EARTH'S ENERGY IMBALANCE

AND ITS IMPLICATIONS FOR UNDERSTANDING CLIMATE CHANGE

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viewgraphs available at www.ecd.bnl.gov/steve

OUTLINE

Importance of EEI

Global energy budget

- Climate sensitivity
- Heating in the pipeline

Approaches to measuring EEI

- Ocean Heat Content
- Satellite radiation measurements

OHC measurements and implications

- Heat content
- Heating rate
- Heat capacity
- Heat exchange coefficient

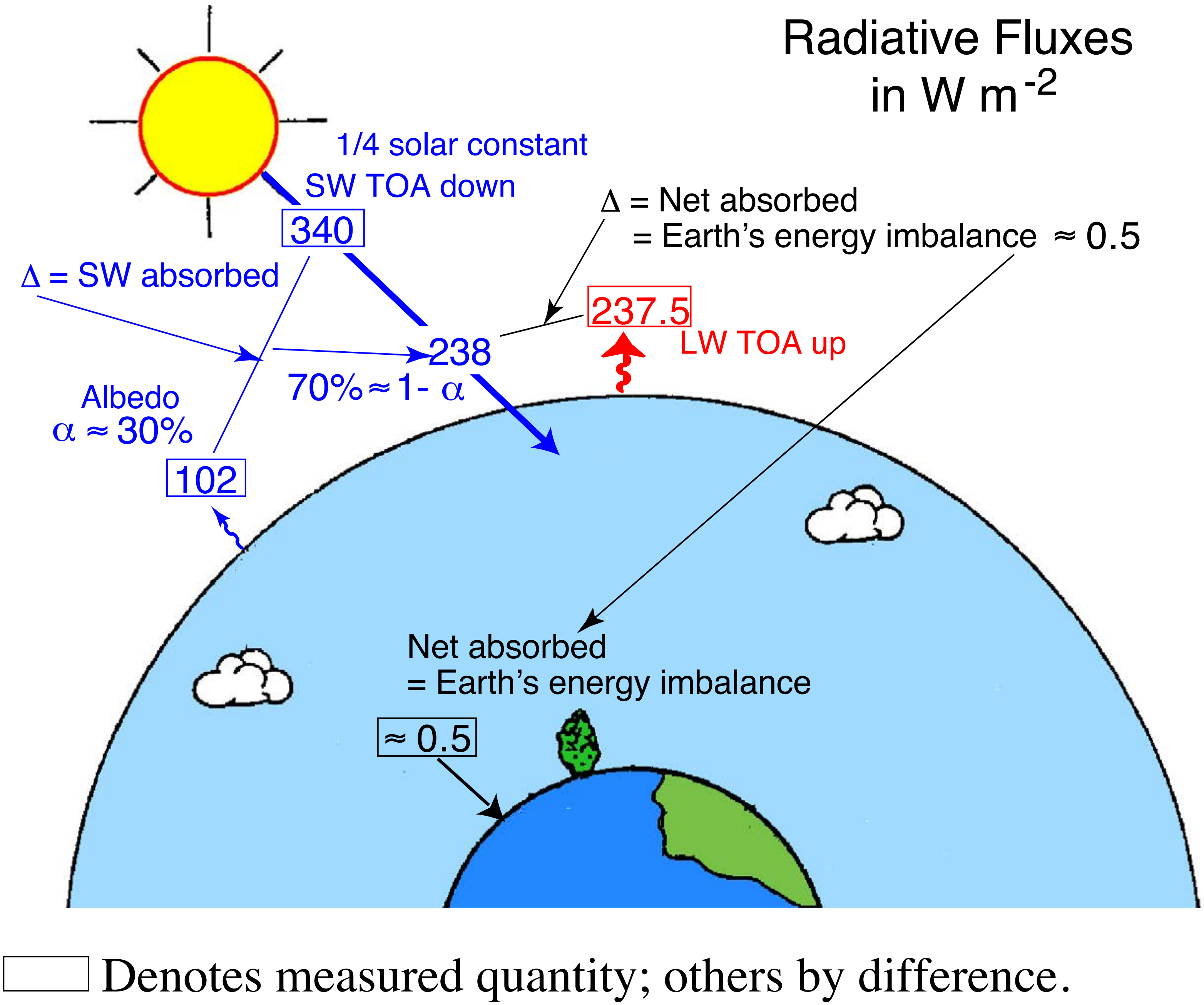
Insights from one and two compartment energy balance models

Measuring EEI from space

- Challenges
- Surprises

Conclusions

EARTH'S ENERGY BUDGET



Denotes measured quantity; others by difference.

IMPORTANCE OF EARTH'S ENERGY IMBALANCE

- ***Key independent and robust measure of climate response to forcing***.
- Permits assessment of ***heating in the pipeline***; heating rate is subtractive from forcing in interpreting observed warming.

  Caveat: this is informative of future commitment only if present forcing is maintained (aerosol commitment).
- Key to ***empirical determination of climate sensitivity*** (need forcing!).
- Leads to ***key properties of Earth's climate system***; effective heat capacity, heat uptake coefficient, time constants.
- Constrains ***climate models***.
- Contributes to interpretation of ***sea level rise***.

GLOBAL ENERGY BUDGET

$$\frac{dH}{dt} \equiv N$$

$$\frac{dH}{dt} \equiv N = J_{\text{abs}} - J_{\text{emit}}$$

For unperturbed climate system (***steady state***),

$$\frac{dH}{dt} \equiv N = J_{\text{abs}} - J_{\text{emit}} = 0$$

Apply a forcing: $$\frac{dH}{dt} \equiv N = F$$

Climate system responds: $$\frac{dH}{dt} \equiv N = F - R$$

Linear response *anzatz*: $R = \lambda \Delta T$

Energy budget equation: $N = F - \lambda \Delta T$

“EQUILIBRIUM” CLIMATE SENSITIVITY

$$N = F - \lambda \Delta T$$

$$\lambda \Delta T = F - N$$

$$\Delta T = \frac{F - N}{\lambda}$$

At new ***steady state*** following response to ***constant forcing*** F, $N \rightarrow 0$ and

$$\Delta T \rightarrow \frac{F}{\lambda} = \Delta T_{\text{eq}} = S_{\text{eq}} F \,,$$

where “equilibrium” climate sensitivity $S_{\text{eq}} \equiv \lambda^{-1}$.

HEATING IN THE PIPELINE

In general $$\Delta T = \frac{F - N}{\lambda}$$

Hence $$\Delta T = S_{\text{eq}}(F - N)$$

Energy imbalance is subtractive from forcing (*effective forcing*); $S_{\text{eq}}N$ is *heating in the pipeline*, ***committed additional warming***.

Caveat: This commitment assumes constant sustained forcing. Temperature would increase substantially if negative aerosol forcing were removed.

IMPLICATIONS FOR DETERMINATION OF CLIMATE SENSITIVITY

From climate models or observations

For known forcing $F(t)$ and known energy imbalance $N(t)$

$$\Delta T = S_{\mathrm{eq}}(F - N)$$

Or S_{eq} is slope of ΔT vs $F - N$.

Alternatively $$S_{\mathrm{eq}} = \frac{\Delta T}{F - N}$$

S_{eq} is quite sensitive to uncertainty in F and N (Gregory *et al.*, 02; Schwartz 04).

Alternatively $$F - N = \lambda \Delta T$$

Or λ is slope of $F - N$ vs ΔT (Gregory, *et al.*, GRL, 04)

APPROACHES TO MEASURING EEI

Ocean heat content (OHC)

Change in heat content over time period.

Robust, long–time-constant measure.

Error in subtraction or taking derivative.

Sea Level Rise

Thermosteric expansion accounts for only 30-40% of sea level rise.

Need to accurately estimate other contributions and uncertainties.

Satellite Measurement

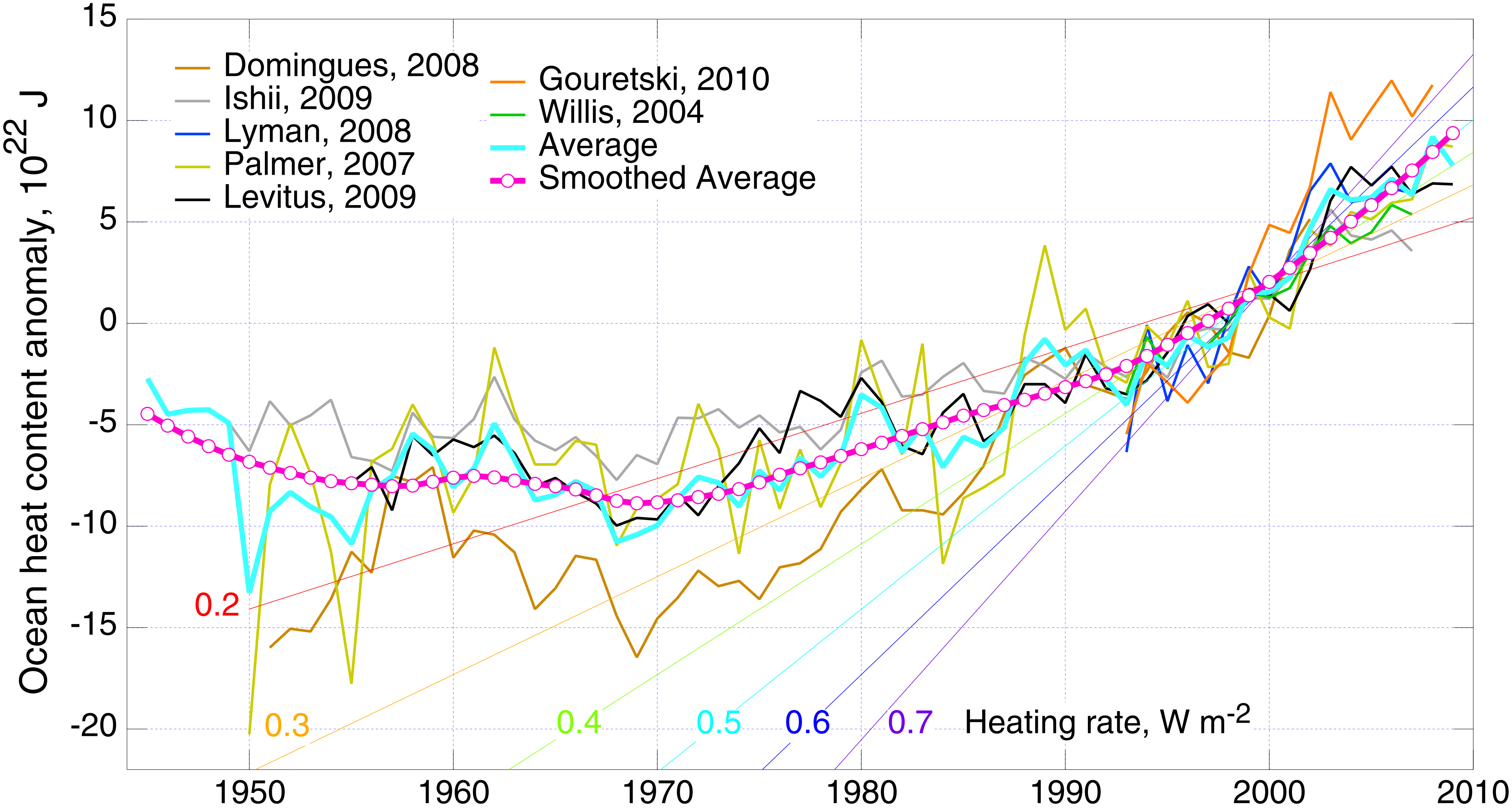
High frequency global measure.

Differences of large numbers.

MEASURING EARTH'S ENERGY IMBALANCE FROM OCEAN HEAT CONTENT

OCEAN HEAT CONTENT ANOMALY

Surface to 700 m, relative to 1993-2002



Schwartz, Surv. Geophys, 2012; Data at http://www.ncdc.noaa.gov/bams-state-of-the-climate/2009-time-series/?ts=ohc

Range of slopes, 0.45 ± 0.25 W m^{-2}, brackets most analyses.

Slope is increasing, from 0.2 W m^{-2} (1970-95) to 0.5 W m^{-2} (2000-08).

