# Earth's energy imbalance since 1960 in observations and CMIP5 models

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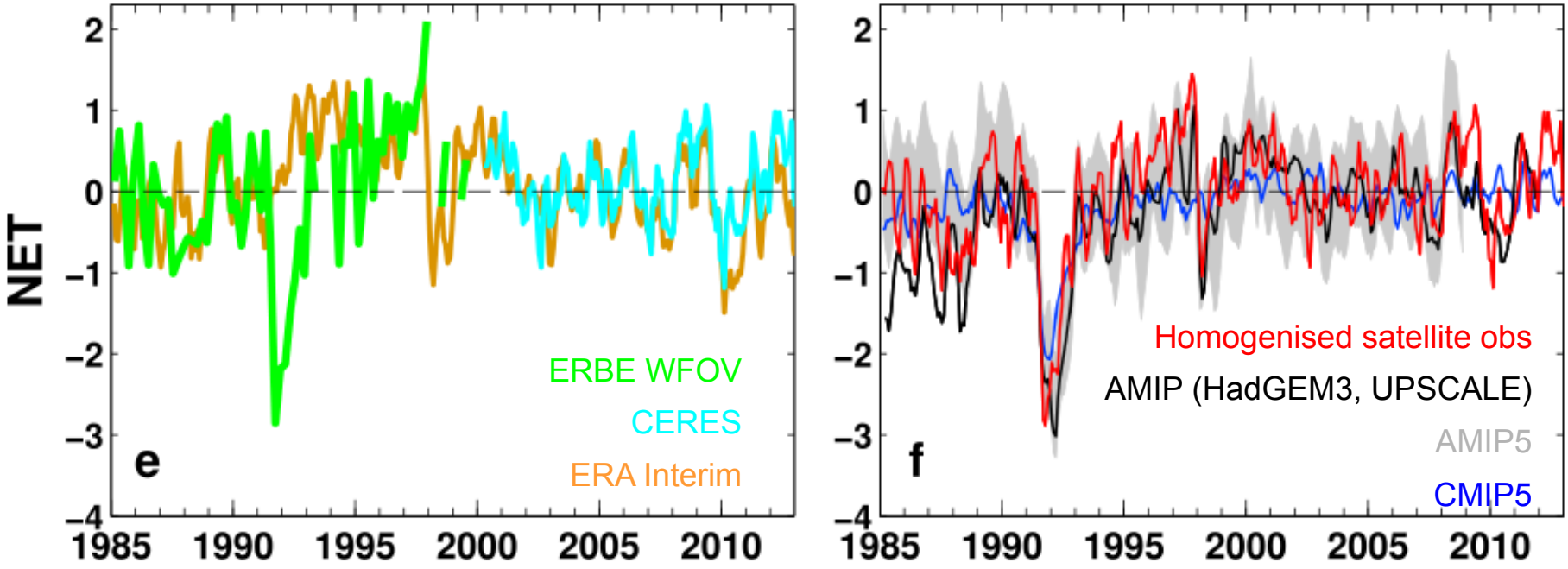
# Satellite observations of TOA flux from 1985

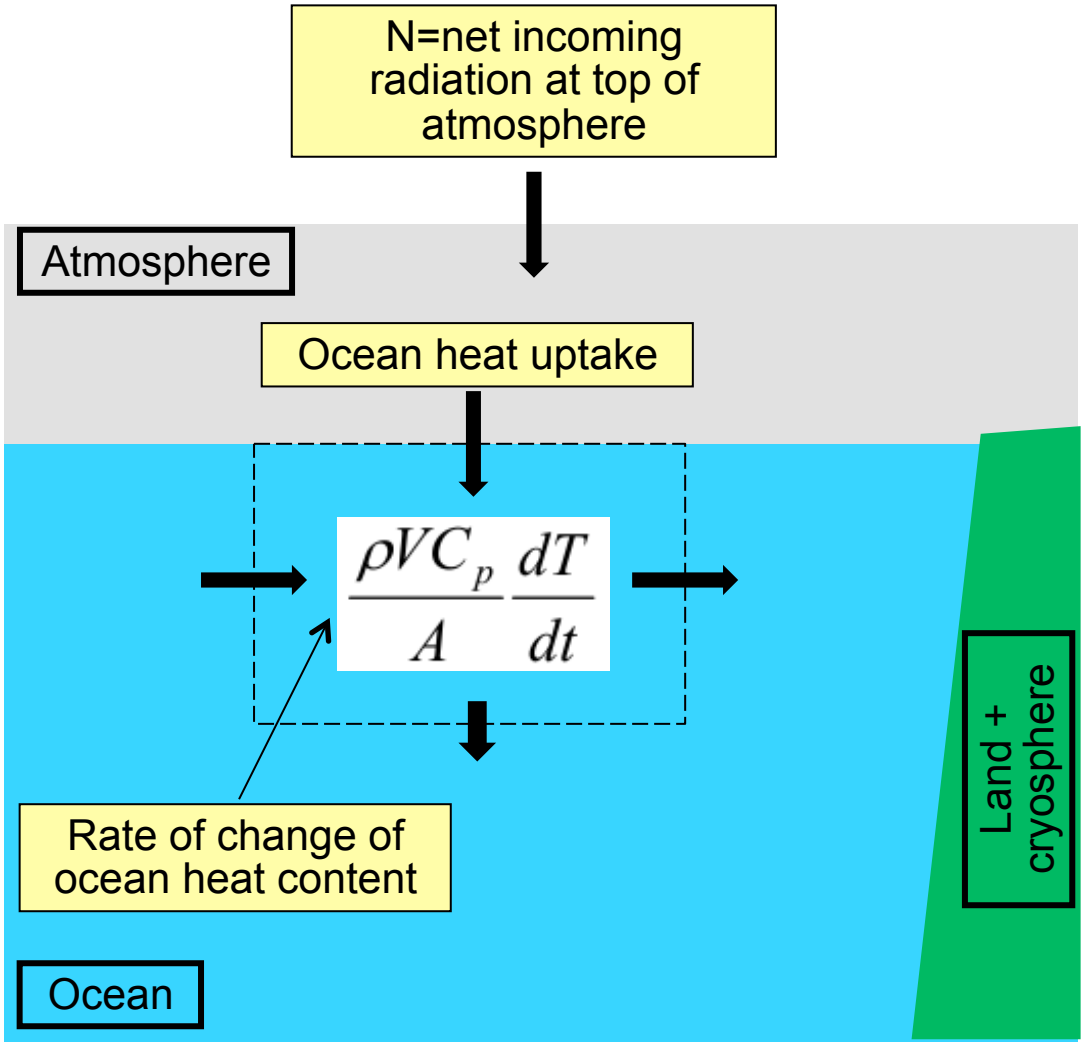
Satellite data

Homogenised satellite data and model simulations




- Monthly anomalies wrt 2001-2005, net incoming TOA radiation
- Homogenised satellite time series created using ERA Interim and UPSCALE AMIP simulations to fill missing data and bridge gap between ERBE-WFOV and CERES satellites
- Good agreement (r~0.6) with AMIP model simulations
- BUT large uncertainties (~4 $Wm^{-2}$) in absolute values → need to anchor using observed changes in ocean heat content
- Only covers period since 1985

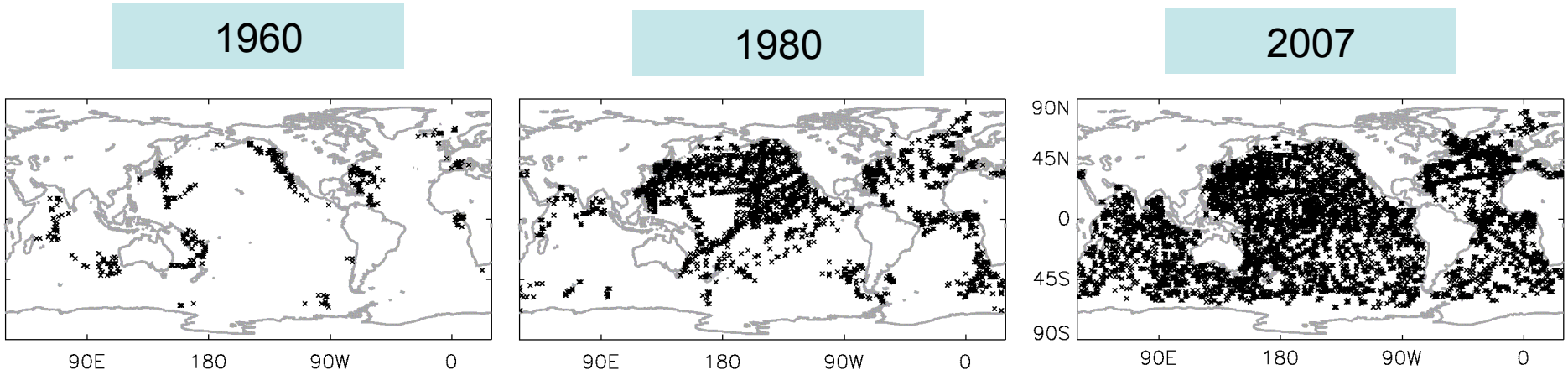
Allan et al 2014




- Compute rate of change of ocean heat content $H_t$
- $H_t = (\rho V C_p/A)\, dT/dt$ $(Wm^{-2})$
- Compute temperature gradients (dT/dt) using linear regression through 5 years of T
- Compare with 5 year mean N

