Tracking Earth's Energy

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Main Science Issue
How well can we track the flow of energy in the climate system?
What challenges limit our ability to track the flow?

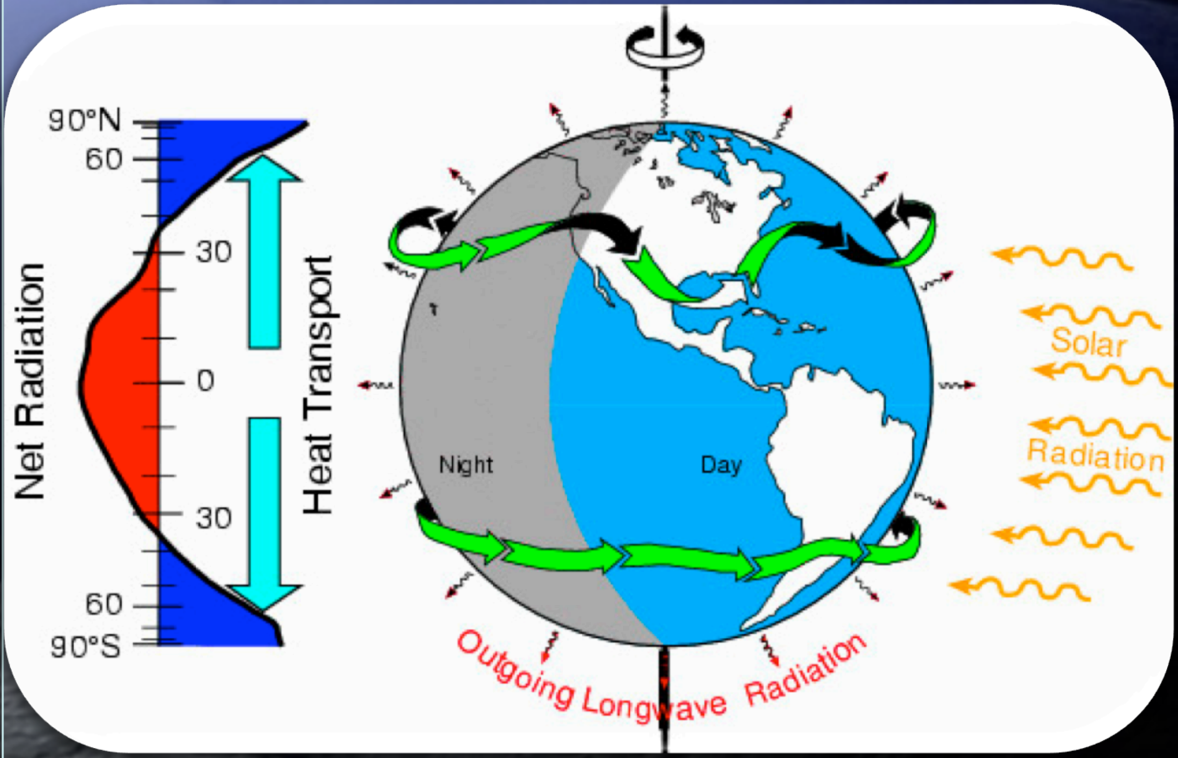
A Summary of:
Fasullo and Trenberth 2008 J. CLIM a,b
Trenberth and Fasullo, 2008 JPO
Trenberth and Fasullo 2010 Science

Outline

- *The Annual Mean Flow of Energy*
- *Annual Variations and Closure of the Budget*
- *Interannual Variability*
- *Closing the Energy Budget on Decadal Timescales: IPCC AR4*
- *The Science Behind "Climate-gate"*
- *Where has (the energy from) global warming gone?*

The Mean Energy Flow: TOA

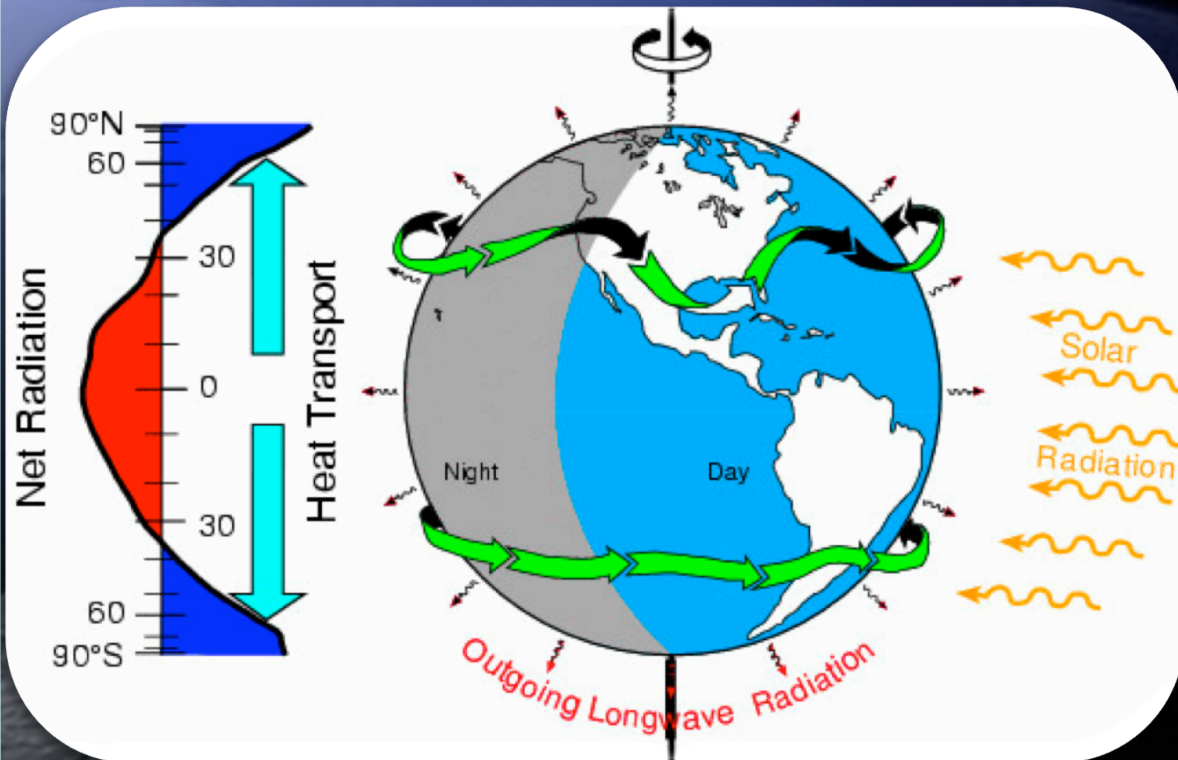
- A strong meridional gradient exists in the solar radiation absorbed (ASR) due largely to basic geometry.
- The gradient is amplified by the latitudinal gradient in albedo which varies approximately in proportion to ^{o}lat such that RSR≈100 W m^{-2}
- In equilibrium, ASR=OLR globally but this also mandates a strong meridional gradient in the net flux since OLR varies with T_{eff}^{4} which does not exhibit as strong of a meridional gradient as ASR.



The Mean Energy Flows: Atm and Ocn

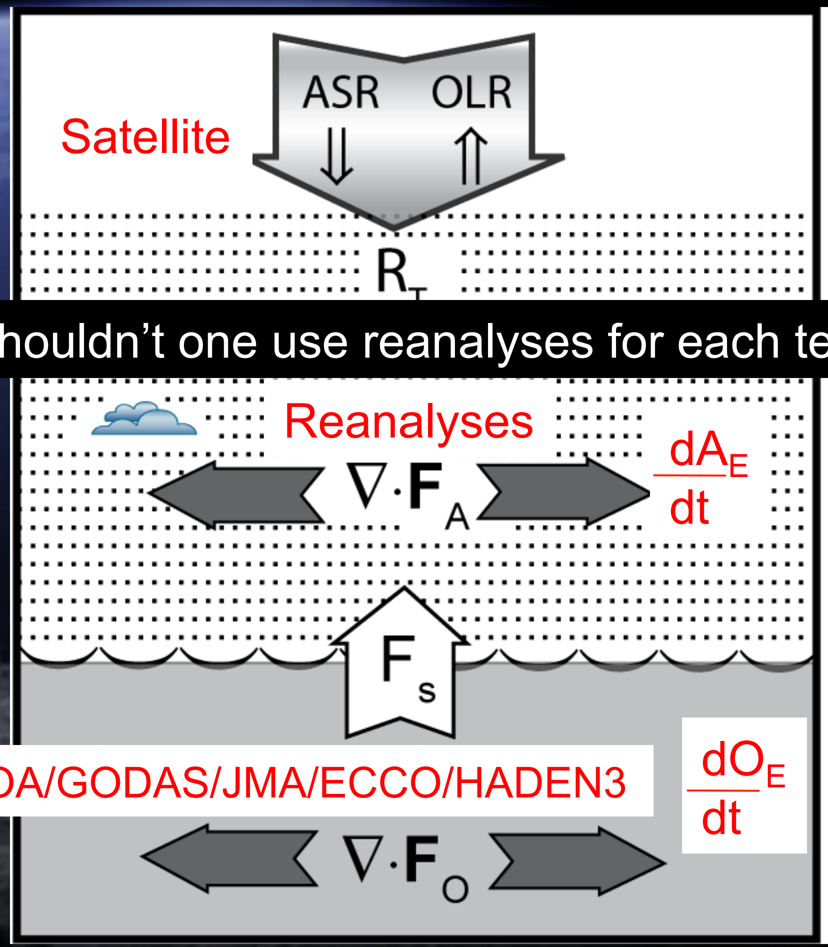
- At the surface, there is also a net flux of radiant energy into the ocean but much of that is balanced by the latent heat flux (there is also a strong upwelling LW flux but this is largely balanced by a compensating downwelling LW component). And so there is a much greater divergence and transport of energy in the atmosphere than the ocean.

- The atmosphere redistributes this energy (latent/dry static energy) poleward through stationary and transient eddies to balance R_T.



Terms of the Energy Flow

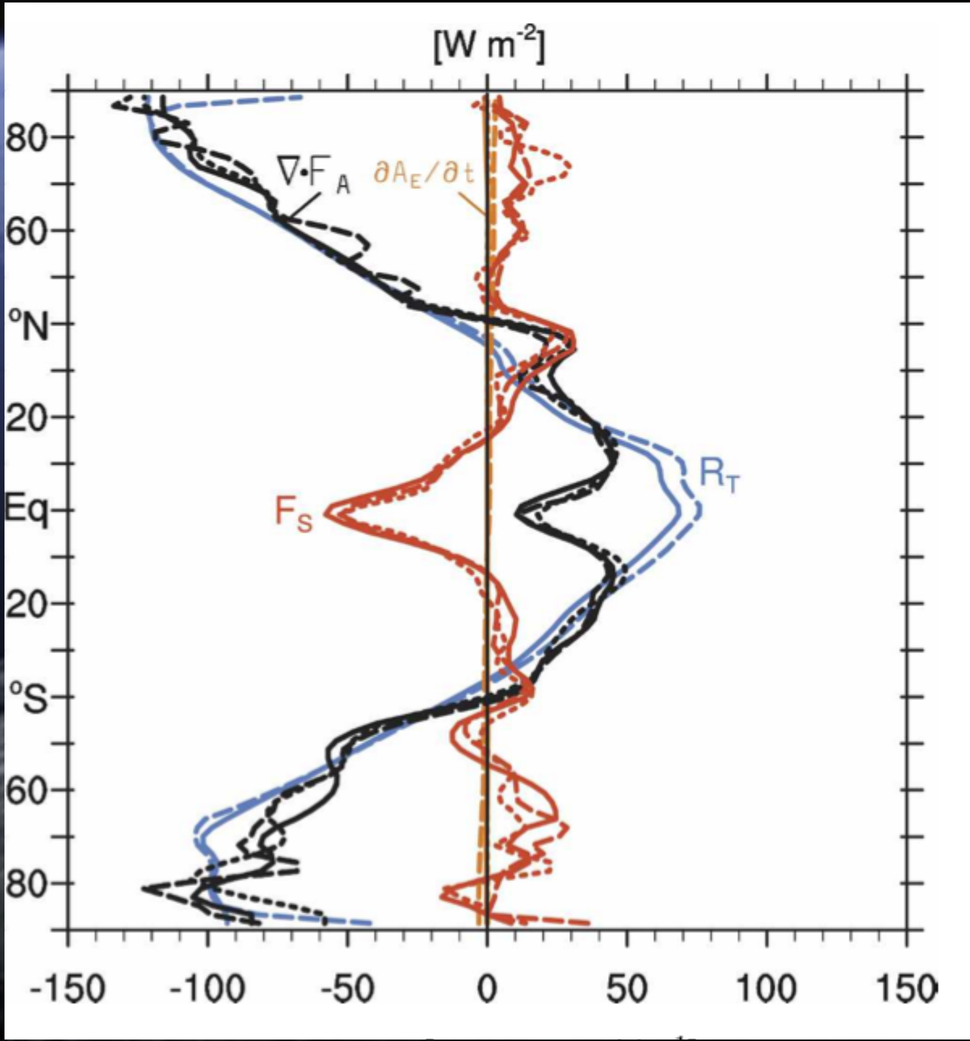
- The TOA budget is determined by absorbed solar radiation (ASR) and outgoing longwave radiation (OLR) to provide net incoming radiation (R_T)
- There are large divergence terms in the atmosphere and oceans and their integrated contributions result in the meridional transport of energy.
- F_S is the net upward surface flux and includes radiative and turbulent fluxes.
- Mean divergences are constrained by F_S and R_T (at equil)



