# Climate Models & Climate Sensitivity

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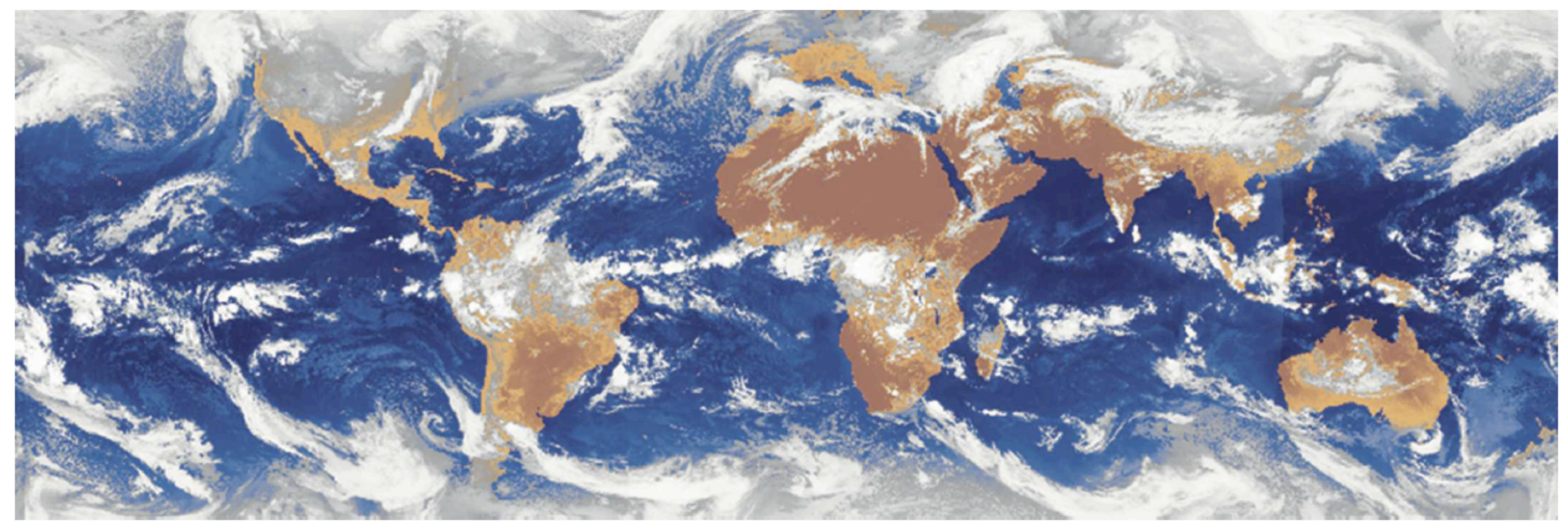
# Infrared Cloud Image



