Quantifying the relative importance of the middle and upper troposphere for the clear-sky outgoing longwave radiation

GEWEX UTCC Process Evaluation Study

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Priyam Raghuraman, Ram Ramaswamy, and David Paynter

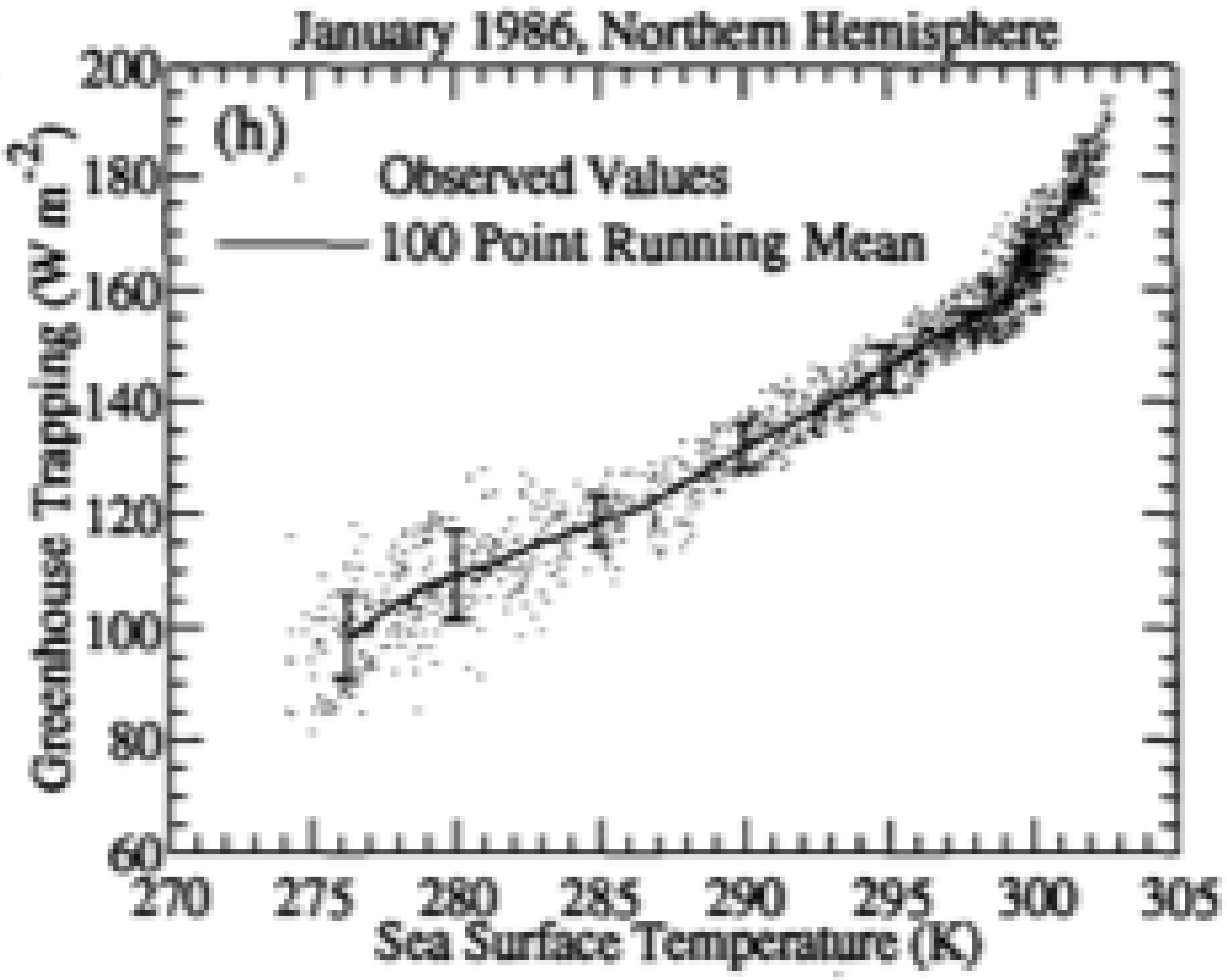
Geophysical Fluid Dynamics Laboratory

Outline

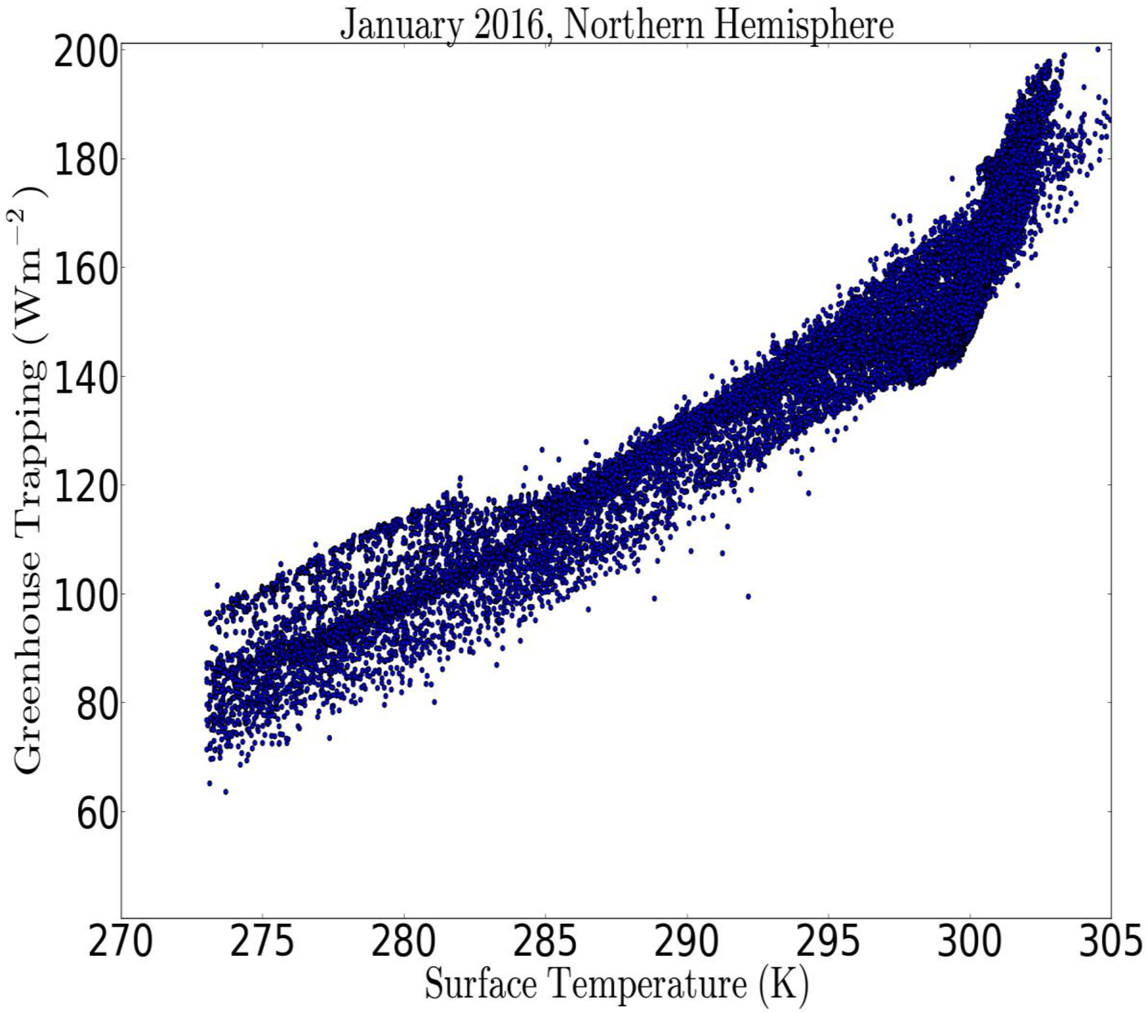
- Greenhouse and “Super” Greenhouse effect
- Dependence of Super Greenhouse Effect on atmospheric state during ENSO events
- Significance of the contributions due to water vapor
- Conclusions

Motivation – Non-linear increase of G

Greenhouse effect, $G = \sigma T_s^4 - OLR$, shows nonlinear increase with high SST, i.e., super greenhouse effect.