Fasullo and Trenberth 2008 JCLIM

Zonal Mean Divergences

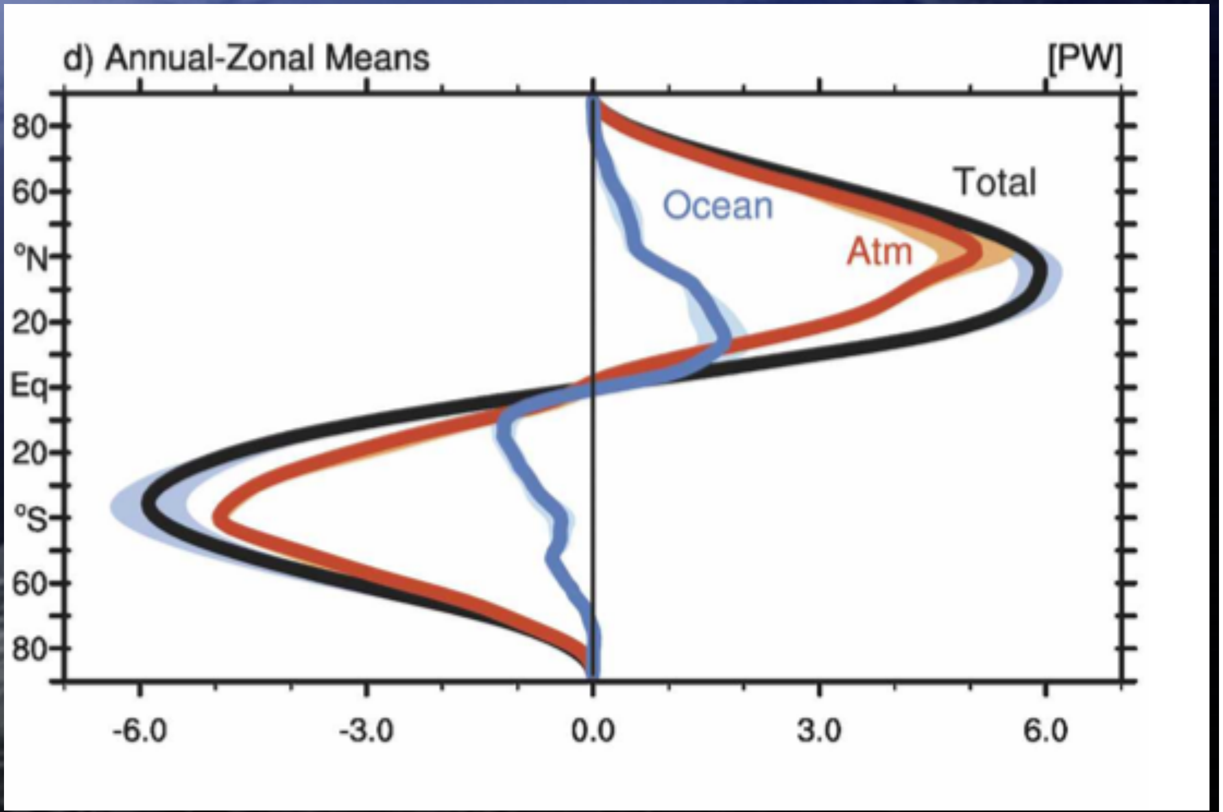
- So there is a strong positive net TOA flux into low latitudes (<40) and out of the higher latitudes.
- In the deep tropics, there is substantial energy entering the ocean, and most of this escapes in the subtropics.
- Thus poleward of ~40°, atmospheric divergences balance R_T in the annual mean.
- The various line types correspond to different data sources and different time periods. Main features are robust.



Fasullo and Trenberth 2008 JCLIM

The Mean Energy Flow: Meridional Transports

- As a consequence of the strong latent component to atmospheric transports and large thermal contrast between high and low latitudes, atmospheric transports dominate those of the ocean for all extra-tropical latitudes.
- The transports are approximately symmetric across hemispheres but are somewhat greater in the NH due to stronger baroclinicity and eddy transports.

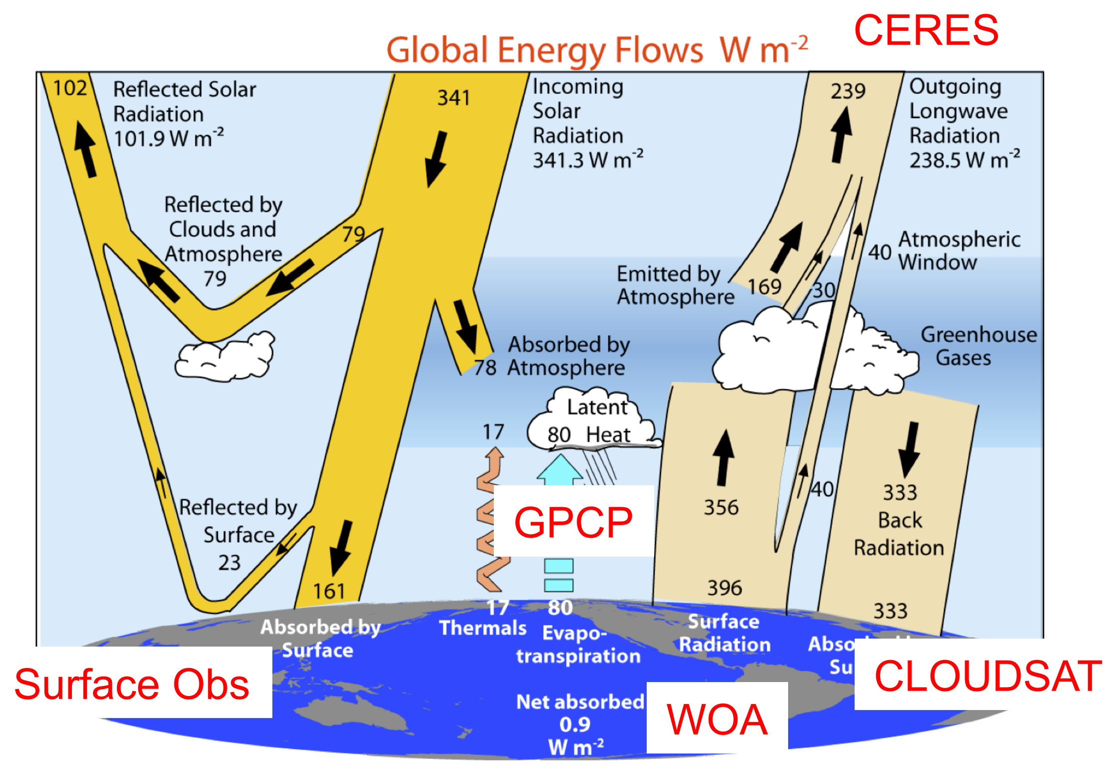


Fasullo and Trenberth 2008

The Mean Energy Flow: Present Day

- R_T is tuned to dO_E/dt.
- At the surface, the various terms must balance and thus the energy and water cycles are linked.
- Changes in atmospheric radiative cooling are balanced primarily by latent heating (hydrologic variability).
- This constraint is particularly useful for understanding the forced response associated with CO_2.

Figure 1. The global annual mean Earth's energy budget for the March 2000 to May 2004 period in W m^{-2}. The broad arrows indicate the schematic flow of energy in proportion to their importance.



Trenberth et al. 2009, BAMS

The Mean Energy Flow: Land-Ocean Contrasts

- By examining TOA fluxes the land-ocean transport can be computed assuming that excess energy is stored in the ocean (tendency of land in the mean is small)

- F_S over land is very small in the annual mean and so R_T=del*F_A

- For ref: 0.5 PW ≈ 1 W m^{-2} (global)

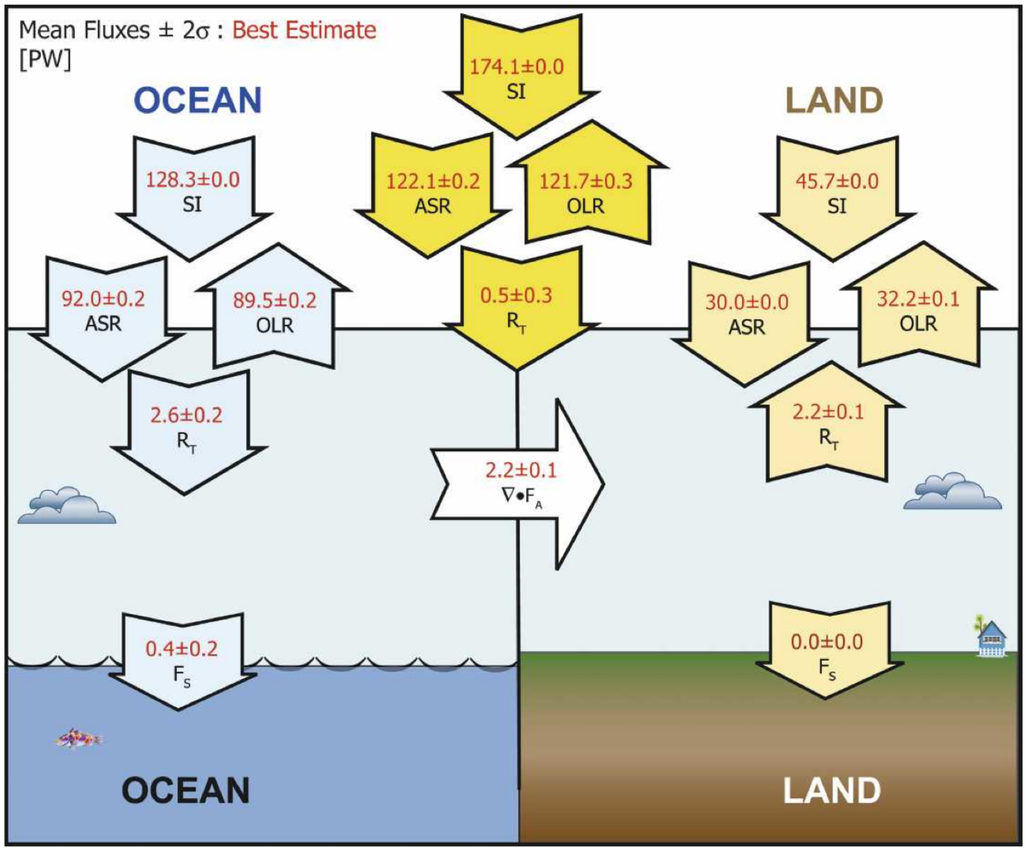


FIG. 2. CERES-period-mean best-estimate FM1 TOA fluxes (PW) globally and for the (right) global land and (left) global ocean regions.

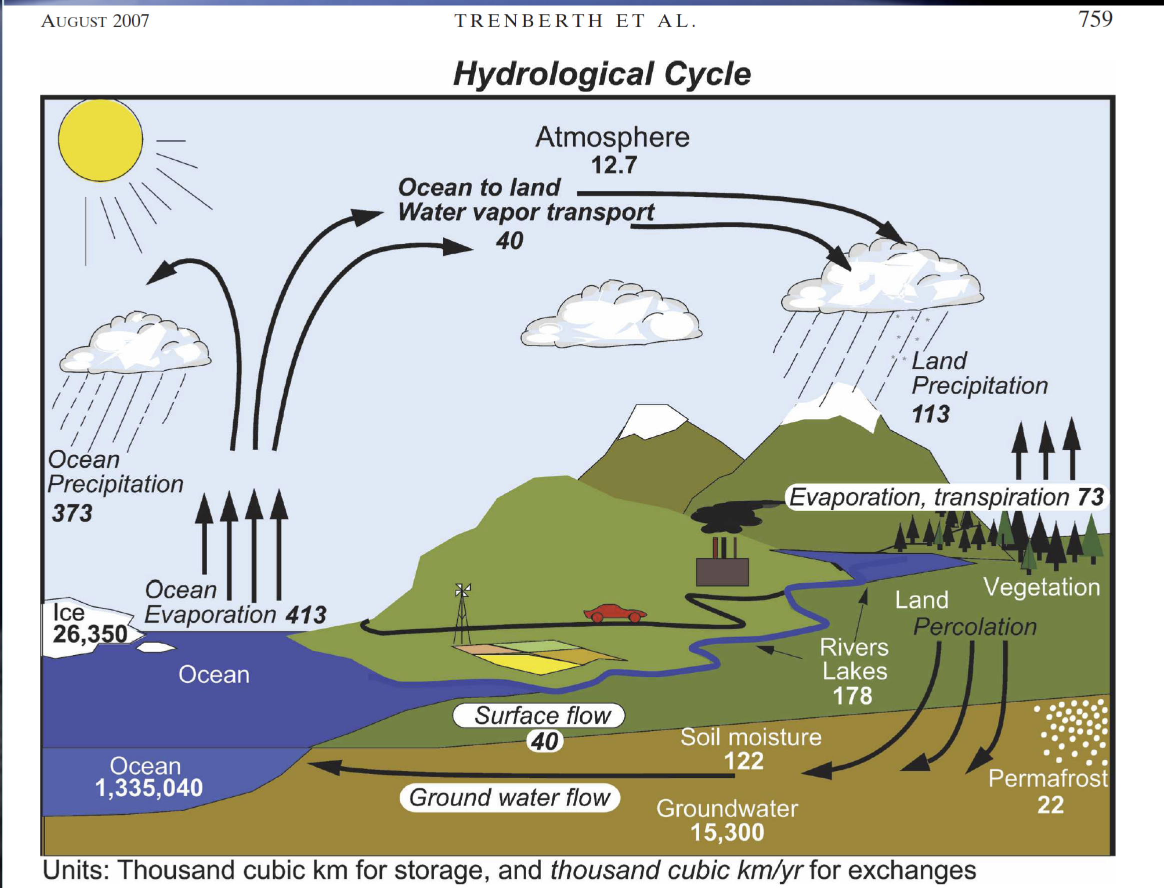
Fasullo and Trenberth 2008 JCLIM

The Mean Energy Flow: Using the Hydrologic Cycle as a Check

- A robust feature of the energy and water cycles is that they experience strong land-ocean contrasts.

- It is possible to compute P-E from the atmospheric "budget" of reanalyses to compare with river runoff observations. This serves as an important check on the reanalysis wind and humidity profiles.

