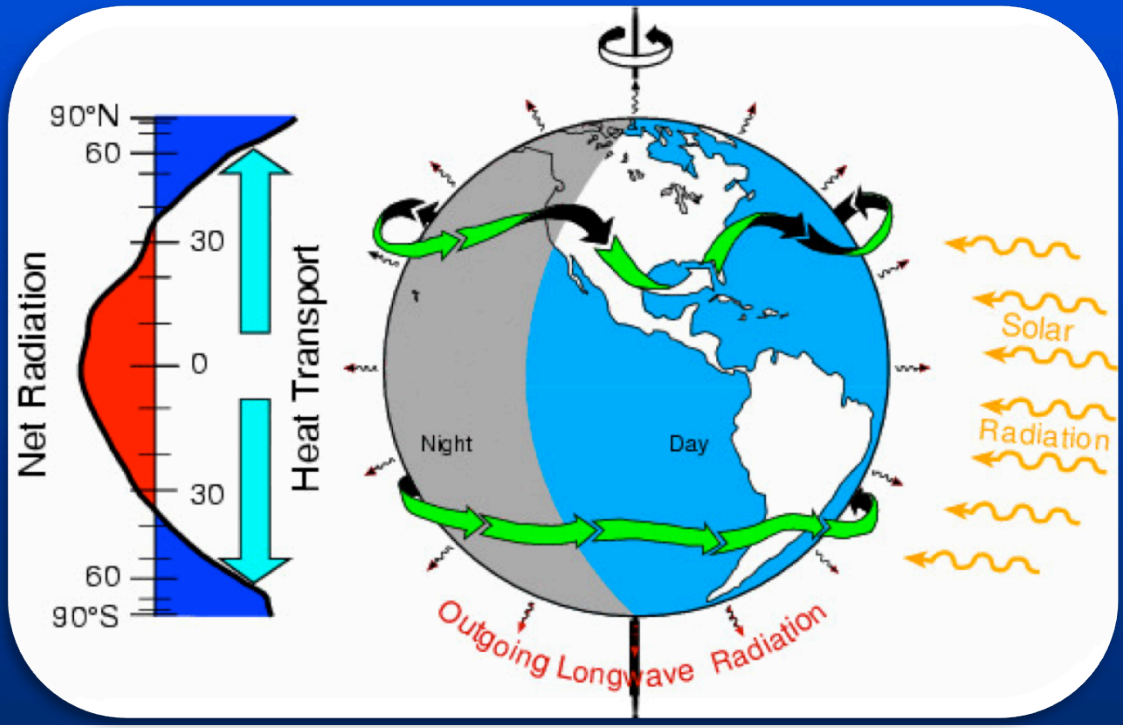
Tracking Earth's Global Energy

Where has global warming from increased GHGs gone?

Kevin E Trenberth

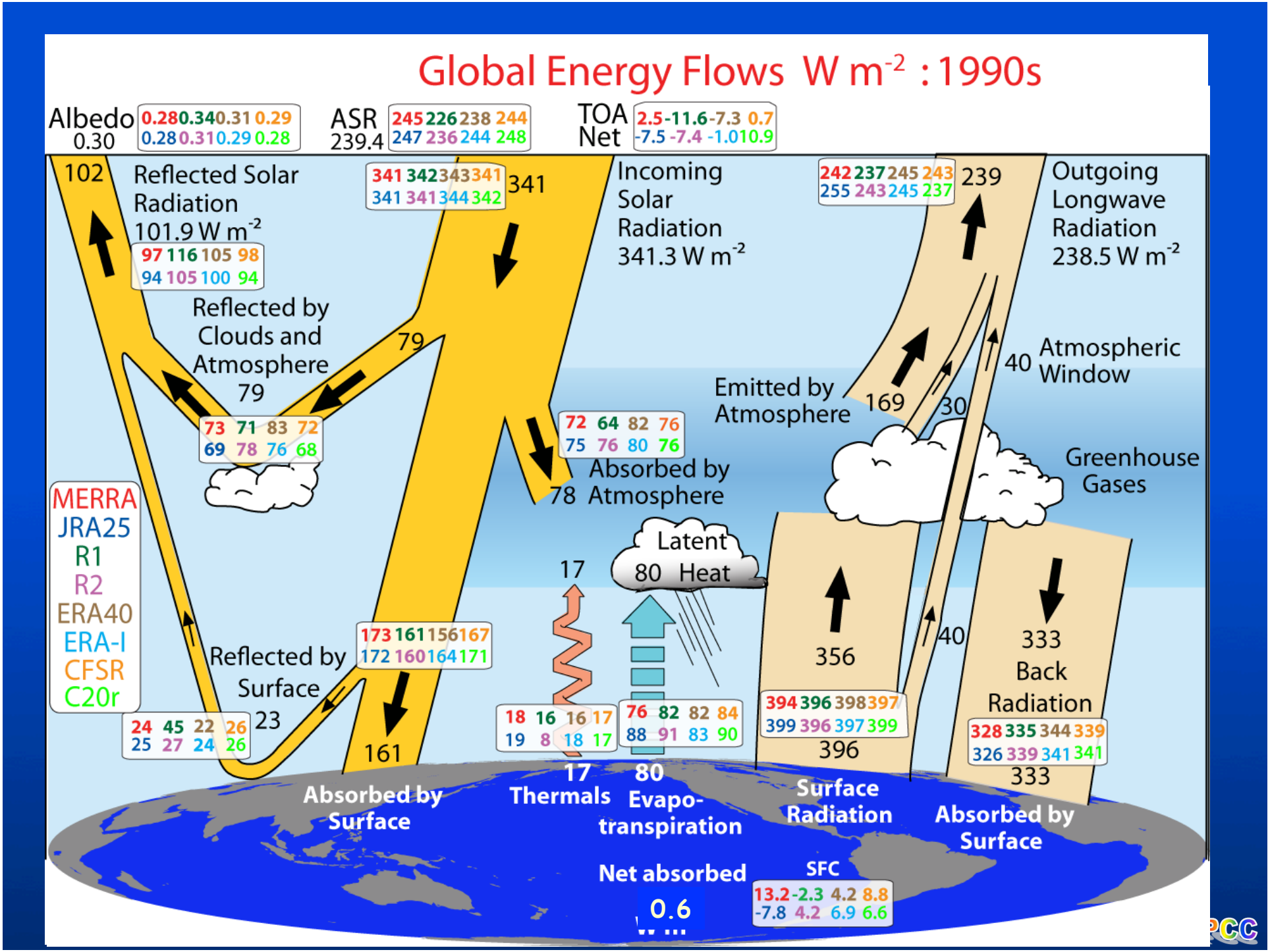
NCAR



IPCC

Where did the heat go?

- 2008 is the coolest year since 2000
- Carbon dioxide continues to rise
- Radiative forcing continues apace
- Where did global warming go?


Global Energy Flows W m-2 : 1990s
Albedo 0.30
0.28 0.34 0.31 0.29
0.28 0.31 0.29 0.28
ASR 239.4
245 226 238 244
247 236 244 248
TOA Net
2.5 -11.6 -7.3 0.7
-7.5 -7.4 -1.0 10.9
102
Reflected Solar Radiation 101.9 W m-2
97 116 105 98
94 105 100 94
341 342 343 341
341 341 344 342
341
Incoming Solar Radiation 341.3 W m-2
242 237 245 243
255 243 245 237
239
Outgoing Longwave Radiation 238.5 W m-2
Reflected by Clouds and Atmosphere 79
79
73 71 83 72
69 78 76 68
72 64 82 76
75 76 80 76
Absorbed by Atmosphere 78
Emitted by Atmosphere
169
30
40 Atmospheric Window
Greenhouse Gases
MERRA
JRA25
R1
R2
ERA40
ERA-I
CFSR
C20r
Latent 80 Heat
17
356
40
333 Back Radiation
328 335 344 339
326 339 341 341
333
394 396 398 397
399 396 397 399
396
173 161 156 167
172 160 164 171
Reflected by Surface 23
24 45 22 26
25 27 24 26
161
18 16 16 17
19 8 18 17
17 Thermals
76 82 82 84
88 91 83 90
80 Evapo-transpiration
Absorbed by Surface
Surface Radiation
Absorbed by Surface
Net absorbed
0.6
SFC
13.2 -2.3 4.2 8.8
-7.8 4.2 6.9 6.6

Energy budget: Reanalyses

- At TOA, most climate models are tuned to get balance or replicate ERBE/CERES
- Depends on equilibrium simulation
- No longer works in reanalyses
  - Specified SSTs
- Global imbalances (hide even bigger local)

	R1	ERA-40	ERA-I	JRA	MERRA	CFSR	
Resolution	1.9°	0.8°	0.5°	1.1°	0.5°	0.5°	
ASR	-13	-1	+5	+8	+6	+5	W m^{-2}
OLR	-2	+6	+6	+16	+3	+4	
Net(TOA)	-12	-8	-2	-8	+2	0	
Net (sfc)	-3	+4	+6	-8	+13	+8	

For 1990s vs climatology

IPCC

Ocean heat content and sea level

Global warming from increasing greenhouse gases creates an imbalance in radiation at the Top-Of-Atmosphere: now order 0.9 W m^{-2}.