- Global average $N \approx H_t$
- Also look at gradients $N_t = H_{tt}$
  - ➢ Overcomes uncertainty in absolute N from satellite observations

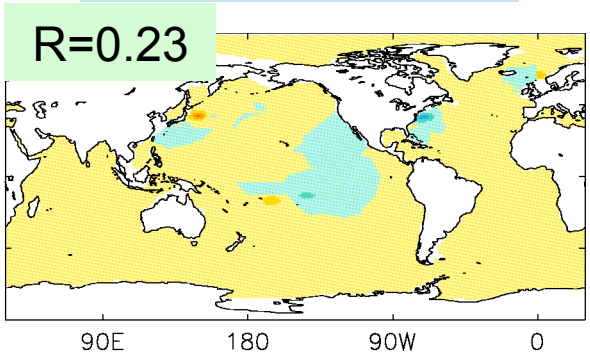
# Sub-surface ocean observations



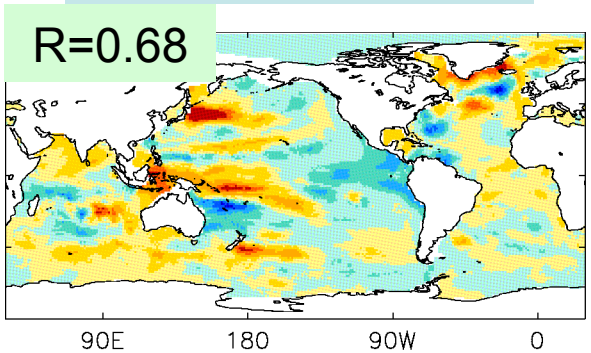

- Reasonable observations of upper 2000m from Argo since about 2005
- Far fewer sub-surface ocean observations in the past – do they contain any useful information?

# Reconstructed model temperature at 300m from Jan 1953 obs locations

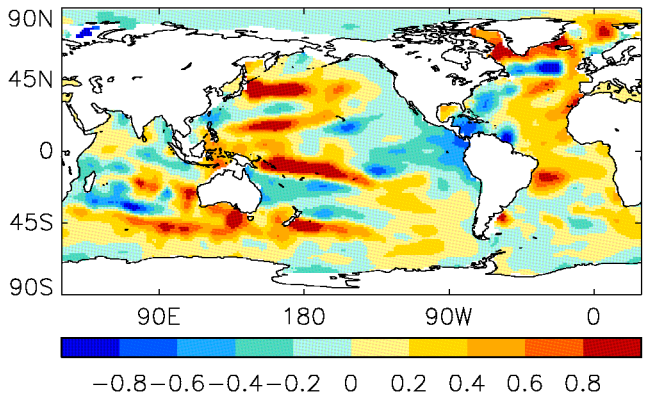
Parameterised covariances



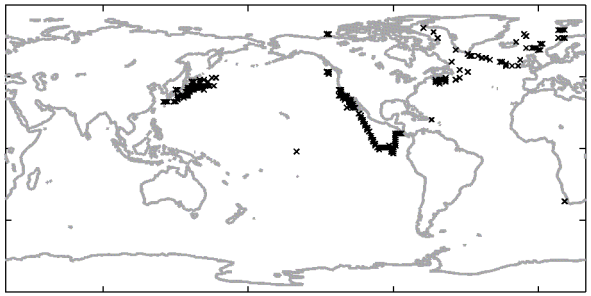

Actual covariances




Truth




Observations: Jan 1953



If covariances are known, accurate re-analyses of historical sub-surface temperature and salinity are possible

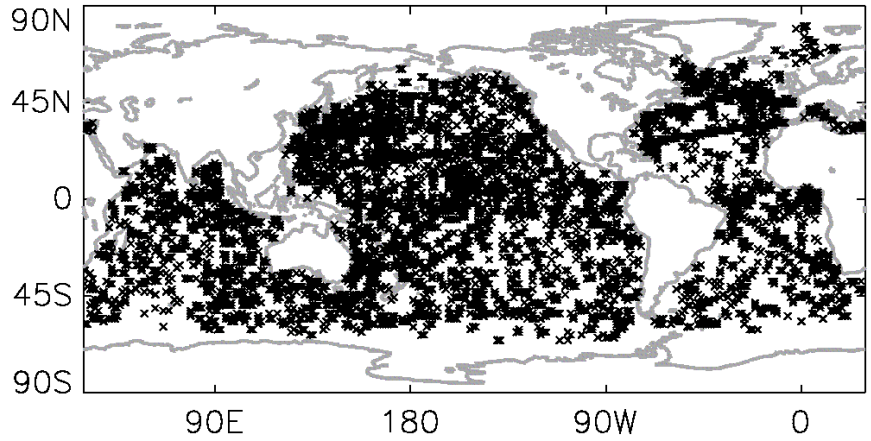


Smith and Murphy 2007

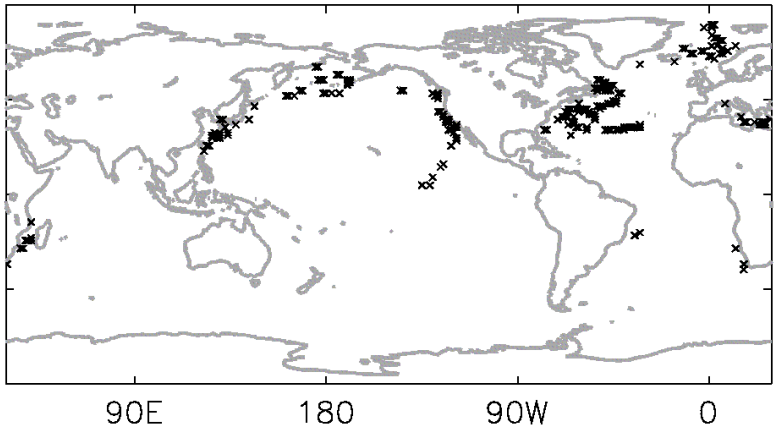
# Met Office Statistical Ocean ReAnalysis (MOSORA)

