Benchmarking climate model top-of-atmosphere (TOA) radiance in the 9.6μm ozone band compared to TES and IASI observations

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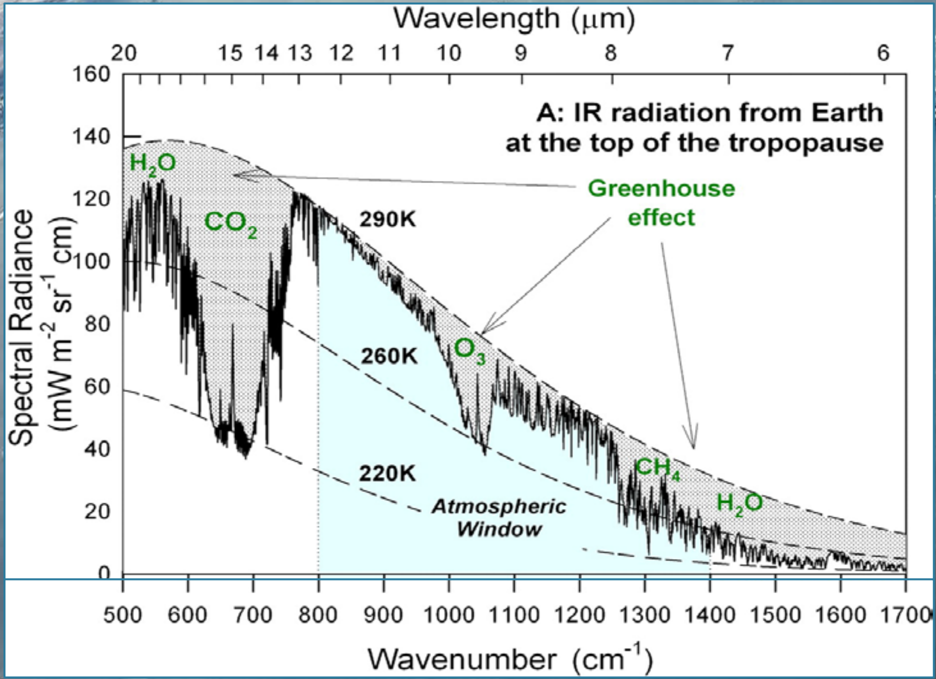
Outline

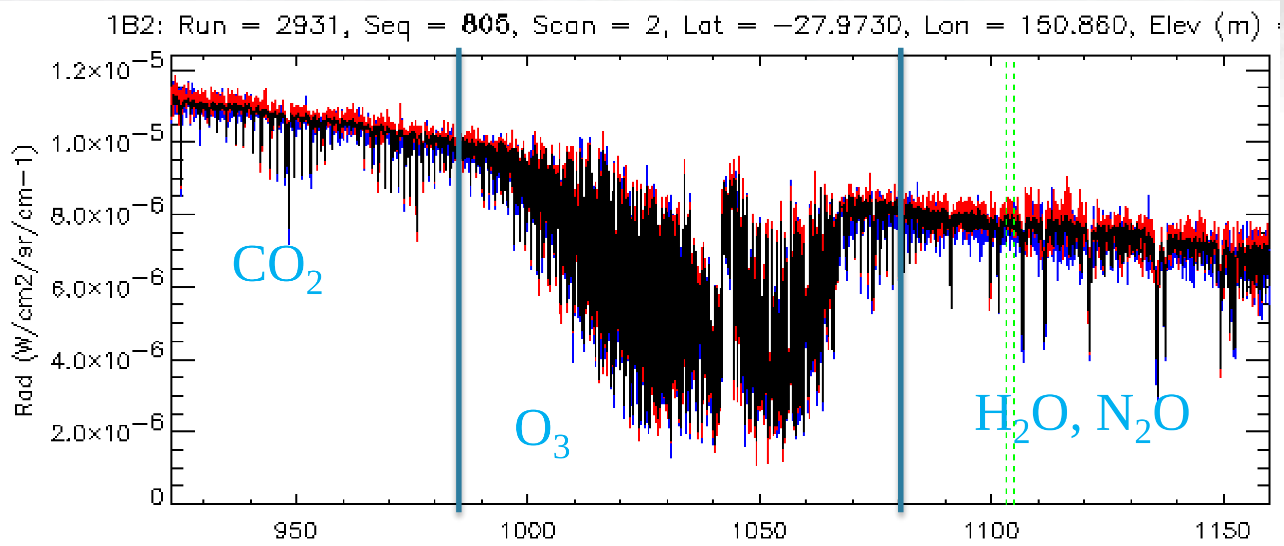
- Flux, IRK (instantaneous radiative kernel) and LWRE (long-wave radiative effect) definitions
- Research goals of benchmarking TOA ozone band flux and flux sensitivity
- Relevance to IPCC O_3 radiative forcing
- Initial model comparisons
- O_3 radiative coupling to H_2O
- Conclusions



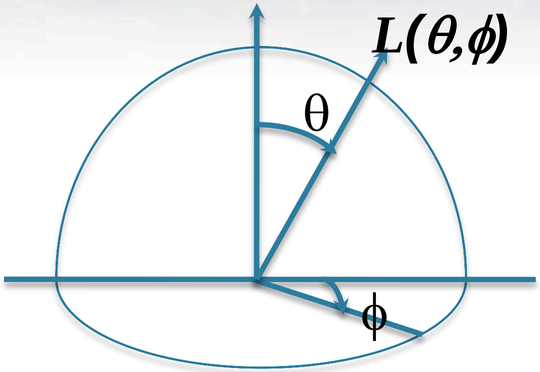
Wallington T J et al. PNAS 2010;107:E178-E179

Satellite IR O_3 observations

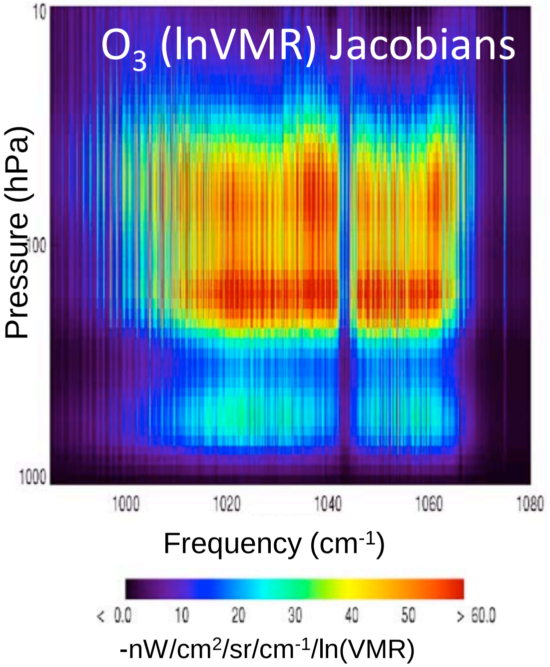
$L(\theta,\phi,\nu)$ = TOA Radiance (W/cm^2/sr/cm^{-1})



TOA flux (W/m^2)



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



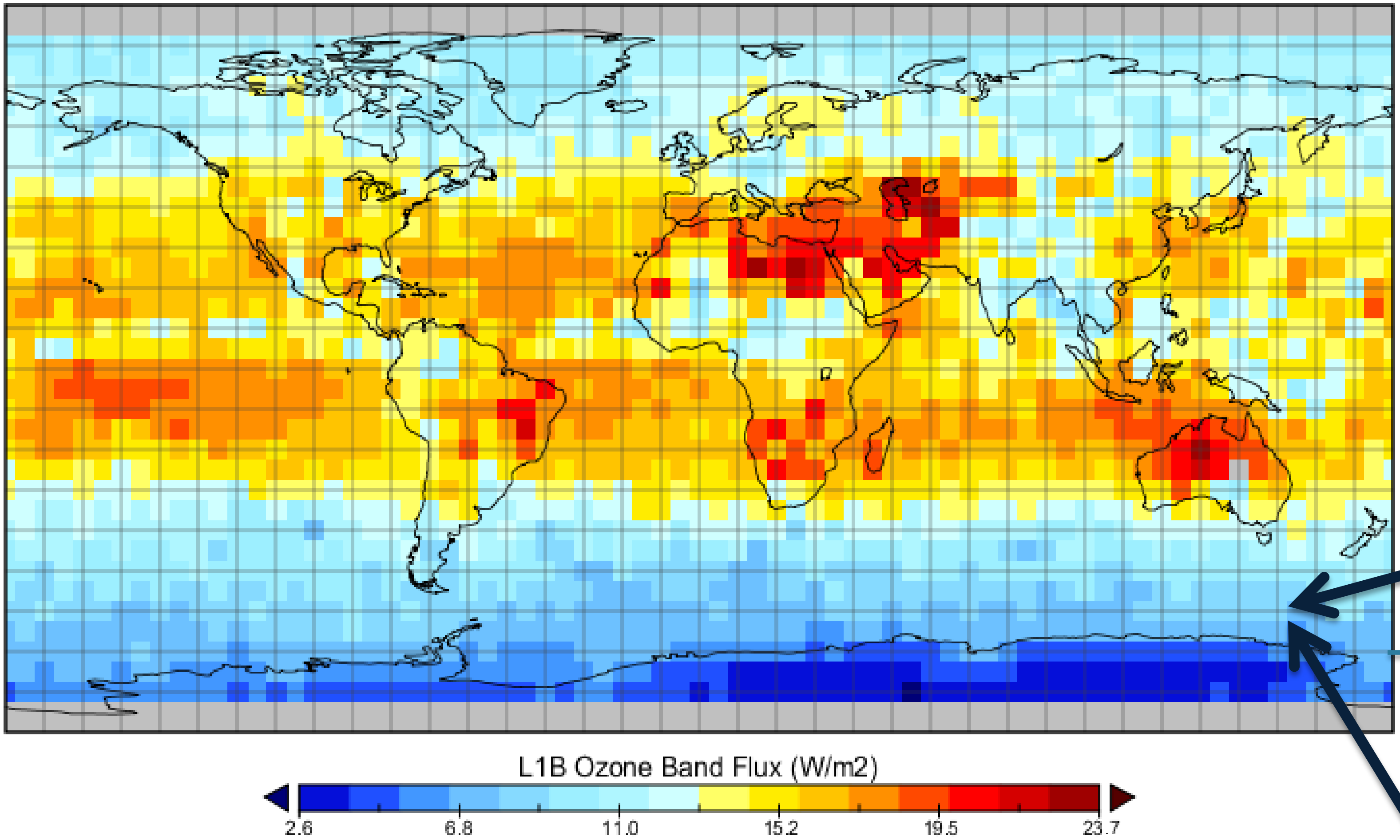
$$\text{IRK} = \frac{\partial F_{TOA}}{\partial q_l} = \int_0^{2\pi}\int_0^{\frac{\pi}{2}} \frac{1}{\partial q_l}\frac{\partial L}{\partial \ln q_l}\cos\theta\sin\theta\, d\theta\, d\phi$$