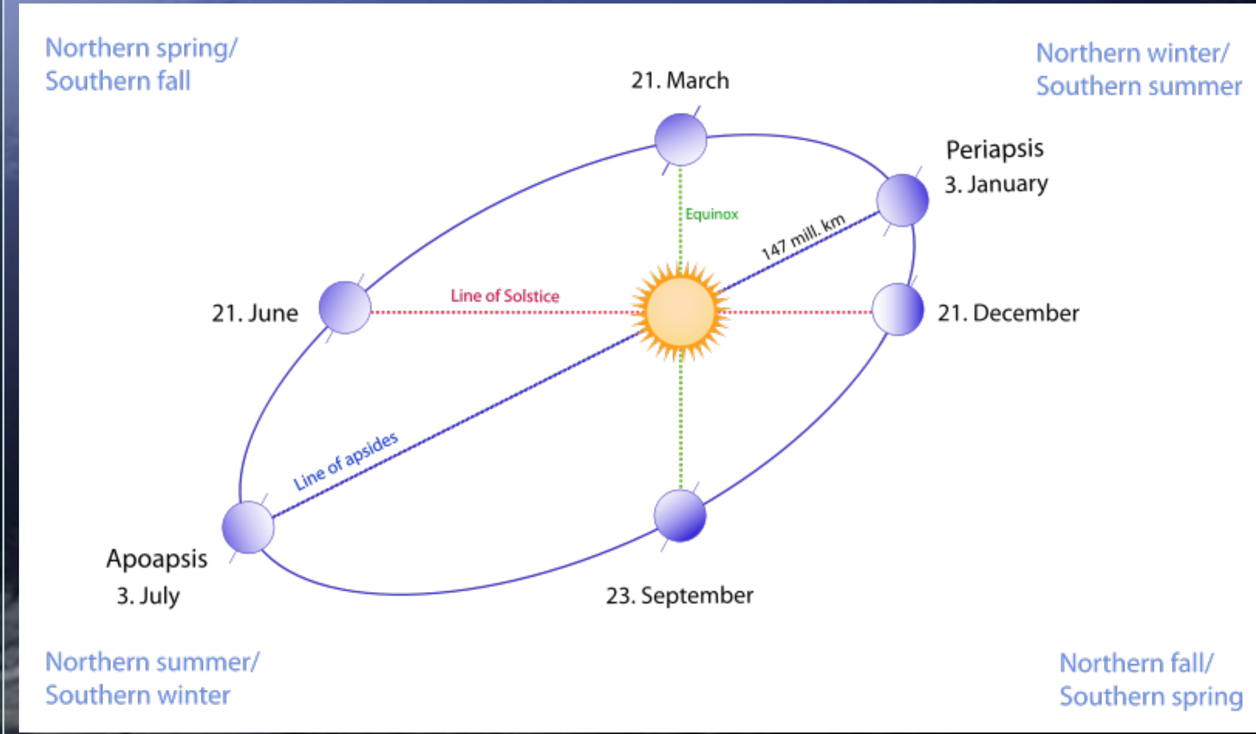
(*Note: P and E from reanalyses is very poor generally and so the budget is computed from Q and U fields.)



Trenberth et al. 2007, HydroMet

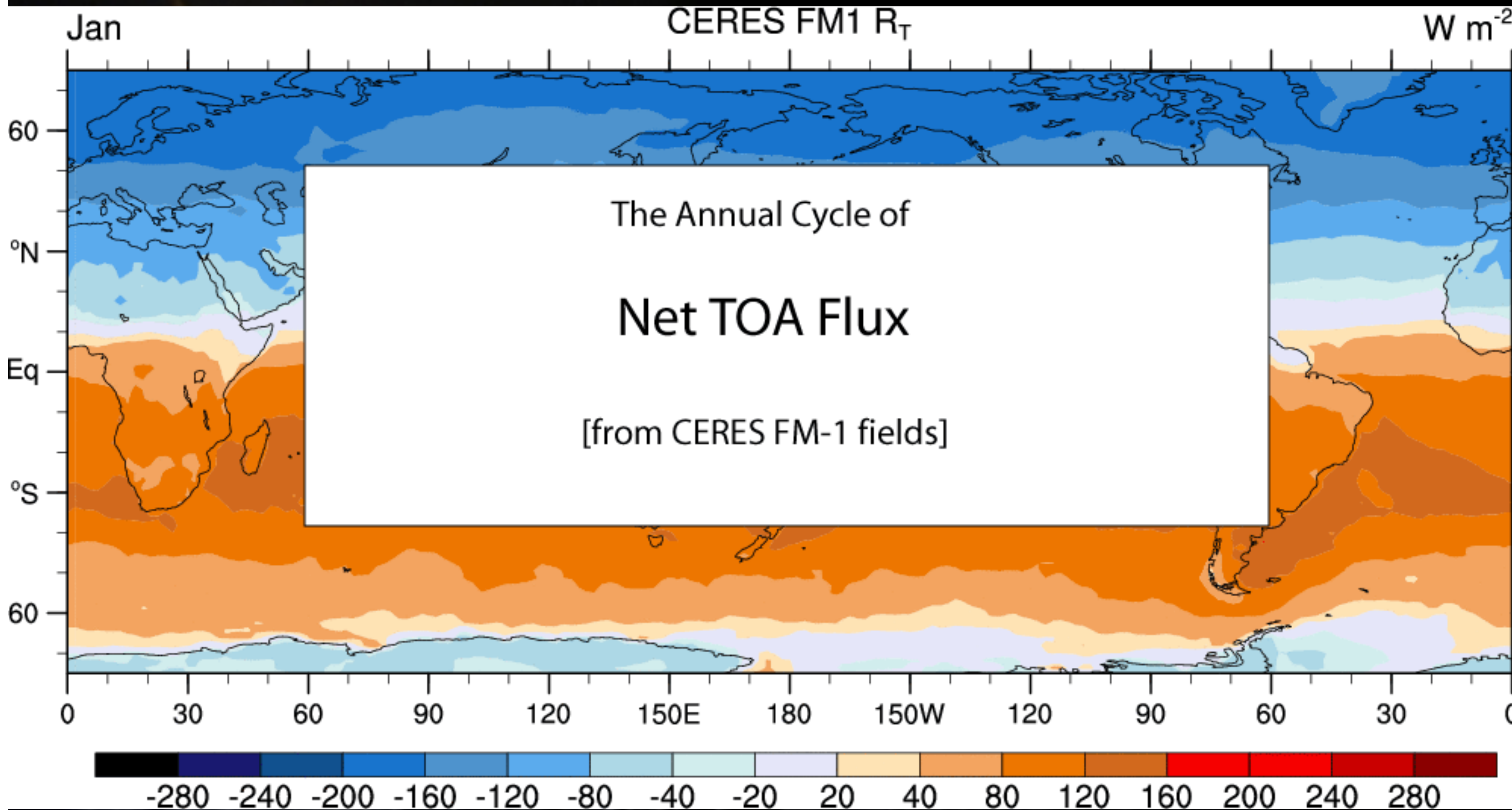
The Annual Cycle of the Energy Flow

- The seasons are driven primarily by the changing inclination of the Earth's axis relative to its orbital plane around the Sun.
- However, the Earth's orbit is also elliptical and this is a key driver of the annual cycle in total energy content.
- *If one were to infer the sensitivity of surface temperature to the change in energy content of the system from the annual cycle, what would one find?*



Orbital distance varies by ~3%
Solar Insolation varies by ~7%(or 25 Wm^{-2})

The Annual Cycle of the Energy Flow



The Annual Cycle of the Energy Flow: The Atmosphere

- With the changing solar insolation, there is also a change in R_T.
- The various satellite products from CERES and ERBE are robust in depicting this annual cycle with a signal to noise ratio of 10:1.
- The changes in albedo with the annual cycle are caused mainly by spatial gradients in albedo and thus do not relate directly to variability within the system.

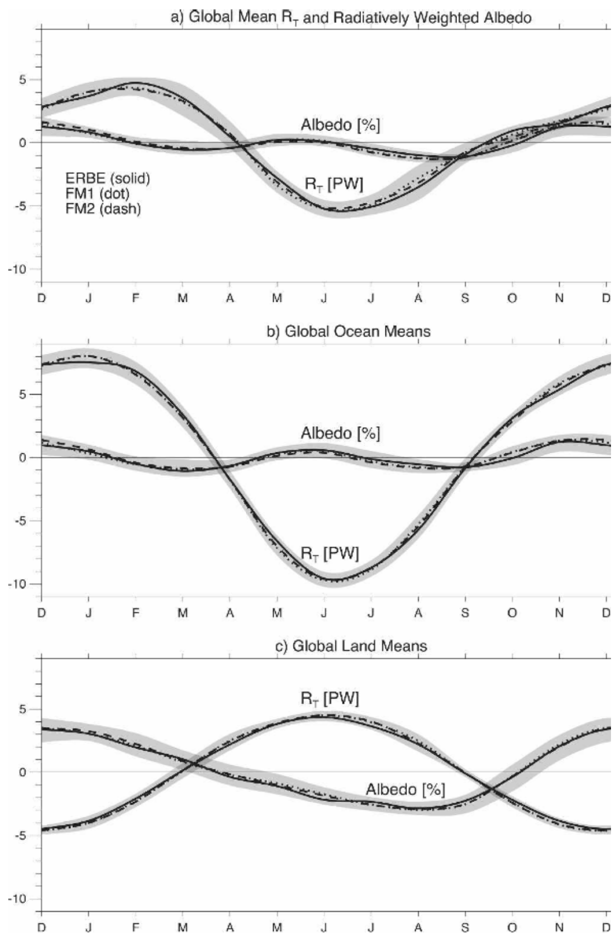


FIG. 3. (a) Global, (b) global ocean, and (c) global land annual cycles of albedo (%) and R_T (PW) where shading r sents $\pm 2\sigma_I$ of the monthly means and the annual mean has removed.

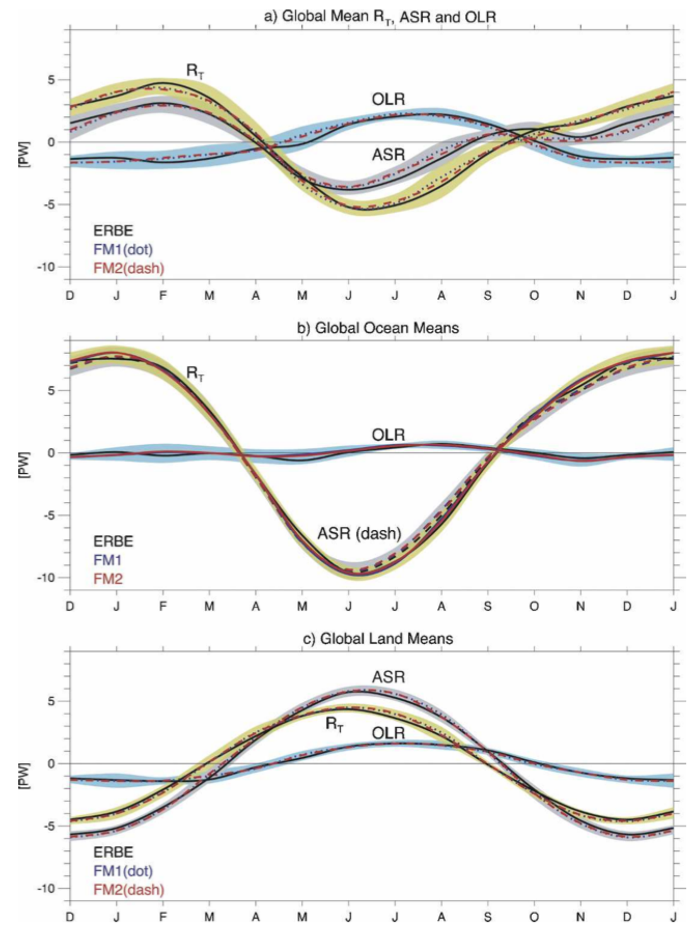
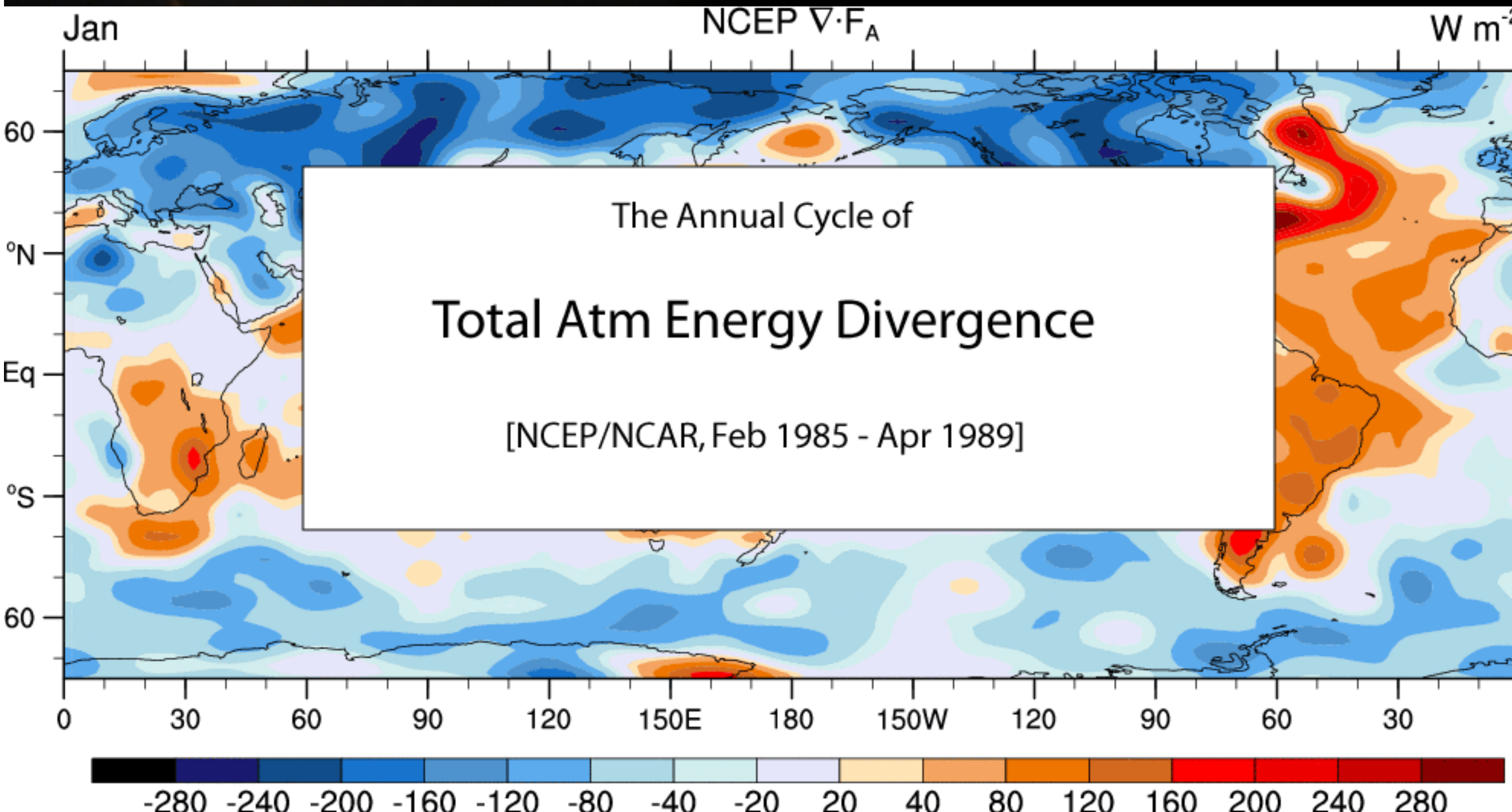


FIG. 4. (a) Global, (b) global ocean, and (c) global land mean annual cycles for ASR, OLR, and R_T (PW), where shading represents $\pm 2\sigma_I$ of the monthly means and the annual mean has been removed.

