Recent Variations in Earth's Radiation Budget, Clouds and Aerosols

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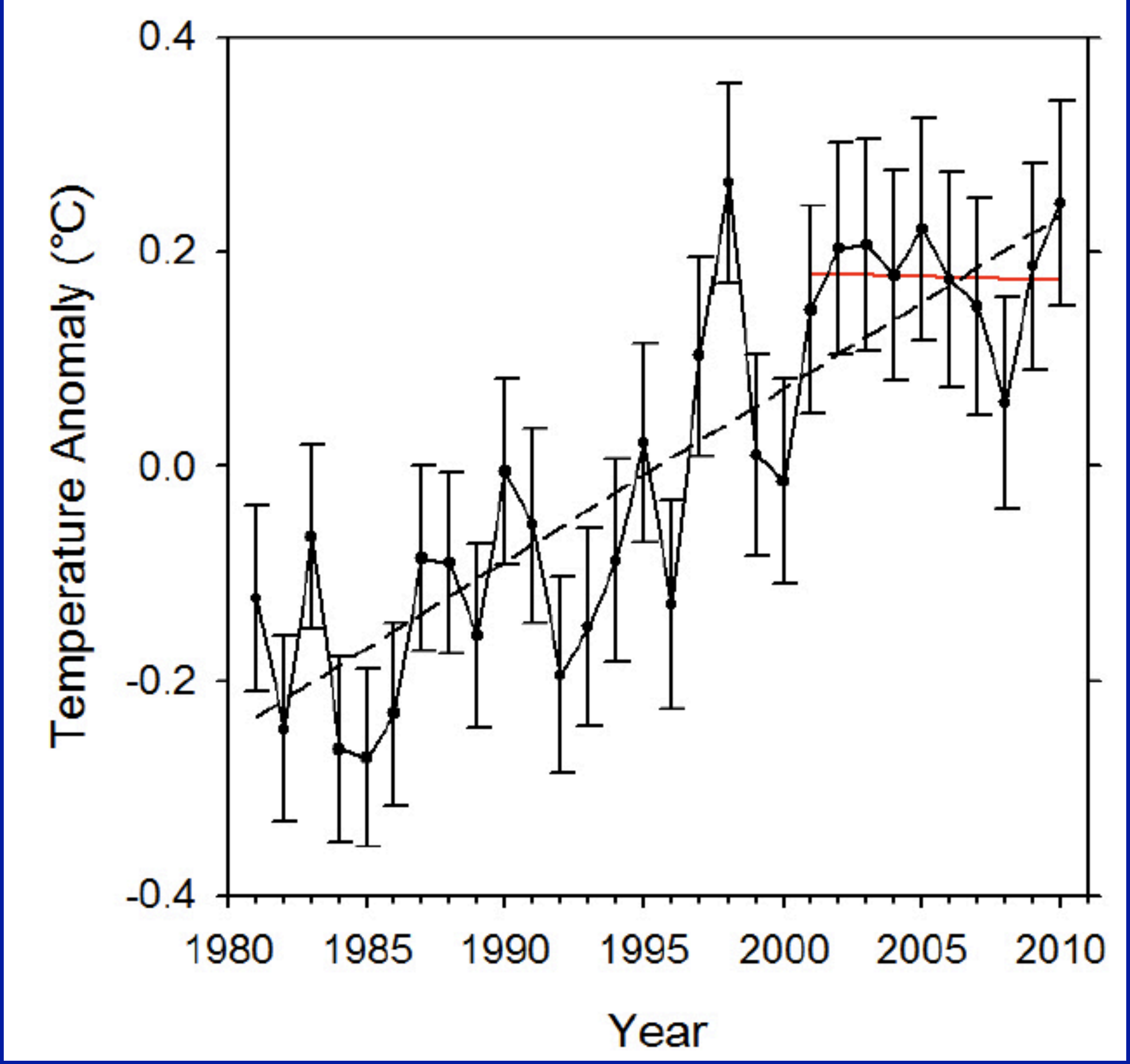
Global Surface Temperature Anomalies During the Past 30 Years



- Trend for the entire period (dashed line) is 0.016±0.002 °C/yr.
- For 2001–2010 the trend (red line) is 0.00±0.01 °C/yr.

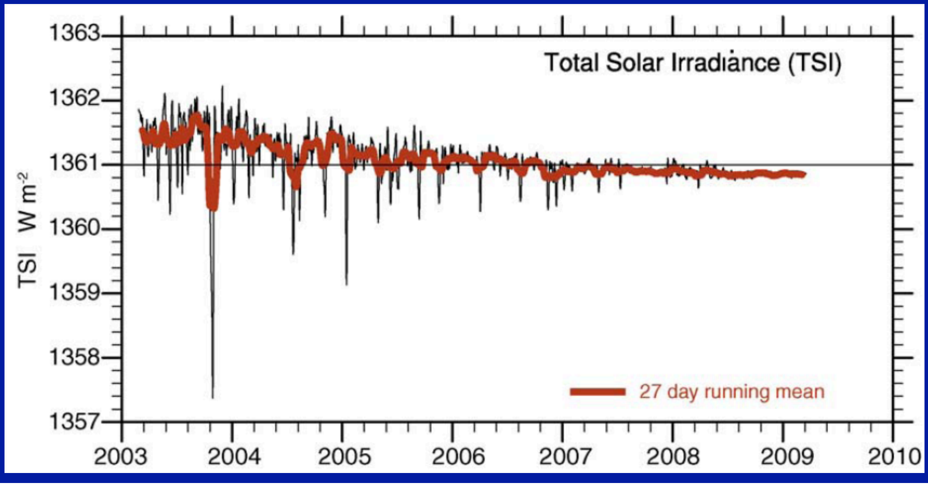
Source: HadCRUT3.

What do the new generation of observations (satellite, ocean) tell us about the associated energy flow during the past decade?

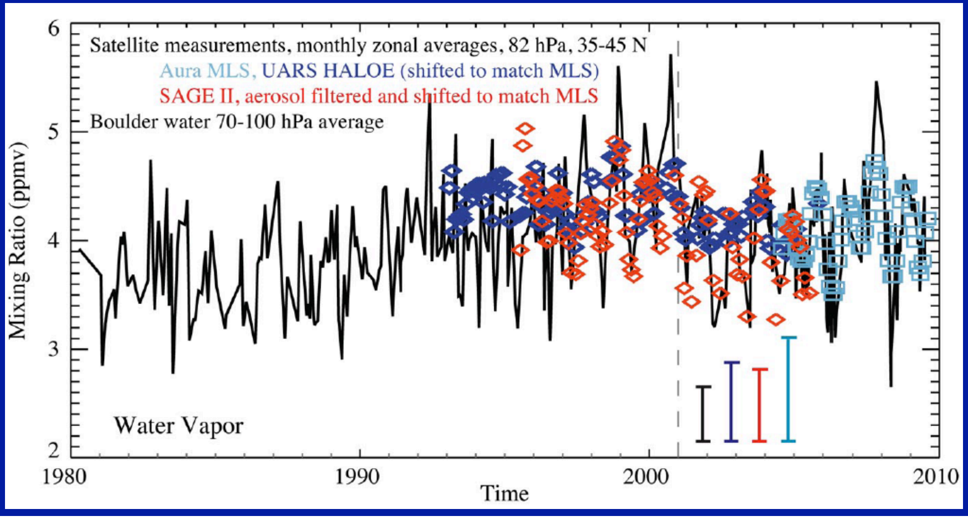
Tracking Earth's Energy

- Measuring net incoming and outgoing radiation at TOA indicates how much energy remains in the Earth system.
- Most of this excess energy (~90%) is absorbed in the ocean; rest goes into melting sea and land ice and heating the land surface and atmosphere.
- Fluctuations in Earth's TOA net energy imbalance and the ocean heating rate should be in phase with one another.
- Sources of short-term variability: ENSO-related changes in atmospheric and oceanic circulations, clouds, aerosols (including volcanic eruptions), surface properties.
- Longer-term variability: Anthropogenic forcing due to greenhouse gases and aerosols, natural forcing by aerosols and solar radiation, and feedbacks involving water vapor, temperature, clouds, and the surface.
- Earth's temperature response depends upon the thermal inertia of the climate system, governed by the ocean (large heat capacity).