*Bony et al. 2006*

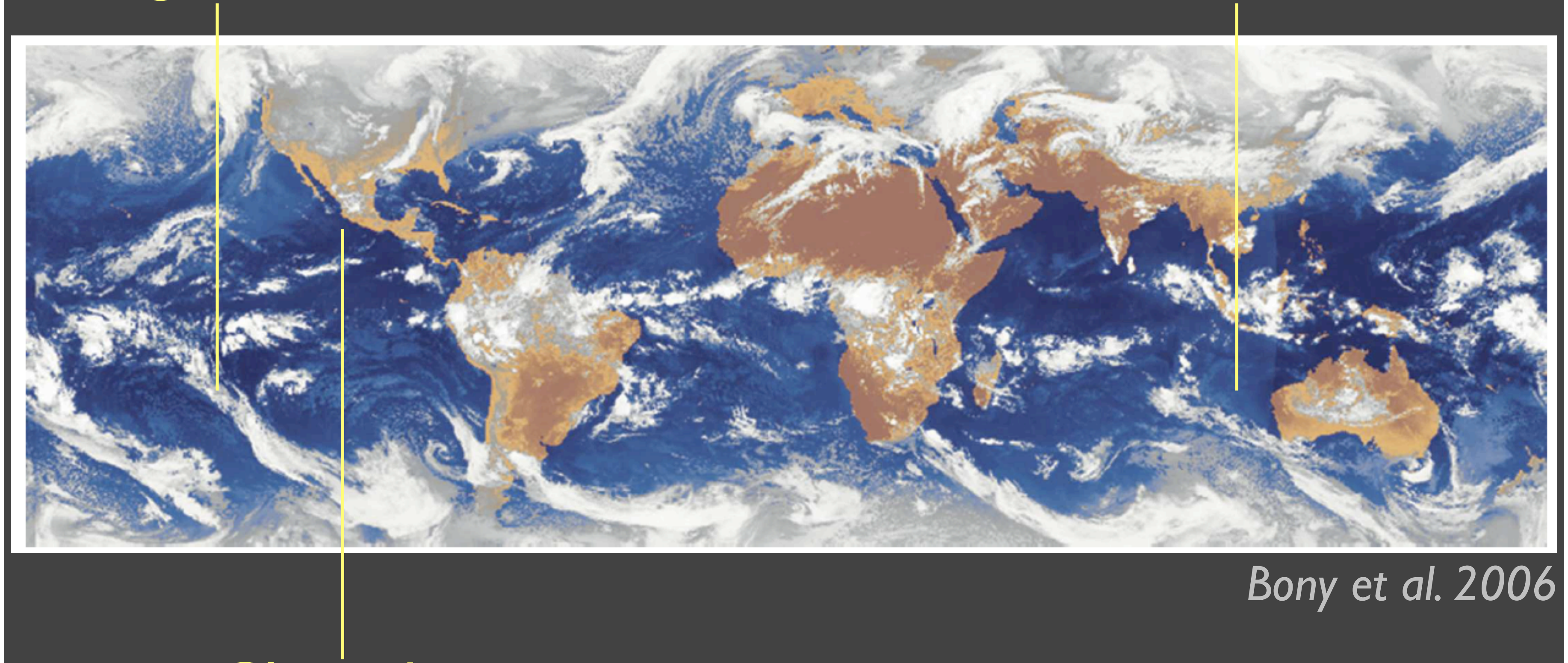
LHC Beam Energy ~ 700 MJ

Infrared light $h\nu \sim$ 0.3 eV ~ 7 x $10^{-29}$ LHC

Infrared flux ~ 240 W/$m^2$ ~ 0.3 $\mu$LHC/($m^2$ s)

