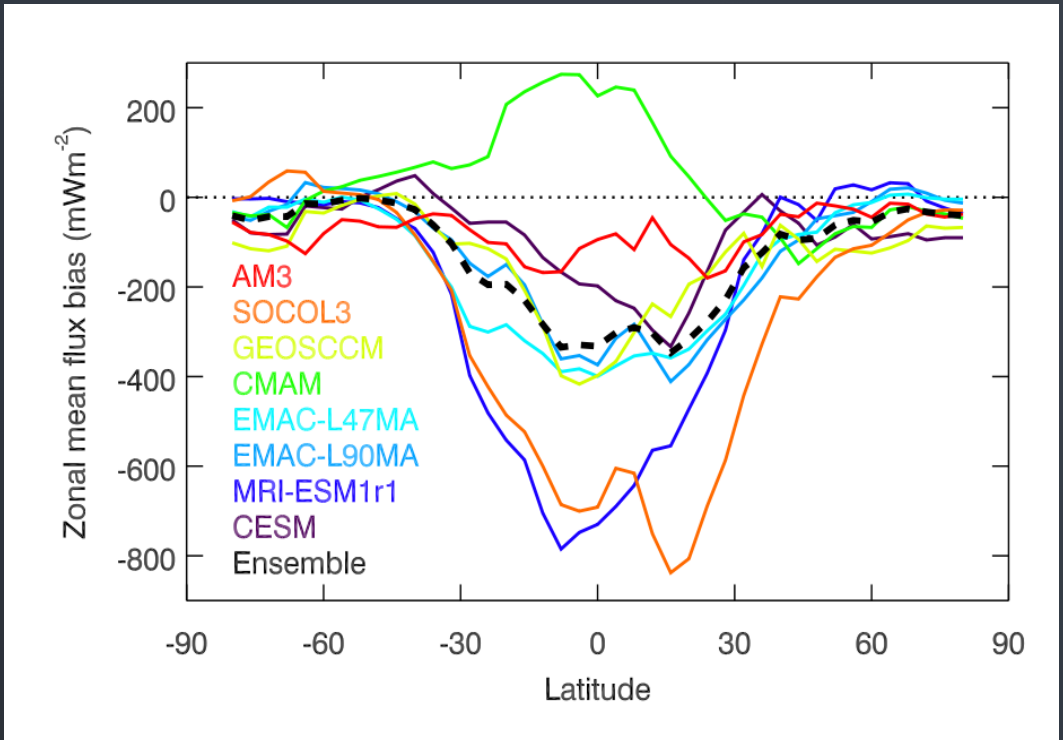
Model bias = model – reanalysis

O_3: tropospheric composition reanalysis (TES+MLS)