The Annual Cycle of the Energy Flow

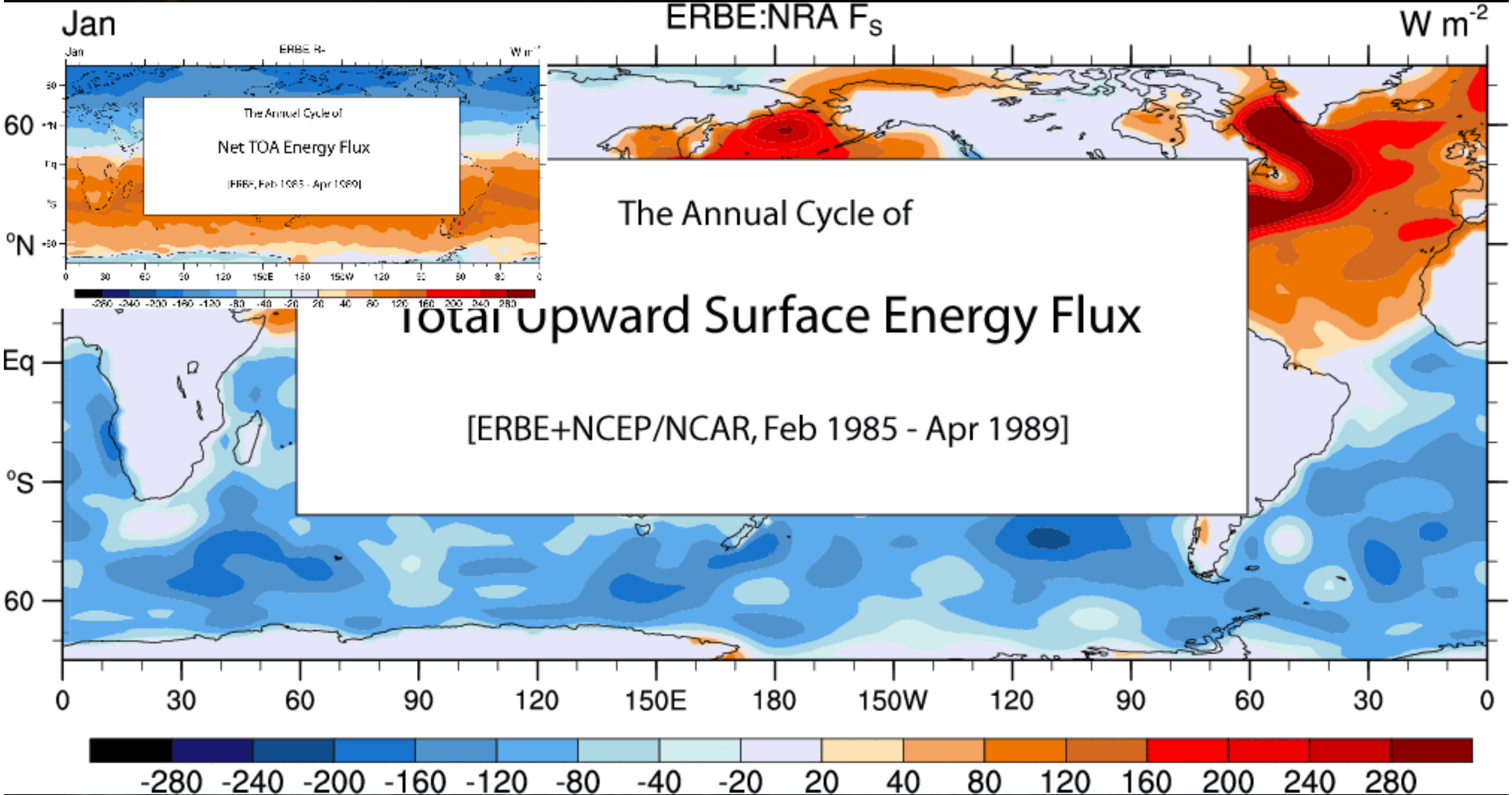


The Annual Cycle of

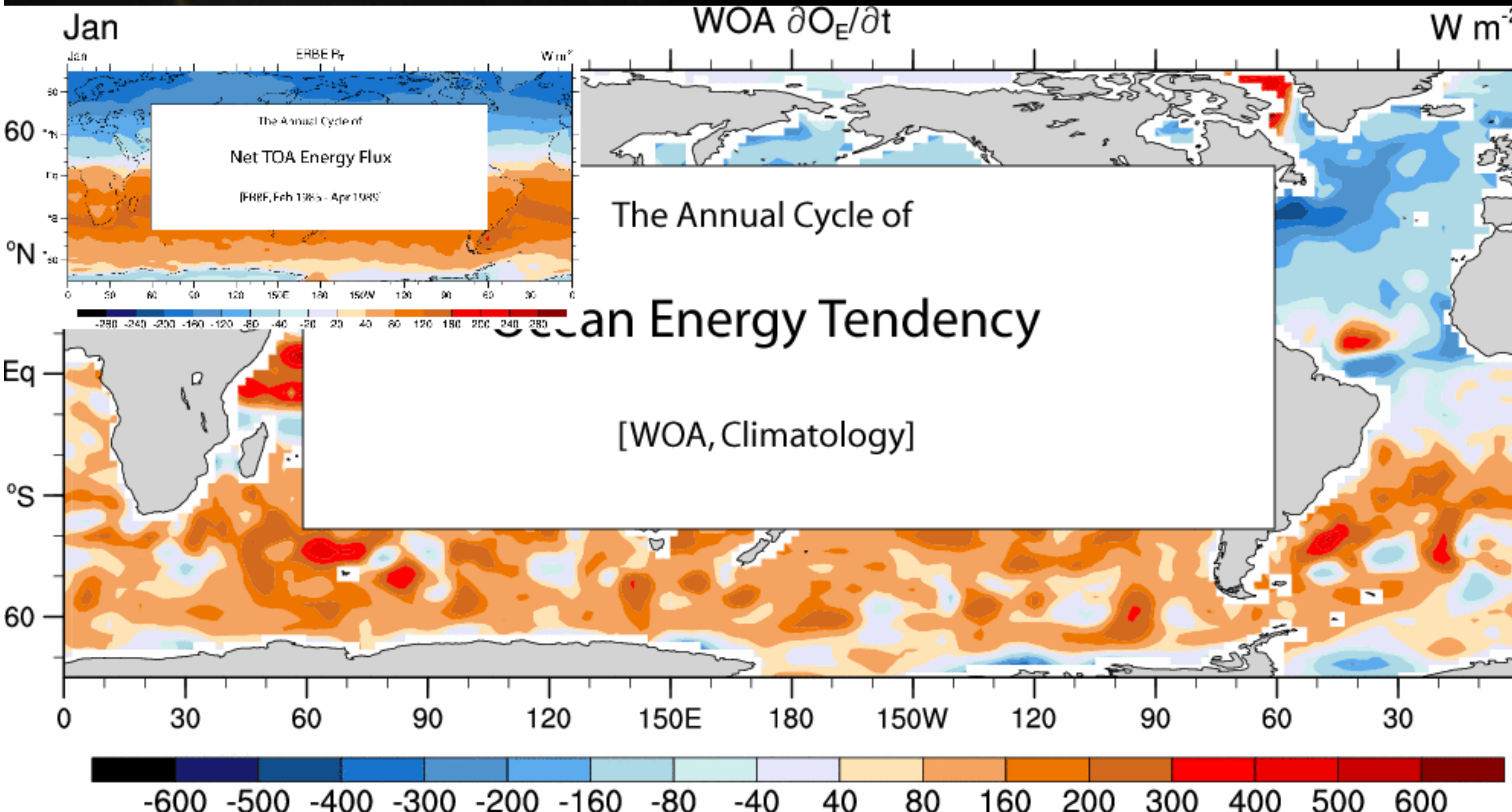
Total Atm Energy Divergence

[NCEP/NCAR, Feb 1985 - Apr 1989]

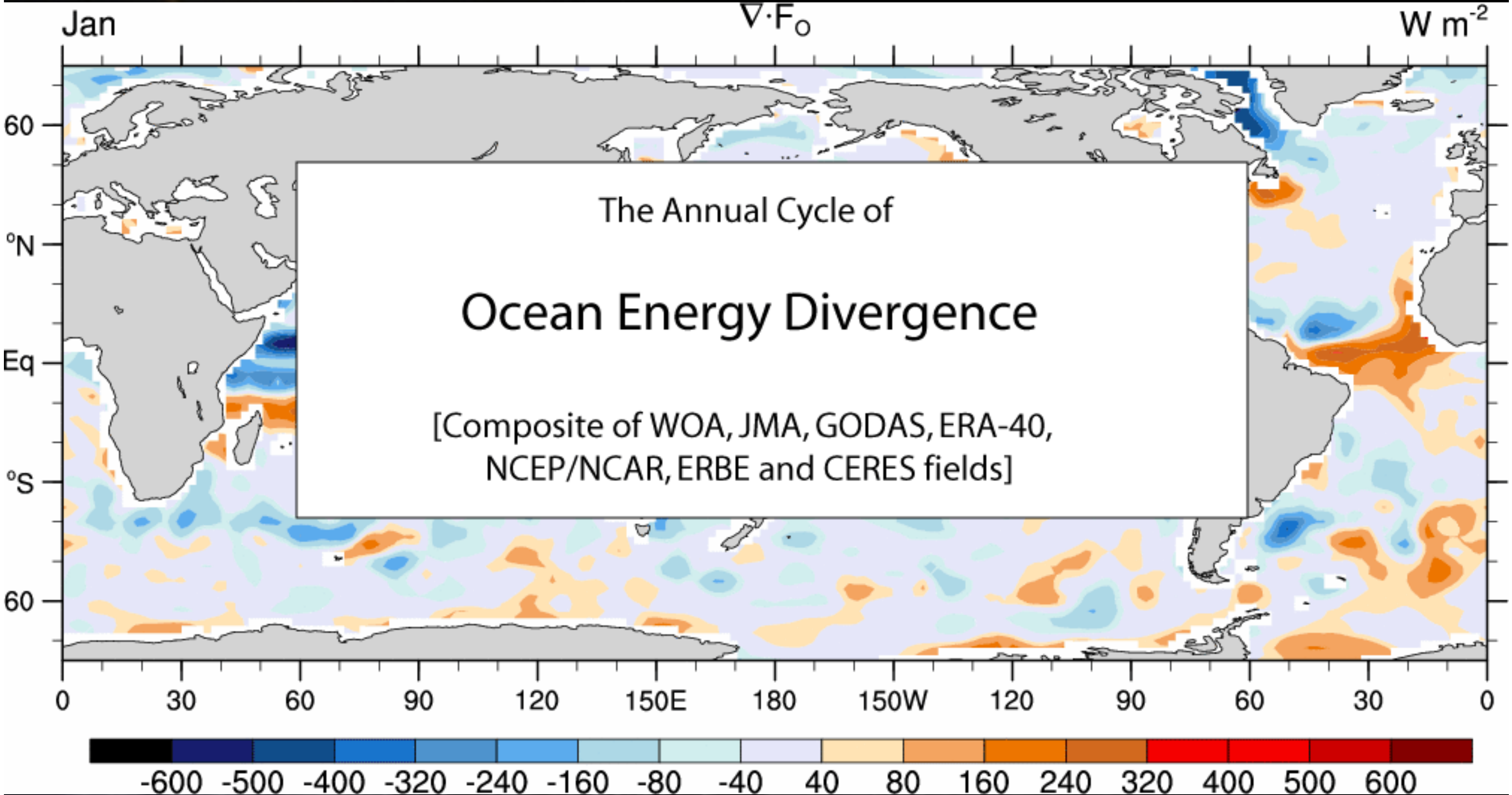
The Annual Cycle of the Energy Flow



The Annual Cycle of the Energy Flow



The Annual Cycle of the Energy Flow



The Annual Cycle of the Energy Flow: Ocean Storage

- Computing the ocean heat content tendency from F_S (derived from R_T and the atmospheric budget) provides a constraint on ocean heat content.
- While similar in form to that derived from F_S, the magnitude of the annual cycles of O_E from WOA and JMA are clearly excessive.
- GODAS variability is closer to that inferred from F_S yet its boreal fall warming is also excessive.
- Thus there is an indication that systematic sampling/methodological biases in the ocean analyses project onto ocean heat content. This will be shown to be particularly problematic for analysis of interannual variability and trends.