Where does this heat go?

Main sink is ocean: thermosteric sea level rise associated with increasing ocean heat content.
Some melts sea ice: no change in SL
Some melts land ice.

SL increases much more per unit of energy from land-ice melt: ratio about 30 to 90 to 1.
Sea-ice melt does not change sea level.

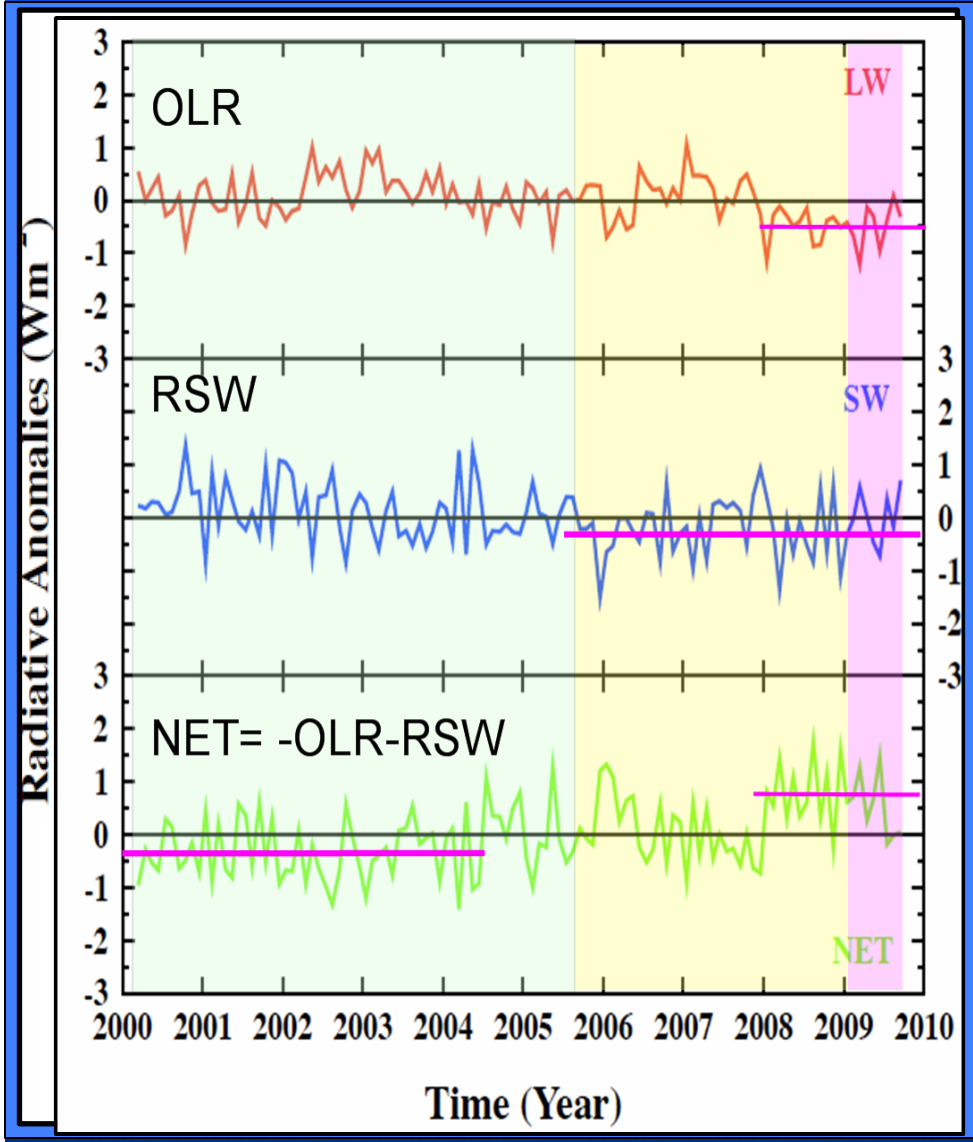
IPCC

Where does energy go?

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

Can we track it?

Deseasonalized Anomalies (Updated)

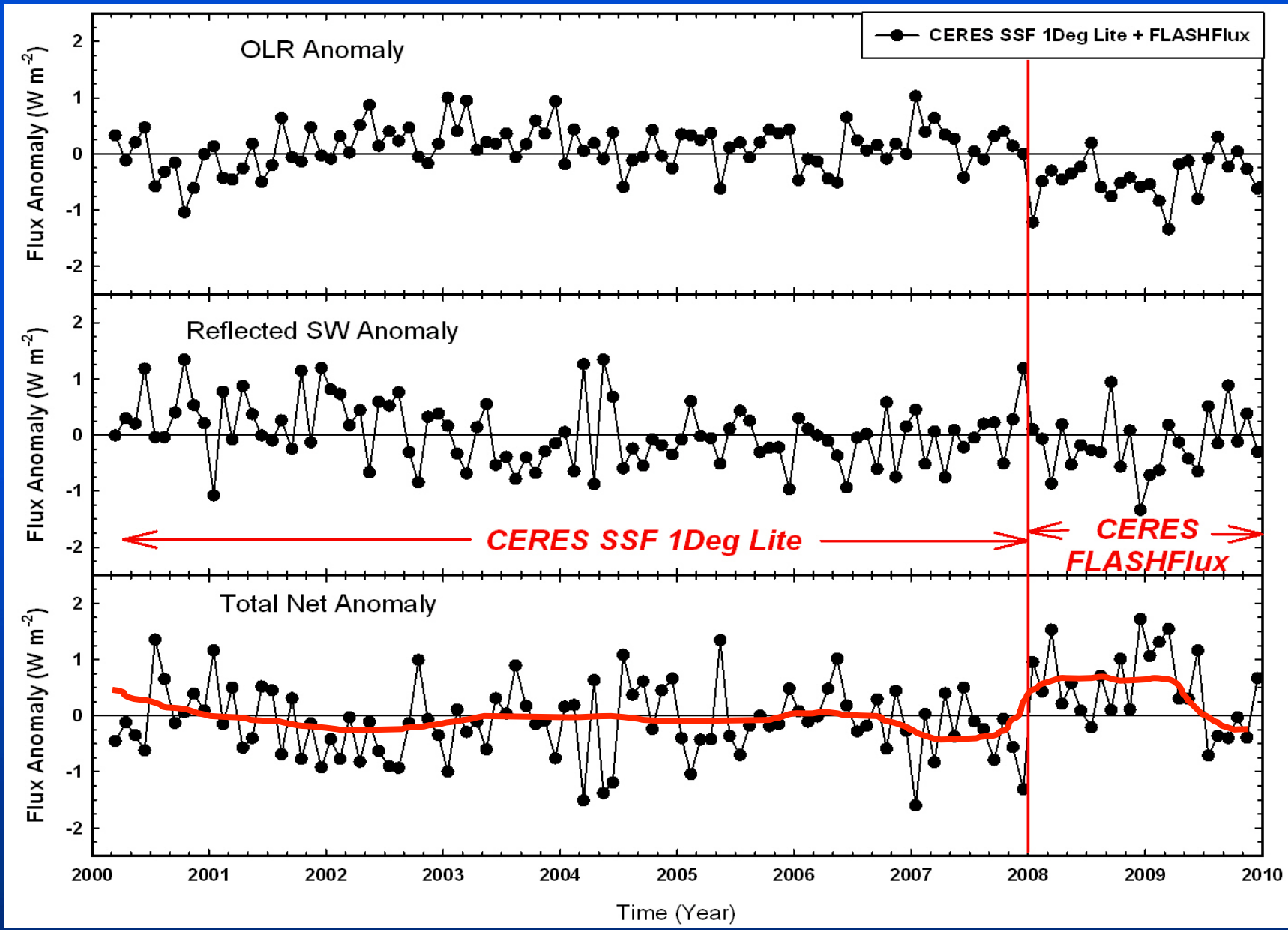


	2008 – 2007 change	2008 anomaly	Interannual variability (2-sigma)
LW	-0.74	-0.48	±0.56
SW	-0.33	-0.33	±0.39
Net	+1.07	+0.81	±0.82