EFFECTIVE HEAT CAPACITY

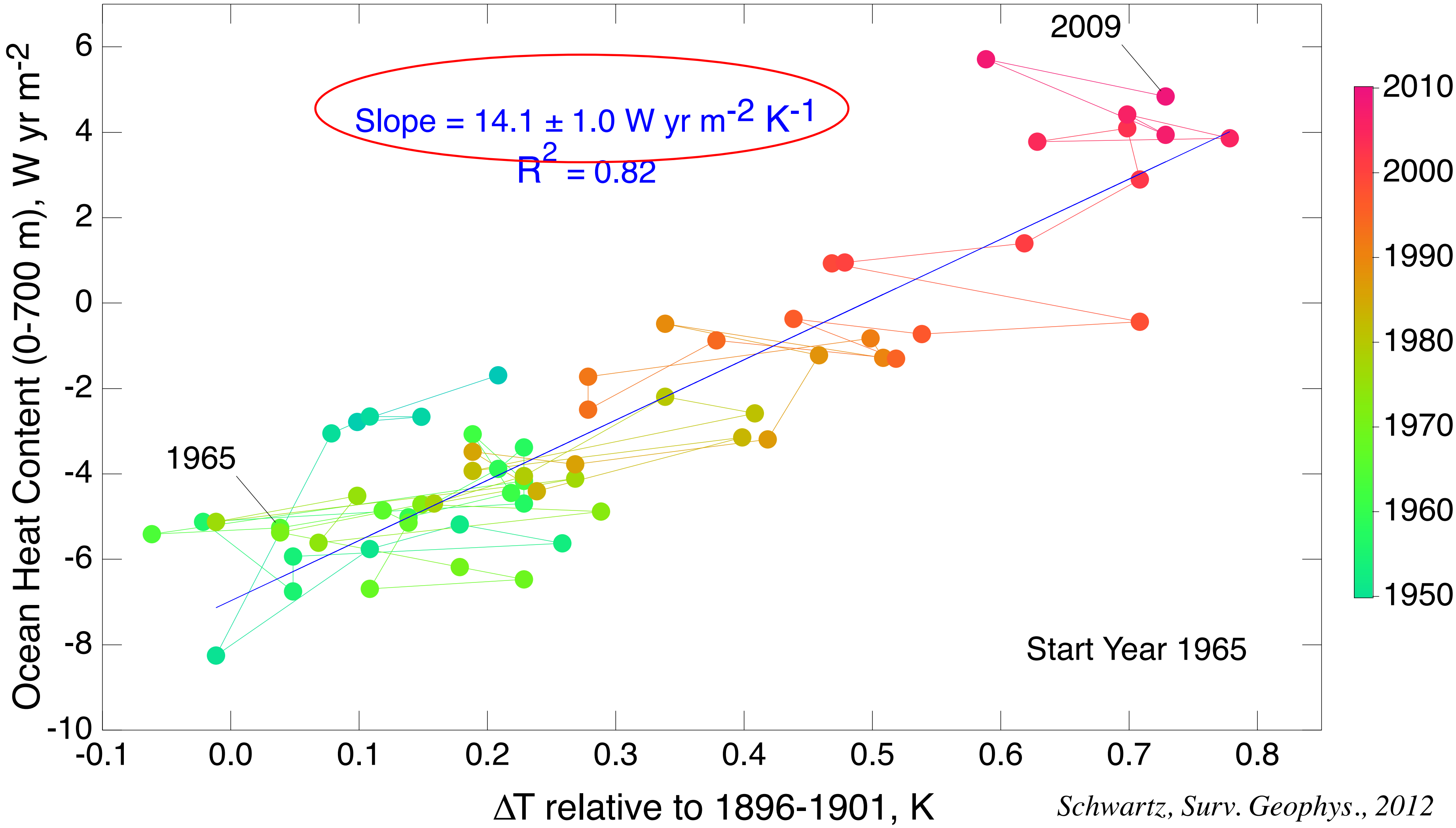
Assume planetary heat anomaly is proportional to ΔT:

$$H = C\Delta T$$

Test by examining plot of H vs ΔT; determine heat capacity C as slope.

OCEAN HEAT CONTENT ANOMALY

0 – 700 m; Dependence on surface temperature anomaly

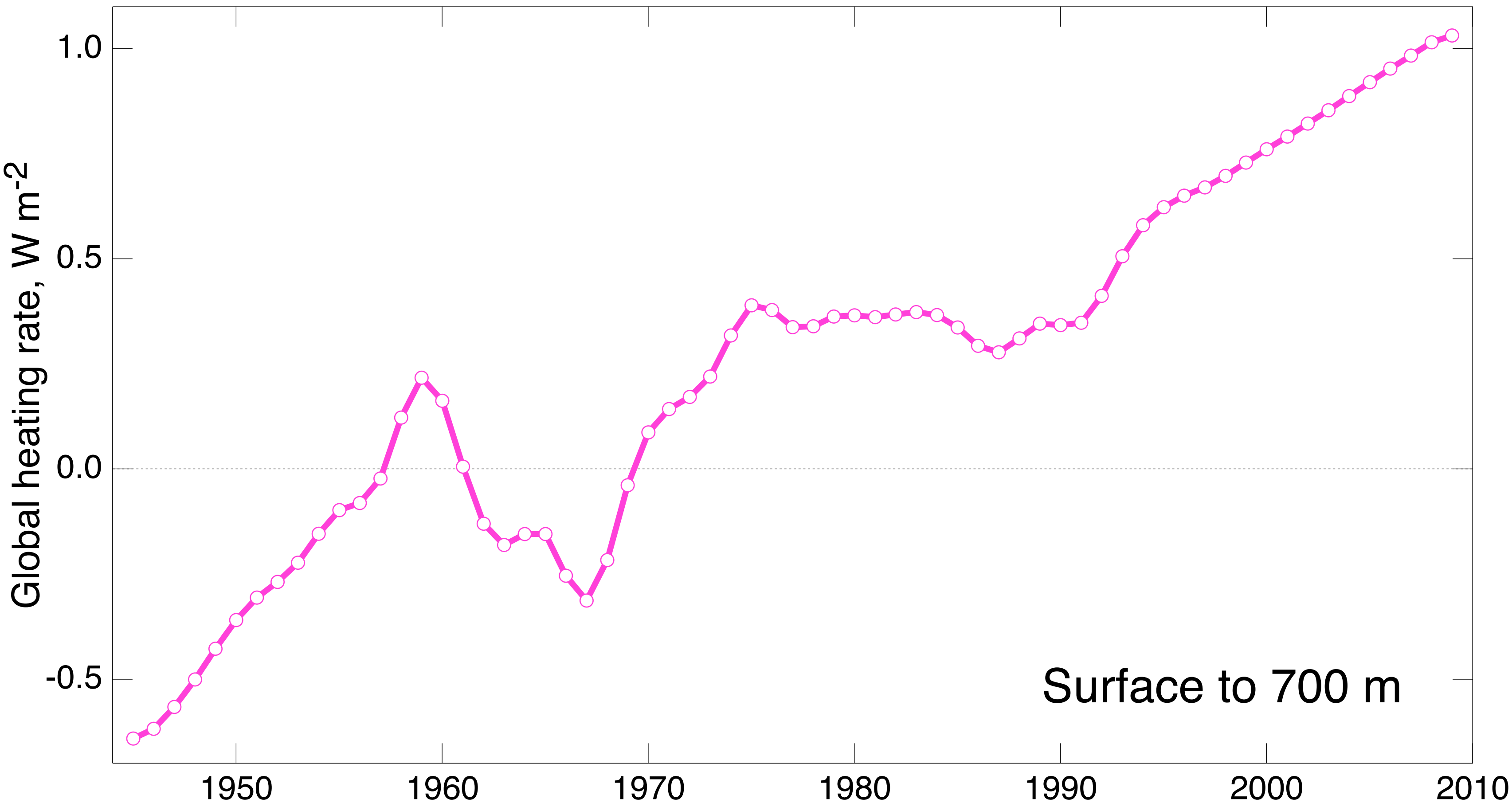


Schwartz, Surv. Geophys., 2012

Slope (1965-2009) is ***effective heat capacity***, ***much less than physical heat capacity*** of 700 m of ocean, 63 W yr m^{-2} K^{-1} (equivalent to 160 m).

GLOBAL OCEAN HEATING RATE

Derivative of global heat content, from smoothed ocean heat content



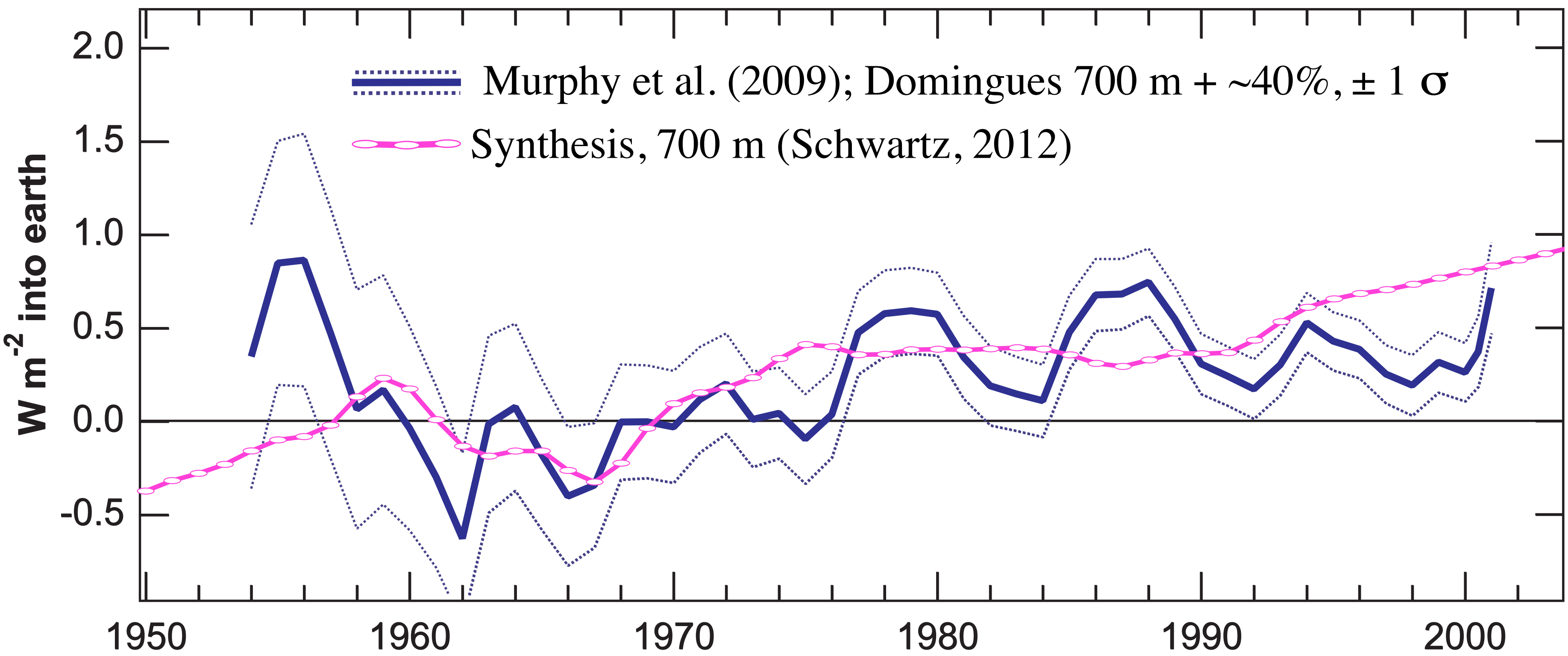
Schwartz, Surv. Geophys, 2012

Are fluctuations “real? What is the uncertainty?

Should do for individual reconstructions of ocean heat content to get sense of uncertainty.

GLOBAL OCEAN HEATING RATE

Derivative of global heat content



Schwartz, Surv. Geophys, 2012; Murphy et al., JGR, 2011

Are fluctuations "real? What is the uncertainty?
What are reasons for differences in different data sets?

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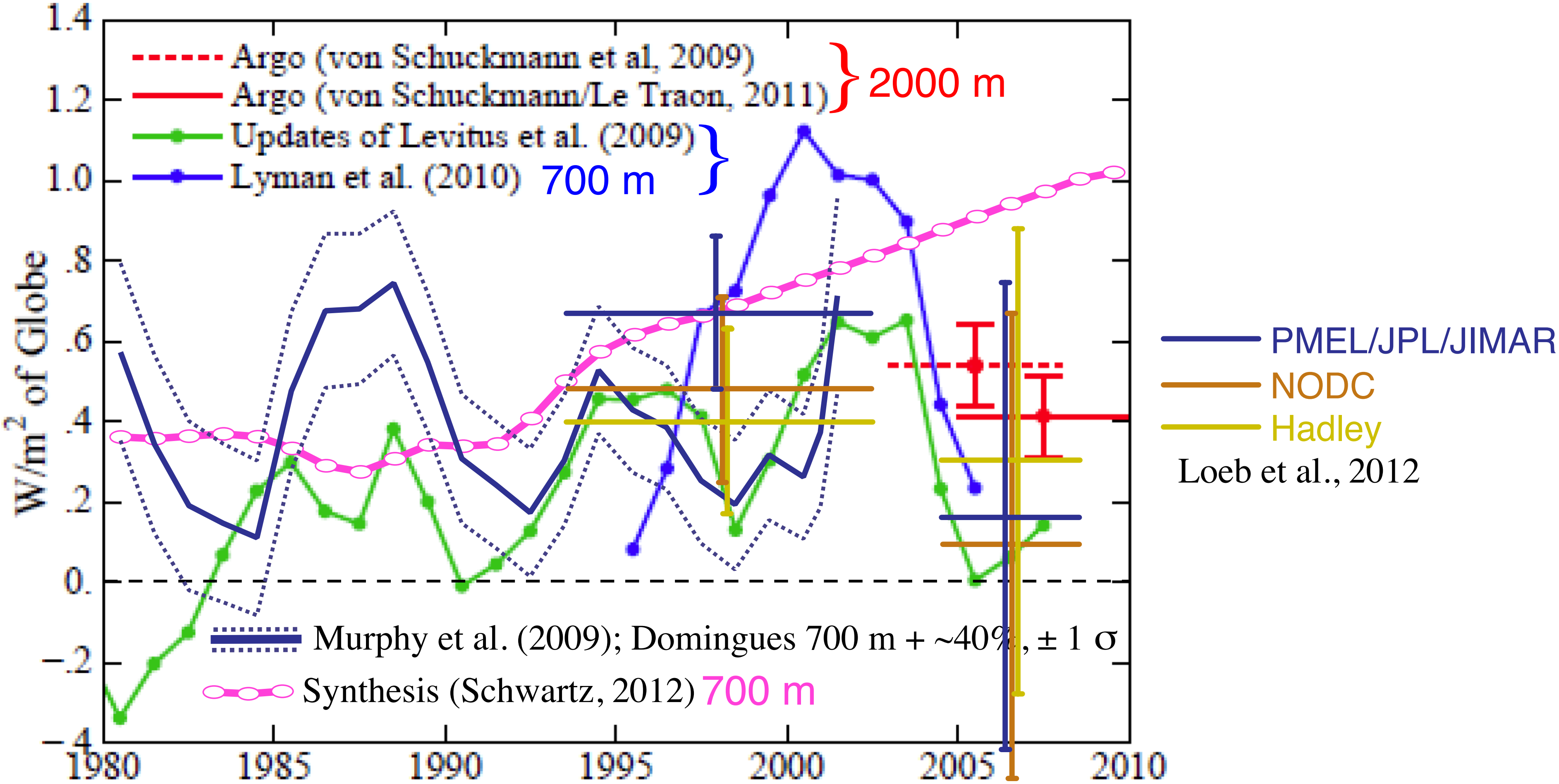

Loeb et al., 2012, NatGeo; Murphy et al., JGR, 2009; Schwartz, Surv.Geophys, 2012; Hansen et al., ACP, 2011

Are fluctuations “real? What is the uncertainty?

