Tracking Earth's Net Energy Imbalance since 2000

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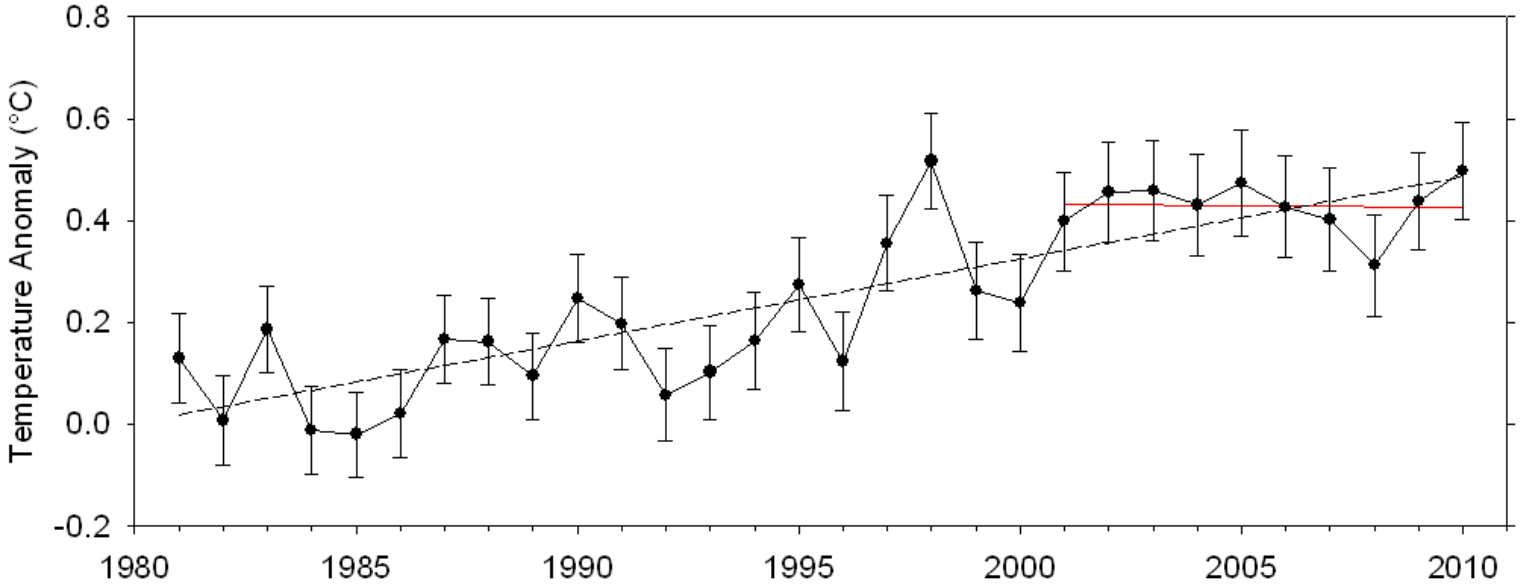
Lack of recent surface warming

- Radiative forcing or energy redistribution?



Global annual average temperature anomalies from the 1961–1990 mean (black dots with 95% confidence limits) from the HadCRUT3 dataset .

But note that HadCRUT3 may underestimate Arctic warming

Hypotheses

- Small but systematic volcanic forcing?
  - e.g. Solomon et al. (2011) Science
- Sulphur emissions?
  - e.g. Kaufmann et al. (2011) PNAS
- Stratospheric water vapour?
  - e.g. Solomon et al. (2010) Science
- Cloud forcing/feedbacks and El Nino?
- Ocean circulation
  - e.g. Modelling studies: Meehl et al. (2011), Palmer et al. (2010) GRL

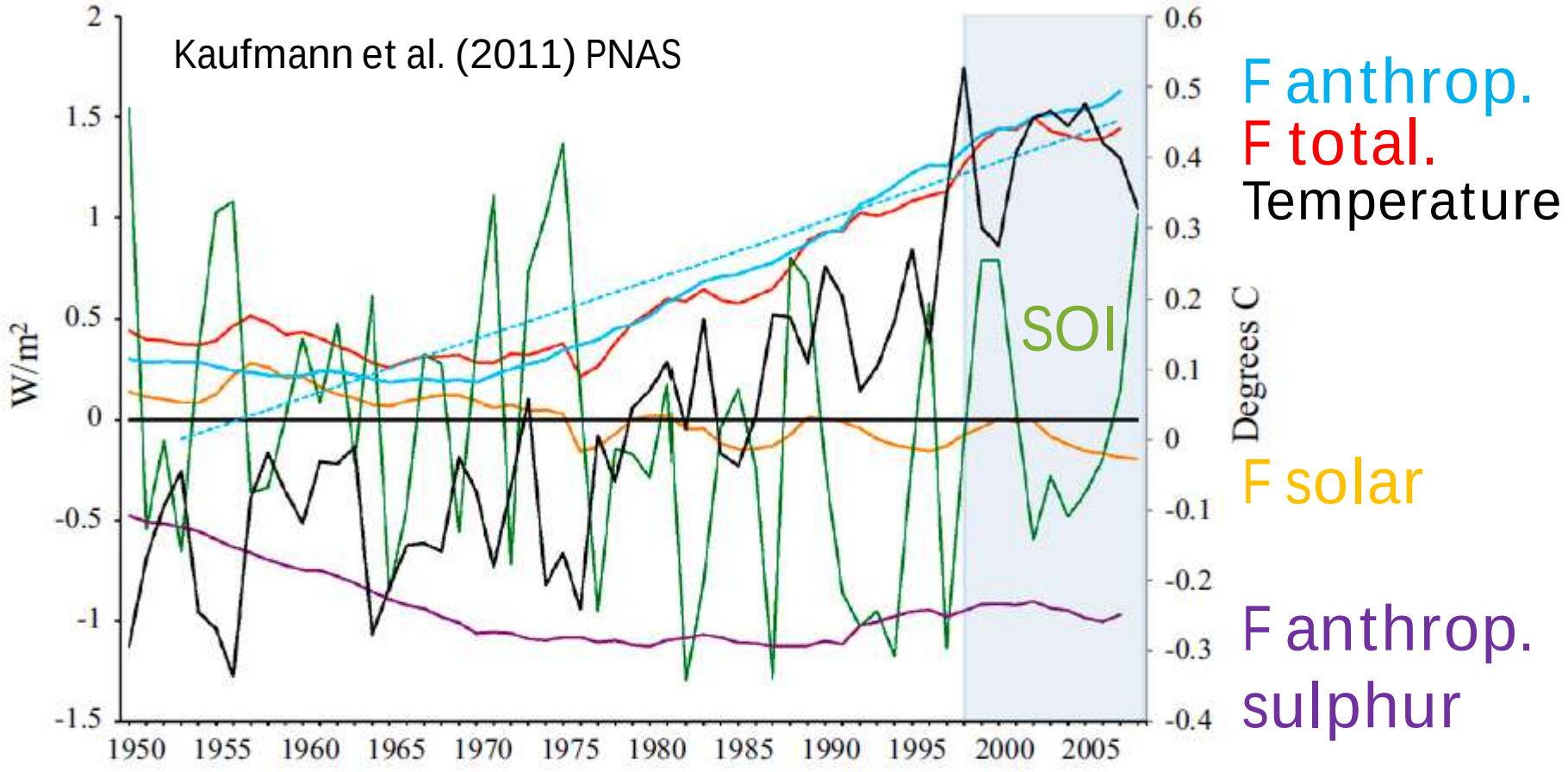


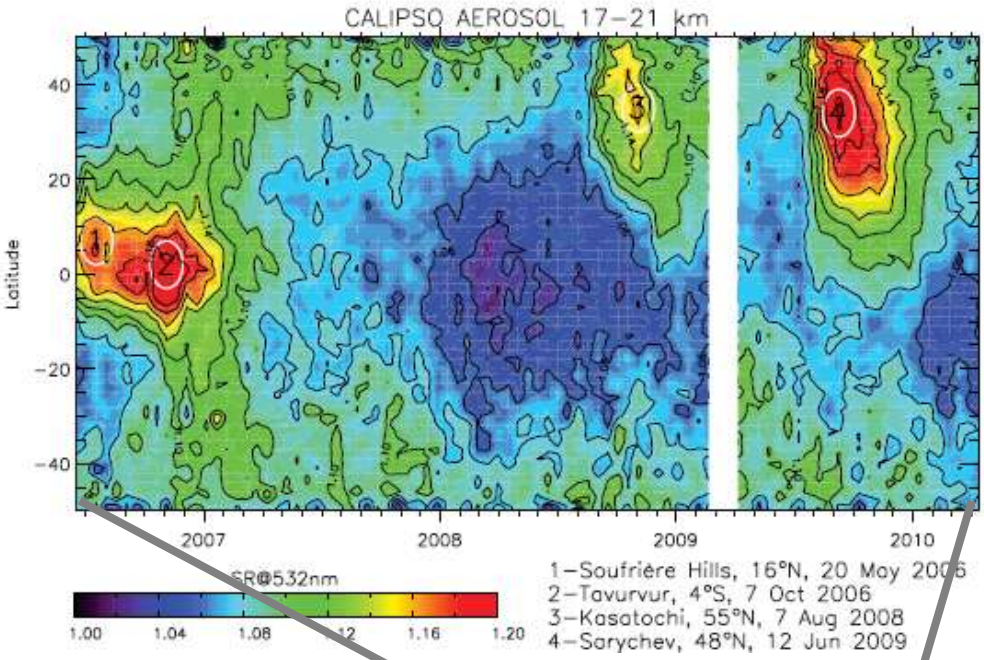
Fig. 1. Radiative forcing of anthropogenic sulfur emissions (purple line), net anthropogenic forcing (blue line), linear estimate of net anthropogenic forcing (blue dash), total radiative forcing (red line), radiative forcing of solar insolation (orange line), and observed temperature (black). The SOI (divided by 10) is given in green. SOI data are presented as annual mean sea level pressure anomalies at Tahiti and Darwin. Post-1998 period of interest (highlighted gray).