## Temperature at 300m : June 2007 from 1960 obs

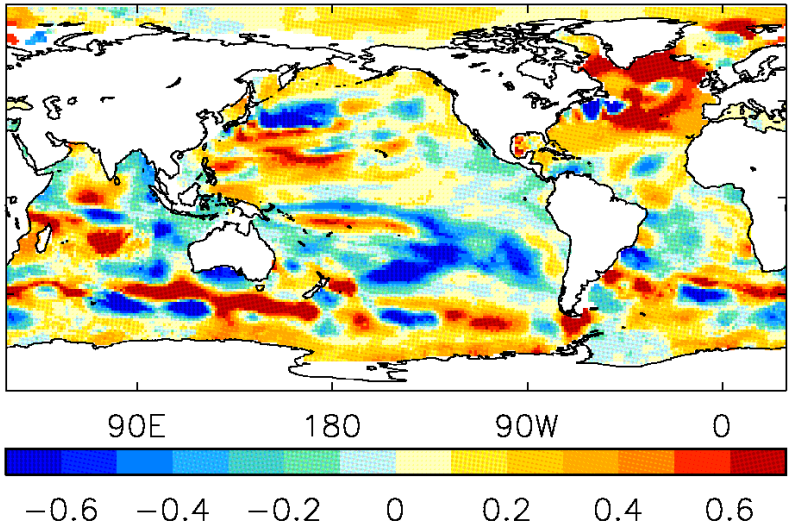
June 2007 obs



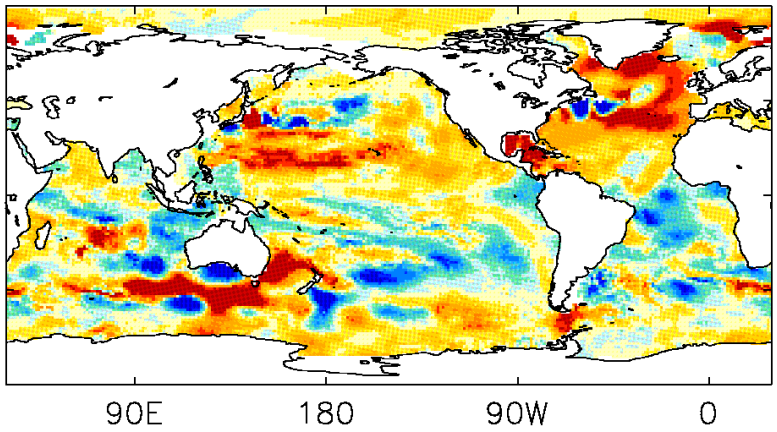

June 1960 obs




Analysis using all obs



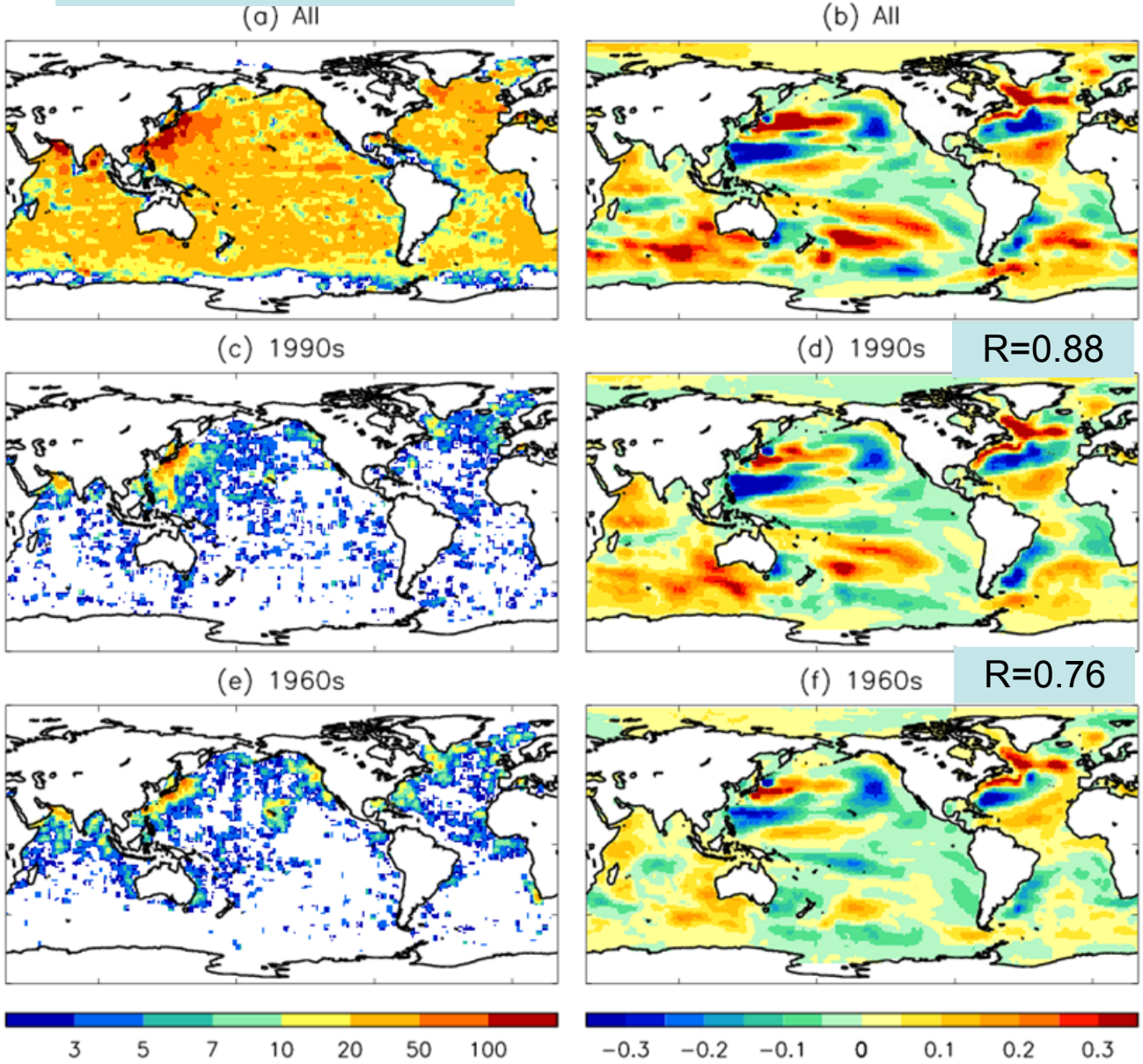

Analysis using sub-sampled (1960) obs



# Assessment of Met Office ocean analysis

Number of observations at 1000m

Heat content trend ($H_t$, $Wm^{-2}$)



