The role of the global ocean in changes of the Earth's climate system

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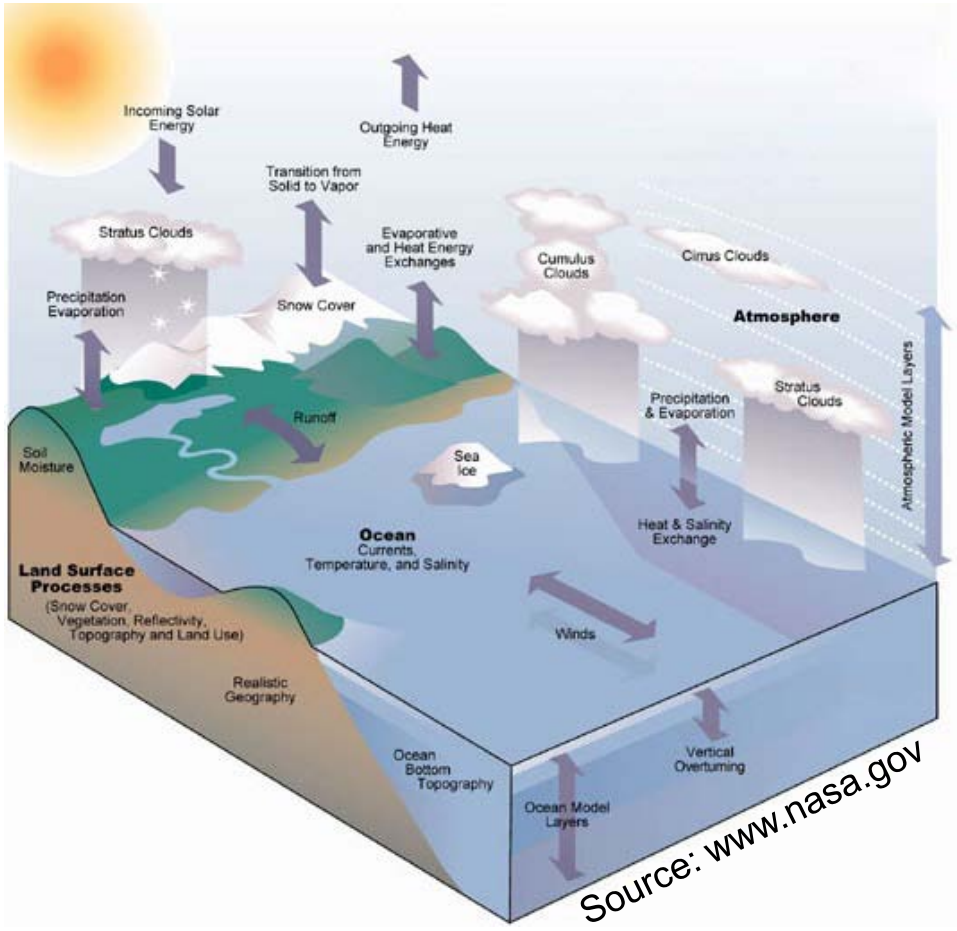
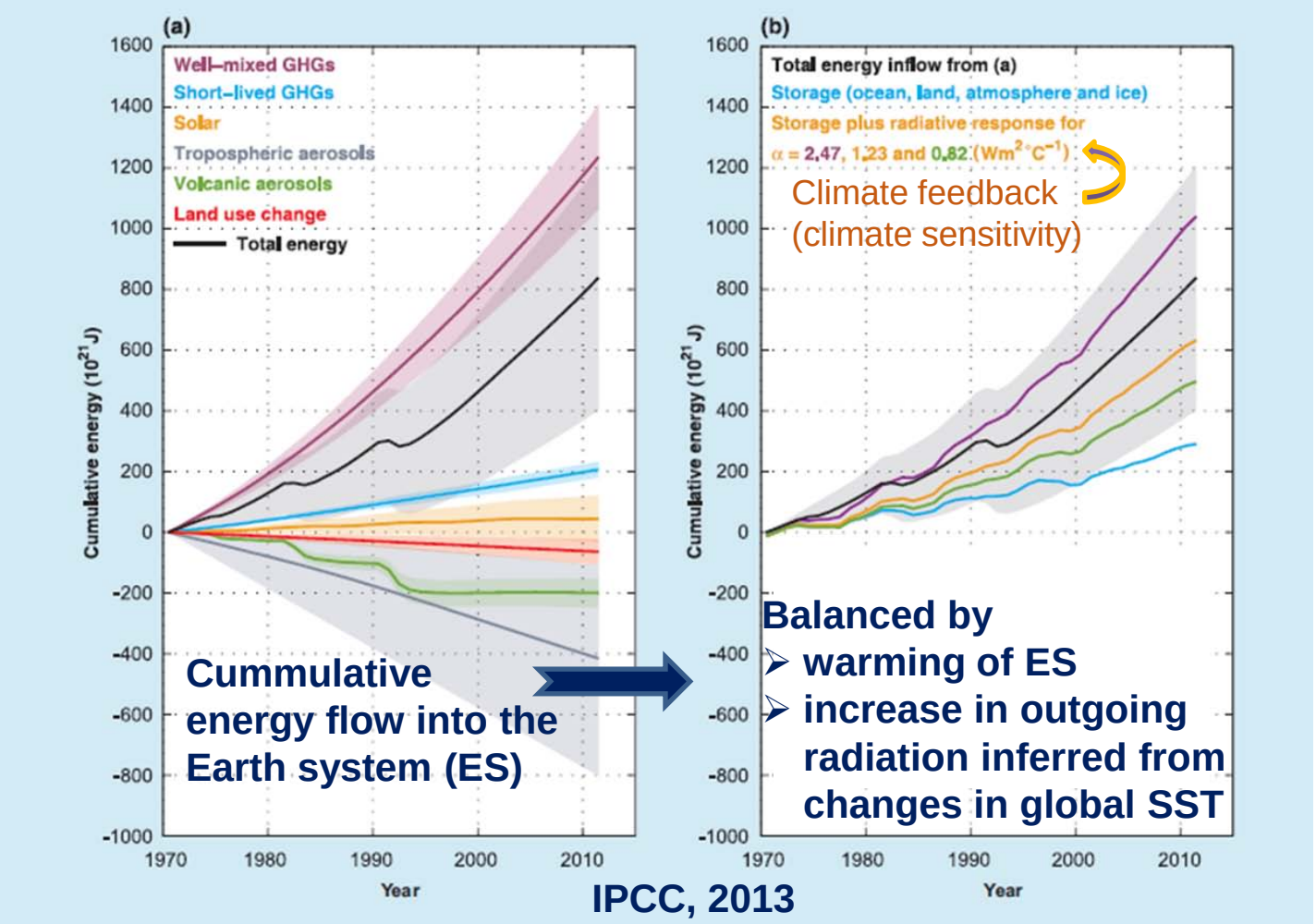
Climate.



- Climate is the result of energy transfer between the different components of the Earth's system.
- Energy flows alter clouds, and weather and internal climate modes can temporarily alter the energy balance for periods of days to several decades.

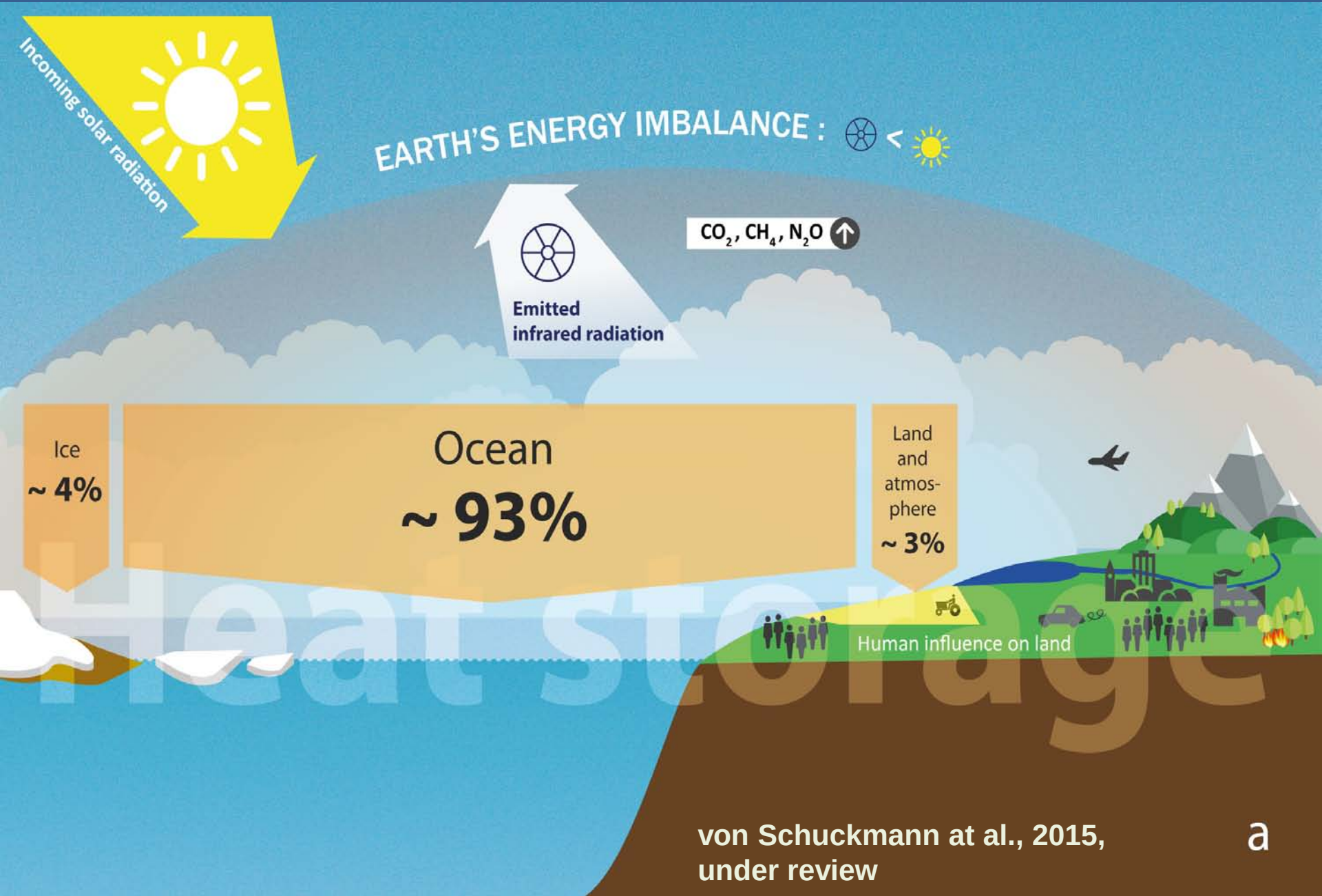
The only practical way to monitor climate change at different time scales is to continually assess the energy, mainly in the form of heat, in the climate system.

Earth's energy budget from 1970-2011.



Since the accelerated increased concentration of greenhouse gases from human activities, energy is not balanced, leading to an accumulation of heat in the climate system

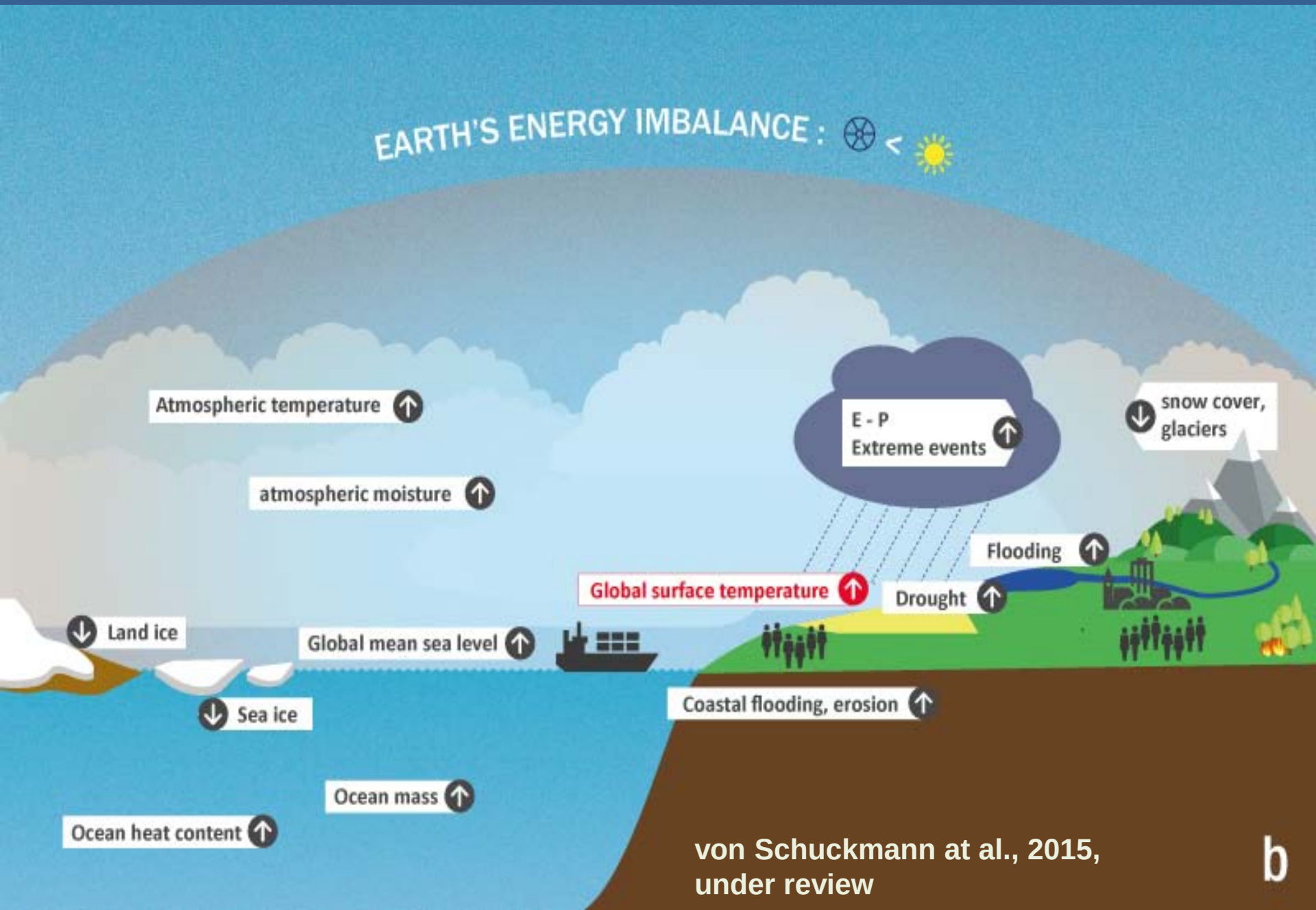
Positive Earth's Energy Imbalance: accumulation and storage of heat



von Schuckmann at al., 2015, under review

a

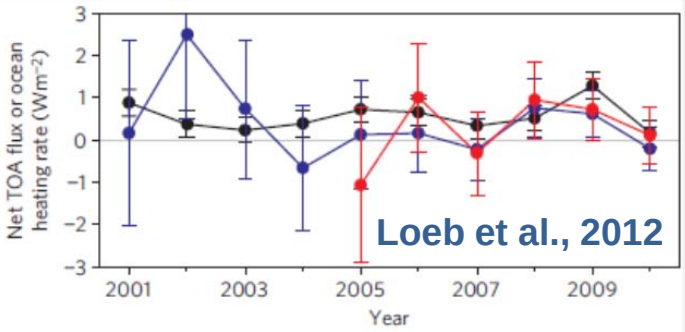
“Symptoms” of positive EEI



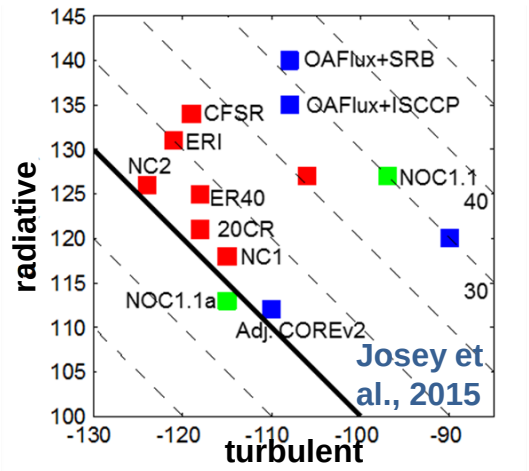
von Schuckmann at al., 2015, under review