Total infrared radiance ~ $10^{11}$MW ~ 200 MLHC/s

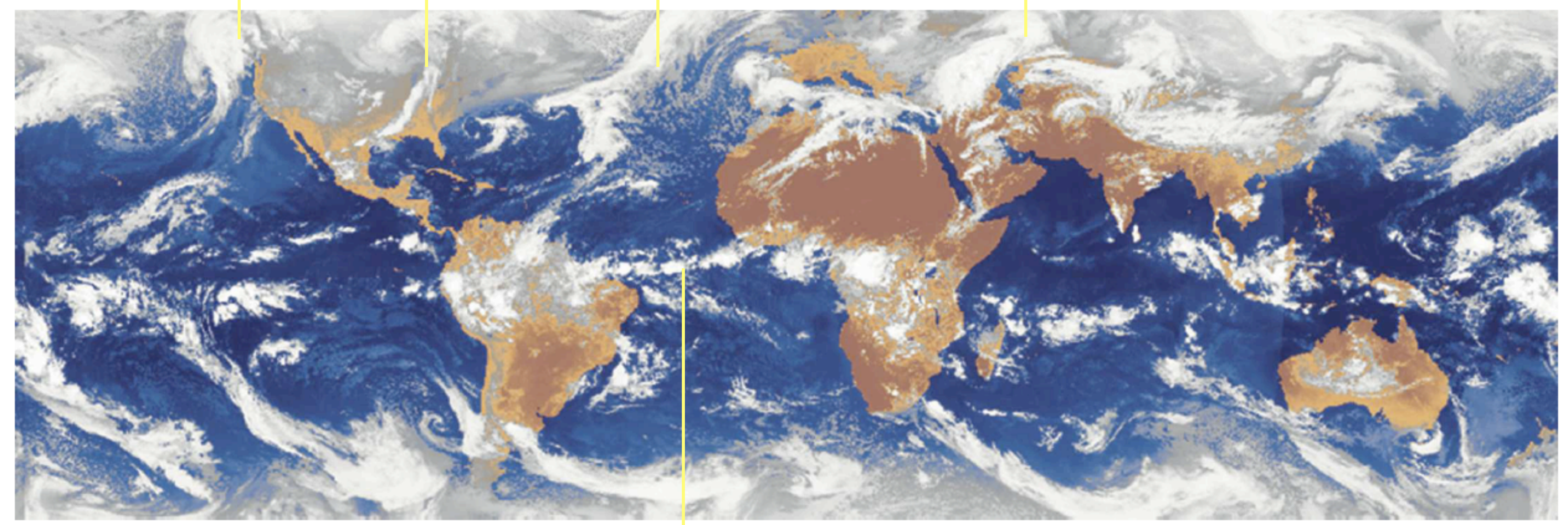
# Infrared Cloud Image



*Bony et al. 2006*

# Infrared Cloud Image

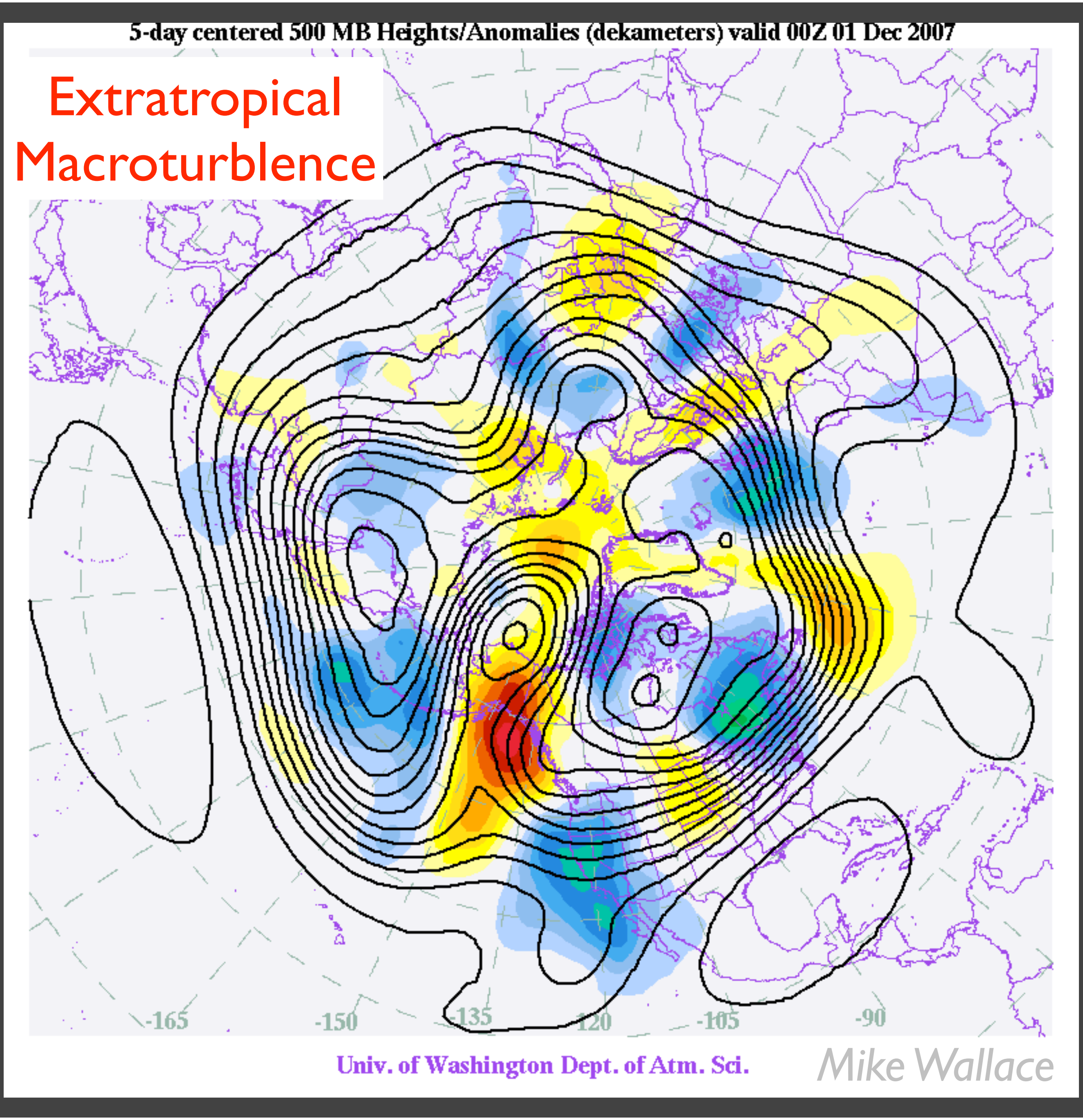
Extratropical Macroturbulence: Baroclinic eddies