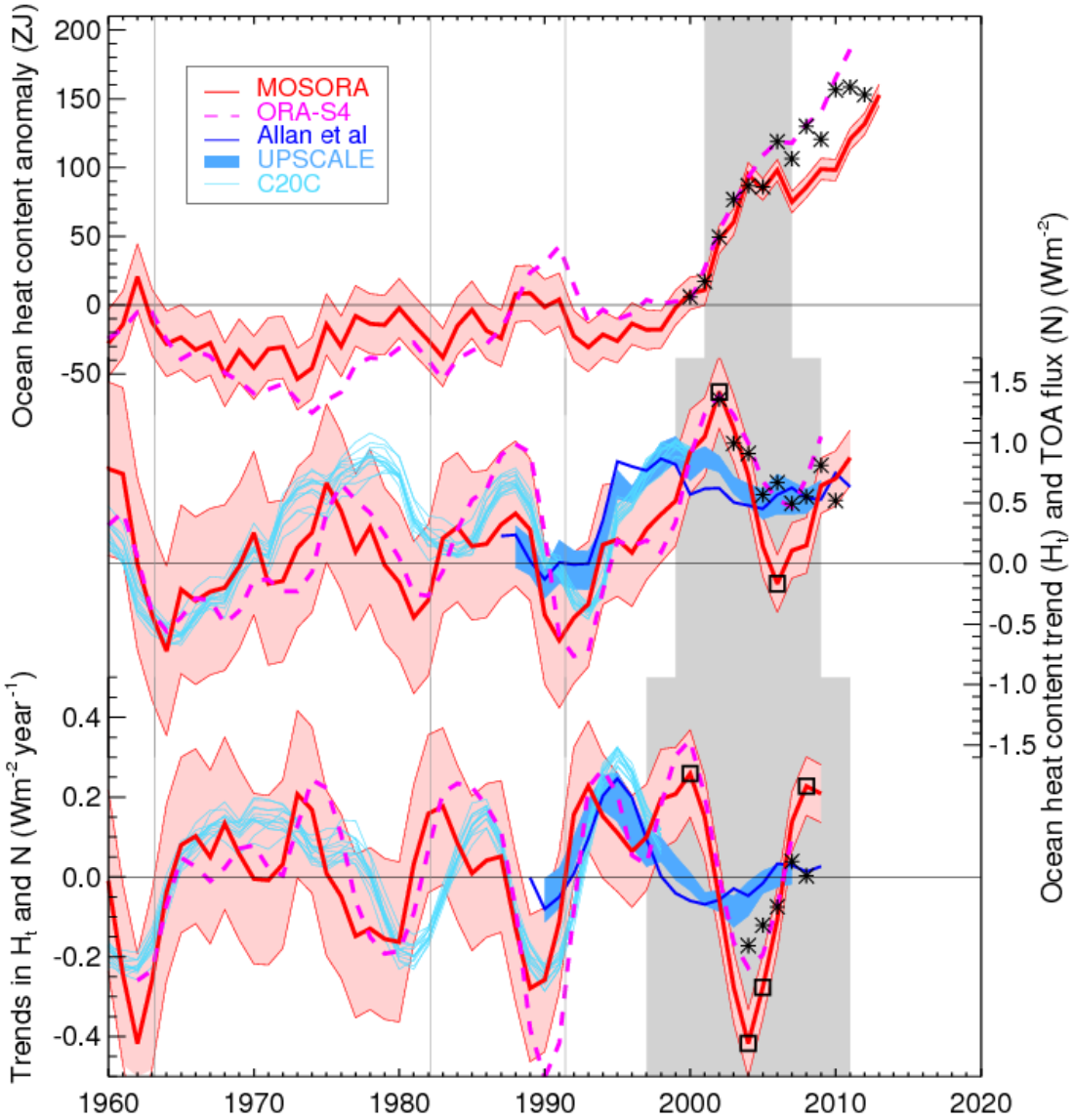

## Data withholding experiments

- **Reconstruct Argo period 2008-12 using sub-sampled observations typical of historical periods**
- **Uncertainties in annual mean global ocean heat content range from 28 ZJ using 1950-56 obs to 8 ZJ using 2005-11 obs**
- **Uncertainties in global $H_t$ range from 0.7 $Wm^{-2}$ using 1950-56 obs to 0.2 $Wm^{-2}$ using 2005-11 obs**
- **Possible instrument errors and regions not adequately sampled are not included**

Smith et al 2015

# Observed energy budget

- Good agreement (r=0.8) between Met Office (MOSORA) and ECMWF (ORA-S4) $H_t$
- Reasonable agreement (r=0.6) between $H_t$ and N from 1960 to 1999
- Also seen in gradients ($N_t$ vs $H_{tt}$)

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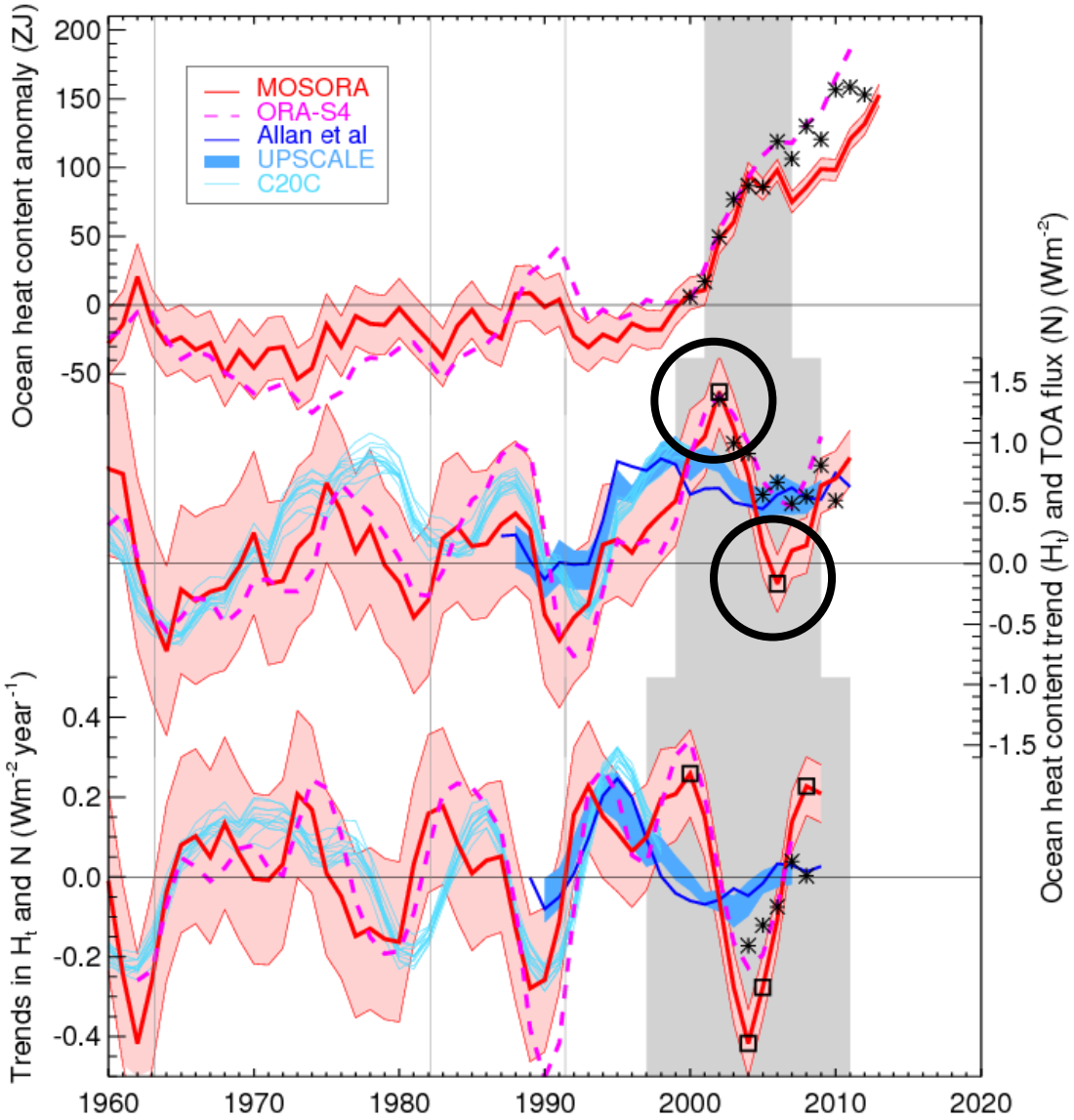
# Observed energy budget

- Maximum $H_t$ in 2002 is inconsistent with N from satellites and AMIP simulations
- Not supported by sea level obs (steady rise would require a dip in freshwater input to give a peak in thermosteric, but not seen)
- Also questioned by Cheng and Zhu, GRL, 2014
- Likely to be spurious!
- Not due to Argo (analysis without Argo also has spike, black asterisks)
- Ocean analyses between 2000 and 2007 (grey shading) may be unreliable

➢ Estimates of energy imbalance covering this period may need revising

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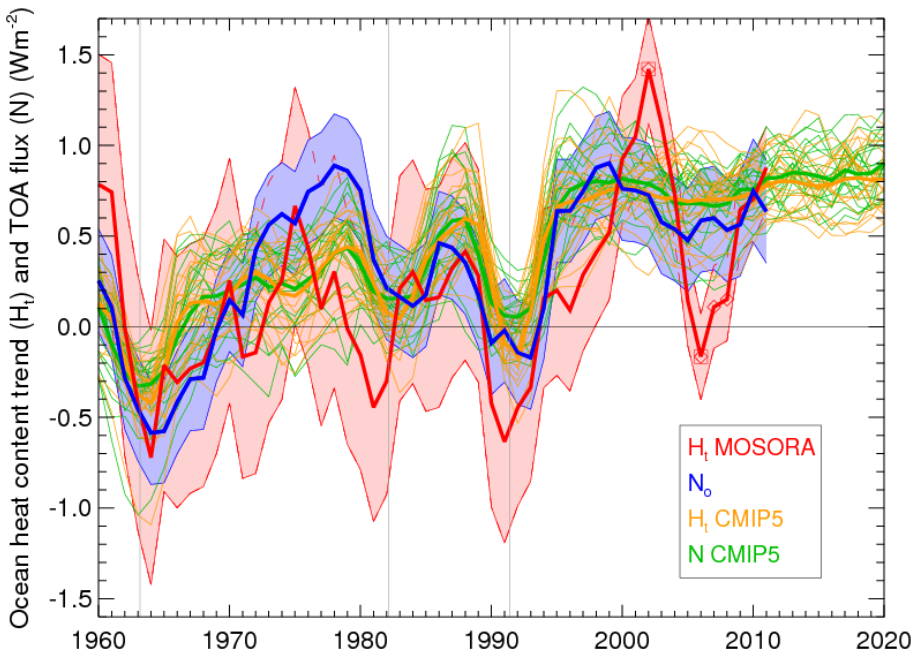
# Comparison with CMIP5 coupled models




- **Observation-based estimate $N_o$ created by averaging satellite and AMIP simulations**
- **Goes back to 1960**
- **Compare with CMIP5 coupled models**
  - **Need to remove CMIP5 control run values because of drifts**
- **Good agreement (r=0.82) with ensemble mean of CMIP5 coupled models**
- **Variations dominated by volcanic eruptions (Agung 1963, El Chichon 1982 and Pinatubo 1991)**