- Large decrease in global mean outgoing longwave radiation in 2008
- Decrease in global mean reflected shortwave in 2008
- Large increase in global mean net flux in 2008
- Majority of net flux increase (~69%) from decrease in longwave
- FLASHFlux showing realistic variability

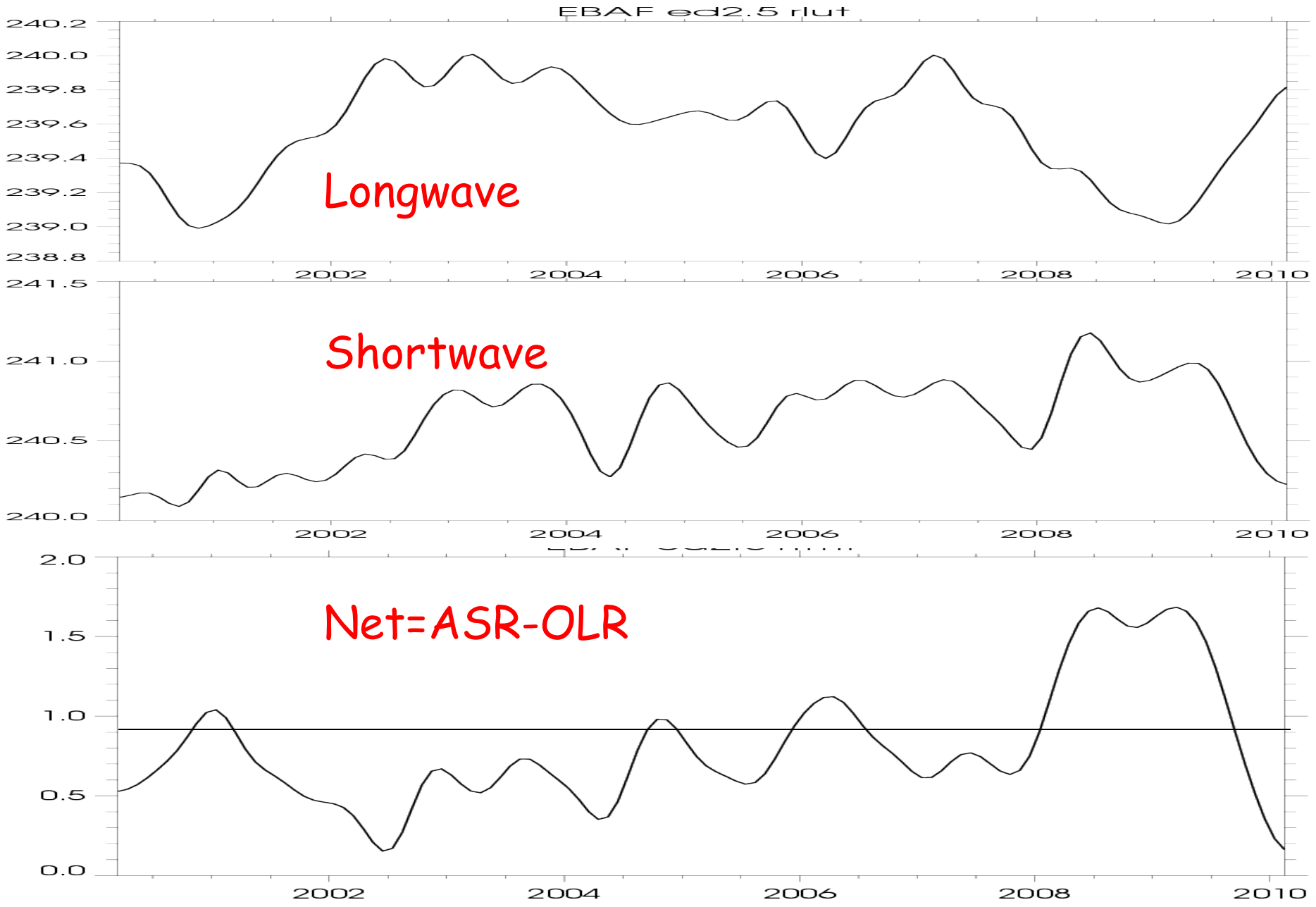
- BAMS 2009

Deseasonalized Anomalies (Updated)