Determining Earth's energy imbalance: 4 different approaches

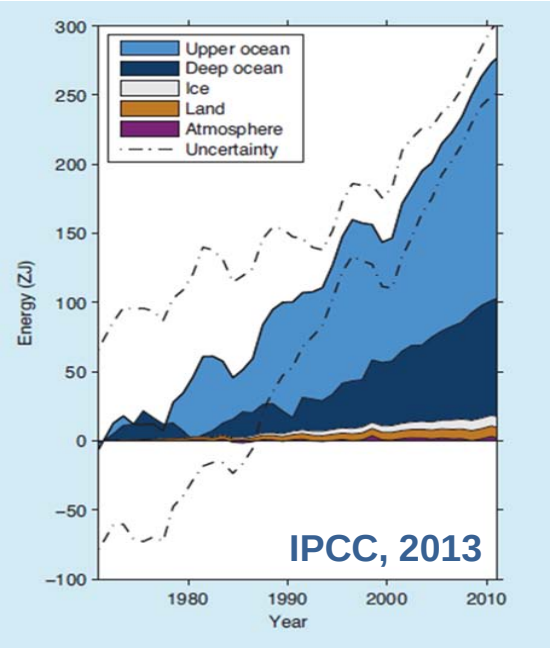
Radiation at TOA



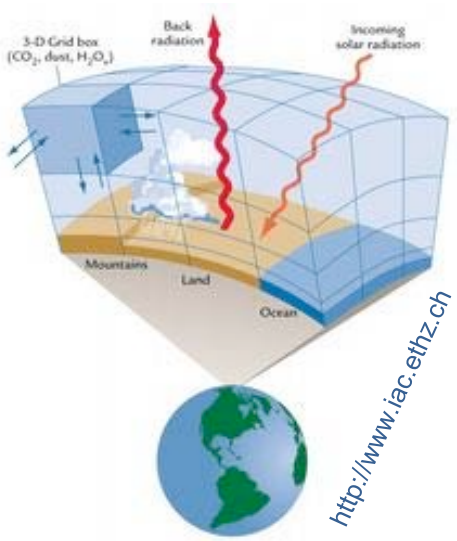
Surface flux



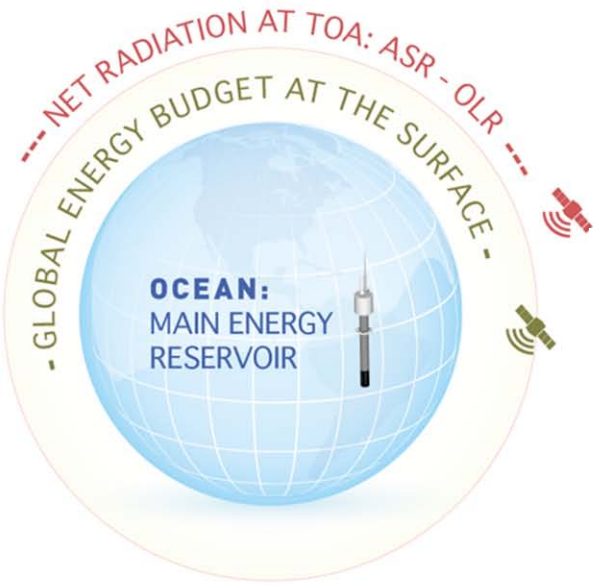
Ocean heat content



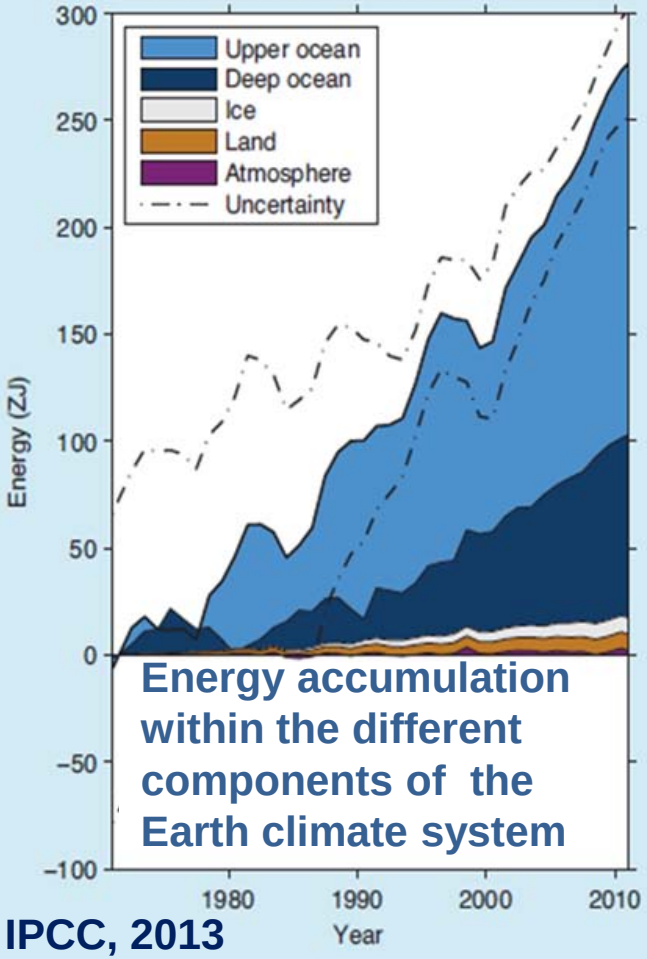
Climate models



Determining Earth's energy imbalance: Heat storage

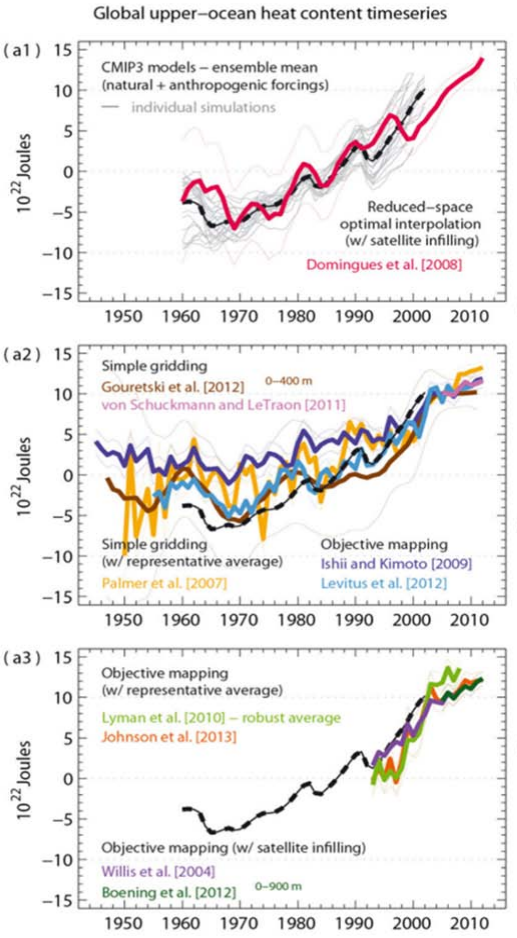


Ocean Heat Content



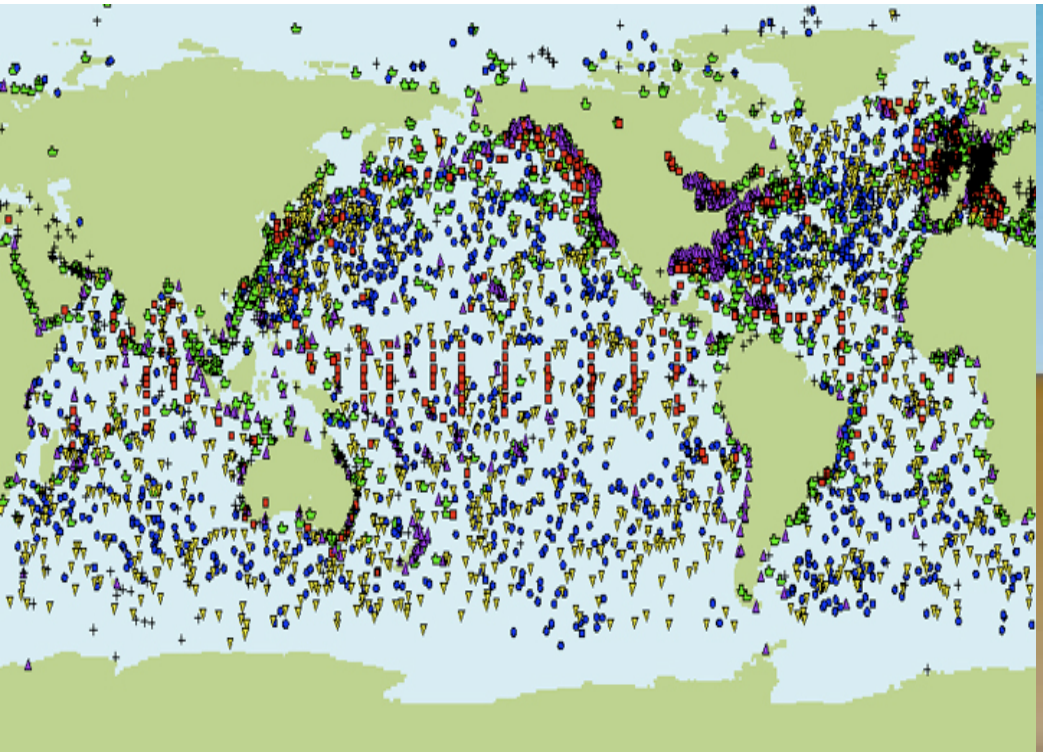
Energy accumulation within the different components of the Earth climate system

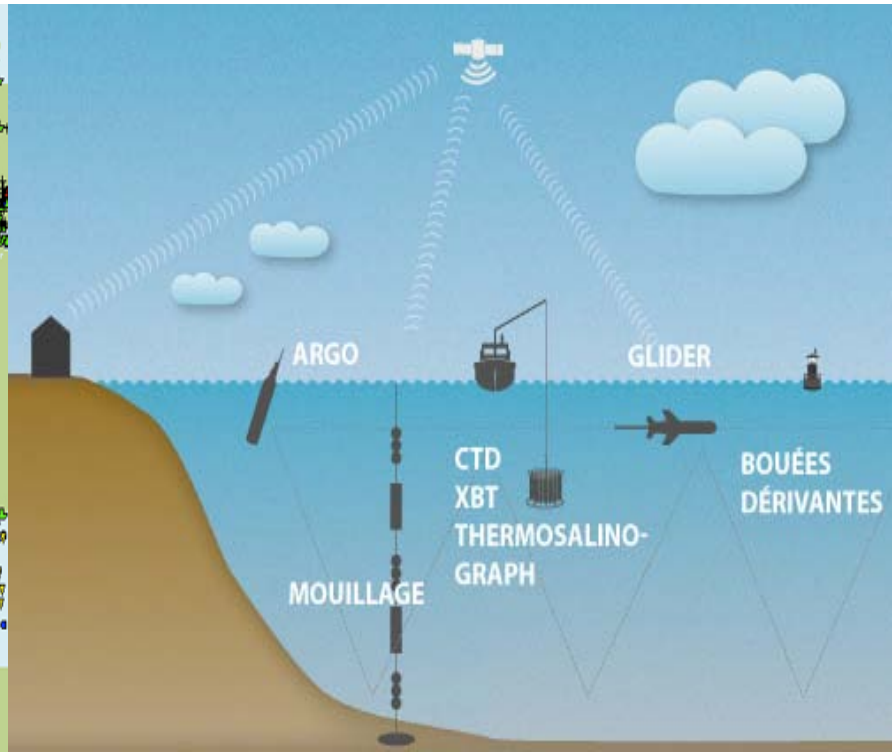
IPCC, 2013



Abraham et al., 2013

Ocean heat content





Main historical obs.:

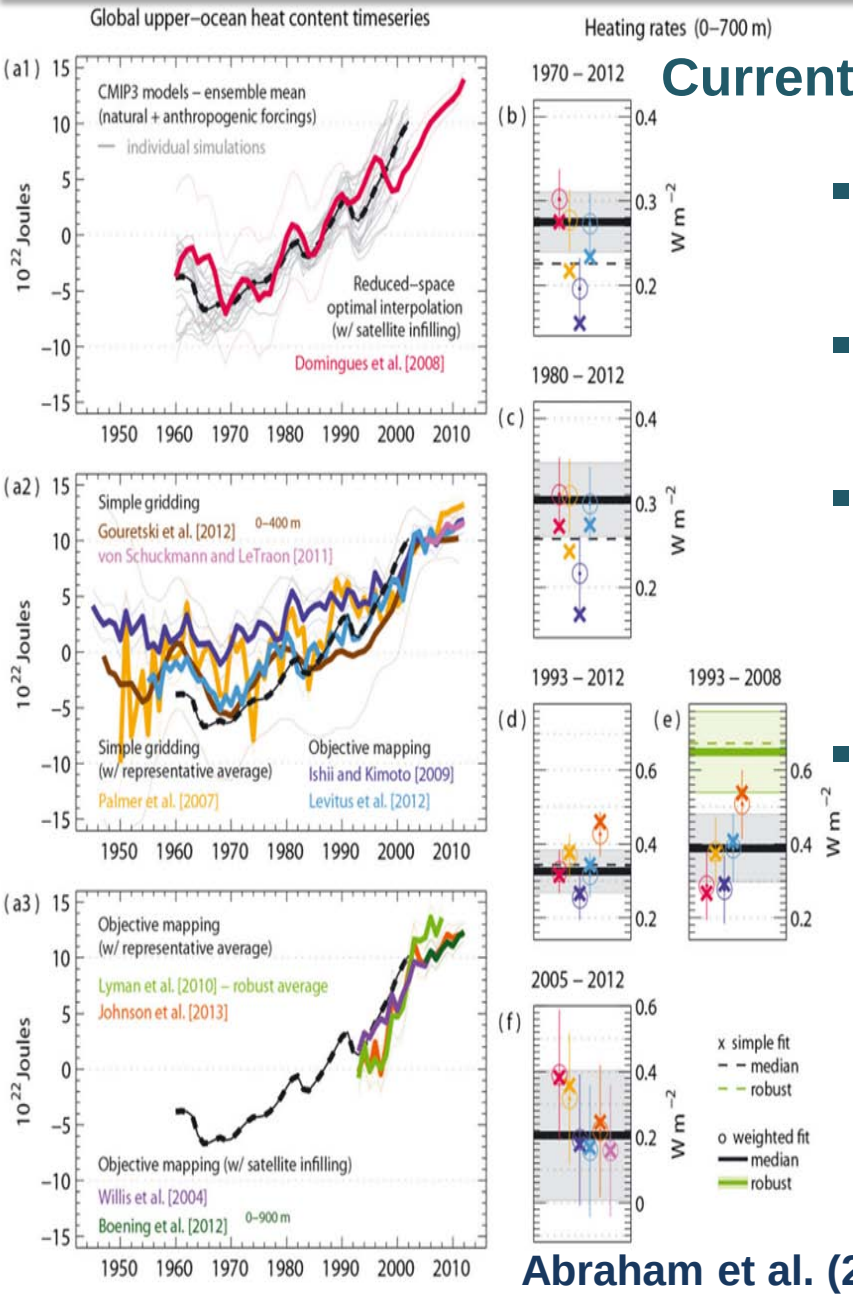
Pre-1970 (Mechanical BathyThermograph (MBT) Gold standard (Reversing therm))

1971–2003 (eXpendable Bathy-Thermograph (XBT) Gold standard ship board CTD

Argo era:

2000-now: 95% Argo profiling floats, shipboard measurements, moorings, gliders, instrumented marine mammals,