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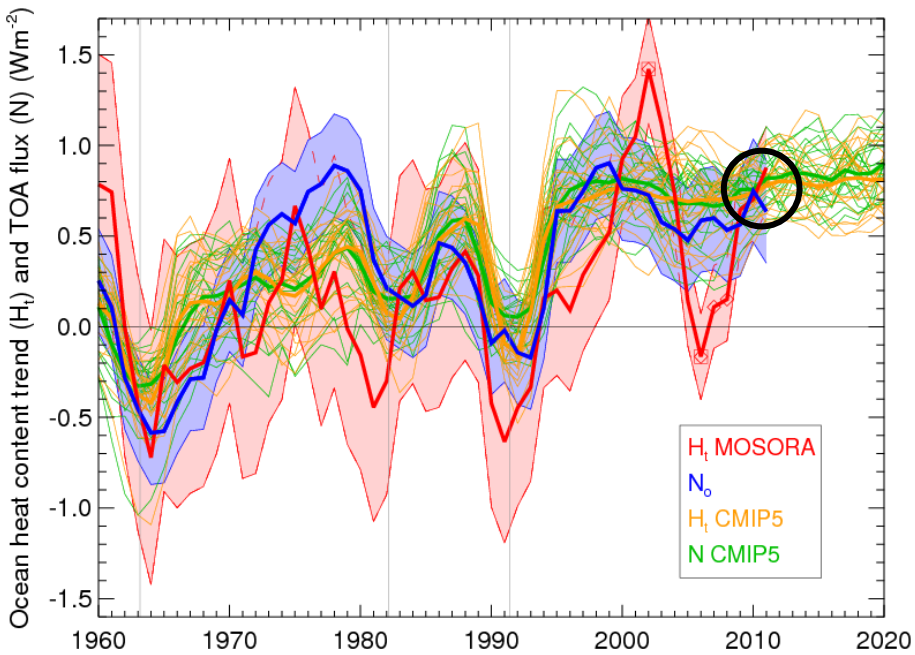
# Comparison with CMIP5 coupled models

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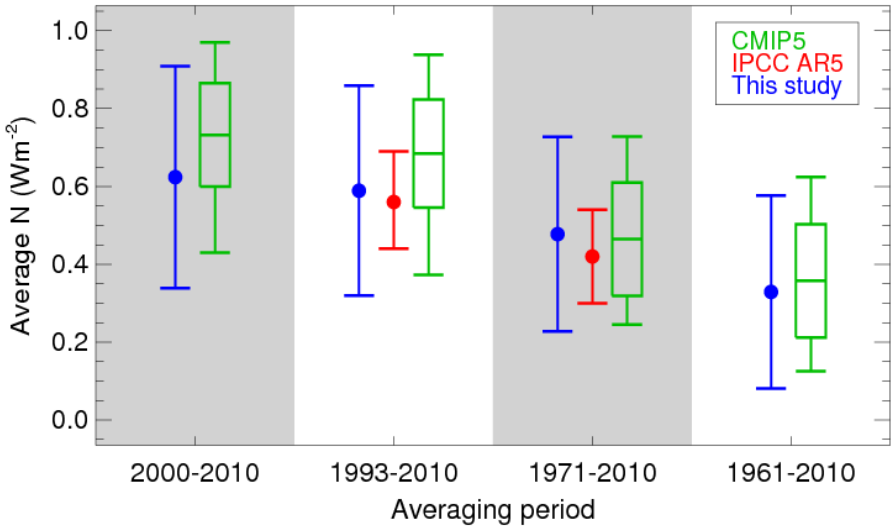


- Absolute values of N for different periods in reasonable agreement with CMIP5 and IPCC
- BUT large uncertainties, dominated by estimates of $H_t$ needed to anchor N – note disagreement in changes in N and U even in the most recent estimates

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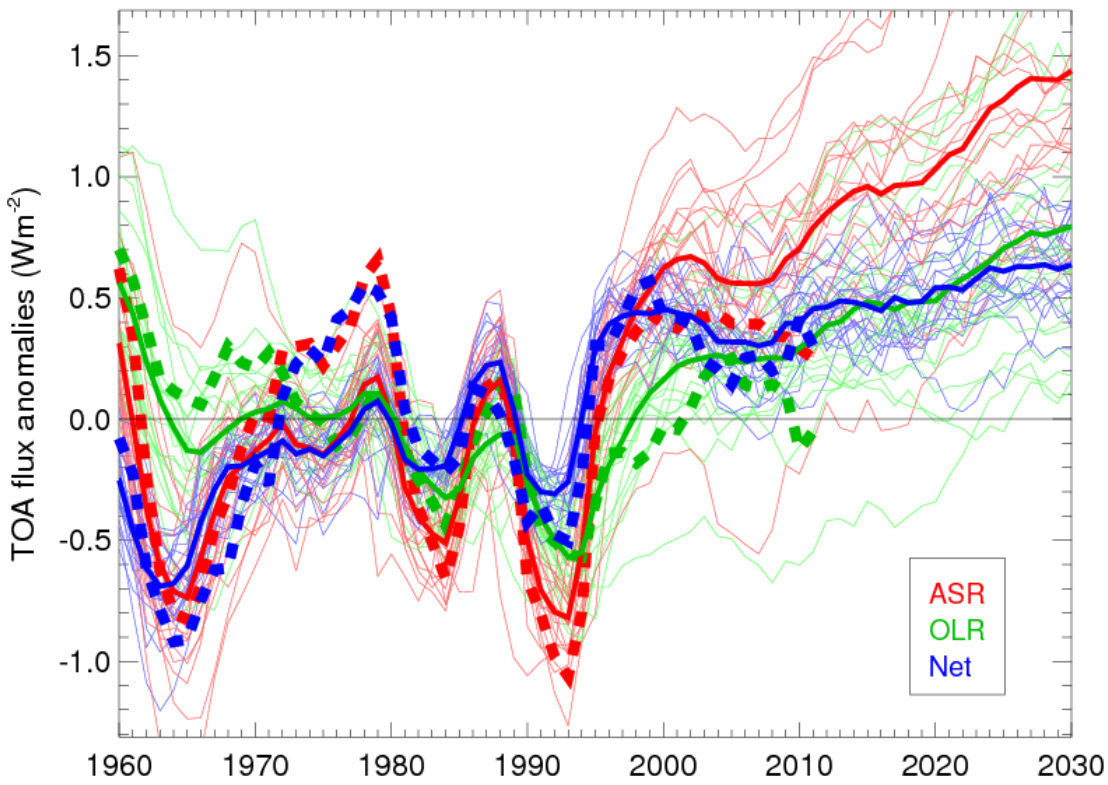
# Observation-based and model anomalies




- **Anomalies wrt 1960-2011 → reduces anchoring uncertainties**
- **Radiative components: absorbed shortwave (ASR, red), outgoing longwave (OLR, green)**
- **N = ASR - OLR**
- **Good agreement between models (solid) and obs (dashed) for ASR (red, r=0.87) and OLR (green, r=0.80)**
- **Models simulate response to volcanoes reasonably well (at least in ensemble mean)**