zero= 0.9 W m^{-2}

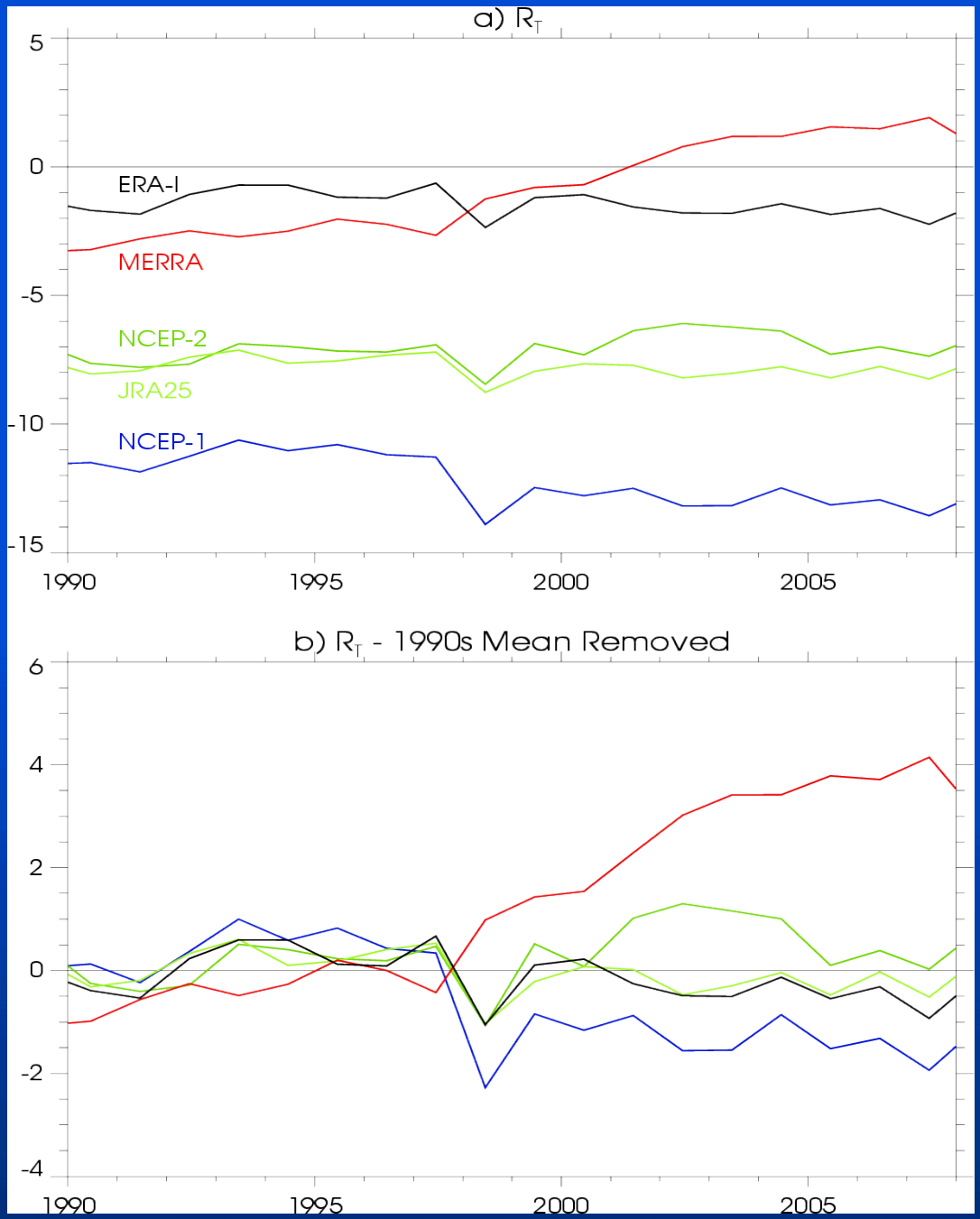
BAMS 2010 corrected



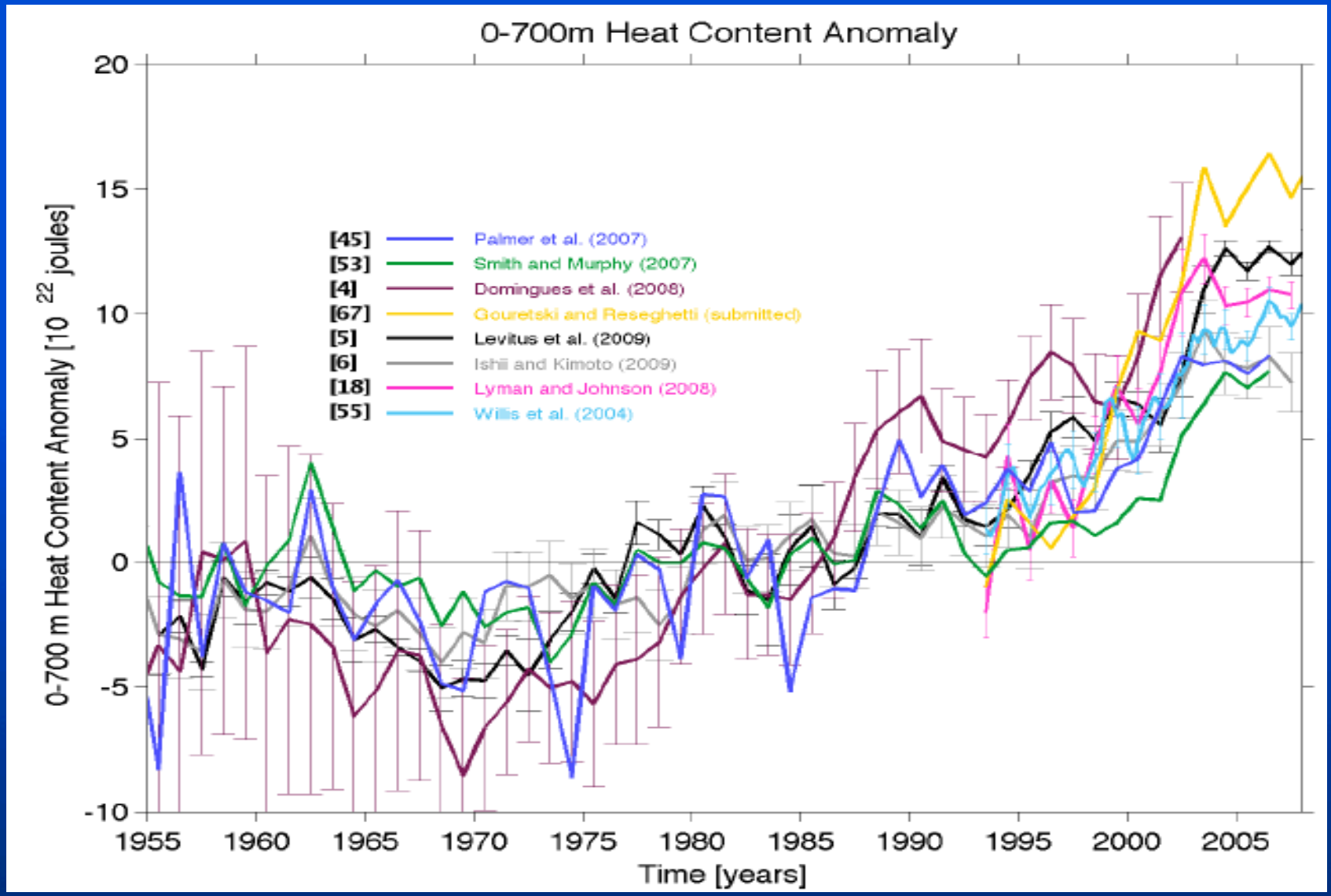
EBAF CERES radiation (Oct 2010 release)