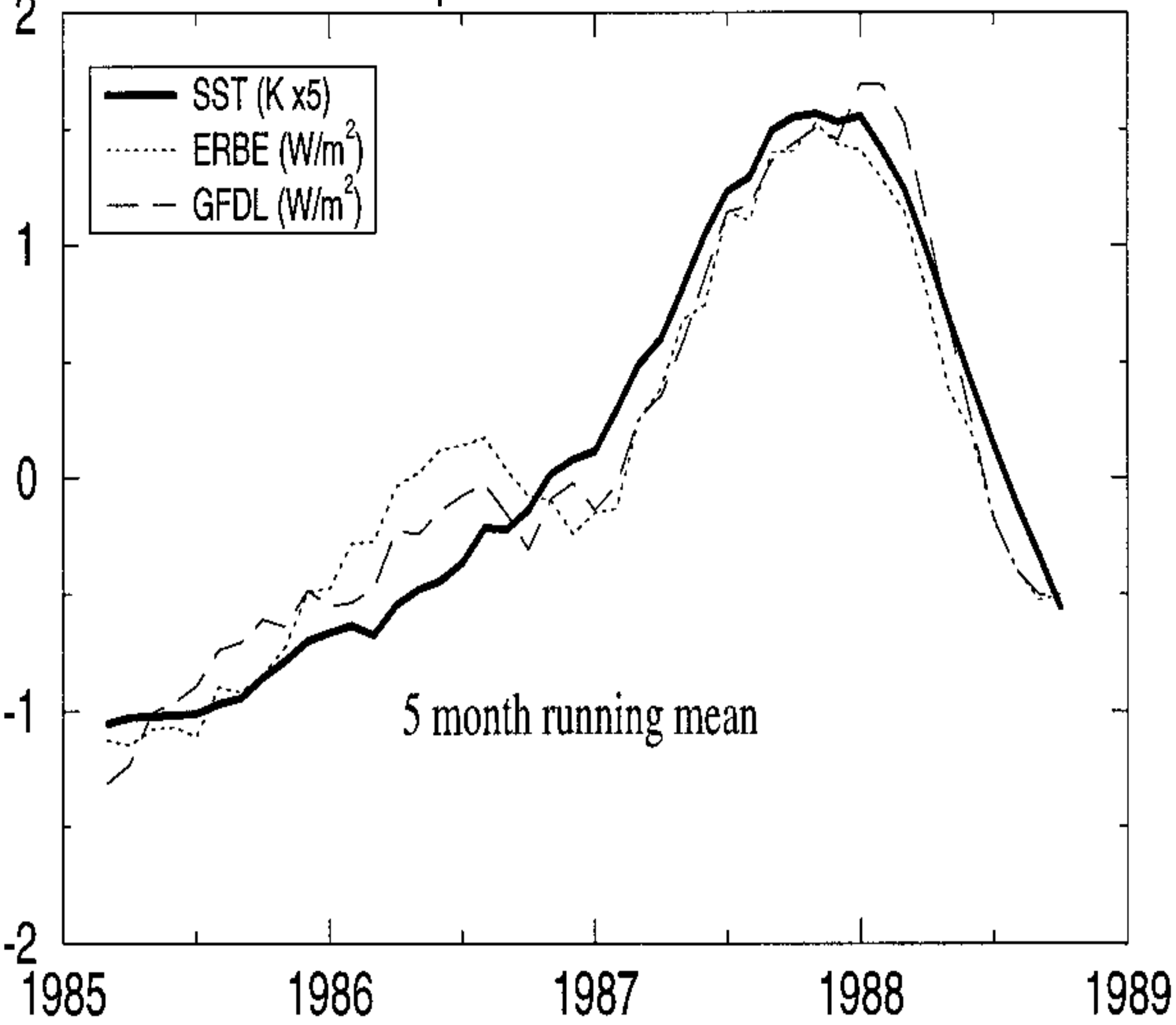


Hallberg and Inamdar, 1993

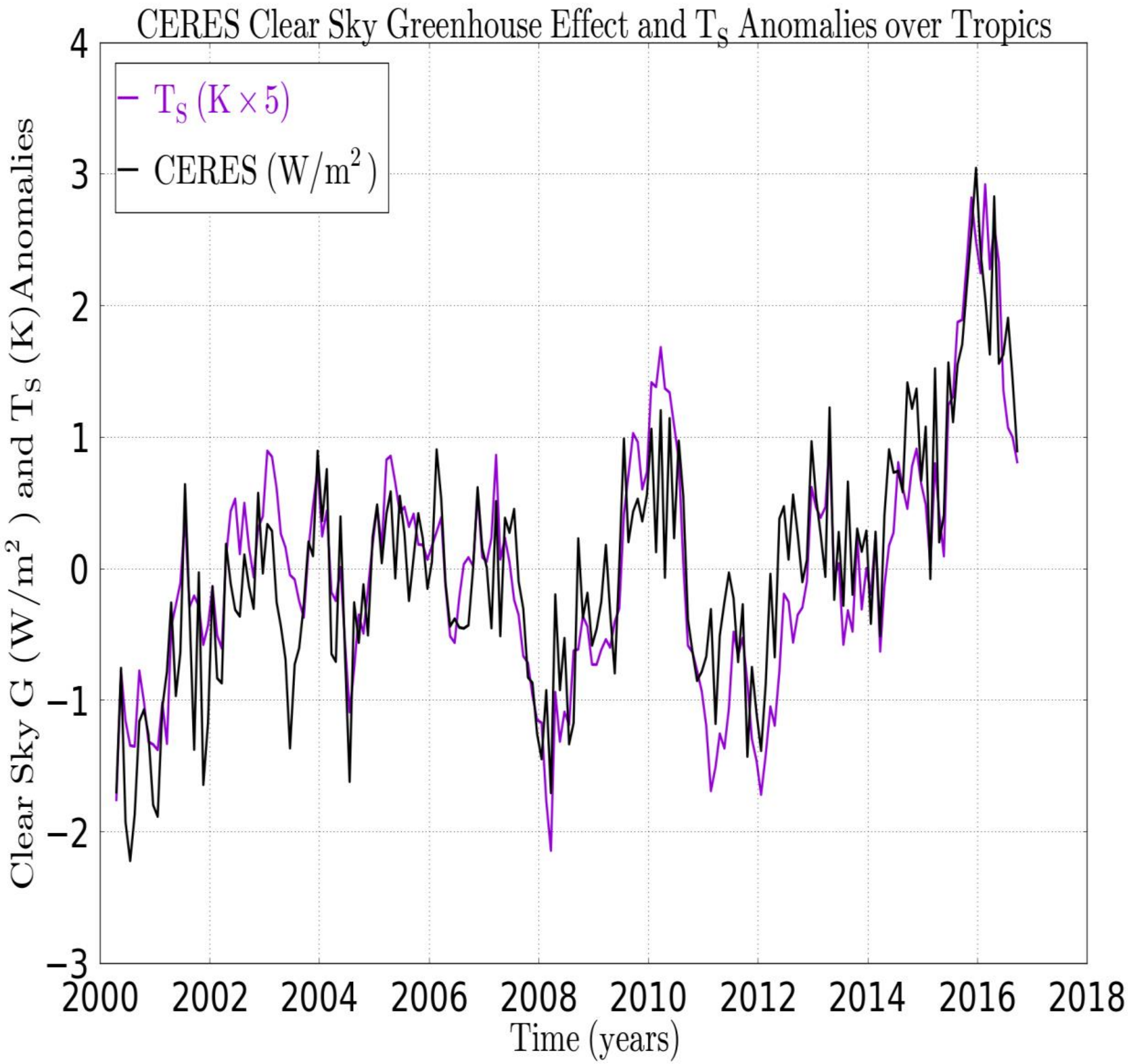


CERES (Cloud and the Earth's Radiant Energy System)

Motivation – Studying SGE via perspective of El Niño



Soden, 1996



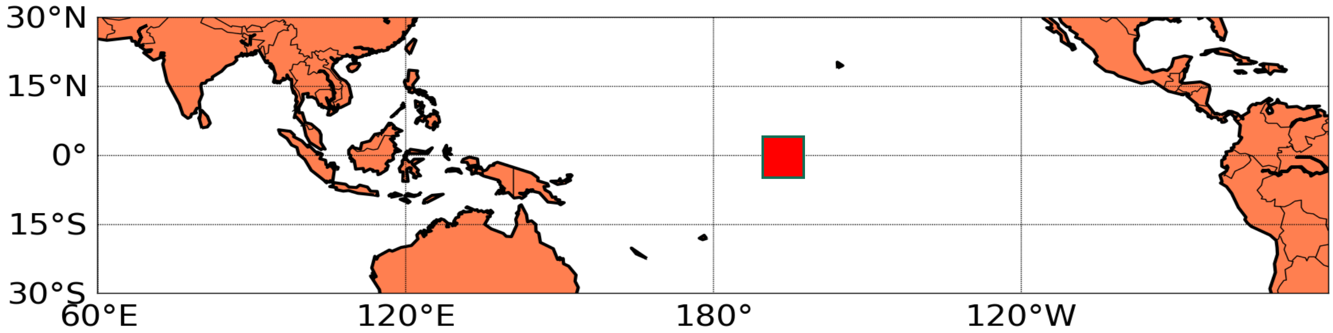
CERES

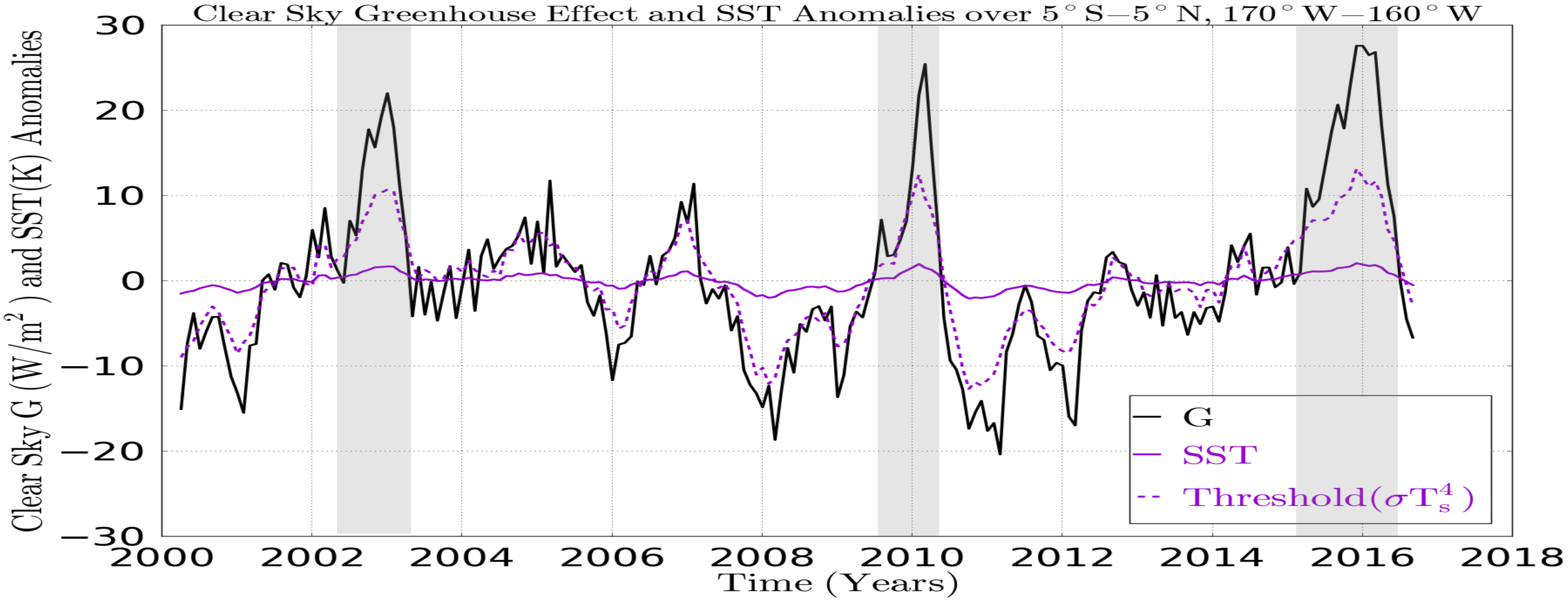
Super Greenhouse Effect– Threshold

Super Greenhouse Effect occurs when:

$$\frac{dG}{dT_s} > \frac{d(\sigma T_s^4)}{dT_s} \Rightarrow \frac{dOLR}{dT_s} < 0$$