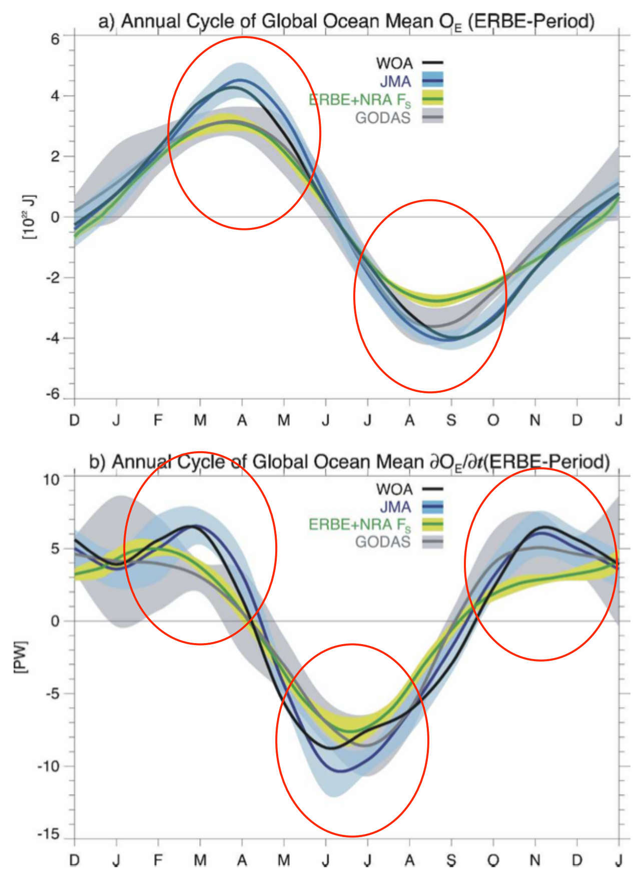


FIG. 7. Annual cycles of (a) O_E ($\times 10^{22}$ J) and (b) $\delta O_E/\delta t$ (PW) are shown with ranges of uncertainty $\pm 2\sigma_I$ for the monthly means from the GODAS and JMA datasets (shading). The GODAS fields have been extended in latitude using the JMA fields, O_E estimates were differenced to provide $\delta O_E/\delta t$, and F_S was integrated in time to provide the O_E anomalies for the ERBE and NRA data.

Interannual Variability

We would like to be able to quantify variability in the energy flow on interannual timescales, for example:

- ***to address the potential sources of year to year variability in global temperatures, and,***
- ***to track the forced imbalance associated with climate change.***

Are the observing systems up to the task?

The Interannual Variability of the Exchange between Land and Ocean

- A major challenge that remains in our understanding of the variability in the energy flow is the lack of well-calibrated global observations over an extended record.
- There is little correlation between various estimates of land-ocean energy transports. ERA/I suggests most variability in other reanalyses is spurious.
- Datasets for which assimilated data are rare (i.e. oceans) would likely contain even larger uncertainty.

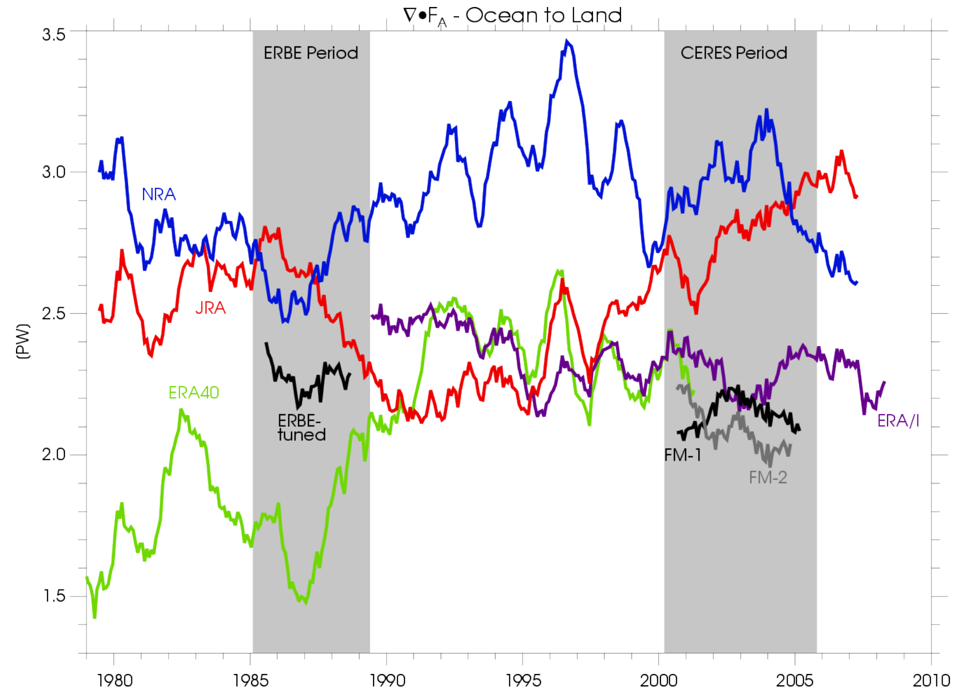


FIG. 8. Interannual variability in the inferred net ocean-to-land energy transport (PW) is shown by 12-month running means for the ERBE and CERES best-estimate R_T over land and NRA $\delta A_E/\delta t$ fields. Transports calculated directly from the NRA and ERA-40 fields are also shown.

Fasullo and Trenberth 2008 J. Clim.

Closing the Energy Budget: IPCC AR4

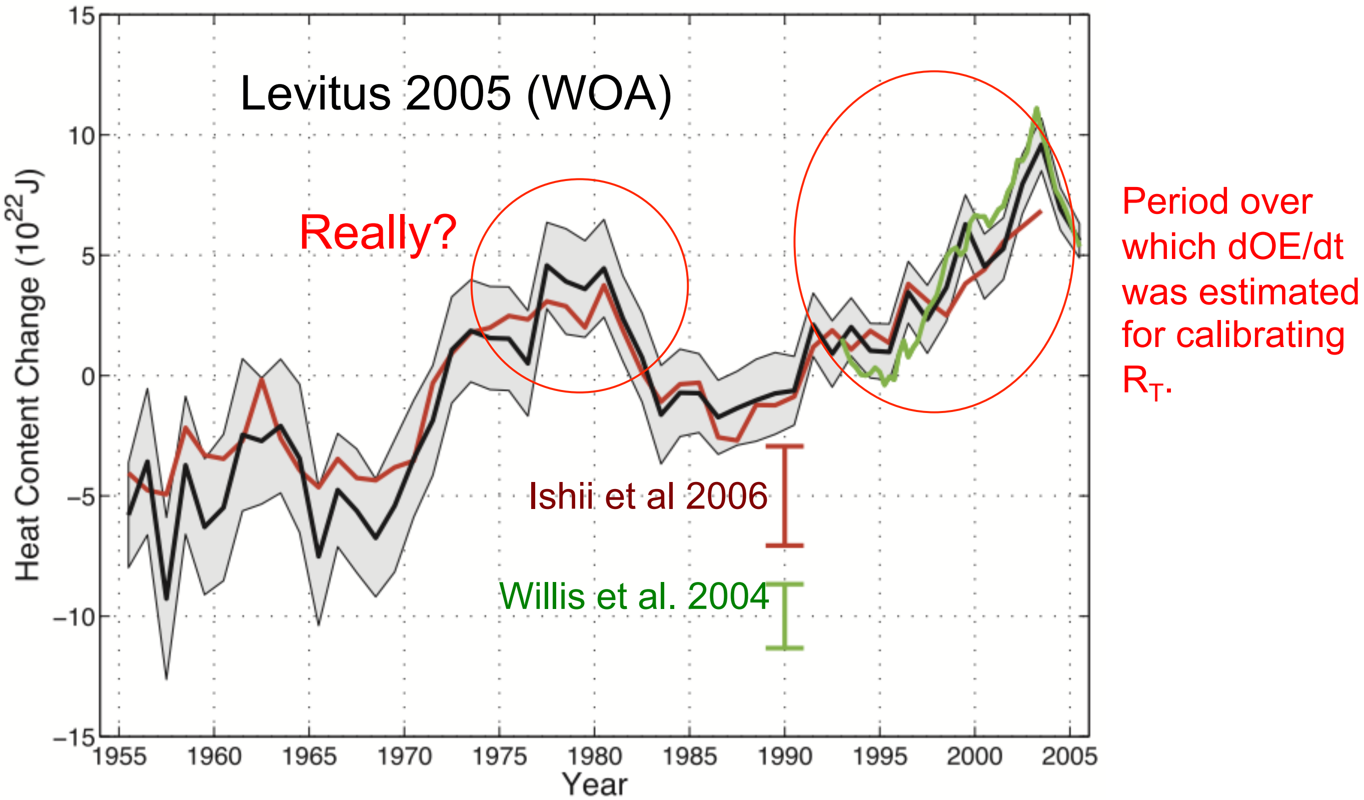


Figure 5.1. *Time series of global annual ocean heat content (10^{22} J) for the 0 to 700 m layer. The black curve is updated from Levitus et al. (2005a), with the shading representing the 90% confidence interval. The red and green curves are updates of the analyses by Ishii et al. (2006) and Willis et al. (2004, over 0 to 750 m) respectively, with the error bars denoting the 90% confidence interval. The black and red curves denote the deviation from the 1961 to 1990 average and the shorter green curve denotes the deviation from the average of the black curve for the period 1993 to 2003.*

Closing the Energy Budget: IPCC AR4

•A major focus of IPCC AR4 was to track the changes in energy storage in the climate system.

•The oceans account for ~90% of the planetary imbalance for both time periods. The analysis suggests that depths 0-700m are primarily involved on decadal timescales (1993-2003).

•Good closure between the ocean storage, total storage, and estimates of the planetary imbalance were obtained.

But are these error bars too small?

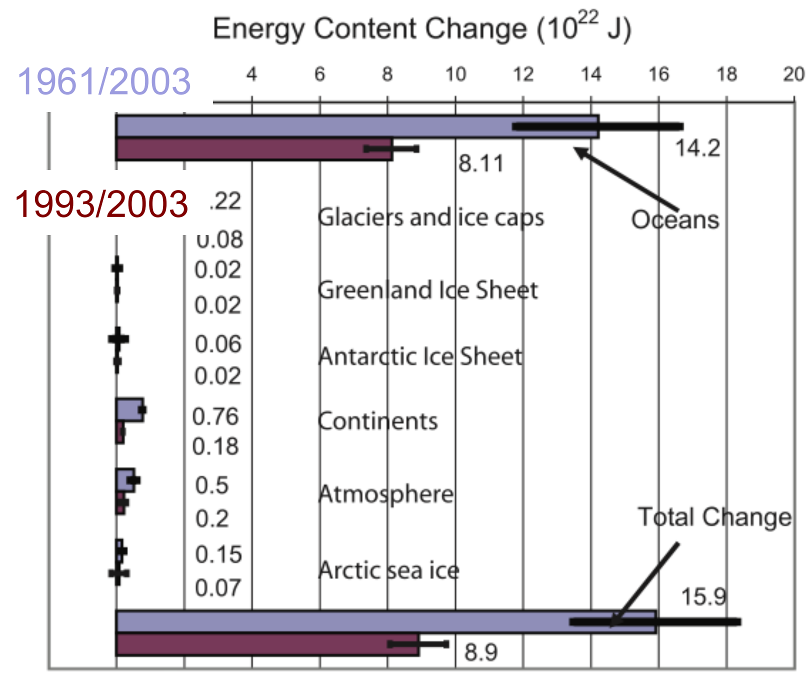


Figure 5.4. *Energy content changes in different components of the Earth system for two periods (1961–2003 and 1993–2003). Blue bars are for 1961 to 2003, burgundy bars for 1993 to 2003. The ocean heat content change is from this section and Levitus et al. (2005c); glaciers, ice caps and Greenland and Antarctic Ice Sheets from Chapter 4; continental heat content from Beltrami et al. (2002); atmospheric energy content based on Trenberth et al. (2001); and arctic sea ice release from Hilmer and Lemke (2000). Positive energy content change means an increase in stored energy (i.e., heat content in oceans, latent heat from reduced ice or sea ice volumes, heat content in the continents excluding latent heat from permafrost changes, and latent and sensible heat and potential and kinetic energy in the atmosphere). All error estimates are 90% confidence intervals. No estimate of confidence is available for the continental heat gain. Some of the results have been scaled from published results for the two respective periods. Ocean heat content change for the period 1961 to 2003 is for the 0 to 3,000 m layer. The period 1993 to 2003 is for the 0 to 700 m (or 750 m) layer and is computed as an average of the trends from Ishii et al. (2006), Levitus et al. (2005a) and Willis et al. (2004).*