IPCC

Reanalyses: TOA 1990-2008 Net radiation



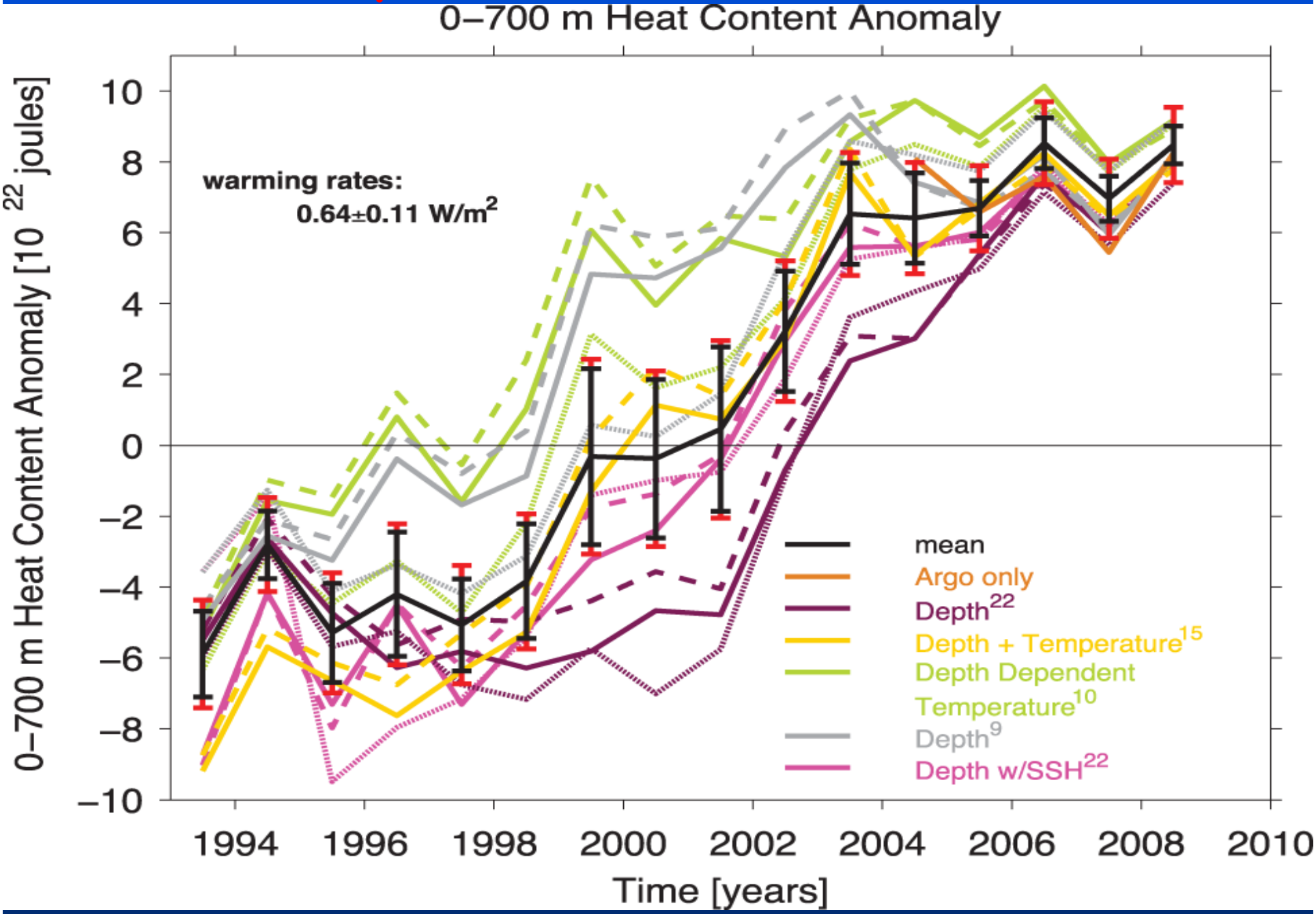
Ocean heat content to 700 m



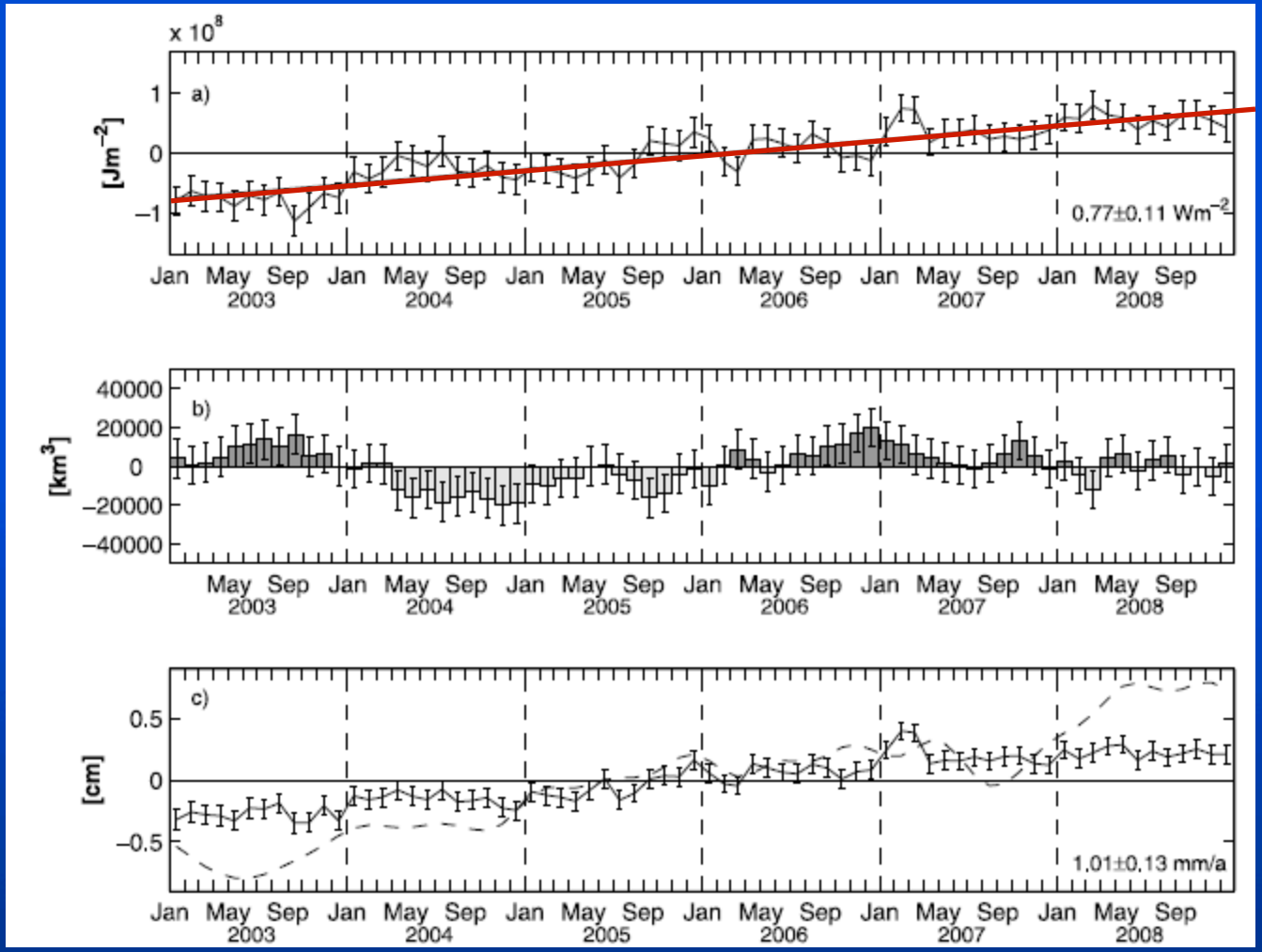
Palmer et al OceanObs'09

IPCC

Lyman et al 2010 Nature



Ocean heat content 0-2000m



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

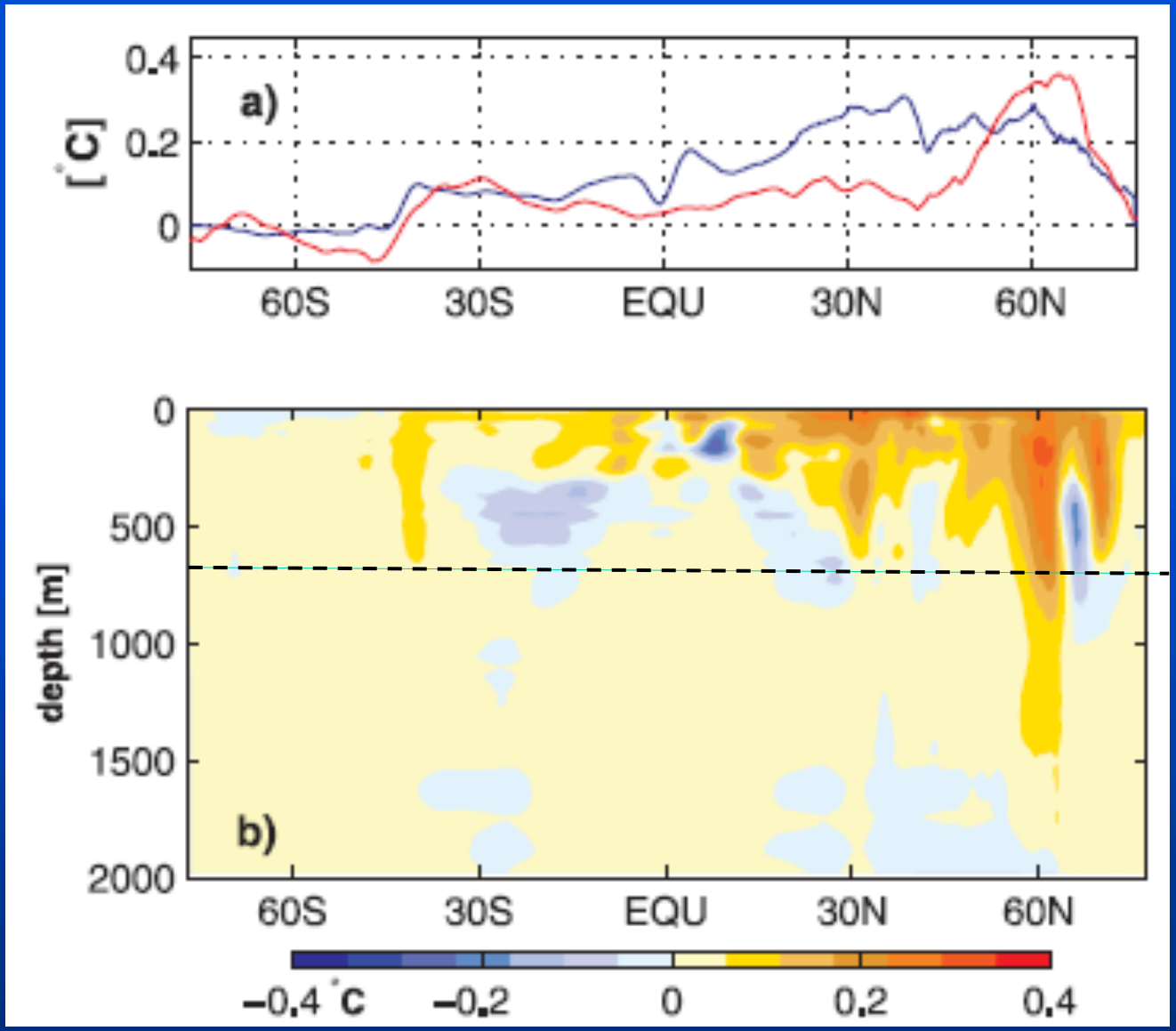
Fresh water

Sea level and thermosteric OHC

Von Schuckmann et al JGR 2009

IPCC

Ocean heat content 0-2000m



SST (red)
2003-2008 - 1990-2008
10 m depth
ARIVO - WOA05

Temps

Difference for 2003-2008 From WOA05 Levitus et al

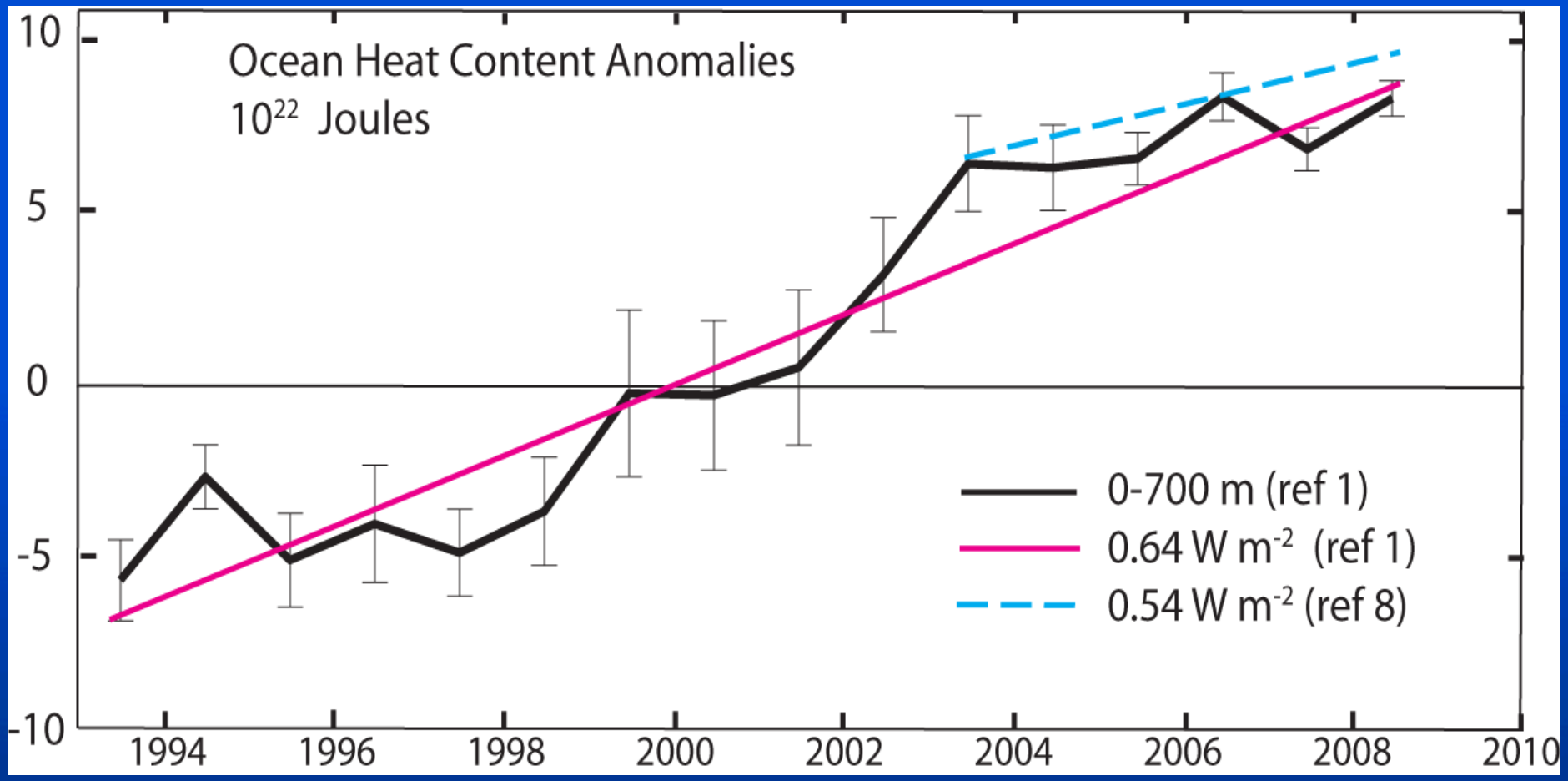
Von Schuckmann et al JGR 2009

IPCC

Comments on Von Schuckmann

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