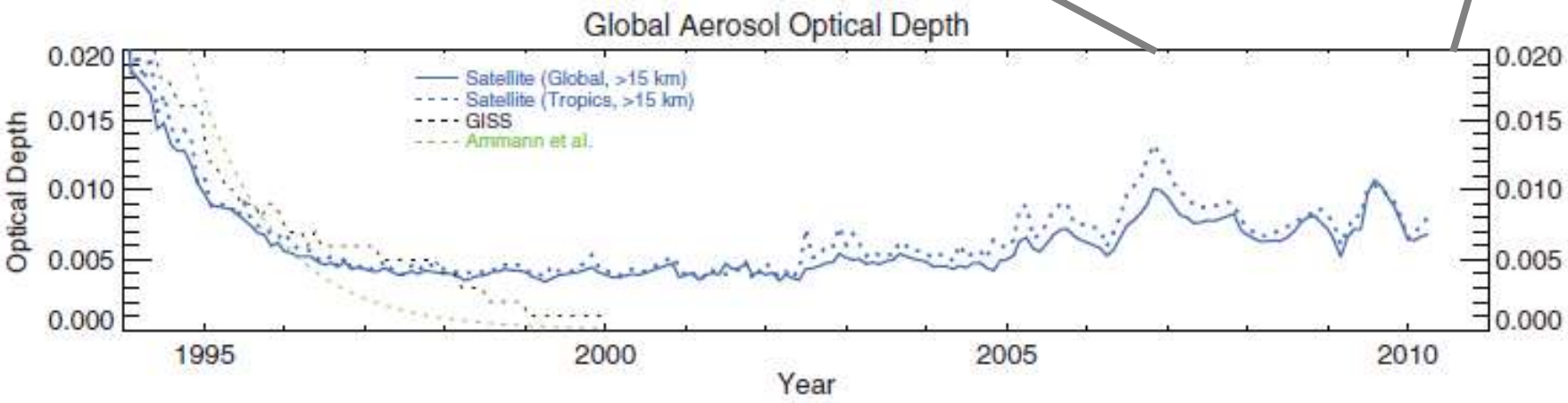
http://www.pnas.org/content/early/2011/06/27/1102467108.short

Volcanic forcing?

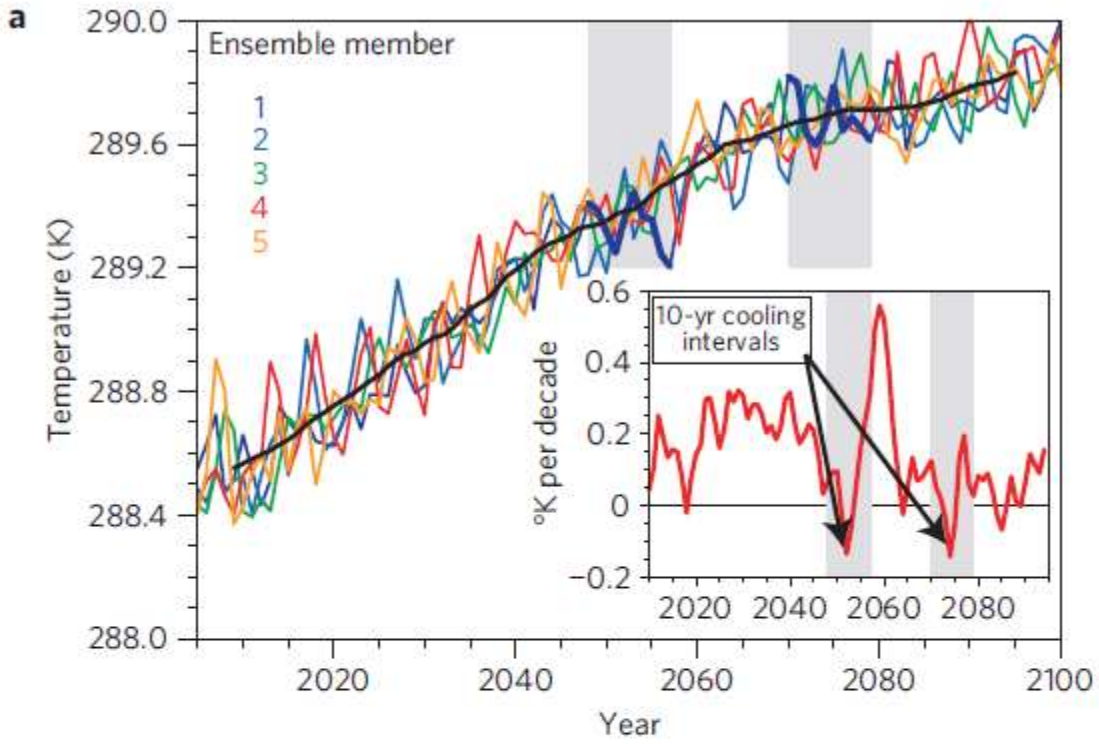
- Solomon et al. (2011) Science

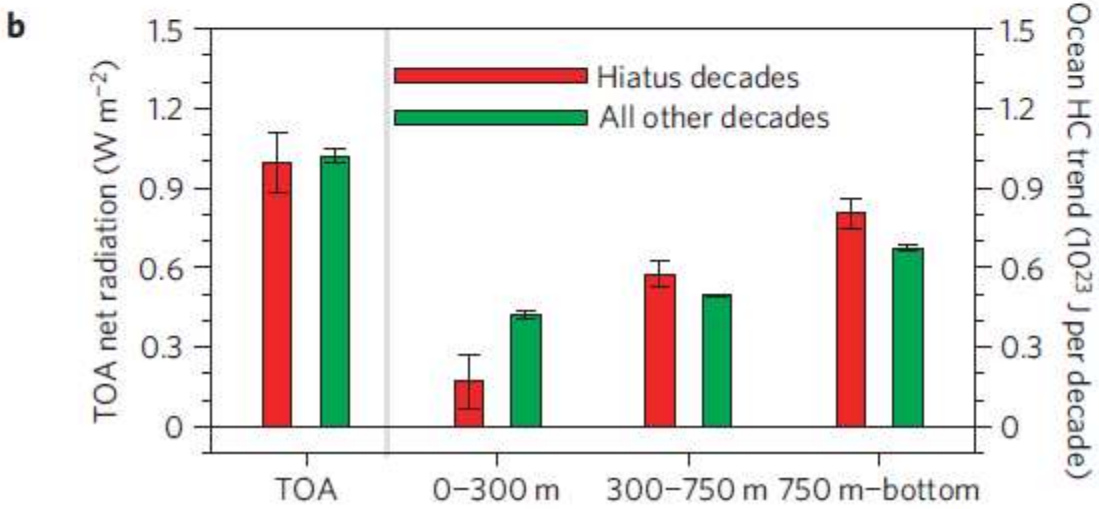
http://www.sciencemag.org/content/333/6044/866.full.pdf