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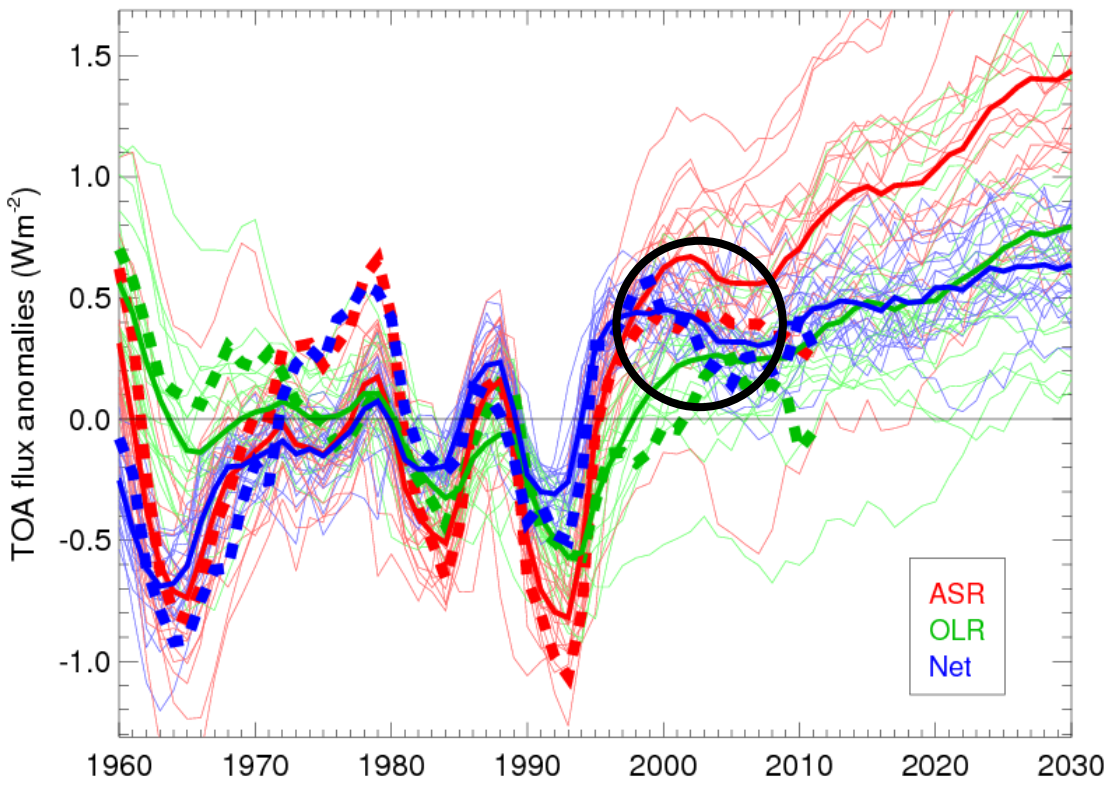
# Observation-based and model anomalies




- **Observation-based decline in N of 0.31±0.21 Wm$^{-2}$ between late 1990s and mid-2000s**
- **Spans different satellites – but also seen in AMIP simulations and ocean models forced by observed winds and fluxes**
- **Role in warming slowdown?**
- **Consistent with minor volcanoes, reduced solar activity**
- **But driven by increasing OLR rather than reduced ASR? – though ASR lower than models**
- **N may also change through internal variability**

➢ **Hence relative roles of external forcing and internal variability remain unclear**

➢ **Increased uptake of heat by the ocean might not be crucial for explaining the warming slowdown**

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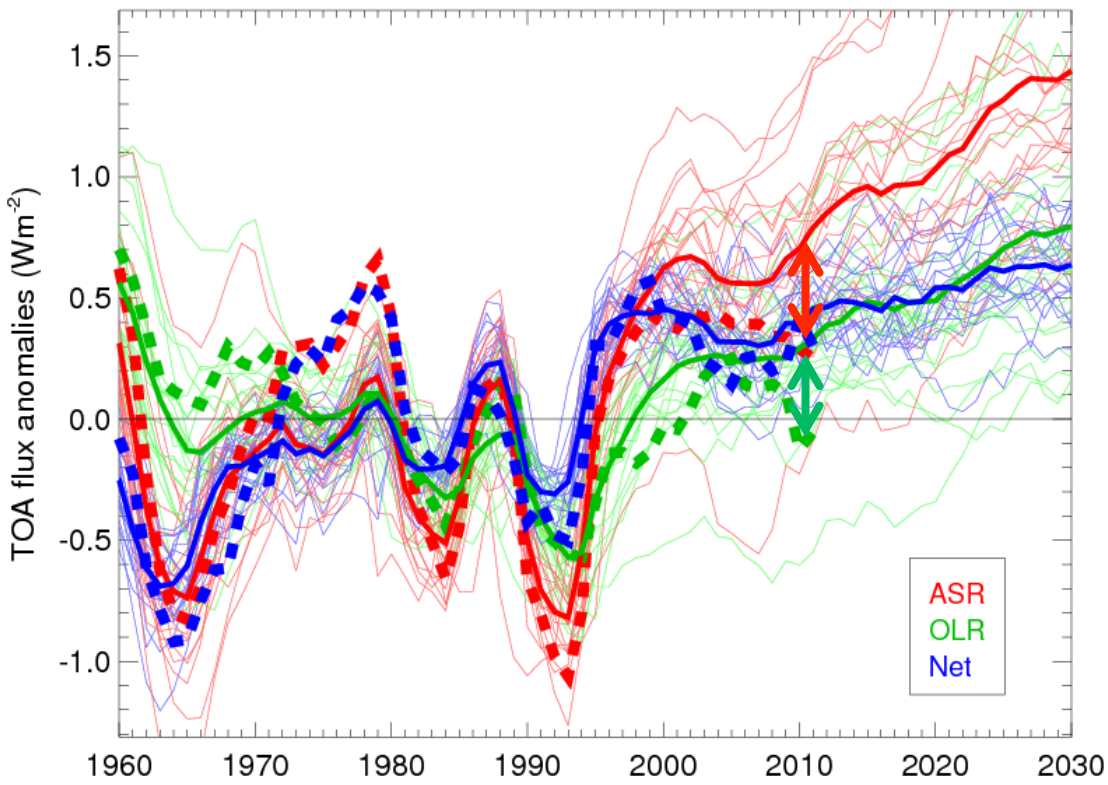
# Observation-based and model anomalies




- **Agreement in N since 2000 but possible cancellation of errors in ASR and OLR**

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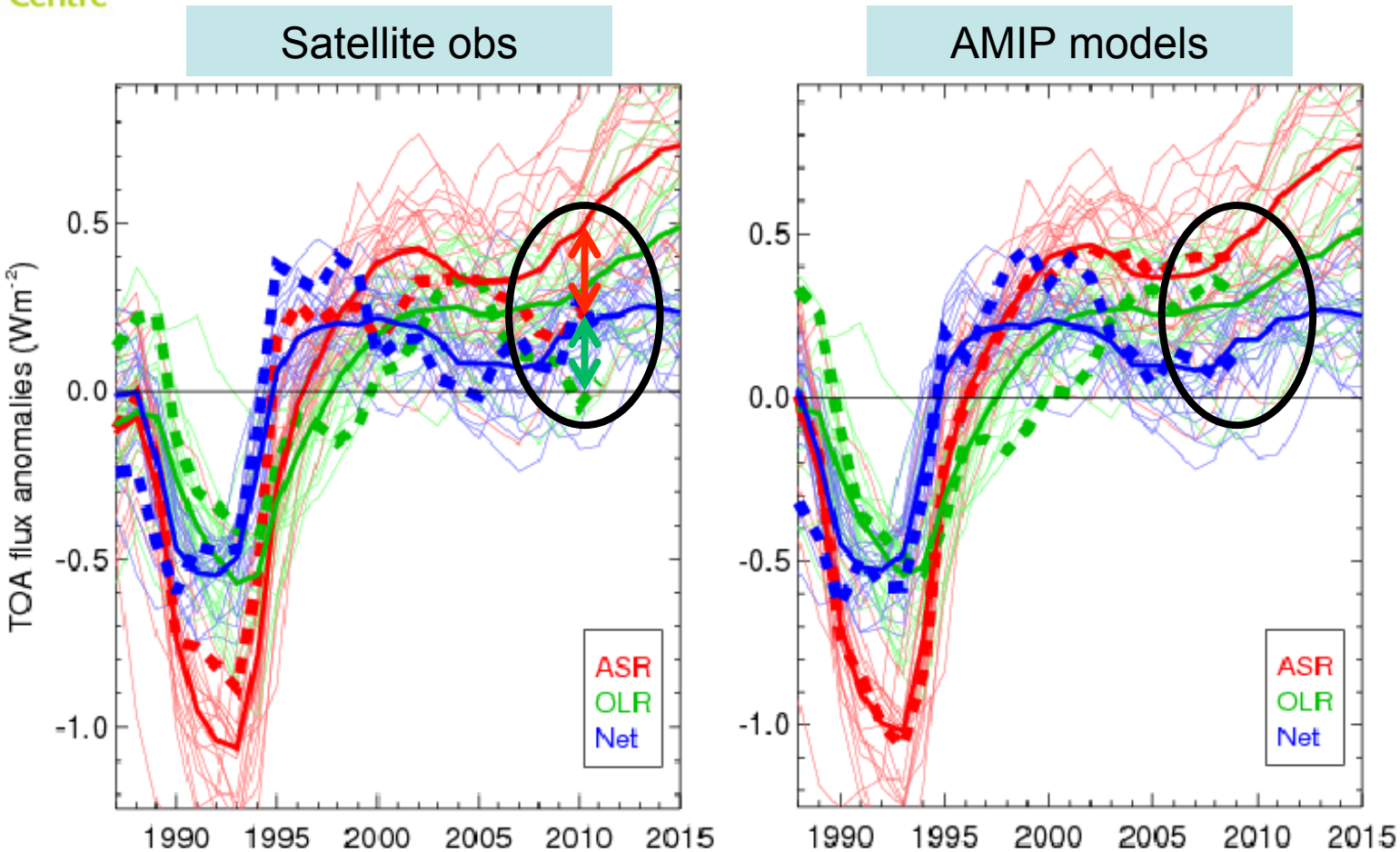
# Compensating errors in OLR and ASR