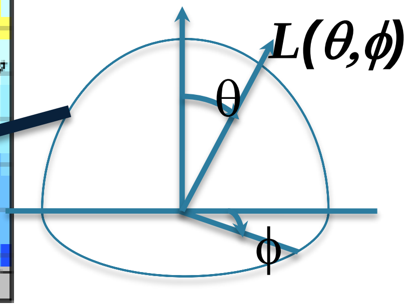
$$\Delta F_{TOA} = \sum_{l=surface}^{tropopause}\left(\frac{\partial F_{TOA}}{\partial q_l}\right)\Delta q_l$$

LWRE (W/m^2)
(long-wave
radiative effect)

O_3 band TOA Flux

All-sky August 2006 Average





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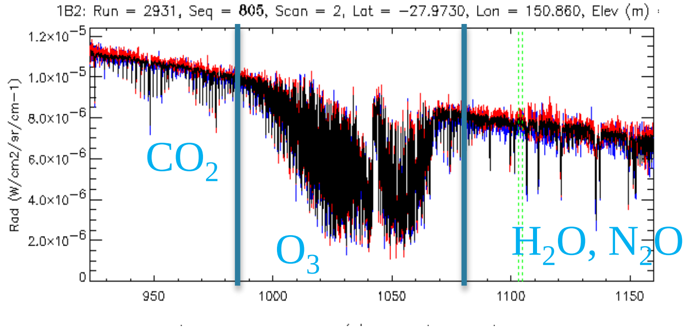


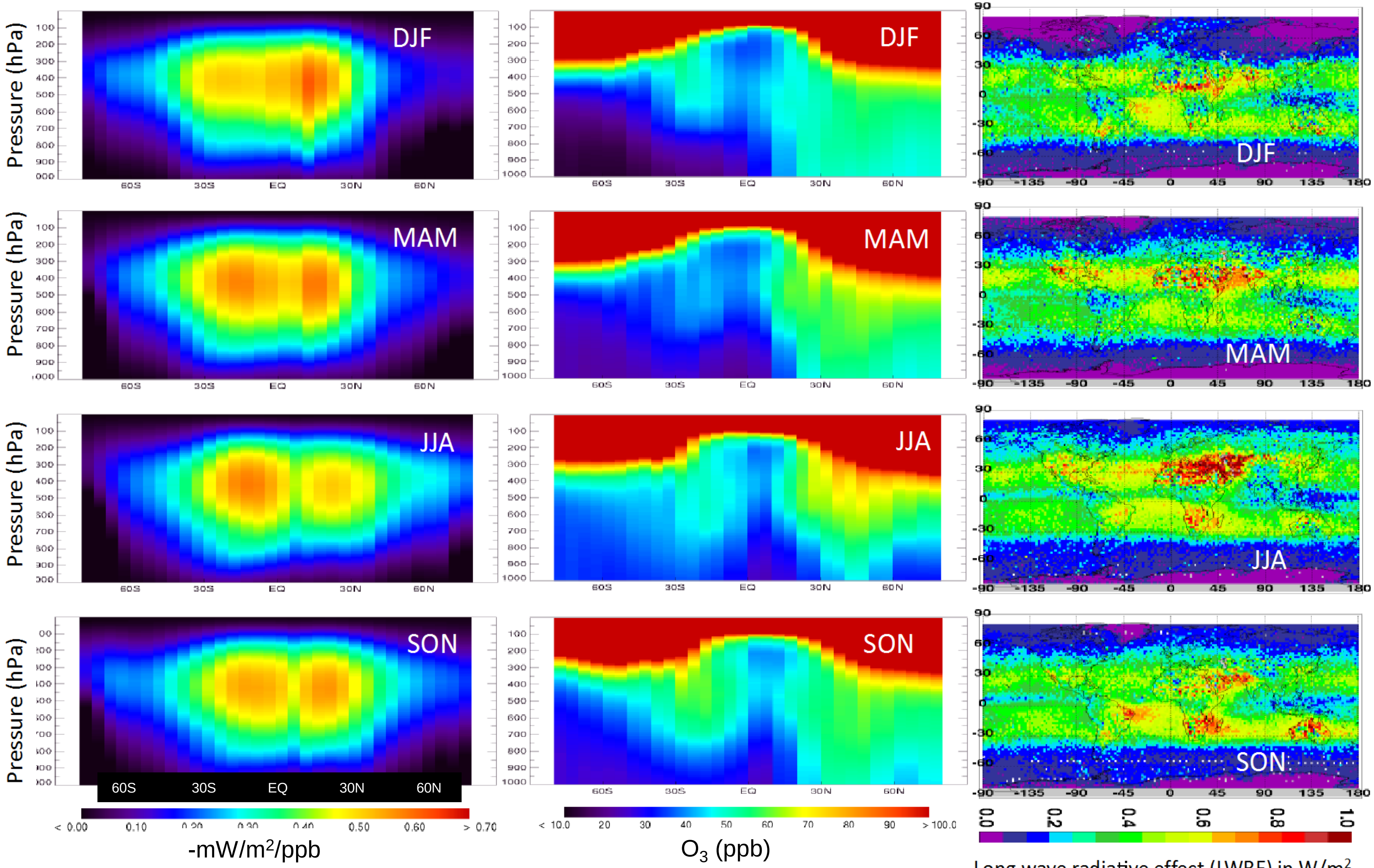
- Similar to OLR but only for the IR ozone band
- This is a fundamental quantity, predicted by climate models, but never tested against observations.

Seasonal Patterns in IRK, LWRE

IRK (-mW/m^2/ppb)

O_3 (ppb)

Tropos. O_3 LWRE (W/m^2)



-mW/m^2/ppb

O_3 (ppb)

Long wave radiative effect (LWRE) in W/m^2

Benchmarking O_3 band TOA flux

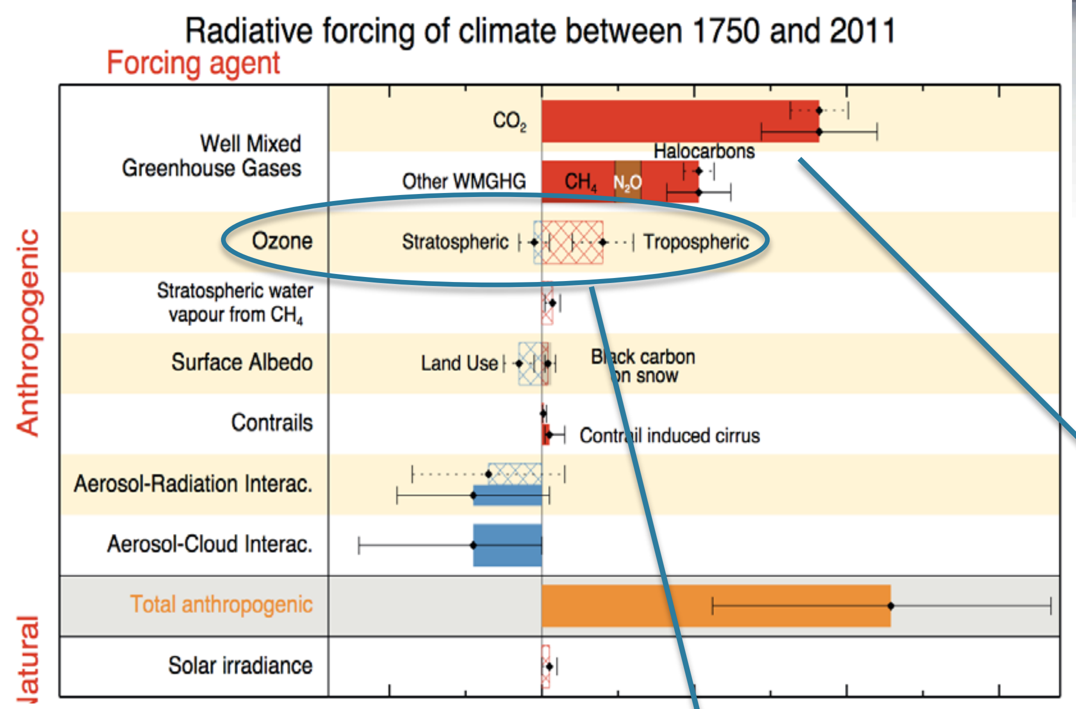
This research addresses two primary questions:

1) ***What is the bias in IPCC climate model predictions of present day top-of-atmosphere (TOA) flux in the 9.6μm ozone band?***

1) ***What is the impact of an ozone band TOA flux bias on present day tropospheric ozone flux sensitivity and pre-industrial to present day ozone radiative forcing estimates?***

The models we will test are GISS RT, CAM-chem with CAM-RT and with RRTMG using TES and IASI TOA flux and IRKs (Instantaneous Radiative Kernels)

IPCC AR5 Radiative Forcing Definitions



Radiative forcing of climate between 1750 and 2011

Direct Ozone RF

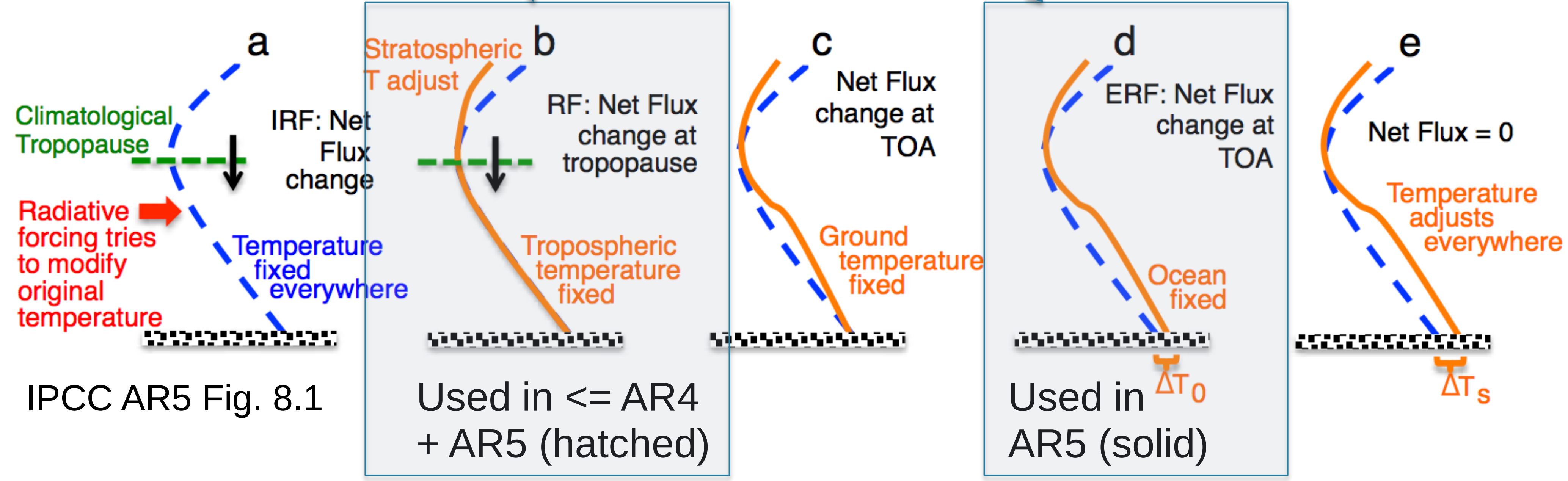
Preindustrial-to-present day: 0.35 W/m^2

through 21st century: 0.89 W/m^2

Indirect Ozone RF

Suppression of carbon uptake due to plant damage: 0.6 to 1.1 W/m^2

(Sitch et al., *Nature*, 2007)