Anomaly: $G_{\text{Month X}} - \overline{G_{\text{Month X}}}$

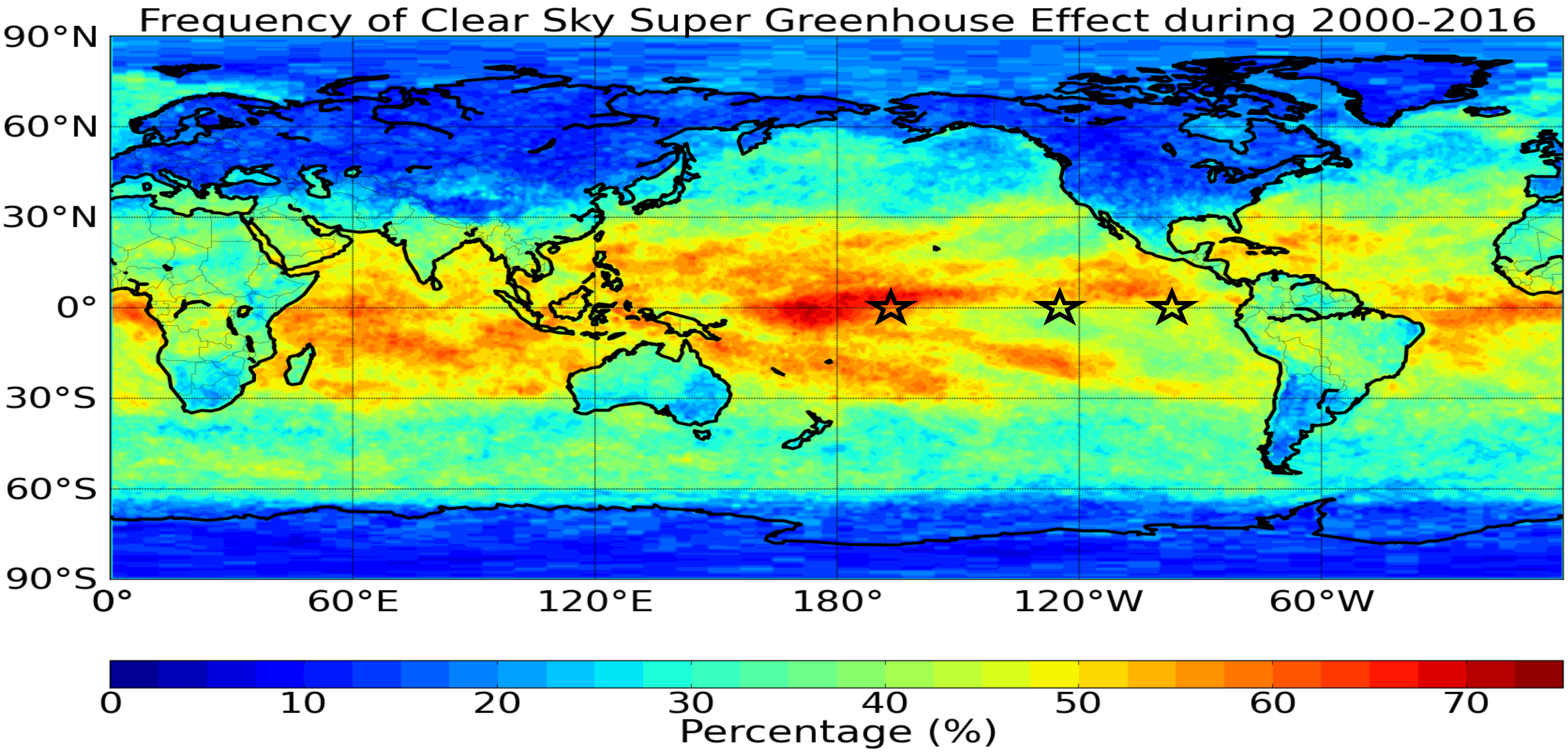




CERES

How often does the Super Greenhouse Effect occur?

Super Greenhouse Effect occurs when: $\frac{dG}{dT_s} > \frac{d(\sigma T_s^4)}{dT_s} \Rightarrow \frac{dOLR}{dT_s} < 0$



CERES

Radiative Contributions to SGE

What is the breakdown and quantification of the roles of surface temperature, atmospheric temperature, and water vapor in determining the Super Greenhouse Effect?

$$G = \sigma T_S^4 - \text{OLR},$$

Adapted from Clough, 1992

$$G = \sigma T_S^4 - \pi \int_{\nu} \left(B_{\nu}(T_s)\Gamma_{atm} + \sum_{i=1}^{N} B_{\nu}(T_i) \cdot \Delta\Gamma_i^{TOA} \right)$$

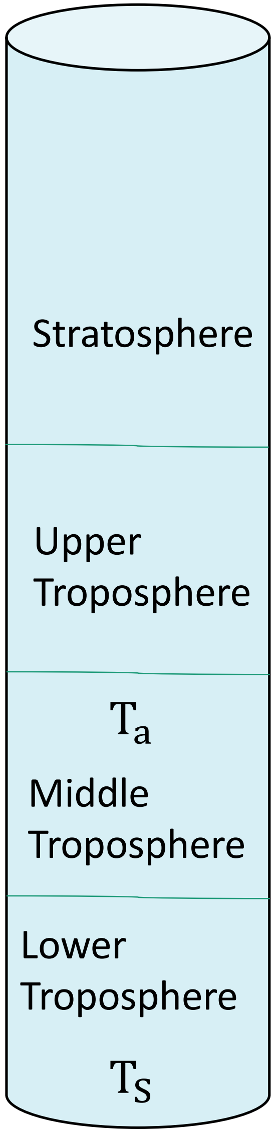
$$B(\nu, T) = \frac{c_1 \nu^3}{e^{\frac{c_2 \nu}{T}} - 1},$$

Surface Temperature

Temperature of atmospheric layer

Opacity of atmosphere

where $B(\nu, T)$ is the Planck function, $\Gamma(\tau, T, p)$ is the transmittance function which depends on τ, the optical depth.



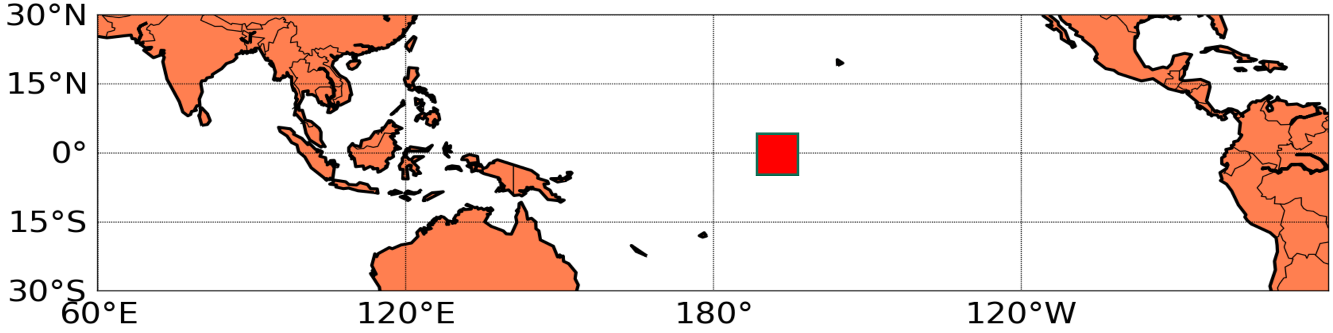
Atmospheric Column Schematic

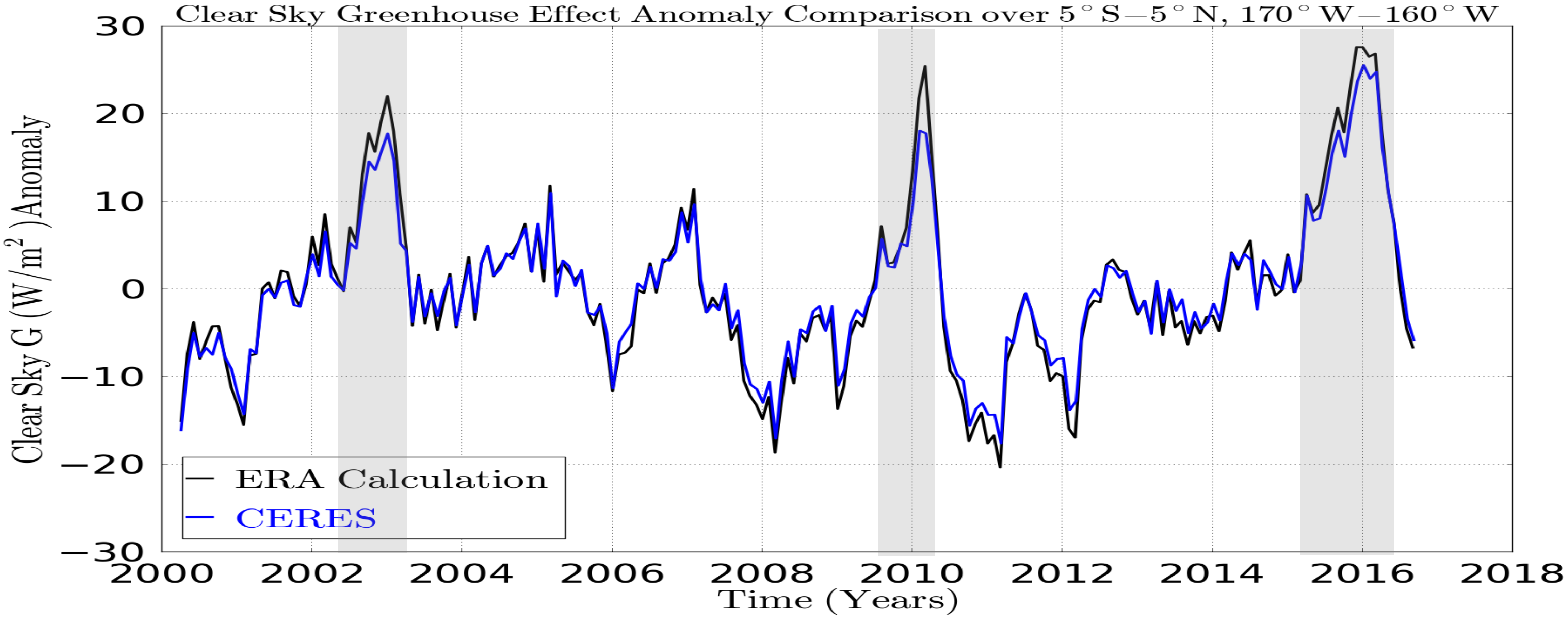
Studying the Super Greenhouse Effect during ENSO events

- Do the assumptions for tropics for SGE apply during ENSO events?
- Hypothesized causes for Super Greenhouse Effect (put forward by Raval and Ramanathan, 1989; Ramanathan and Collins, 1991; Hallberg and Inamdar, 1993; Kahn et al., 2016, Stephens et al., 2016):
    - Changes in middle and upper tropospheric humidity.
    - Thermodynamically controlled increases in water vapor.
    - Excess trapping from “window” region.

Confidence Check – Can we reproduce the time series?