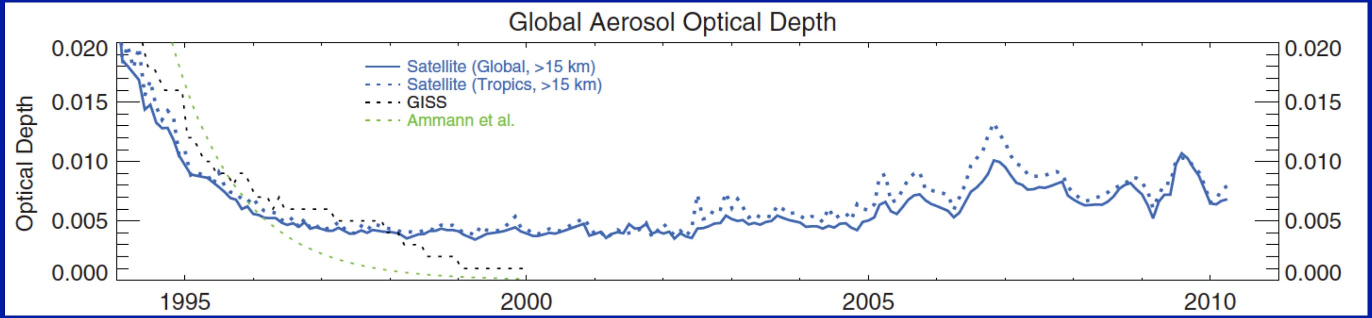
The Sun, Stratospheric Aerosols, and Lower-Stratospheric Water Vapor



Total solar irradiance changes: -0.5 Wm^{-2} ⇒reduction in absorbed solar radiation of 0.1 Wm^{-2} (Trenberth, 2009)

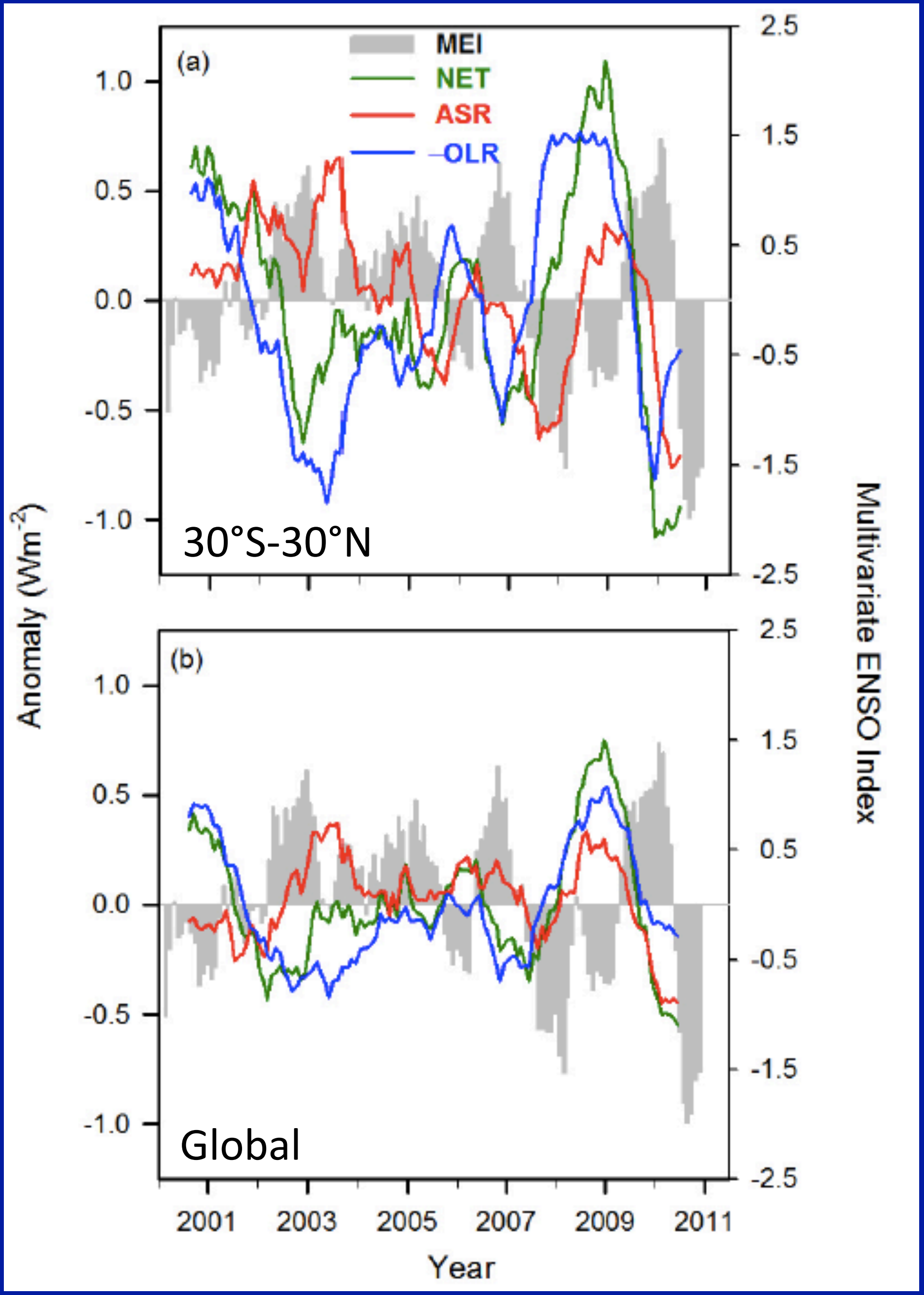


Lower stratospheric water vapor changes: -0.4 ppmv
⇒0.04°C reduction in warming
Solomon et al. (2010)



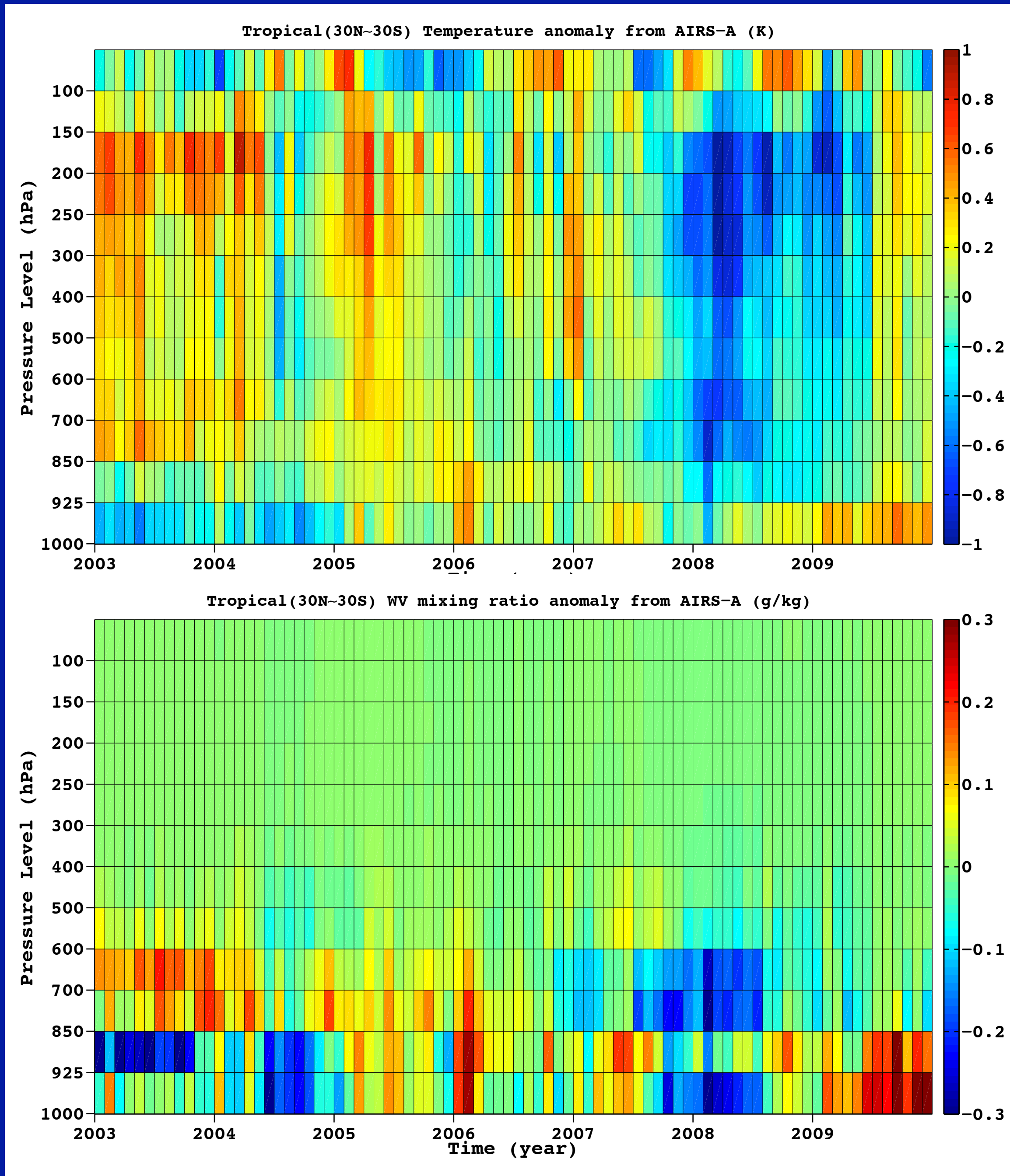
Stratospheric aerosol changes: +7% per yr
⇒ 0.07°C reduction in warming
Solomon et al. (2011)