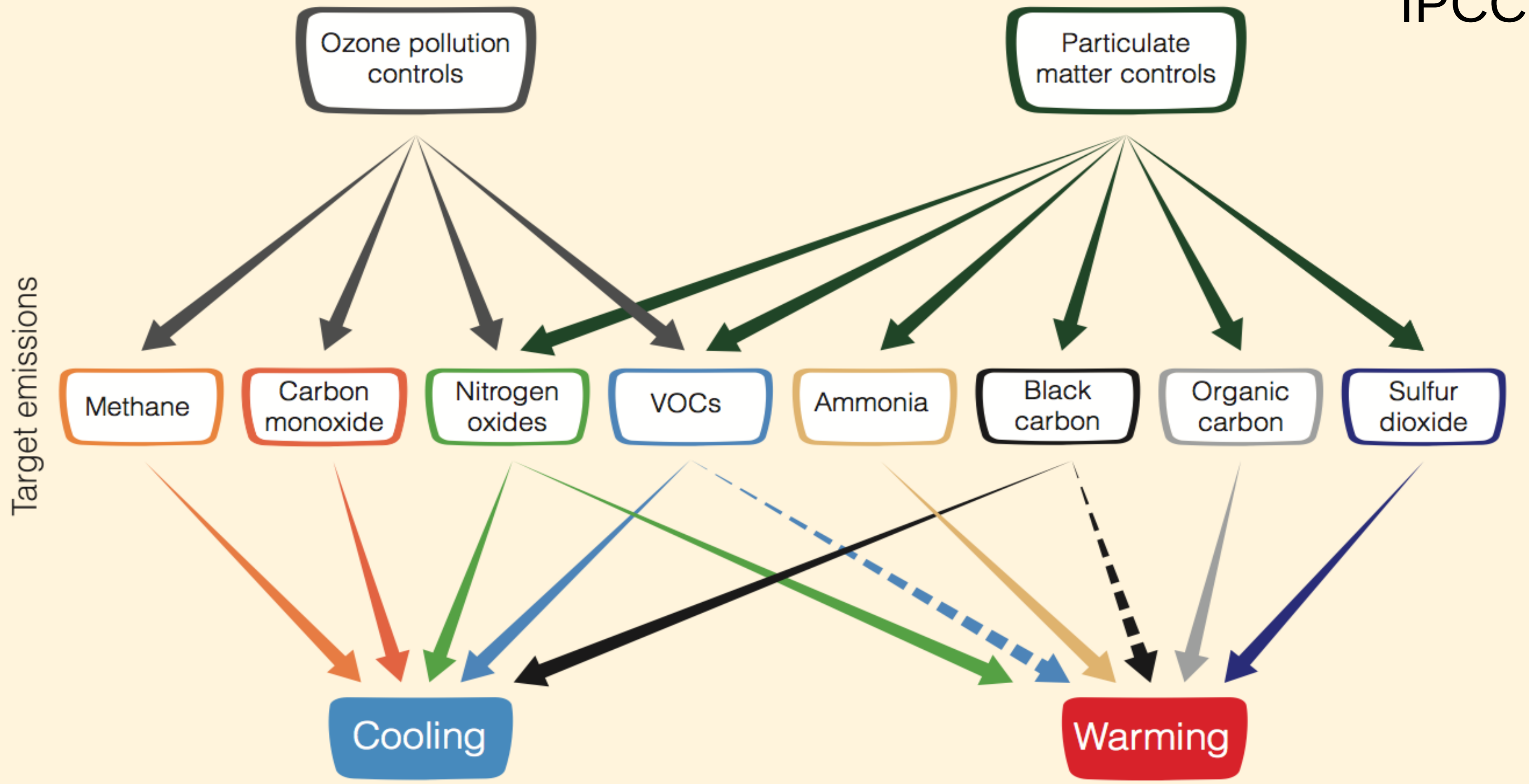
IPCC AR5 Fig. 8.1

Used in <= AR4 + AR5 (hatched)

Used in AR5 (solid)

Trade-offs for air-quality controls and climate benefits

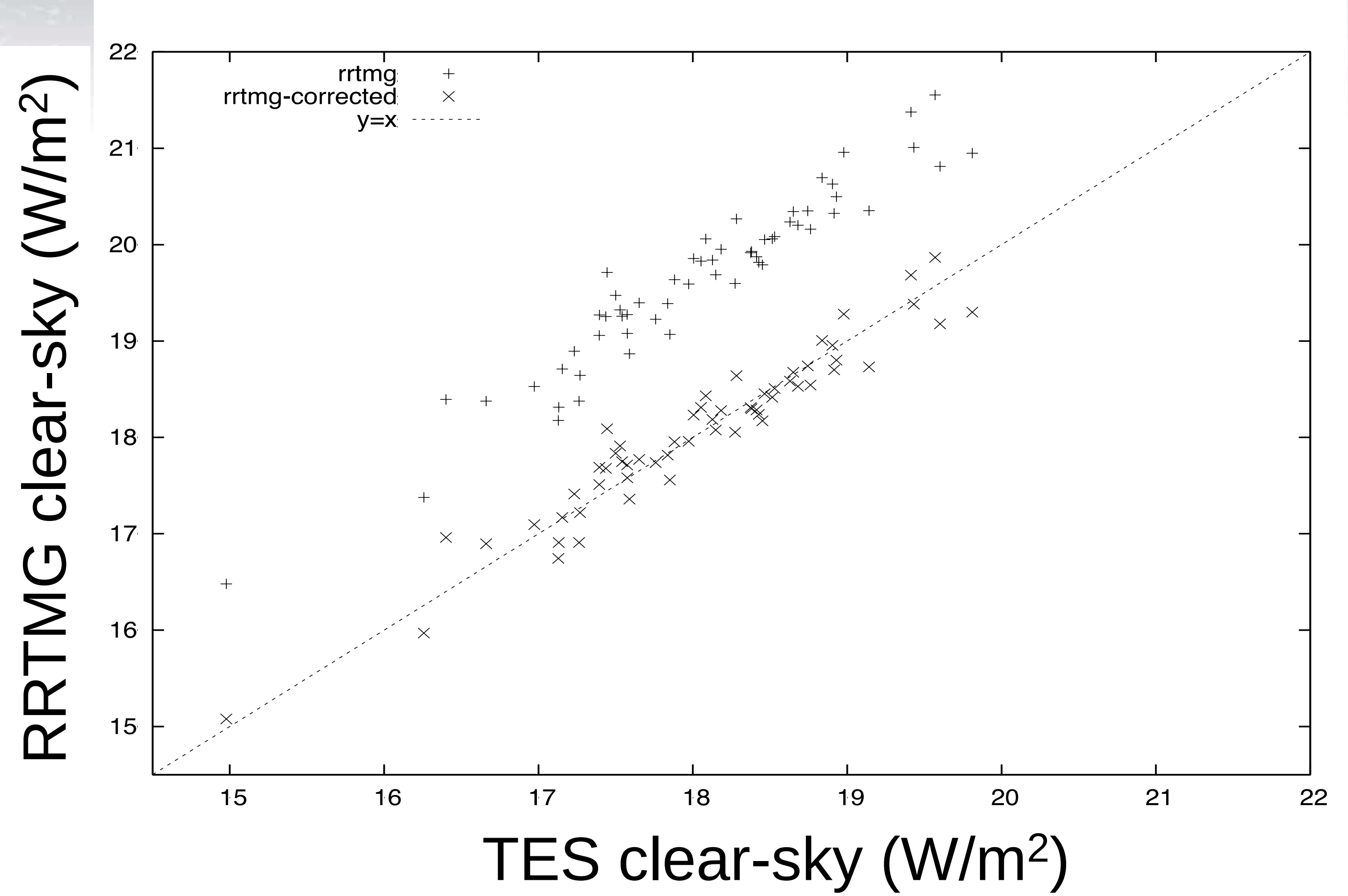
IPCC AR5



FAQ 8.2, Figure 1 | Schematic diagram of the impact of pollution controls on specific emissions and climate impact. Solid black line indicates known impact; dashed line indicates uncertain impact.