*Bony et al. 2006*

Tropical Macroturbulence: Convective systems

# Extratropical Macroturblence



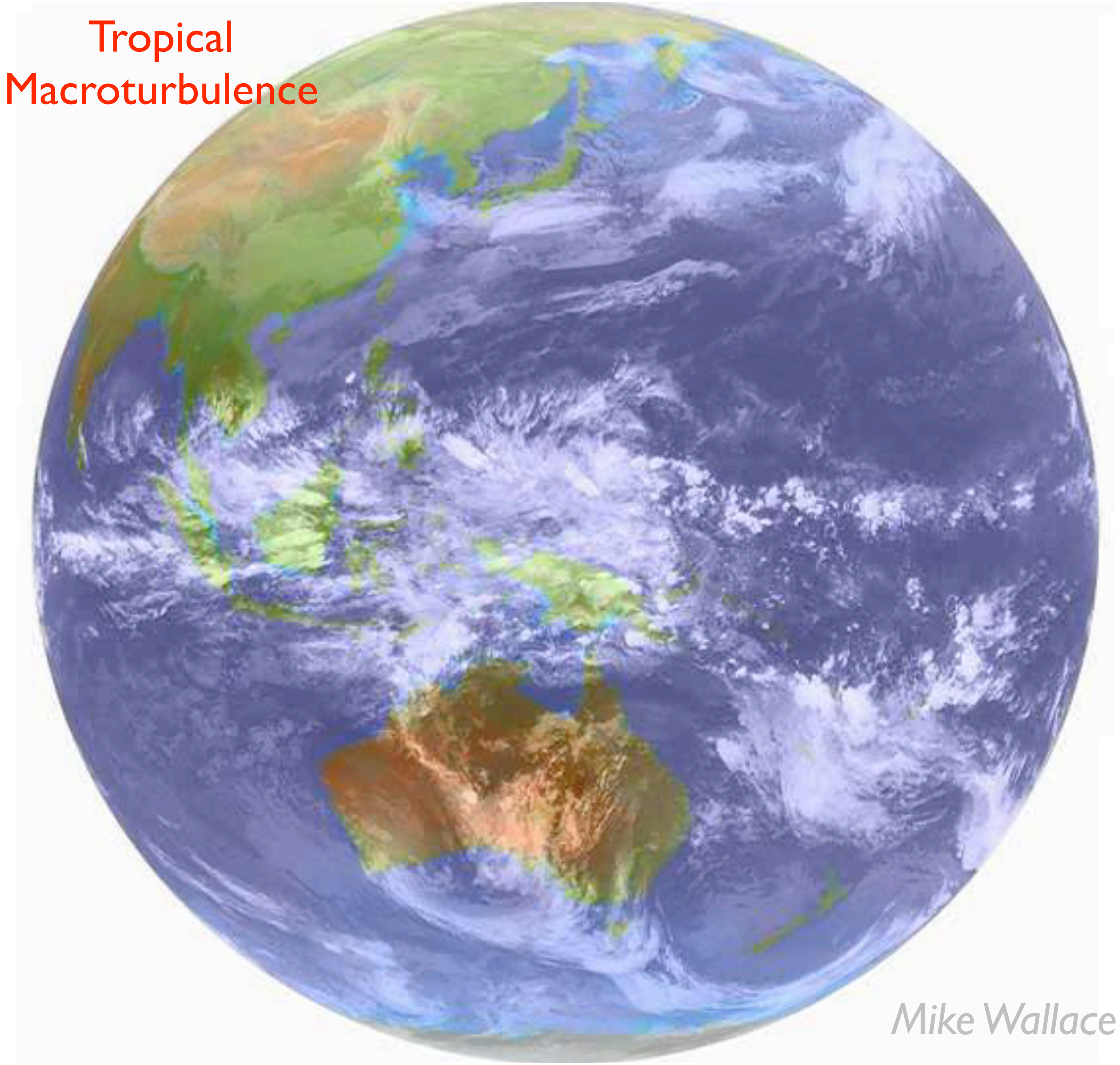
5-day centered 500 MB Heights/Anomalies (dekameters) valid 00Z 01 Dec 2007