CERES SW, LW and Net TOA Radiation & ENSO



Loeb et al., 2011 (Nature Geosc.)

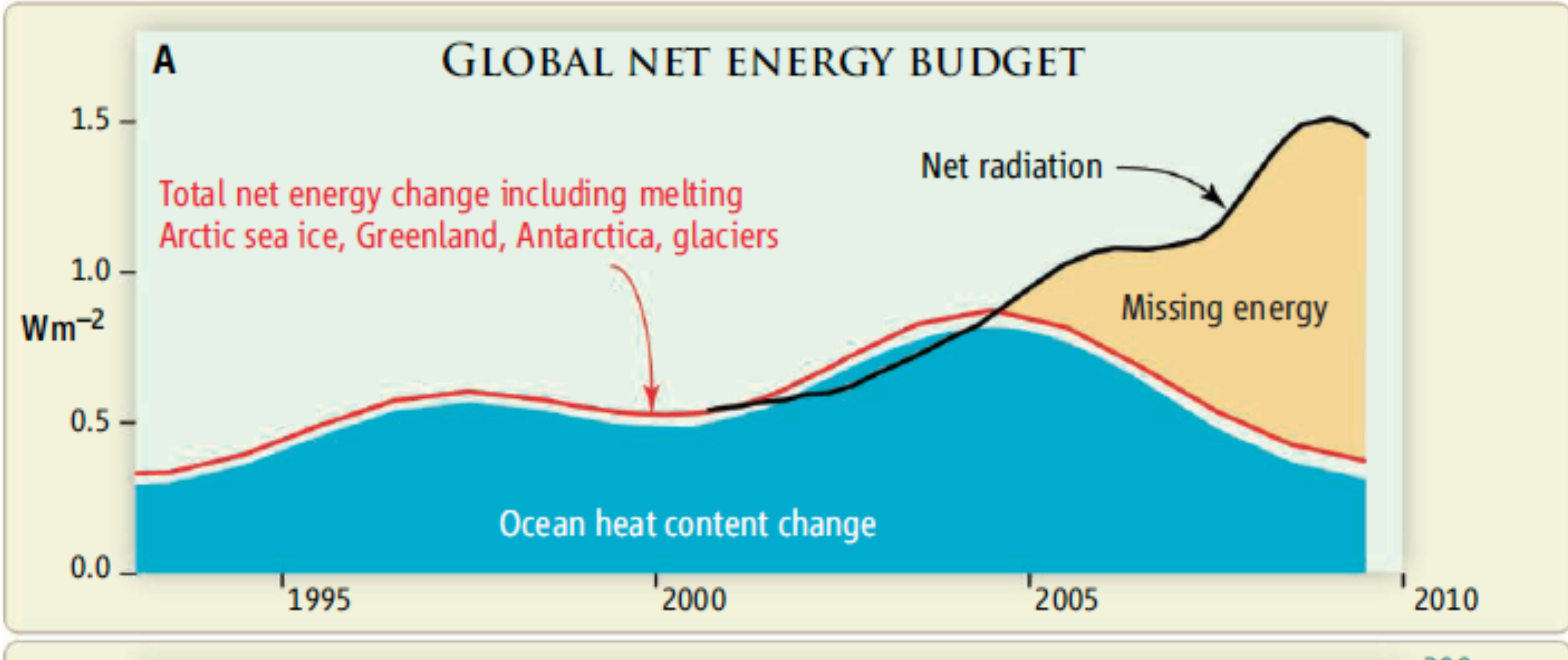
AIRS Temperature and Water Vapor Mixing Ratio Anomalies (30°S-30°N)



Temperature Anomaly (K)

Water Vapor Mixing Ratio Anomaly (g/kg)

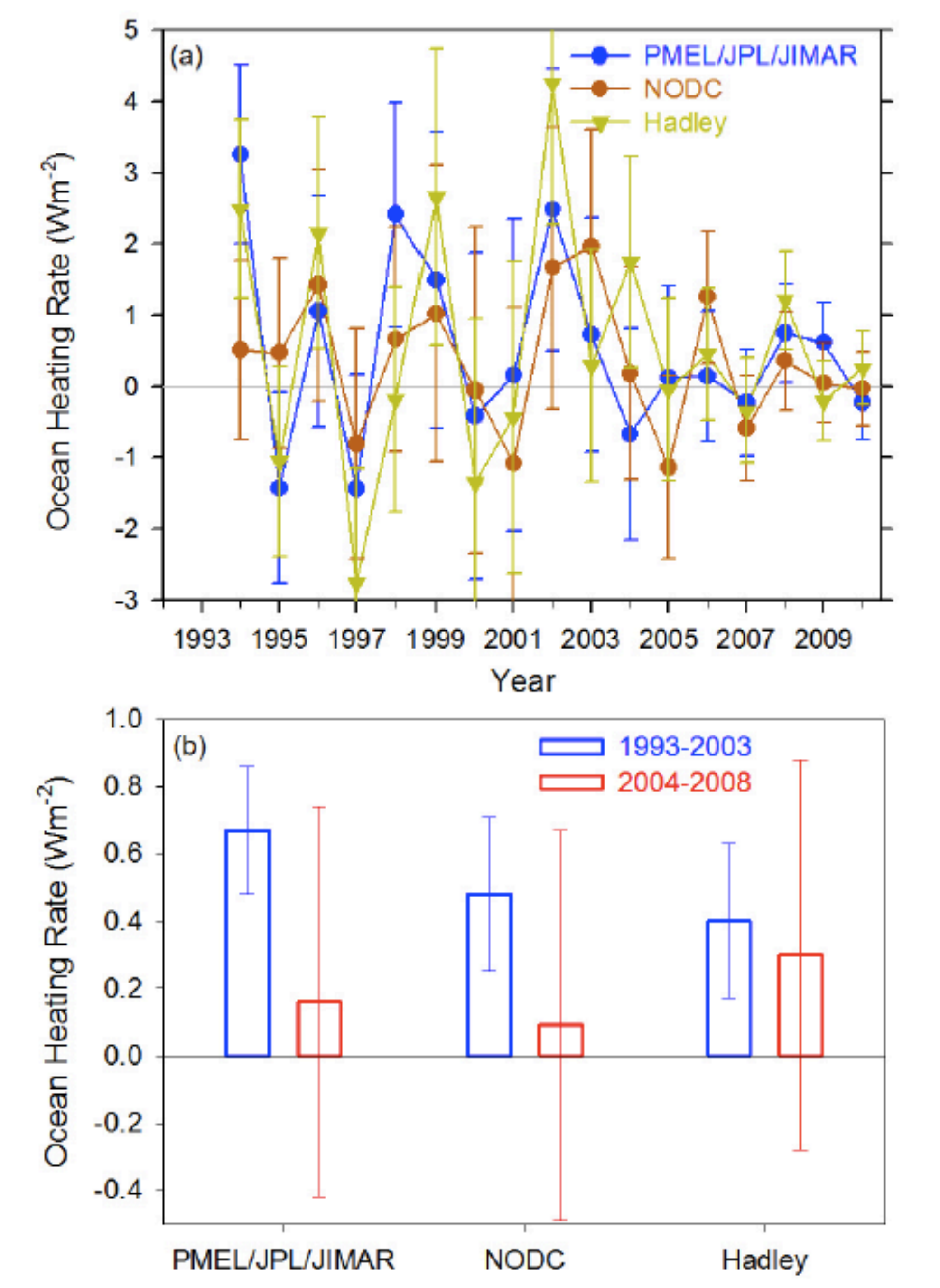
Loeb et al., 2011 (Surv. Geophys.)