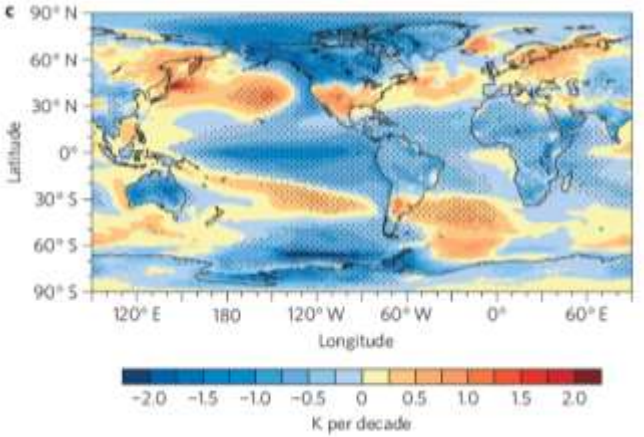
Ocean mixing



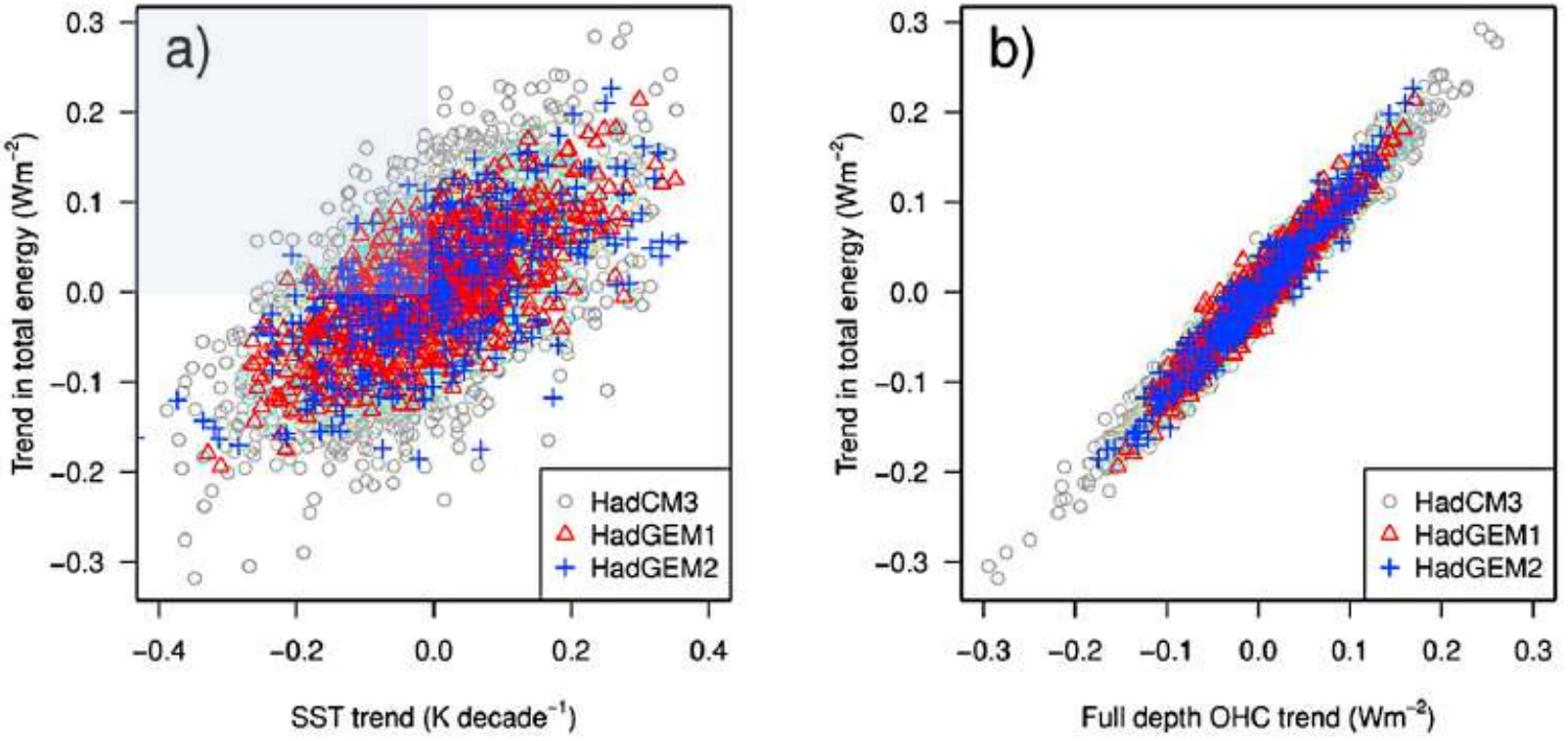


- Meehl et al. (2011) Nature Climate Change

http://www.nature.com/nclimate/journal/v1/n7/full/nclimate1229.html



Ocean heat content, surface temperature and radiative energy balance



- Palmer et al. (2011) GRL

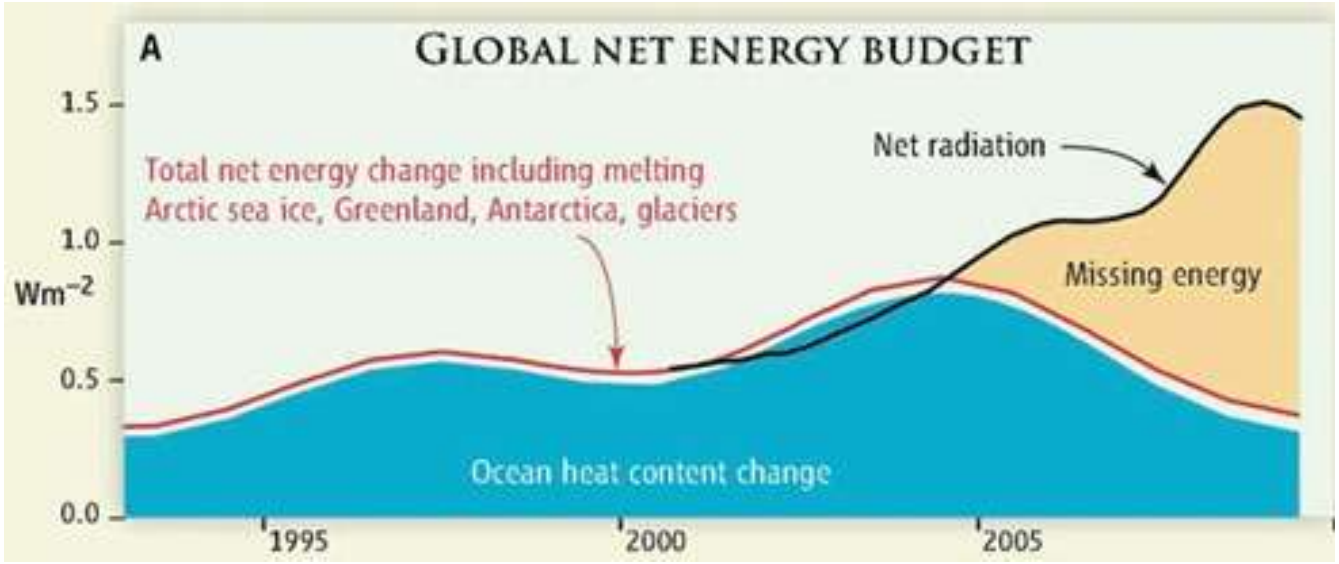
http://www.agu.org/journals/gl/gl1113/2011GL047835/2011GL047835.pdf

- See also: Katsman and van Oldenborgh (2011) GRL

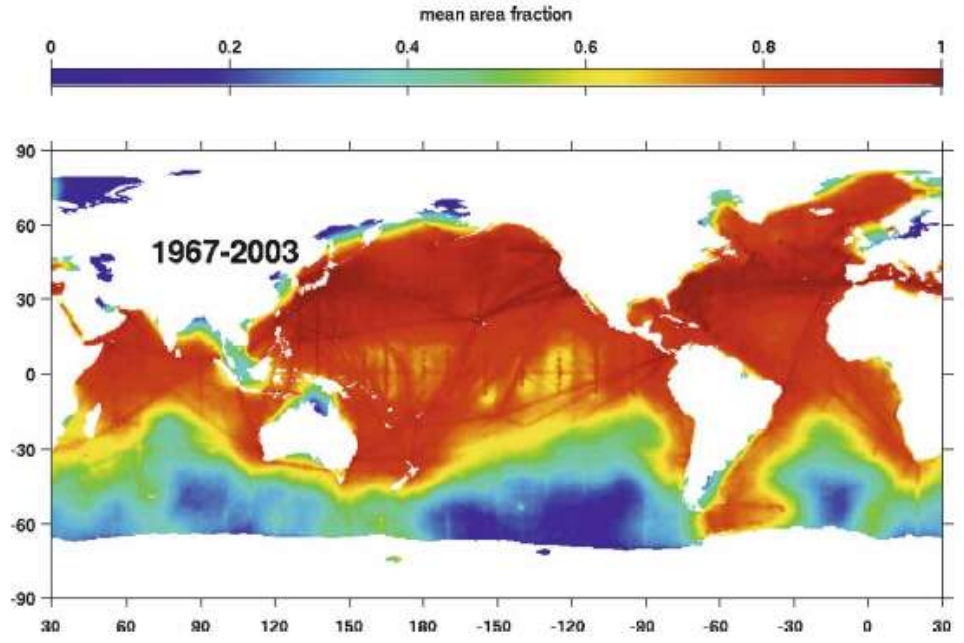
http://www.agu.org/pubs/crossref/2011/2011GL048417.shtml

Missing energy?

- Trenberth and Fasullo (2010, Science) highlight large discrepancy between net radiation and ocean heat content changes



Estimates of net radiation from satellite data and total net energy estimated primarily from ocean heat content data, do not appear to correspond (Trenberth & Fasullo 2010)



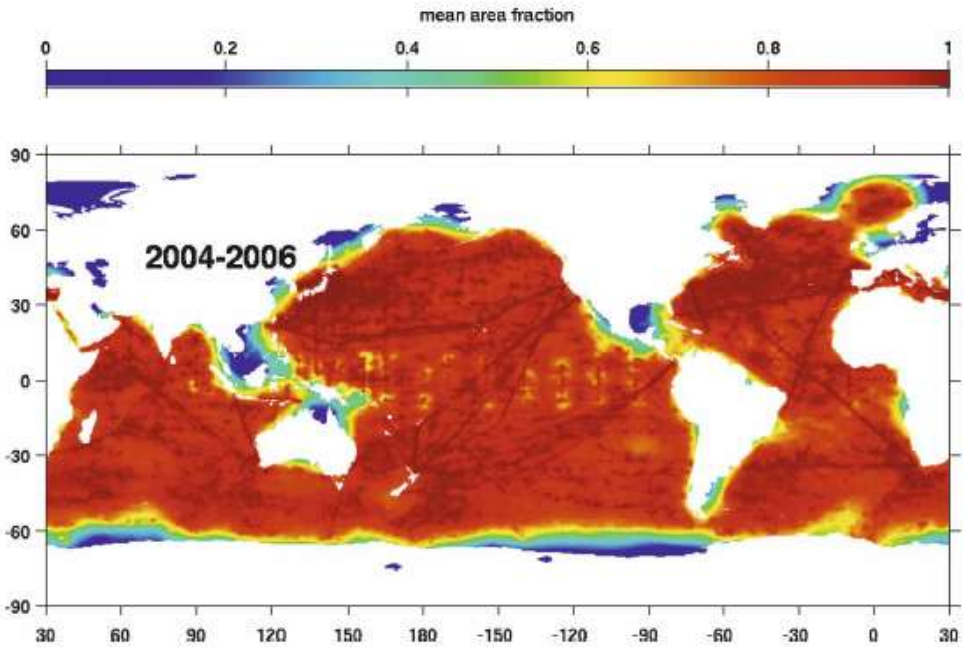


FIG. 4. Mean of annual "observed" area coverage from 2004 to 2006.

