

# Towards the fingerprinting of radiative forcing: Inhomogeneity of homogeneous greenhouse gas forcing

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**Acknowledgements (Related ROSES project):**

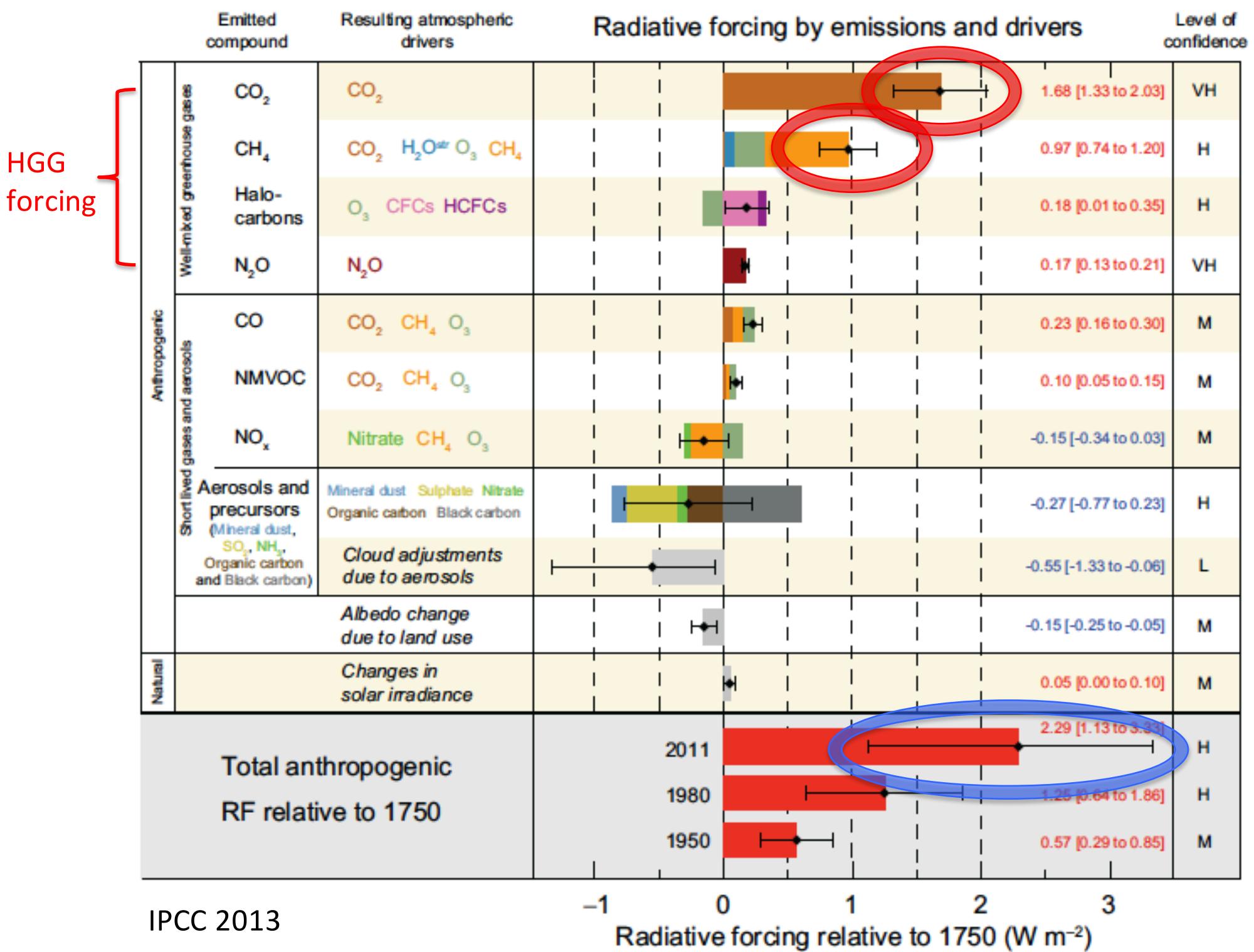
**Atmospheric Composition: Spectral Climate Signal**