G calculated from ERA input captures CERES variability





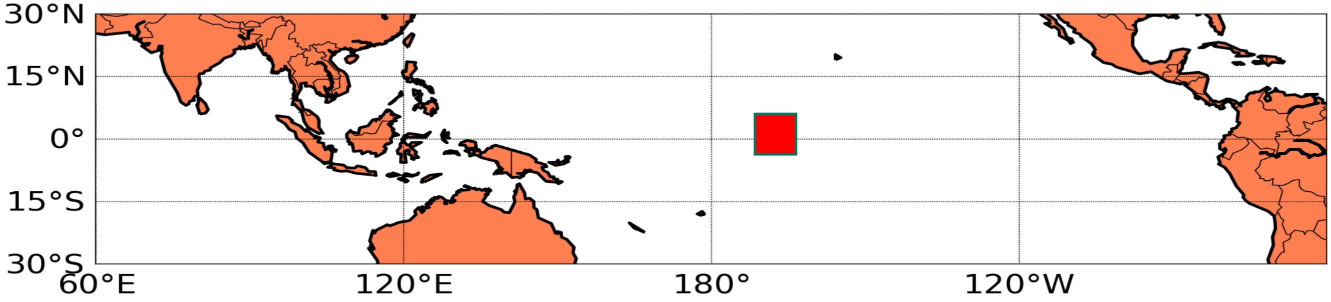
Experimental Setup – Component Calculation

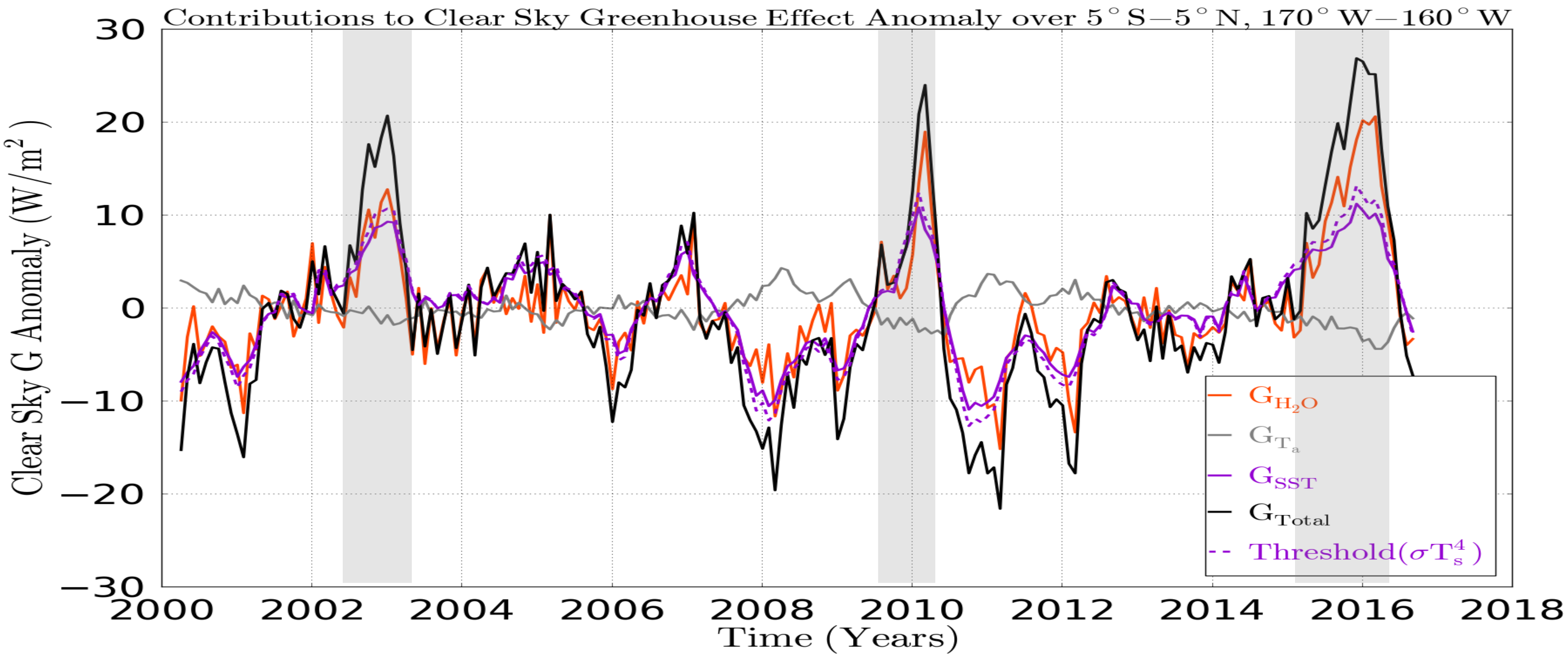
Experiment Name	Quantity Varying Monthly	Quantity with Monthly Climatology
Run 0	H_2O, T_a, T_S	None
Run 1	T_a, T_S	H_2O
Run 2	T_S	H_2O, T_a
Run 3	None	H_2O, T_a, T_S

Experiment Name	Impact of quantity varying
Run 0-1	H_2O
Run 1-2	T_a
Run 2-3	T_S
Run 0-3	H_2O, T_a, T_S

Contributions to Greenhouse Effect

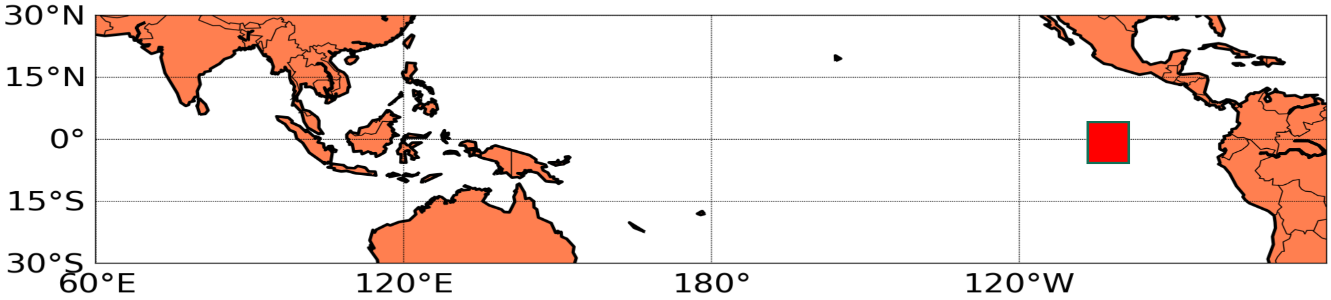
Water vapor contributing most to SGE

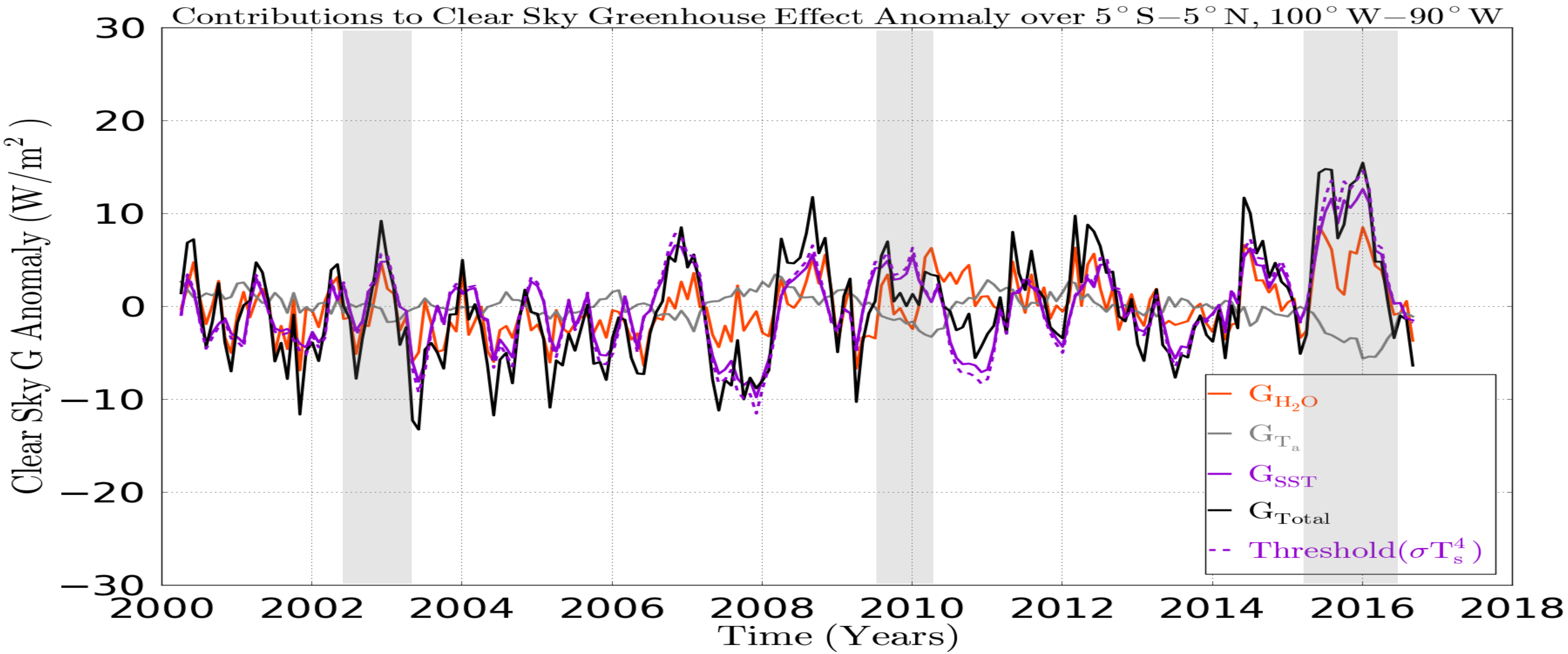




Contributions to Greenhouse Effect

Water vapor contribution to SGE decreases eastward

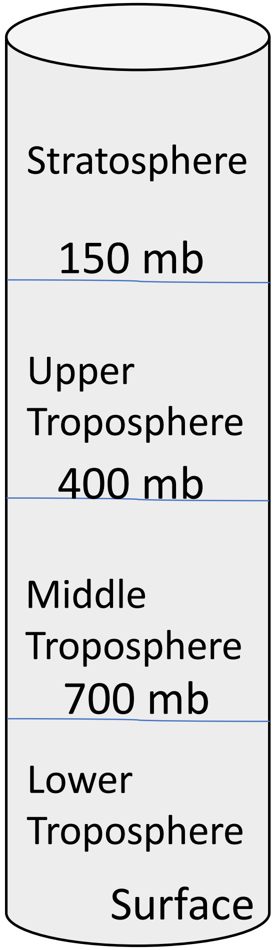




Experimental Setup – Water Vapor Components

Experiment Name	Quantity Varying Monthly	Quantity with Monthly Climatology
Run 1a	H_2O_{LT}, T_a, T_S	$H_2O_{MT}, H_2O_{UT}, H_2O_{Strat.}$
Run 1b	H_2O_{MT}, T_a, T_S	$H_2O_{LT}, H_2O_{UT}, H_2O_{Strat.}$
Run 1c	H_2O_{UT}, T_a, T_S	$H_2O_{LT}, H_2O_{MT}, H_2O_{Strat.}$
Run 1d	$H_2O_{Strat.}, T_a, T_S$	$H_2O_{LT}, H_2O_{MT}, H_2O_{UT}$
Run 1	T_a, T_S	H_2O