Ocean heat content



Current estimates of GOHC: Historical + Argo era

- Differences in **upper-ocean heat storage** between analyses/periods.
- Differences in **“interannual to decadal variability”** between analyses.
- All estimates show **a multi-decadal increase in OHC** in both, upper and deep ocean regions.
- Warming rates:

1970-2012, 0-700m: 0.27±0.04 Wm^{-2},
1980-2012, 0-700m: 0.30±0.04 Wm^{-2},
1993-2012, 0-700m: 0.33±0.06 Wm^{-2}
2005-2012, 0-700m: 0.21±0.20 Wm^{-2}
2005-2012, 0-2000m: 0.30±0.10 Wm^{-2}

Abraham et al. (2013)

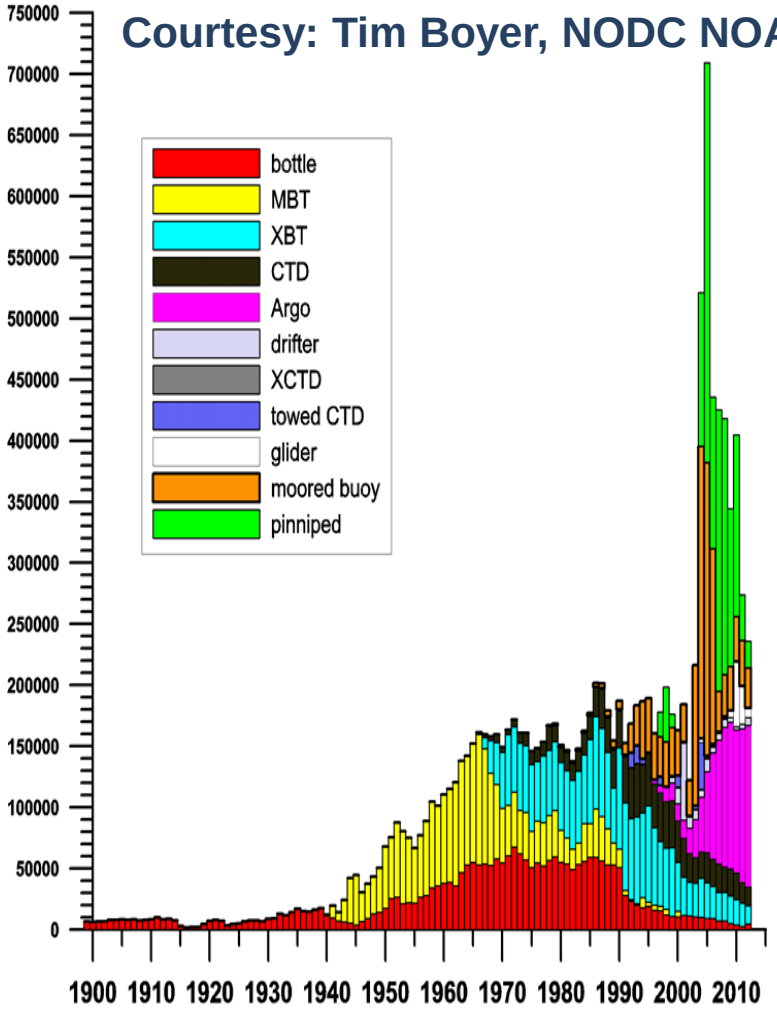
Ocean heat content: Historical data

Spread in the OHC analyses mainly reflects the sensitivity of the calculations to different choices of:

- quality, types, and amount of data included
- correction for instrumental biases
- mapping approach
- climatological reference

Palmer et al. (2010); Lyman et al. (2010); Abraham et al. (2013)

Ocean heat content: Historical data



•Significant contributions from various **independent efforts** in terms of assembling, rescuing and QCing historical ocean temperature profiles.

•But still... global database contains a relatively **large fraction of biased, duplicated and substandard quality** (e.g., lack of original and full-resolution) **data and metadata** that can confound climate-related research & applications.

Need for timely/effective action: a globally-coordinated approach.

Global data base: Millions of temperature profiles ($$ Tens of billions dollars)

•Historical obs. system not purposely designed for climate change monitoring

•Mix of instruments/evolving technology (various accuracies & biases)

Courtesy: IQuOD

The IQuOD initiative

www.iquod.org

International Quality-Controlled Ocean Database

Although internationally-coordinated efforts exist for the ocean surface and atmosphere-ocean observations, **no similar effort has been undertaken for the historical subsurface ocean observations to this date.**

Overarching goal:

An internationally-coordinated approach to **maximize the quality, consistency and completeness of a long-term and irreplaceable subsurface ocean temperature archive for a wider range of Earth system, climate & oceanographic applications of societal benefit.**

How:

Development/implementation of an internationally-agreed framework

By pooling expertise and resources into a single best practice community effort:

- expect best outcome over the shortest timeframe
- avoid duplication of human and infrastructure resources
- (particularly welcome in times of budget cuts)

Current partners/expertise/levels of involvement

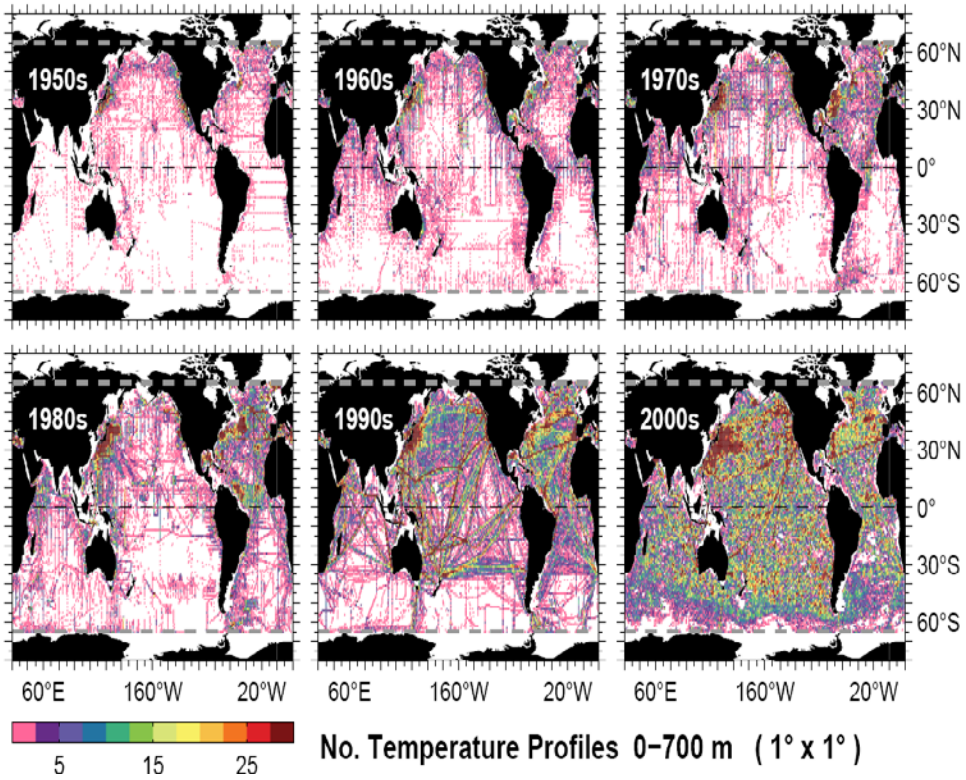
Argentina, Australia, Brazil, Canada, China, France, Germany, India, Japan, Mexico, Norway, Russia, Spain, South Africa, UK, USA.

Ocean heat content: Historical data

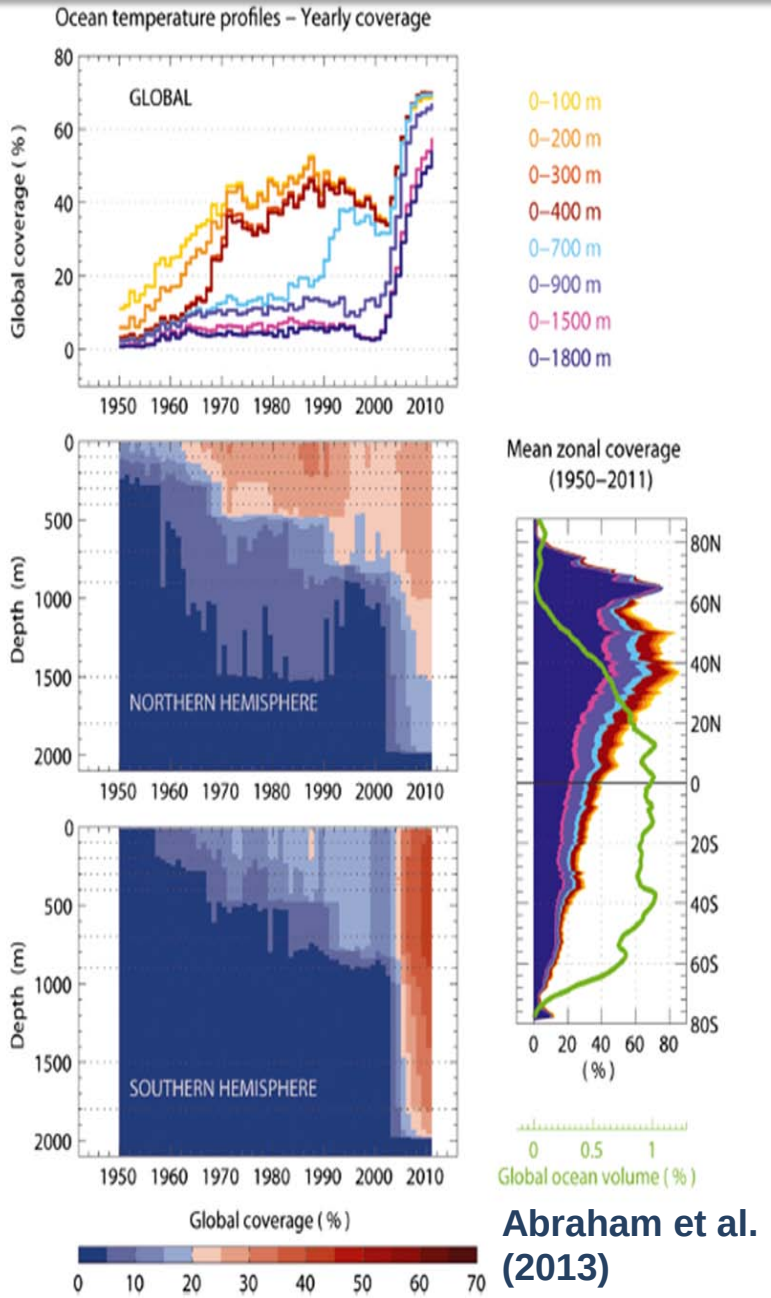
Courtesy: T. Boyer

Mapping approaches:

how to deal with observational gaps

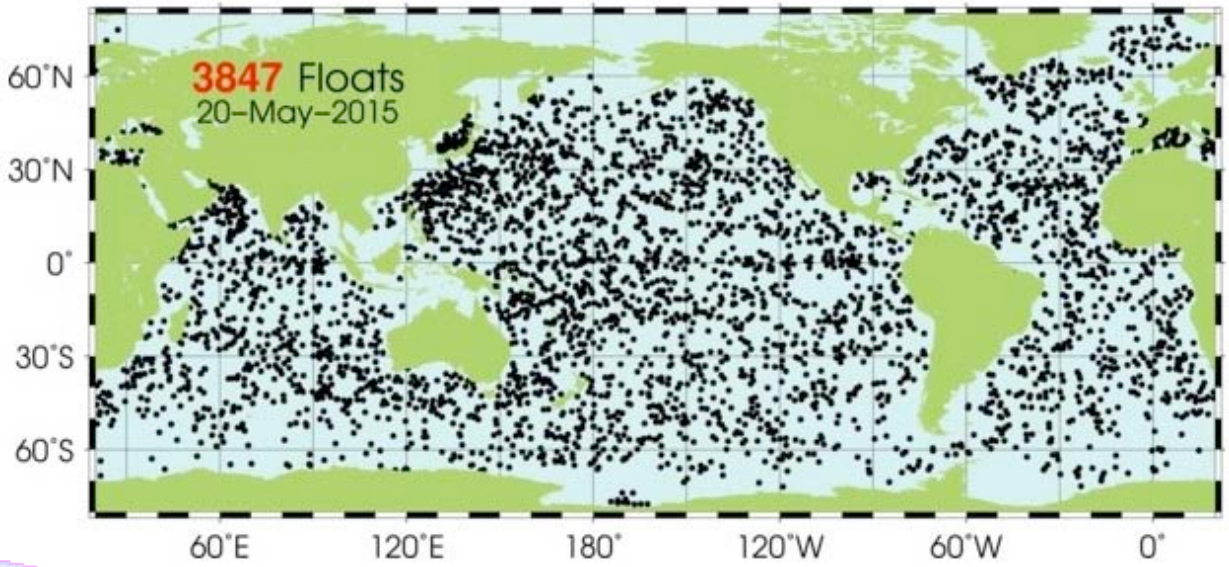


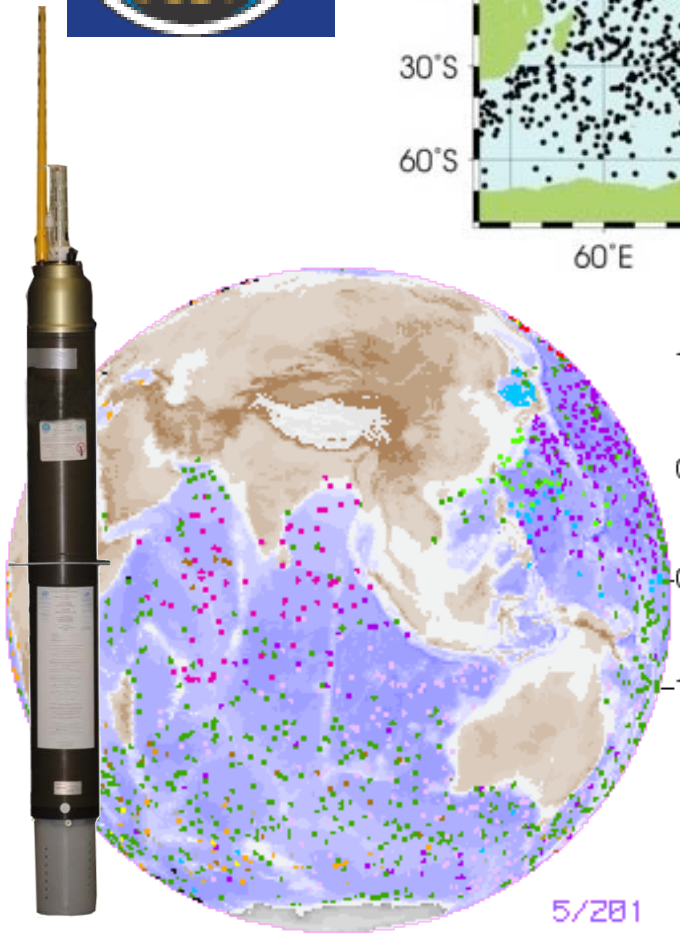
Observational coverage is historically sparse (particularly earlier in the record, south of 30°S and towards deeper levels) prior to the Argo era (from ~2005).