Radiative Forcing of Climate Using A-Train Data and

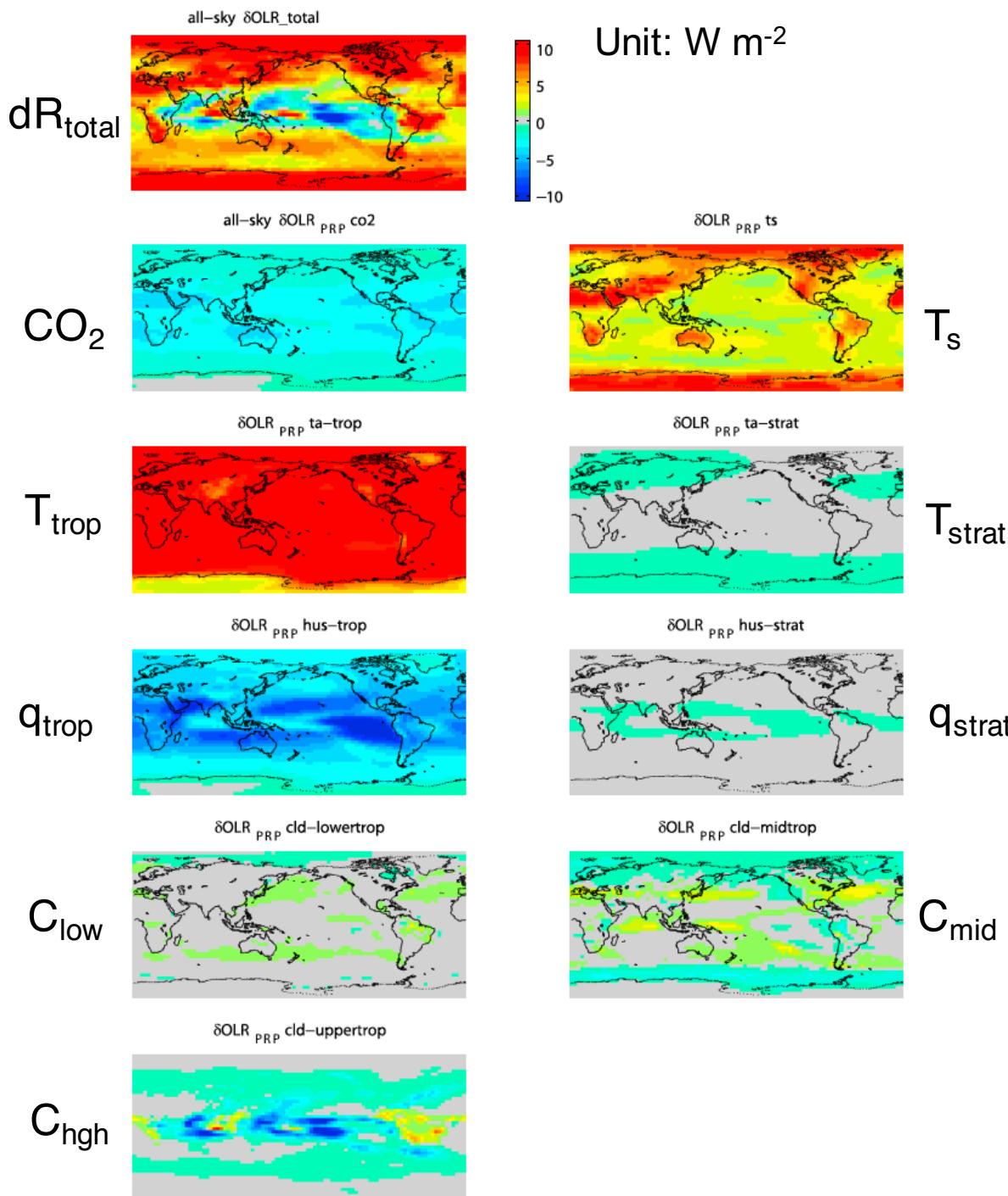
Infrared Spectral Fingerprinting

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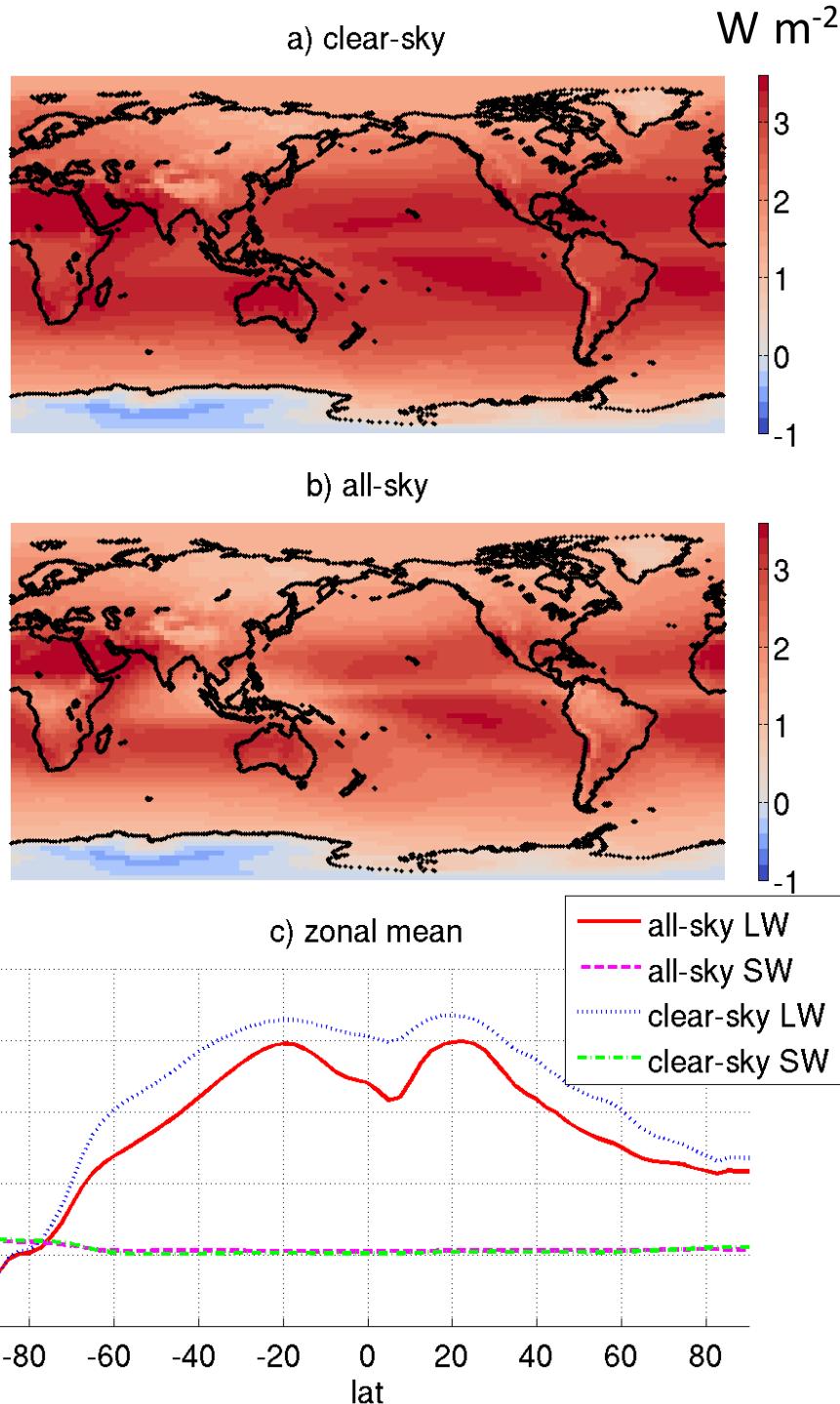
# Joint (IR+RO) fingerprinting performance



	RMS (IR)	RMS (IR+RO)	G.M.
$\text{CO}_2$	0.10	0.11	-2.73
$T_s$	3.27	3.88	3.35
$T_{\text{strat}}$	2.02	0.98	9.78
$q_{\text{strat}}$	0.25	0.09	-0.47
$q_{\text{trop}}$	1.32	0.73	-4.99
$C_{\text{low}}$	0.10	0.12	-0.27
$C_{\text{mid}}$	3.76	3.66	0.18
$C_{\text{high}}$	1.36	1.25	0.07
	3.05	1.07	-1.18

# Outline

- Homogeneous Greenhouse Gas (HGG) forcing
  - Distribution features
  - Reasons behind inhomogeneity and a regression model
  - Implications for Poleward Energy Transport (PET)
- Distinction of this work
  - Previous works were concerned with global mean value  
e.g. for CO<sub>2</sub> forcing:  $F = F_0 \log(C/C_0)$   
 $\Delta F \leq 10\%$  [Shi et al. 1990 ... Myhre et al. 1998 ... Byrne & Goldblatt 2014 ...IPCC AR1-5]
  - We are concerned with spatial and temporal variation  
“It is not practical to develop simplified expressions for meridionally resolved forcings.” [Byrne & Goldblatt 2014] - Is it?