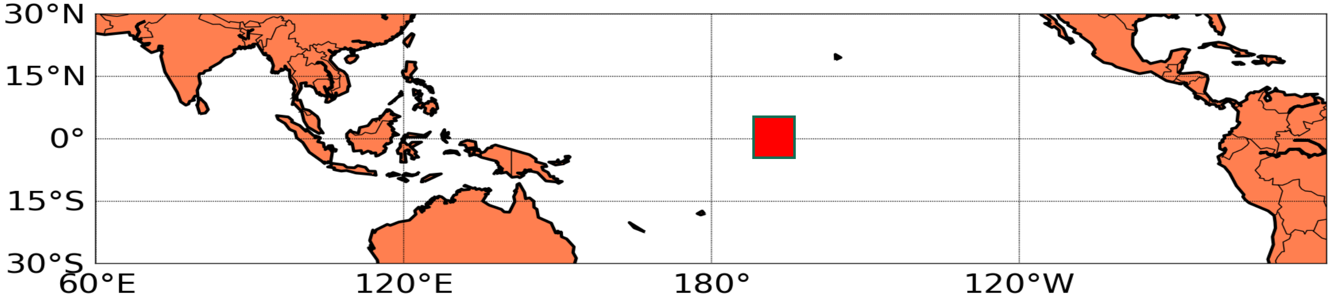
Experiment Name	Impact of quantity varying
Run 1a-1	H_2O_{LT}
Run 1b-1	H_2O_{MT}
Run 1c-1	H_2O_{UT}
Run 1d-1	$H_2O_{Strat.}$
Run 0-1	H_2O

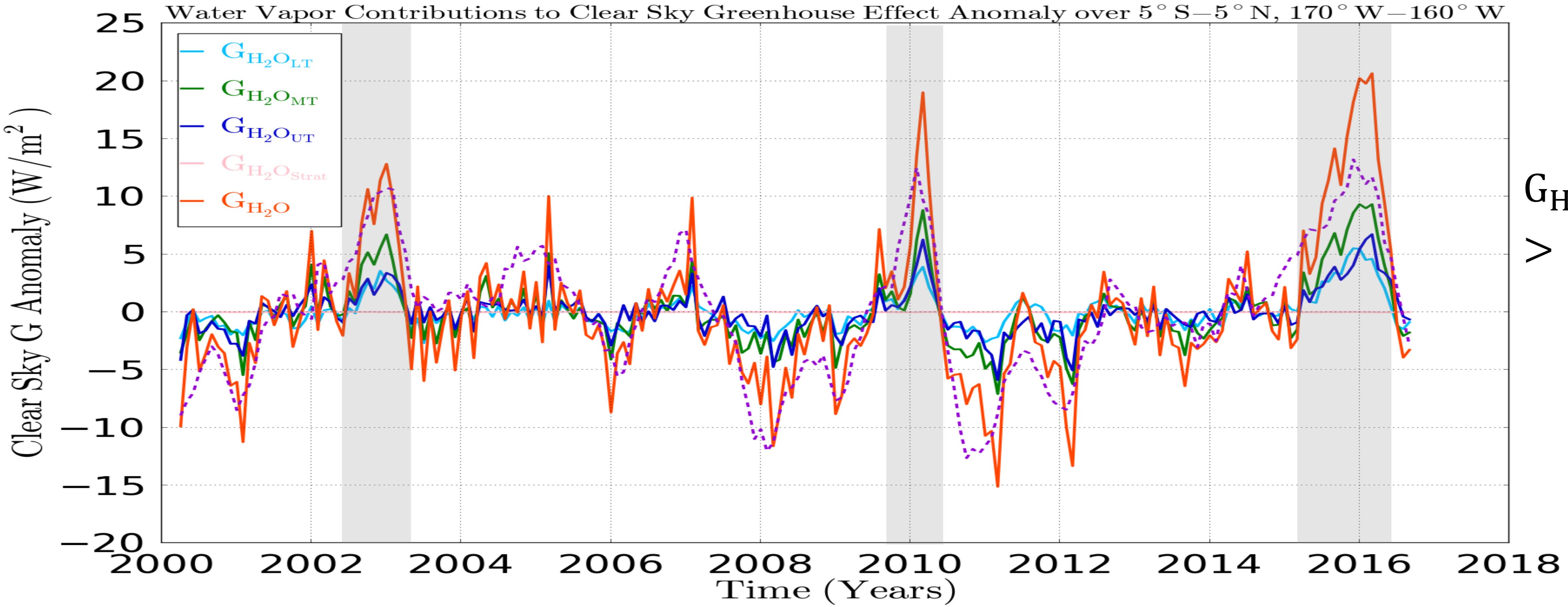


Water Vapor Contributions to Greenhouse Effect

"…tropics exhibit a strong positive coupling between T_s, G_a, and water vapor distributions with large increases in the midtroposphere humidity…." IR, 1998

"Upper tropospheric water vapor contributes most to the SGE…" HR, 2008





$G_{H_2O_{MT}} > G_{others}$

Why does the MT contribute the most to the Super Greenhouse Effect?

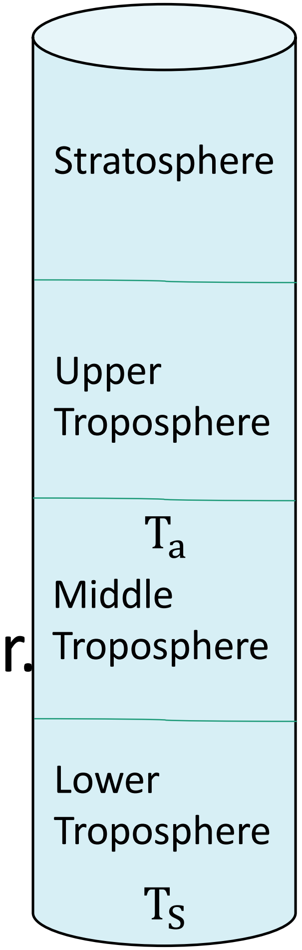
$$\Delta G_{MT} = \left(\frac{\partial G_{MT}}{\partial H_2O_{MT}}\right) \times \Delta H_2O_{MT},$$

$$\Delta H_2O_{MT} = H_2O_{MT} - \overline{H_2O_{MT}},$$

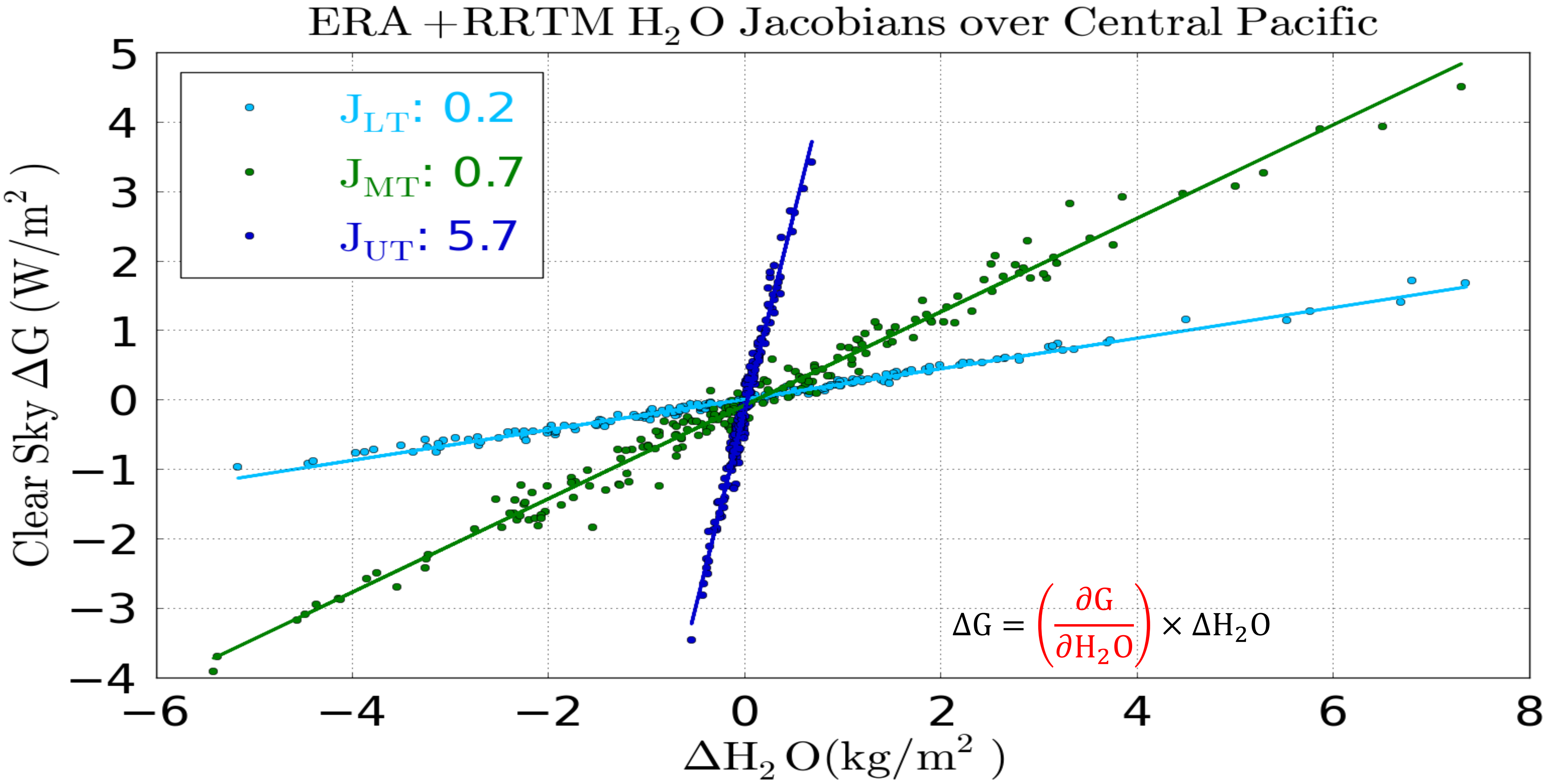
$$J_{MT} = \frac{\partial G_{MT}}{\partial H_2O_{MT}},$$

which is the Jacobian, i.e., sensitivity of G to changes in water vapor.