Ts, Ta, H_2O: ERA-Interim reanalysis

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

Total TOA Flux Bias: inter-model comparison

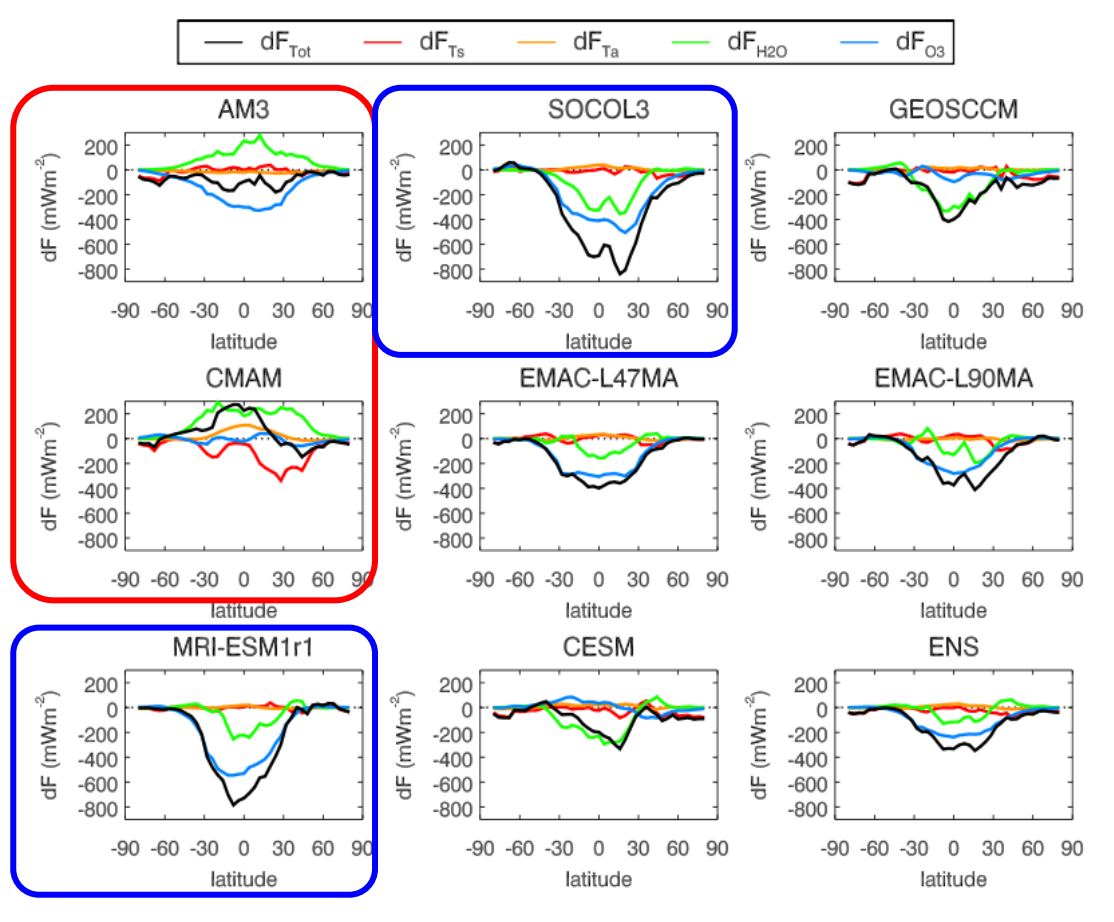


- Significant differences between the models
- Major biases in tropics and subtropics for most models.
  - Large negative bias except CMAM (positive bias).
  - SOCOL3 and MRI-EMS1r1 both have the larger negative biases (–400 to – 600 mW/m^2) than other models within ±30°.

Implications:

- The model ensemble emitted 133 mW/m^2 less ozone band flux globally.
- Model's atmospheres are too opaque than the atmosphere for the reanalysis data
- An opaque atmosphere will too weaker IRKs than a transparent atmosphere.

Attribution



Red: > 30 mW/m2
Gray < 30 mW/m2

Quantification (mWm^{-2})

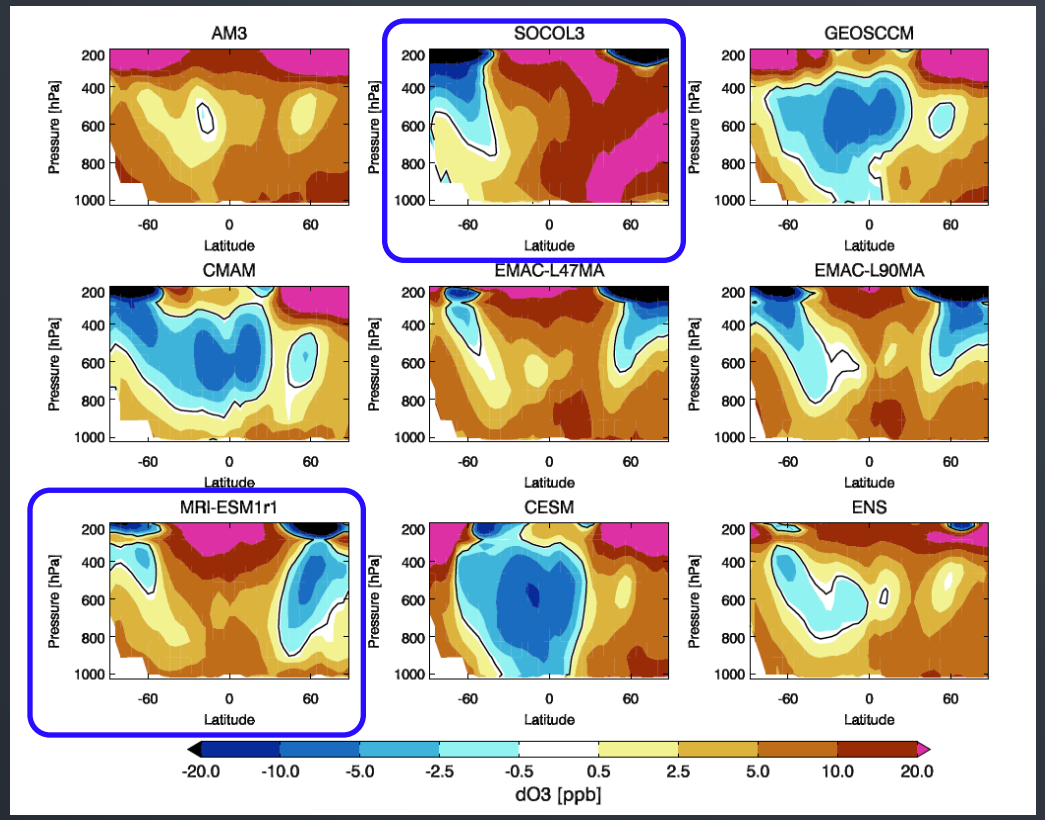
Models	$\overline{\delta F}$	$\overline{\delta F_{O_3}}$	$\overline{\delta F_{H_2O}}$	$\overline{\delta F_{T_s}}$	$\overline{\delta F_{T_a}}$
AM3	**–78.1 (46.2)**	–140 (117.1)	87.7 (76.4)	–11.7 (30.0)	–14.2 (7.8)
SOCOL3	**–283.6 (290.0)**	–183.5 (187.5)	–94.5 (124.6)	–11.6 (22.3)	5.9 (13.9)
GEOSCCM	–139.9 (112.0)	**–33.5 (28.0)**	–80.3 (120.9)	–27.2(38.5)	1.1 (12.0)
CMAM	**42.9 (118.5)**	**–7.3 (28.8)**	127.9 (100.7)	**–100.2 (93.3)**	**22.5 (40.5)**
EMAC-L47MA	–154.4 (150.0)	–125.9 (128.2)	**–28 (56.1)**	–3.3 (27.3)	2.9 (14.8)
EMAC-L90MA	–130.2 (142.7)	–86.9 (108.7)	**–30.5 (63.0)**	–8.7 (36.0)	–4.1 (6.6)
MRI-ESM1r1	**–228.5 (281.8)**	–182 (213.7)	–43.6(86.6)	–2.7 (17.9)	–0.1 (6.8)
CESM	–91.1 (89.0)	**3.3 (43.8)**	–69.7 (113.0)	–31.1 (33.9)	6.4 (13.9)
Ensemble	**–132.9 (98)**	**–94.5 (75)**	**–16.4 (81)**	**–24.6 (32)**	**2.6 (10)**