## 2xCO<sub>2</sub> Forcing (Instantaneous Forcing)

- $F(2\text{xCO}_2)$  computed using RRTM and 5 yr 4x daily ERA-interim global atmos profiles (T, q, Cld, O3).
  - CO<sub>2</sub> 380 → 760 ppm.
  - Multi-year global Mean: 2.3  $\text{W m}^{-2}$  (all-sky)
  - Range of all monthly mean values: -2.5–5.1  $\text{W m}^{-2}$
- Note there is >300% variability – in comparison to <=10% variability in the global mean value [log formula from IPCC, ...])

# What causes forcing to vary?

- Consider  $F$  as resulting from change in greenhouse effect (trapping of surface emission)
  - =>  $F$  proportional to surface emission
  - => Predictor:  $T_s$  (surface temperature)
- Consider  $F$  as resulting from lifting of emission level
  - =>  $F$  proportional to atmospheric temperature change in the vertical
  - => Predictor:  $\Gamma$  (temperature lapse rate =  $T_s - T_{10\text{hPa}}$ )
- Cloud and water vapor masking effect
  - => Predictor: WVP (water vapor path), CRF (cloud radiative forcing =  $R_{\text{clear-sky}} - R_{\text{all-sky}}$ : Zhang&Huang [2014] found it is perfect for predicting  $F_c - F_a$ )

# Statistics

- Regression model:  $\underline{F} = F_0 + A^*(y-y_0)/y_0$ 
  - Solved by minimizing  $\sum W_i (\underline{F}_i - \underline{F})^2$ ,  $W_i = \cos(\text{latitude}_i)$ .
- Best predictor for clear-sky forcing  $F_c$  :  $\Gamma$

		Predictors: y							
		Ts	$\Gamma$	Ts, Ta	Ts, Ta, WVP		CRF		$F_c$ , CRF
$F_c$ GM=2.75, STD=1.06	r	0.91	0.96	0.91, 0.05	0.91, 0.05, 0.65	$F_c-F_a$ GM=0.51, STD=0.27	0.99	$F_a$ GM=2.24, STD=0.95	0.95, 0.06
	$y_0$	288.4	60.2	288.4, 228.2	288.4, 228.2, 26.30		18.1		n/a
	A	12.94	3.13	15.34, -8.33	18.99, -8.14, -0.42		0.48		n/a
	$R^2$	0.82	0.93	0.96	0.97		0.99		0.95
	err	0.48	0.50	0.23	0.21		0.04		0.22
	$GM_p$	2.75	2.75	2.75	2.75		0.51		2.24
	$STD_p$	0.94	0.93	1.00	1.08		0.26		0.96

# Prediction model

- Clear-sky

$$\hat{F}_c = 2.75 + 18.99 \frac{T_s - 288.4}{288.4} - 8.14 \frac{T_a - 228.2}{228.2} - 0.42 \frac{WVP - 26.3}{26.3} \quad \text{Eq. 1}$$