Apparent inconsistencies after 2004 between short-term variations in ocean heating rate from in situ ocean heat content data and net TOA flux from CERES cast doubt on our ability to account for flows of energy in the climate system, and the lack of closure has given rise to the idea of "missing energy" in the climate system.

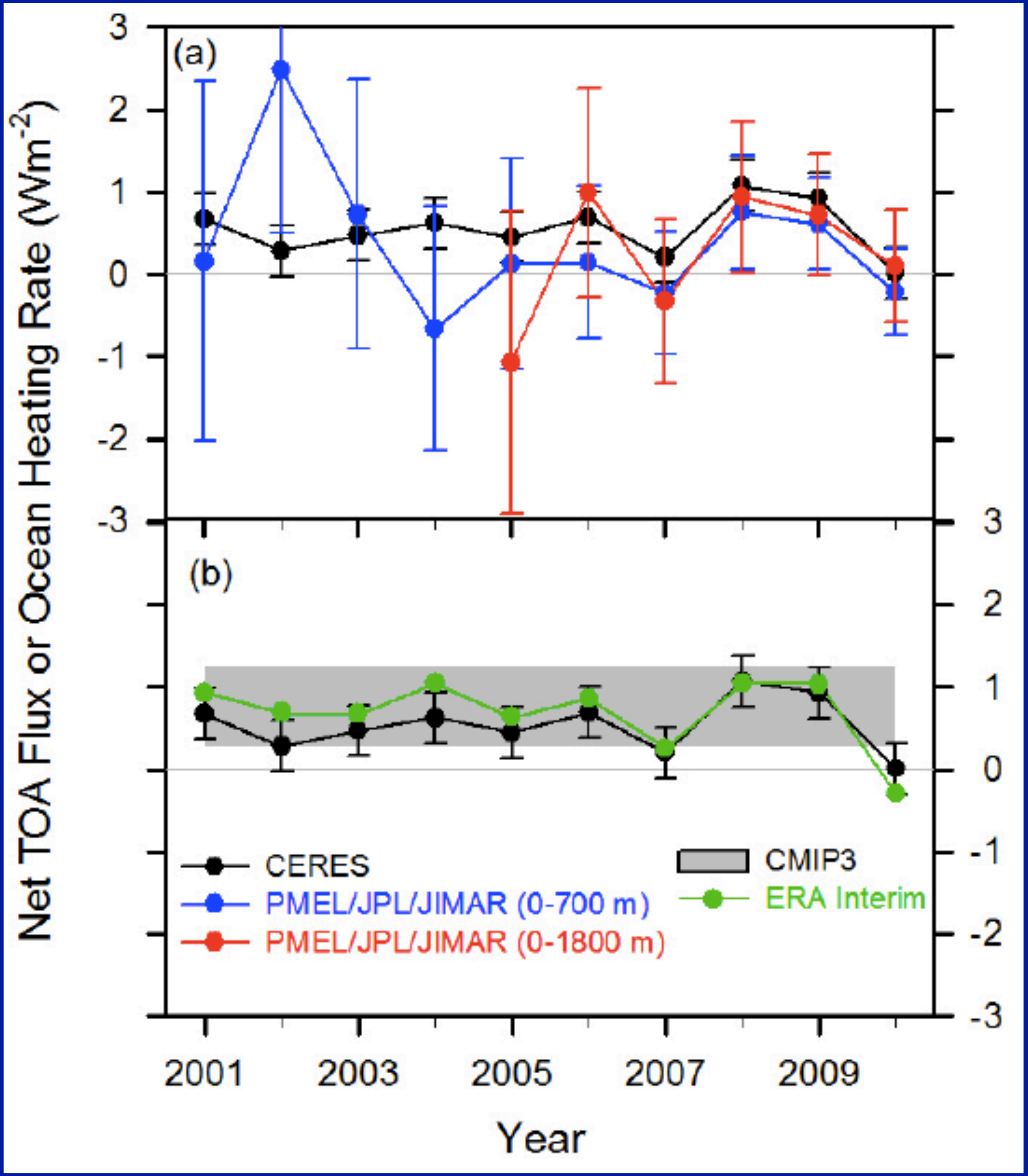
Trenberth and Fasullo, 2010 (Science)

Global Average Upper Ocean Heating Rates from 3 Different Teams



Loeb et al., 2011 (Nature Geosc.)

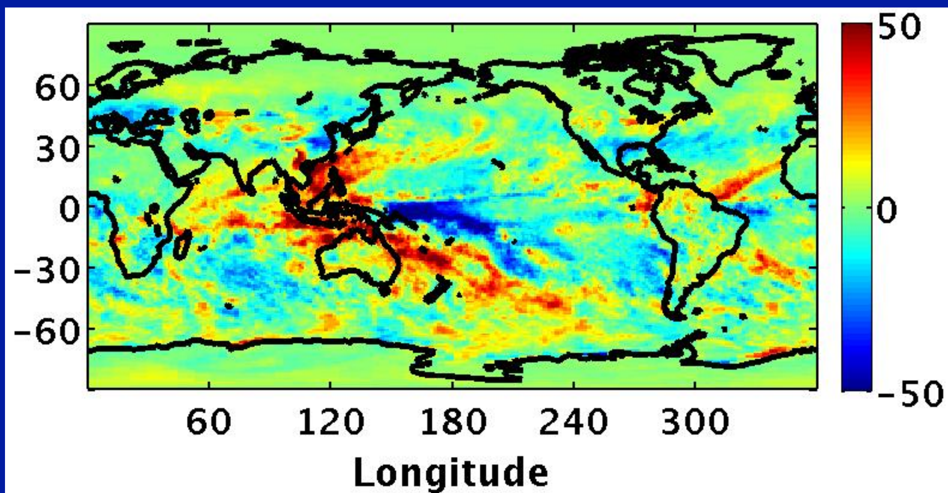
Comparison of net TOA flux and Upper Ocean Heating Rates



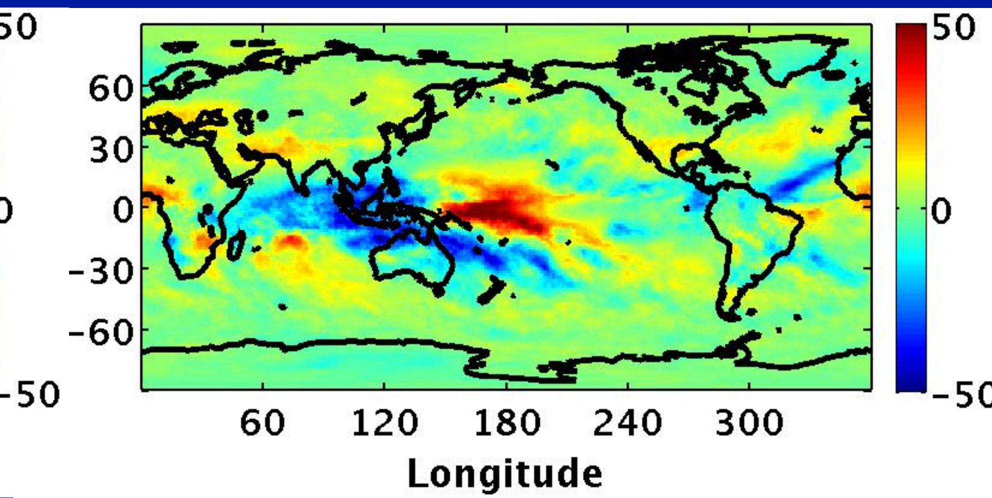
Loeb et al., 2011 (Nature Geosc.)