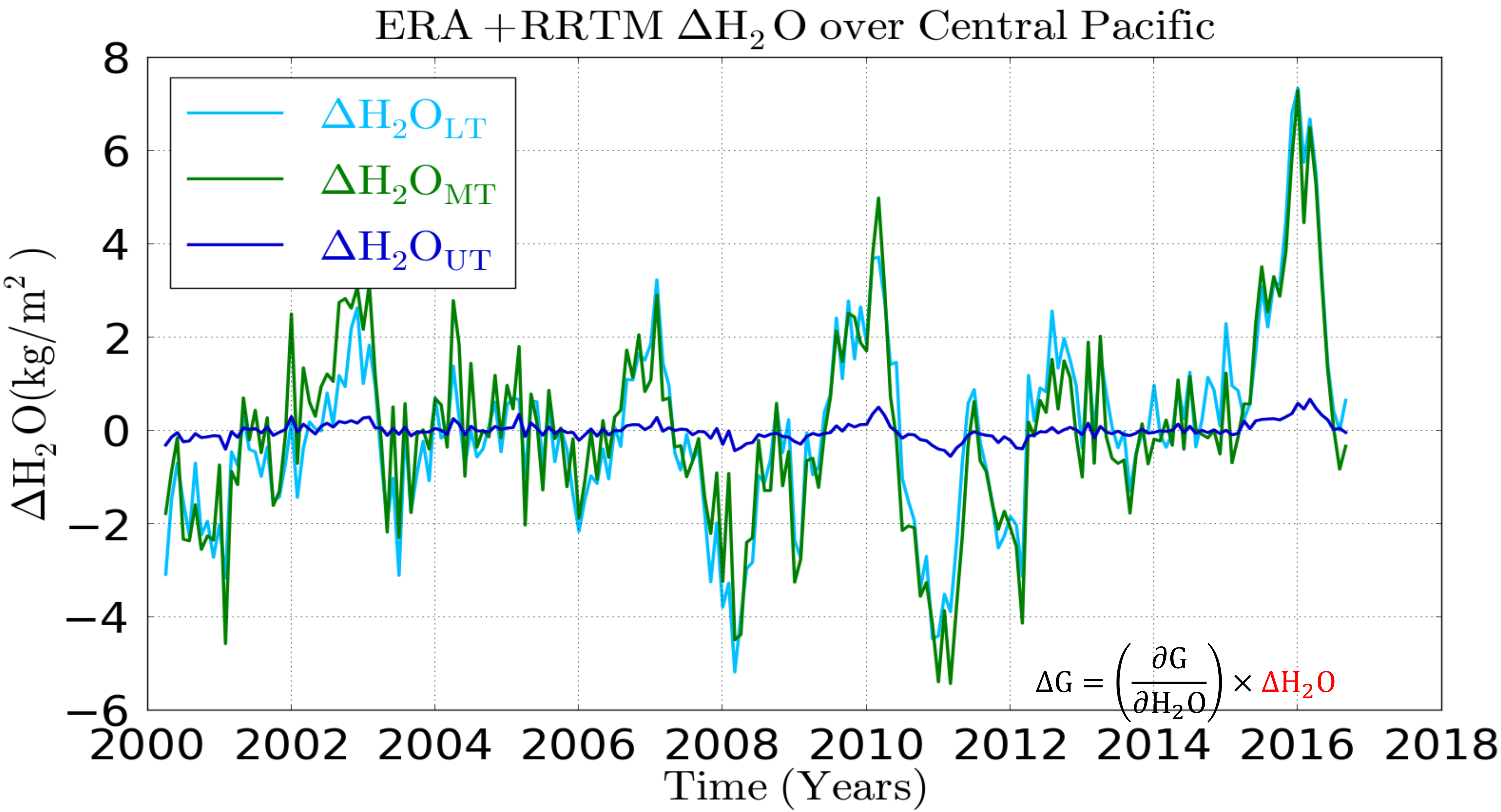
Units of Jacobian: $\left(\frac{\frac{\frac{W}{m^2}}{kg}}{m^2}\right) = \frac{W}{kg}$



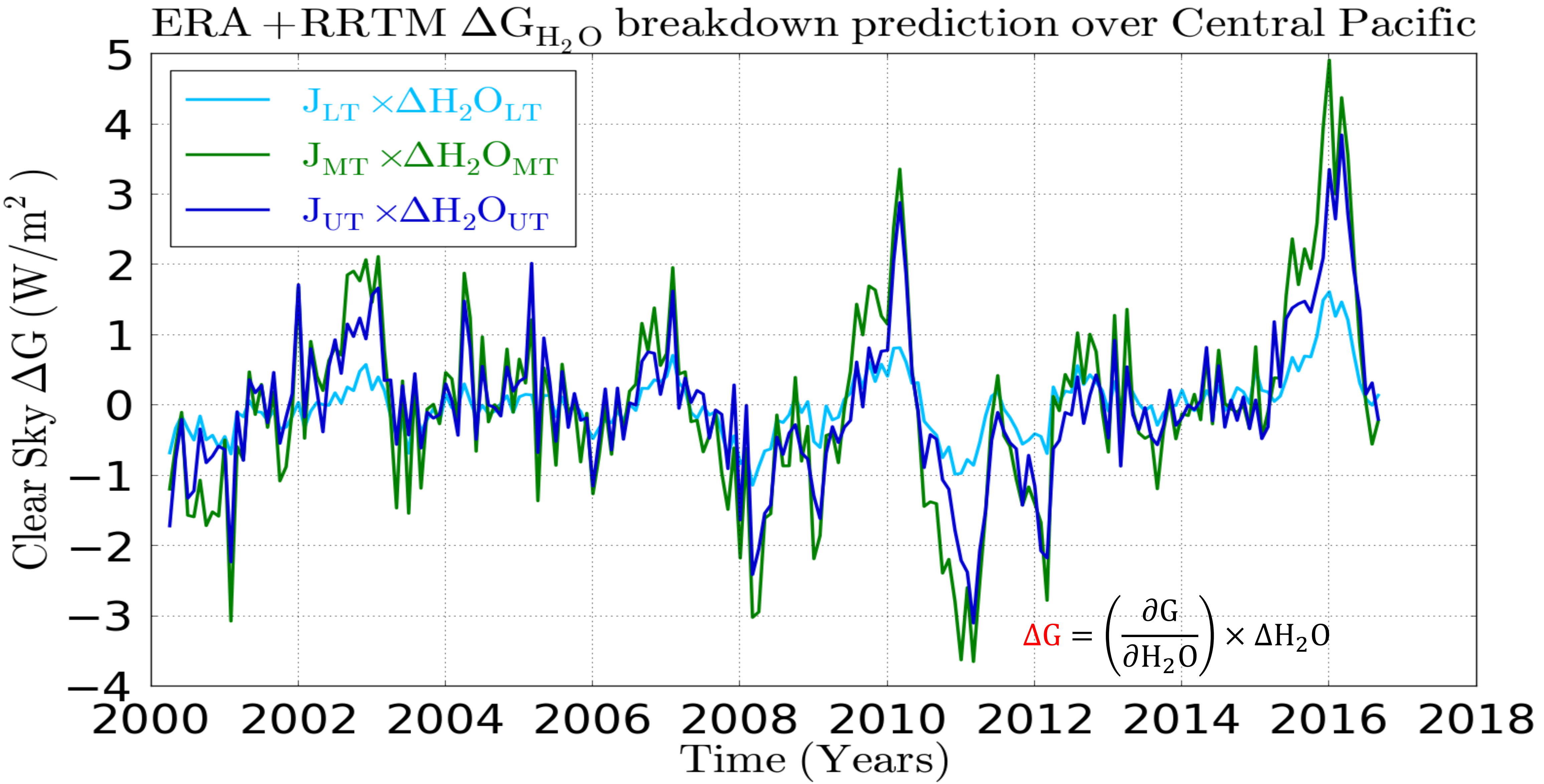
Why does Middle Tropospheric Water Vapor trap the most energy?