Need accurate measurements and model assessments for informed policy decisions

Initial Results: O_3 band TOA Flux



O_3 band flux comparison for atmospheres specified from TES retrievals

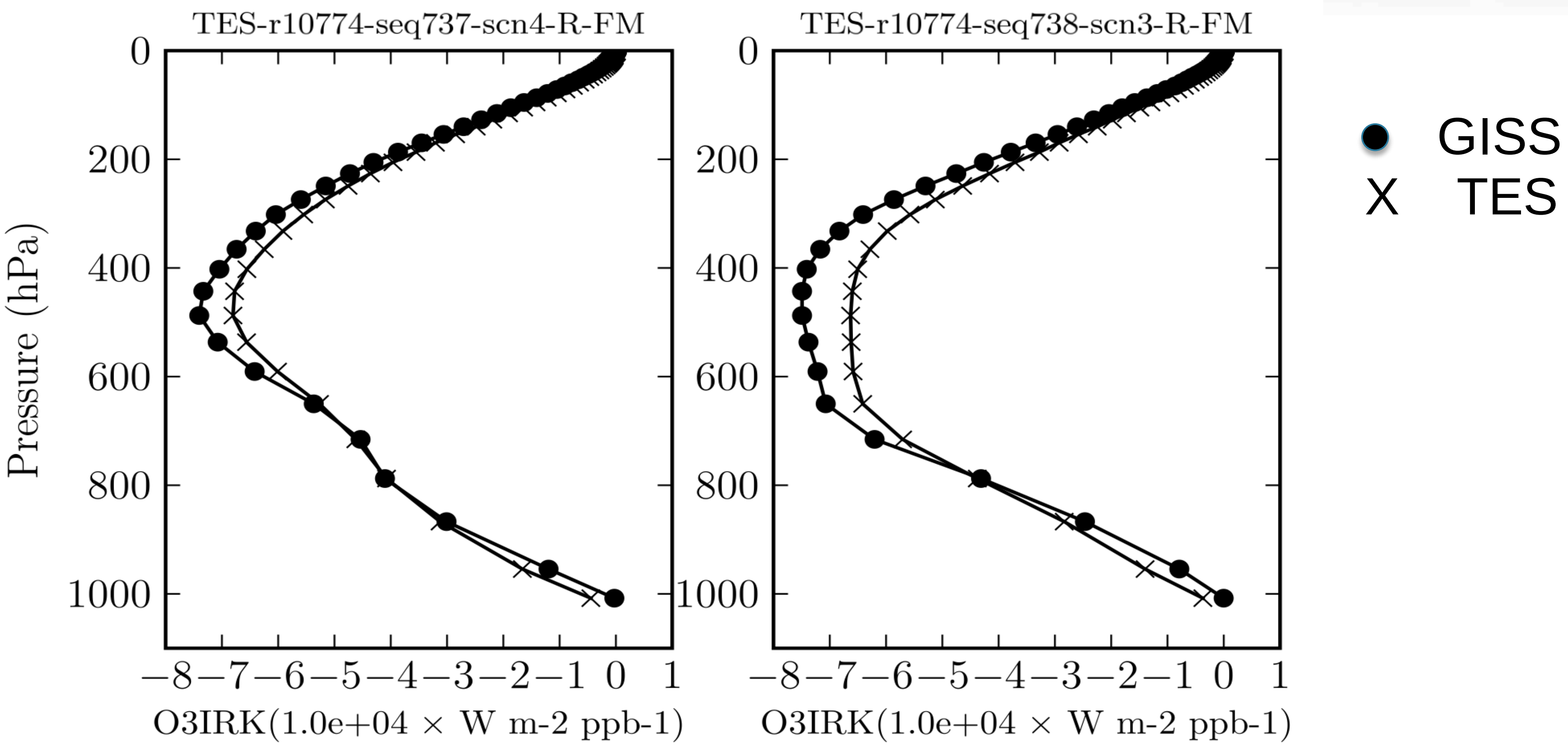
Thanks to A. Conley (NCAR)

Known issues:

- RRTMG band is 980-1080; TES band is 985-1080 (~1.1 to 1.7 W/m^2)

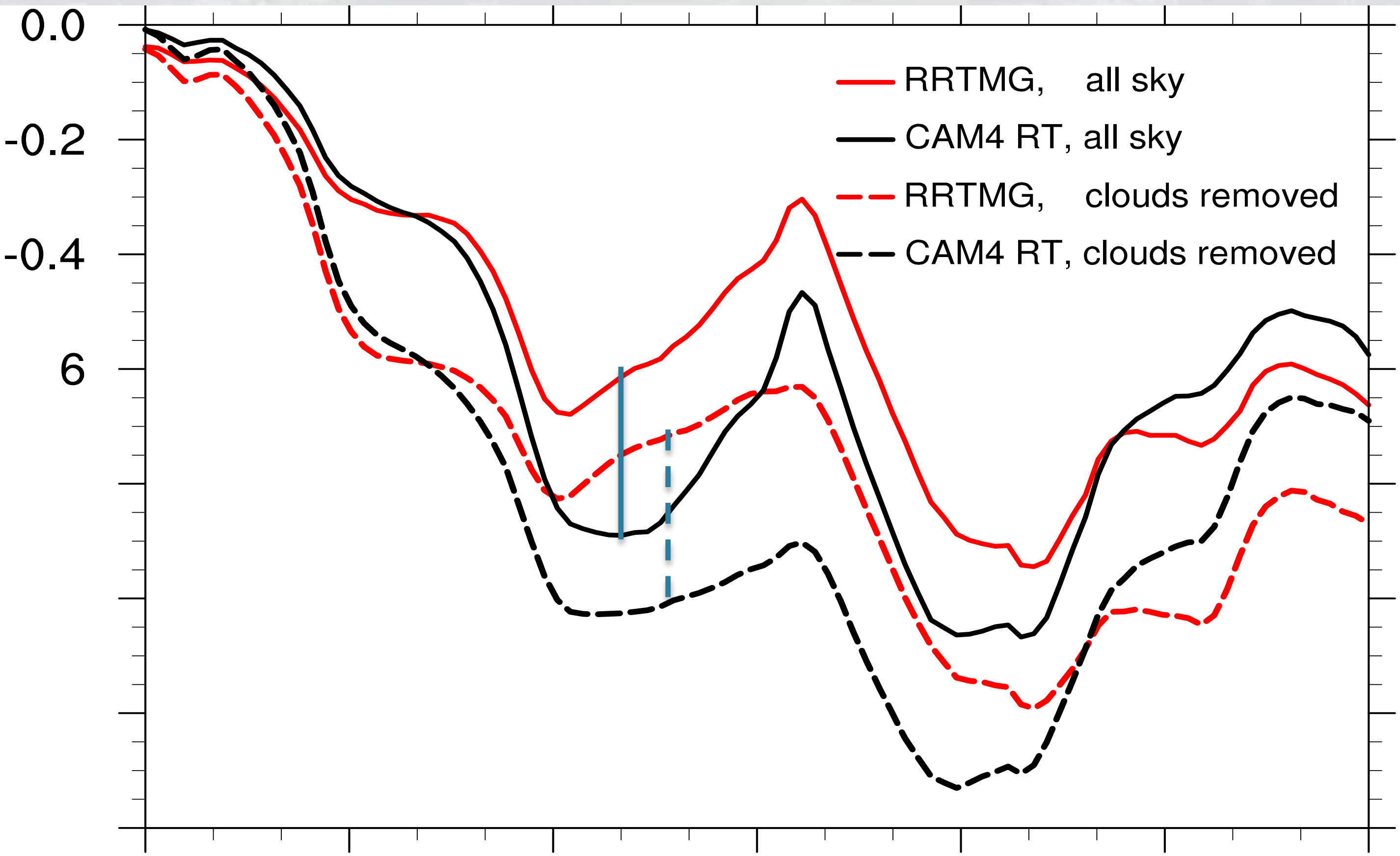
Initial Results: O_3 IRKs

Model-TES IRK comparison



GISS RTM for TES retrieved atmospheric state
TES IRK with single-angle integration for flux (known low magnitude bias)