Ocean heat content is increasing



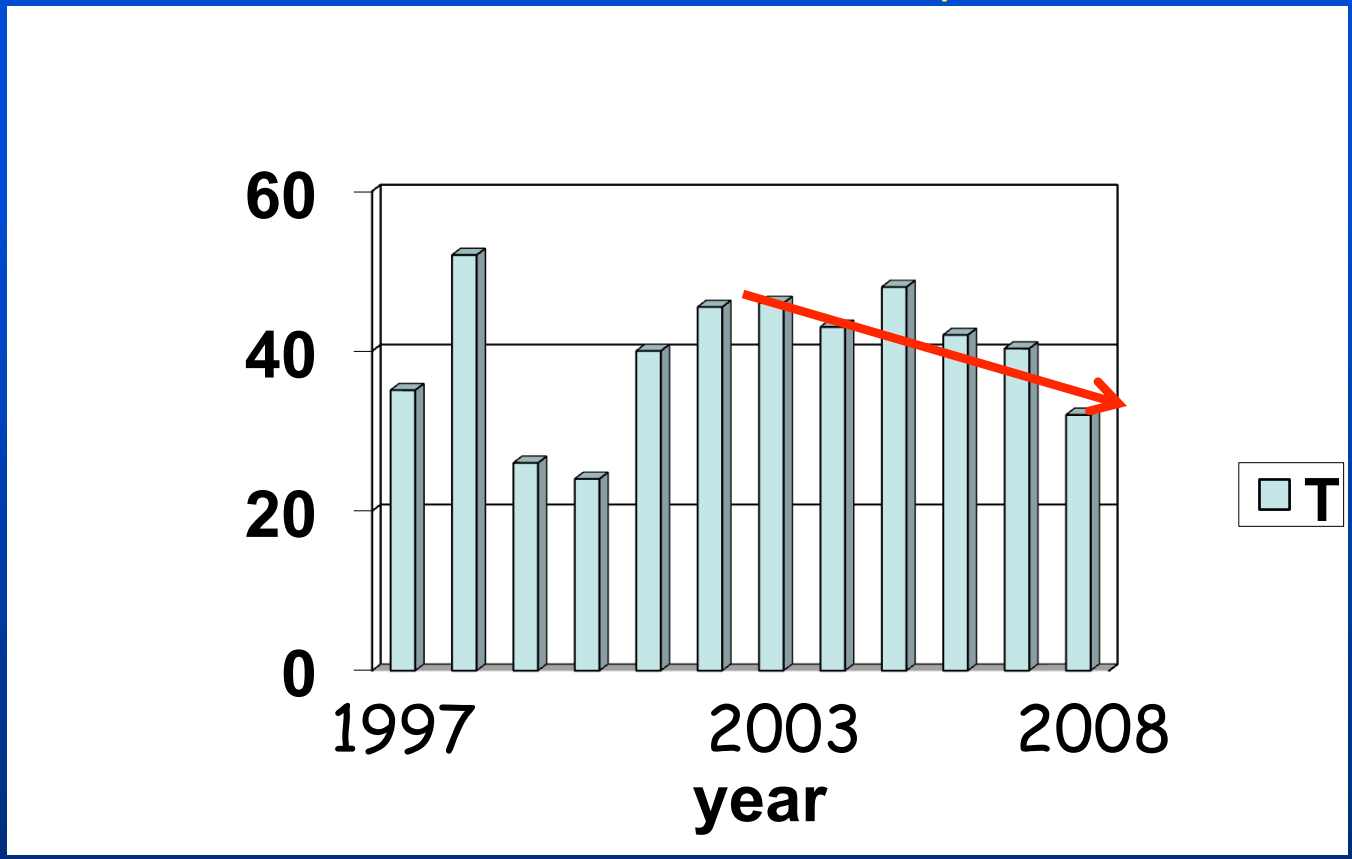
1. Lyman et al 2010 : to 700m
8. von Schuckmann et al 2009 :to 2000m

From Trenberth 2010 *Nature*

IPCC

What about 2003 to 2008?

Global mean surface temperatures



What about post-2003?

Several studies: disparate results:

Thermosteric sea level rise (mm/yr):

Willis et al 2008 JGR:	-0.5 ± 0.5
Cazenave et al 2009 GPC:	0.4 ± 0.1
Leuliette and Miller 2009 GRL:	0.8± 0.8

Implication: since 2003, main source of sea level rise is melting of Greenland and Antarctica, and glaciers.

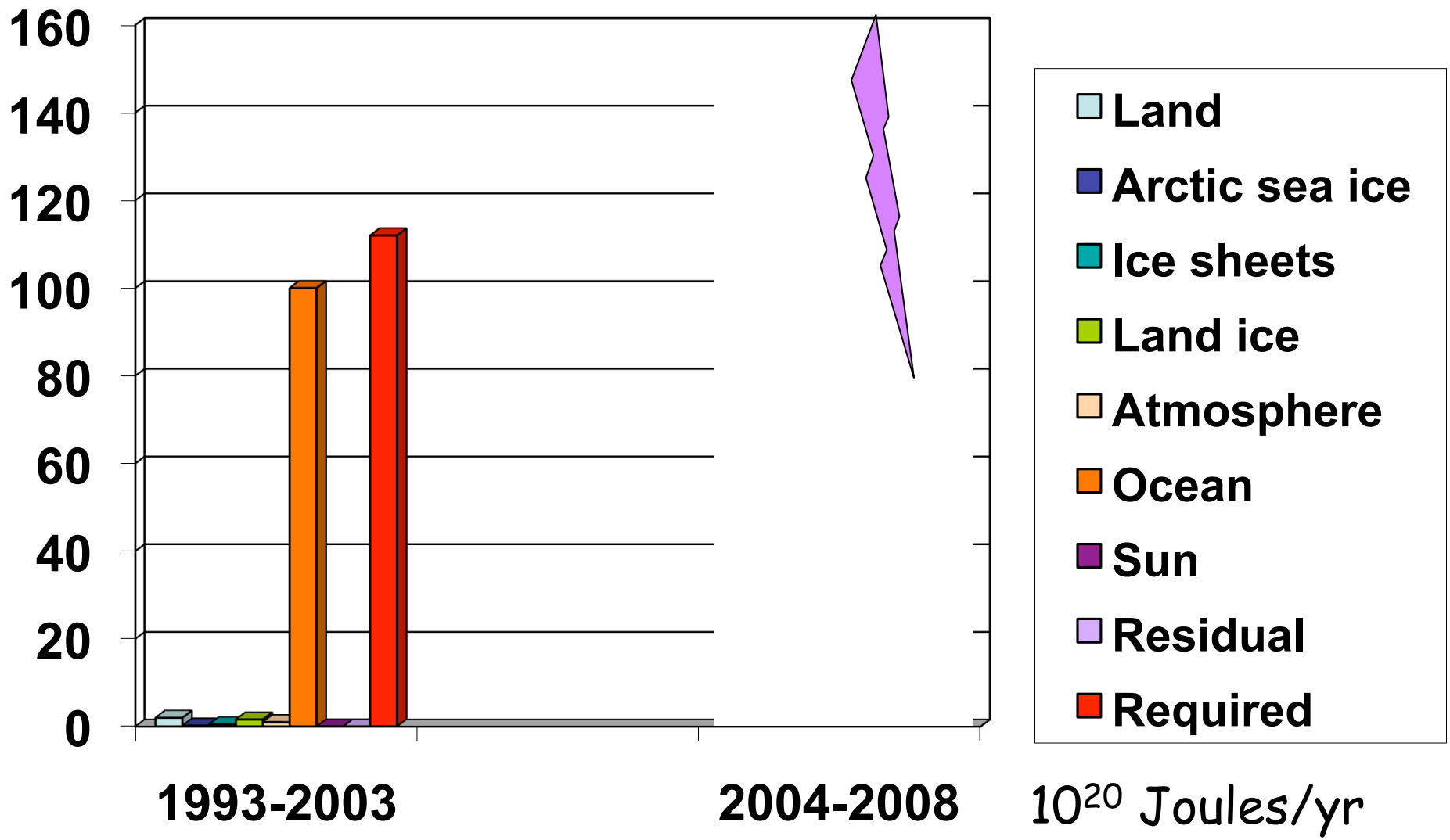
These require about a **factor of ~50 less heat to produce same sea level rise as ocean expansion**