- **Compensating error in CMIP models between OLR and ASR not seen against AMIP models**

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# Summary (1)

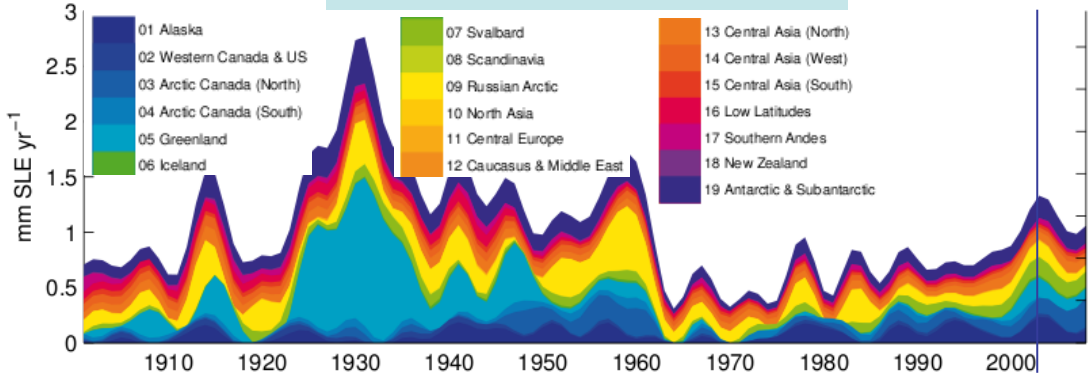
- N and $H_t$ are fundamental for understanding climate variability and change
- Very sparse ocean observations before ~2005 (Argo)
- However, reasonable agreement between obs global mean N and $H_t$ between ~1960 and 1999
  - $H_t$ obs analyses before 1999 potentially useful for process studies
  - Obs variability in $H_t$ in 2000s likely spurious
- Use AMIP simulations, combined with satellites (from 1985), to create observation-based estimates of N (currently back to 1960)
- Variability of N since 1960 dominated by volcanoes
- Well simulated by ensemble mean of CMIP5 models

# Summary (2)

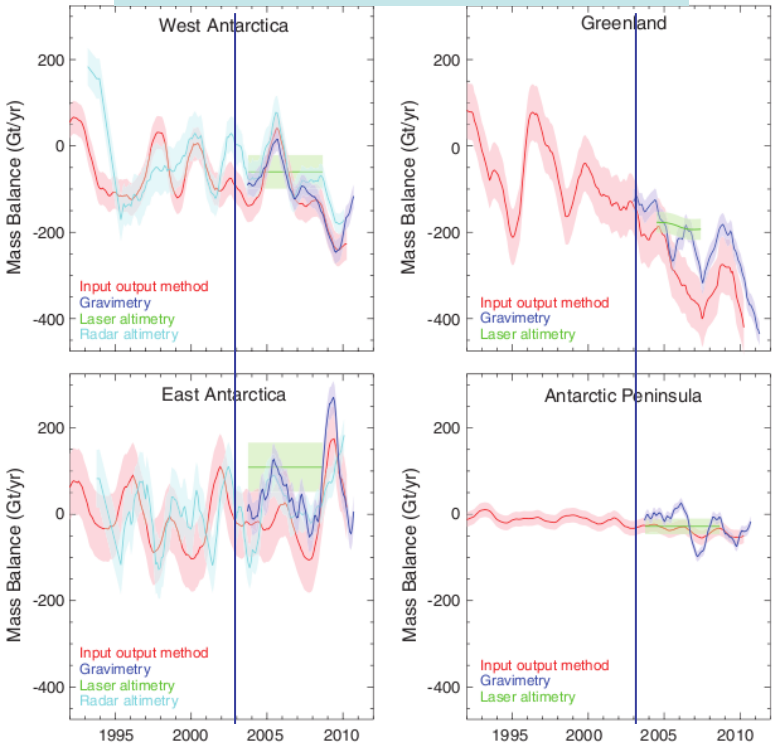
- Observation-based decline in N of 0.31±0.21 $Wm^{-2}$ between late 1990s and mid-2000s → possible role in warming pause?
  - Consistent with minor volcanoes, reduced solar activity
  - But driven by increasing OLR rather than reduced ASR? – though ASR lower than models
  - Hence relative roles of external forcing and internal variability remain unclear
  - Increased uptake of heat by the ocean might not be crucial for explaining the hiatus
- Present-day agreement between obs and model N potentially achieved through cancellation of errors in ASR and OLR

# 2002 $H_t$ peak not supported by sea level

Glaciers (Marzeion et al 2012)