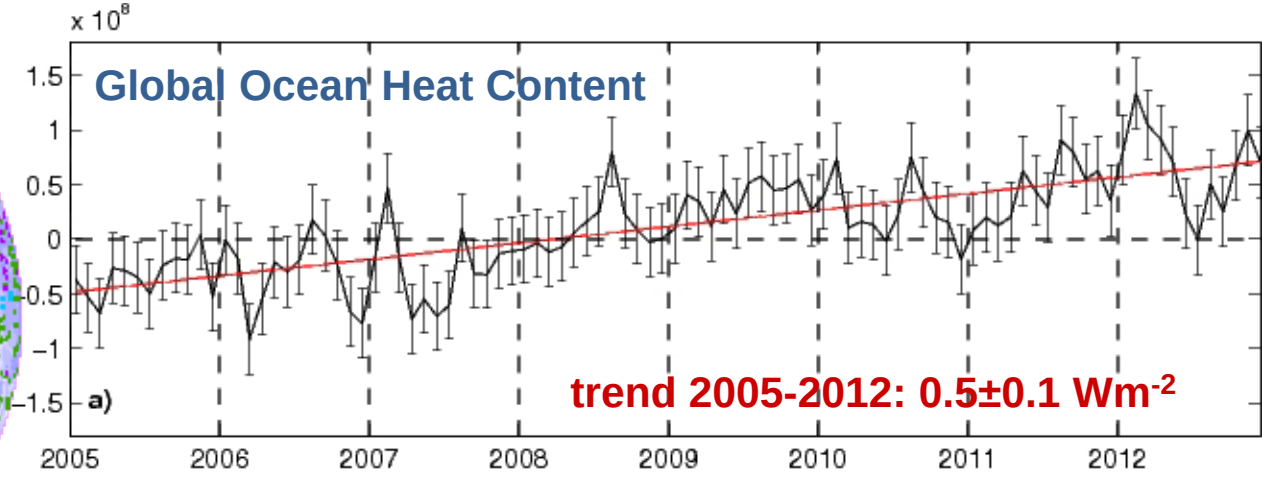


Abraham et al. (2013)

Ocean heat content: Argo-era



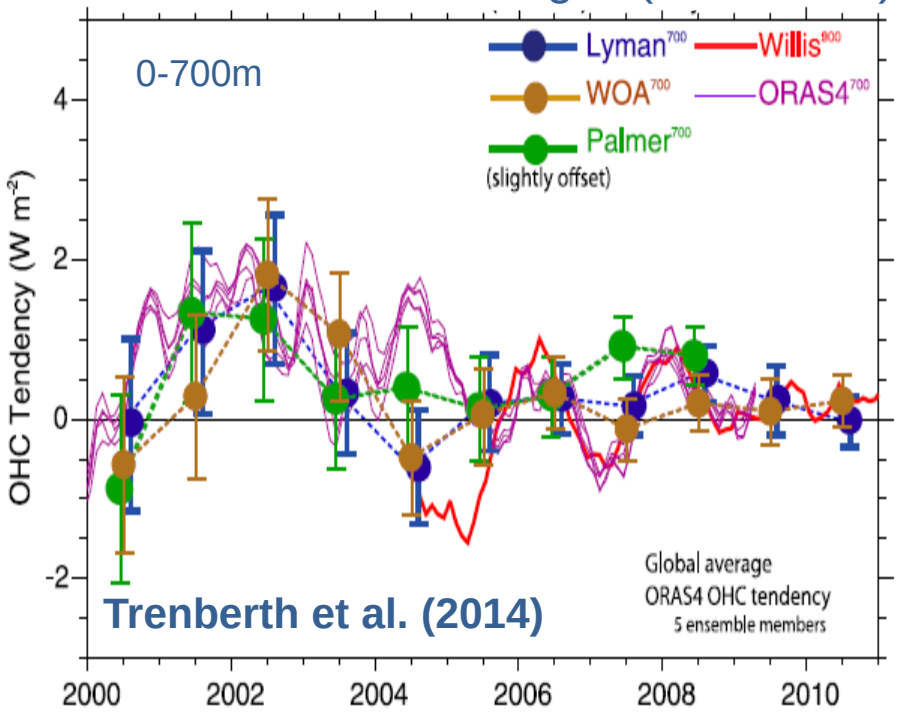




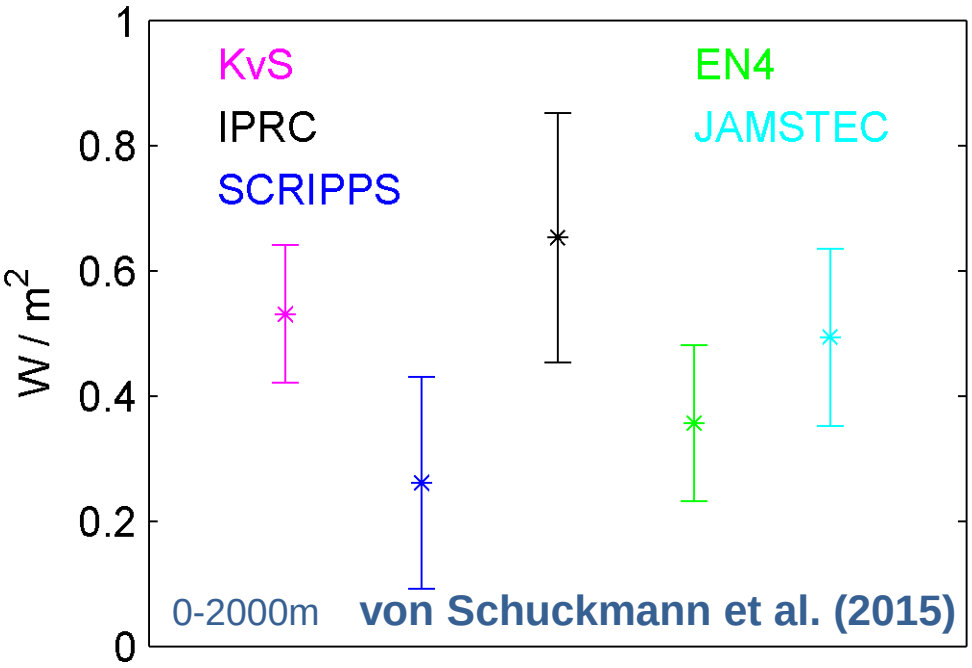
von Schuckmann and Le Traon, 2011
von Schuckmann et al., 2014

Interannual to decadal changes as derived from different Argo products

Interannual OHC changes (2000-2011)



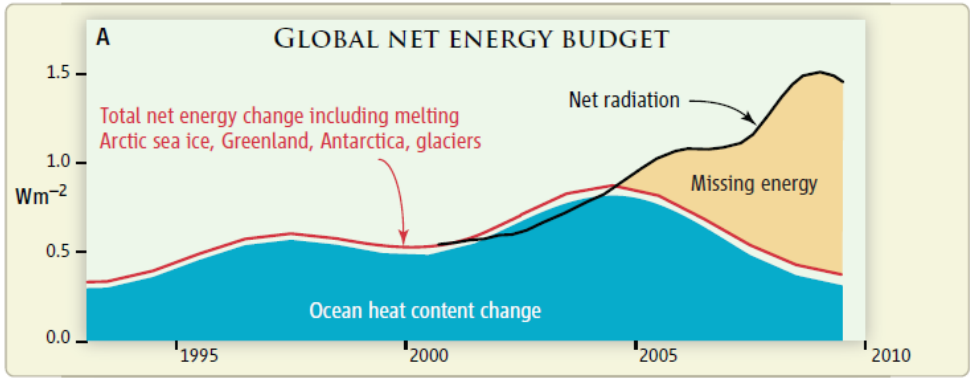
Decadal OHC changes (2006-2012)



Still too large spread in different estimates !!!

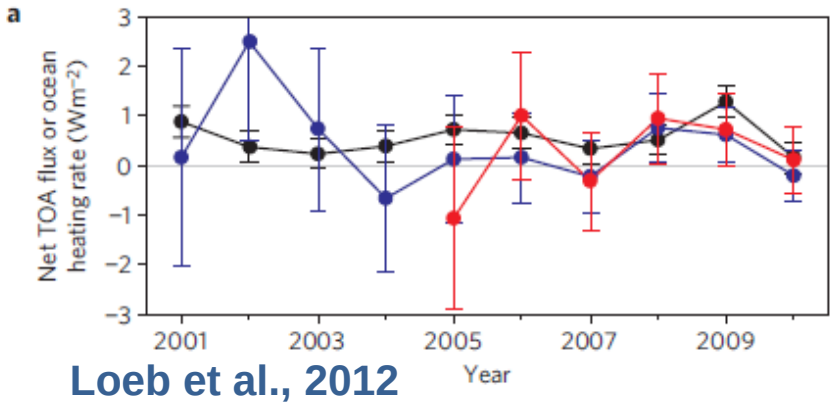
Consequences of these discrepancies for climate change studies.

Estimated rates of change of global energy: « **Missing Energy** «

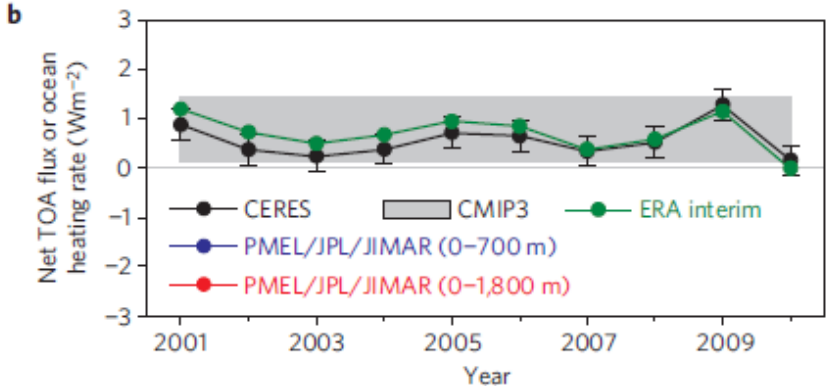


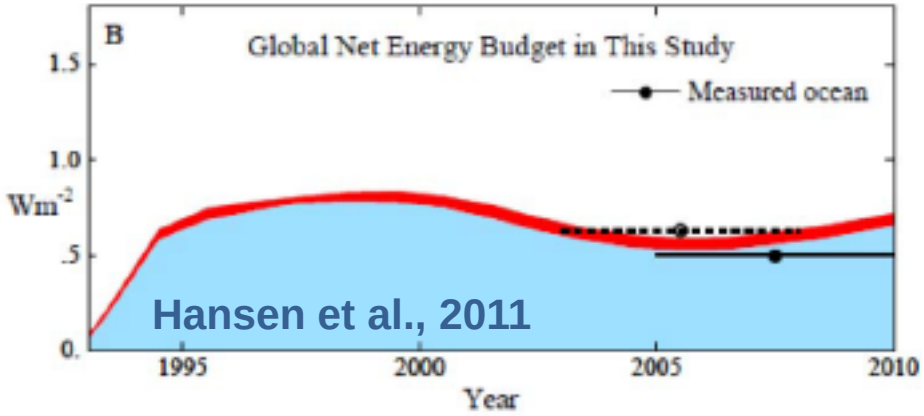
The key purpose of this paper was to challenge the different communities to work on these inconstistencies.

Trenberth and Fasullo, 2010



Loeb et al., 2012

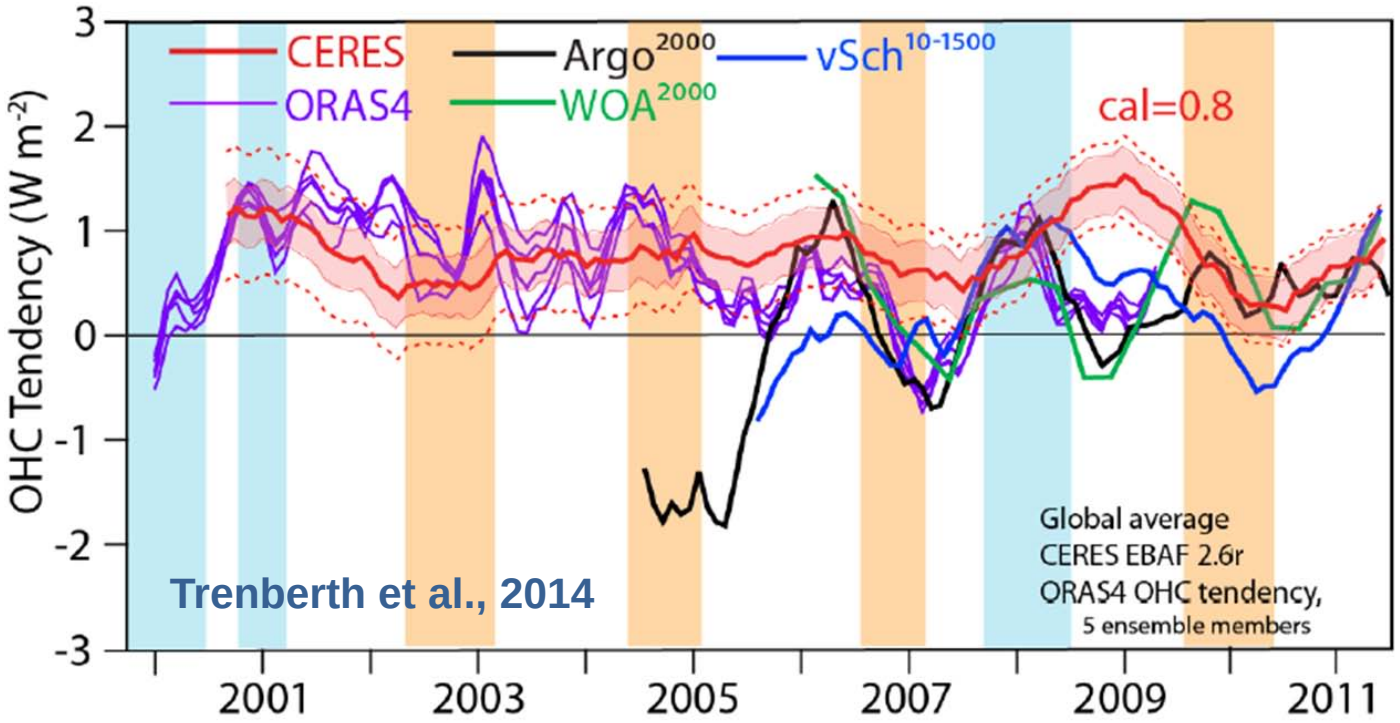




Hansen et al., 2011

Communities have improved their estimates, especially for GOHC, but there remain some major problems. Indeed, budgets can be closed « within uncertainties », but the uncertainties are still large and unclear.

Consequences of these discrepancies for climate change studies.