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

Vertical-resolved Radiative bias by O_3

O_3 1
H_2O 2
Ta 3
Ts 4

O_3 bias to TCR -1



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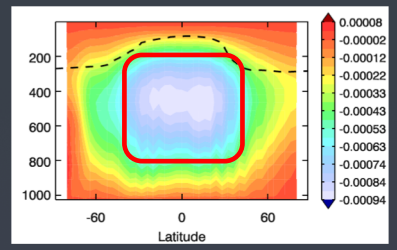
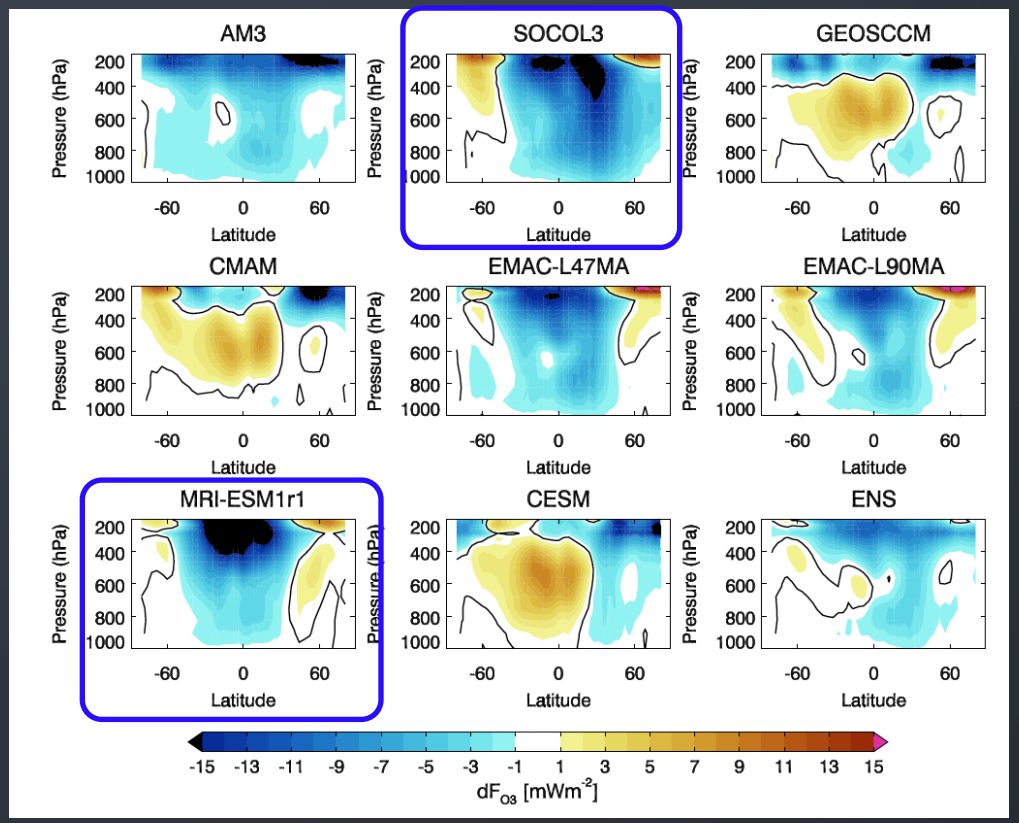