Ocean Heat Content measurements

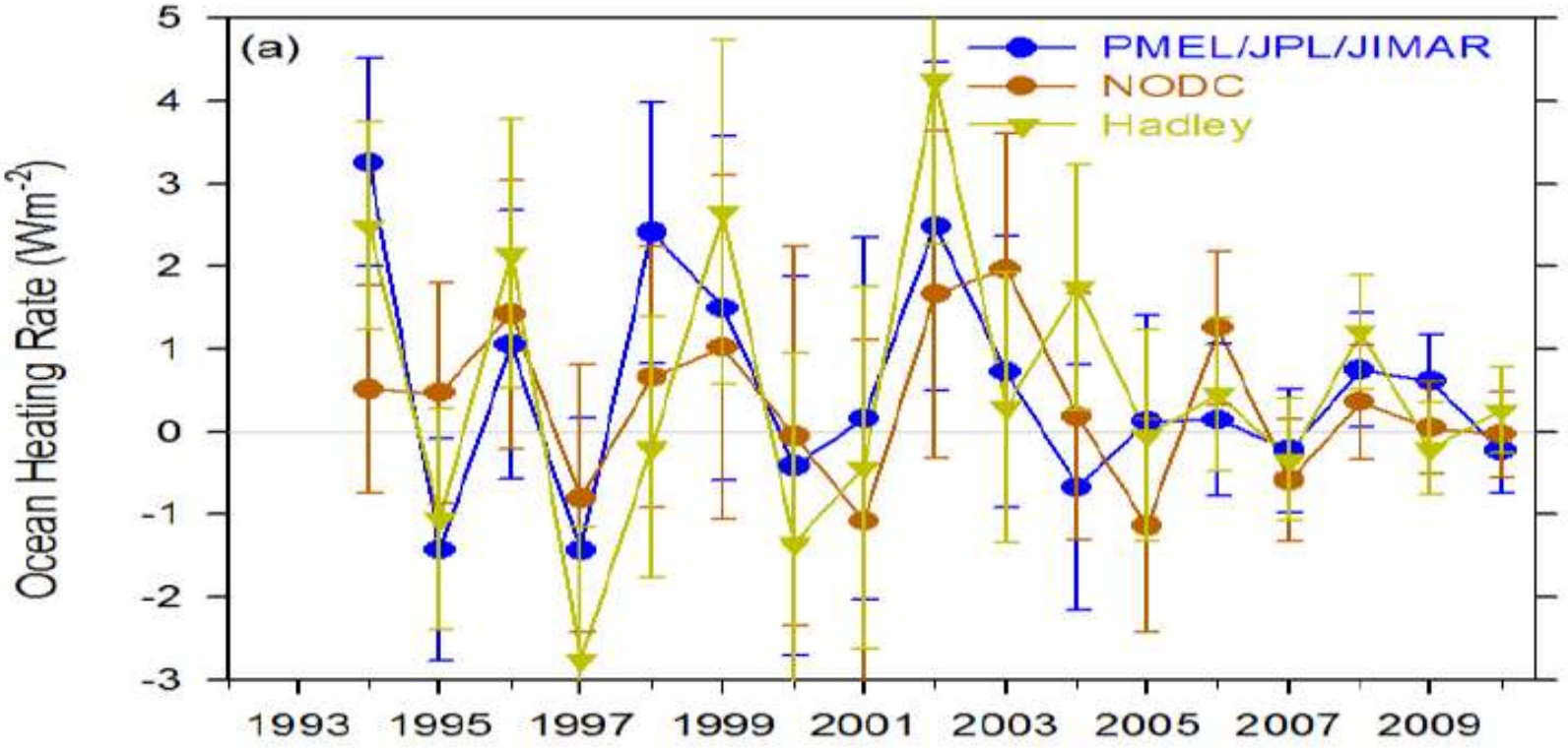
Lyman & Johnson (2008) J Clim

http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2259.1

- Use weighted integral to account for changes in data coverage
- Ensures transition to ARGO era does not introduce spurious variability
- Integrate ocean heat content trend over time and divide by Earth's surface area → Wm^{-2}

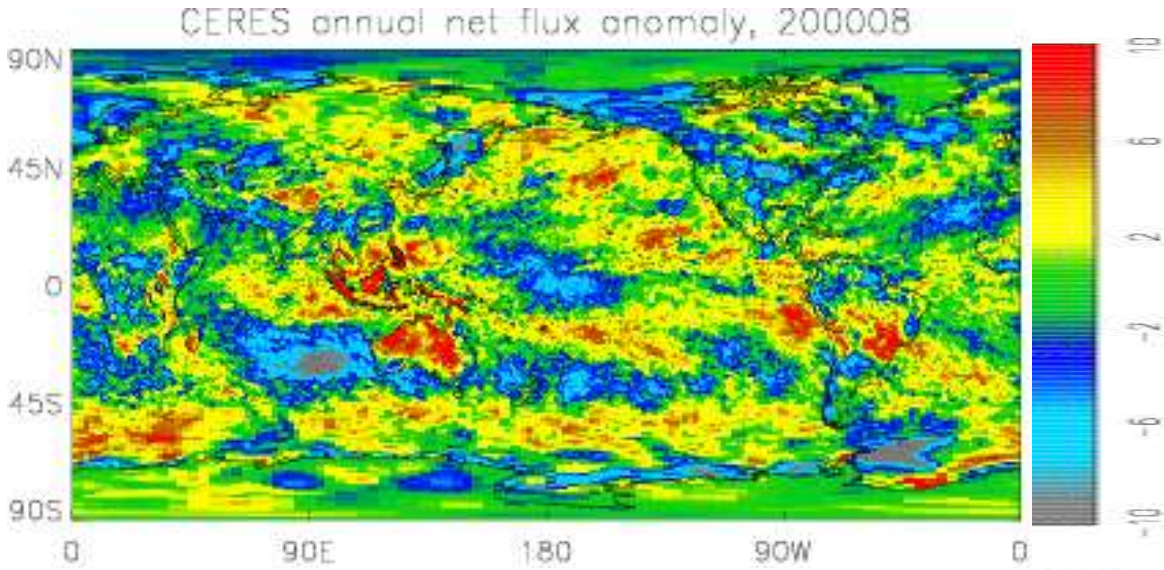
Ocean heat content data

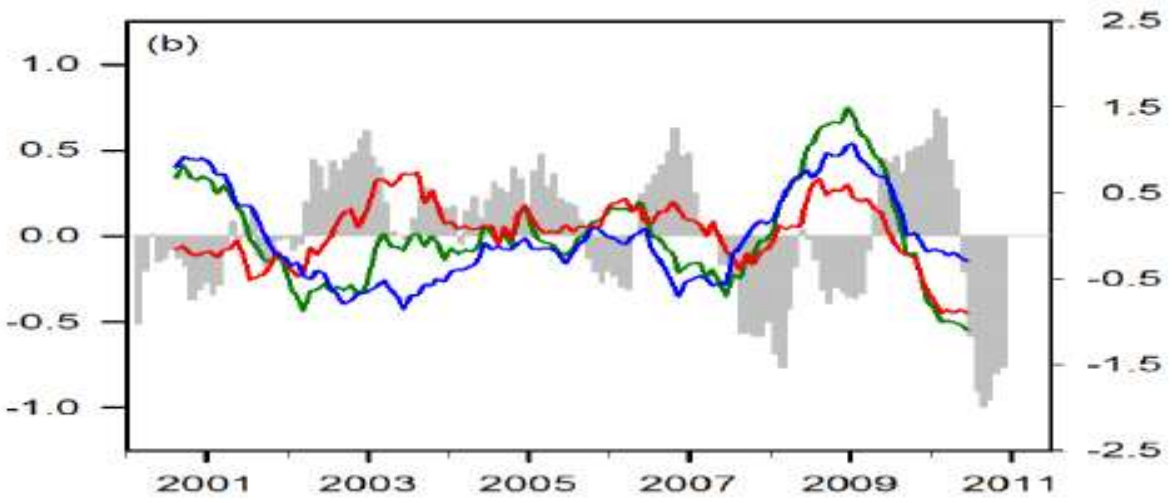
- Accounting for considerable sampling/structural uncertainty we find no evidence for a robust decline in ocean heating rate since 2005



CERES radiation budget data

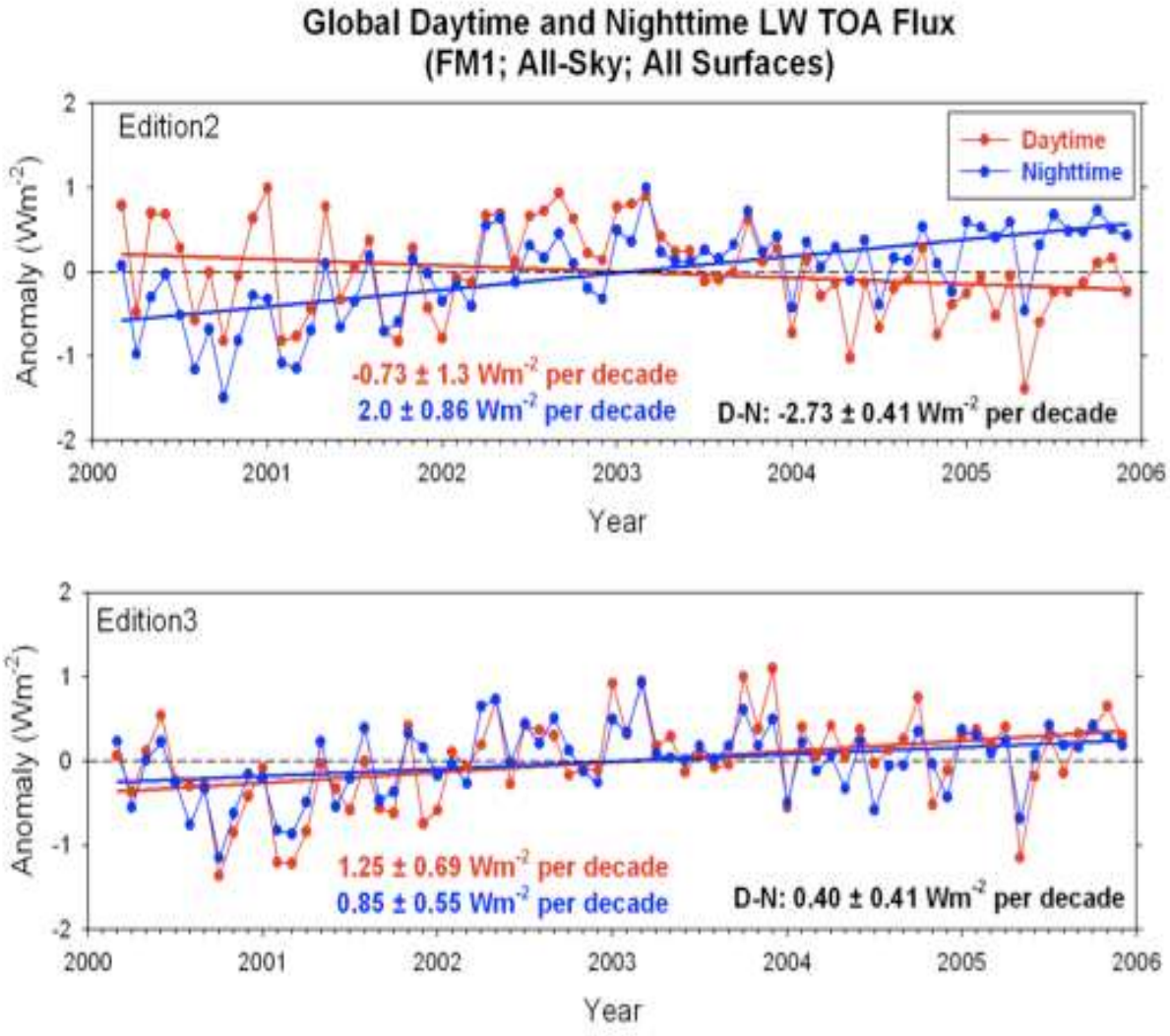
- Total, shortwave and window broadband radiance
- Converted to irradiance using scene-specific angular dependence models
- On polar-orbiting Terra and Aqua satellites
- Geostationary data to improve diurnal cycle model