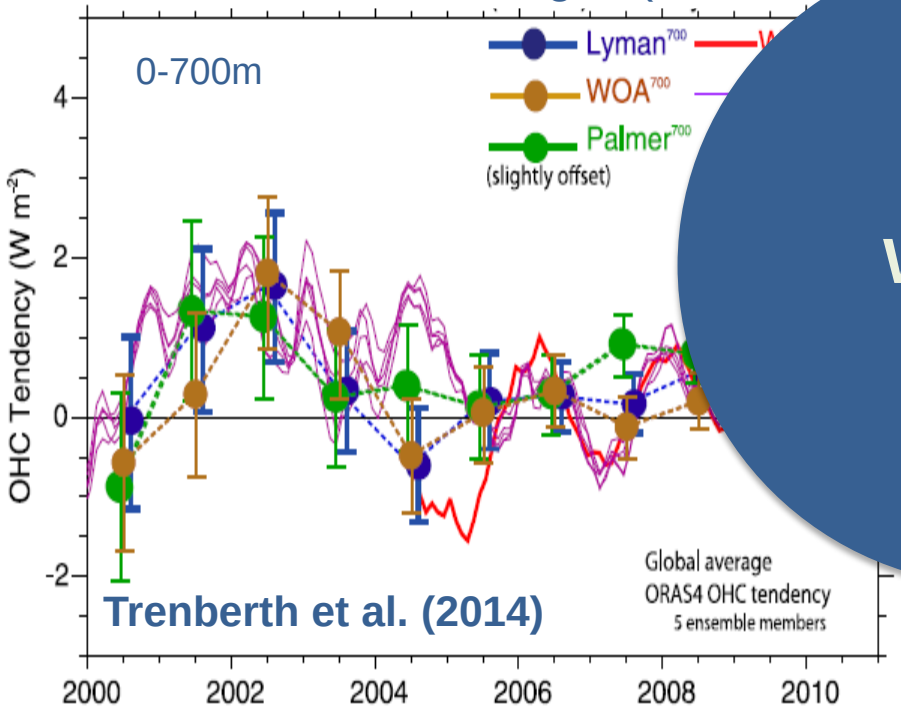
"Missing energy" at interannual scales:

All OHC estimates show CERES 2007 cooling, all miss CERES warming in 2008/2009

- unable to achieve closure at interannual scales
- remaining errors either in CERES or **OHC**

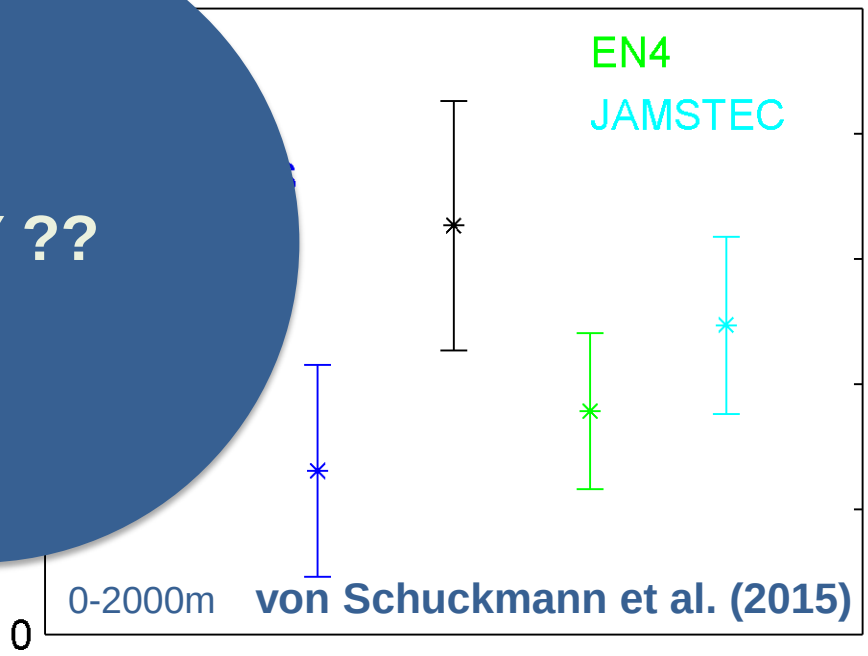
Interannual to decadal changes as derived from different Argo products

Interannual OHC changes (2000-2011)



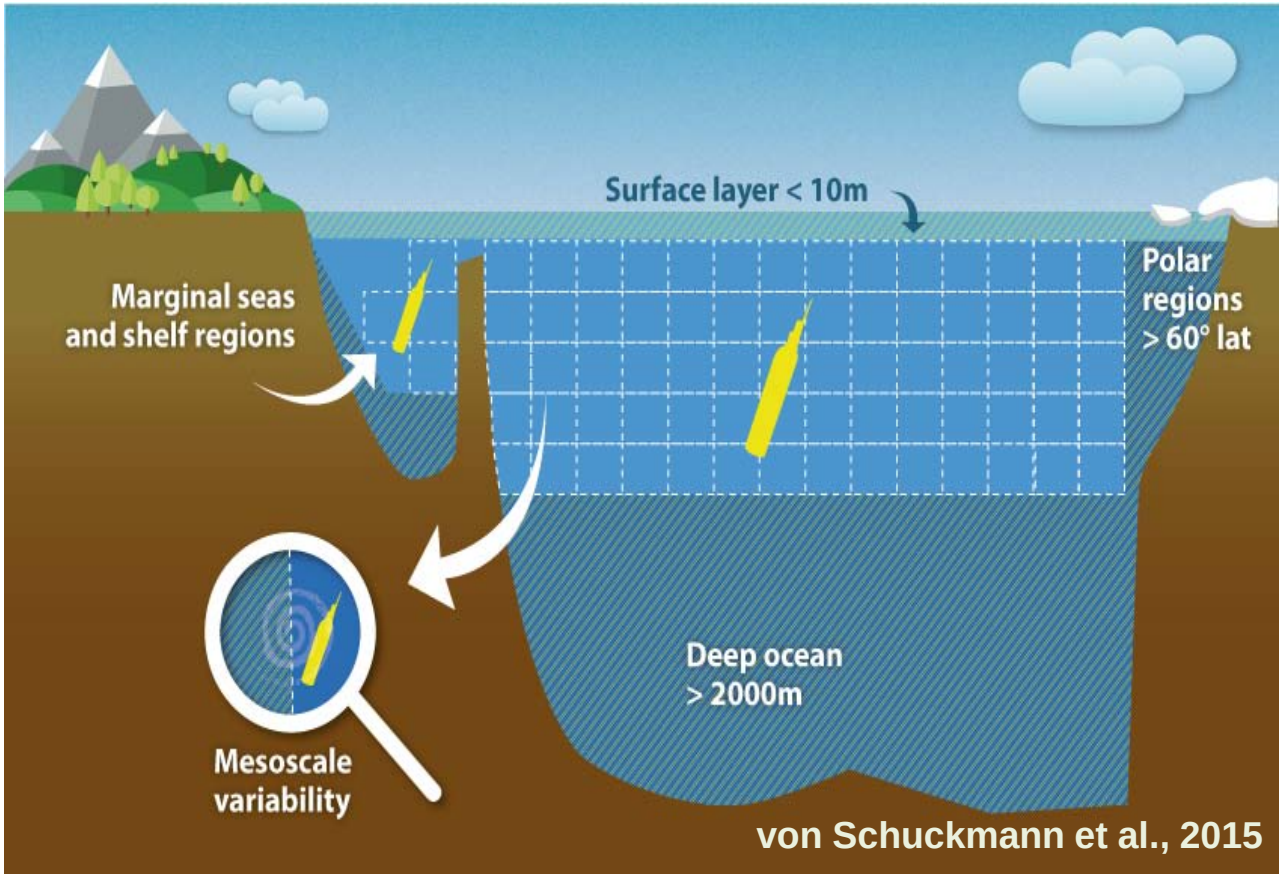
WHY ??

Decadal OHC changes (2006-2012)



Still too large spread in different estimates !!!

While there have hence been significant advancements in the quantity and quality of ocean temperature measurements, accurately measuring the thermal energy of the ocean and its related volume changes remains a challenging problem for climate scientists.



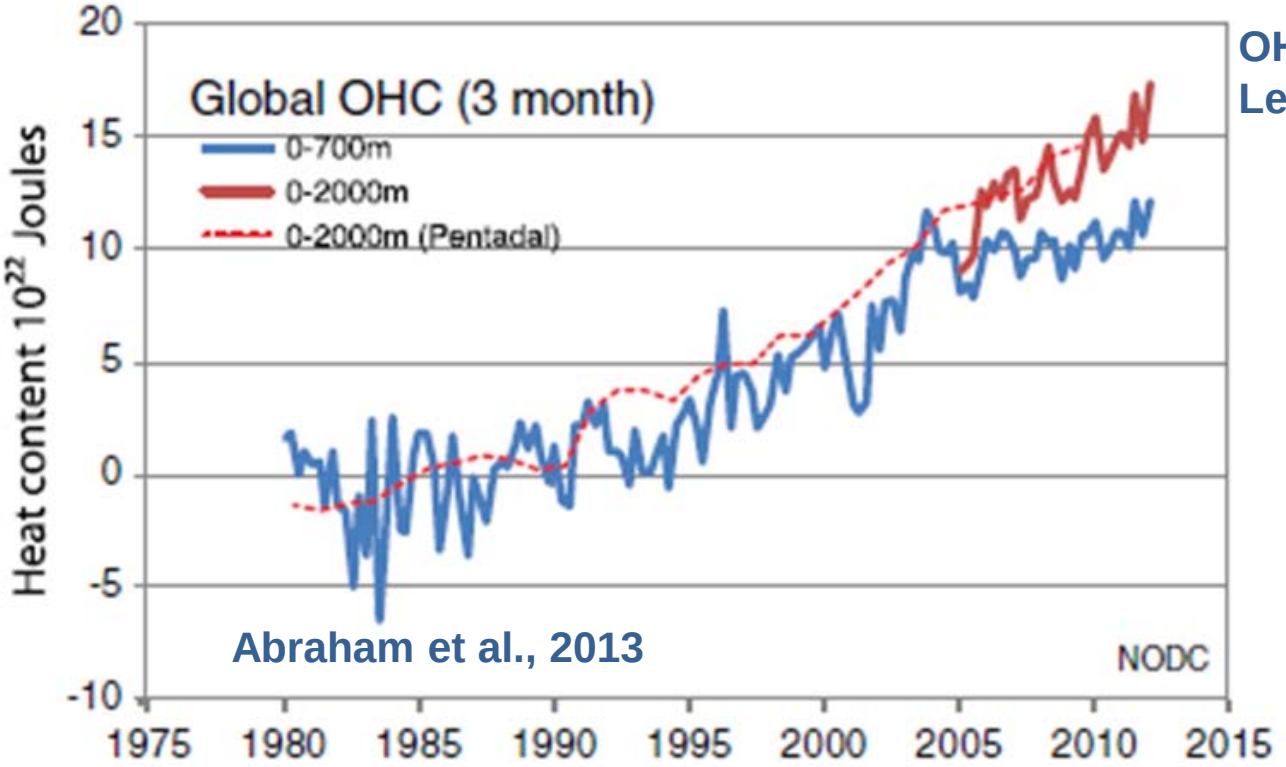
Coverage is not yet truly global, as Argo does not cover:

- the deep ocean below 2000m depth
- the shelf areas and marginal seas
- pole wards of 60 latitude
- the near surface layer

What can we expect to see from these different under-sampled regions?

Role of the deep ocean

Under-sampling of the ocean, especially below 700m and in the deep ocean may account for the main discrepancy



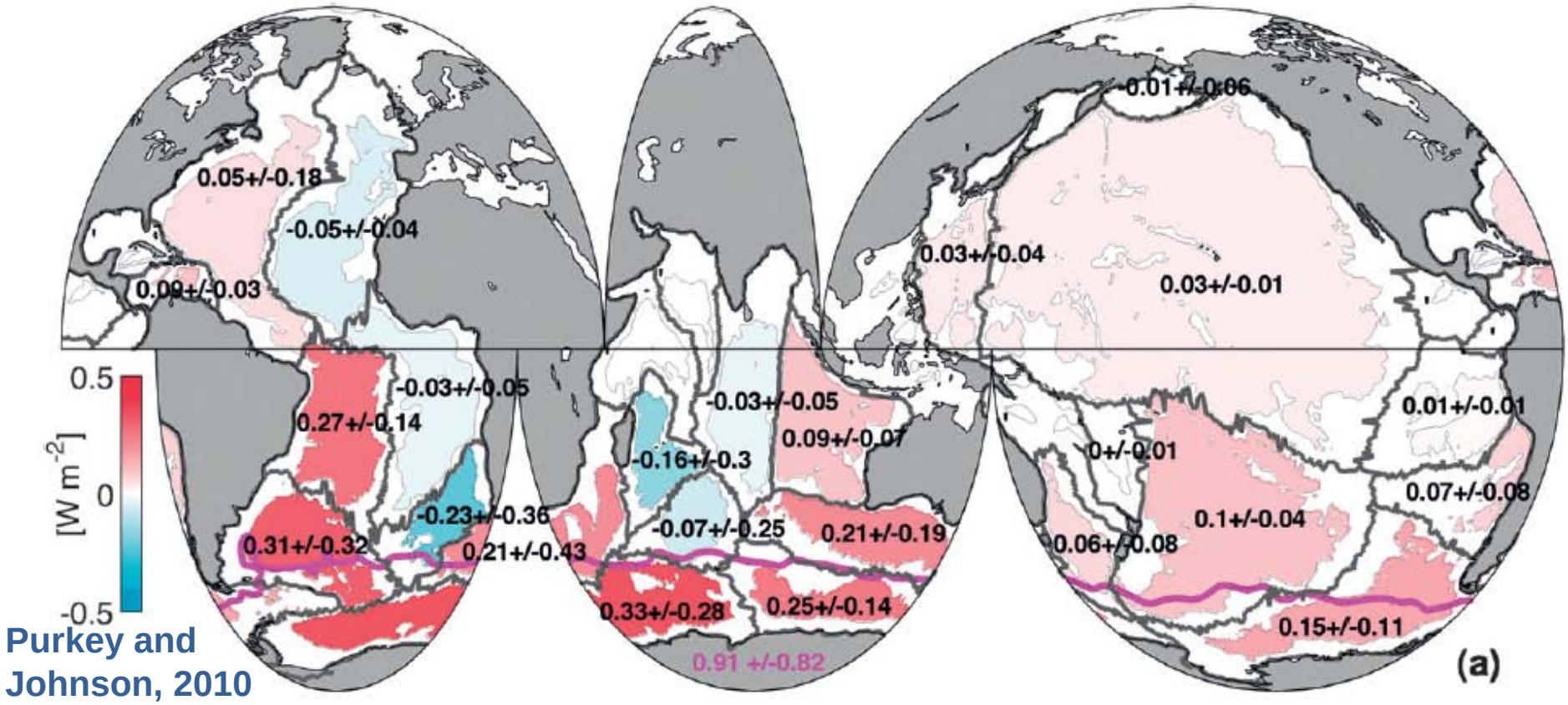
OHC updated from Levitus et al. (2002)

Growing disparity between the OHC changes in the upper 700m and down to 2000m after 2005:

➔ warming has occurred in the 700–2000m layer

Estimates of deep ocean contributions.

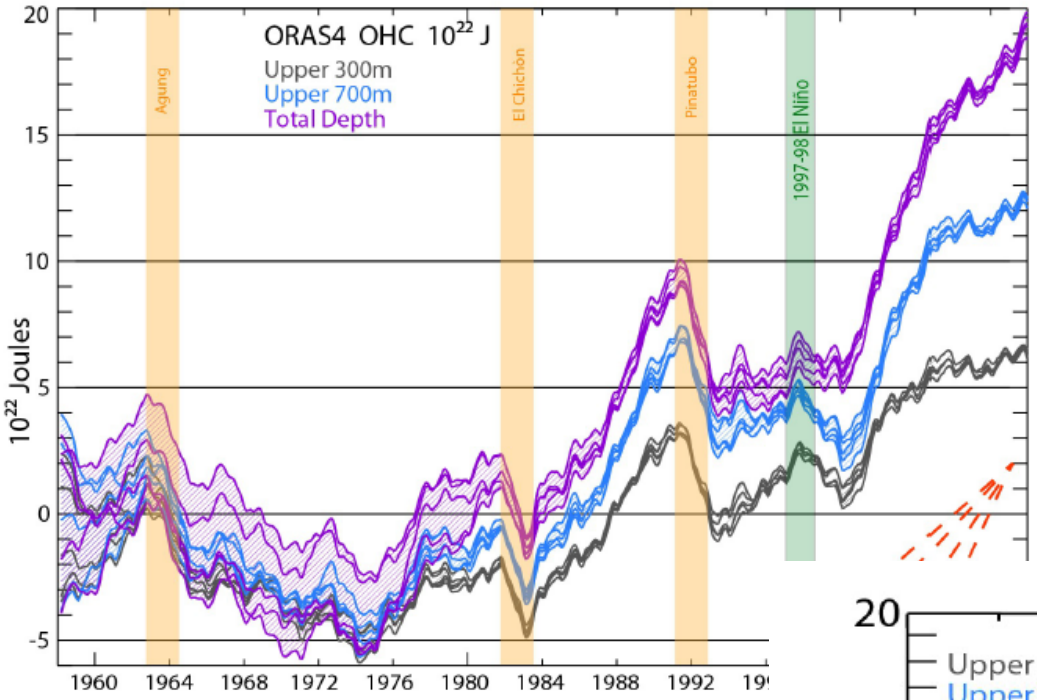
Abyssal warming from the 1990s to the 2000s (> 4000m; > 1000m SO)



Purkey and Johnson, 2010

- Thermosteric contributions strongest around Southern Ocean, where AABW is formed
- Most rates statistically significant at 95% confidence

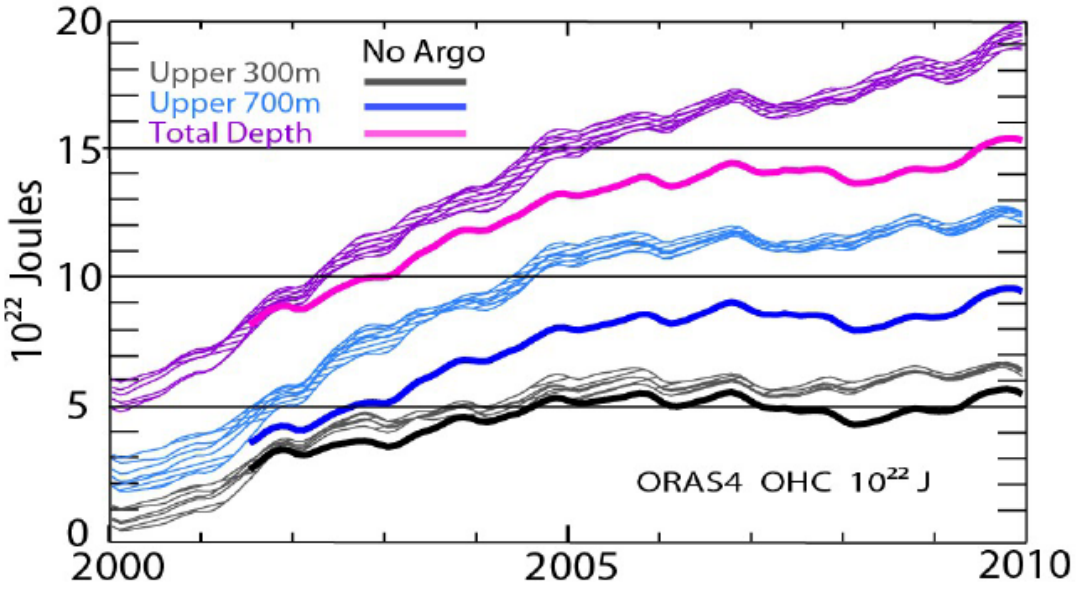
Estimates of deep ocean contributions from ORA-IP.