Univ. of Washington Dept. of Atm. Sci.

Mike Wallace

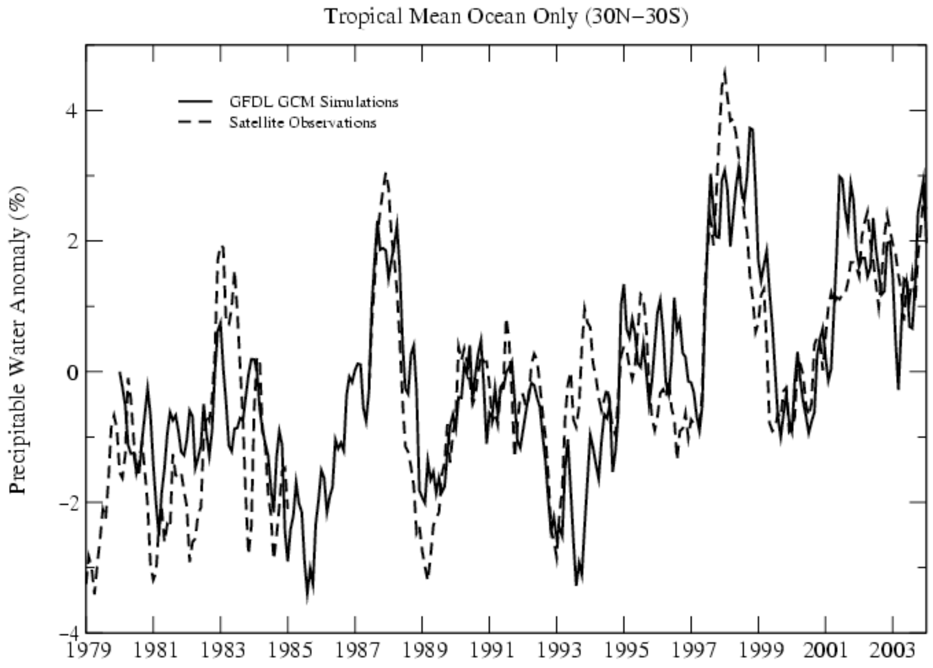
1 midlatitude weather system ~ 3 GLHC

# Tropical Macroturbulence



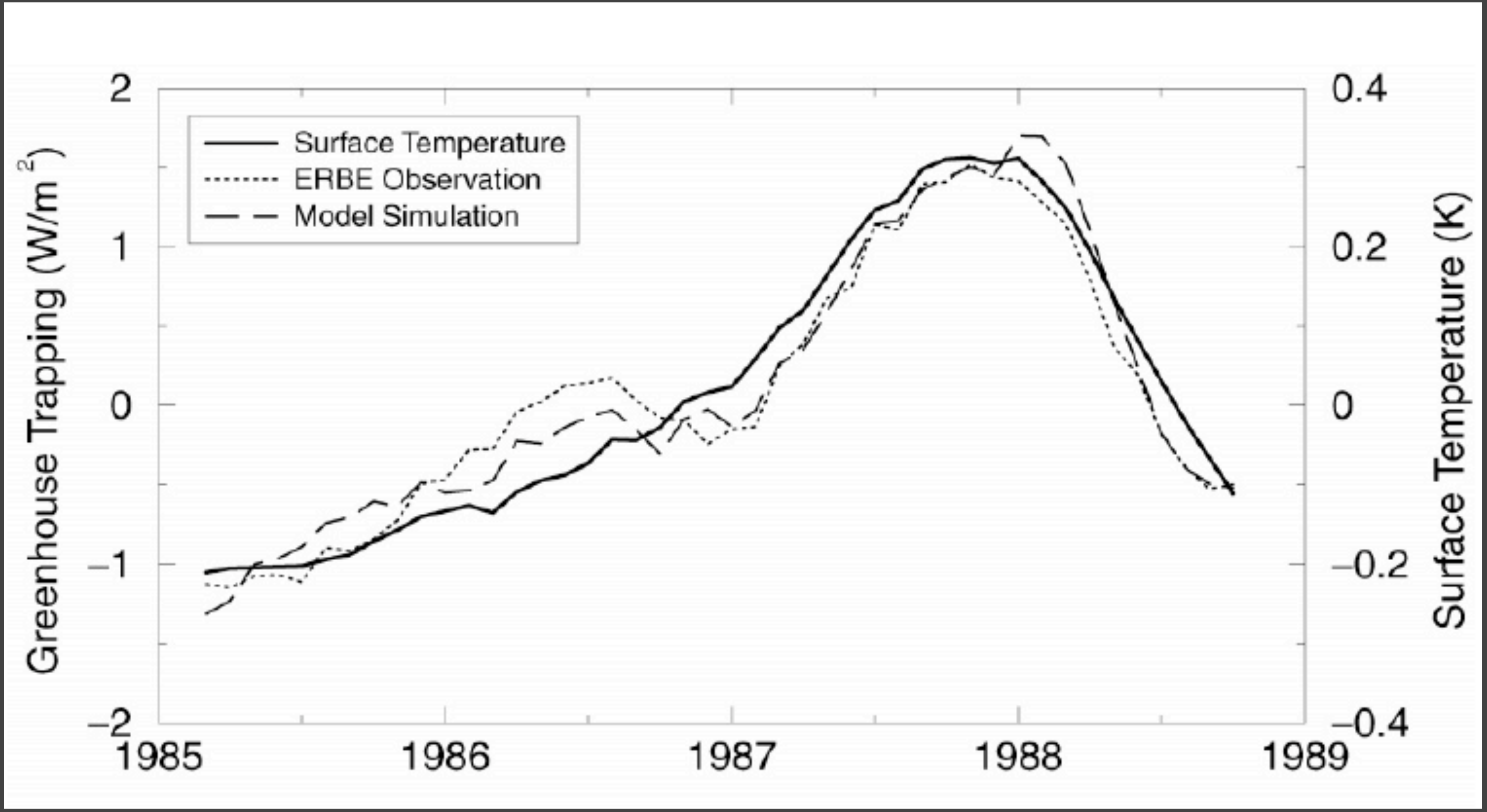
Mike Wallace

GCMs match observed trend and interannual variations of tropical mean (ocean only) column water vapor when given the observed ocean temperatures as boundary condition