Initial Results: Tropos. O_3 LWRE



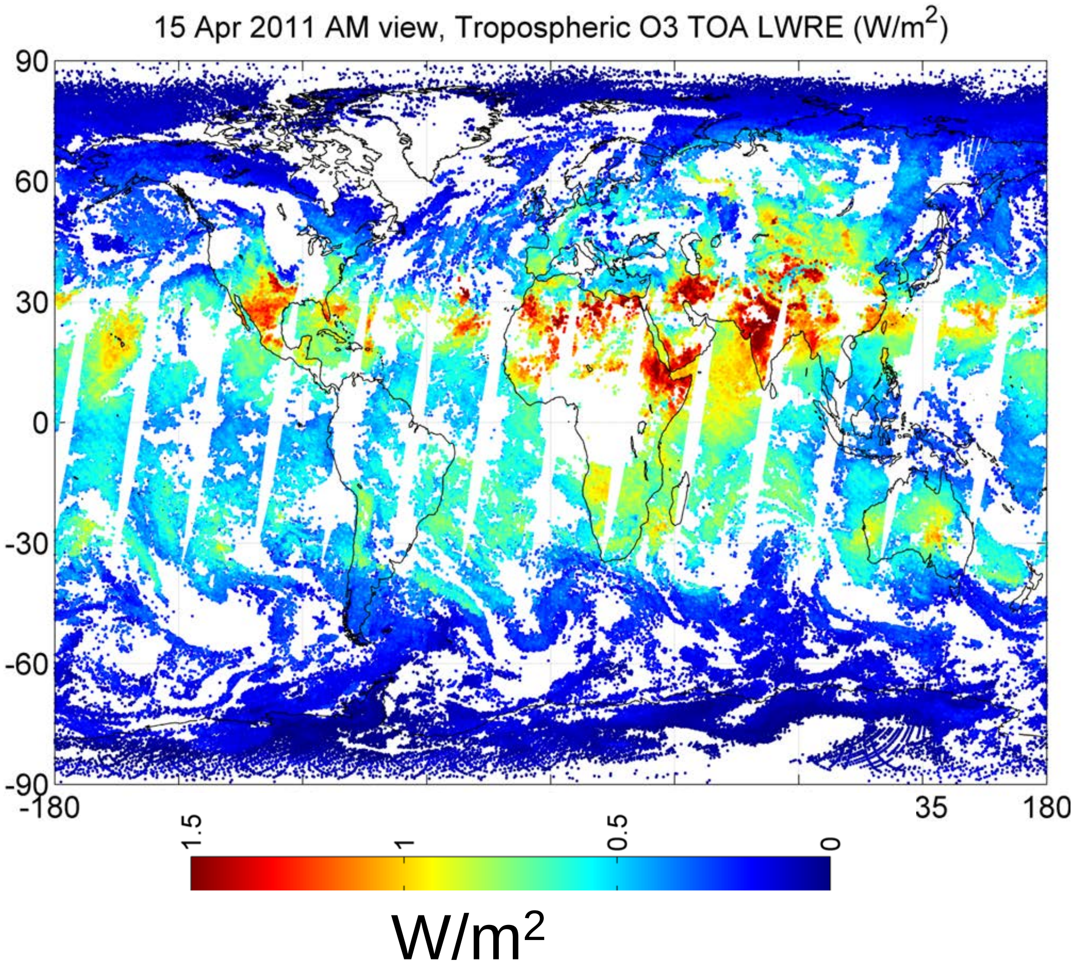
From A. Conley, NCAR

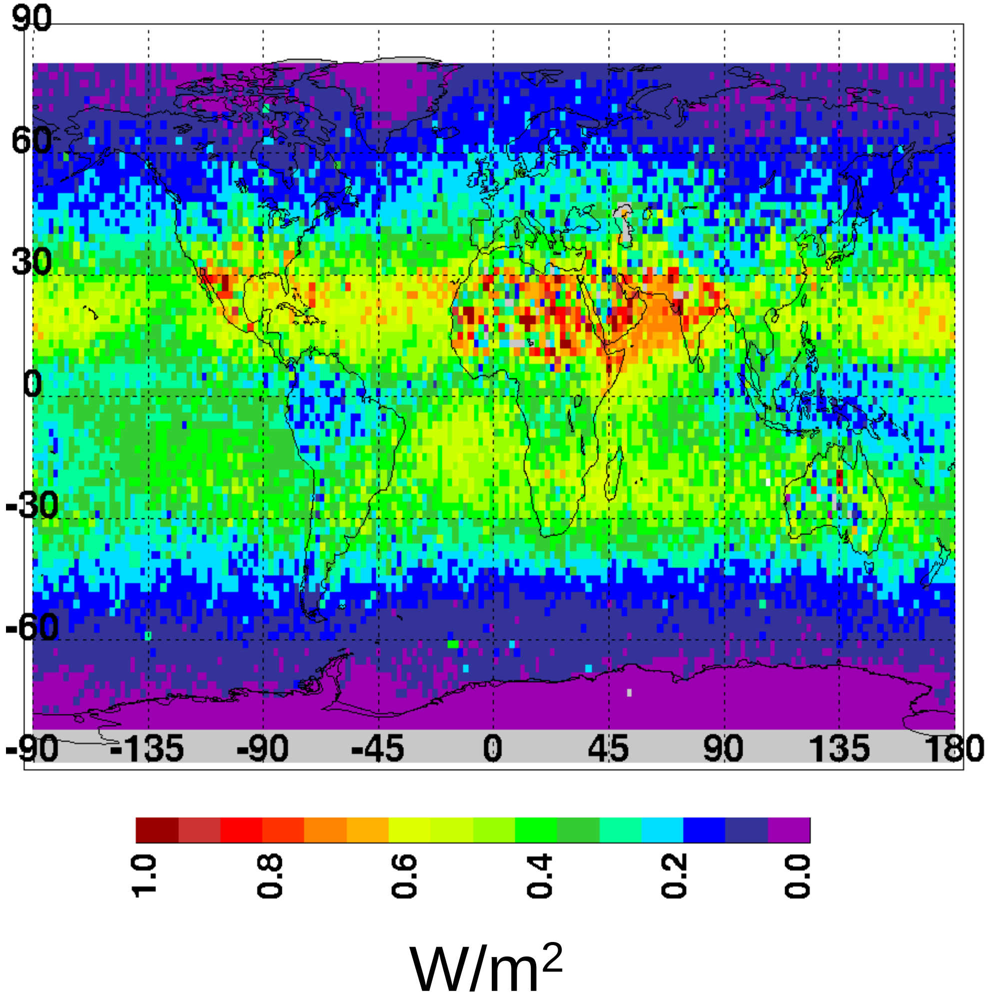
- Same atmosphere and surface conditions
- Large model-model differences for both clear and all-sky cases

Initial Results: Tropos. O_3 LWRE

IASI Tropospheric LWRE for
15 April, 2011

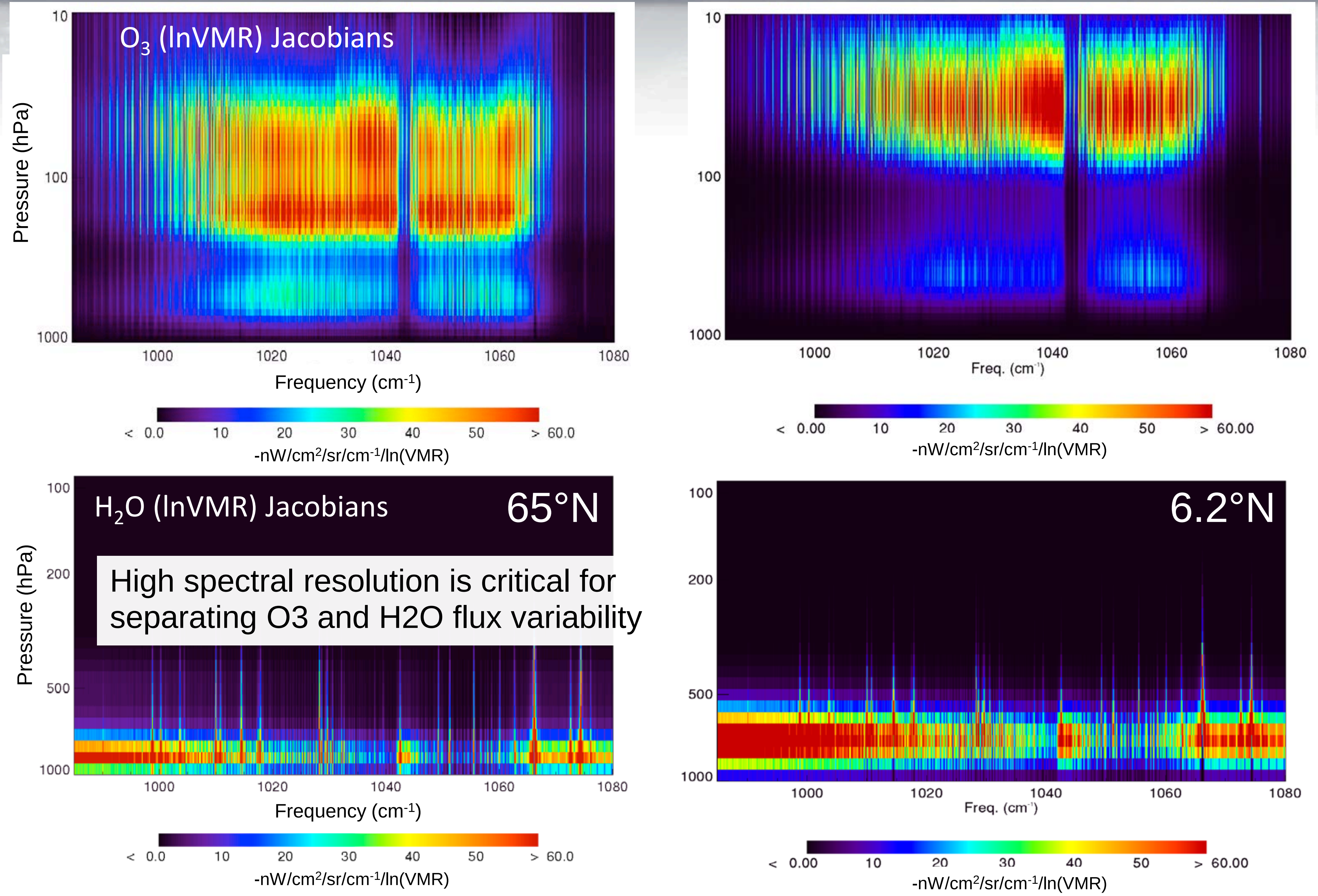
TES Tropospheric LWRE
for MAM 2005-2009


15 Apr 2011 AM view, Tropospheric O3 TOA LWRE (W/m^2)



Thanks to S. Doniki, ULB, Brussels

H_2O and O_3 are radiatively coupled



O_3 (lnVMR) Jacobians

H_2O (lnVMR) Jacobians

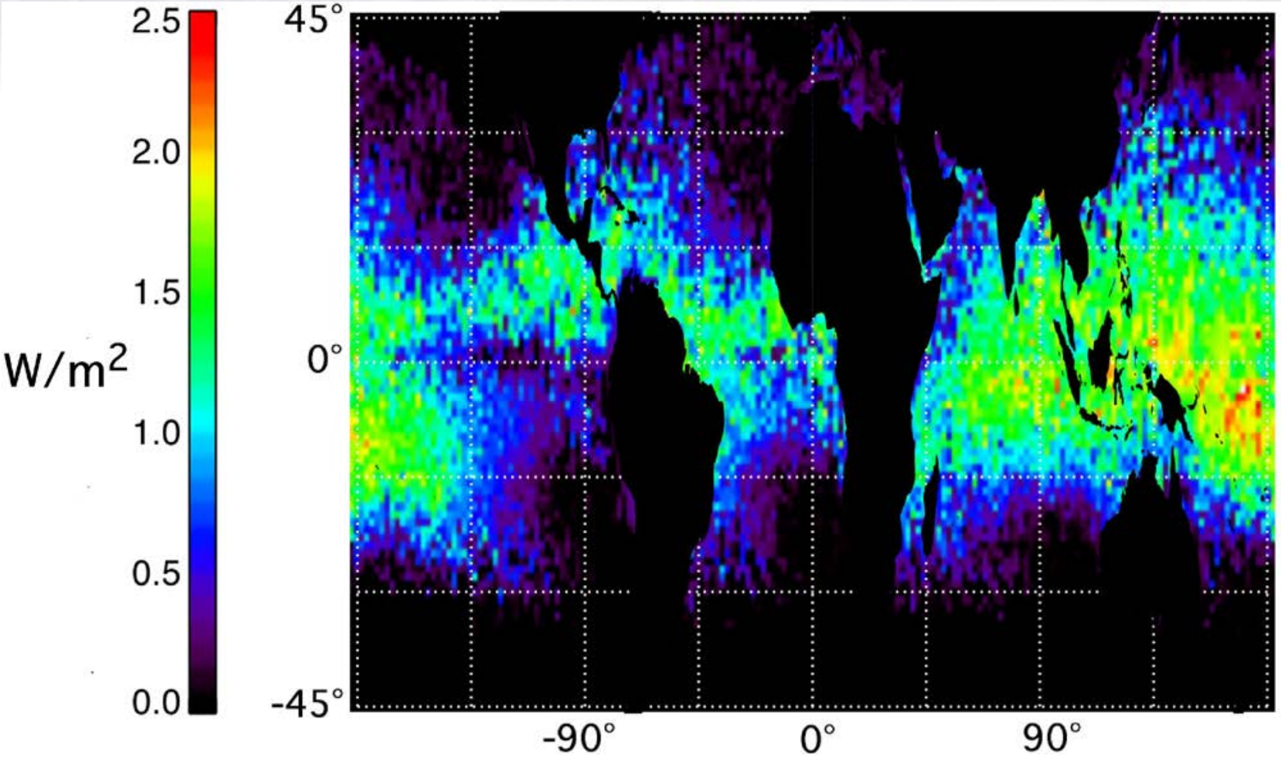
65°N

6.2°N

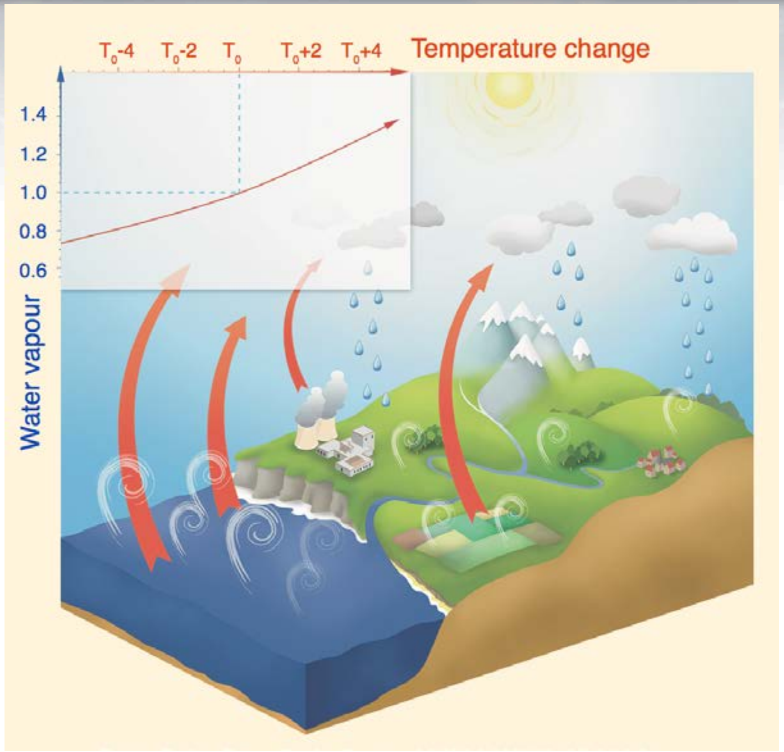
High spectral resolution is critical for separating O3 and H2O flux variability

