Earth’s energy imbalance since 1960 in observations and CMIP5 models

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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
N = net incoming radiation at top of atmosphere

Atmosphere

Ocean heat uptake

Rate of change of ocean heat content

Ocean

Land + cryosphere

- Compute rate of change of ocean heat content $H_t$
  - $H_t = \frac{\rho V C_p}{A} \frac{dT}{dt}$ (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

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

Observations: Jan 1953

Parameterised covariances: R=0.23  Actual covariances: R=0.68  Truth

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
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 $H_{tt}$)

Observed energy budget

Smith et al 2015
• 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

Smith et al 2015
Comparison with CMIP5 coupled models

- Observation-based estimate $N_0$ 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

Smith et al 2015
Comparison with CMIP5 coupled models

- 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

- 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

Smith et al 2015
Observation-based and model anomalies

- Anomalies wrt 1960-2011 → reduces anchoring uncertainties
- Radiative components: absorbed shortwave (ASR, red), outgoing longwave (OLR, green)
  \[ N = \text{ASR} - \text{OLR} \]
- 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)

Smith et al 2015
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

Smith et al 2015
Agreement in N since 2000 but possible cancellation of errors in ASR and OLR

Smith et al 2015
Compensating errors in OLR and ASR

Satellite obs

AMIP models

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

Smith et al 2015
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.
• 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

- 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

Glaciers (Marzeion et al 2012)

Ice sheets (Shepherd et al 2012)
• Ocean reanalysis 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

Smith et al 2015
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

Smith et al 2015