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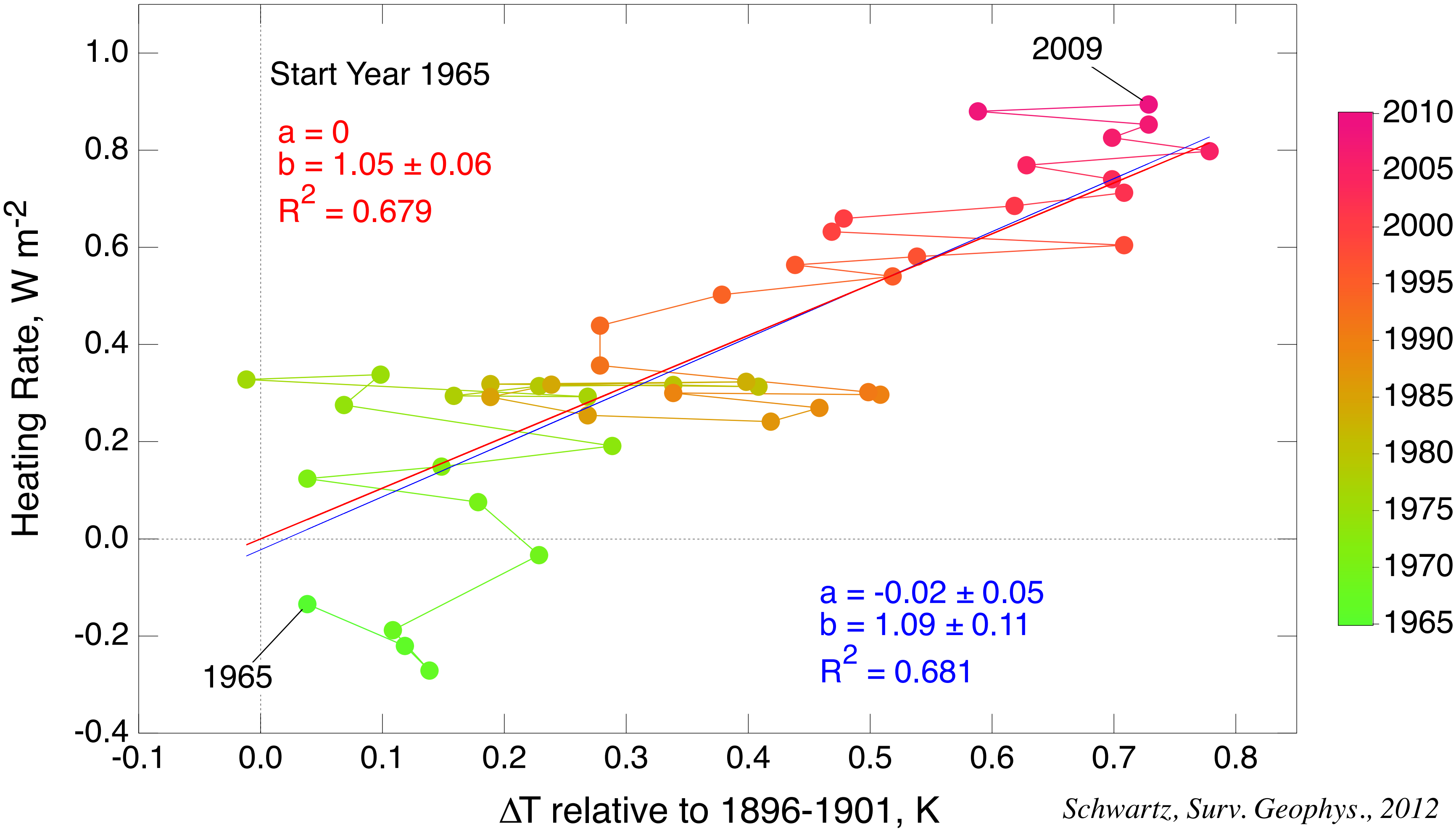
GLOBAL OCEAN HEATING RATE

0 – 700 m; Dependence on surface temperature anomaly



Schwartz, Surv. Geophys., 2012

Heating rate is linearly proportional to temperature anomaly.

Slope (1965-2009) gives ***heat uptake coefficient of upper ocean***, ~1 W m^{-2} K^{-1}.

HEAT UPTAKE COEFFICIENT

Assume planetary heating rate (energy imbalance) is proportional to ΔT: $N = \kappa \Delta T$.

Test by examining plot of N vs ΔT; determine κ as slope.

This implies that observed temperature change is proportional to forcing:

$$\lambda \Delta T = F - N = F - \kappa \Delta T$$

$$\Delta T = (\kappa + \lambda)^{-1} F = S_{\mathrm{tr}} F$$

Where $S_{\mathrm{tr}} \equiv (\kappa + \lambda)^{-1}$ is transient sensitivity.

For known forcing, S_{tr} is slope of ΔT vs F. Then evaluate λ as

$$\lambda = S_{\mathrm{tr}}^{-1} - \kappa$$

MEASUREMENT NEEDS AND CHALLENGES

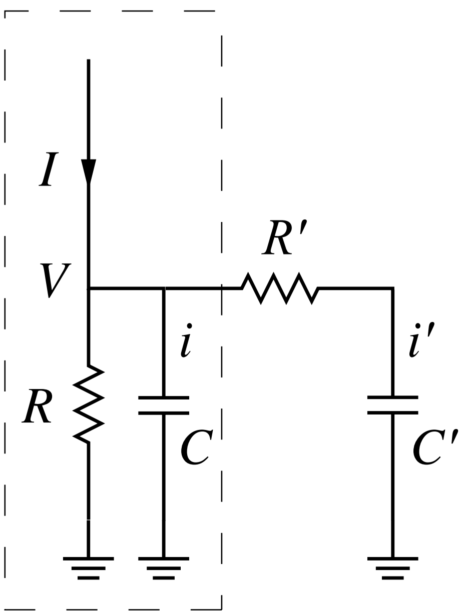
Earth heat content:

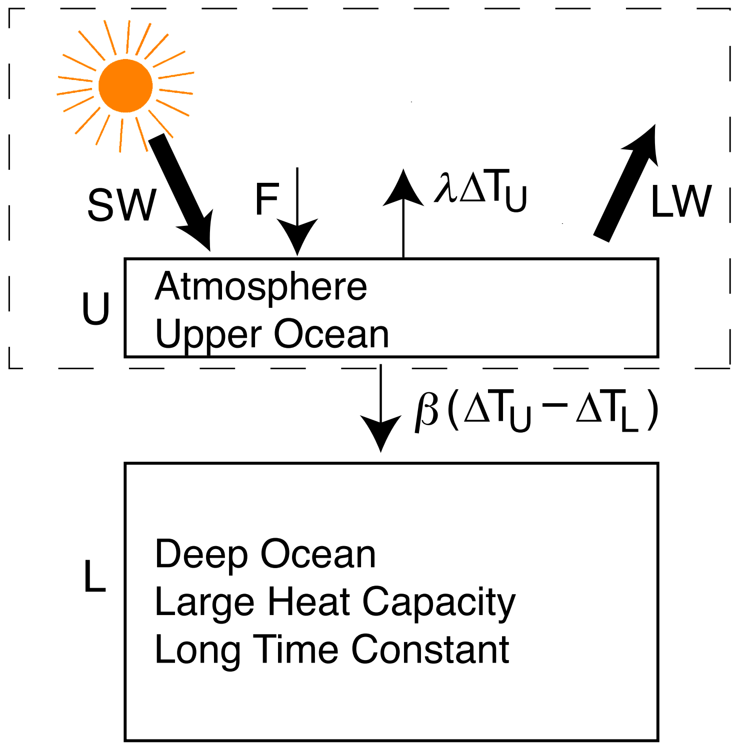
- Measurements denser in space, time?
- Measurements deeper?
- Ocean heat content (derivative).
- Global mean sea level (derivative)??
- Need to take derivative: variability, noise.
- Inherently slow (years).
- Other heat sinks; other contributions to sea level change.
- ***Others***??

INSIGHTS FROM SIMPLE ENERGY-BALANCE MODELS

TWO COMPARTMENT ENERGY BALANCE MODEL

Two Resistor–Capacitor circuit as analog to climate system





$$C_U \frac{dT_U}{dt} = F - \lambda \Delta T_U - \beta(\Delta T_U - \Delta T_L)$$

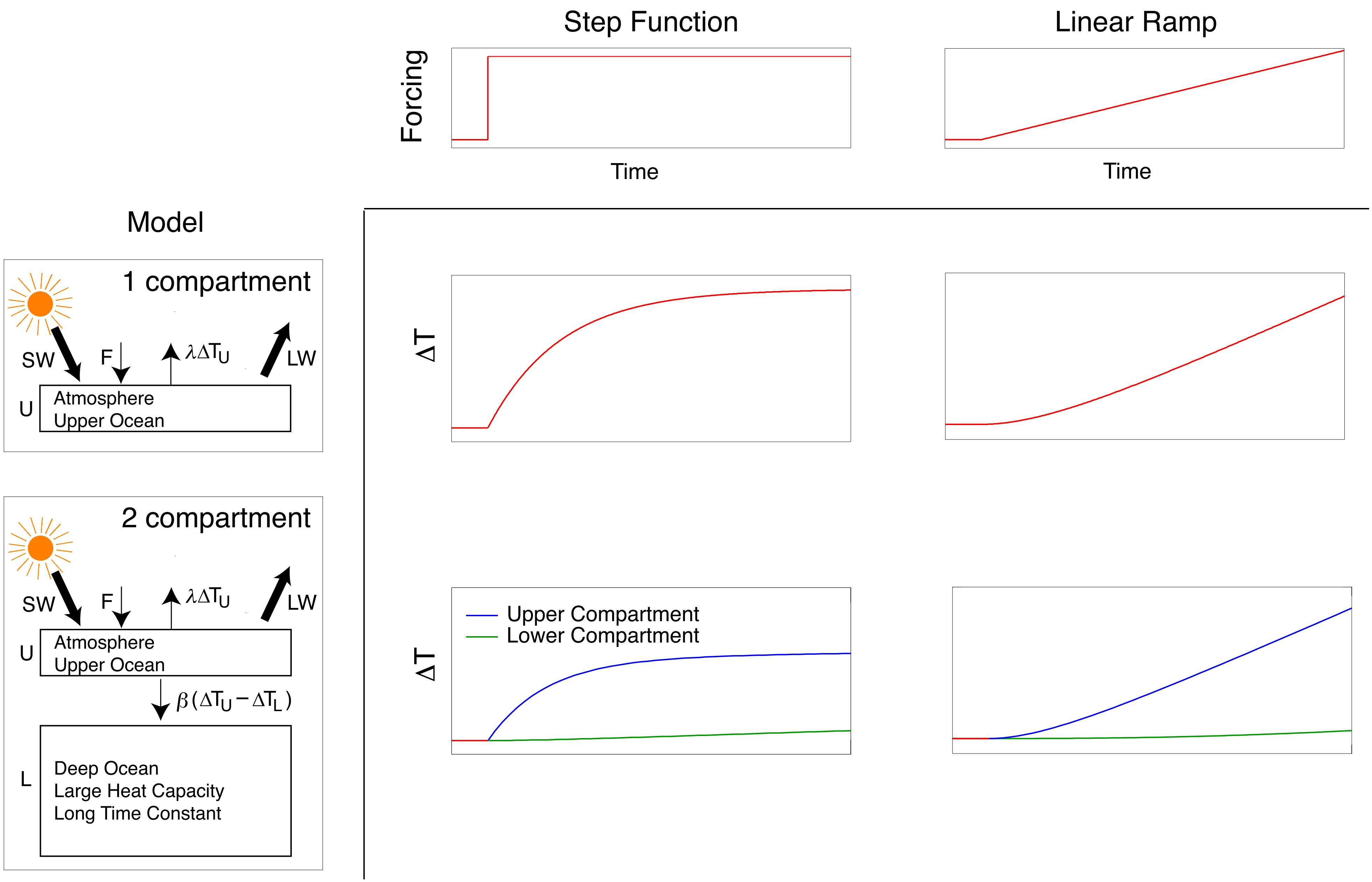
$$C_L \frac{dT_L}{dt} = \beta(\Delta T_U - \Delta T_L)$$

Flow of heat into large, deep compartment (current into large capacitor) acts in parallel to emitted longwave radiation (current through primary resistor) to decrease temperature (voltage) of upper compartment, until deep compartment (large capacitor) fills up.