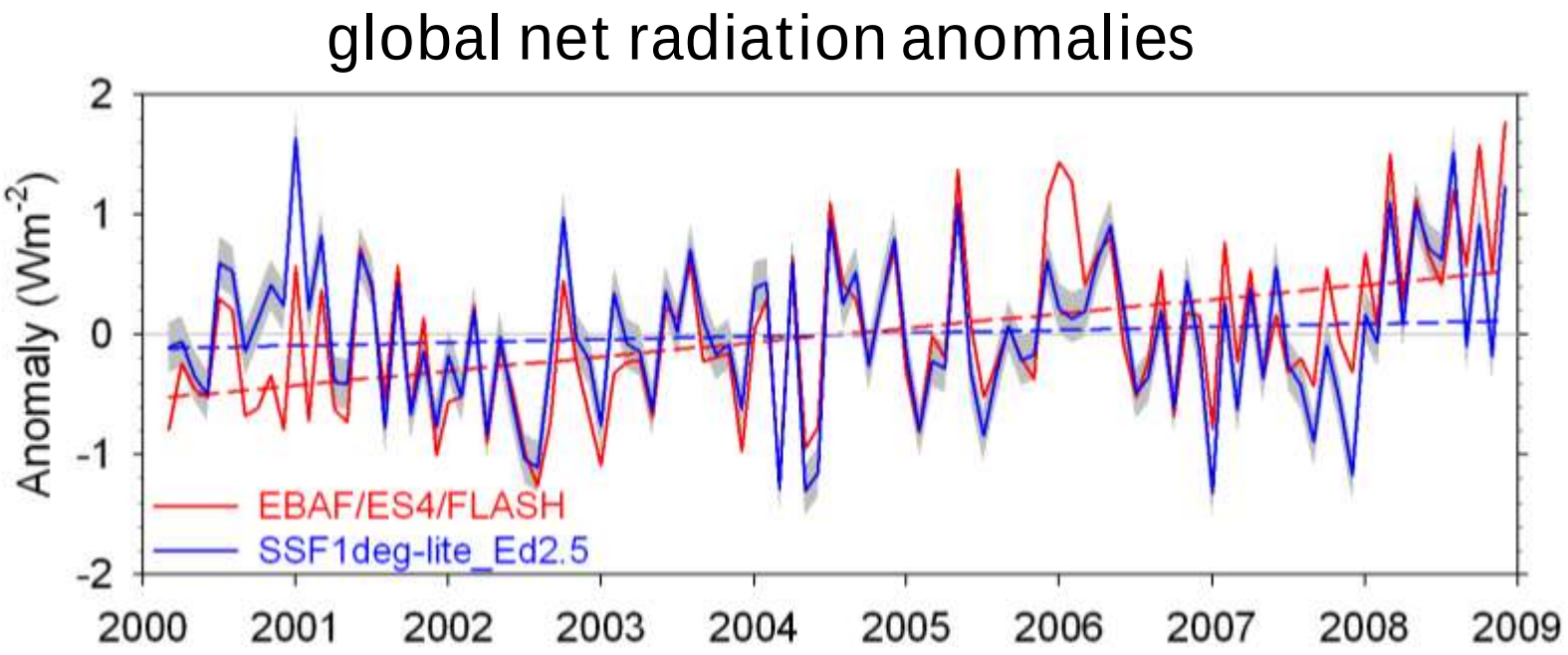
Corrections to CERES →Edition 3.

- Correction for degradation of shortwave filter
- Correction also improves physical consistency of trends in daytime longwave



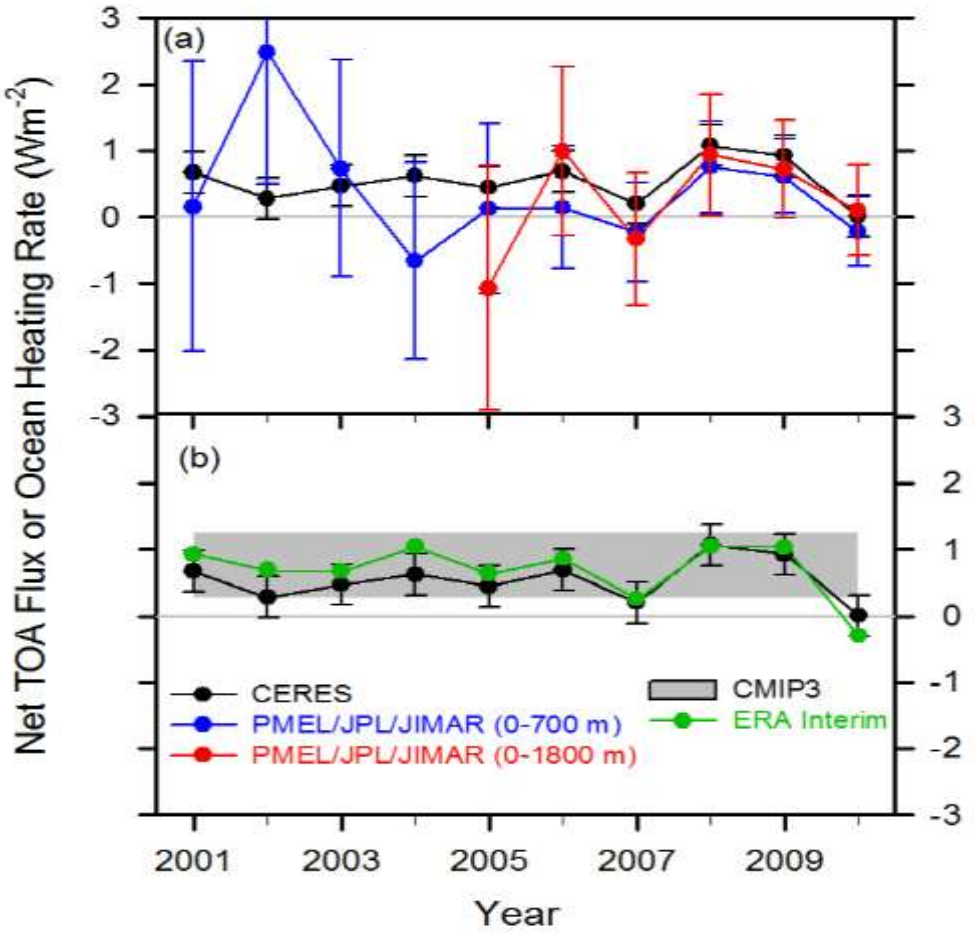
Trends in net radiation

- Errors in satellite sensors and inappropriate use of satellite products explain much of large rise in net radiative flux shown by Trenberth and Fasullo (2010)



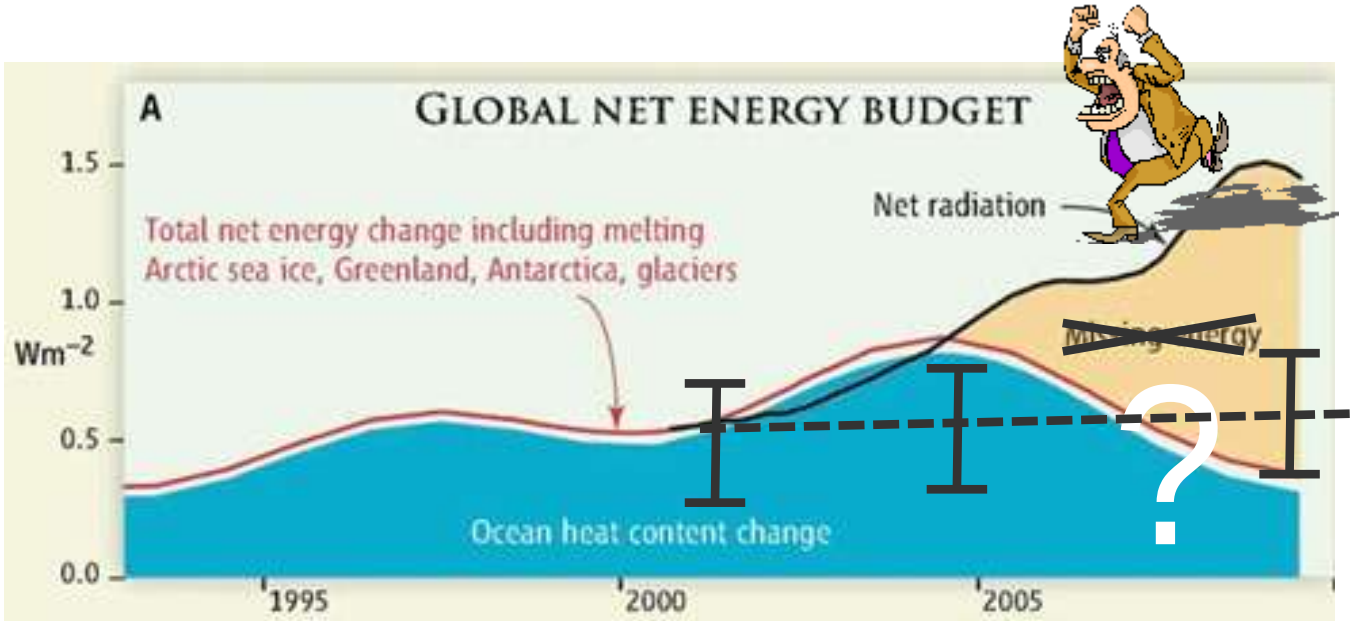
Combining Earth Radiation Budget and Ocean Heat Content data

- Tie 10-year CERES record to ARGO-estimated heating rate 2006-2010
- Variability relating to ENSO reproduced by CERES, ARGO and ERA Interim since 2005
- Estimate of decade long net energy imbalance of 0.54 ± 0.43 Wm^{-2}.
- Where has energy gone? Presumably heating up sub-surface ocean.



Missing energy?