2009 Update: Ocean heat content to 700 m

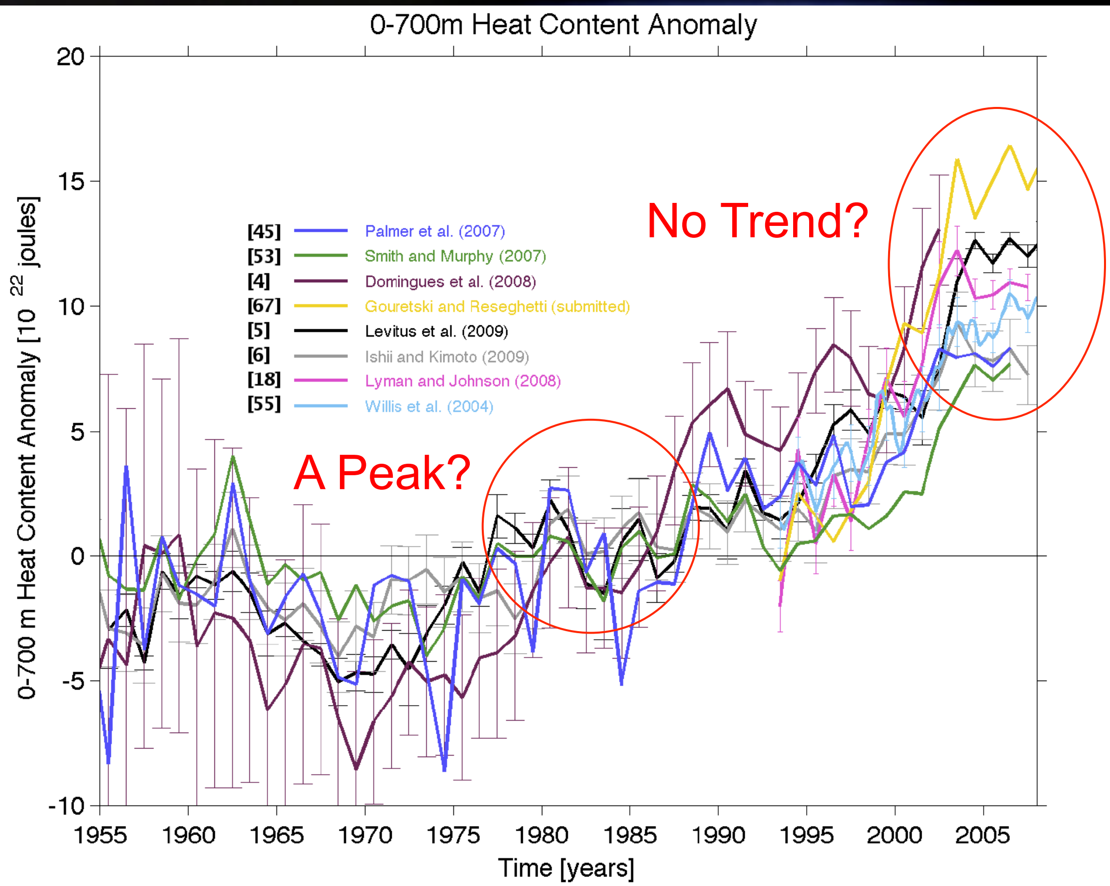
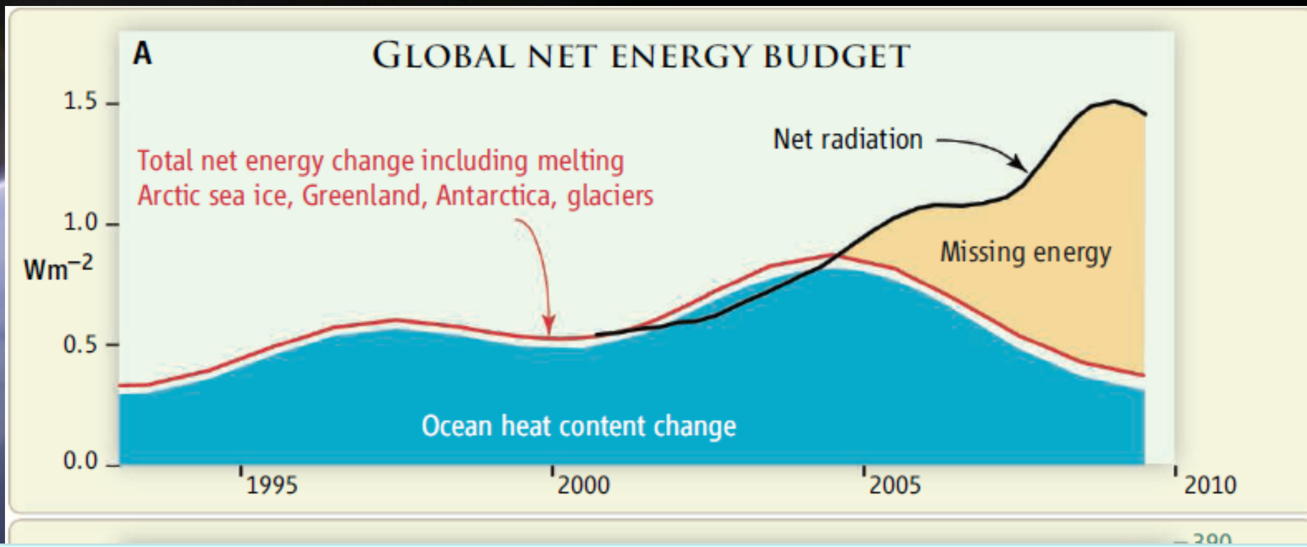


Figure 2: A number of observation-based estimates of annual ocean heat content anomaly (1022 J) for the 0-700 m layer. Differences among the time series arise from: input data; quality control procedure; gridding and infilling methodology (what assumptions are made in areas of missing data); bias correction methodology; and choice of reference climatology. Anomalies are computed relative to the 1955-2002 average.

Significant differences exist among the various datasets. Palmer et al 2009

Error Bars are understated in general, even here.

Climate-Gate: Energy Closure 2004-09



"The fact is that we can't account for the lack of warming at the moment and it is a travesty that we can't."

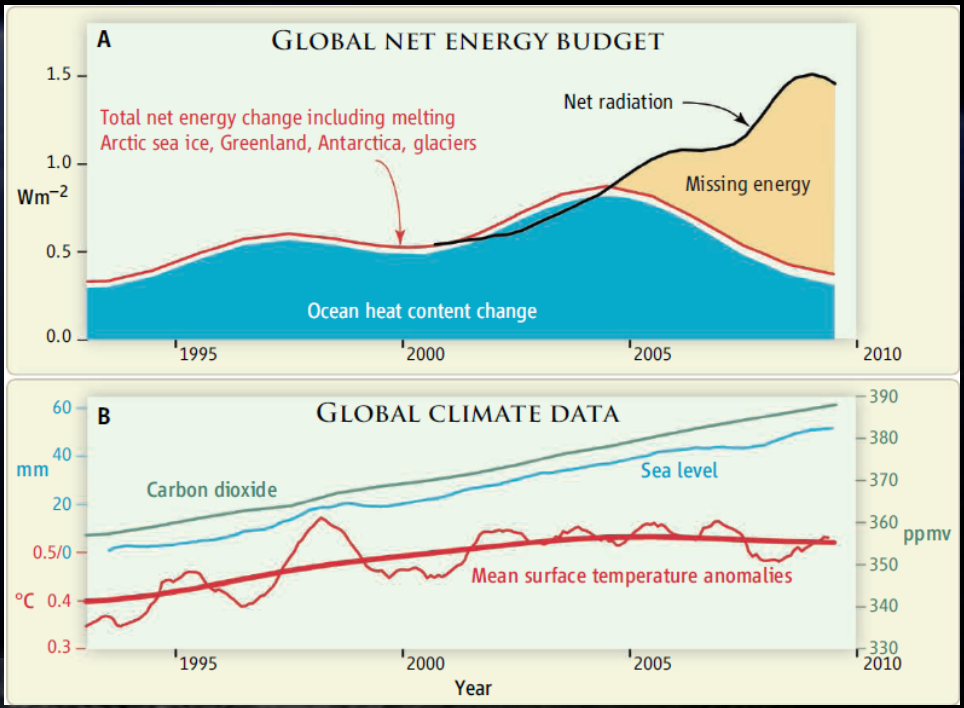
Kevin Trenberth: "It is quite clear from the paper that I was not questioning the link between anthropogenic greenhouse gas emissions and warming, or even suggesting that recent temperatures are unusual in the context of short-term natural variability.“

The Case for "Missing" Energy

Trenberth and Fasullo 2010 Science

Top: **Rates of change of global energy** in W m^{-2} heavily smoothed.

From 1992 to 2003 the decadal ocean heat content changes (blue) along with the contributions from melting glaciers, ice caps, Greenland, Antarctica and Arctic sea ice plus small contributions from land and atmosphere warming (red) suggest a total warming for the planet of 0.6±0.2 W m^{-2} (95% error bars) . After 2000, observations from TOA (black) referenced to the 2000 values, show an increasing discrepancy (gold) relative to the total warming observed (red).



Lower: **The observed changes in T, MSL, and CO_2**

•12-month running means of global mean surface temperature anomalies relative to 1901-2000 from NOAA (red (thin) and decadal (thick)) in °C,

• carbon dioxide concentrations (green) in ppmv from NOAA, and

• global sea level from AVISO (blue, relative to 1993, scale at left in mm).

Where Did the Heat Go?

- *2008 is the coolest year since 2000*
- *But Carbon dioxide and radiative forcing continue to rise.*
- *Where did global warming go?*
- *Note that a near monotonic sea level rise has continued unabated. If ocean heat content really has leveled off, how is this achieved?*

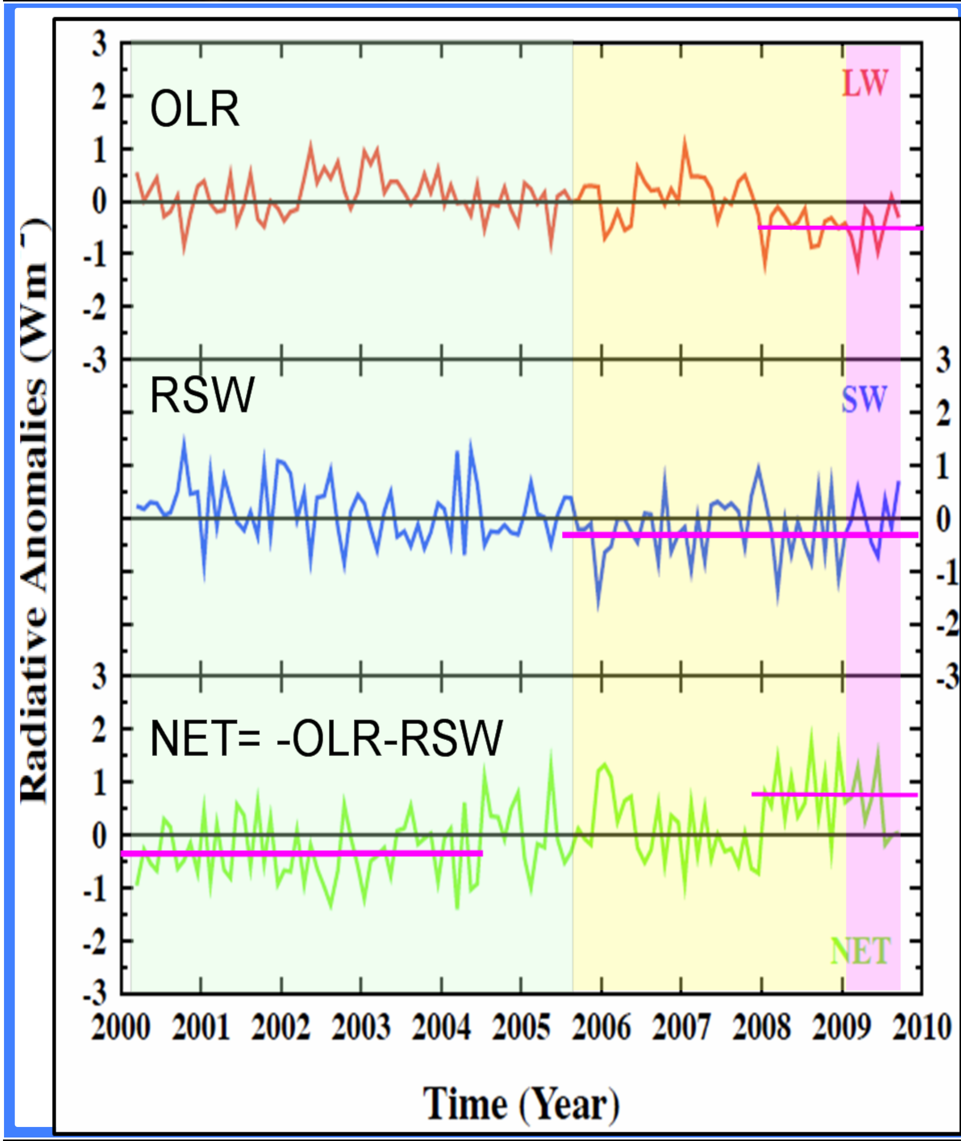
Where does energy go?

Potential Candidates

1. *Heat storage in the ocean (sea level ⇧)*
2. *Warms land and atmosphere*
3. *Melts land ice (sea level ⇧⇧⇧)*
4. *Melts sea ice*
5. *Evaporates moisture ⇒ cloud ⇒ reflection = lost to space*

Can we track these terms?

Deseasonalized TOA Anomalies (Updated)

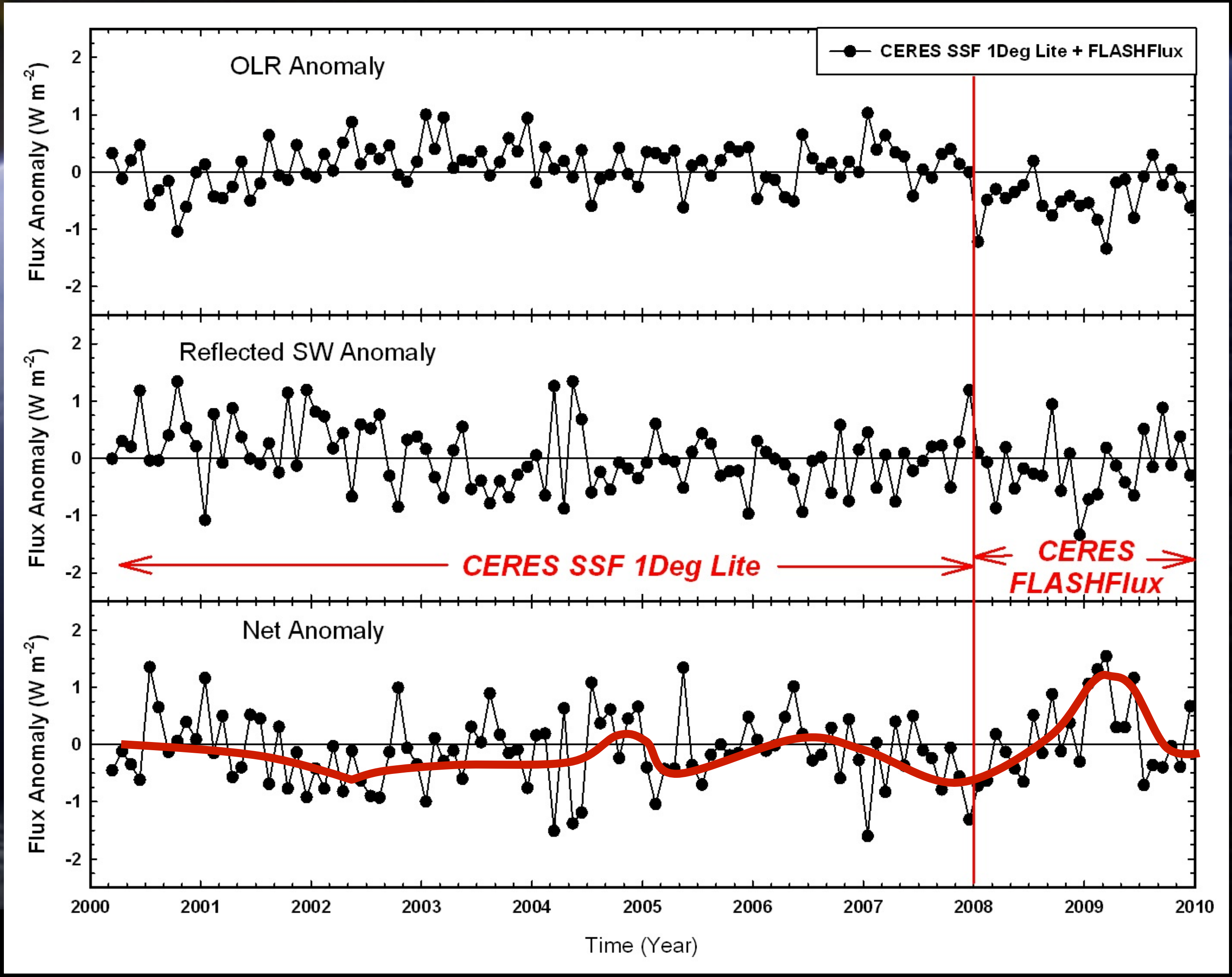


	2008 – 2007 change	2008 anomaly	Interannual variability (2-sigma)
LW	-0.74	-0.48	±0.56
SW	-0.33	-0.33	±0.39
Net	+1.07	+0.81	±0.82