Same model used to interpret GCM results by Gregory 02; Held *et al*., 10.

“MATRIX” OF CASES CONSIDERED

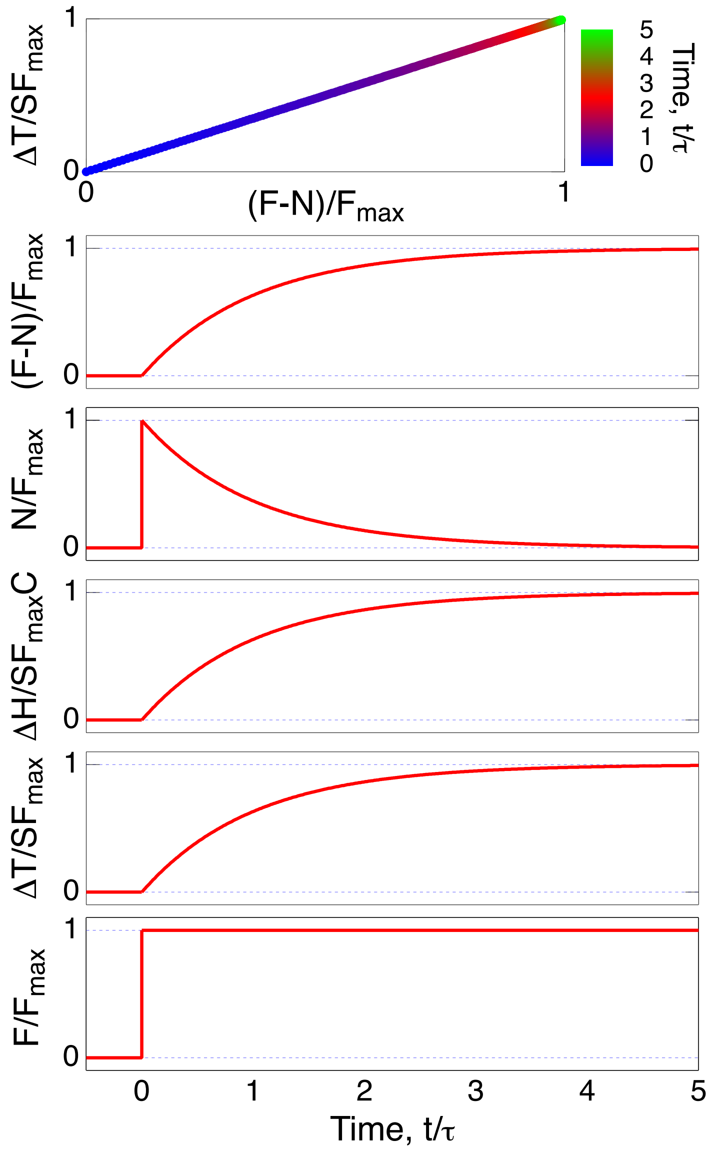
Examination of response to forcing



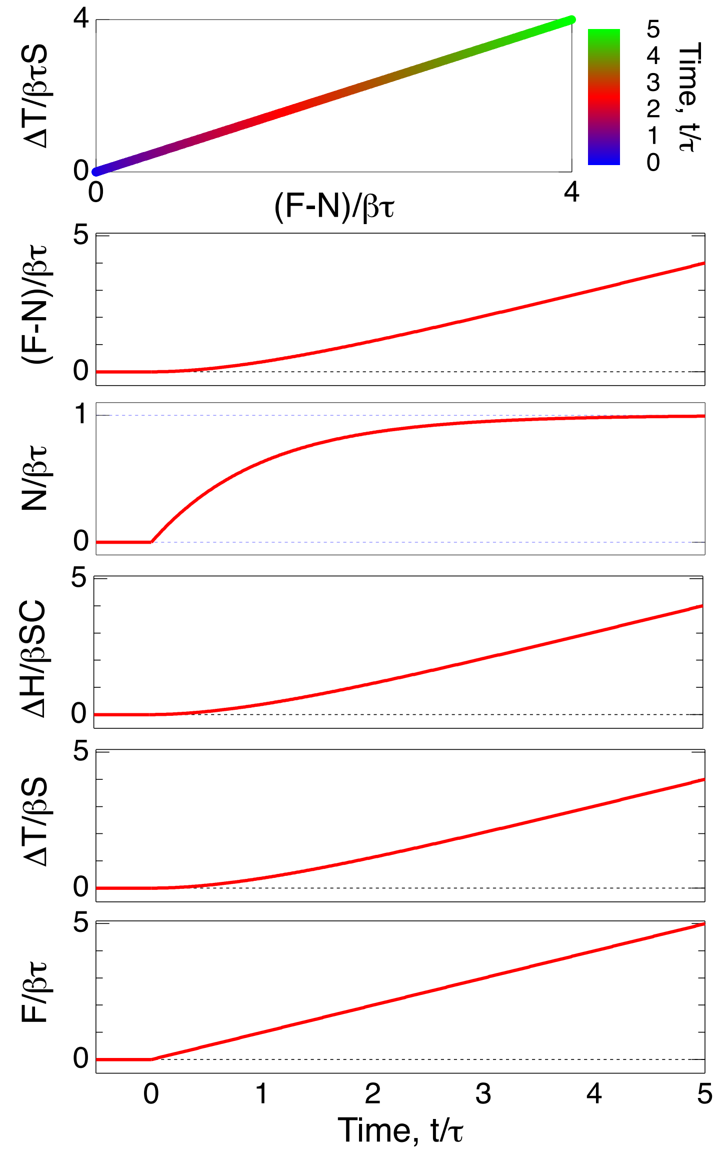
RESPONSES TO IDEALIZED FORCINGS

One compartment model

Step function forcing



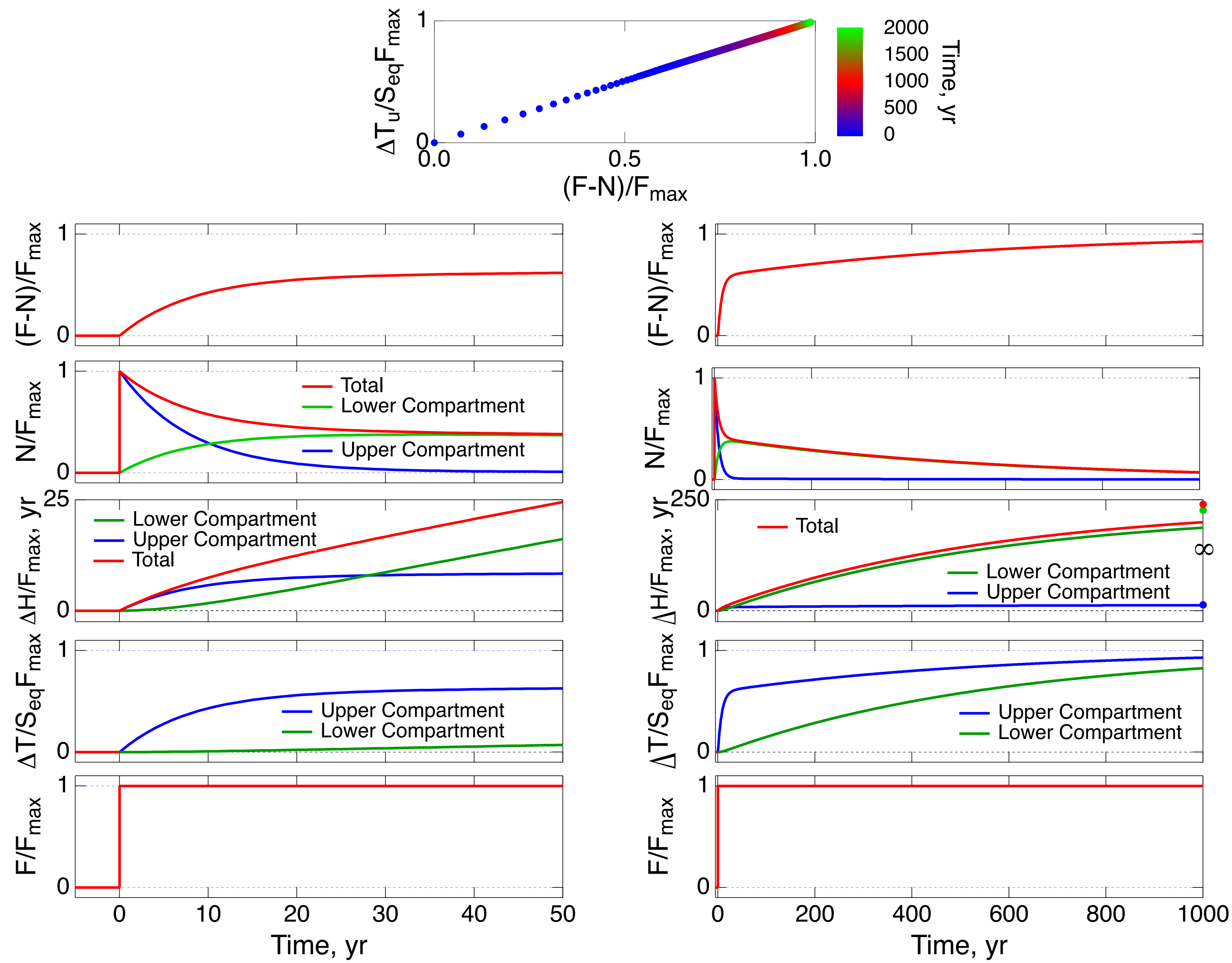
Linear ramp forcing



RESPONSES TO IDEALIZED FORCINGS

Two compartment model; $\kappa = 1$ W m^{-2} K^{-1}; Step function forcing

Time constants 8, 567 yr; Heat capacities 20, 340 W yr m^{-2} K^{-1}



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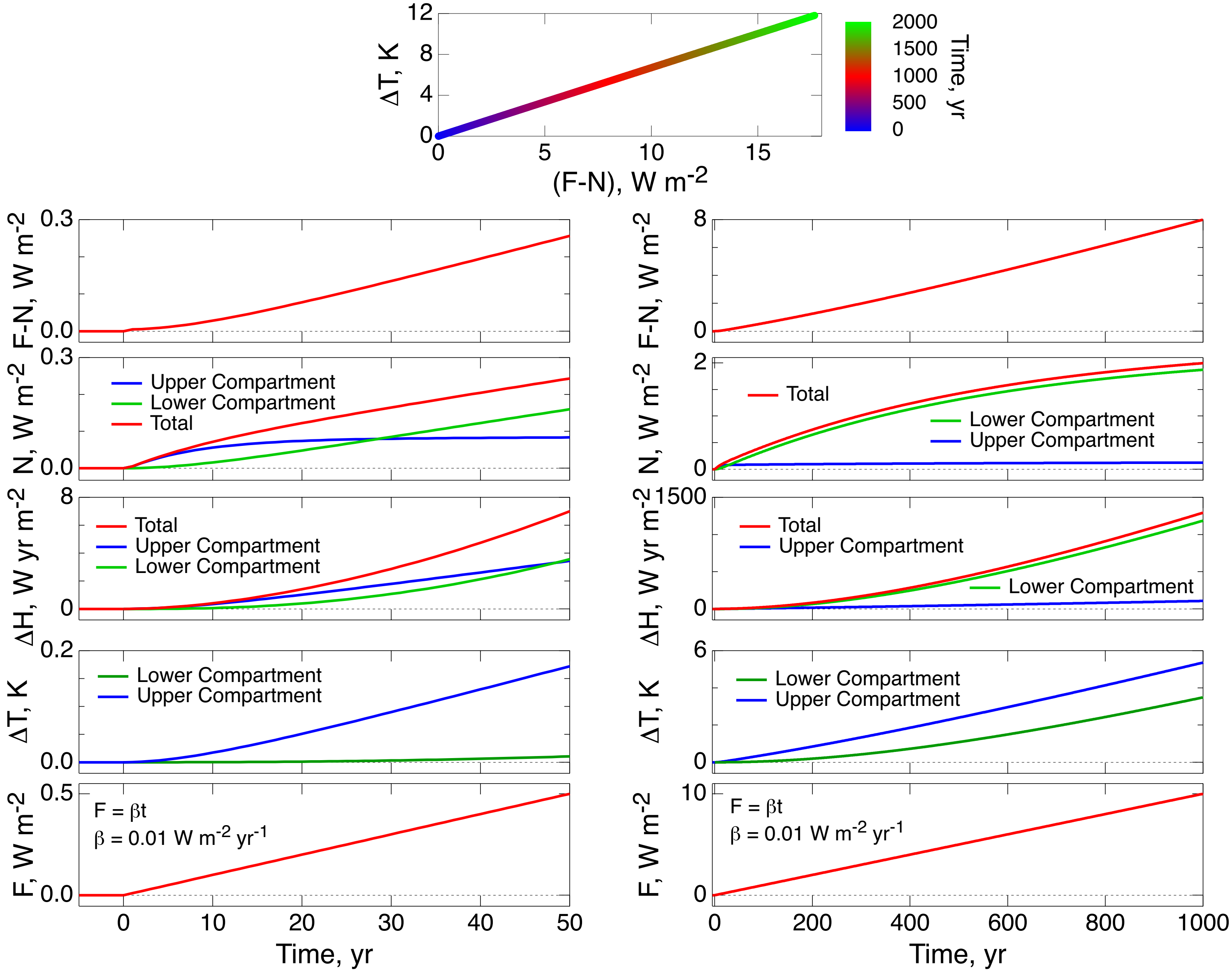