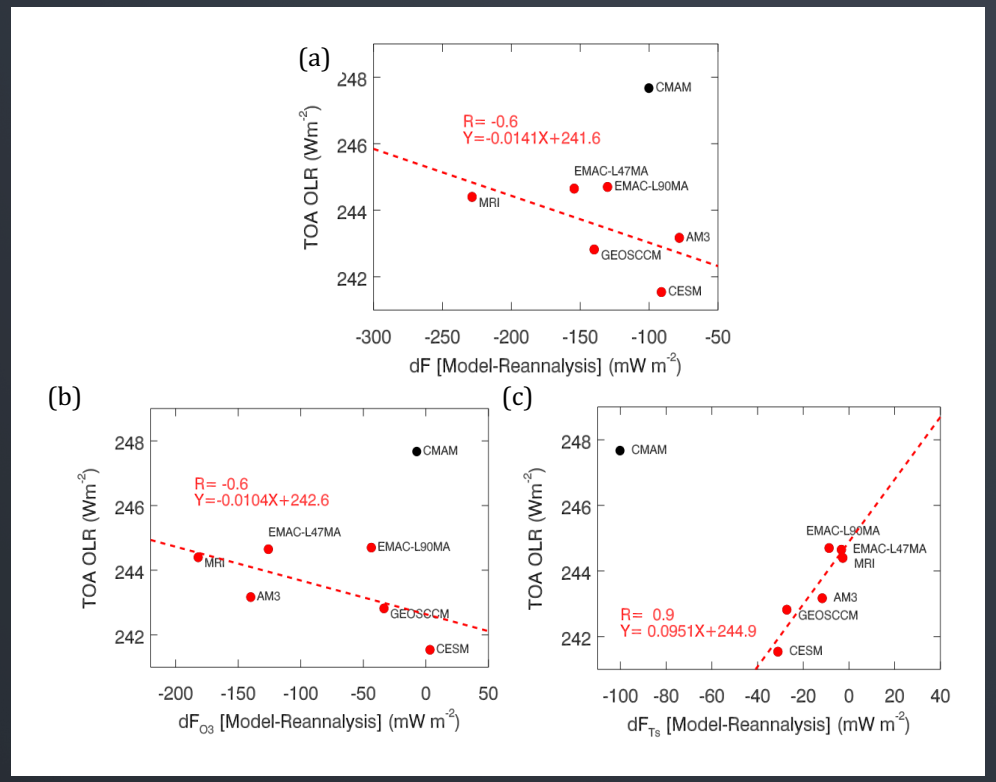
O_3 IRK

O_3 radiative bias



Kuai, L., et al., 2019.: Attribution of Chemistry-Climate Model Initiative (CCMI) ozone radiative flux bias from satellites, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-231, in review, 2019.

The correlation of the O_3 band flux biases to the model calculated broadband OLR



01 A strong anti-correlation between O_3 band flux bias and the model estimated broadband OLR (-0.6).

02 A similar anti-correlation between O_3 radiative bias and the model OLR (-0.6).

03 A strong correlation between Ts radiative bias and the model OLR (0.9).

04 No significant correlation between Ta radiative bias and OLR and between H_2O radiative bias and OLR.

Conclusions

- We expanded TES IRK for O_3 to IRK for H_2O, Ta, and Ts.
- We used new O_3 reanalysis data (tropospheric composition reanalysis) for the model biases
- We demonstrate a method to benchmark the model TOA fluxes with the 9.6-μm O_3 band satellite observations
  - O_3 and H_2O are the primary drivers for the flux bias
  - Most model atmosphere: more opaque than reanalysis atmosphere
  - AM3 seems to has the smallest flux bias but right for wrong reason.
  - SOCOL3 and MRI-ESM1r1 have large potential to improve their fluxes.
  - The strong anti-correlation between O_3 band flux bias and OLR suggests that radiative compensation between the 9.6-micron band and the other parts of the OLR.