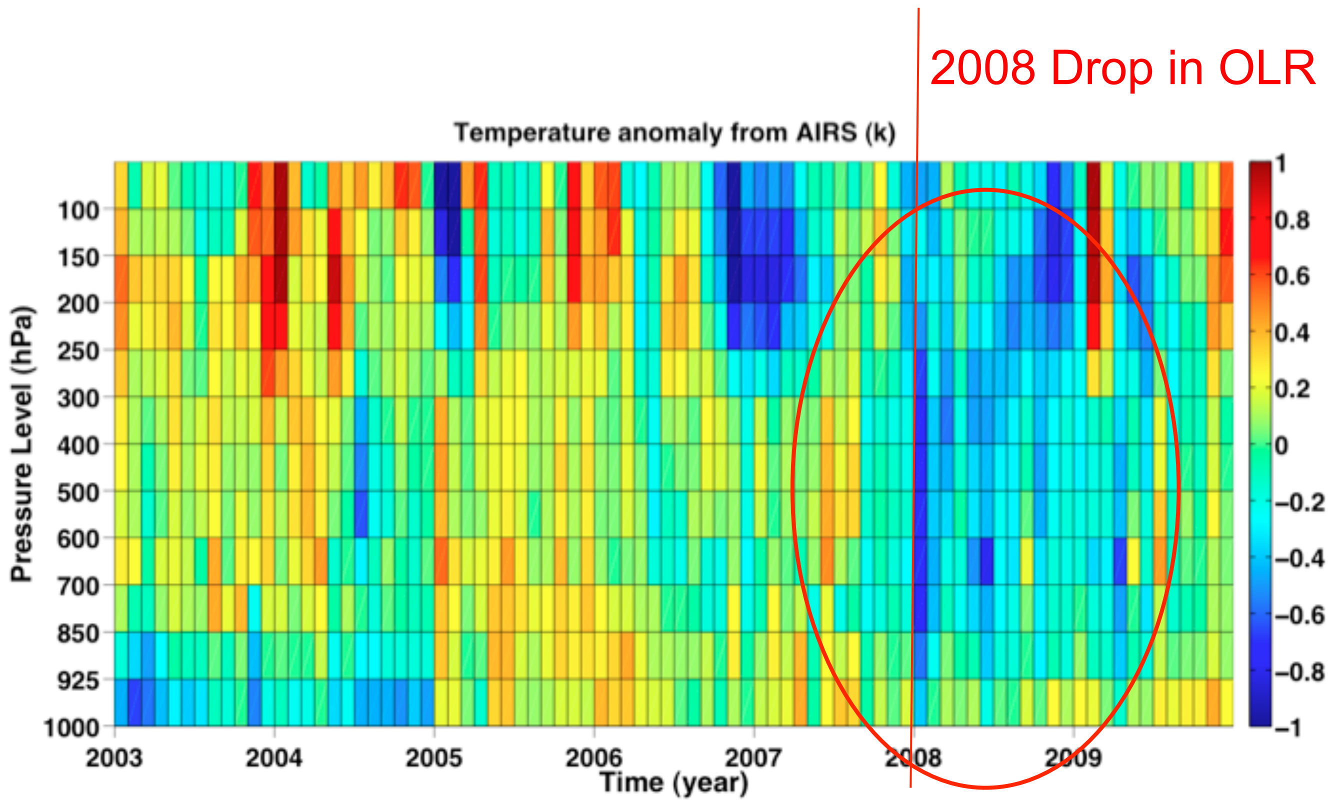
- Large decrease in global mean outgoing longwave radiation in 2008 – same
- Decrease in global mean reflected shortwave in 2008 (+0.19 Wm^{-2})
- Large increase in global mean net flux in 2008 (slightly larger +0.18 Wm^{-2})
- Majority of net flux increase (~69%) from decrease in longwave
- FLASHFlux showing realistic variability

Deseasonalized Anomalies

(Updated, State of the Climate 2009)



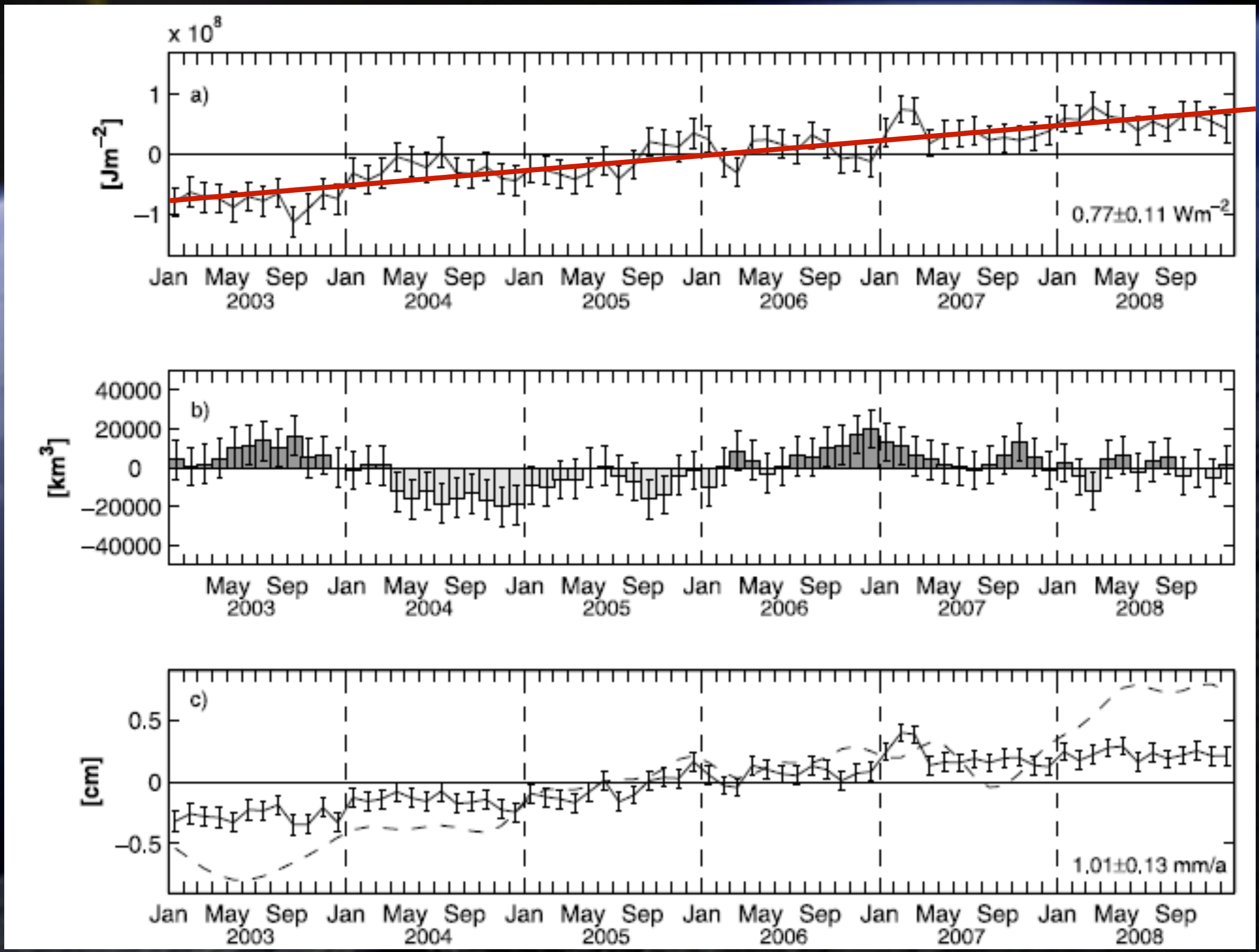
Corroborating CERES OLR: AIRS



Courtesy Norm Loeb

AIRS shows a strong deep tropospheric cooling when OLR falls. These are independent sensors -> The OLR drop is likely real. T is driving OLR.

Ocean heat content 0-2000m



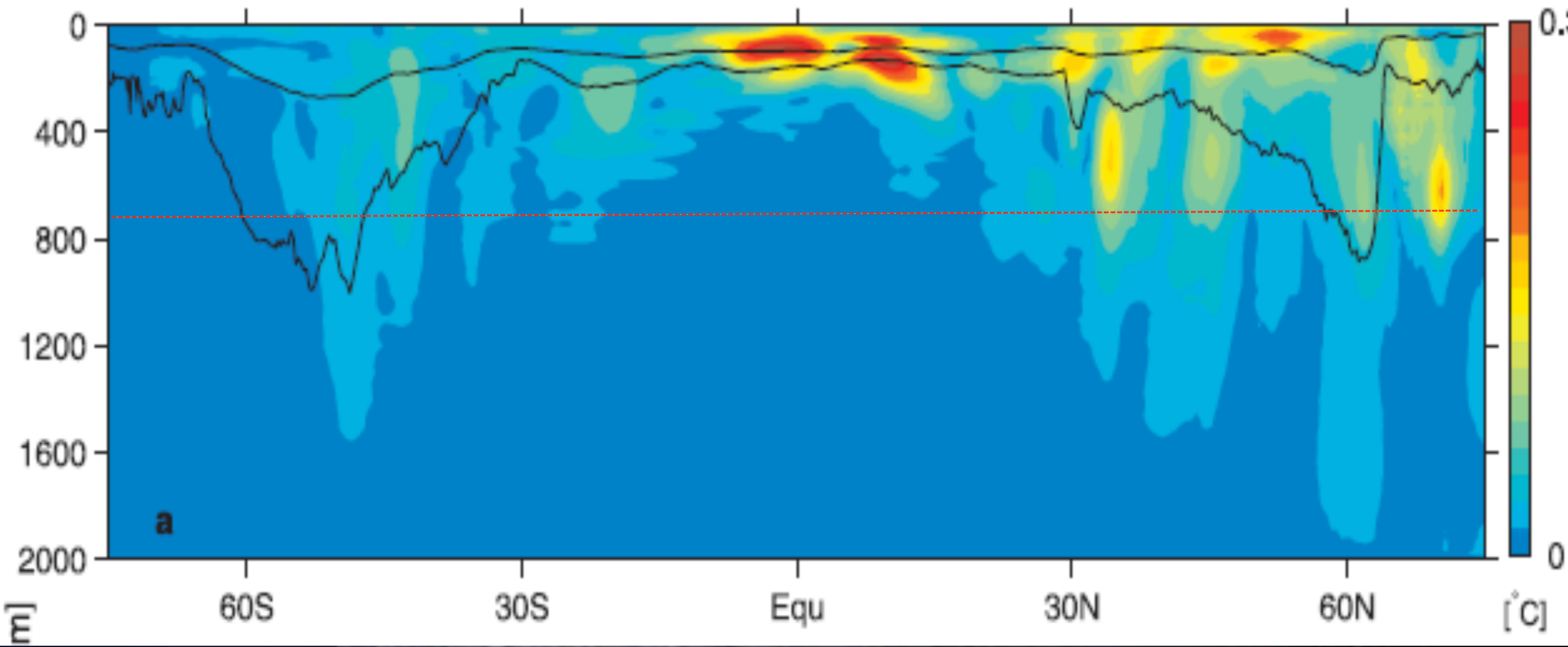
OHC
0.77 W m^{-2}
global ocean
0.54 W m^{-2}
Global

Fresh water

Sea level (dashed) and thermosteric height.

Von Schuckmann et al JGR 2009

Ocean heat content 0-2000m



OHC
Standard deviations of annual means 2003-2008

Von Schuckmann et al JGR 2009

Comments on Von Schuckmann

- VS did not provide 0-700 m OHC vs 0 to 2000m
- Some ARGO floats are programmed to go only to 1000 m and do not go to 2000 m, so that coverage decreases with depth.
- The error bars shown are constant over time even though ARGO coverage is increasing. Why?
- How good is the quality of the sensors over this time? Up to 30% report negative pressures at the surface. Is the ARGO array stable and reliable?

Need to monitor the deep oceans?

- *Abyssal ocean warming is a key part of the global energy and sea level budgets.*

Warming of Global Abyssal and Deep Southern Ocean Waters Between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets*

Sarah G. Purkey[1,2] and Gregory C. Johnson[2,1]

[1]*School of Oceanography, University of Washington, Seattle WA 98195, USA*

[2]*NOAA/Pacific Marine Environmental Laboratory, Seattle WA 98115, USA*

for *Journal of Climate*

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Revised 28 July 2010

Need to monitor the deep oceans?