In the last decade, about 30% of the warming has occurred below 700 m, contributing significantly to an acceleration of the warming trend.

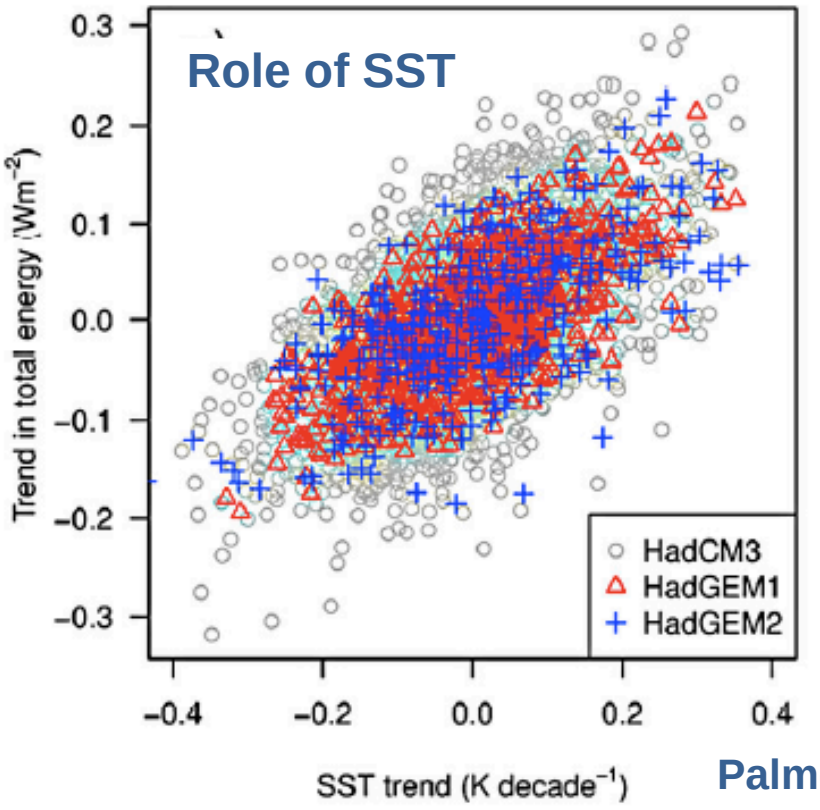
Balmaseda et al., 2013

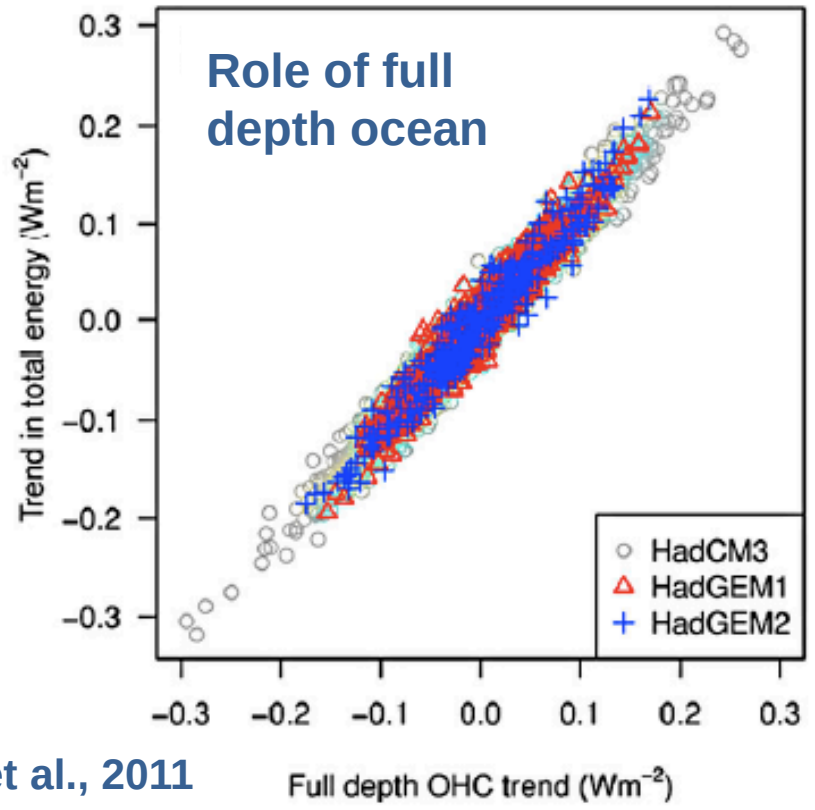
The warming below 700 m remains even when the Argo observing system is withdrawn although the trends are reduced.



Role of deep ocean in Earth's energy balance: MetOffice climate model

Decadal Variations in Net TOA Radiation, SST Trend and Ocean Heating Rate





Palmer et al., 2011

- Approximately 30% of decades show a trend in net TOA radiation and SST that are of opposite sign.
- Ocean re-distribution of heat is the primary reason for the larger scatter between SST and total energy.

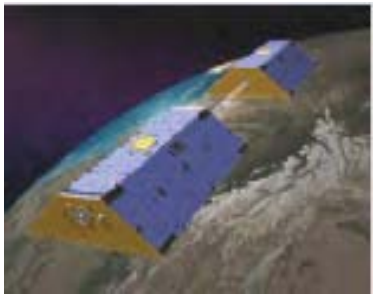
Role of undersampled regions?

$$SL_{steric}(Argo) + SL_{res} = SL_{total} - SL_{mass}$$

Argo: 2000-2012

Changes below Argo depths & Estimation errors (sampling and processing issues, systematic biases)

Altimetrie: 1993-2012



GRACE: 2002-2012

Overlapping time window for global and re-qualified data 2005-2010:
Methods developed for global estimations

von Schuckmann and Le Traon, 2011

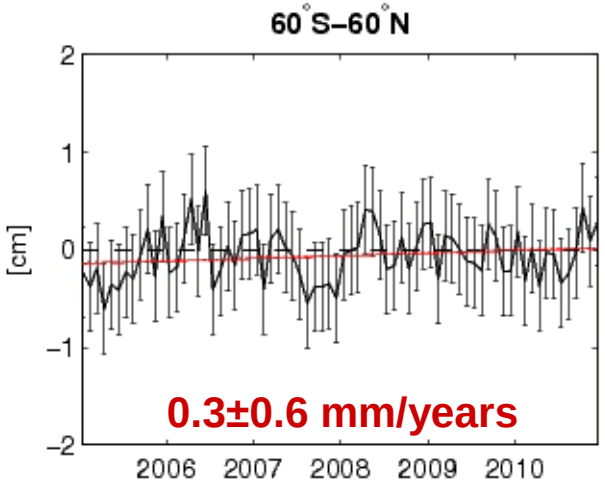
Averaged DM gridded product, AVISO

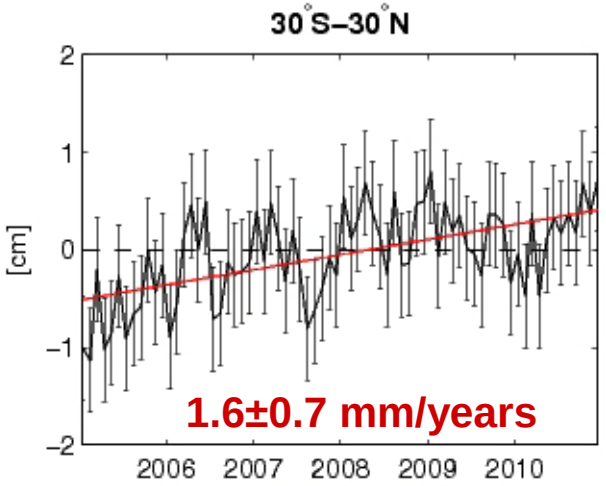
Chambers and Schröter, 2011

Role of other under-sampled regions ? $SL_{res} = SL_{total} - SL_{steric}(Argo) - SL_{mass}$

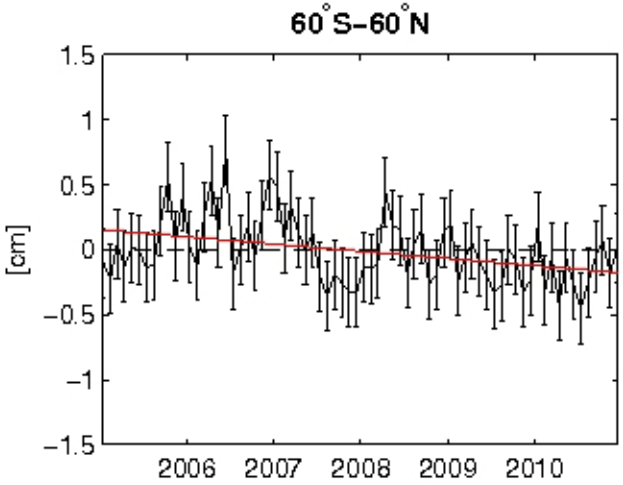
Residual of the Sea level budget: 2005-2010

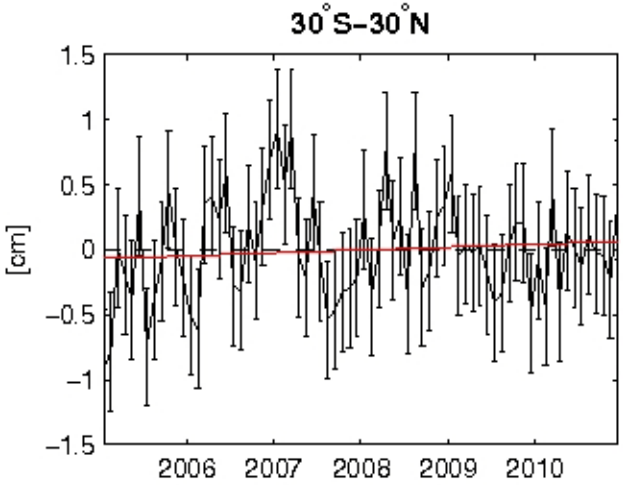
Altimeter: full grid





Altimeter: Sampled on Argo profile positions ➔ Argo sampling issue

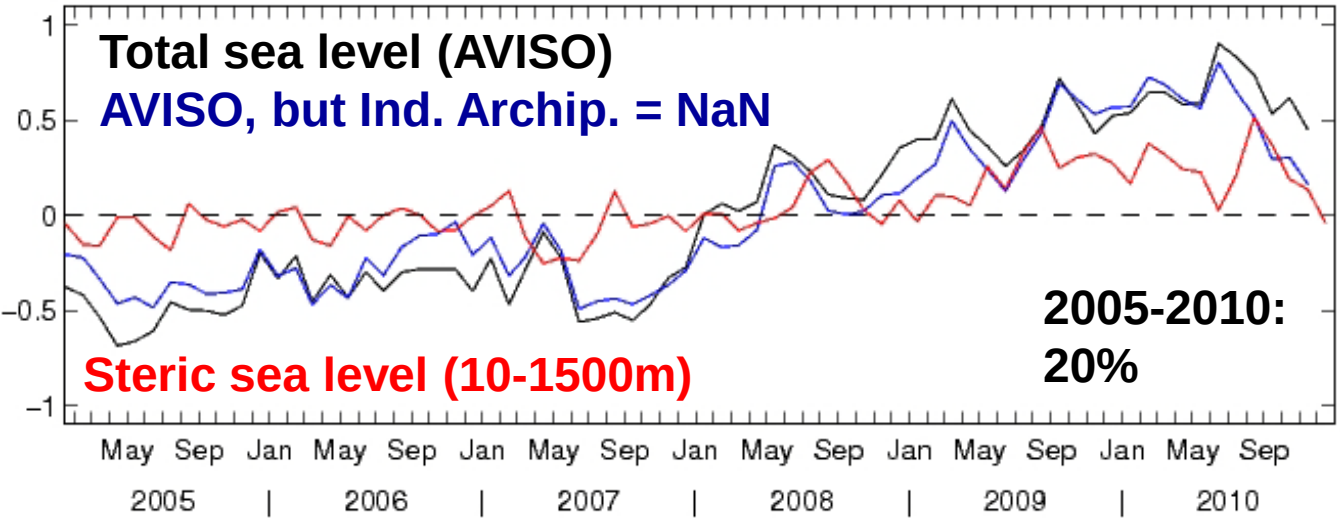


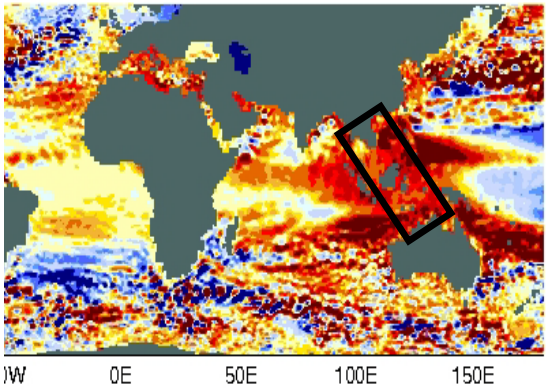


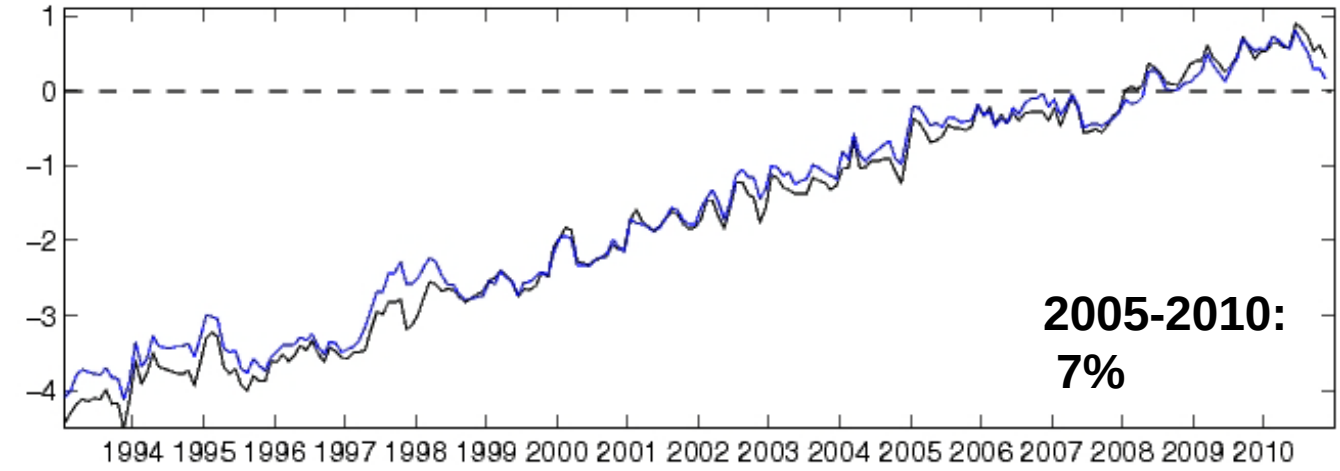
von Schuckmann et al., 2014

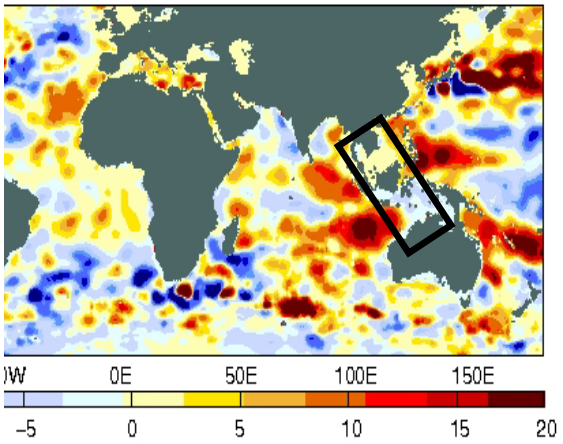
Role of other under-sampled regions ? $SL_{res} = SL_{total} - SL_{steric}(Argo) - SL_{mass}$