If correct, implies reduction in ocean heat uptake and TOA energy imbalance in past 4 years.

Does NOT solve energy imbalance problem

IPCC

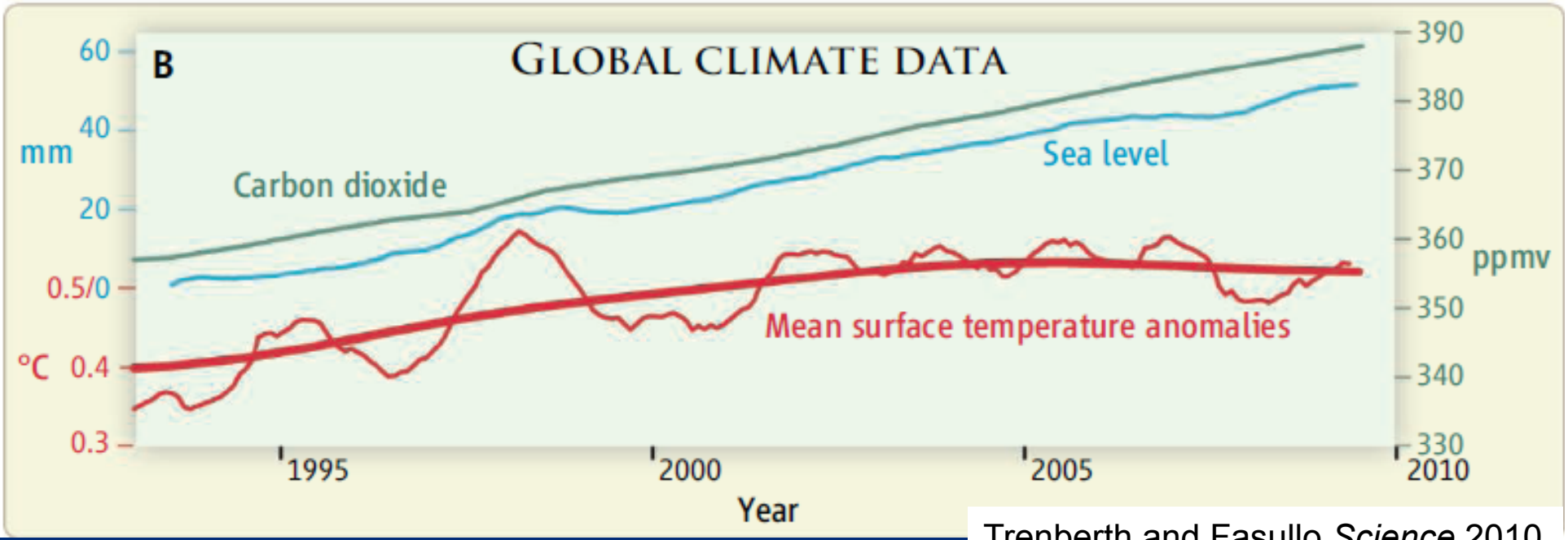
Where does energy go?



10^{20} Joules/yr

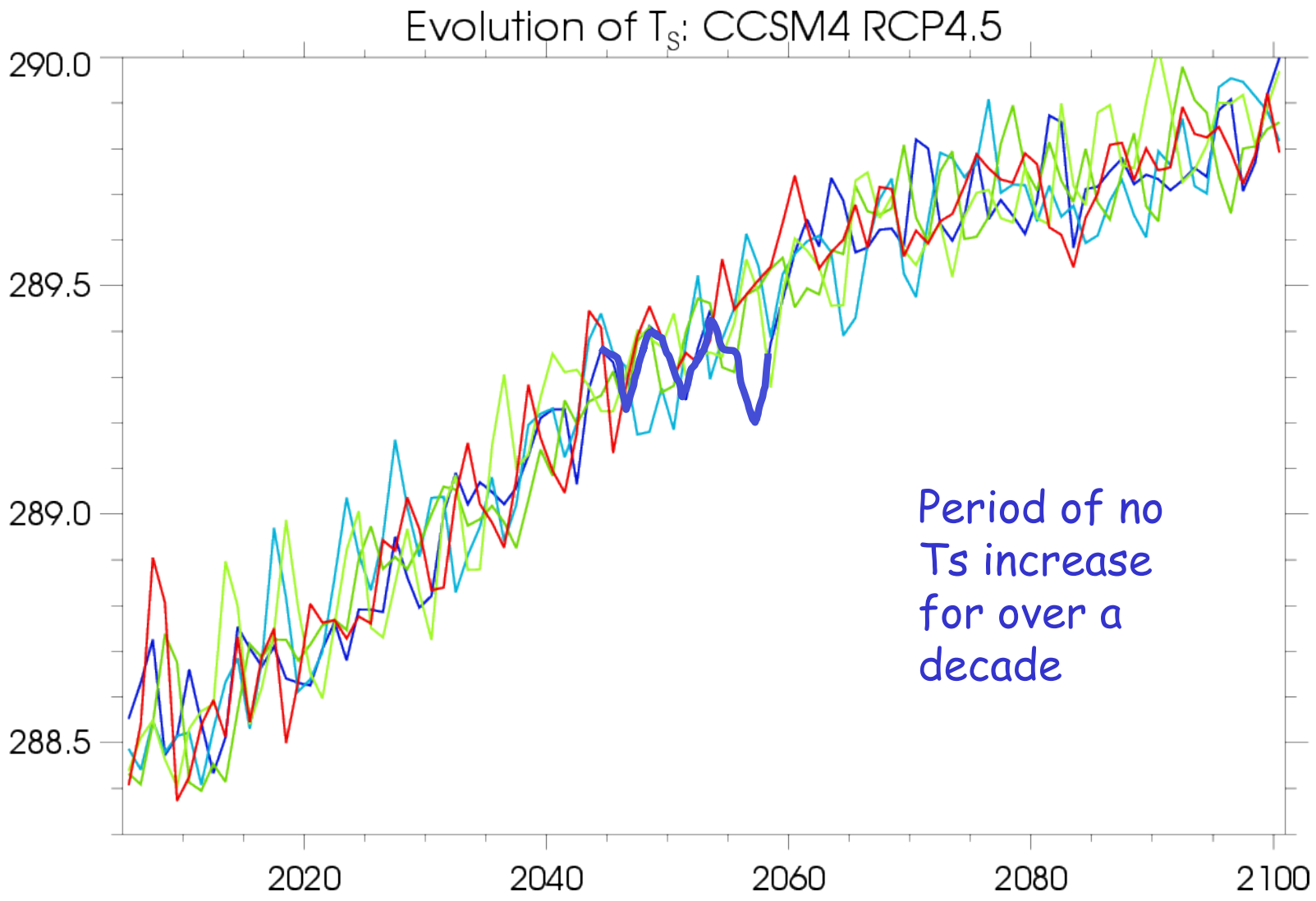
Trenberth 2009

Can we track energy since 1993 when we have had good sea level measurements?