- Clear-all-sky difference

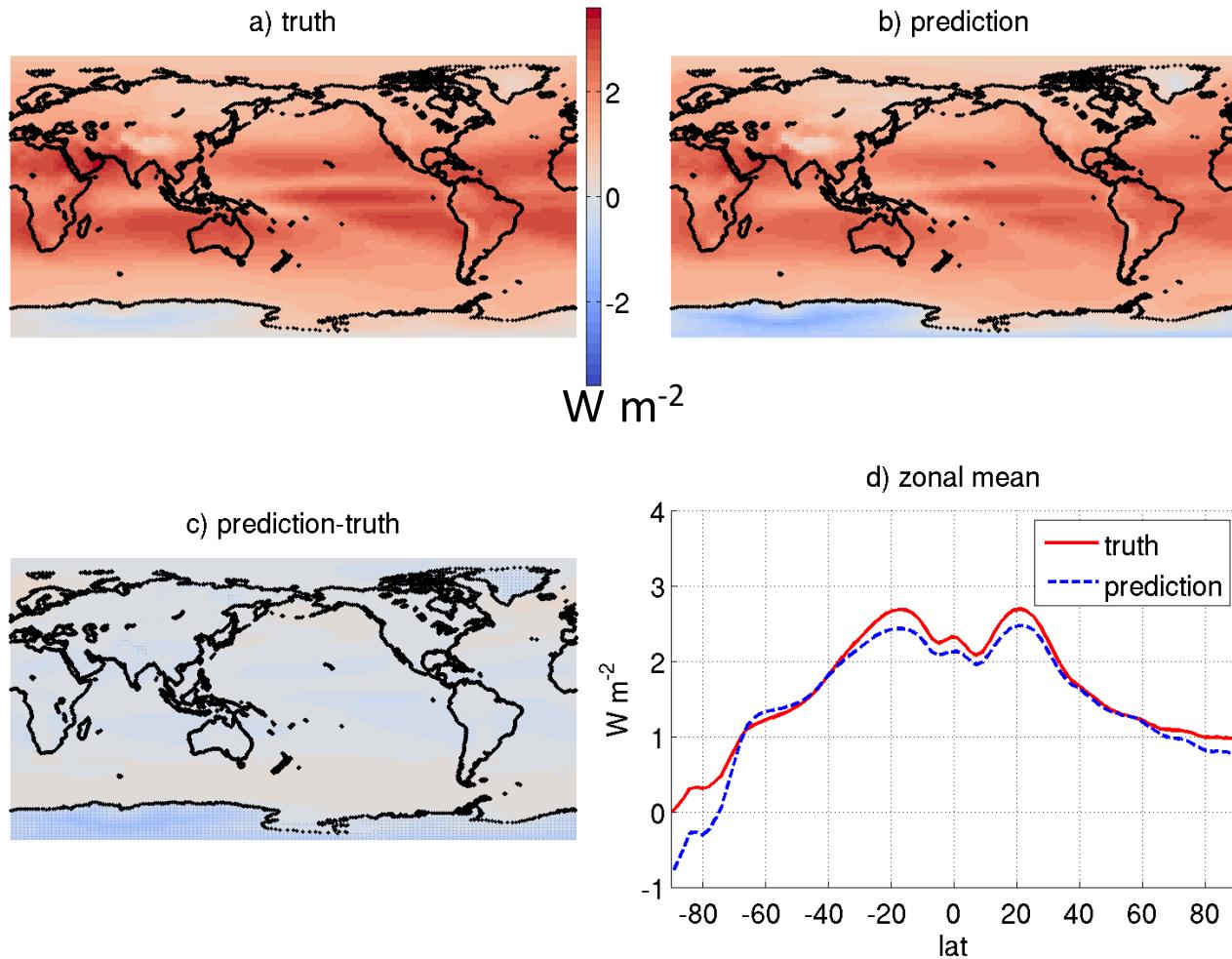
$$\Delta F = 0.51 + 0.48 \frac{CRF - 18.1}{18.1} \quad \text{Eq. 2}$$

- All-sky

$$\hat{F}_a = 2.24 + 18.99 \frac{T_s - 288.4}{288.4} - 8.14 \frac{T_a - 228.2}{228.2} - 0.42 \frac{WVP - 26.3}{26.3} - 0.48 \frac{CRF - 18.1}{18.1} \quad \text{Eq. 3}$$

A  $1.0 \text{ W m}^{-2}$  change in the doubling  $\text{CO}_2$  forcing can result from 15 K change in  $T_s$ , or 28 K change in  $T_a$ , or 63  $\text{kg m}^{-2}$  change in  $WVP$ , or 38  $\text{W m}^{-2}$  change in  $CRF$ .