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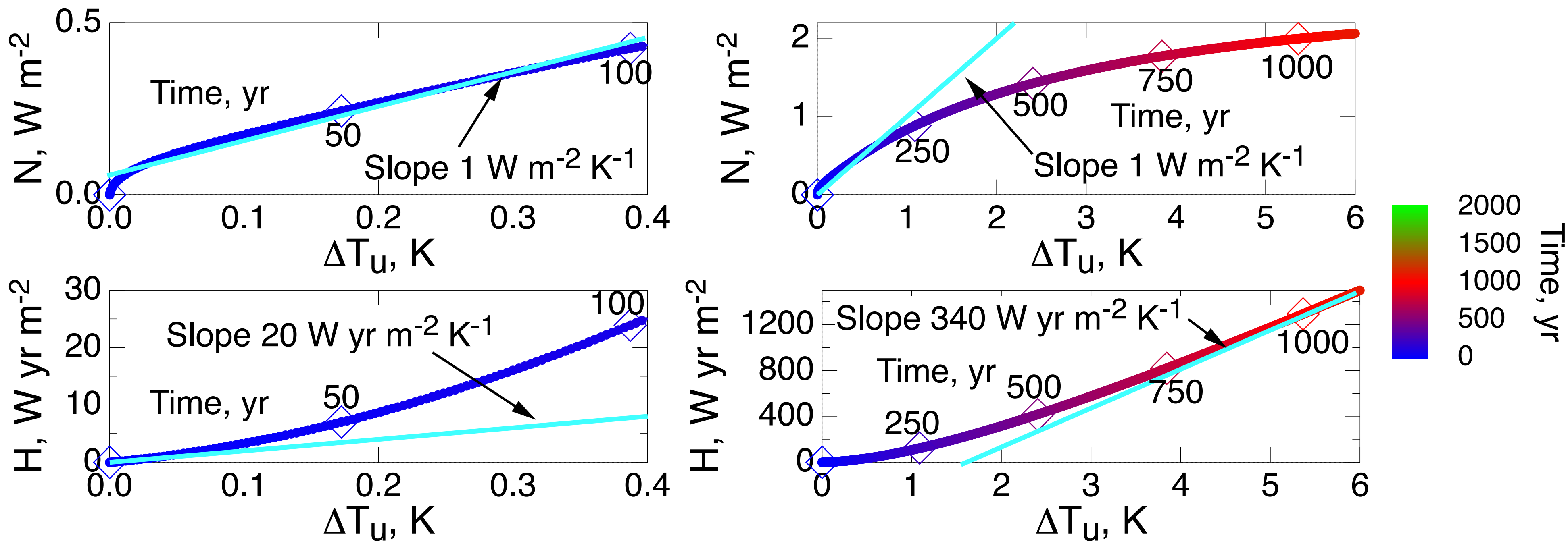


Over a given time period both heat content and heating rate increase more or less linearly with temperature of upper compartment.

This result supports inferring heat capacity and heat uptake coefficient from slopes. This result seems specific to case of linear ramp forcing.

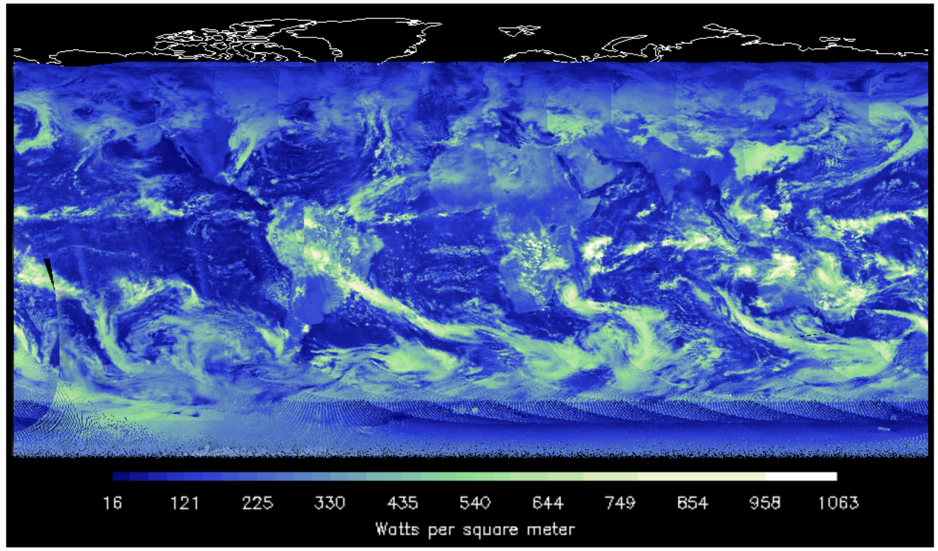
Value of κ inferred as dN/dT ***agrees closely*** with input to calculation.

Value of C inferred as dH/dT is bracketed by inputs to calculation.

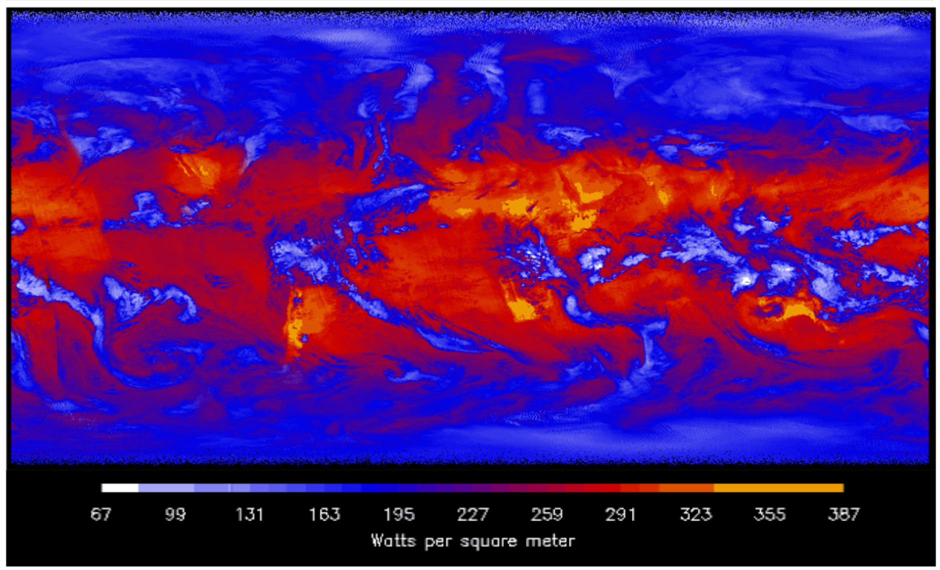
MEASURING EARTH’S ENERGY IMBALANCE FROM SPACE

INSTANTANEOUS SPATIALLY RESOLVED VIEW OF EARTH'S IRRADIANCE COMPONENTS

Shortwave



Longwave



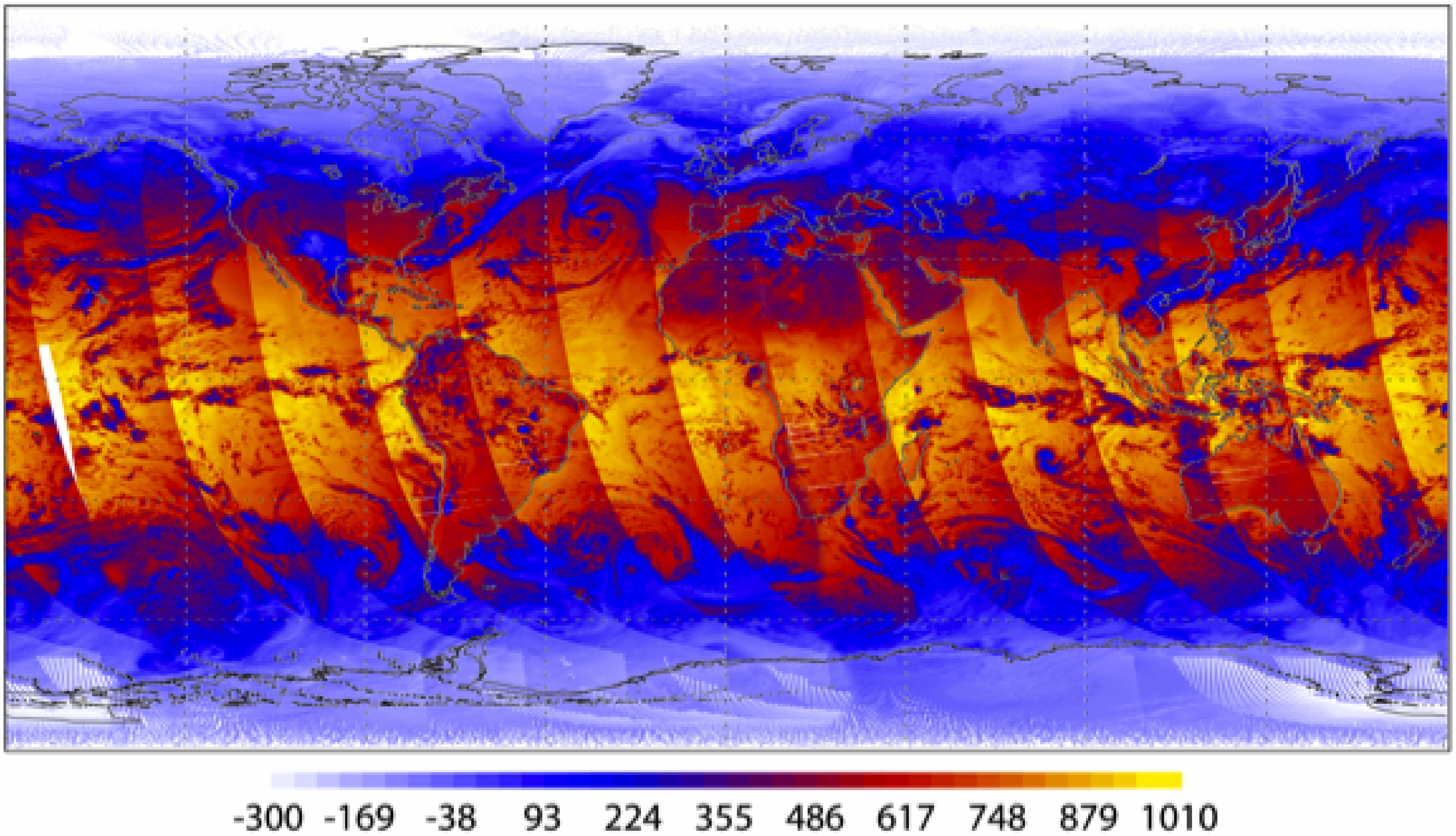
Suomi-NPP and CERES

Note dynamic range: ~ 300 W m^{-2} longwave; ~1000 W m^{-2} shortwave.

TOA INSTANTANEOUS NET FLUX

(Daytime)

CERES FM5; ERBE-Like: March 10, 2012



Courtesy, Norman Loeb

$N = 1361\cos(\theta_0) - (F^{SW} + F^{LW})$. Dynamic range: ~1300 W m^{-2}.

METERING GASOLINE

$0.1\ ¢\ /\ \$3.47$
$= 0.3\ ‰$

Pricing gasoline to 0.1 cent per gallon implies measurement accuracy of 0.3 ‰.

Equivalent to 1 cubic centimeter in a gallon.

STATE OF THE ART TOA IMBALANCE MEASUREMENTS

1 FEBRUARY 2009 JOURNAL OF CLIMATE VOLUME 22

Toward Optimal Closure of the Earth's Top-of-Atmosphere Radiation Budget

NORMAN G. LOEB, BRUCE A. WIELICKI, DAVID R. DOELLING, G. LOUIS SMITH,
DENNIS F. KEYES, SEIJI KATO, NATIVIDAD MANALO-SMITH, AND TAKMENG WONG

TOA flux and heat storage in the earth–atmosphere system. The 5-yr global mean CERES net flux from the standard CERES product is 6.5 W m^{-2}, much larger than the best estimate of 0.85 W m^{-2} based on observed ocean heat content data and model simulations. The major sources of uncertainty in the CERES estimate are from instrument calibration (4.2 W m^{-2}) and the assumed value for total solar irradiance (1 W m^{-2}). After

Uncertainty in TOA imbalance exceeds estimate from ocean heat content anomaly by an order of magnitude.