CERES TOA Flux and MODIS Cloud Property Anomalies (Feb 2008)

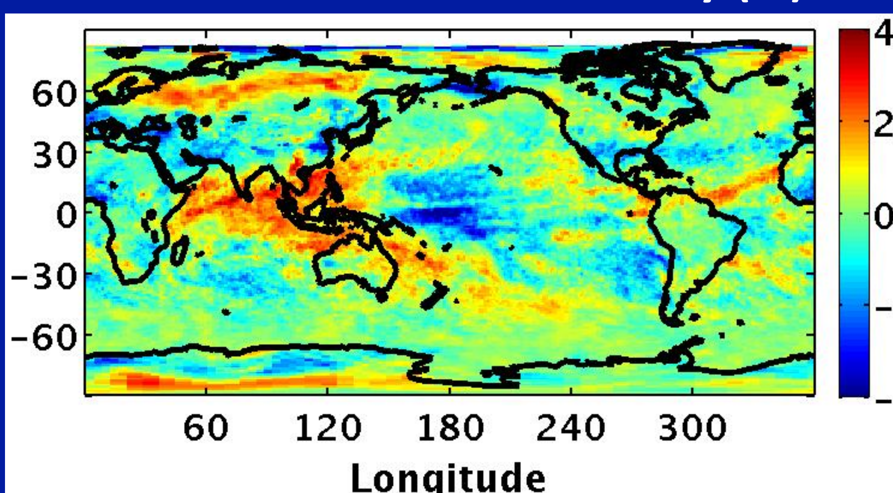
CERES SW TOA Flux Anomaly (Wm^{-2})



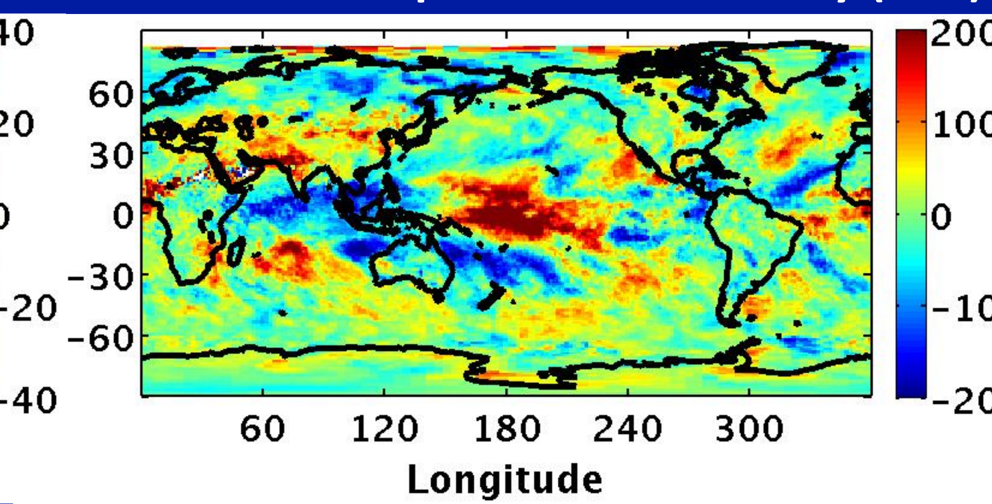
CERES LW TOA Flux Anomaly (Wm^{-2})



MODIS Cloud Fraction Anomaly (%)



MODIS Cloud Top Pressure Anomaly (hPa)



Loeb et al., 2011 (Surv. Geophys.)

Diagnosing CERES Tropical Mean LW TOA Flux Variability

Consider the time series of computed monthly mean LW TOA flux:

$$F^{LW}(T(z),w(z),T_s,P_c,f,\tau_c)$$

Compute contribution to LW TOA flux variability from each variable:

$$\delta F^{LW}(T(z)) = F^{LW}(T(z),w(z),T_s,P_c,f,\tau_c) - F^{LW}(\overline{T(z)},w(z),T_s,P_c,f,\tau_c)$$

$$\delta F^{LW}(w(z)) = F^{LW}(T(z),w(z),T_s,P_c,f,\tau_c) - F^{LW}(T(z),\overline{w(z)},T_s,P_c,f,\tau_c)$$

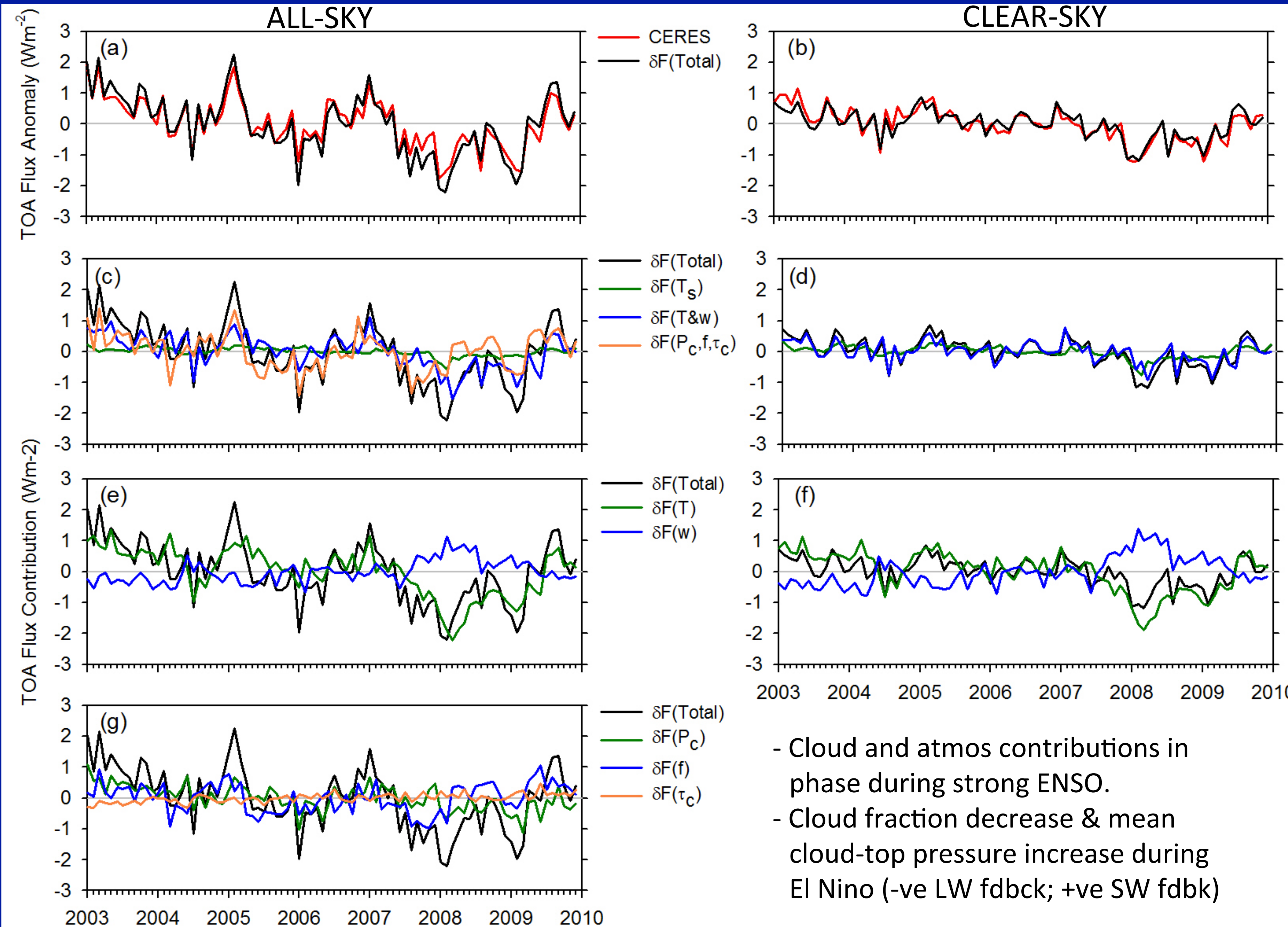
$$\delta F^{LW}(T_s) = F^{LW}(T(z),w(z),T_s,P_c,f,\tau_c) - F^{LW}(T(z),w(z),\overline{T_s},P_c,f,\tau_c)$$