Outlooking:

- Developing 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

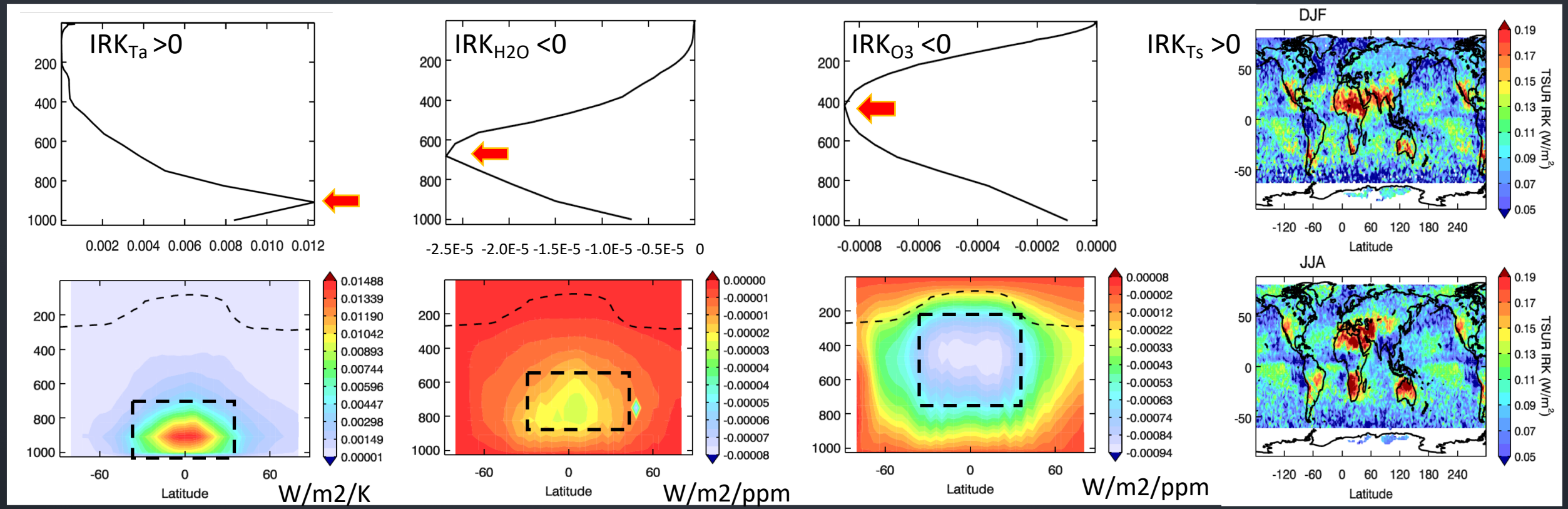
Thank you!

Jet Propulsion Laboratory
California Institute of Technology

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

- The TOA flux is most sensitive to
  - tropical lower troposphere for Ta (~900 hPa) & H_2O (~700 hPa)
  - Tropical mid-tropospheric O_3 (~400 hPa)
- Strong Ts IRK found at deserted region

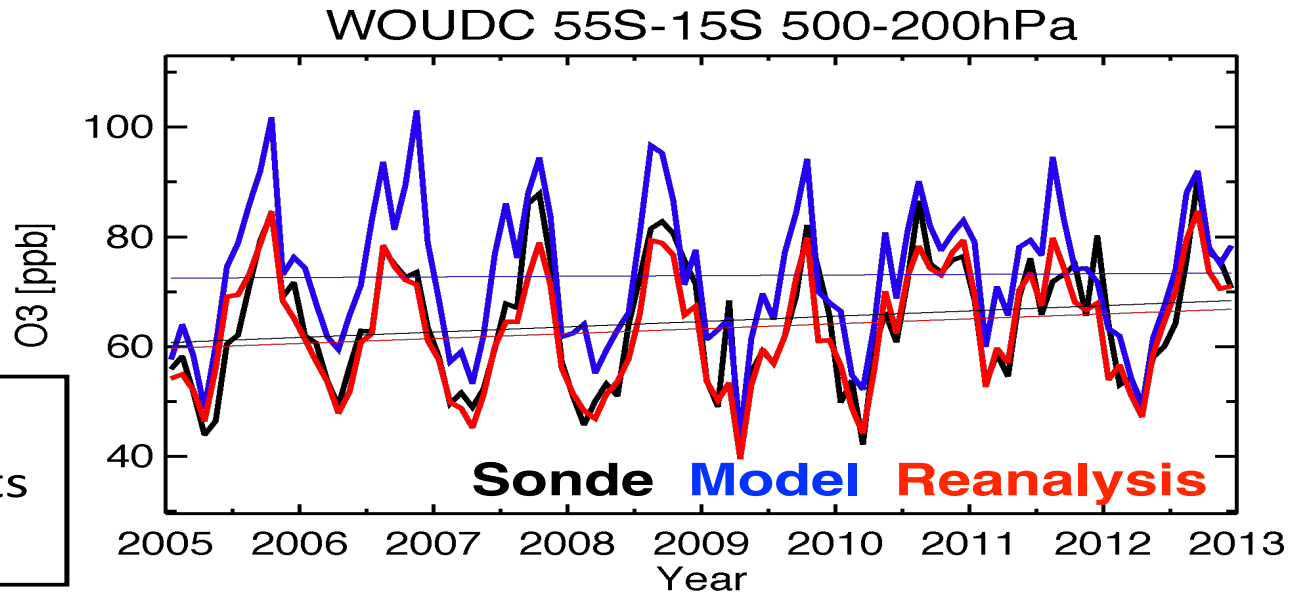
- All kernels are large at low latitudes and decrease to high latitudes.
- The model bias at the regions with strong IRKs would more efficiently propagate to the flux bias.