Potential Feedbacks to O_3 RF from H_2O

Water vapor LWRE in the IR ozone band



Worden et al., Nature GEO, 2008



IPCC AR5 FAQ 8.1 Fig. 1: Water cycle with water vapour feedback ~7%/°C

$$\Delta F = \frac{\partial F}{\partial q_{O_3}} \Delta q_{O_3} + \frac{\partial F}{\partial q_{H_2O}} \Delta q_{H_2O} + \frac{\partial F}{\partial T_{srf}} \Delta T_{srf} + \frac{\partial F}{\partial T_{atm}} \Delta T_{atm} + \ldots$$

Understanding the feedback of water vapor on ozone RF (more water = less O_3 RF) due to changes in the hydrological cycle from climate change will require the long-term measurements of IASI (A,B,C-2016) and IASI-NG (2021,2028,2035)

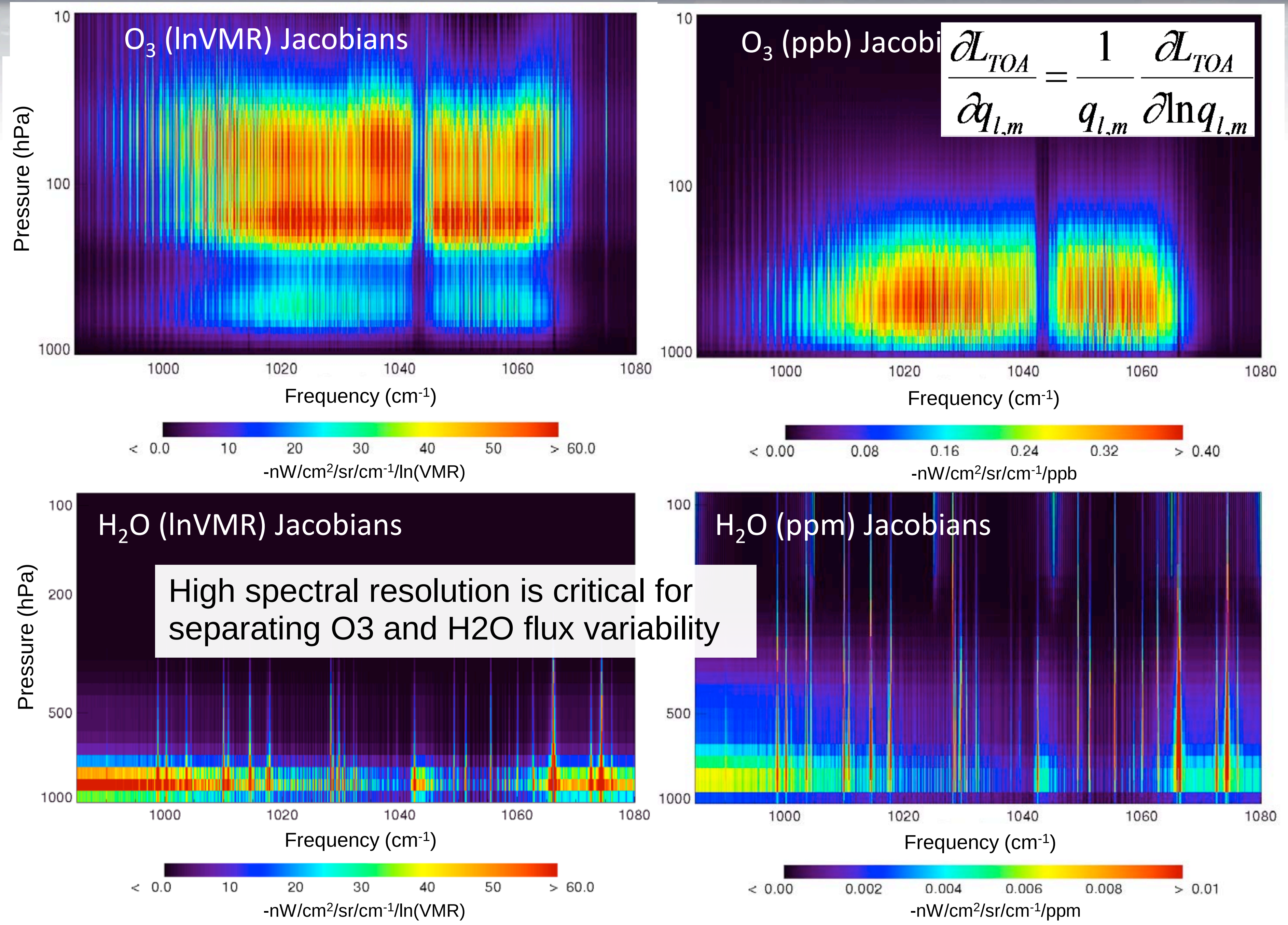
Conclusions

- TOA flux from the IR Ozone band is a fundamental quantity in climate models that has not been compared to measurements. Potential ECVs?
- Continuing the TES record with IASI data is critical for understanding present day to future changes in O_3 radiative forcing, such as cloud coverage and water vapor feedback.
- Initial results show differences for both flux and flux sensitivity between models and data that need to be reconciled.

Backup

Spectral sensitivity of TOA flux to ozone and water vapor

TES obs. at 65°N, Aug. 2006

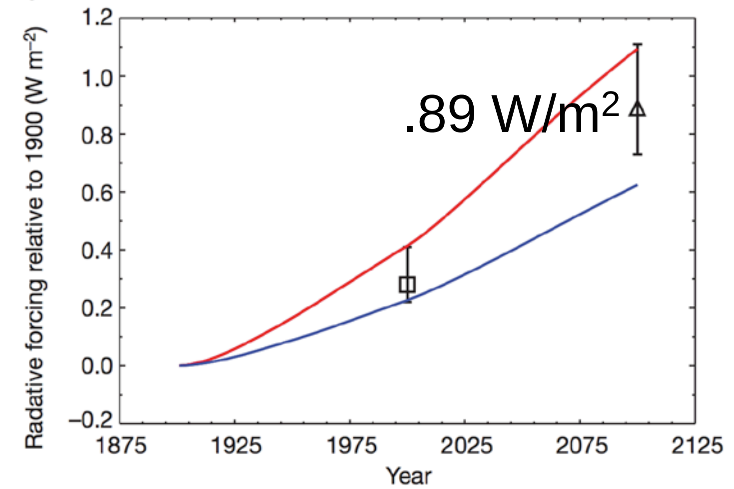


$$\frac{\partial L_{TOA}}{\partial q_{l,m}} = \frac{1}{q_{l,m}} \frac{\partial L_{TOA}}{\partial \ln q_{l,m}}$$

High spectral resolution is critical for separating O3 and H2O flux variability

Worden et al., JGR, 2011

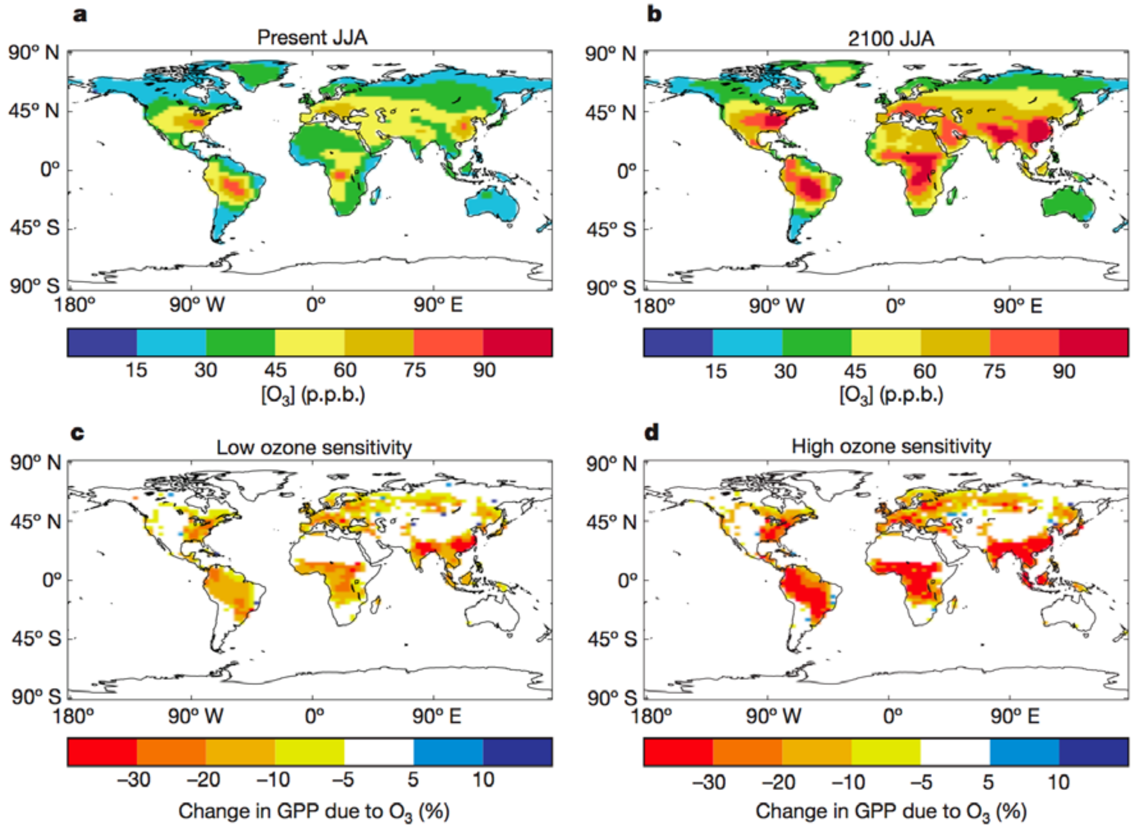
Role of ozone in chemistry-carbon-climate coupling