- Older ocean heat content analysis combined with inappropriate net radiation products appear to explain "missing energy" in the climate system (Trenberth and Fasullo, 2010, Science)



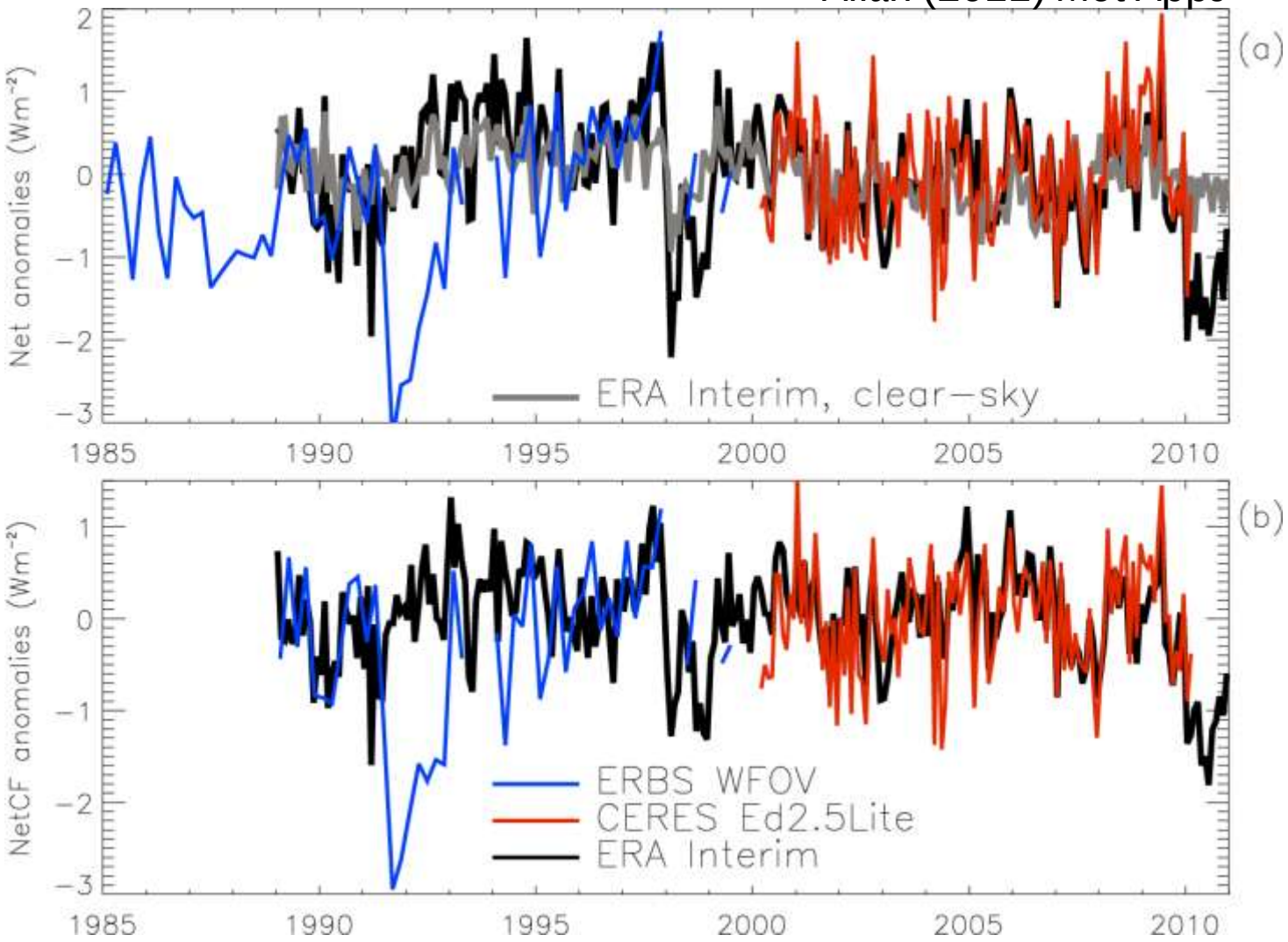
Estimates of net radiation from satellite data and total net energy estimated primarily from ocean heat content data, do not appear to correspond (Trenberth & Fasullo 2010)

Net Radiation since 1985

Allan (2011) Met Apps

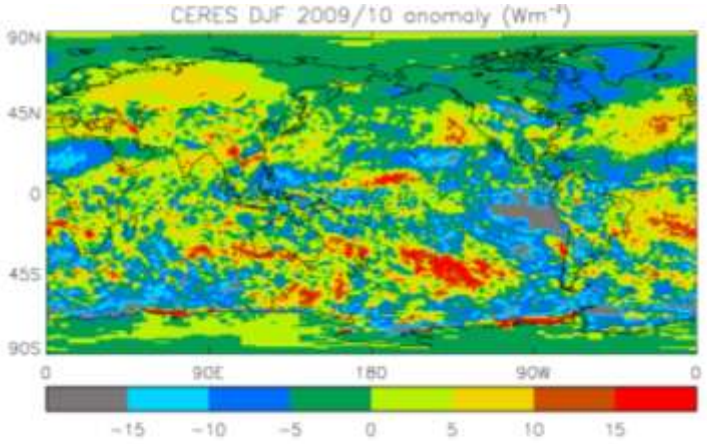
60S-60N Net radiation

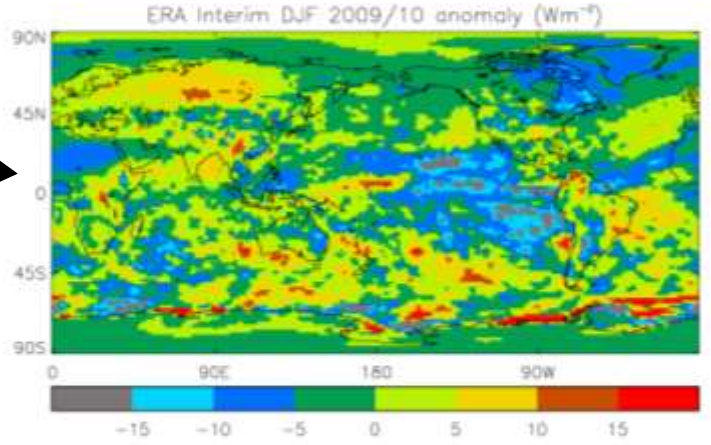
Estimated cloud radiative effect

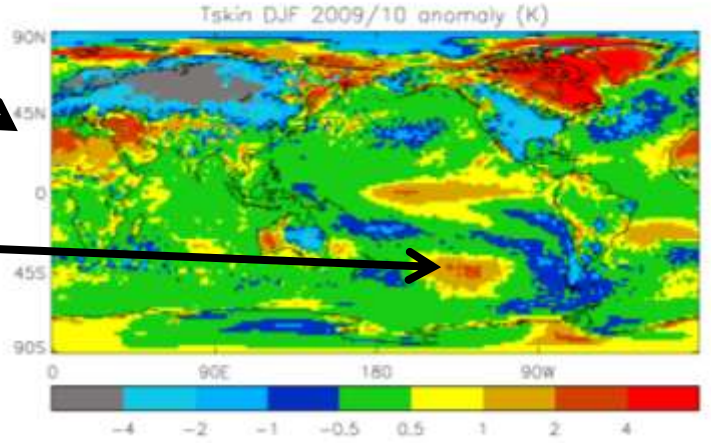


Spatial signatures

- DJF 2009/10 – net radiation anomalies:
  - CERES
  - ERA Interim
- El Niño and cold Eurasia/USA, warm Canada/Greenland
- Energy transports by ocean and land crucial
- Heating induced warming at 45°S 120°W







Links to ocean circulation?

- Wind-driven changes in sea surface height (Merrifield 2011)

http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI3932.1

- Has a stronger Walker circulation enhanced ocean mixing and precipitation changes 1990-2000s?

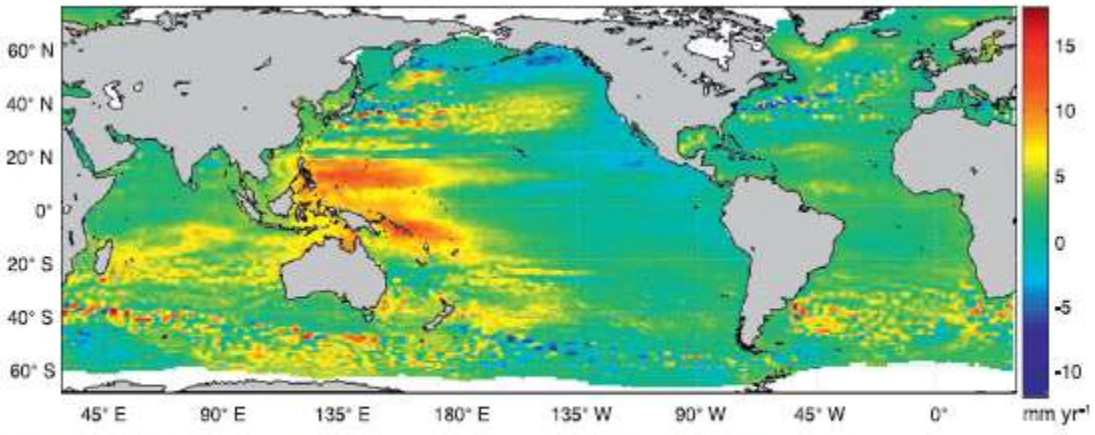
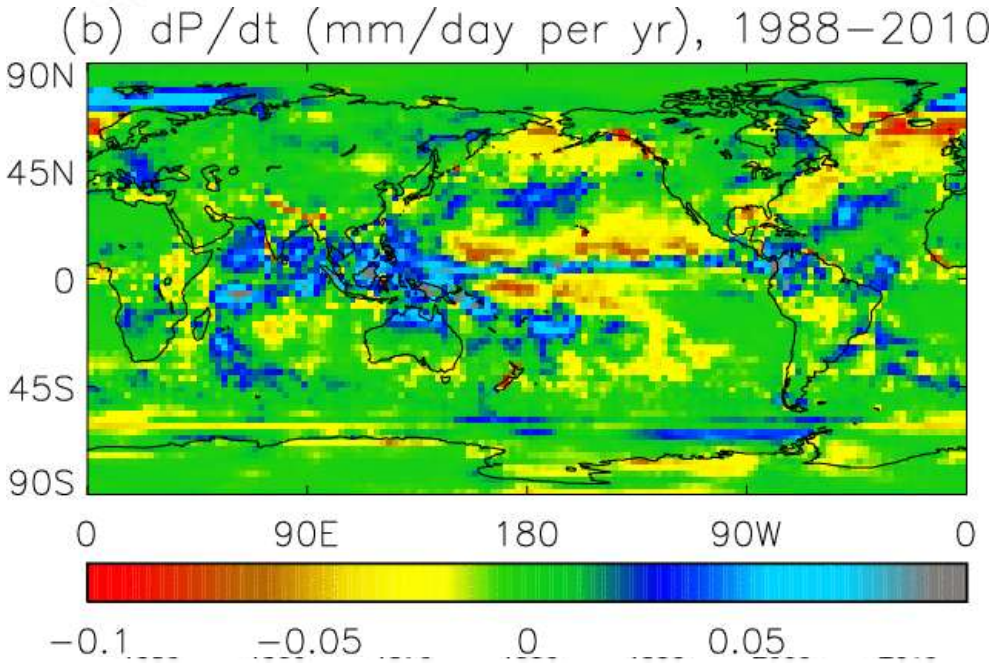


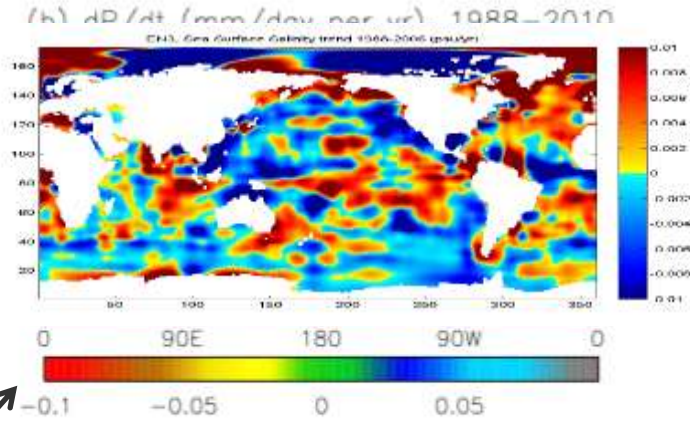
FIG. 1. The linear trend in satellite altimetry SSH for the period 1993–2009 based on the Aviso multimission altimeter data product.