Tropospheric Chemistry Reanalysis (TCR-1)

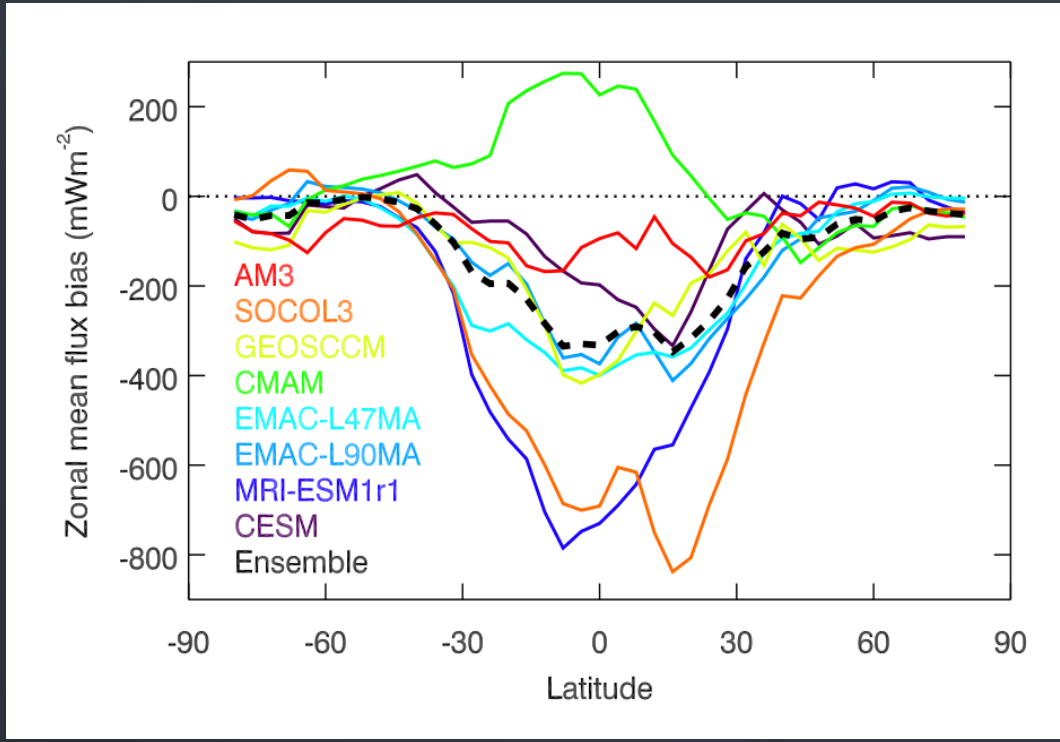
Assimilation scheme	Ensemble Kalman filter, 32 members
Forecast model	MIROC-Chem, 92 species & 262 reactions
State vector	NOx & CO emissions, lightning NOx, 35 chemical species
Assimilated data	OMI, SCIAMACHY, GOME-2 NO_2 (DOMINO2), TES O_3 (v6), MOPITT CO (v7 NIR), MLS O_3,HNO_3 (v4.2)
A priori emissions	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: CCMI and ACCMIP