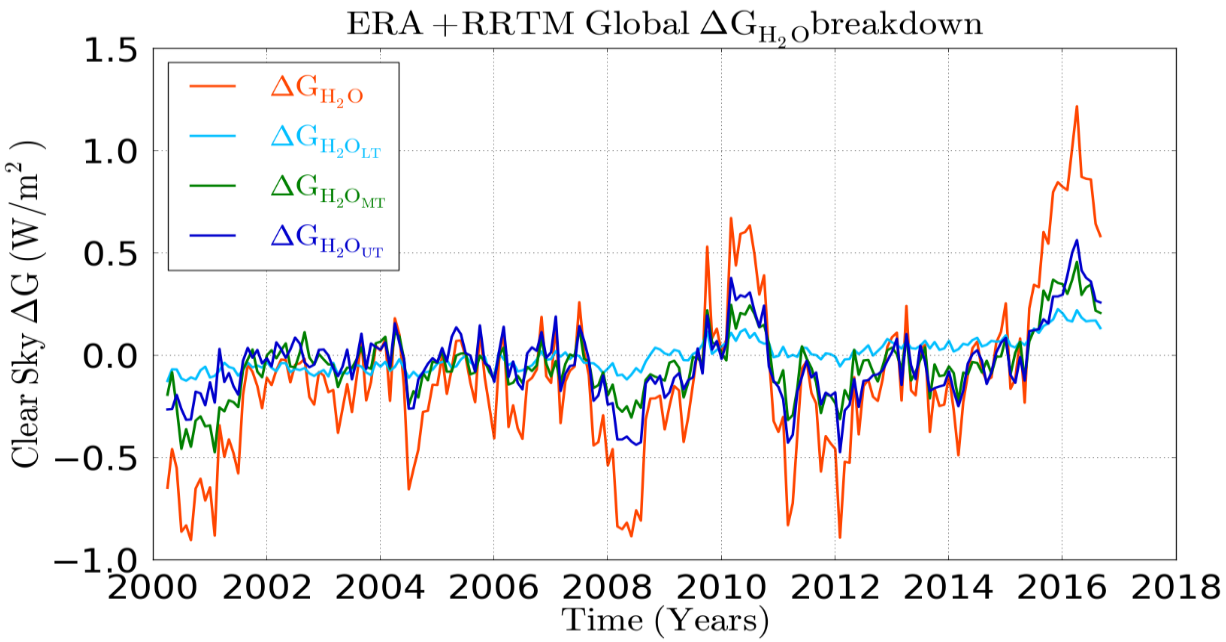
Change in Water Vapor

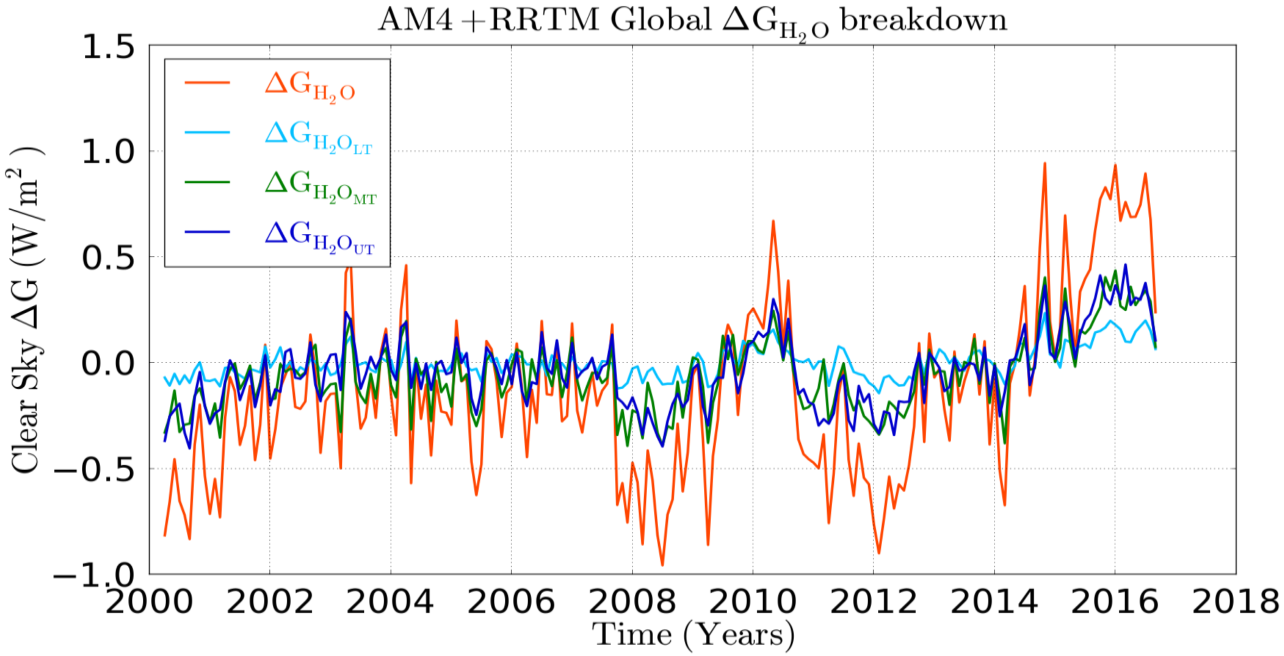


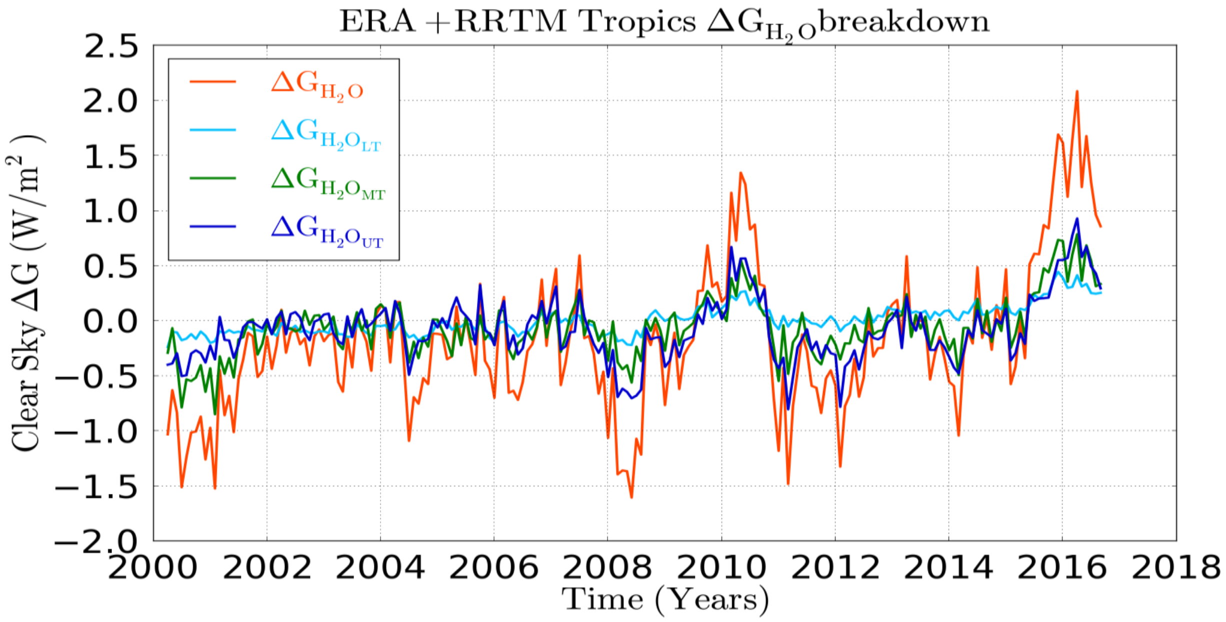
Middle Troposphere most important contributor to the Greenhouse Effect