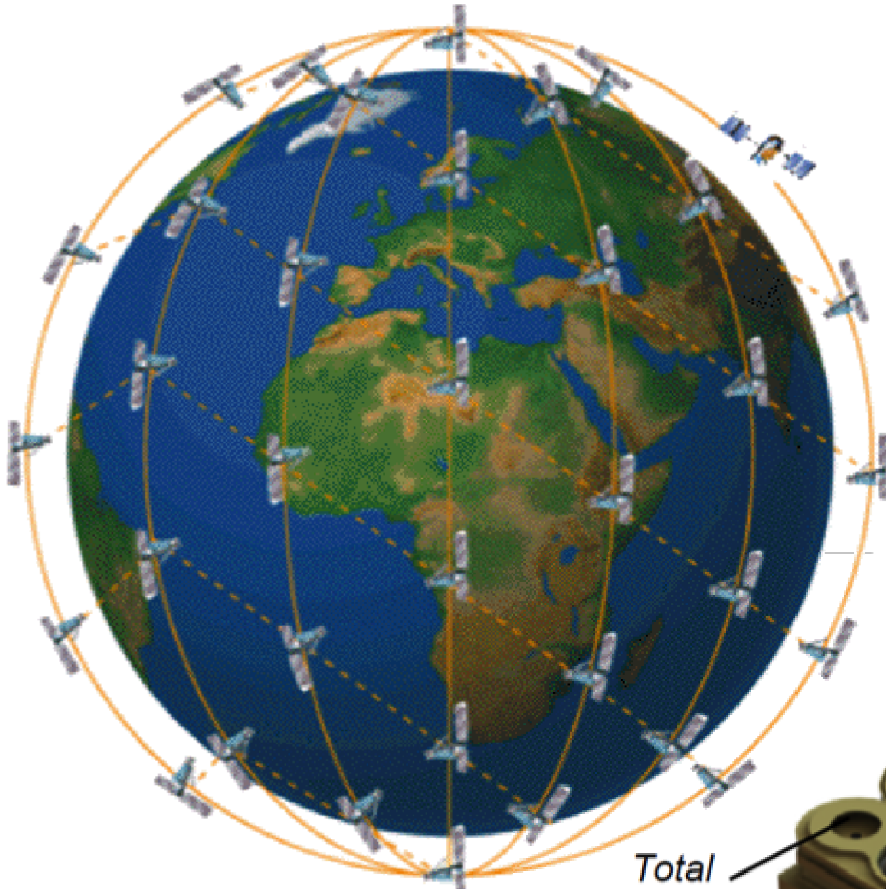
MEASUREMENT NEEDS AND CHALLENGES

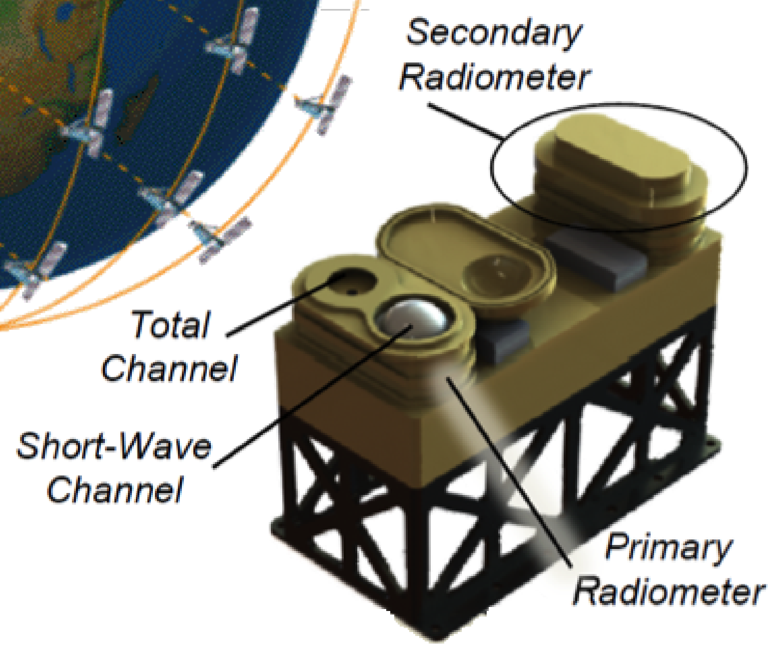
Satellite borne:

- Difference of large numbers.
- Accuracy requirement: 1‰ (per mil, part per thousand).
- Absolute calibration: three classes of sensors (solar down, shortwave up, longwave up).
- Sampling: spatial, temporal (time of day)
- Large dynamic range of local instantaneous fluxes – locally and instantaneously up to 1000 W m^{-2} in SW, 400 W m^{-2} in LW.
- ***Others***??
  What could we learn if (when) there is another Pinatubo?

ERIS: EARTH'S RADIATION IMBALANCE SYSTEM

A new concept for measuring Earth's radiation budget





Eris, a constellation of 66 flux radiometers, 11 each in 6 orbital planes. Hosted payload on Iridium Communications Satellite Network. Total cost including instruments, launch, spares, and data download, $150 M.

MODELING NEEDS AND CHALLENGES

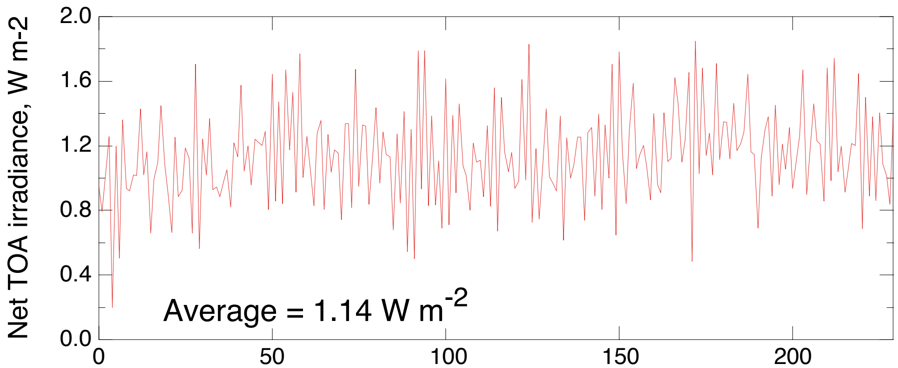
- Need to represent energy flows accurate to sub W m^{-2}, function of location and time on variety of time scales.
- Large spatial and temporal variability in upwelling SW, upwelling LW, and Net.
- Requirement of accurate representation of radiation, clouds, hydrological cycle . . . , spatially, seasonally.
- Imbalance is difference of large numbers.
- ***Others***??

ENERGY IMBALANCE IN CLIMATE MODELS

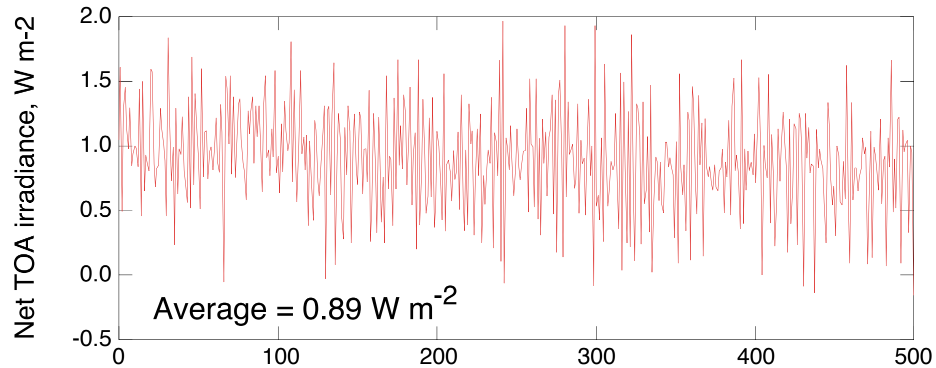
Global-annual average net flux and temperature, preindustrial control runs

Net TOA flux evaluated as $J^{\downarrow\,\mathrm{toa}}_{\mathrm{net}} = J^{\downarrow\,\mathrm{toa}}_{\mathrm{sw}} - J^{\uparrow\,\mathrm{toa}}_{\mathrm{sw}} - J^{\uparrow\,\mathrm{toa}}_{\mathrm{lw}}$

NCAR-CCSM3.0



GFDL-CM2.0



Data source: PCMDI IPCC AR4 Archive

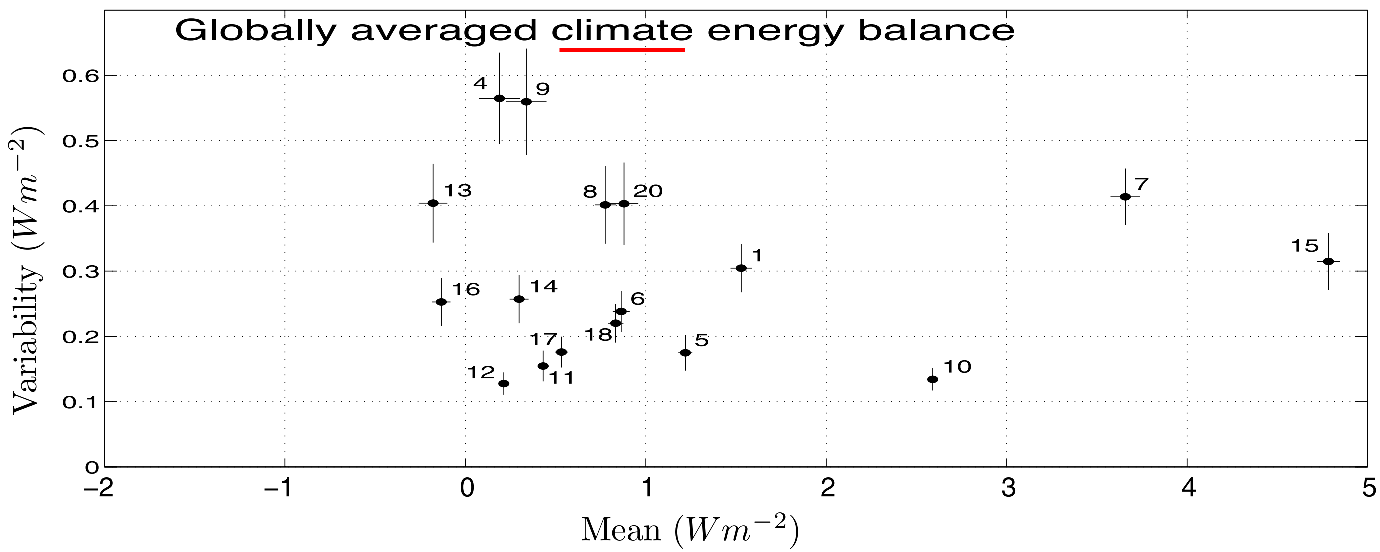
Net TOA flux is ***distinctly and substantially non-zero*** for preindustrial control runs, implying substantial imbalance (heating) of the climate system.

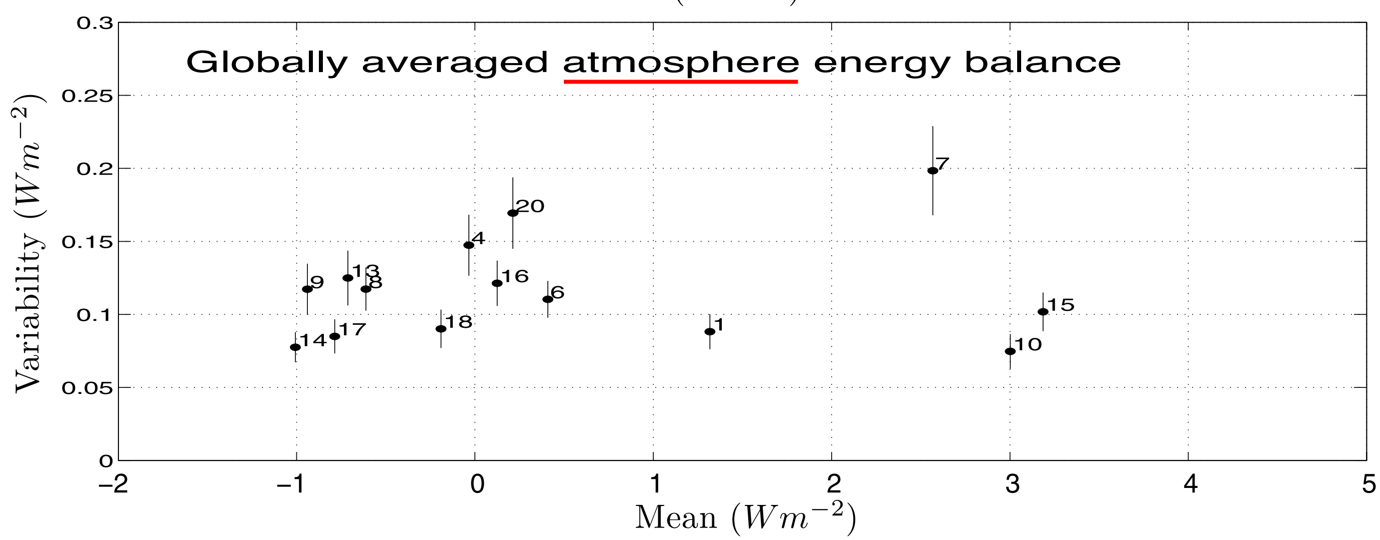
This flux ***exceeds average heat flux into planet*** even during global warming (second half of twentieth century).

This flux is comparable to forcings of concern over the industrial period.