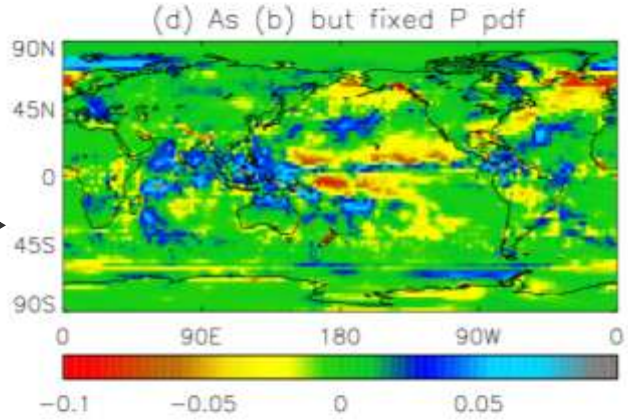
Precipitation trends

And salinity trends?

- GPCP v2.2 precipitation

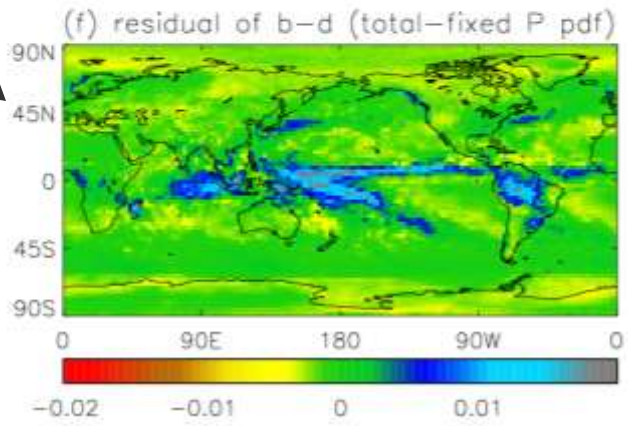


total trend (top)



dynamical changes only (middle)
estimated using fixed precip pdf

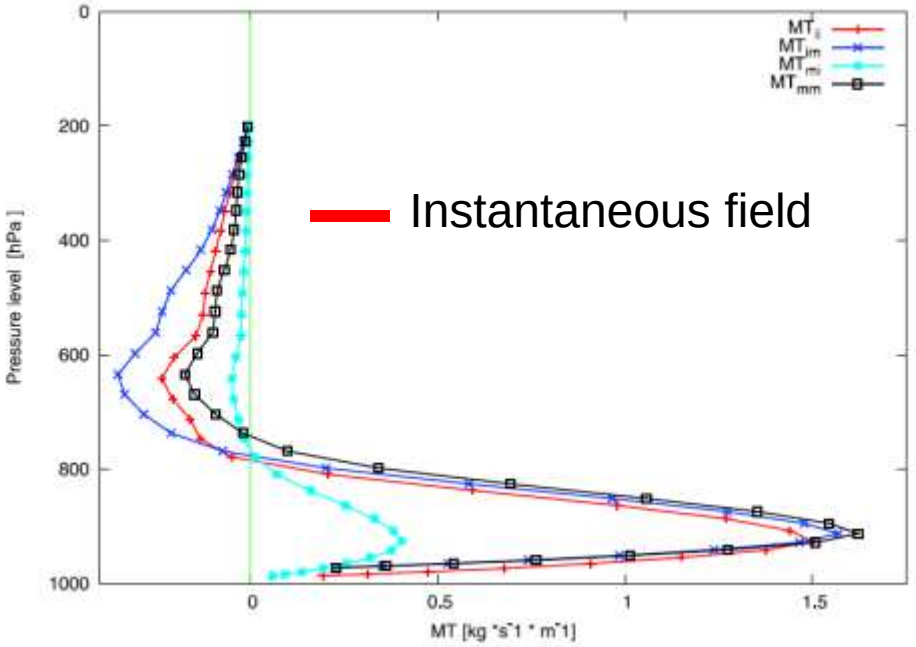
Residual trend (combination of thermodynamic change and observing system error) (bottom)