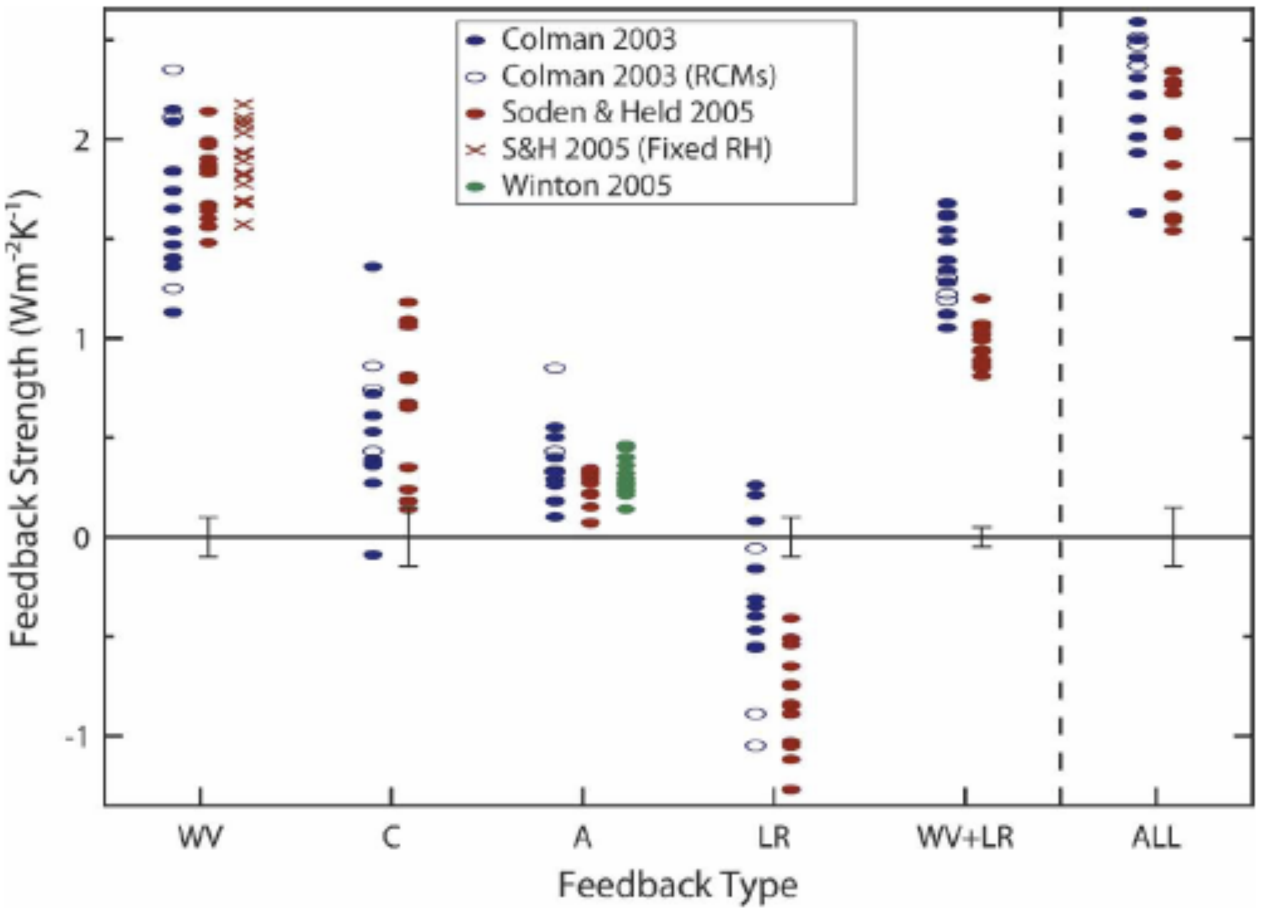
Courtesy of Brian Soden & Isaac Held

# Greenhouse Trapping: 1987-1988 El Niño



*Bony et al. 2006*

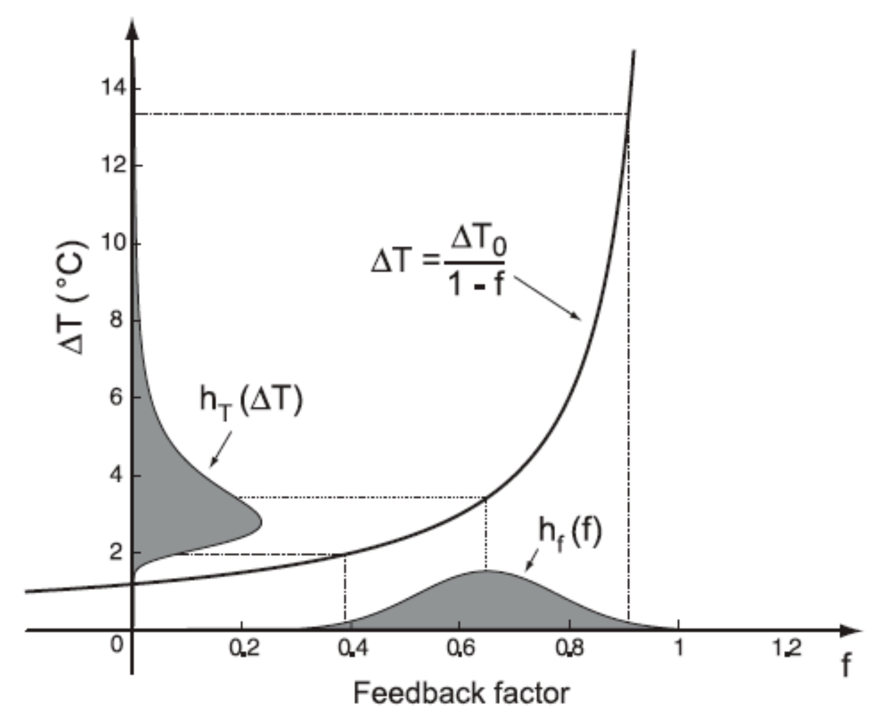
# Climate Sensitivity in Climate Models



*Bony et al. 2006*

# Climate Sensitivity in Climate Models

Uncertainty in gain factors normally distributed.
But uncertainty in climate sensitivity is right skewed.

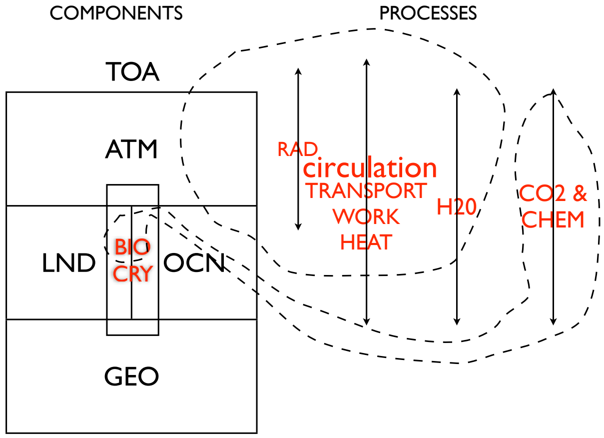


*Roe & Baker 2007*

Finite probability of large climate change from remaining feedbacks (e.g. biospheric --- Torn and Harte)

## Climate Models and Climate Sensitivity,

## Earth System Schematic



## Physics of Climate Change Program @ KITP ’08

Context: Key quantity of interest: “climate sensitivity”

$\left(\frac{\partial T_s}{\partial CO_2}\right)_R$ ,CO2: $\log_2[CO_2]$,$T_s$ surface temperature, R = 0 radiative equilibrium.

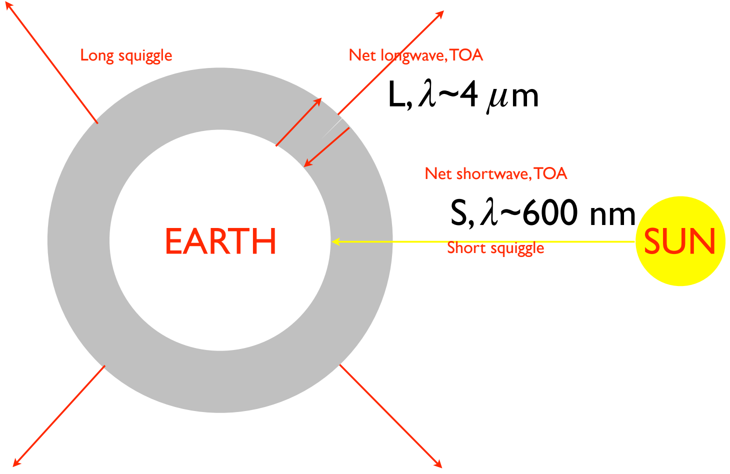
## Program themes:

1. “Macroturbulence”
2. “Clouds”
3. “Ecology”

## Tools for cross-talk:

1. Global observing system & data
2. Quantitative numerical models
3. Theory

## Simple Climate Model

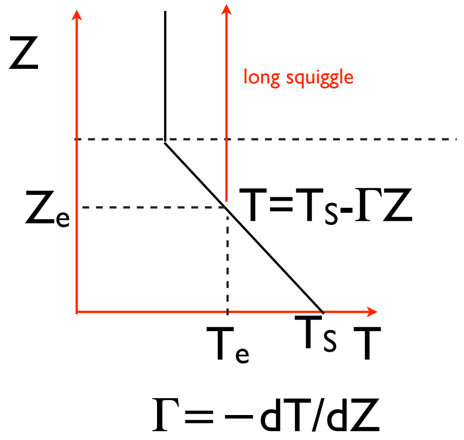


Radiative equilibrium, blackbody: $S=L=\sigma T_e^4 \sim 240\ \mathrm{W/m^2}$

Emission temperature: $T_e=T(Z=Z_e)\sim 255\mathrm{K}$

Emission height: $Z_e \sim 5$ km.

Surface temperature: $T_s=T(Z=0)\sim 288\mathrm{K} > T_e$ --- greenhouse effect (Fourier)



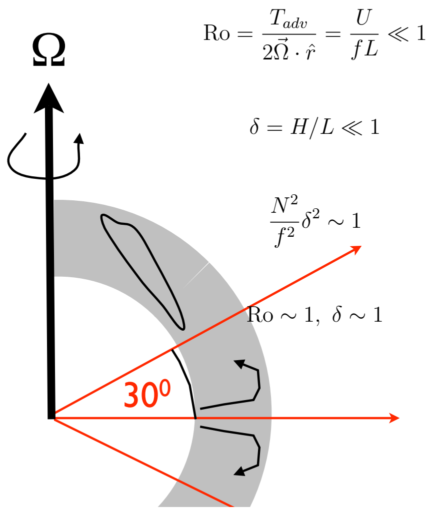
$\Gamma_{rad}=a\tau/(\tau+b)$, a&b positive.
$\tau$: optical thickness from main GHGs –– H20, CO2

$\Gamma > \Gamma_c =$"$g/c_p$": atmosphere is convectively unstable.

**Macroturbulence & climate questions:**
What sets $T_s=T_s(x,y,z)$?
What sets $\Gamma=-dT/dz$ (stratification)?
How will climate change affect $T_s$ and $\Gamma$?
Radiation, fluid dynamics, water vapor, clouds.

[Slides.]

**Macroturbulence regimes:**



*Extratropical regime*:

Well simulated by models

Theory:

“Weather”: dry, quasi-horizontal, non-divergent

“baroclinic turbulence” and teleconnections (ENSO, NAO, annular modes): linear and nonlinear.

Eddies transport heat poleward, maintain jets, maintain $\Gamma$.

Jets arise from $\beta = \mathrm{d}f/\mathrm{d}y$

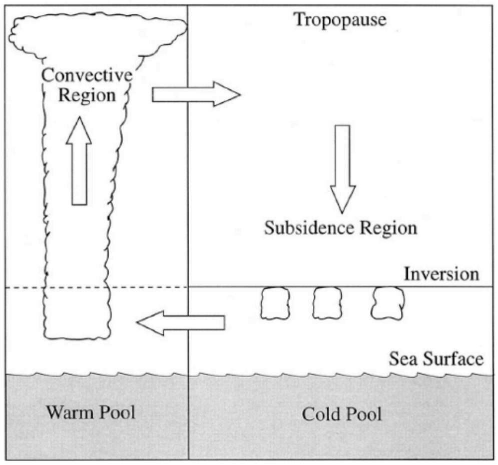
Clouds and moisture passive.

*Tropical regime:*

Not so well simulated

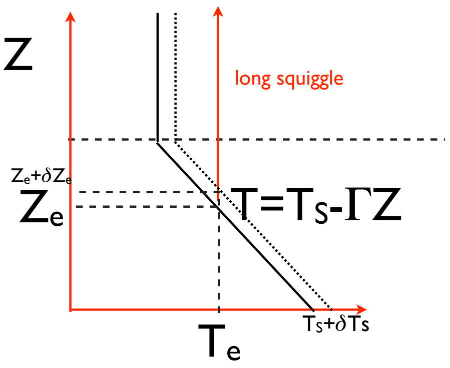
Clouds and moisture active.

Highly divergent; 3-D but coherent, not fully turbulent. Convective ascent + radiative descent maintains T.



## Model-based Climate Feedback Analysis:

E.g. in our simple climate model



$$\Gamma = -dT/dZ$$

Double CO2, keep Γ, S fixed. "ceteris paribus"

Does emission temperature $T_e$ change? No! Instead, $Z_e$ increases.

$\Delta Z_e \sim 100$ m per CO2 doubling.