ENERGY IMBALANCE IN AR4 MODELS

Preindustrial runs





Lucarini and Ragone, RG, 2011

"An imbalance of 1 W m^{-2} for the atmosphere corresponds to a ***staggering drift*** of about 3 K yr^{-1} of its average temperature.

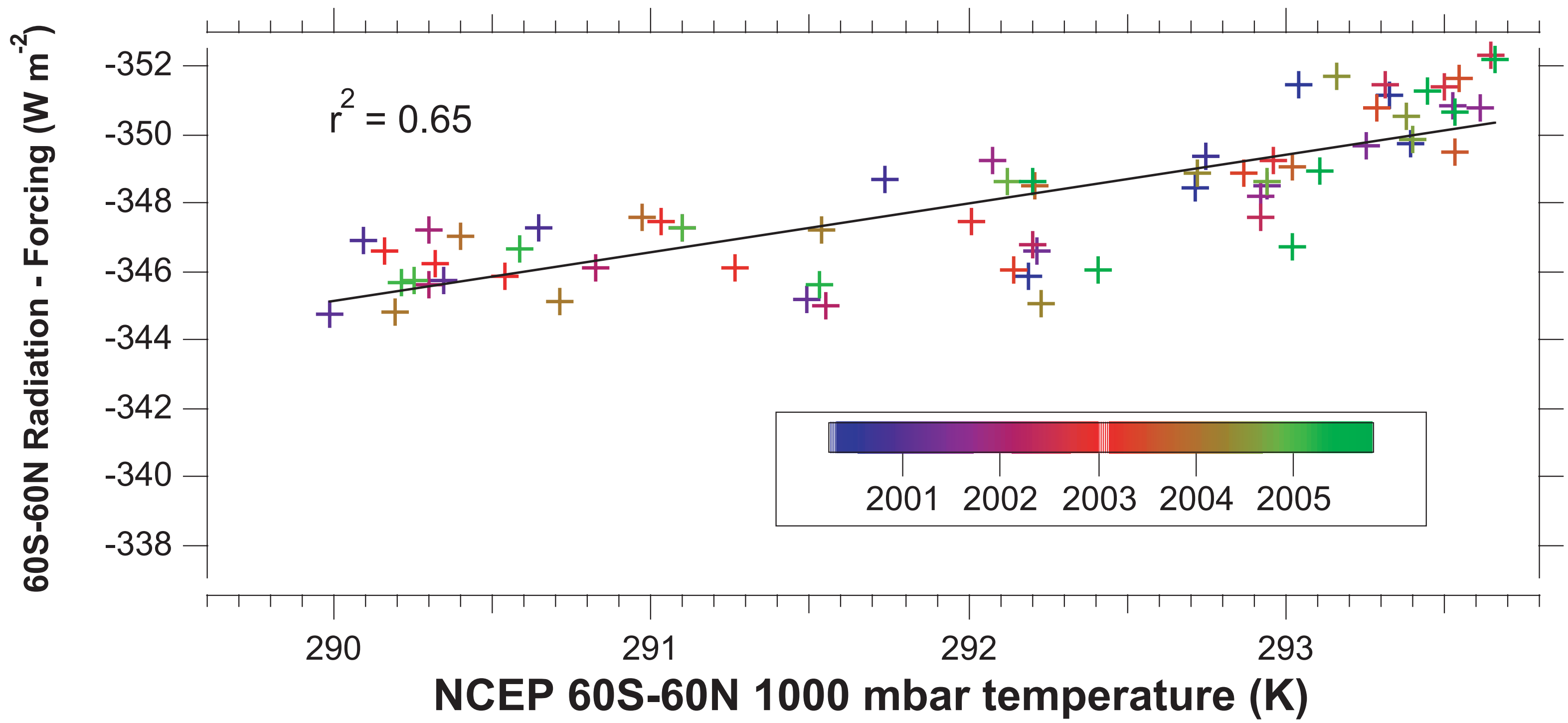
DIRECT DETERMINATION OF CLIMATE SENSITIVITY FROM MEASUREMENT OF EEI ??

DETERMINATION OF CLIMATE SENSITIVITY FROM SATELLITE RADIATION MEASUREMENTS

Slope of (Flux – Forcing) vs 60˚N–60˚S Mean Surface Temperature

CERES ***Monthly Average*** Total Upwelling TOA Flux

Accounting for secular increase in LW GHG forcing



Murphy, Solomon, Portmann, Rosenlof, Forster & Wong, JGR 09

Slope is ***well constrained***, $\lambda = 1.43 \pm 0.13$ W m^{-2} K^{-1} (1 σ); sensitivity $S = 0.70 \pm 0.06$ K/(W m^{-2}); $\Delta T_{2\times} = 2.6 \pm 0.24$ K .

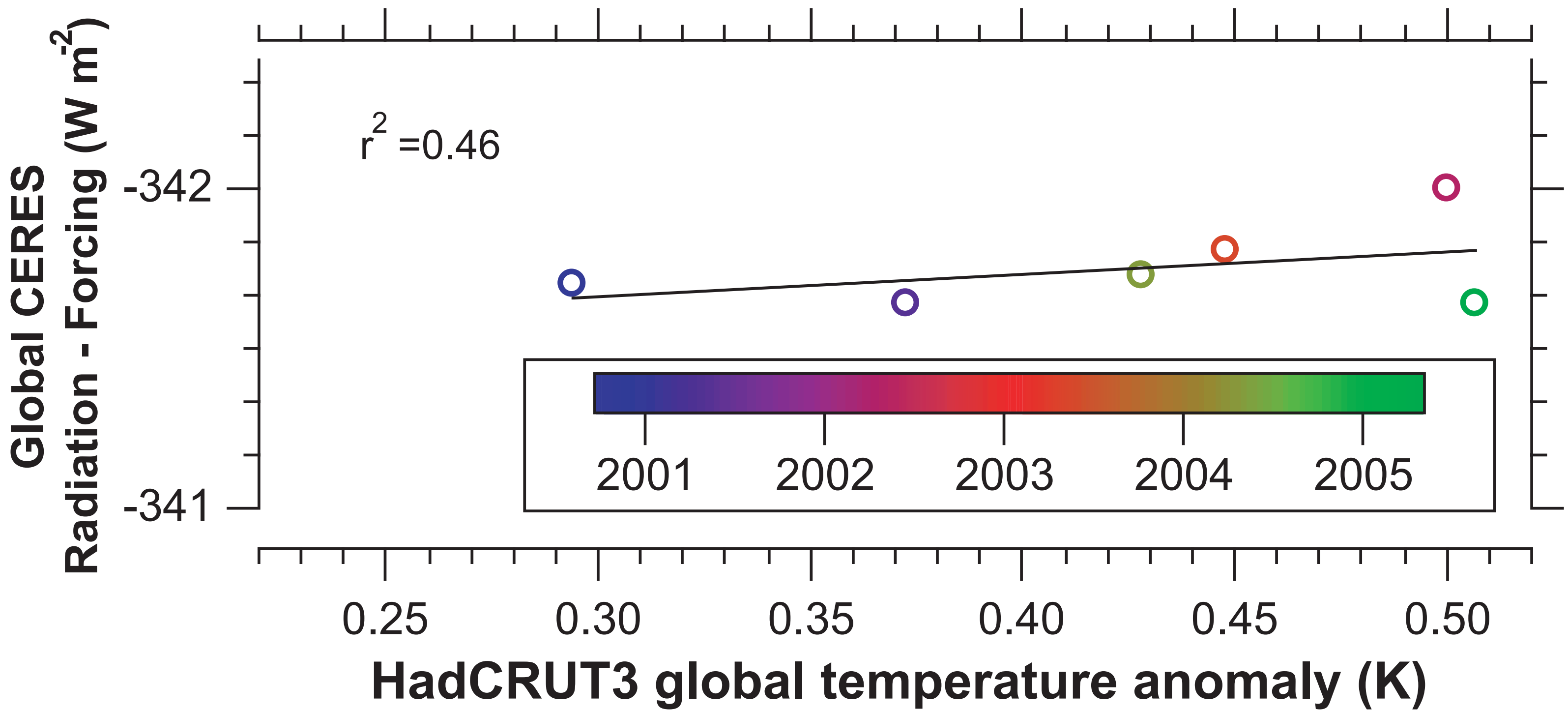
Large span in GMST is due to seasonal variation; requires seasonal forcings; question over applicability to secular temperature change.

DETERMINATION OF CLIMATE SENSITIVITY FROM SATELLITE RADIATION MEASUREMENTS

Slope of (Flux – Forcing) vs Global Mean Surface Temperature

CERES ***Annual Average*** Total Upwelling TOA Flux

Accounting for secular increase in LW GHG forcing

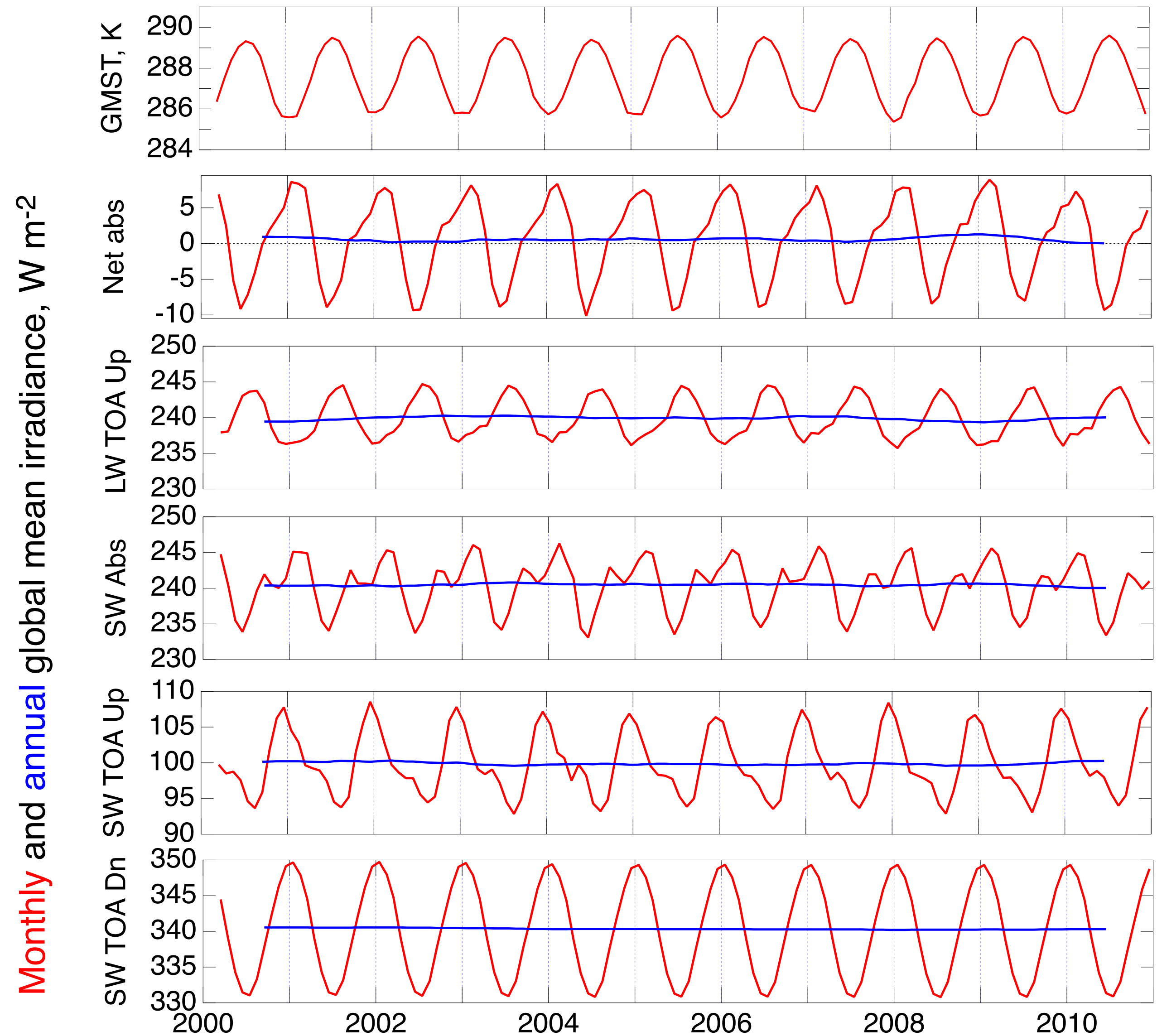


Murphy, Solomon, Portmann, Rosenlof, Forster & Wong, JGR 09

Slope is ***ill defined***: $\lambda = 0.69 \pm 0.78$ W m^{-2} K^{-1} (1 σ)
sensitivity is ***unconstrained*** $S = 1.4^{+\infty}_{-0.8}$ K/(W m^{-2}); $\Delta T_{2\times} = 5.4^{+\infty}_{-2.8}$ K.