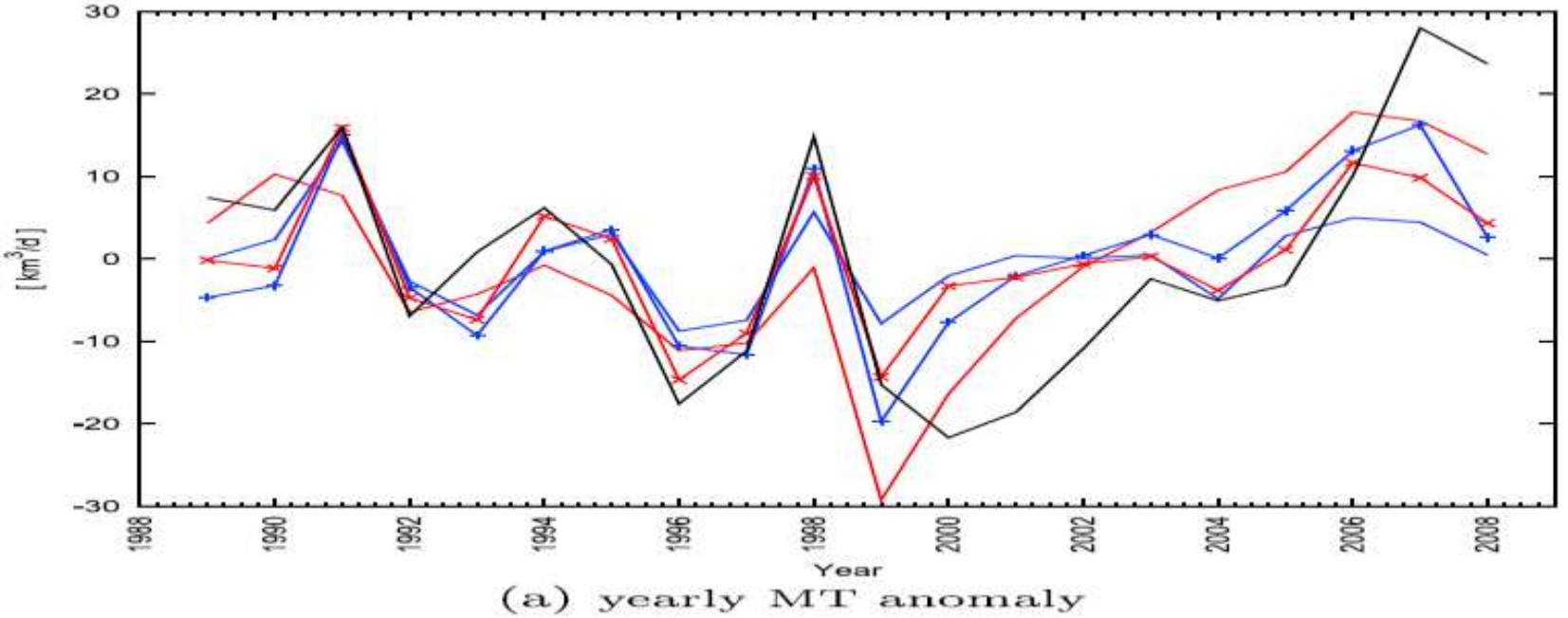
Note smaller magnitude

Moisture transports from ERA Interim

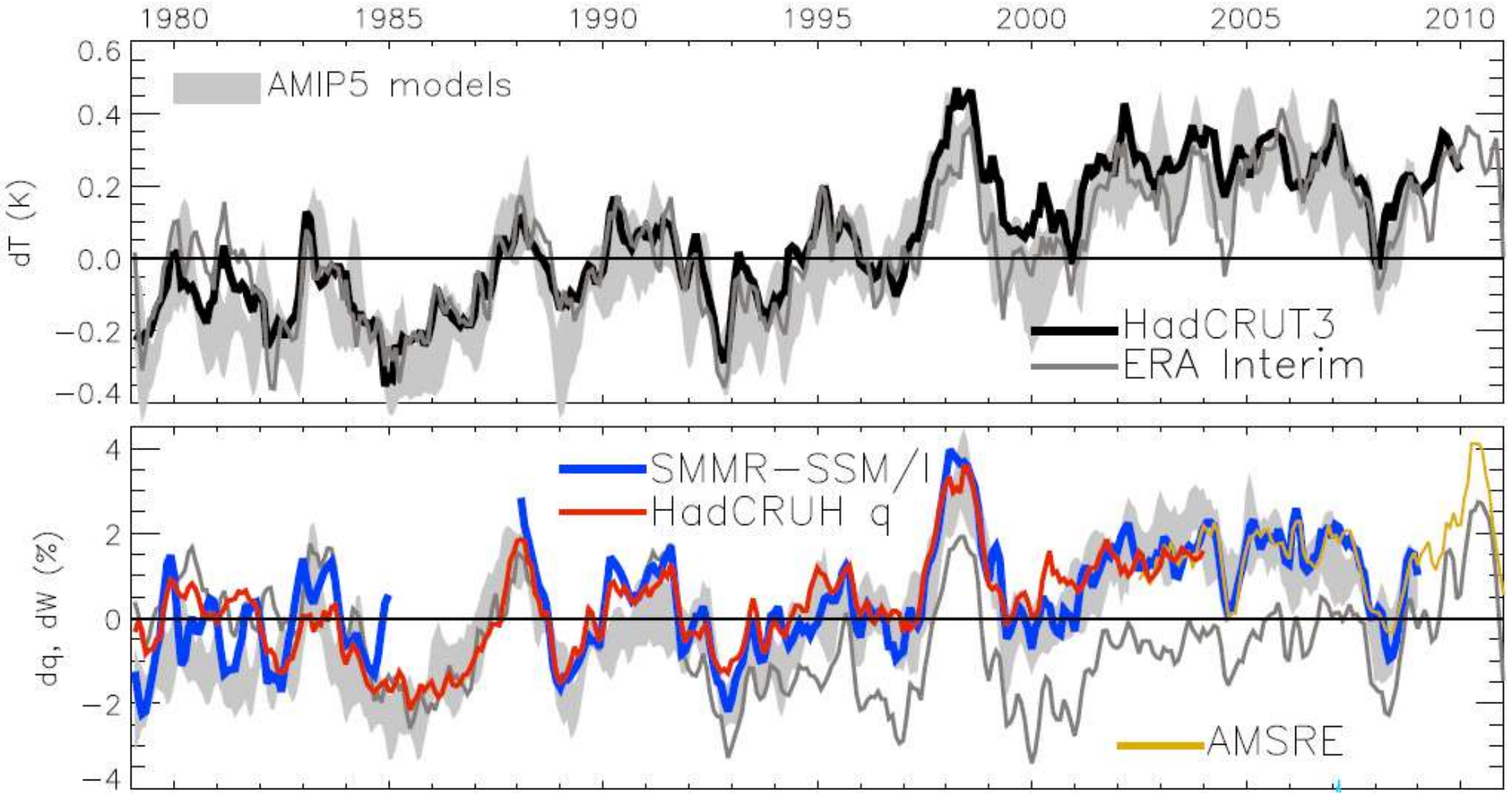
- Moisture transport into tropical ascent region
- Significant mid-level outflow



Zahn and Allan (2011) JGR; see also Sohn and Park (2010) JGR



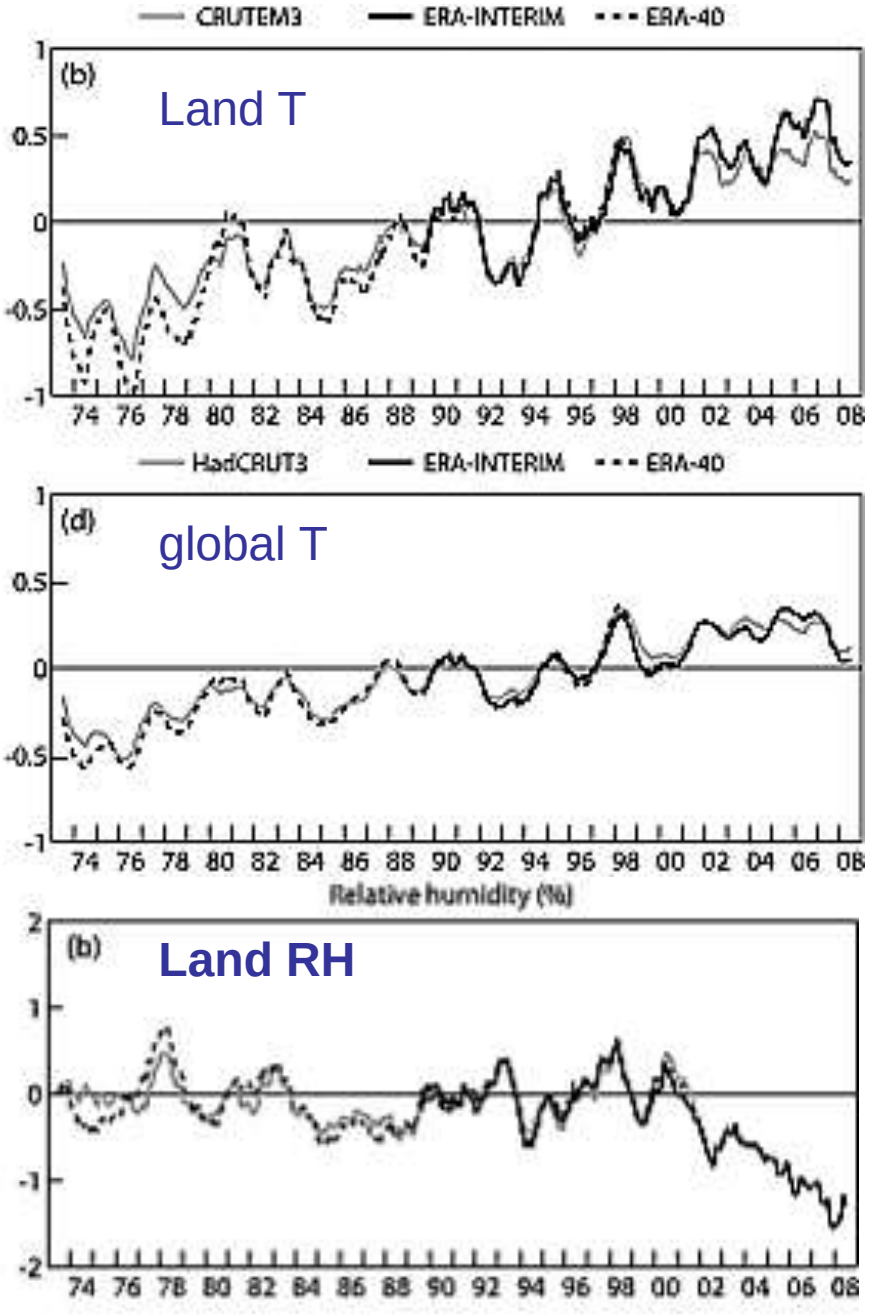
Some Implications of warming hiatus



Updated from O'Gorman et al. (2012) submitted; see also John et al. (2009) GRL

Declining RH over land?

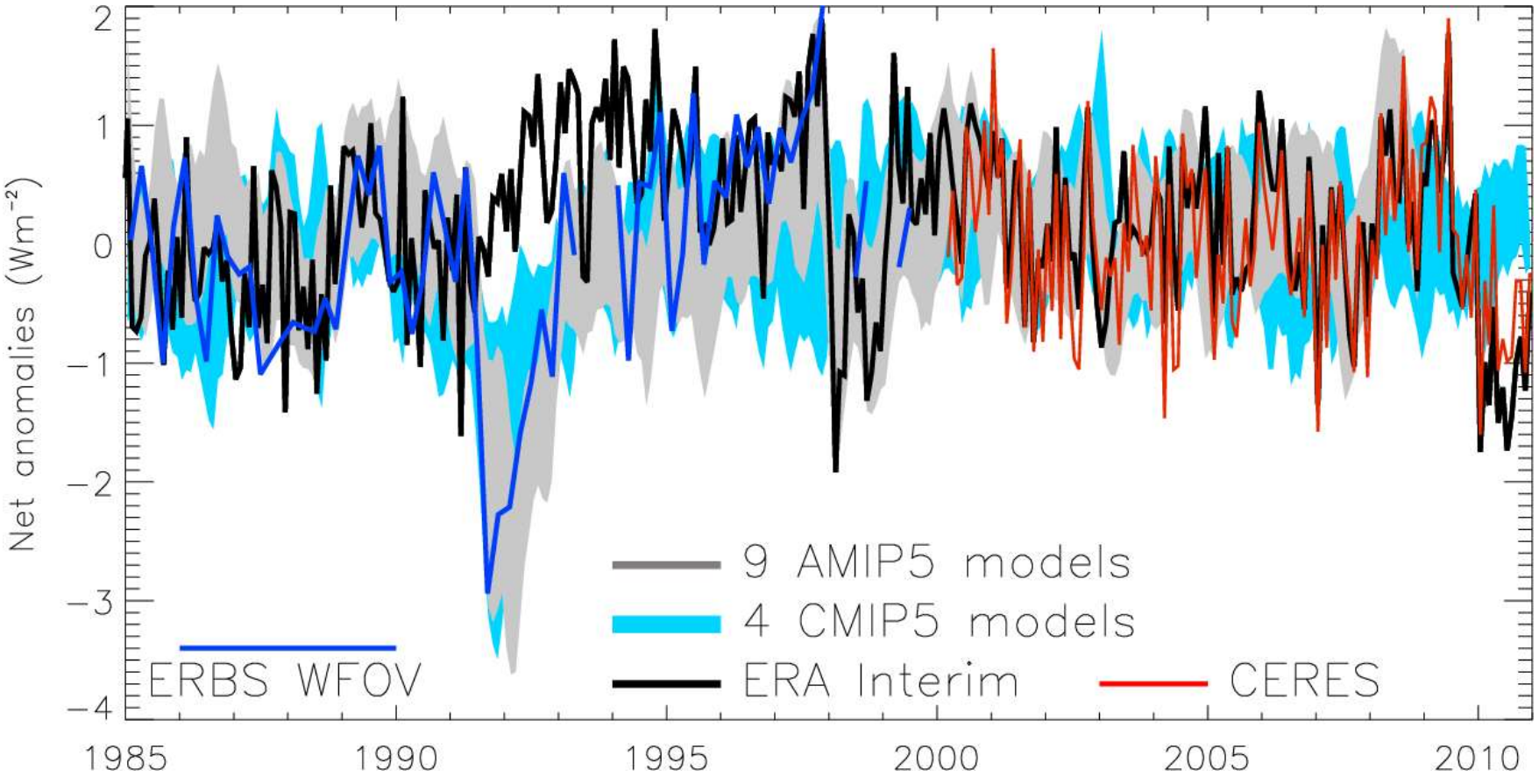
- Stalling of ocean temperatures in 2000s
- Continued warming of land
- Reduced relative humidity over land?



Simmons et al. (2010) JGR

Future work

- Assess/evaluate variability in observed and simulated net radiation since 1985



Conclusions

- Surface warming in 2000s is small
  - HadCRUT3 underestimates Arctic warming
  - Ocean temperatures have certainly stalled
- Heating of Earth continues (~0.5 Wm^{-2})
  - Negative radiative forcing from aerosols does not appear to strongly contribute
- The "missing" energy is probably being mixed below the ocean surface
  - Strengthening of Walker circulation? Forced/unforced?
  - Implications for drying of land and ocean rainfall