$$\delta F^{LW}(P_c) = F^{LW}(T(z),w(z),T_s,P_c,f,\tau_c) - F^{LW}(T(z),w(z),T_s,\overline{P_c},f,\tau_c)$$

$$\delta F^{LW}(f) = F^{LW}(T(z),w(z),T_s,P_c,f,\tau_c) - F^{LW}(T(z),w(z),T_s,P_c,\overline{f},\tau_c)$$

$$\delta F^{LW}(\tau_c) = F^{LW}(T(z),w(z),T_s,P_c,f,\tau_c) - F^{LW}(T(z),w(z),T_s,P_c,f,\overline{\tau_c})$$

Contributions to LW TOA Flux by Surface, Atmos & Clouds (30S-30N)

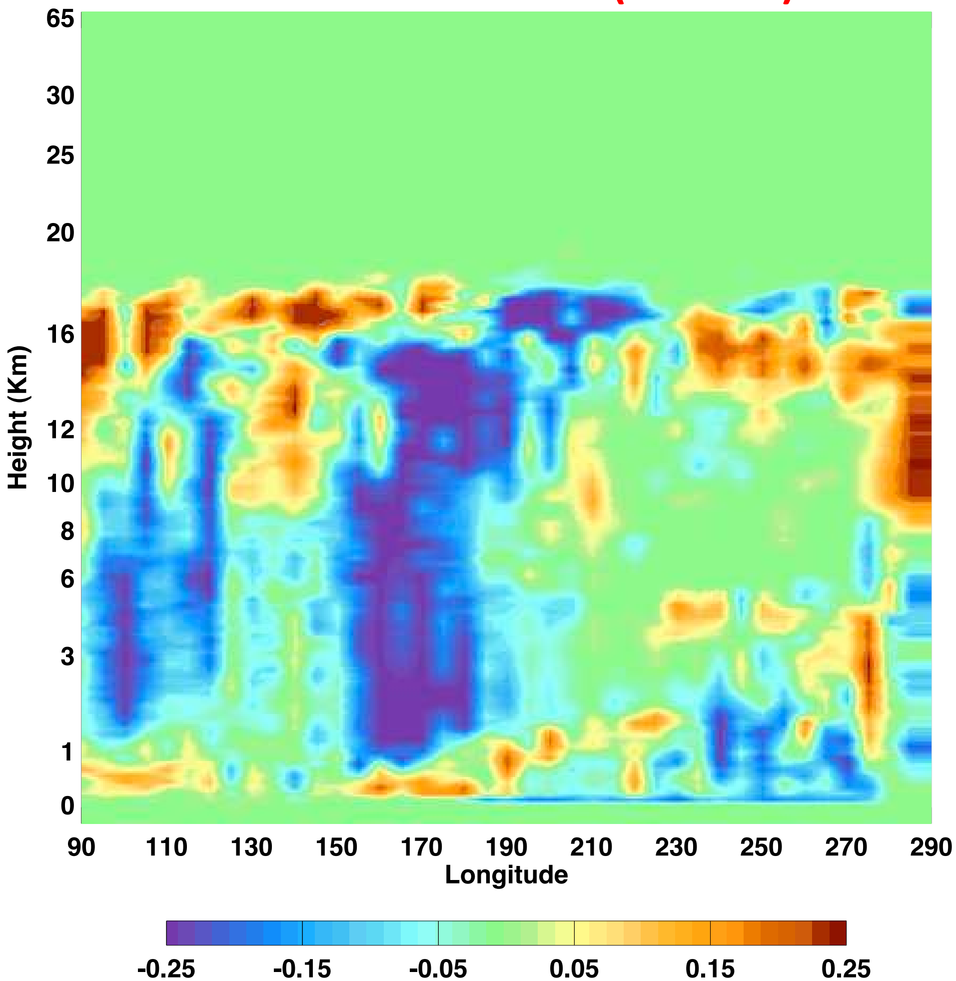


- Cloud and atmos contributions in phase during strong ENSO.
- Cloud fraction decrease & mean cloud-top pressure increase during El Nino (-ve LW fdbck; +ve SW fdbk)

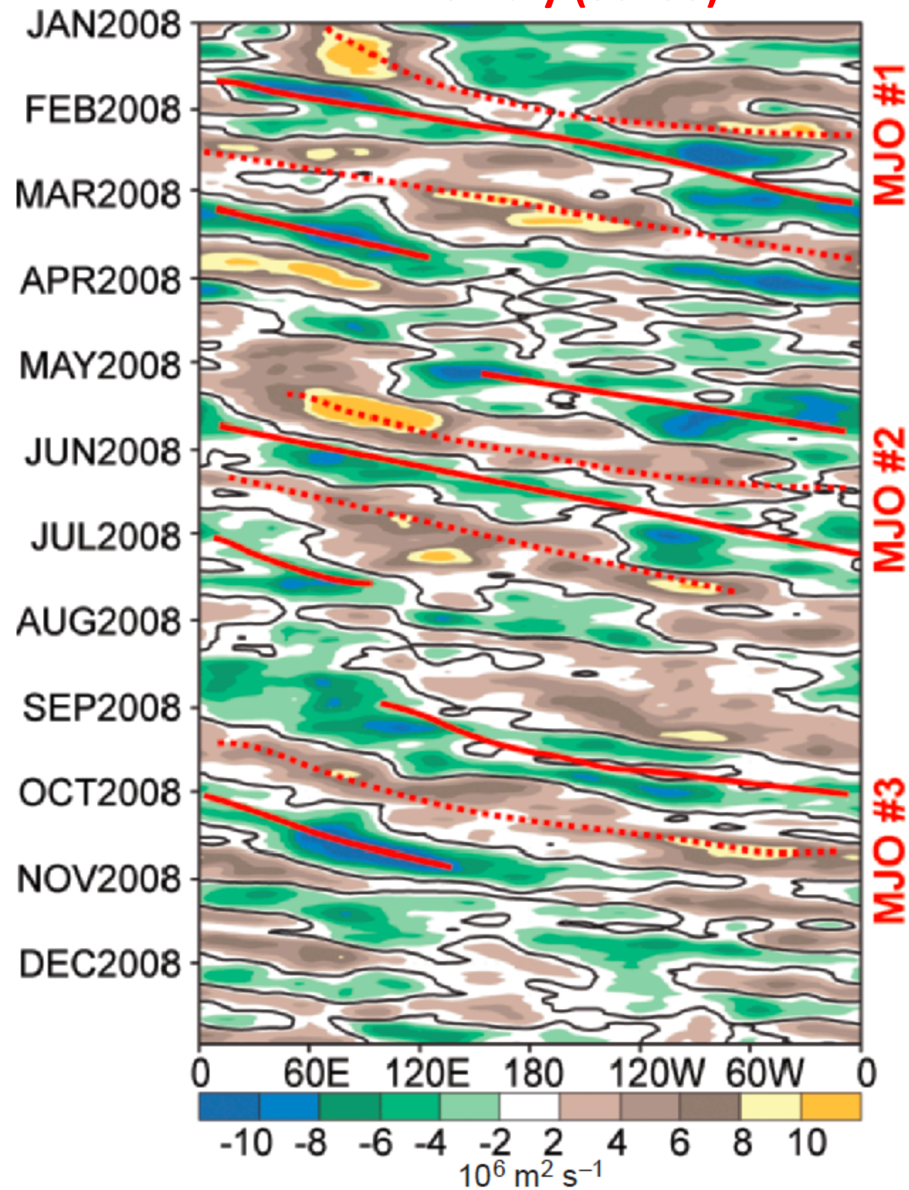
Conclusions

- We calculate that during the past decade Earth has been accumulating energy at the rate 0.54±0.43 Wm^{-2}, suggesting that while Earth's surface has not warmed significantly during the 2000s, energy continued to accumulate in the subsurface ocean.
- The apparent decline in ocean heating rate after 2004 noted in other studies is not statistically robust.
- Our results do not support the claim that there is missing energy in the system.
- Synergistic use of satellite and in-situ ocean heat content anomaly measurements provide critical data for quantifying short and longer-term changes in the Earth's net TOA radiation imbalance.
- New cloud data from satellite (MODIS, CALIPSO) key to unraveling role of clouds in a changing climate.