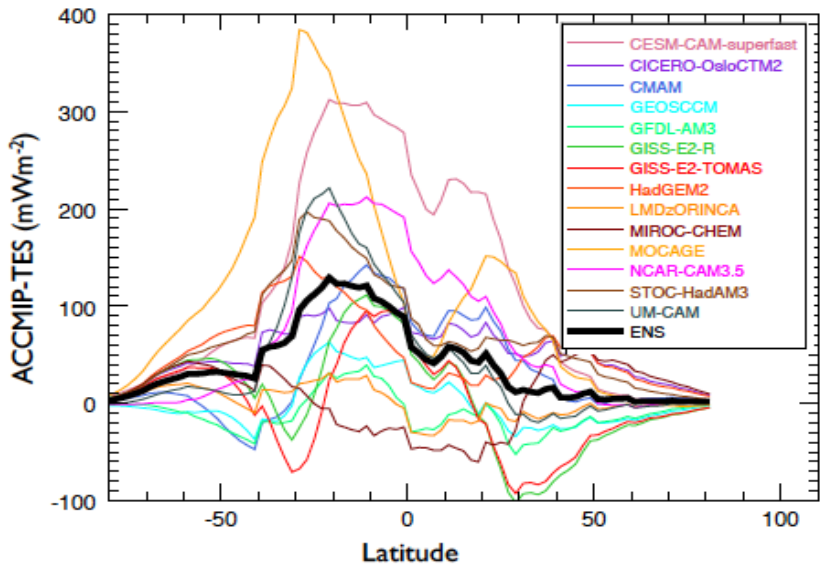


Fig. 5. Zonal δOLR_m^j between ACCMIP and TES from 2005-2010, limited to 80° S–80° N, and is based on a TES diagnosed chemical tropopause ($q = 150$ ppb). The "ENS" refers to the ACCMIP ensemble average, $\overline{\delta OLR}_j$. Positive values indicate model ozone is biased low relative to TES ozone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