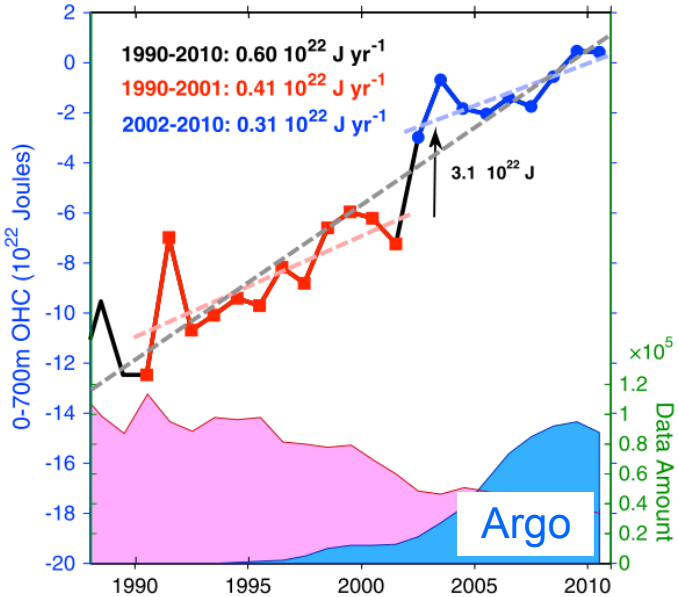


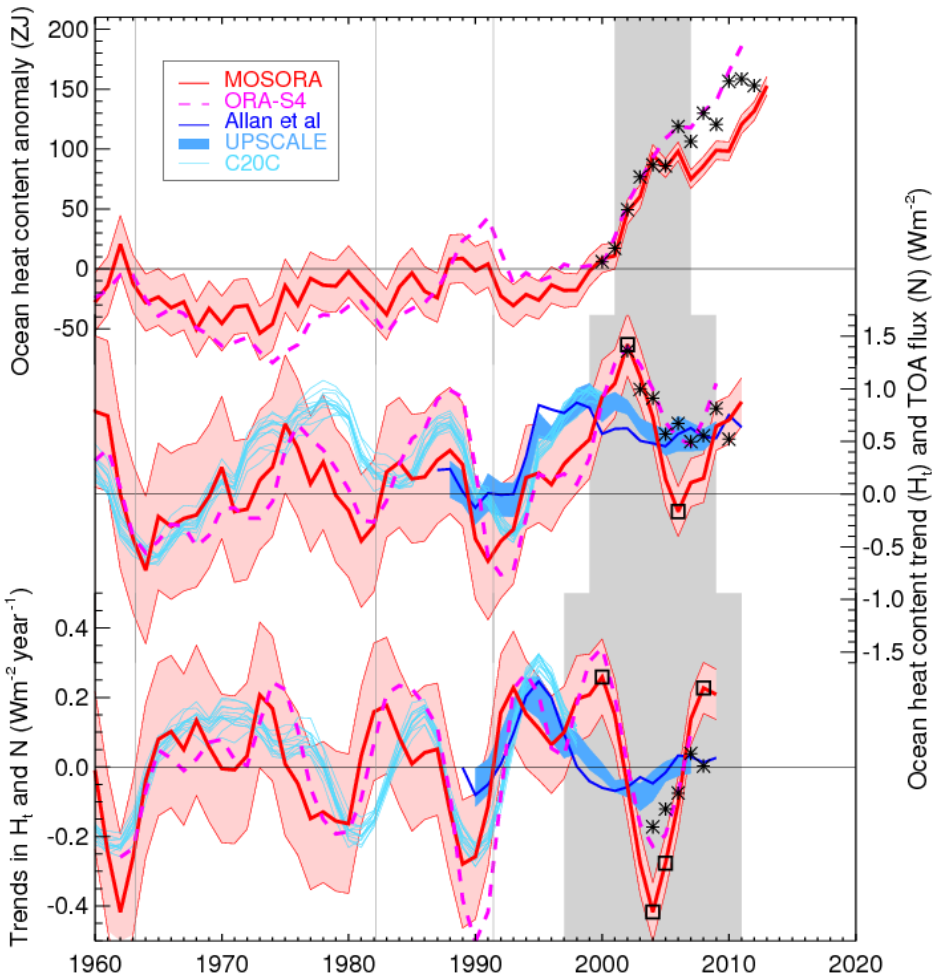

Ice sheets (Shepherd et al 2012)




- **Steady sea level rise**
- **Peak in $H_t$ implies peak in thermosteric steric sea level rise (expansion)**
- **Would require compensating dip in freshwater input**
- **Glaciers: if anything, a peak in freshwater input around 2002**
- **Ice sheets: no evidence of reduced melting around 2002**

➢ **Peak in $H_t$ therefore not supported by sea level estimates**

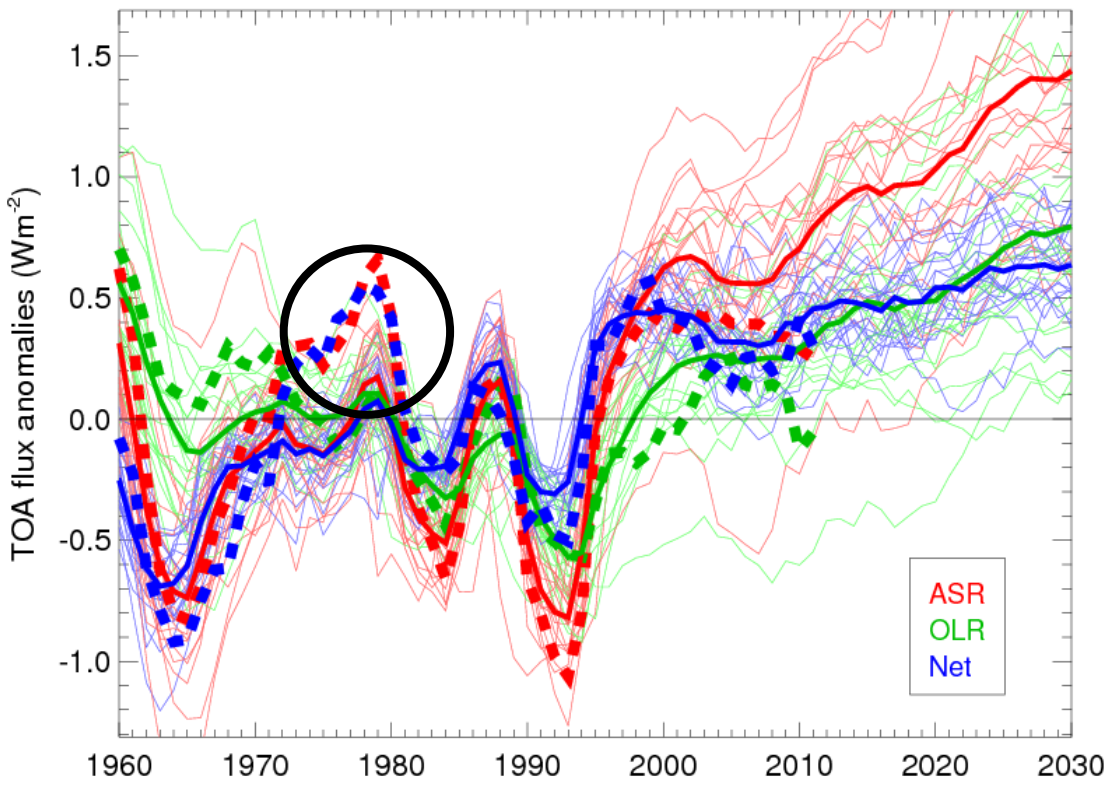



- **Ocean reanlaysis in early 2000s also questioned by Cheng and Zhu, GRL, 2014**
- **Suggested to be caused by spin-up of Argo data**

- **Not caused by spin up of Argo array in MOSORA because also seen in analysis without Argo (black asterisks)**
- **More work needed to understand cause!**

# Observation-based and model anomalies




- **Large difference in 1970s**
- **Possible contribution from PDO shift?**
- **But model ensemble mean also shows increase in ASR → external forcing may play a role**
- **More work needed to understand**

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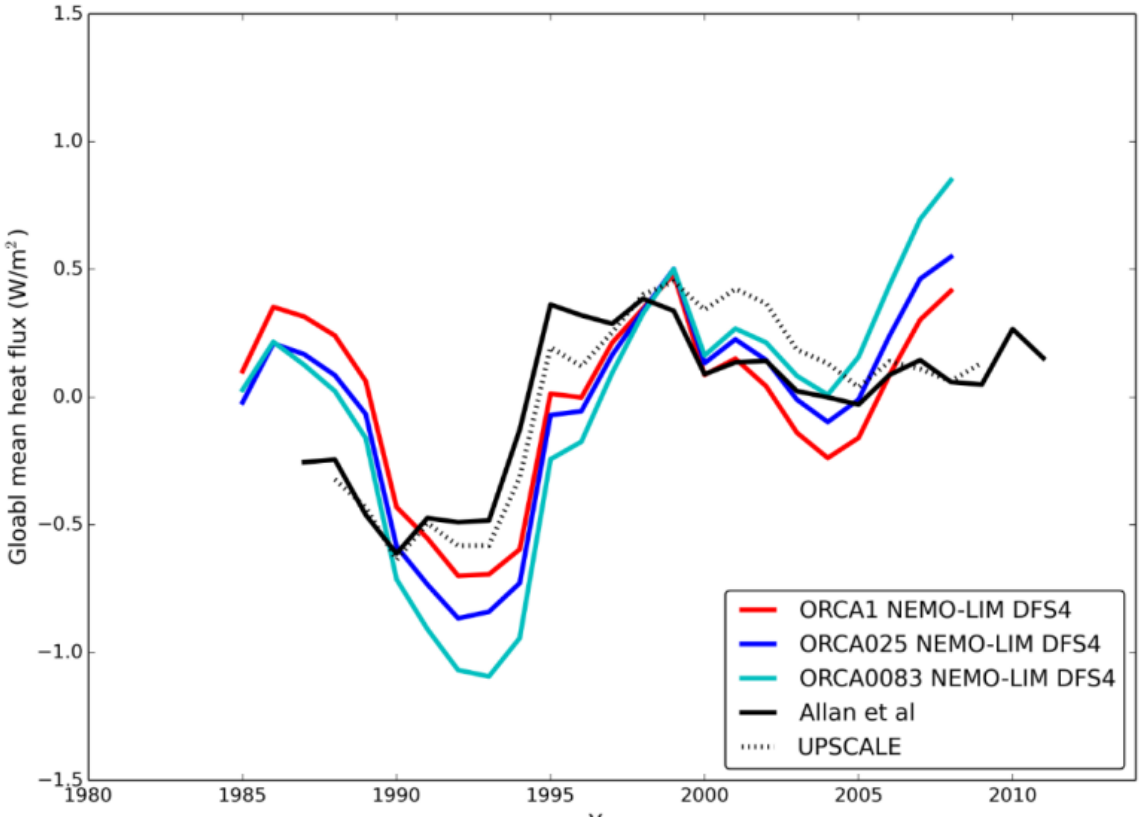
# Robust decrease in N during warming slowdown




- **Satellite estimate (Allan et al 2014) spans transition from ERBS to CERES**
- **But decrease is also seen in:**

✓ **AMIP atmosphere simulations forced by observed SSTs**

✓ **Ocean model simulations forced by observed winds and fluxes**

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