CALIPSO/Cloudsat Cloud Frequency of Occurrence Difference
Jan08 minus Jan07 (0S–2.5S)

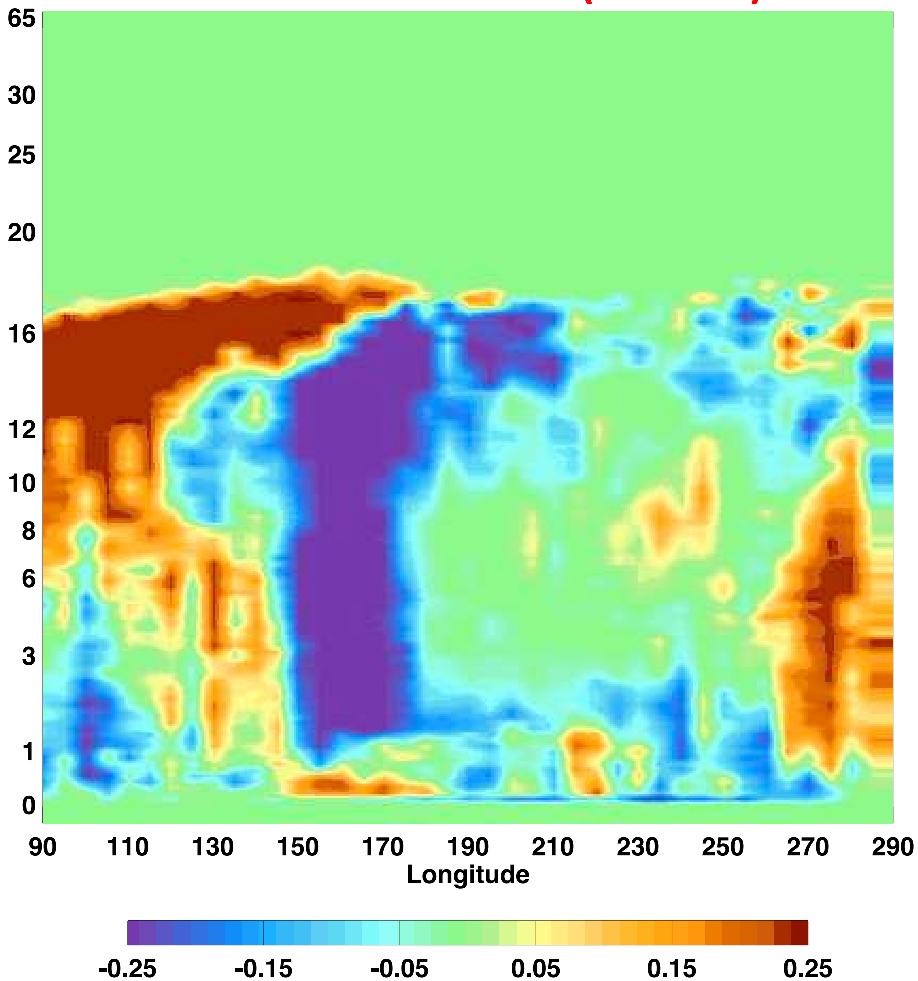


Filtered 200-hPa Velocity Potential Anomaly (5S–5S)

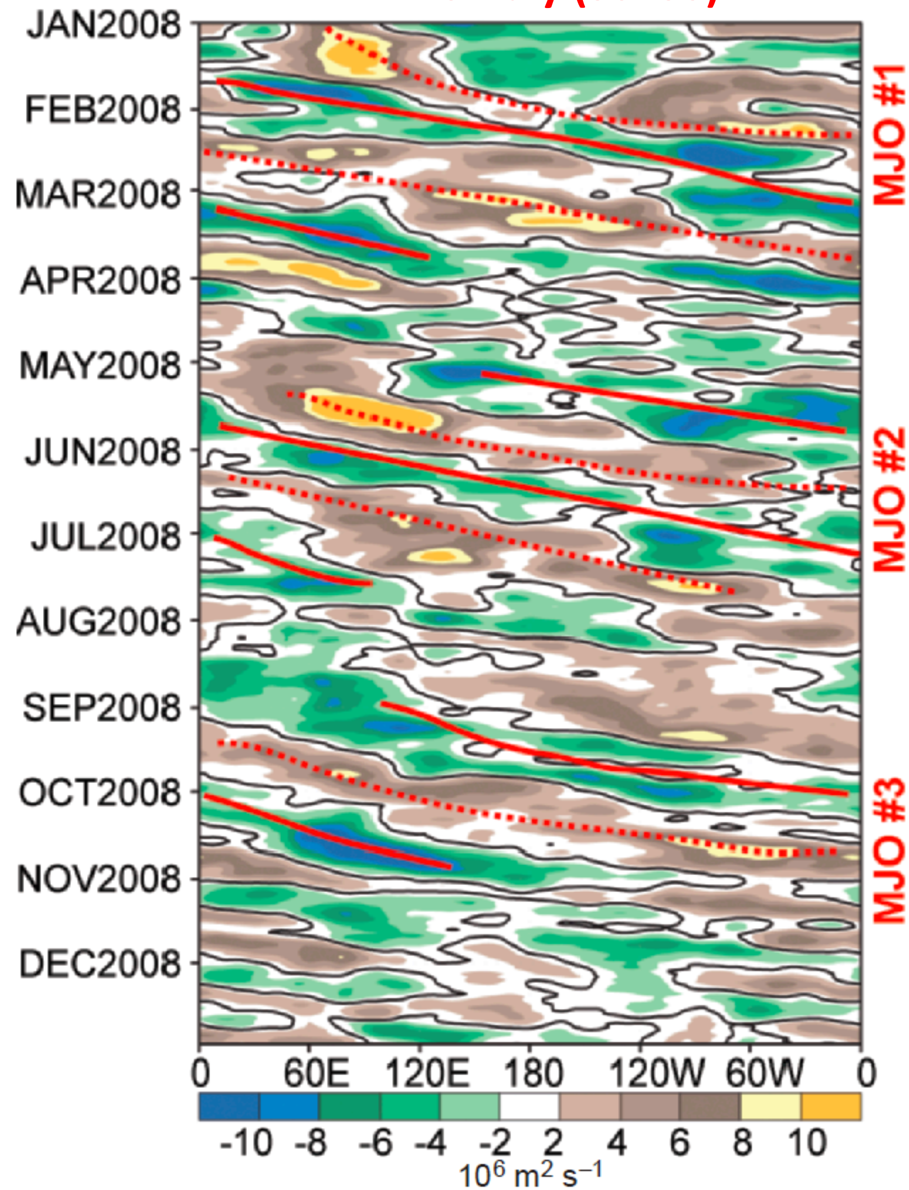


- MJO and La Nina convection out of phase: Negative phase of MJO masks La Nina Convection

CALIPSO/Cloudsat Cloud Frequency of Occurrence Difference
Feb08 minus Feb07 (0S–2.5S)