Underestimating sea level changes in the Indonesian Archipelago affects the global mean by 20%





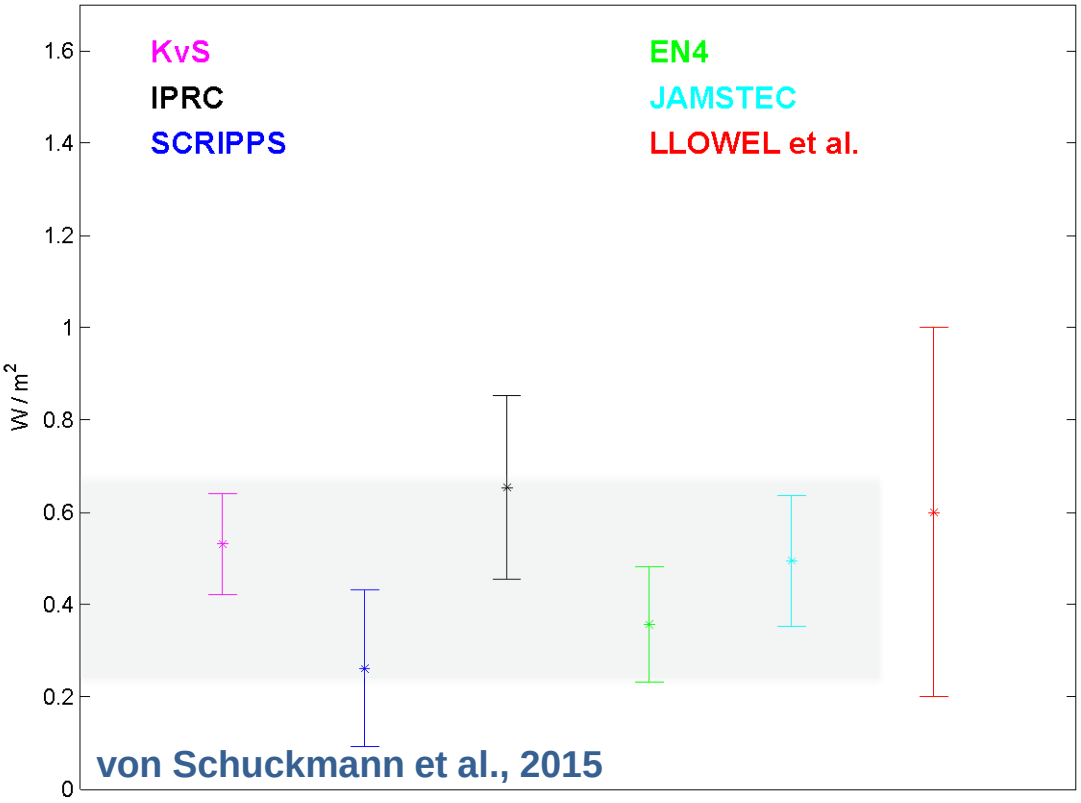




von Schuckmann et al., 2014

Other reasons for observed discrepancies between Argo products?

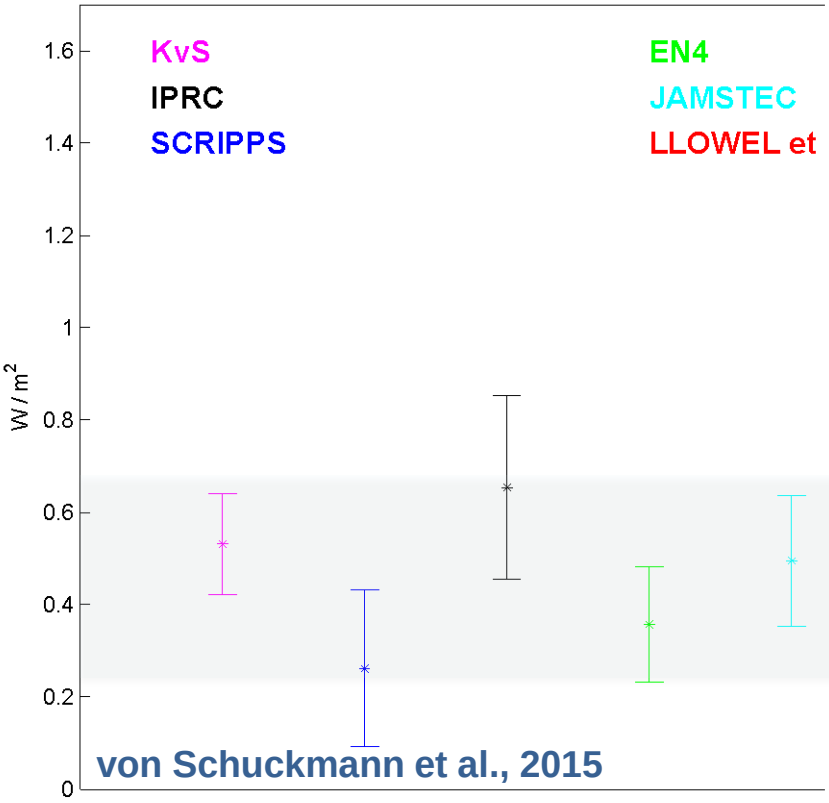
GOHC trend: 2006-2012



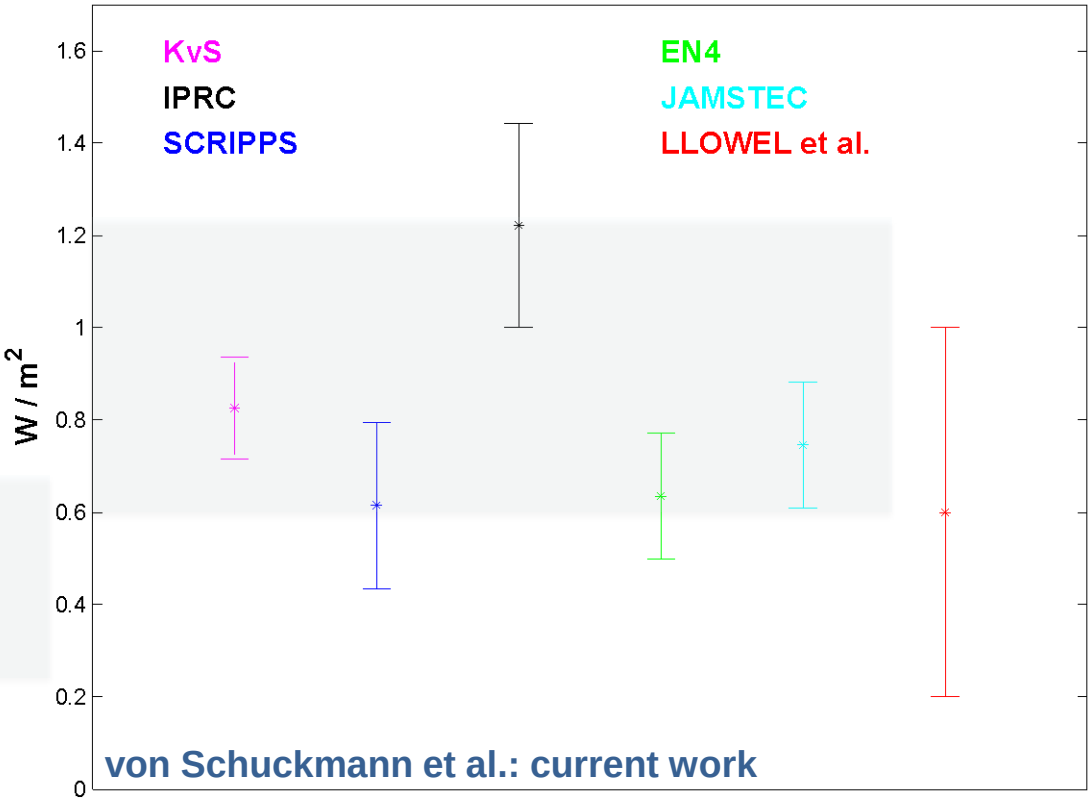
Range of decadal GOHC trend between different products:
~0.2 to 0.7 Wm-2

Other reasons for observed discrepancies between Argo products?

GOHC trend: 2006-2012



GOHC trend: 2006-2014

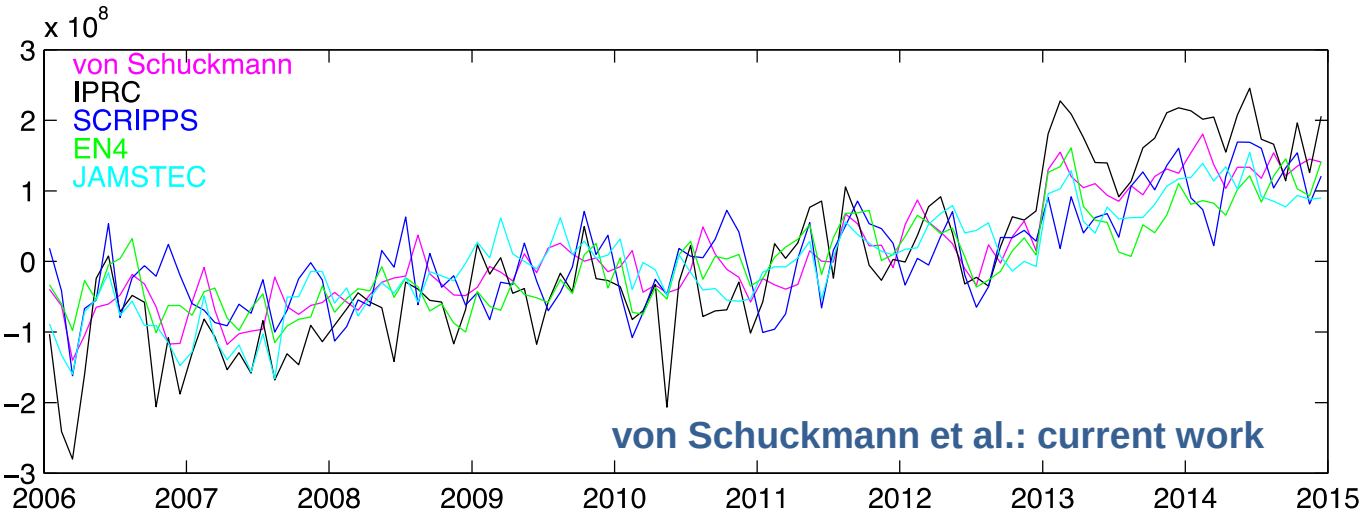


Range of decadal GOHC trend between different products: ~0.2 to 0.7 Wm-2

?

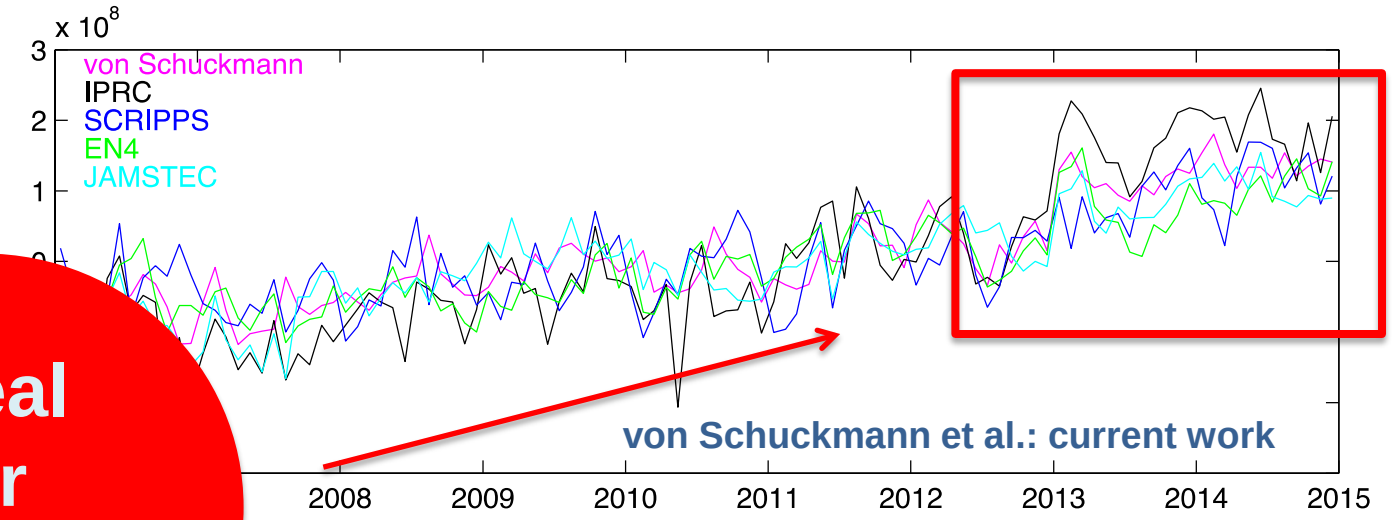
Range of decadal GOHC trend between different products: ~0.6 to 1.2 Wm-2

Other reasons for observed discrepancies between Argo products?