# Validation test



Truth: Simulated by MODTRAN (a diff RT model!) from CM2 atmosphere

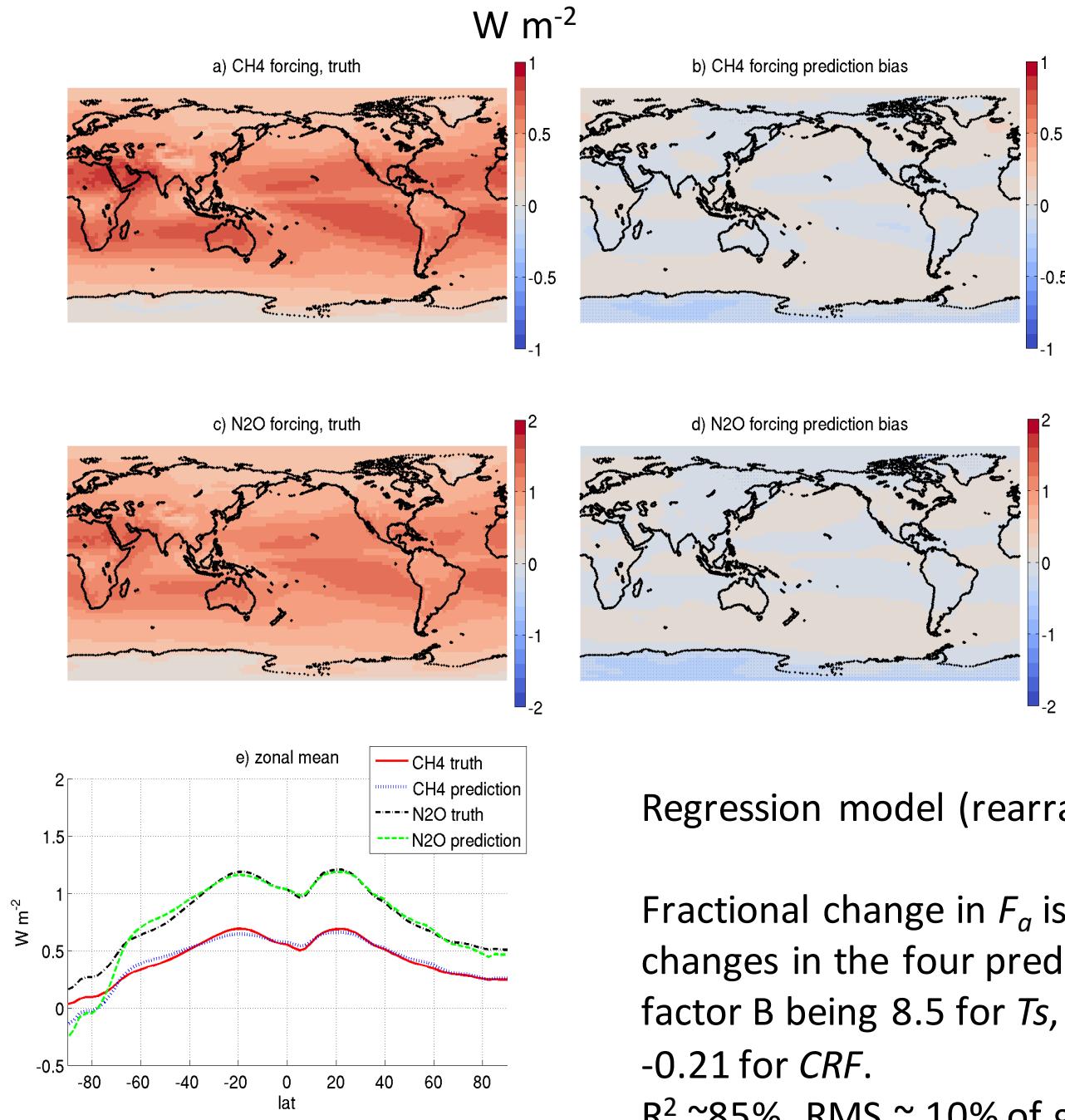
Prediction: Regression model (Eq. 3) + CM2 climatology ( $T_s$ ,  $T_a$ , WVP and CRF)

$R^2 = 0.94$ ; Mean standard error =  $0.2 \text{ W m}^{-2}$  (<10%)

Double-ITCZ bias disclosed by prediction – Climatology related bias detected!