Radiative equilibrium: $R=L-S=R(T_s, \Gamma, CO2, H20, C, I, V \ldots) = 0$[explain symbols]

- $CO2 \to CO2 + \delta CO2, T_s \to T_s + \delta T_s,$ Everything else, "$E$" fixed
- $\delta R = R(T_s + \delta T_s, CO2 + \delta CO2, E) - R(T_s, CO2, E) \approx \left(\frac{\partial R}{\partial T_s}\right)_{CO2,E} \delta T_s + \left(\frac{\partial R}{\partial CO2}\right)_{T_s,E} \delta CO2 = 0$
- $\delta T_s = -\frac{\left(\frac{\partial R}{\partial T_s}\right)_{CO2,E}}{\left(\frac{\partial R}{\partial CO2}\right)_{T_s,E}} \delta CO2 = \left(\frac{\partial T_s}{\partial CO2}\right)_{R,E} \delta CO2$
- Radiative transfer: $\frac{\partial R}{\partial CO2} = -4\text{W/m}^2$.
- $\sigma T^4$: $\frac{\partial R}{\partial T_s} = 4\text{W/m}^2 \cdot \text{K}$.
- So $\boxed{\left(\frac{\partial T_s}{\partial CO2}\right)_{R,E} = 1K = \Delta_0}$ "climate sensitivity", no feedbacks

## Direct Feedbacks: Water Vapor, Clouds …

"Feedback": quantity affected by $\delta T_s$ and this affects R.

Direct: water vapor $H20=e(T_s)$, $de/dT_s>0$, $\partial R/\partial H20|_{T_s}<0$. For variation in $T_s$,

$$H20(T_s) \to H20(T_s) + \delta H20(T_s) \approx H20(T_s) + e'(T_s)\delta T_s$$

Climate sensitivity with water vapor feedback.

- $\boxed{\left(\frac{\partial T_s}{\partial CO2}\right)_{R,E}^{H20} = \frac{\Delta_0}{1 - g_{H20}}}$, gain: $g_{H20} = -\frac{\left(\frac{\partial R}{\partial H20}\right)_{CO2,T_s,E} e'(T_s)}{\left(\frac{\partial R}{\partial T_s}\right)_{CO2,H20,E}}$

| | |
|---|---|
| -ve feedback | $g_{H20} < 0$ |
| No feedback | $g_{H20} = 0$ |
| +ve feedback | $g_{H20} > 0$ |
| Runaway greenhouse | $g_{H20} \geq 1$ |
| Current estimate | $g_{H20} \sim 0.4$ |

Note: this is an inaccurate definition of a runaway greenhouse condition.

$\left(\frac{\partial T_s}{\partial CO2}\right)_{R,E}^{H20} = \frac{\Delta_0}{1 - g_{H20}}$ ~1.7K

$\left(\frac{\partial R}{\partial H20}\right)_{CO2,T_s,E}$ <0. Radiative transfer model calculation: Critical region: tropical free troposphere (clouds).

$e'(T_s)>0$. Climate model calculations: Transport, clouds.

Water vapor feedback: robust, well simulated for climate variations (volcanoes, El Niño).

**Climate sensitivity with cloud feedback:**

Gains are **additive.**

- $\left(\frac{\partial T_s}{\partial CO2}\right)_{R,E}^{H20,C} = \frac{\Delta_0}{1 - g_{H20} - g_C}$
- Cloud feedback gain: $g_C = -\frac{\frac{\partial R}{\partial C}\frac{\partial C}{\partial T_s}}{\frac{\partial R}{\partial T_s}}$
- $\frac{\partial R}{\partial C}$ +ve for high clouds and -ve for low clouds.
- $\frac{\partial C}{\partial T_s}$ is model dependent.
- $g_C$ model dependent and controlled by low clouds (Pierrehumbert talk).

**Biospheric feedbacks (e.g. indirect on CO2)**

$R = R(T_s, CO2)$ is independent of V but V depends on CO2.

Model for vegetation: V=*f*(CO2, T), $(\partial f/\partial CO2)|_T<0$, $(\partial f/\partial T)_{CO2}>0?<0?$

Model for CO2, given emissions A and vegetation V: CO2=CO2(A,V), $(\partial CO2/\partial A)_V > 0$, $(\partial CO2/\partial V)_A < 0$

- $\delta CO2 = \overset{\delta CO2_{\text{emitted}}}{\left(\frac{\partial CO2}{\partial A}\right)_V \delta A} + \left(\frac{\partial CO2}{\partial V}\right)_A \delta V$
- $\delta V = \left(\frac{\partial f}{\partial CO2}\right)_T \delta CO2 + \left(\frac{\partial f}{\partial T}\right)_{CO2} \delta T$

$$\delta CO2 = \frac{\delta CO2_{\text{emitted}}}{1 - g_V^{CO2}} \left[1 + \left(\frac{\partial CO2}{\partial A}\right)_A \left(\frac{\partial f}{\partial T}\right)_{CO2} \delta T\right];$$

$$\text{CO2 gain } g_V^{CO2} = \left(\frac{\partial CO2}{\partial V}\right)_A \left(\frac{\partial f}{\partial CO2}\right)_T < 0$$

$$\delta T_s = \frac{\Delta_0}{1 - g_V^{CO2} - g_T^{CO2}} \delta CO2_{\text{emitted}}$$

$$\text{Indirect } T \text{ gain } g_T^{CO2} = \Delta_0 \left(\frac{\partial CO2}{\partial V}\right)_A \left(\frac{\partial f}{\partial T}\right)_{CO2}$$

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