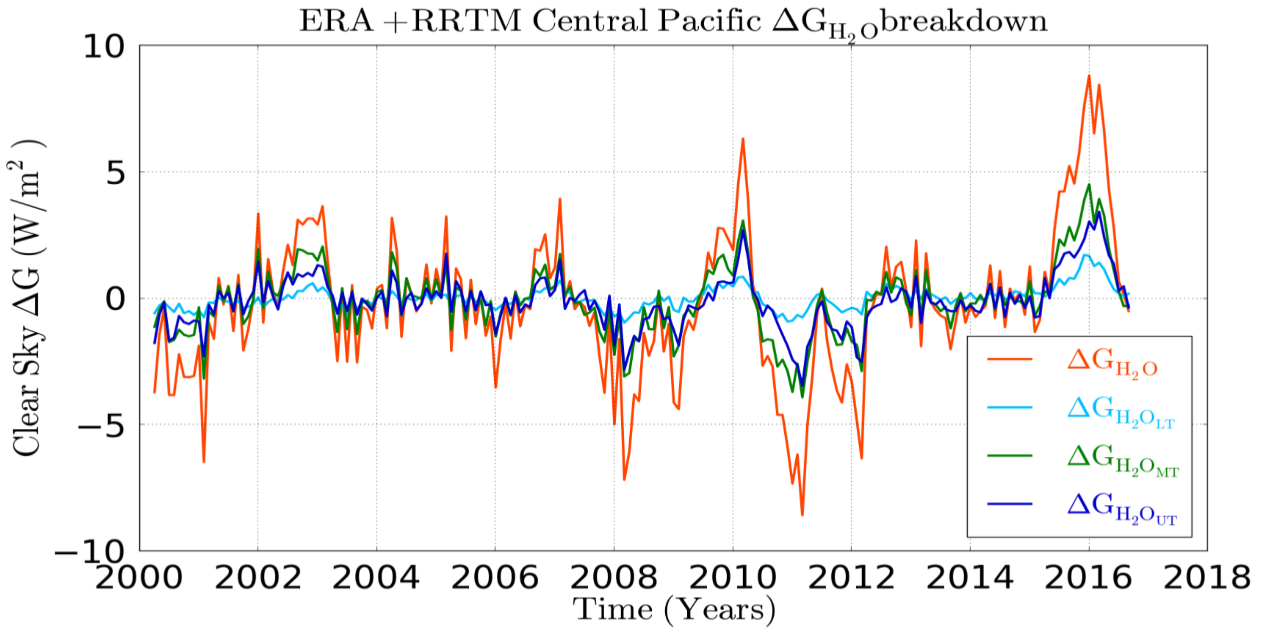


Water Vapor Contributions to the Greenhouse Effect





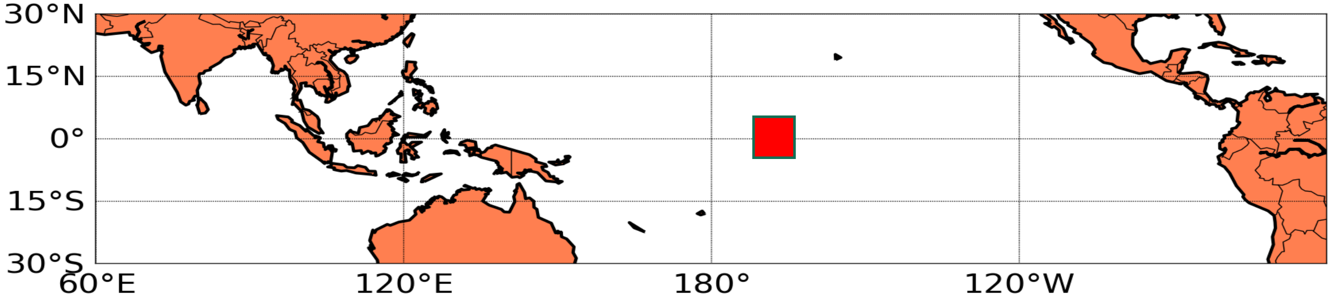


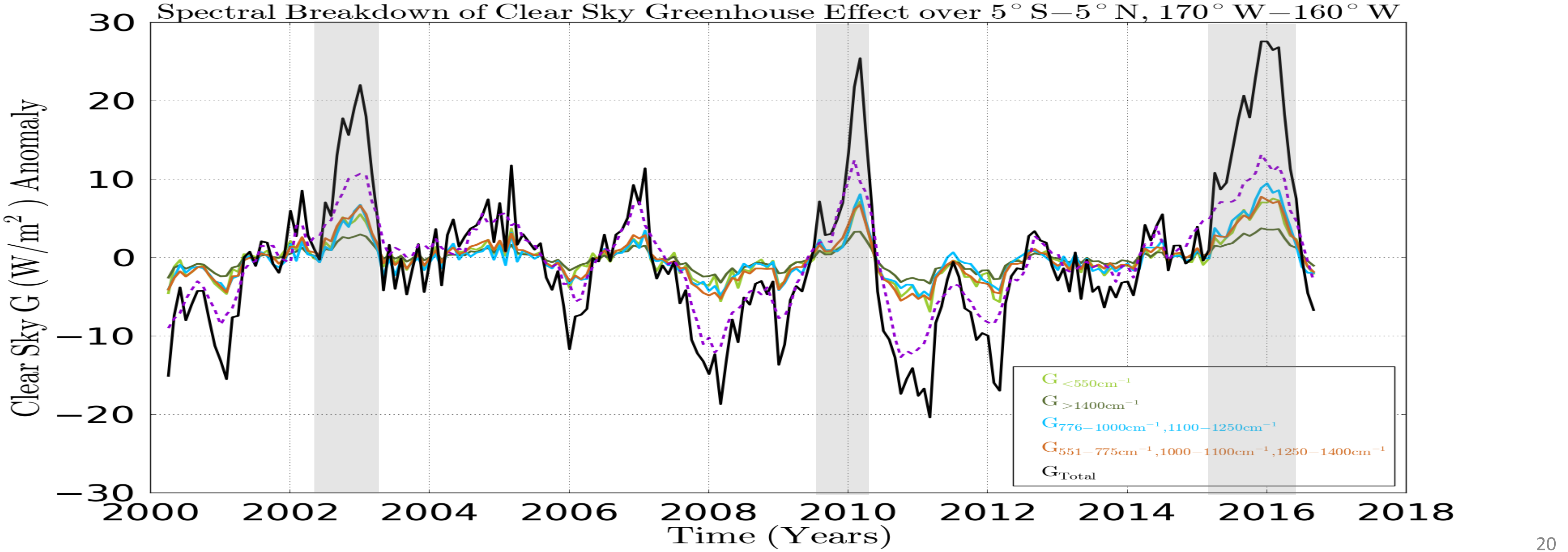


Spectral Contributions to Greenhouse Effect

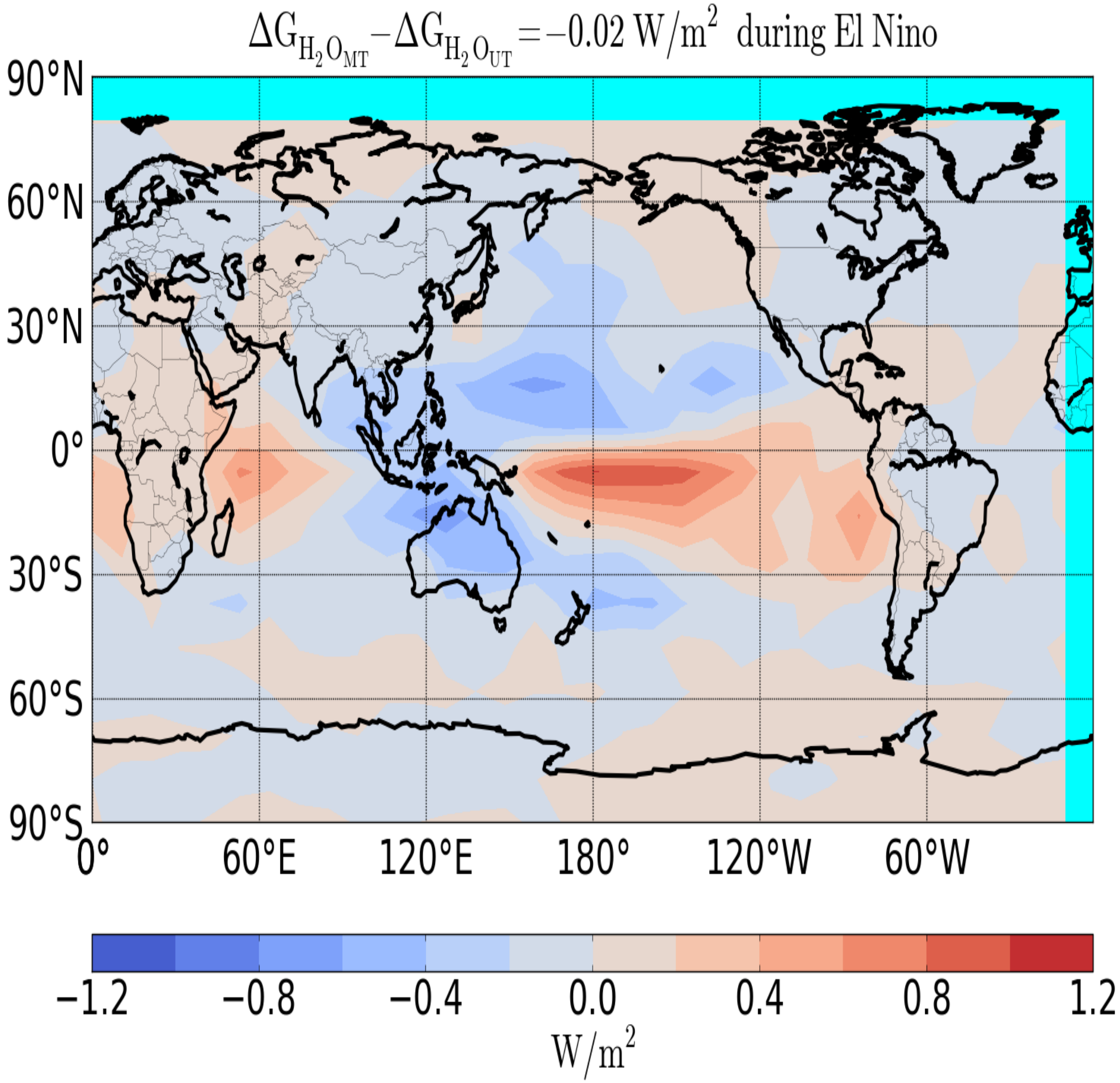
"…water vapor continuum plays an important role in the super greenhouse effect of the atmosphere." IR,1994

"Most of the SGE arises from the water vapor vibration-rotational band and the rotational band" HR, 2008

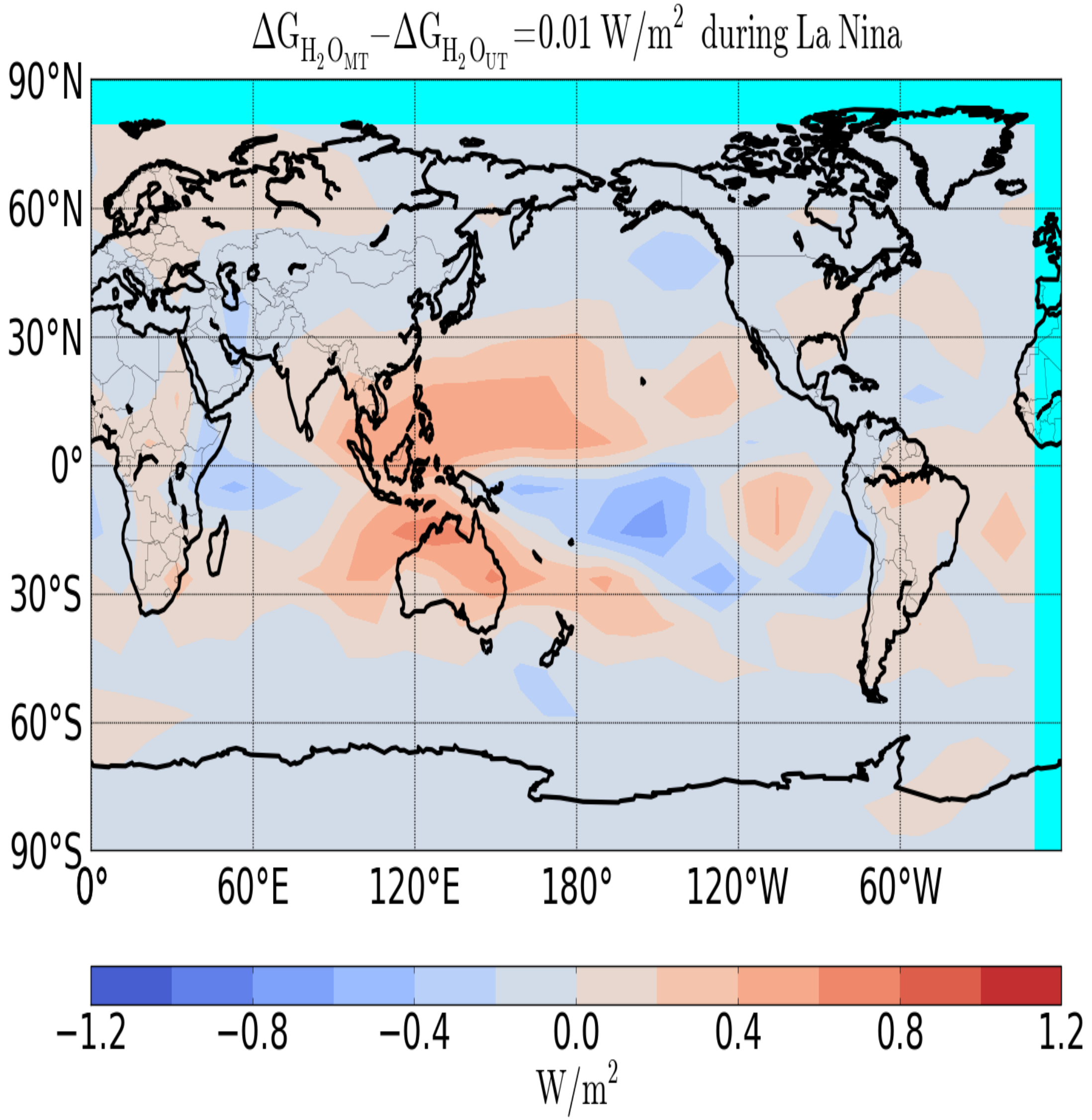




MT-UT



$\Delta G_{H_2O_{MT}} - \Delta G_{H_2O_{UT}} = -0.02\ W/m^2$ during El Nino
90°N
60°N
30°N
0°
30°S
60°S
90°S
0°
60°E
120°E
180°
120°W
60°W
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
W/m^2



$\Delta G_{H_2O_{MT}} - \Delta G_{H_2O_{UT}} = 0.01\ W/m^2$ during La Nina
90°N
60°N
30°N
0°
30°S
60°S
90°S
0°
60°E
120°E
180°
120°W
60°W
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
W/m^2

Summary and Conclusions

- Quantifying the factors important for generating the Super Greenhouse Effect (SGE) during recent ENSOs using satellite observations and line-by-line radiative transfer model.
- Entire LW spectrum important for the SGE but middle troposphere a dominant contributor to the SGE, challenging conclusions from previous studies.
- Enhanced radiative significance of clouds to moisture in UT during warming situations.

Future Work

- Use global line-by-line model and spectral observations (Atmospheric Infrared Sounder (AIRS) satellite) to further quantify factors driving SGE globally.
- Use observations and GCMs to understand role of deep convection in MT and UT moistening processes.
- Outcomes for Climate Sensitivity and moistening of the atmospheric column during SST increases/decreases.
- Impact of Global Warming on SGE.

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