# Other HGG forcing

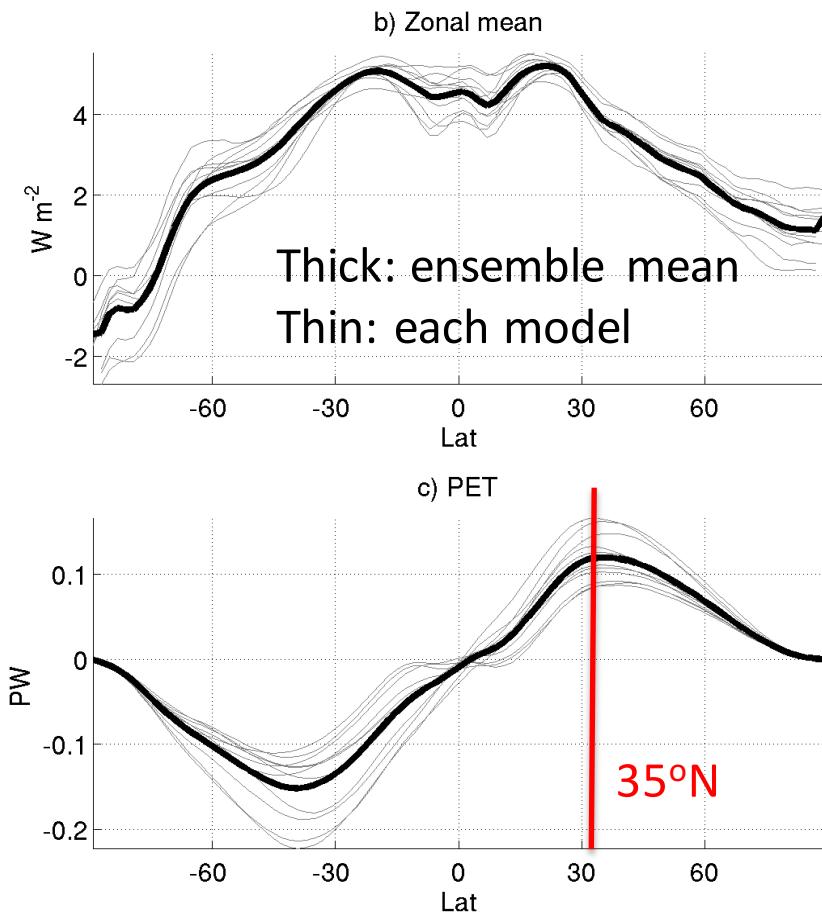
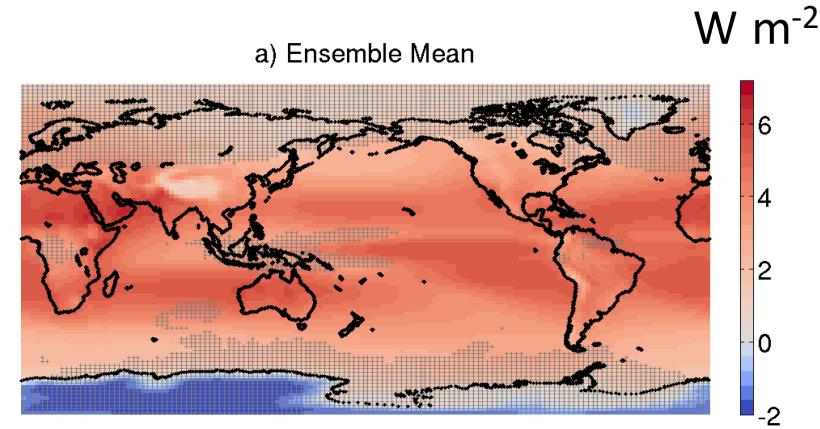
- 2xCH<sub>4</sub> and 2xN<sub>2</sub>O forcing greatly resembles 2xCO<sub>2</sub> forcing.  
=> Similar reason(s) behind forcing variation  
=> Same regression model may work?



Regression model (rearranged):  $\frac{\hat{F} - F_0}{F_0} = B \frac{y - y_0}{y_0}$

Fractional change in  $F_a$  is proportional to the fractional changes in the four predictor variables, with the scaling factor B being 8.5 for  $T_s$ , -3.6 for  $T_a$ , -0.19 for  $WVP$ , and -0.21 for  $CRF$ .

$R^2 \sim 85\%$ , RMS  $\sim 10\%$  of global mean.