Direct effect:
Preindustrial-to-present day:
.35 [.25, .65] W/m^2

Preindustrial through 21st century:
.89 W/m^2

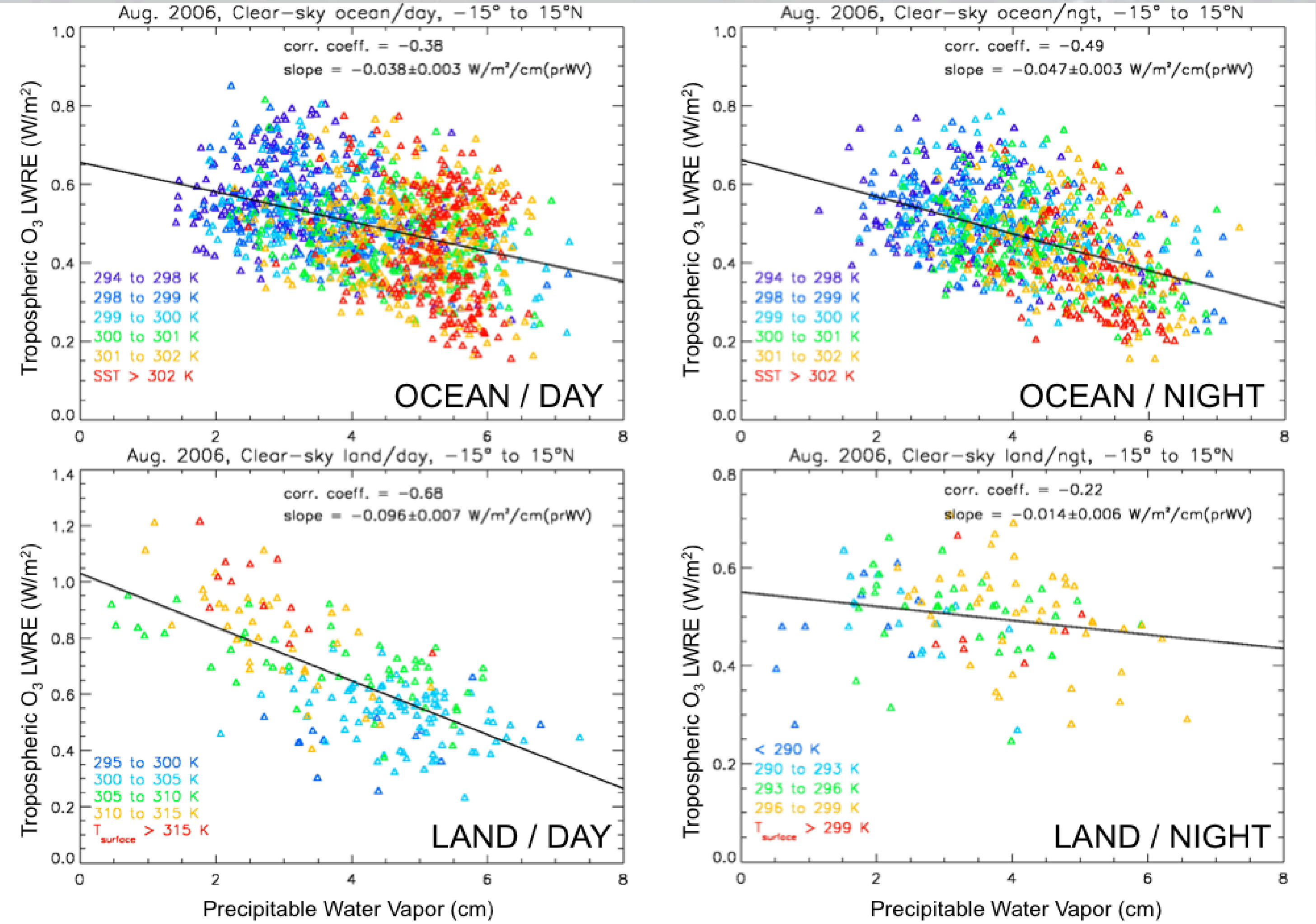
But O_3 RF is also coupled to changes in H_2O



Indirect effects:
Suppression of carbon uptake by ozone damage to plants could lead to additional 0.62 to 1.09 W/m^2 CO_2 radiative forcing

Sitch et al,(2007), *Nature*

H_2O and O_3 are radiatively coupled

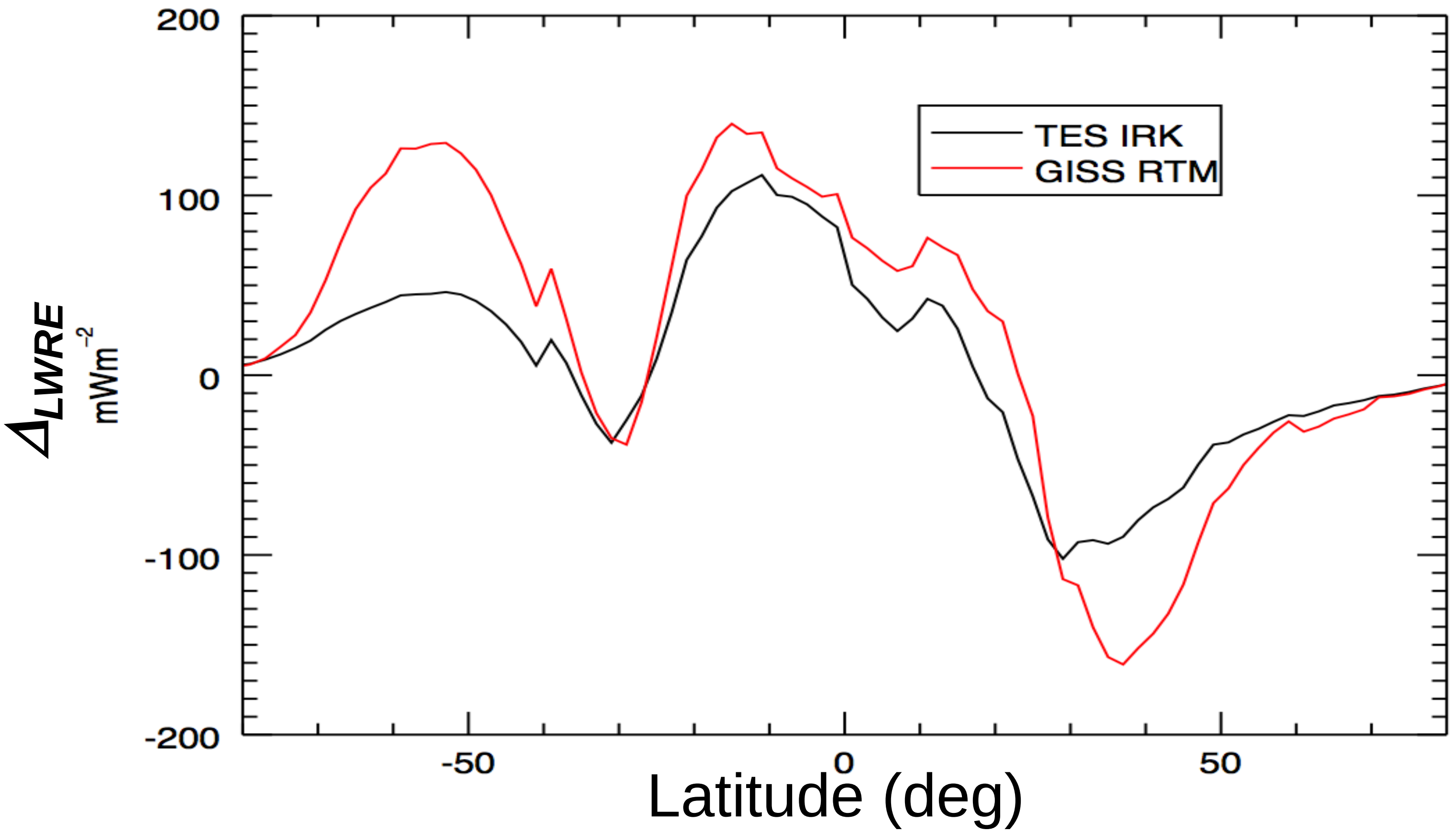


Worden et al., JGR, 2011

Tropospheric ozone LWRE has a strong dependence on water vapor in the tropics.

Initial Results: Tropos. O_3 LWRE

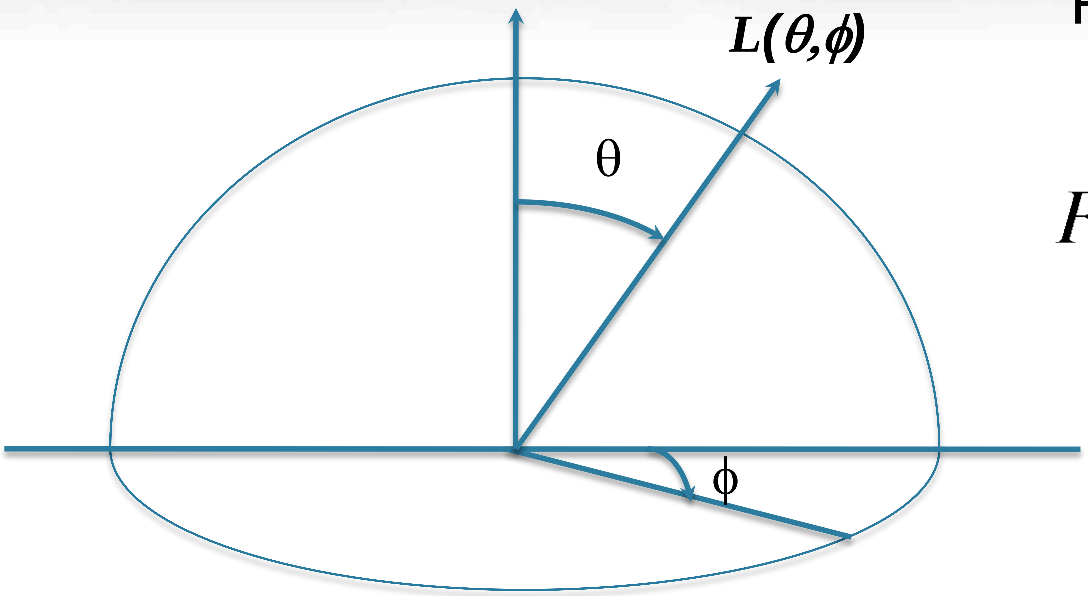
Model-TES ΔLWRE comparison



Bowman et al., ACPD, 2013

- Zonal averages: GISS RTM TOA flux sensitivity and TES IRKs applied to same model differences
- Dry bias in UT at mid-latitudes for GISS

Flux Estimate and Anisotropy



Flux:

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

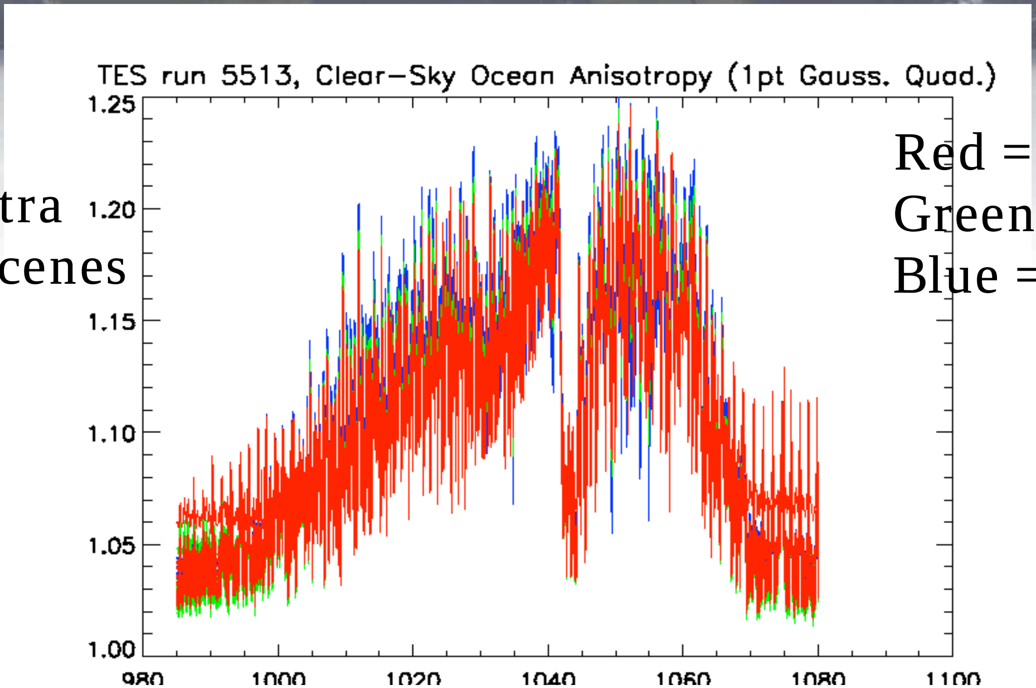
Anisotropy:

$$R_\nu(\theta) = \frac{\pi L_\nu(\theta)}{F_\nu}$$

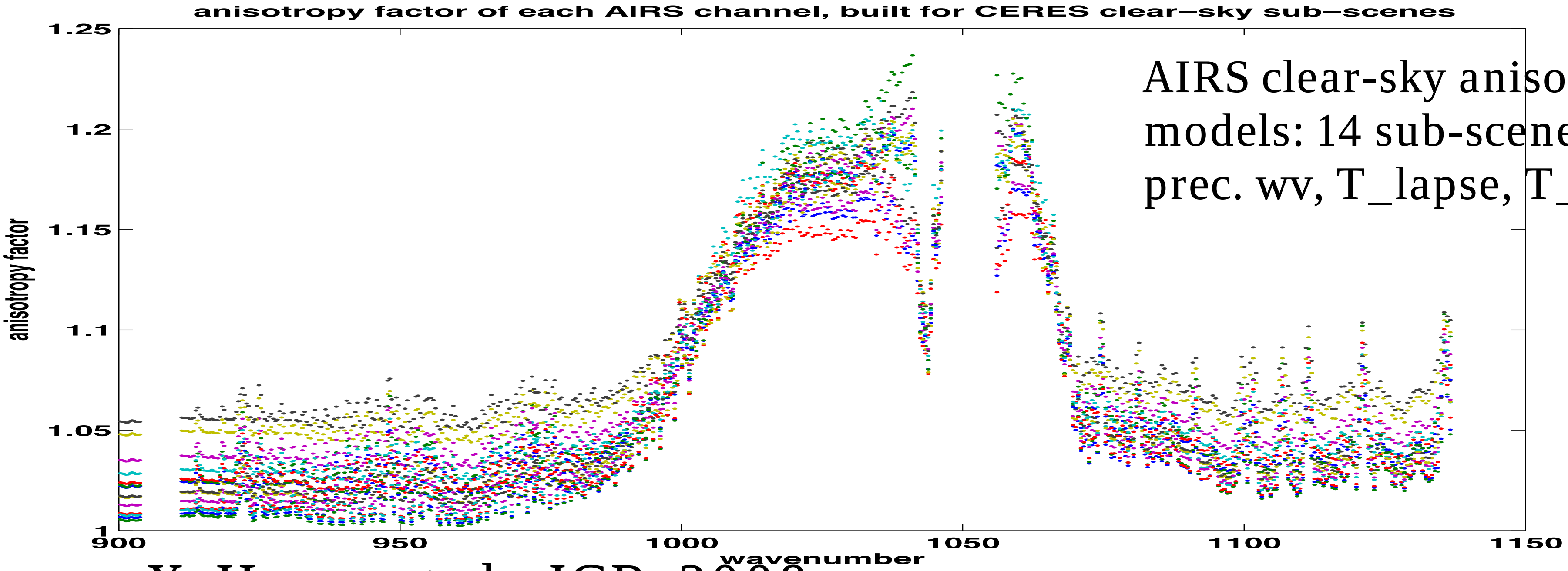
H. Worden, K Bowman, et al.

Anisotropy Results

TES anisotropy spectra for clear-sky ocean scenes



Red = -5° -15° N
Green = 15° -30° N
Blue = 30° -45° N

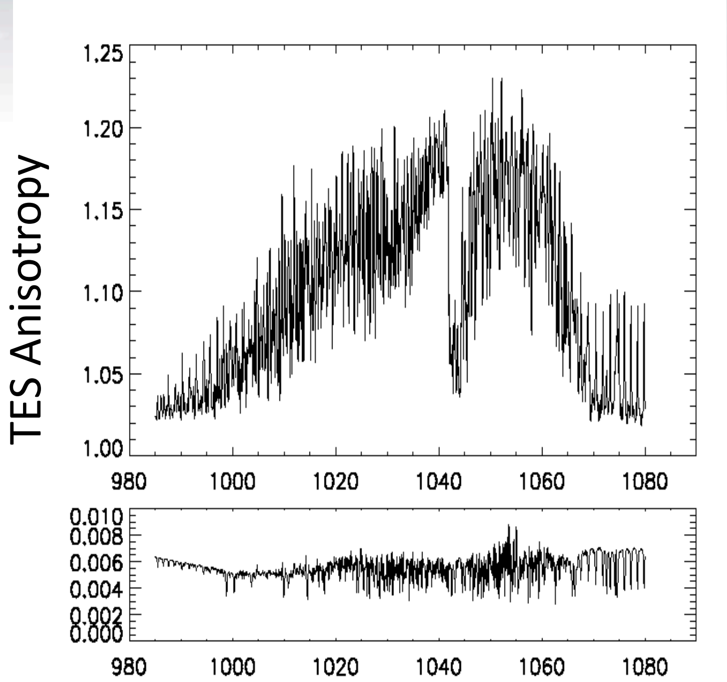


AIRS clear-sky anisotropy models: 14 sub-scenes for prec. wv, T_lapse, T_sur

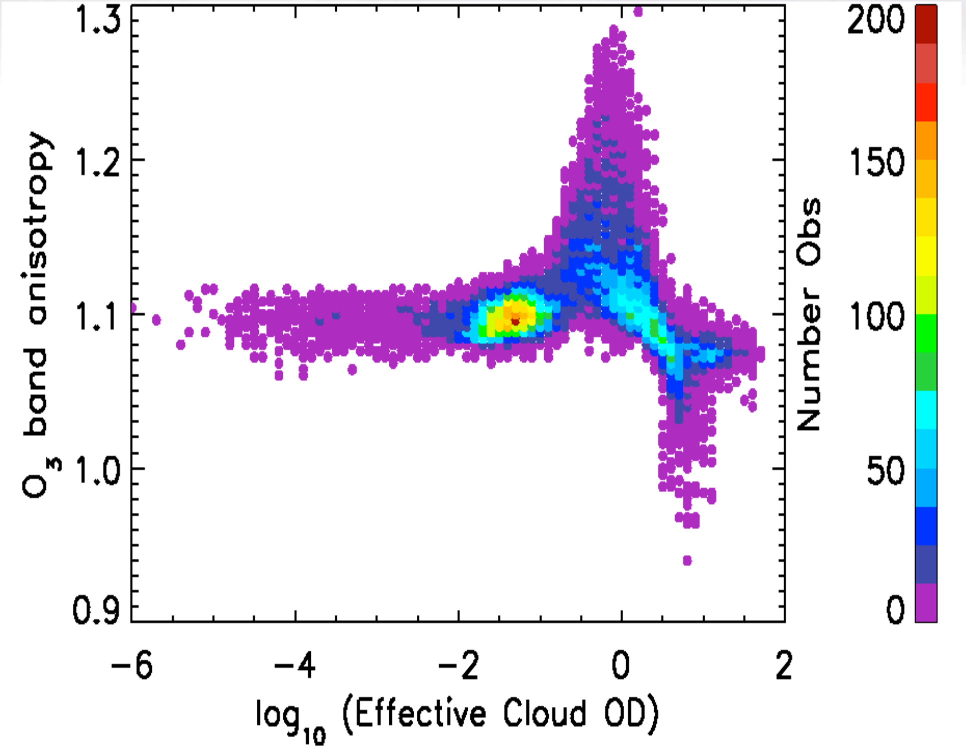
X. Huang et al., JGR, 2008

ANISOTROPY ESTIMATE

R spectral dependence



R cloud OD dependence



Worden et al., JGR, 2011

Spectral Anisotropy Estimate

$$R_\nu(\theta=0)=\frac{\pi L_\nu(0)}{F_\nu}=\frac{\pi L_\nu(0)}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L_\nu(\theta)\cos\theta\sin\theta\,d\theta\,d\phi}=\frac{L_\nu(0)}{2\int_0^{\frac{\pi}{2}} L_\nu(\theta)\cos\theta\sin\theta\,d\theta}$$

R = anisotropy, F = flux, L = radiance, θ=nadir angle, ν=frequency (assumes azimuthal symmetry)

Let $x = \sin\theta$, then dx = $\cos\theta$dθ

$$\int_0^{\frac{\pi}{2}} L_\nu(\theta)\cos\theta\,\sin\theta\,d\theta = \int_0^1 L(\sin^{-1}x)x\,dx = \int_0^1 x^k f(x)\,dx \approx \sum_{i=1}^{n} w_i f(x_i)$$

using Gaussian integration of moments. From Abramowitz & Stegun for n=1, k=1: x_i = 0.666667 and w_i = 0.50

$$R_\nu(\theta=0)=\frac{L_\nu(0)}{2*[0.5L_\nu(41.8°)]}=\frac{L_\nu(0)}{L_\nu(41.8°)]}$$