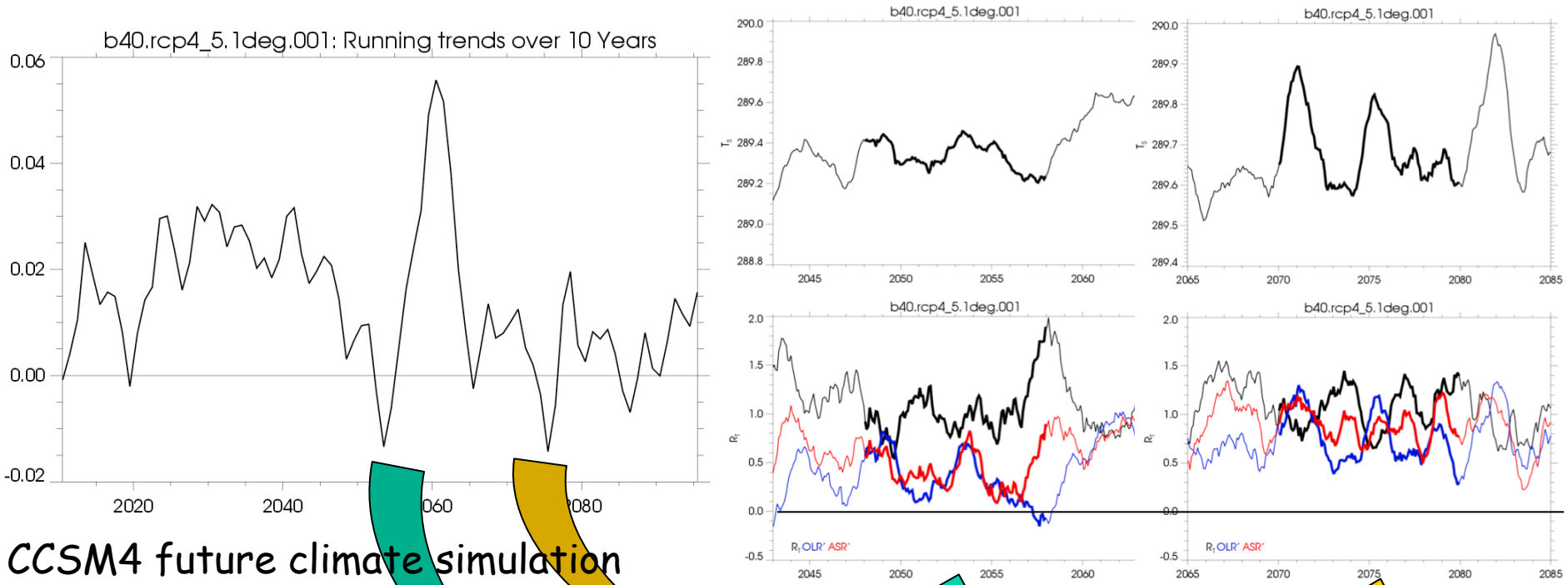
Trenberth and Fasullo *Science* 2010

Missing energy in CCSM4?



In CCSM4, during periods with no sfc T rise, the energy imbalance at TOA remains about 1 W m^{-2} warming. So where does the heat go?

Missing energy in CCSM4?

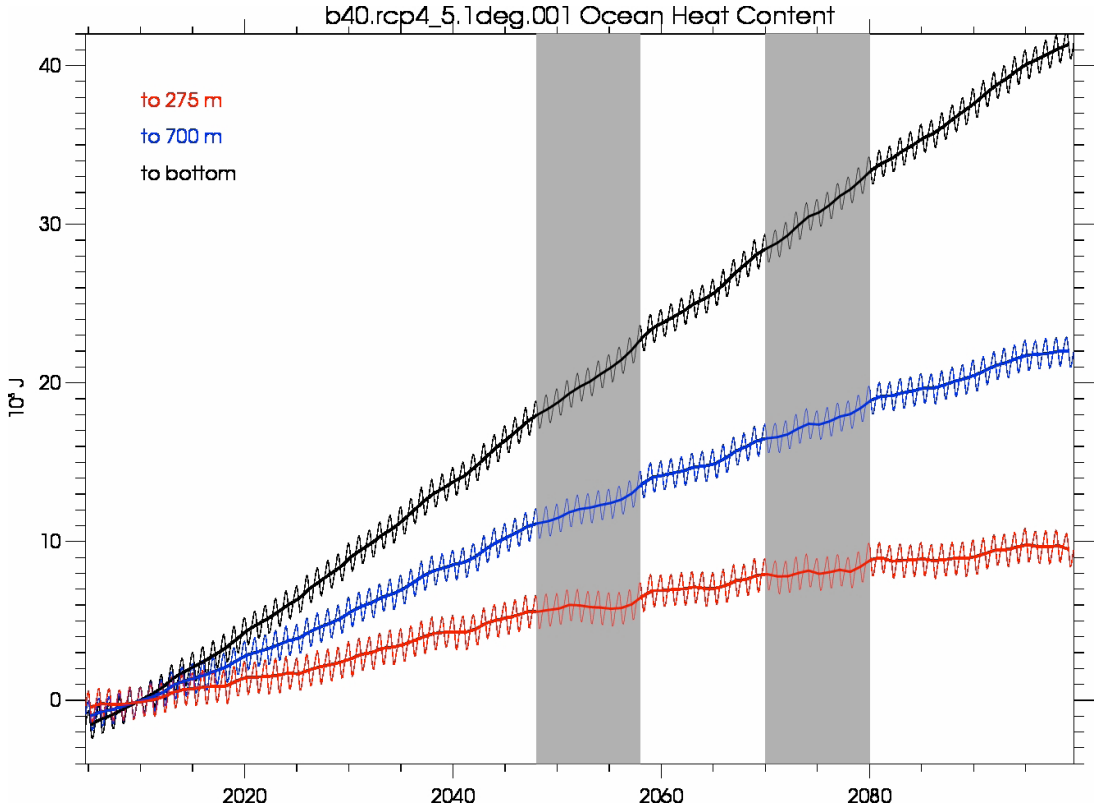


CCSM4 future climate simulation (RCP4.5) showing running 10 year trends of surface air temperature

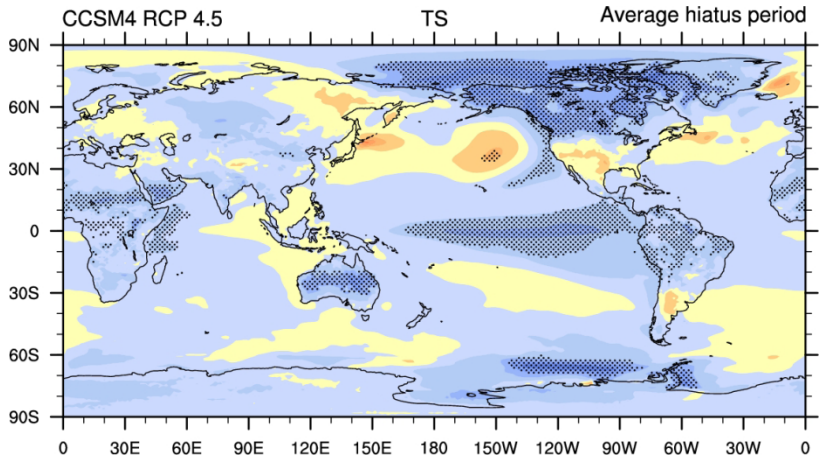
In CCSM4, during periods with no sfc T rise, the energy imbalance at TOA remains about 1 W m^{-2} warming. So where does the heat go?

NCAR

Missing energy in CCSM4?



Ocean heat content for those two periods shows no warming trend in the upper 275 meters, little trend down to 700 meters, but an ongoing warming trend in the deep ocean; the heat is going into the deep ocean, but where and how?



Taking five ensemble members of RCP4.5 and compositing seven distinct 10-year periods with either zero or slightly negative globally averaged temperature trend shows these time periods are characterized by a negative phase of the Interdecadal Pacific Oscillation (IPO)
(the t-test was based on the variance across the 5 year differences in these 7 periods compared to the 5 year differences from the entire run.)

In CCSM4, during periods with no sfc T rise, the energy goes into the deep ocean, somehow.

Need to know energy balance

- *A 1% increase in clouds is about -0.5 W m^{-2}*
- *Need reliable clouds and radiation data in closer to real time.*
- *We need better, more complete observations*
- *We need much better reanalyses: atmosphere, ocean, ice.*

Is global warming continuing?