- *Mean heat fluxes through 4000m implied by abyssal warming.*
- *While a few regions are cooling, overall they are warming and there is a net flux of heat into the abyssal oceans (>4000m)*

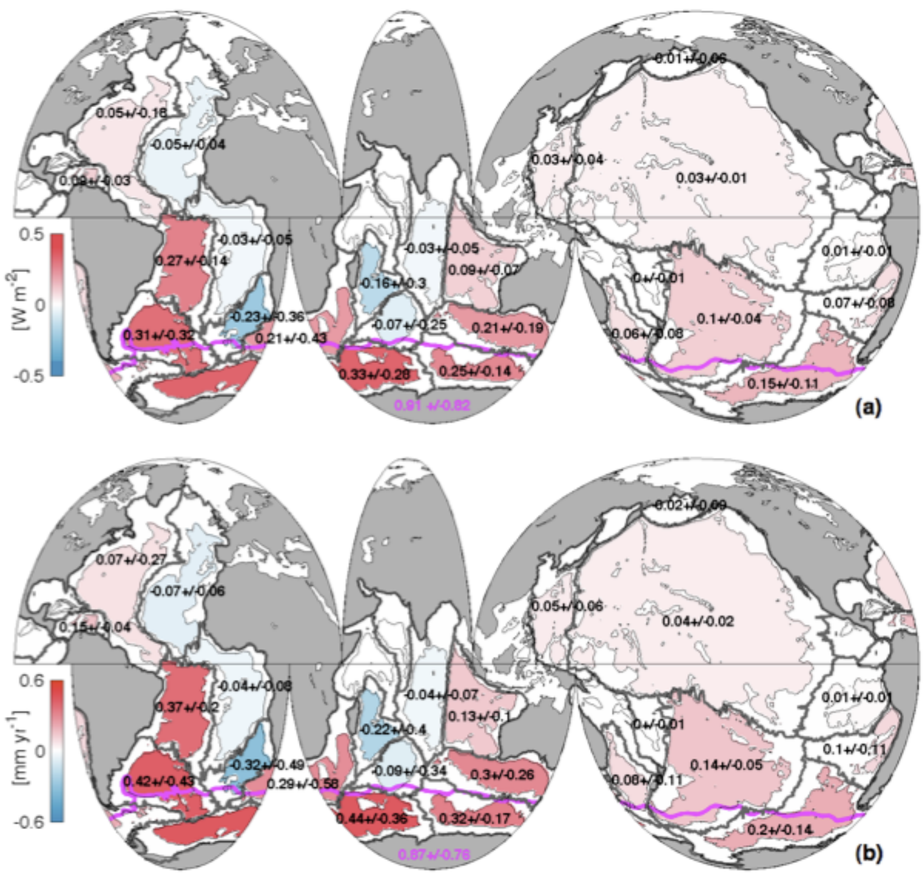
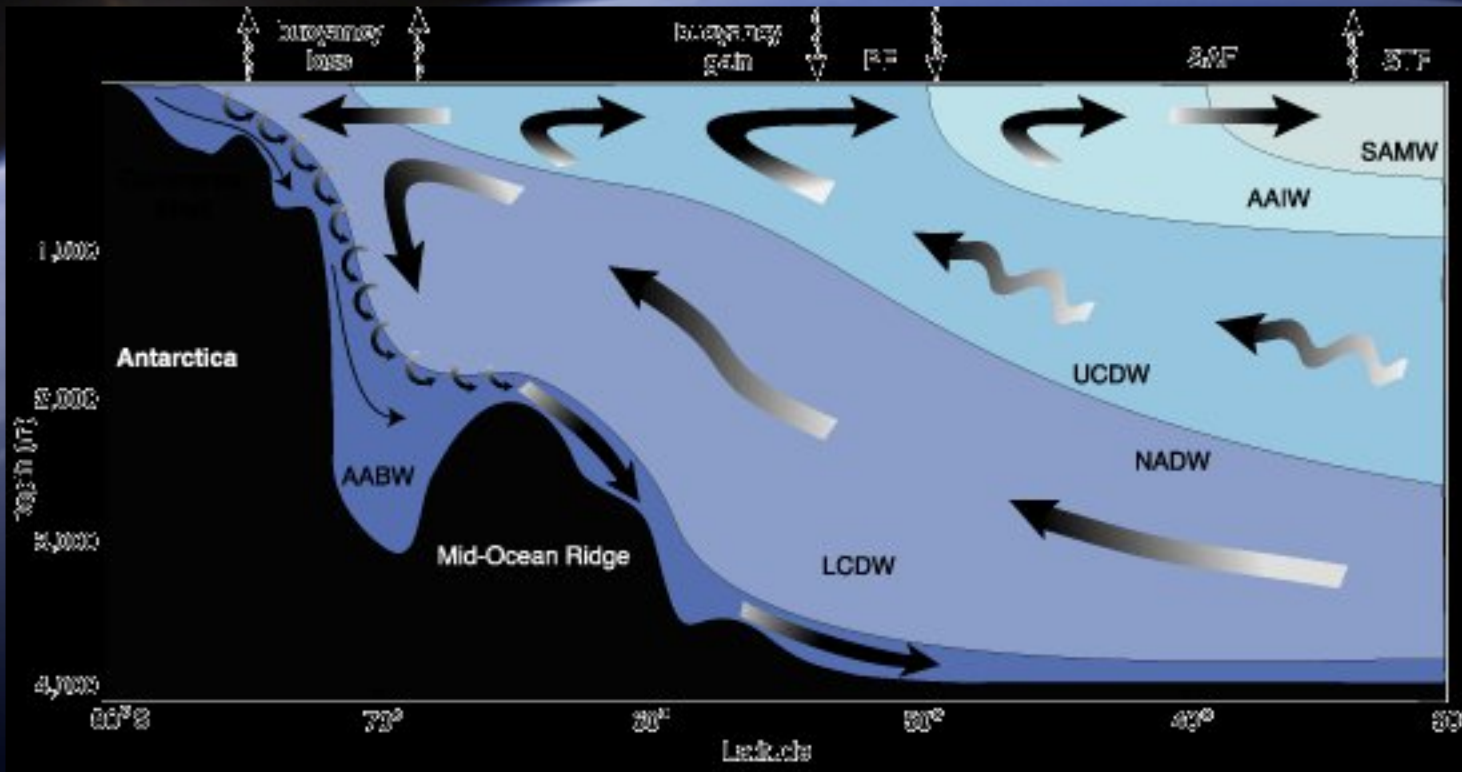


FIG. 8. (a) Mean local heat fluxes through 4000 m implied by abyssal warming below 4000 m from the 1990s to the 2000s within each of the 24 sampled basins (black numbers and colorbar) with 95% confidence intervals and the local contribution to the heat flux

Mechanism of Abyssal Warming: AABW



Ventilation from Antarctic Bottom Water (AABW) is primarily responsible for abyssal warming.

Need to monitor the deep oceans?

- *Abstract from Purkey and Johnson 2010, JCLIM*
- *But while important, these terms account for only about 20% of the "missing" energy and are small contributors to MSL rise (~3 mm/yr).*

sampled basins. The three southernmost basins show a strong statistically significant abyssal warming trend, with that warming signal weakening to the north in the central Pacific, western Atlantic, and eastern Indian Oceans. Eastern Atlantic and western Indian Ocean basins show statistically insignificant abyssal cooling trends. Excepting the Arctic Ocean and Nordic seas, the rate of abyssal (below 4000 m) global ocean heat content change in the 1990s and 2000s is equivalent to a heat flux of 0.027 (±0.009) W m^{-2} applied over the entire surface of the Earth. Deep (1000–4000 m) warming south of the Sub-Antarctic Front of the Antarctic Circumpolar Current adds 0.068 (±0.062) W m^{-2}. The abyssal warming produces a 0.053 (±0.017) mm yr^{-1} increase in global average sea level and the deep warming south of the Sub-Antarctic Front adds another 0.093 (±0.081) mm yr^{-1}. Thus warming in these regions, ventilated primarily by Antarctic Bottom Water, accounts for a statistically significant fraction of the present global energy and sea level budgets.

Can We Compute Upper Ocean Heat?

Uncertainties in the computation of upper ocean heat content are large.

Shortly after publication of our 'missing' energy article, came this new analysis of ocean heat content in Nature in May 2010.

This analysis demonstrates the large influence of the bias correction employed for XBT data. It dominates the spread amongst the estimates.

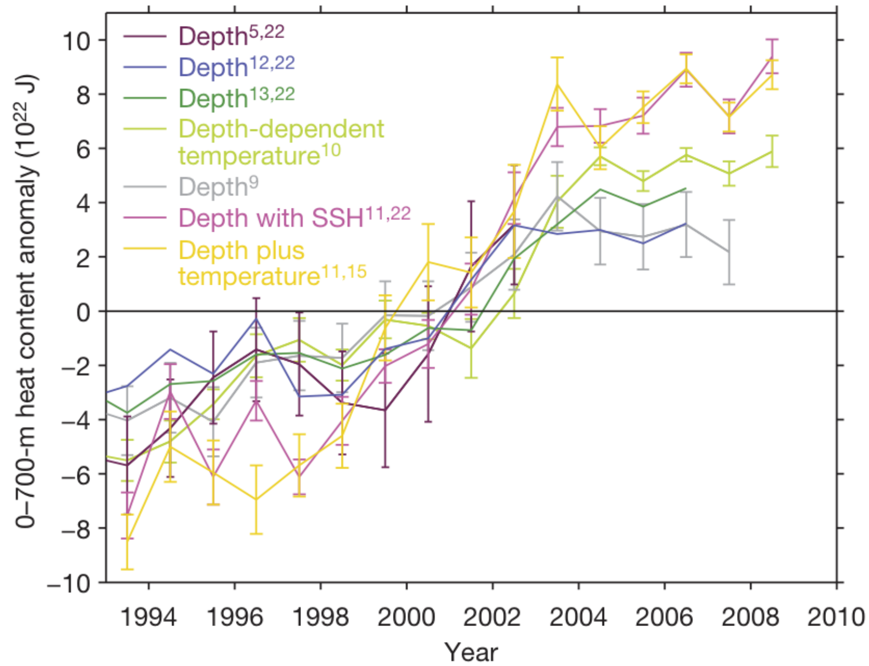


Figure 1 | OHCA curves using published methods. Globally integrated annual average OHCA curves from 0 to 700 m, estimated using methods published in papers cited in the key. All OHCA curves are estimated using different baseline climatologies, mapping methods and XBT corrections (first reference). Types of XBT bias corrections used include depth, depth-dependent temperature and depth with sea surface height (SSH; second reference, if different from first). Each curve has had its 1993–2006 mean removed to aid comparison, except for the depth[5,22] curve, which has been aligned with the 1993–2002 mean of the other curves. Error bars, 1 s.e.m. (Supplementary Information).

Lyman et al 2010 Nature

By computing heat content with all published XBT corrections and taking the composite mean behavior a more comprehensive estimate of the imbalance can be made.

Mean Trend=0.64±0.11 W m^{-2} (global)

90% confidence 0.53-0.75 W m^{-2}

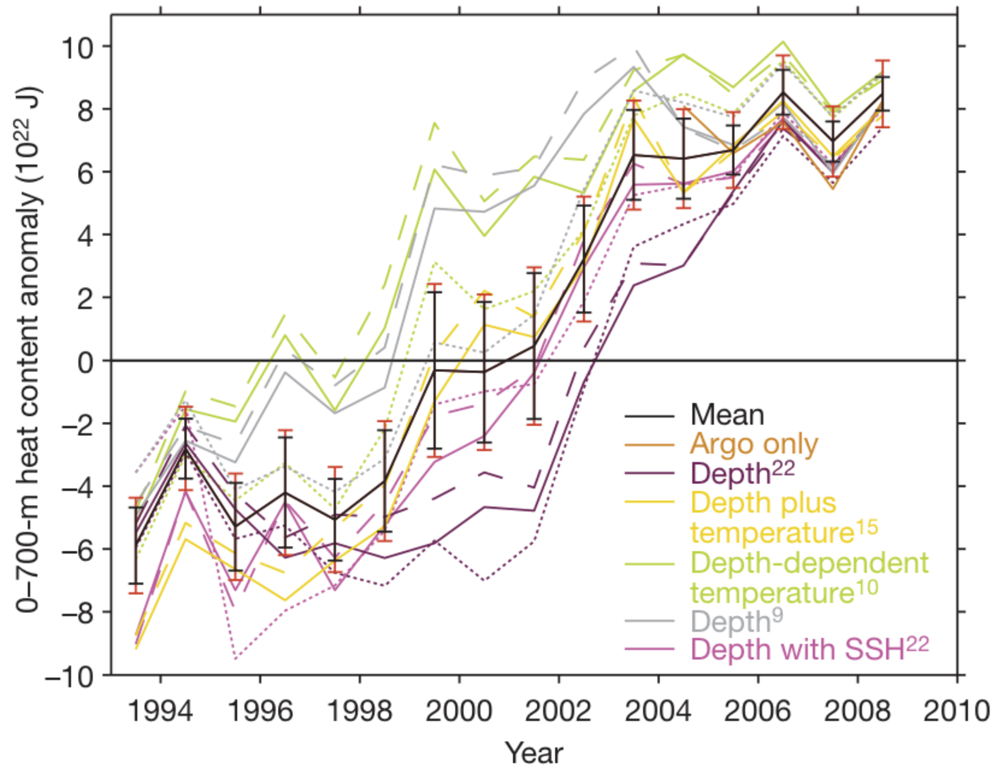


Figure 2 | OHCA curves produced using the same mapping technique. Solid lines are OHCA curves with a single 1993–2002 climatology and variously corrected XBT data provided by individual research teams. Dashed and dotted lines show the same thing as the solid lines, but using a single 2005–2008 climatology (dashed) or applying different published XBT corrections to the identical EN3 (version 2a) XBT data set (dotted). The key describes the type of XBT bias correction, with references. The trend estimate of the mean curve (black line; red error bars, 90% confidence intervals) is 0.64 ± 0.11 W m^{-2} and has 5.7 effective degrees of freedom (Supplementary Information); red error bars show the overall uncertainty, determined from combining all of the individual uncertainties in Fig. 3 assuming they are uncorrelated. Black error bars show XBT correction and XBT quality-control uncertainty from Fig. 3. The difference between the global means of the two climatologies has been added to the dashed lines.

Conclusions

- *The mean state and annual cycle of TOA, atmospheric, and oceanic energy flows are able to be resolved with a strong signal to noise ratio (e.g. meridional transports, land/ocean contrasts)*

- *Bias in ocean heat content estimates of the annual cycle are evident.*

- *Considerable uncertainty remains regarding interannual variations and trends for both the atmosphere and ocean.*

Conclusions: Challenges for Monitoring

- ***A 1% increase in clouds corresponds to a decrease in net flux of about -0.5 W m^{-2}. We thus need reliable clouds and radiation data in closer to real time. Currently, the calibrated CERES data lags by ~5yrs.***

- ***But there is also a need to improve our analysis of ocean heat storage – both in the upper ocean and deep ocean - and these uncertainties undermine our understanding of the 2008-9 cool period.***