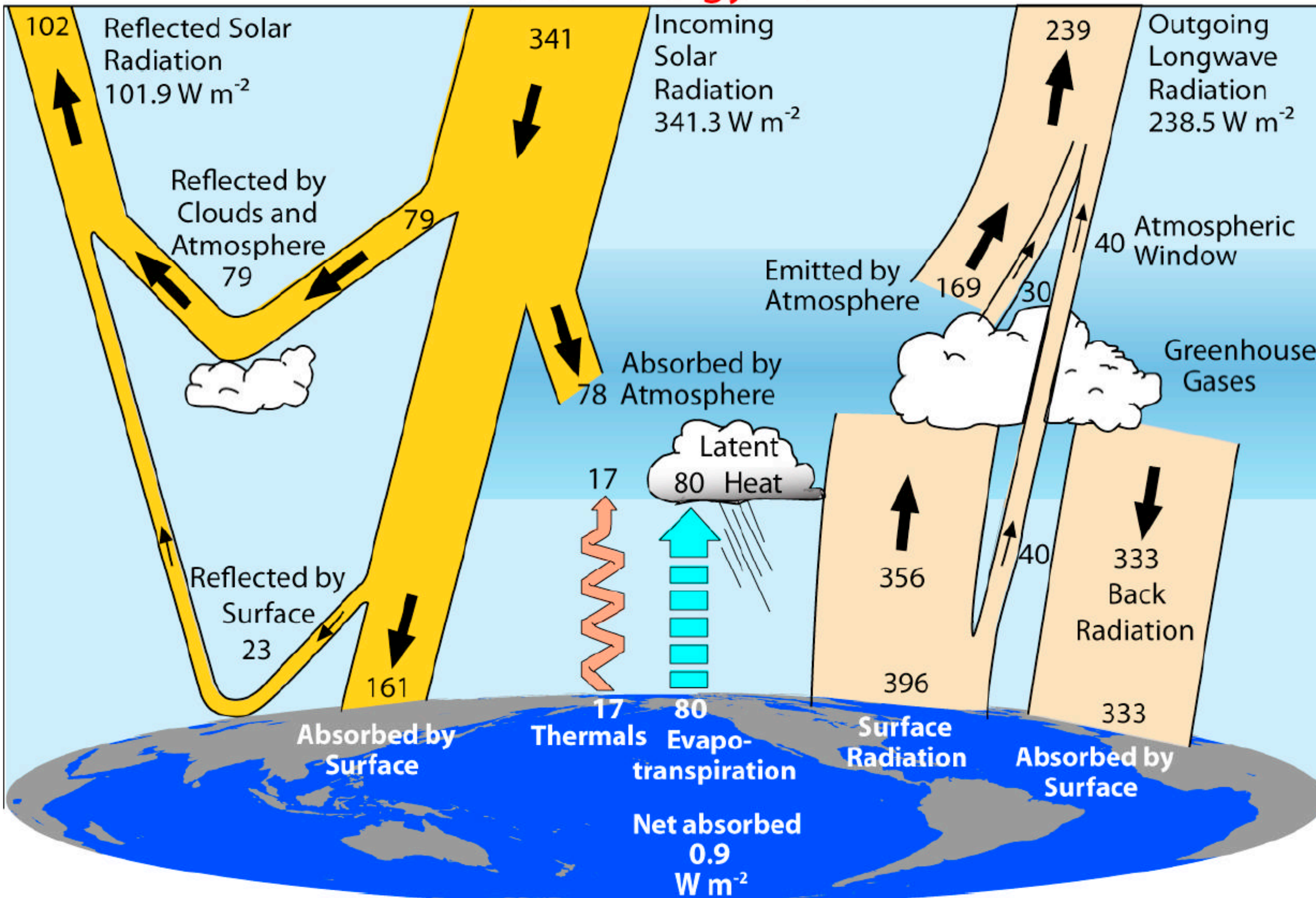


Filtered 200-hPa Velocity Potential Anomaly (5S–5S)



MJO and La Nina convection in phase

Global Energy Flows W m^{-2}



Trenberth et al., 2009

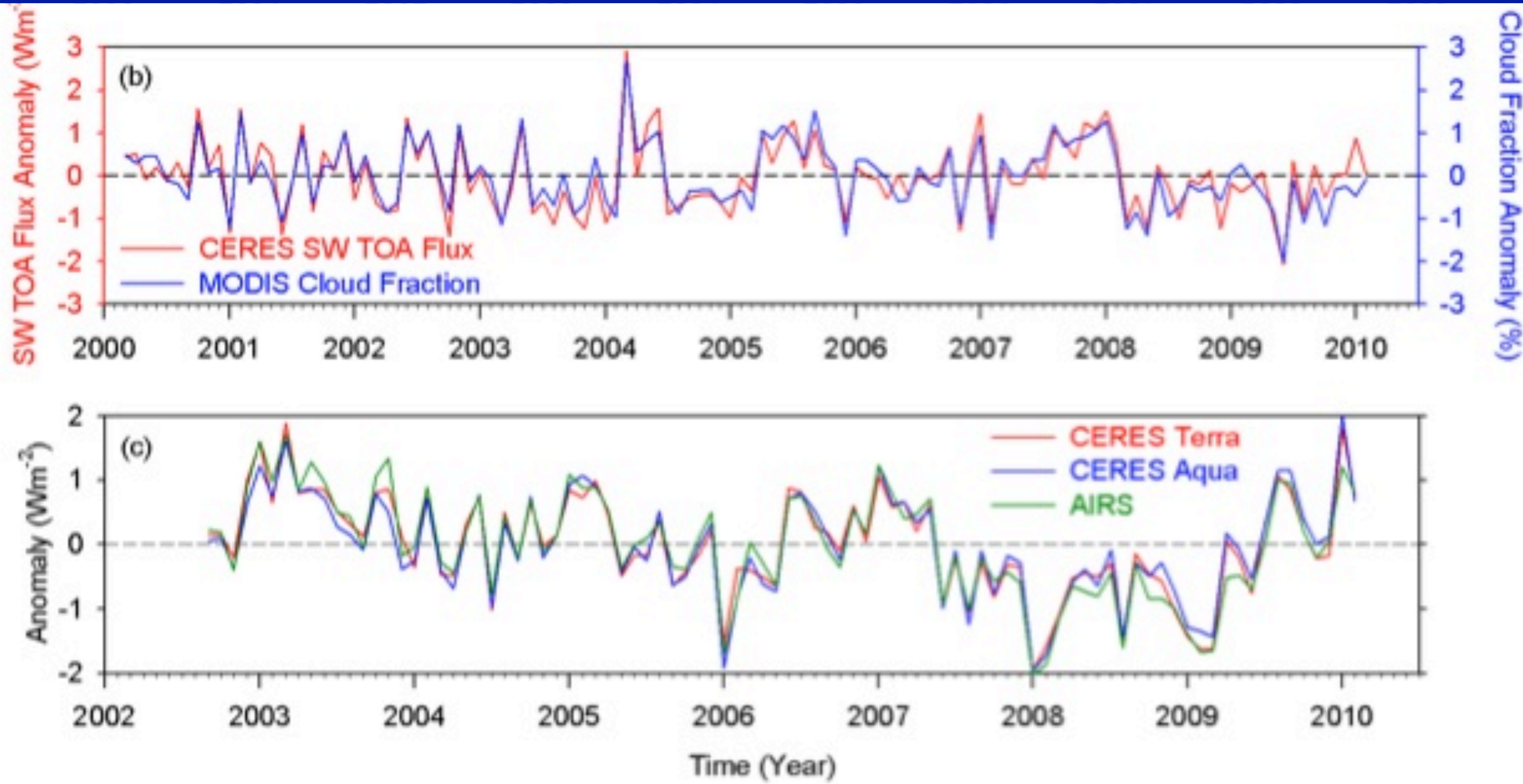


Figure 4 Monthly anomalies in (a) CERES Terra SW TOA flux from SSF1deg-lite_Ed2.5 and SeaWiFS PAR scaled by a factor of -6.09 (corresponding to the slope of the regression line fit relating CERES SW TOA flux and SeaWiFS PAR anomalies) over ocean for 30°S–30°N from March 2000 to December 2009, (b) CERES Terra SW TOA flux and MODIS cloud fraction for 30°S–30°N between March 2000 and February 2010, and (c) global LW TOA flux from CERES Terra, CERES Aqua and AIRS Aqua for September 2002-February 2010.