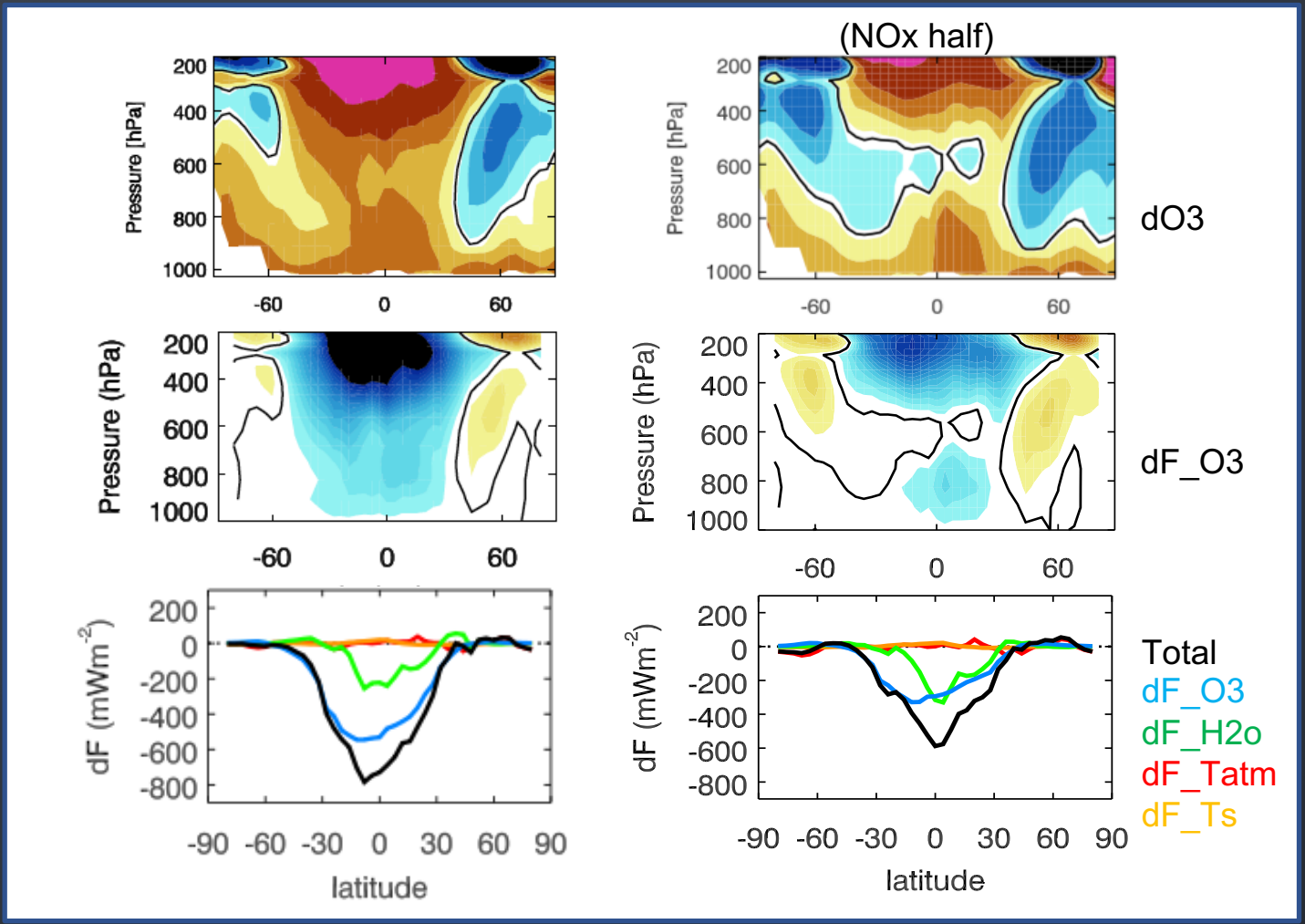
Bowman et al., 2013

4 components: O3, H2O, Ta, Ts
Current CCMI project

Only Ozone component
Past ACCMIP project

Radiative impact by the reduced lightning NOx emissions in MRI-EMS1r1

- Improved the O_3 bias in tropical mid and upper troposphere
- O_3 radiative bias also reduced in the same region
- The total flux bias are reduced due to better O_3 representation in MRI.



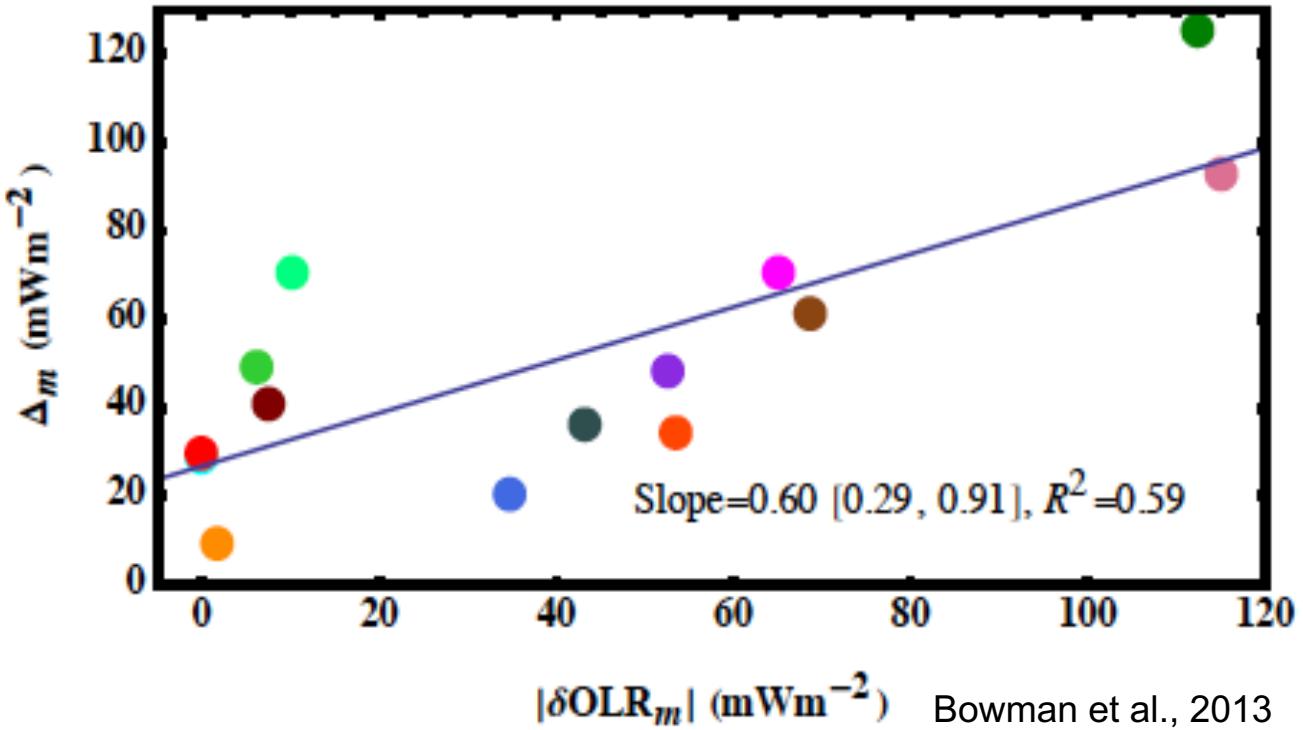
The history of the studies used O_3 IRK

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

Chemistry-Climate Model Initiative (CCMI) models & reanalysis

	Models		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	-	-	-

- 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

refC1:

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