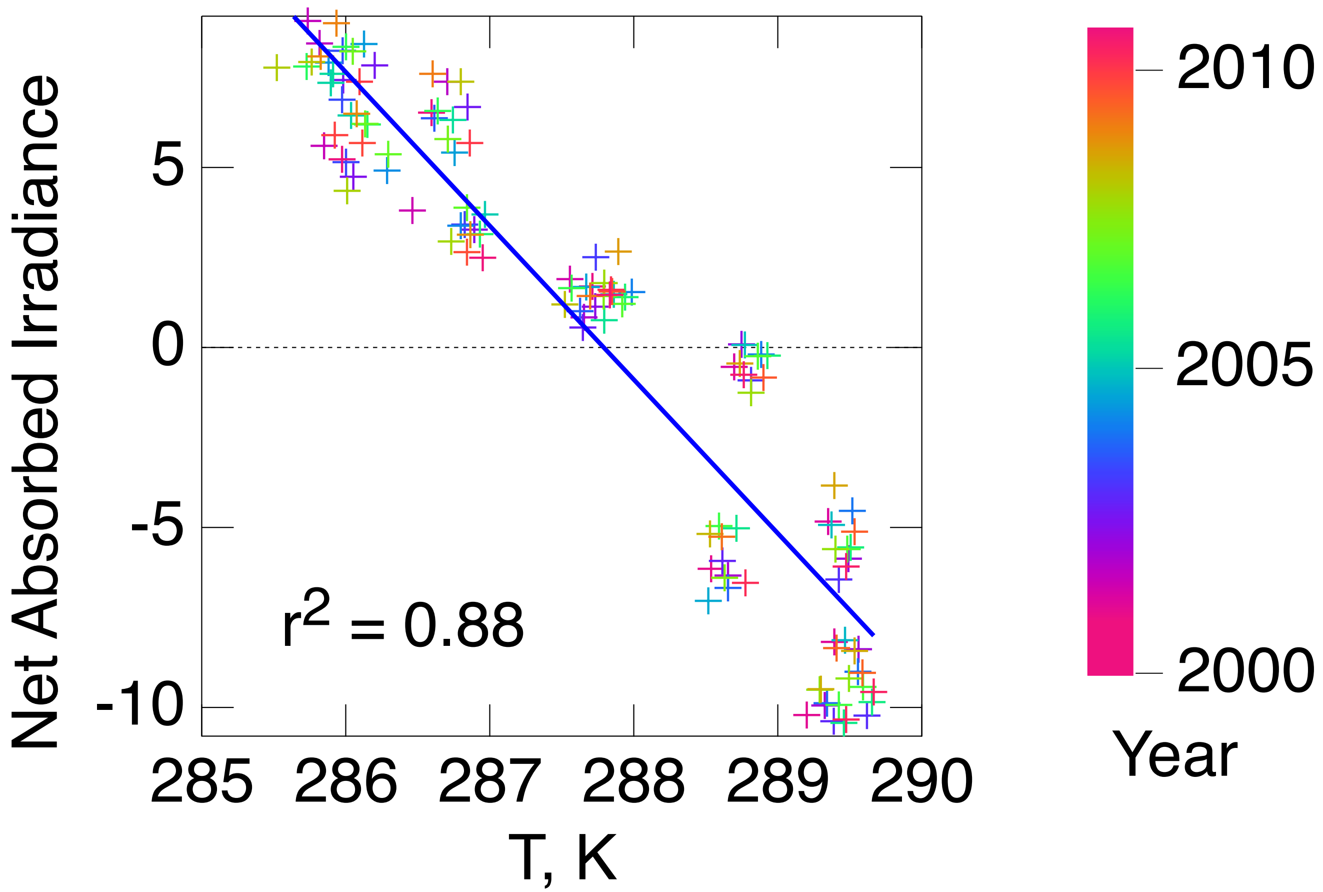
Cause of interannual variability is not known; might be extended to 2010 to better determine slope.

SEASONAL VARIATION OF RADIATIVE FLUXES AND GMST



CERES, CRU

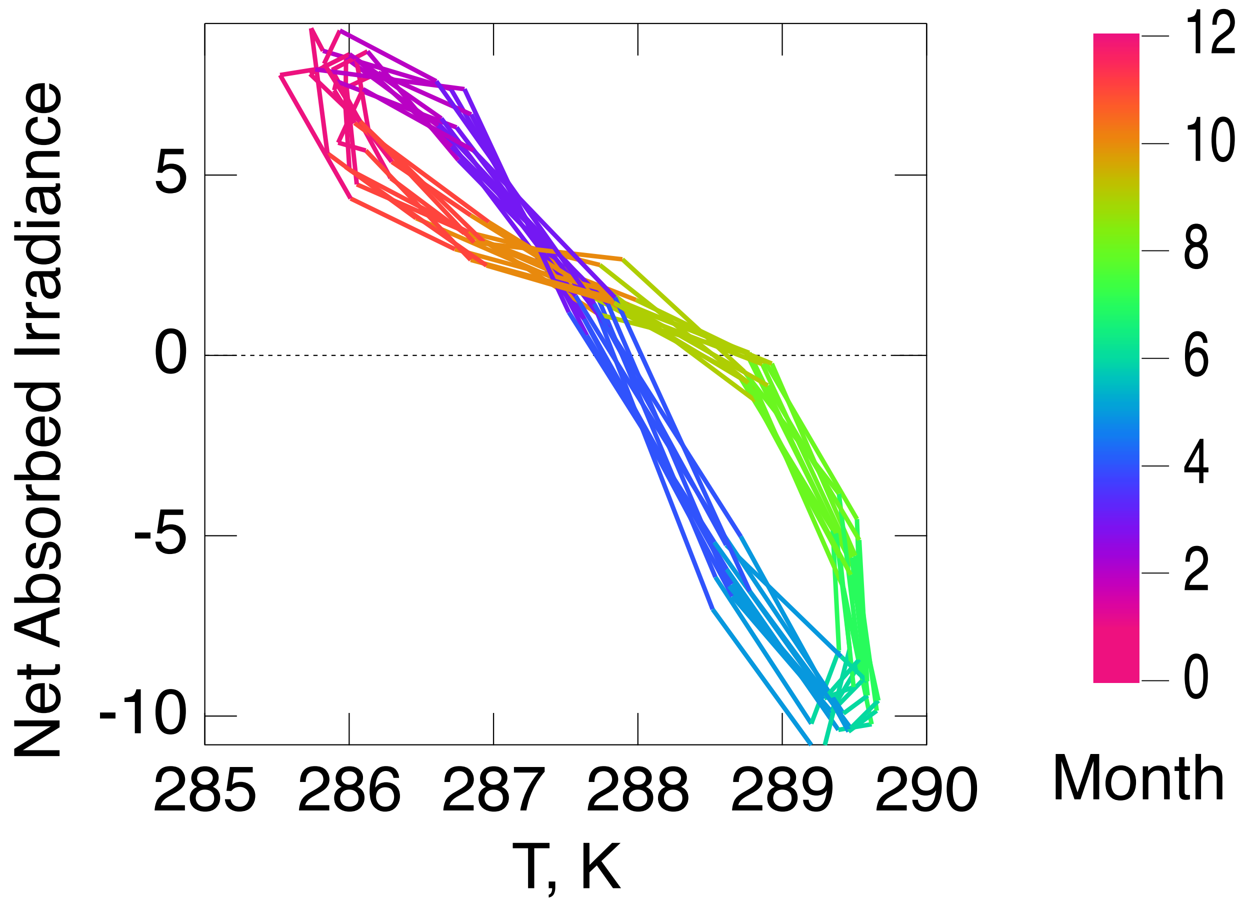
TEMPERATURE DEPENDENCE OF GLOBAL NET ABSORBED IRRADIANCE



CERES, CRU

Slope is ***well constrained***, $\lambda = 4.27 \pm 0.14$ W m^{-2} K^{-1} (1 σ);
sensitivity $S = 0.234 \pm 0.008$ K/(W m^{-2}); $\Delta T_{2\times} = 0.87 \pm 0.03$ K .

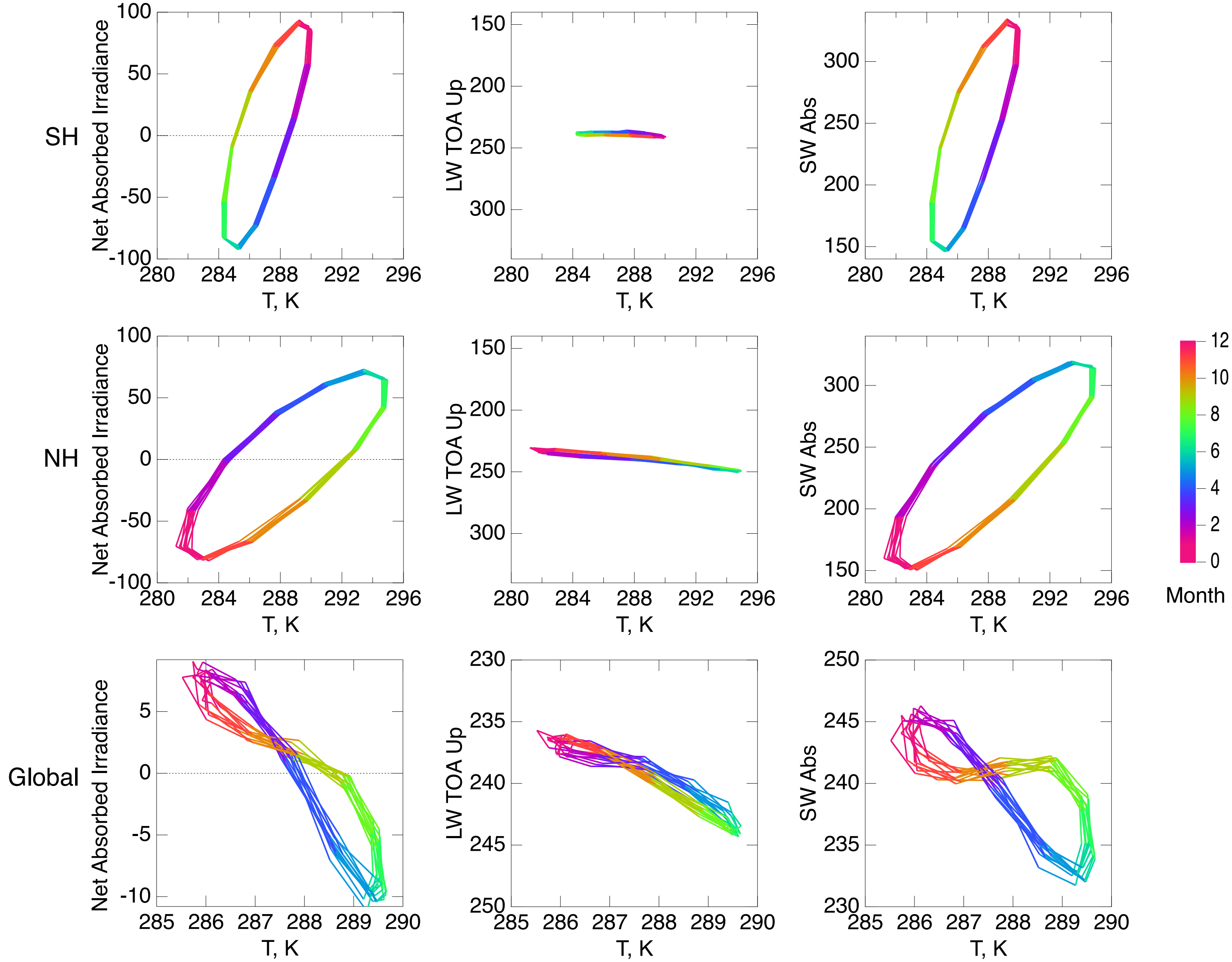
TEMPERATURE DEPENDENCE OF GLOBAL NET ABSORBED IRRADIANCE



CERES, CRU

Variation in net absorbed irradiance is seasonal, with a twist.

TEMPERATURE DEPENDENCE OF RADIATIVE FLUXES



CERES, CRU

CONCLUSIONS RE SEASONAL DEPENDENCE OF IRRADIANCE COMPONENTS

- Temperature dependence of ***global*** irradiance components is confounded by opposite dependences in two hemispheres.
- It seems unlikely that sensitivity (λ) can be meaningfully inferred from temperature dependence of ***global*** irradiance components.
- It seems likely that seasonal variation of ***hemispheric*** total upwelling and net irradiances are strongly influenced by seasonal variation of downwelling SW and hence unlikely to lead directly to sensitivity (λ).
- Hemispheric irradiance components exhibit rich seasonal variation that might usefully serve as constraint on models.

CONCLUSIONS

- ***EEI is a key independent measure of climate response to forcing***.
- EEI permits assessment of ***heating in the pipeline***; heating rate is subtractive from forcing in interpreting observed warming.

  Caveat: this is informative of future commitment only if present forcing is maintained (aerosol commitment).
- EEI is key to ***empirical determination of climate sensitivity*** (need forcing!).
- EEI leads to ***key properties of Earth's climate system***; effective heat capacity (~20 W yr m^{-2} K^{-1}) and heat uptake coefficient (~1 W m^{-2} K^{-1}).
- Accurate determination of EEI on a variety of space and time scales can be expected to usefully constrain ***climate models***.

CONCLUSIONS (*cont'd*)

- EEI is a ***tough measurement*** from space: accuracy requirements, large dynamic range; high space and time variability.
- EEI is a ***tough measurement*** from OHC: accuracy requirements for meaningful differences.
- Two-compartment model seems consistent with EEI inferred from OHC measurements.
- It seems unlikely that climate sensitivity (λ) can be meaningfully inferred from temperature dependence of TOA irradiance components.
- TOA irradiance components exhibit rich seasonal variation that might usefully serve as constraint on models.