## 4xCO<sub>2</sub> forcing in CMIP5 models

- Forcing predicted from GCM climatology using regression model

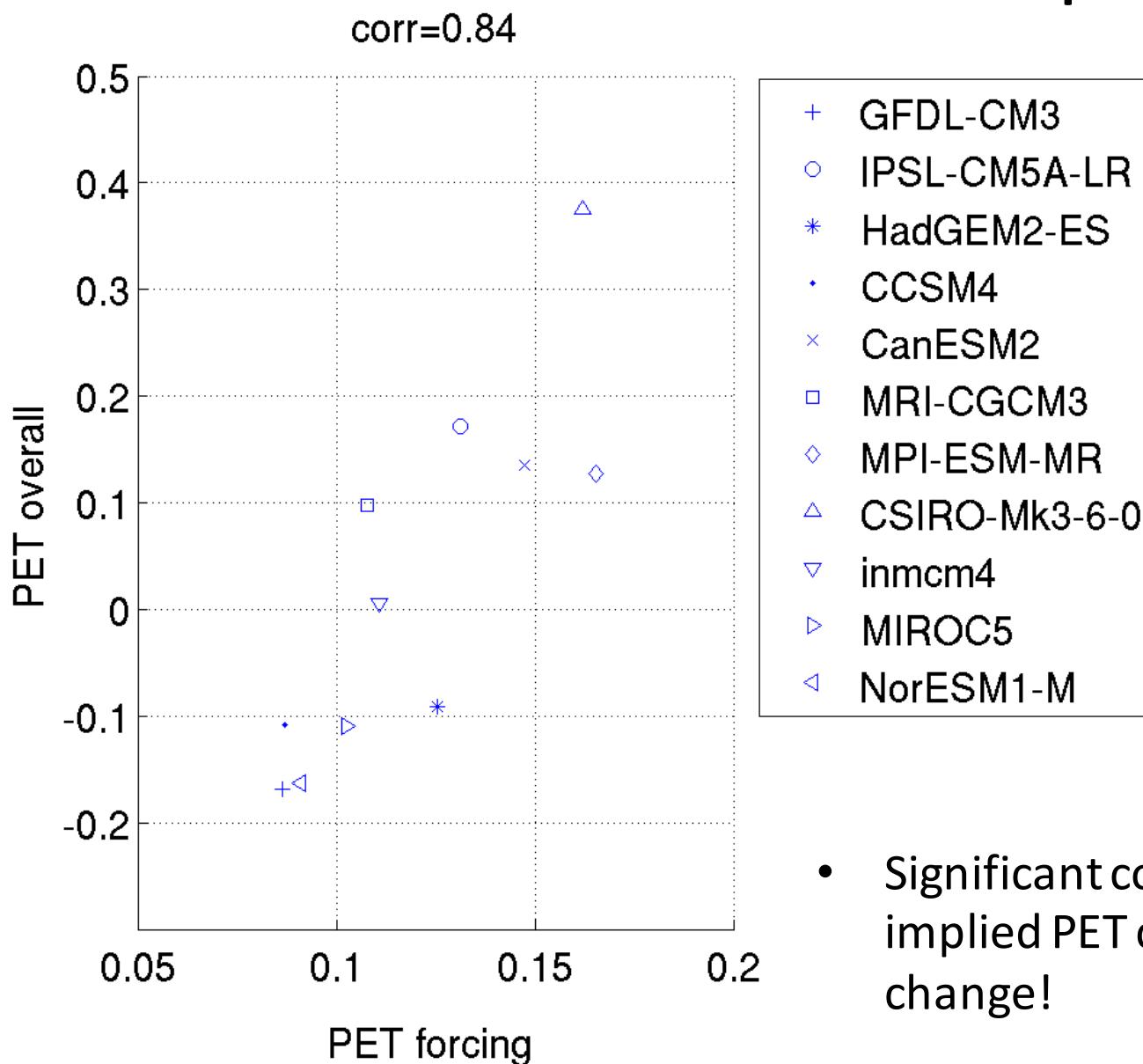
$$\hat{F} = F_0 + A \frac{y - y_0}{y_0}$$

- Implied PET calculated by integrating radiation anomaly from pole to pole [Eq.4 of Huang&Zhang 2014]

$$F(\phi) = \int_{-\frac{\pi}{2}}^{\phi} \int_0^{2\pi} R'_X(\lambda, \phi) \alpha^2 \cos \phi d\lambda d\phi$$

- Inter-model difference in forcing distribution => inter-model difference in implied PET (a factor of 2 at mid-latitudes)

# Impact on PET



- PET forcing: implied by forcing distribution
- PET overall: overall PET change in the models (assessed at the end of the abrupt $4\times\text{CO}_2$  experiment)
- Correlation shown for  $35^\circ\text{N}$  (typical of extratropics)
- Significant correlation between forcing implied PET change and actual PET change!

# Conclusions

- This study has
  - Demonstrated strong inhomogeneity in the radiative forcing of HGGs
  - Found the key factors that cause forcing variation (and built a regression model for estimating forcing)
  - Exemplified the important implications of forcing inhomogeneity
- These initial results suggest
  - Forcing distribution pattern have fundamental and profound impacts on the dynamical and circulation responses during global warming
  - Observational determination of HGG forcing needs global coverage – CLARREO!

## References

- Huang, Y., X. Tan and Y. Xia (submitted), Inhomogeneous forcing of homogeneous gas, JGR-Atmosphere.
- Huang, Y. and M. Zhang (2014), The implication of radiative forcing and feedback for poleward energy transport, GRL.