Spurious “jump” in GOHC in almost all Argo products: brusque change of GOHC from Dec. 2012 to Jan 2013, and GOHC continue at a somewhat higher level

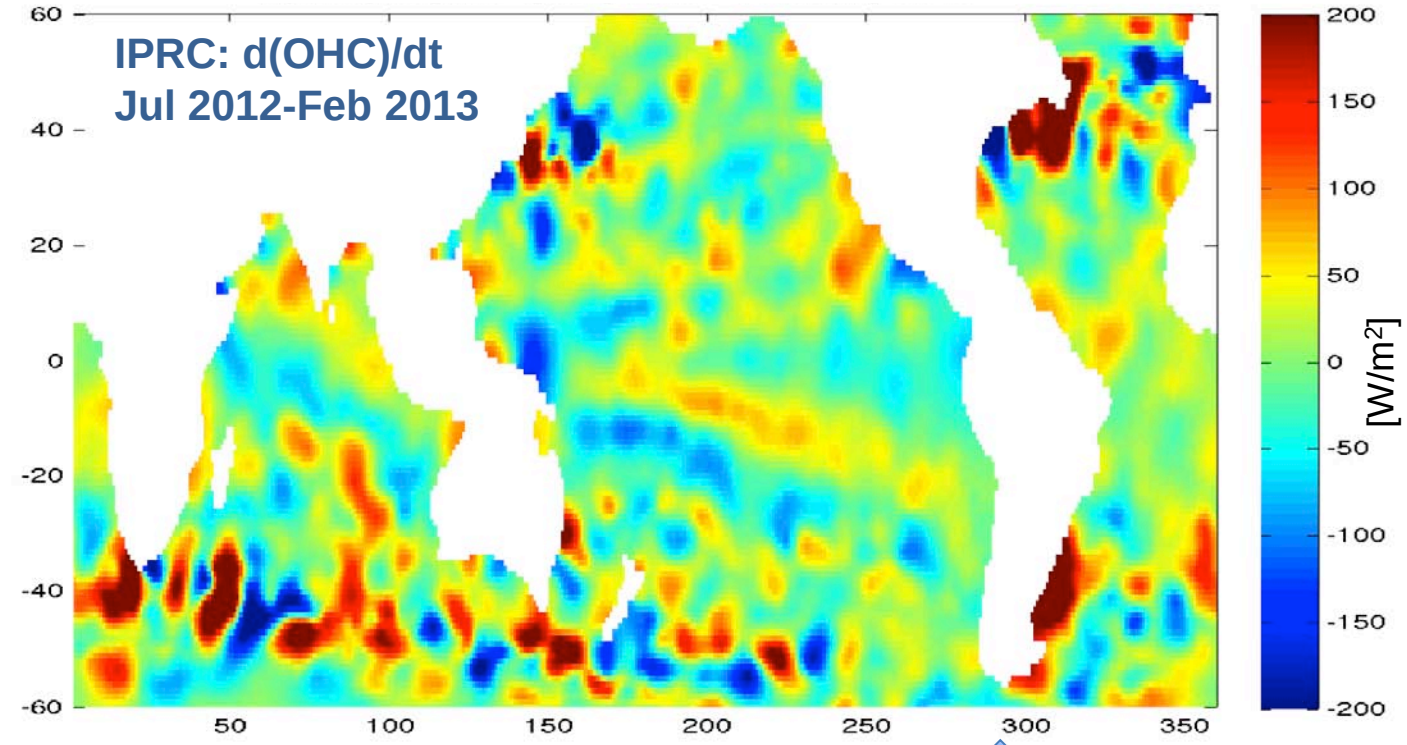
Other reasons for observed discrepancies between Argo products?

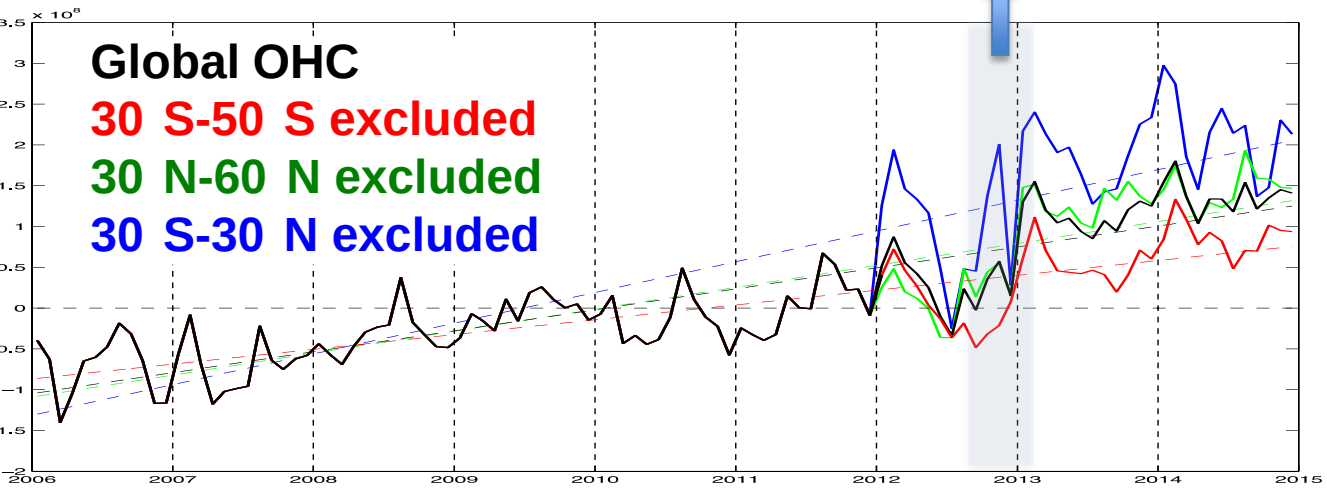


Real or spurious?

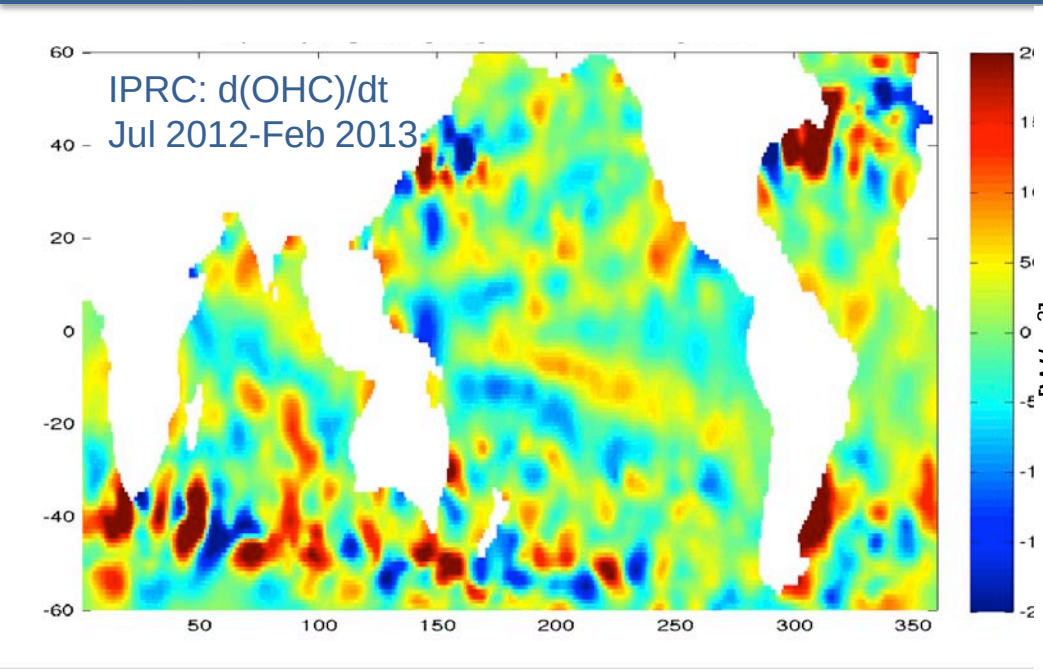
Spurious "jump" in GOHC in almost all Argo products: brusque change of GOHC from Dec. 2012 to Jan 2013, and GOHC continue at a somewhat higher level

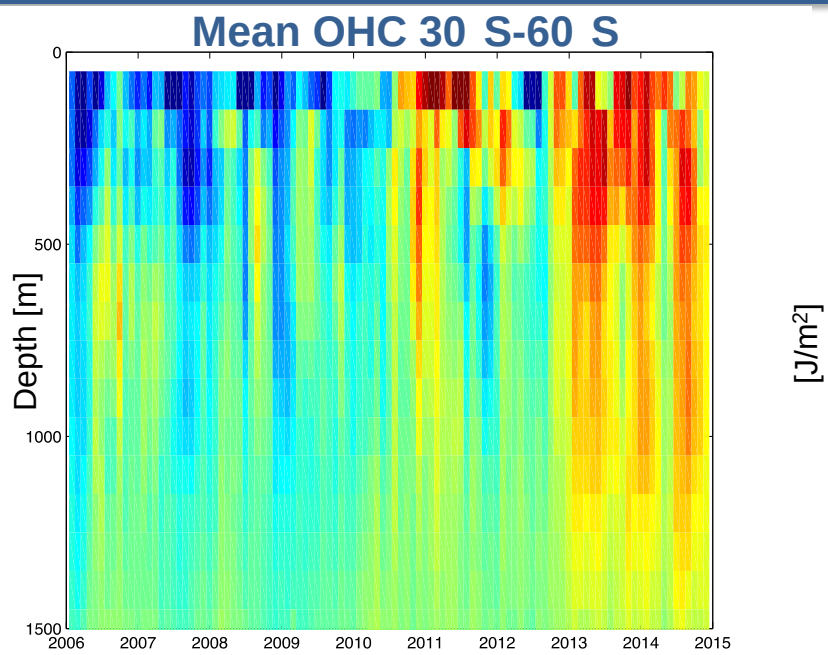
Other reasons for observed discrepancies between Argo products?

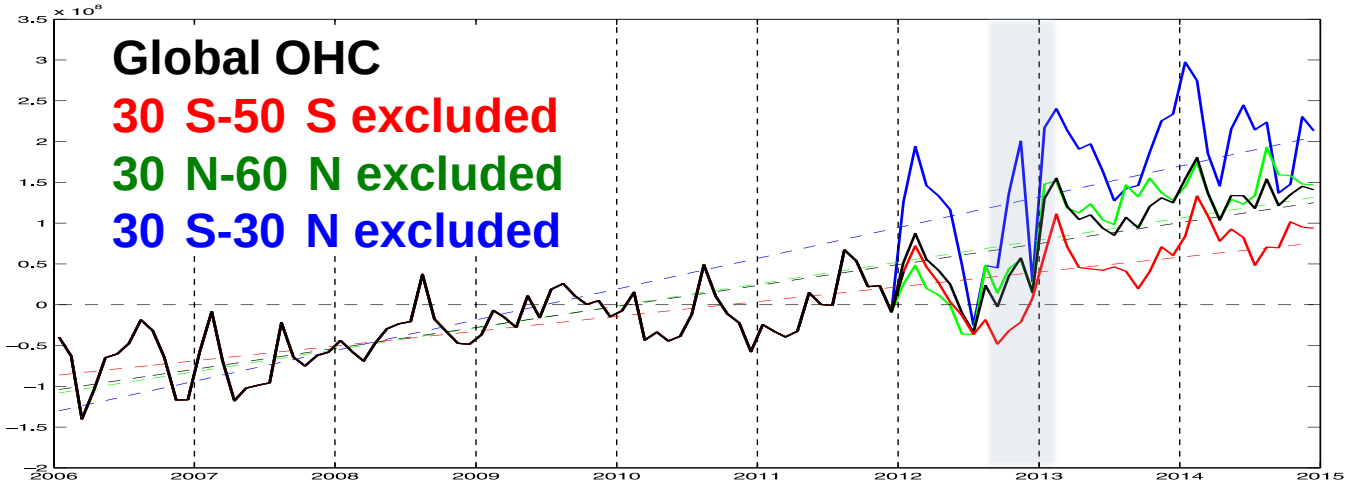




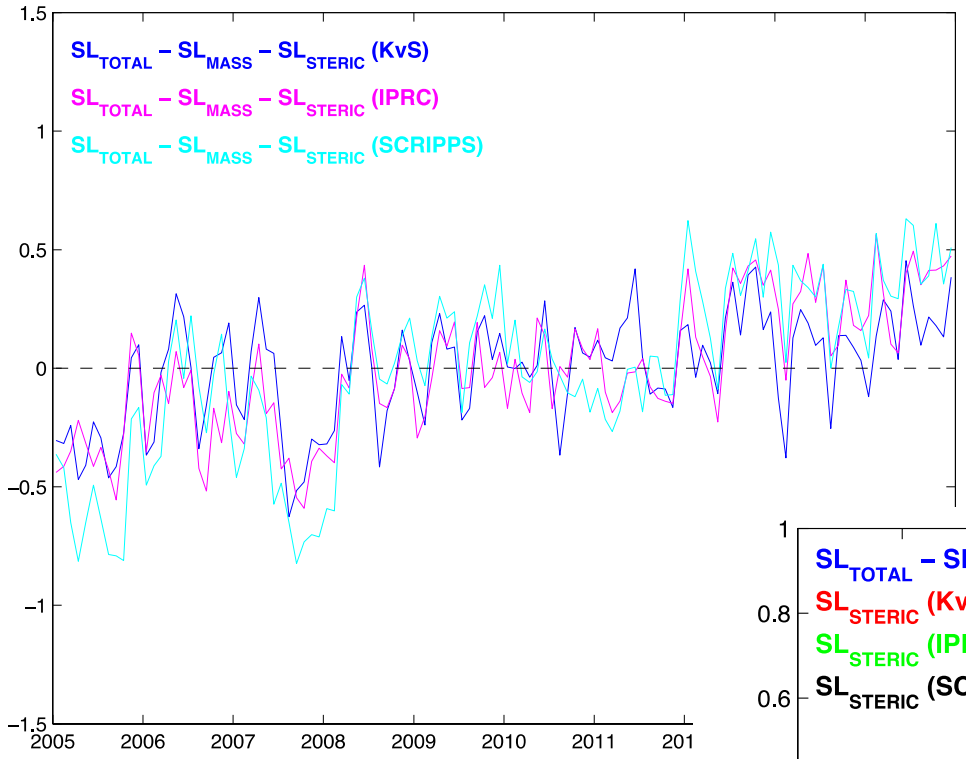
Other reasons for observed discrepancies between Argo products?



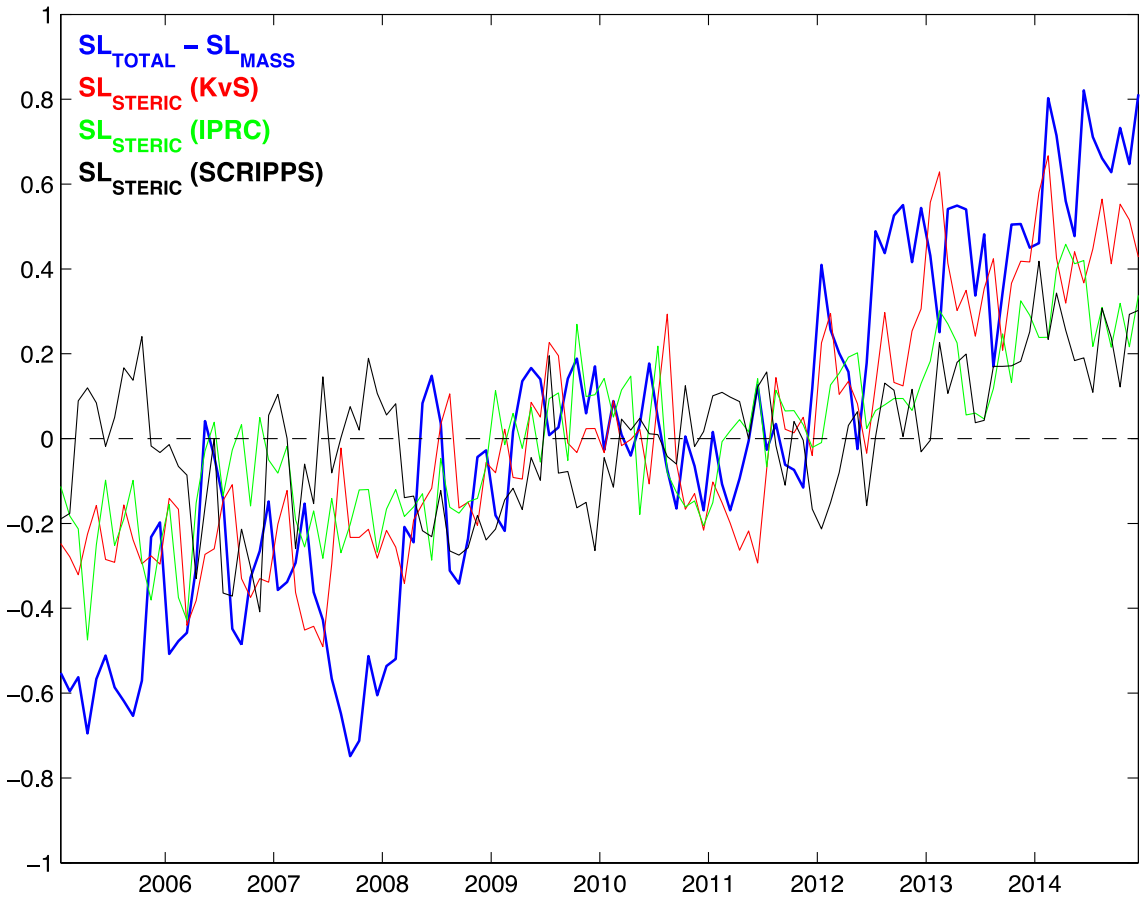




Quality assessment via sea level budget



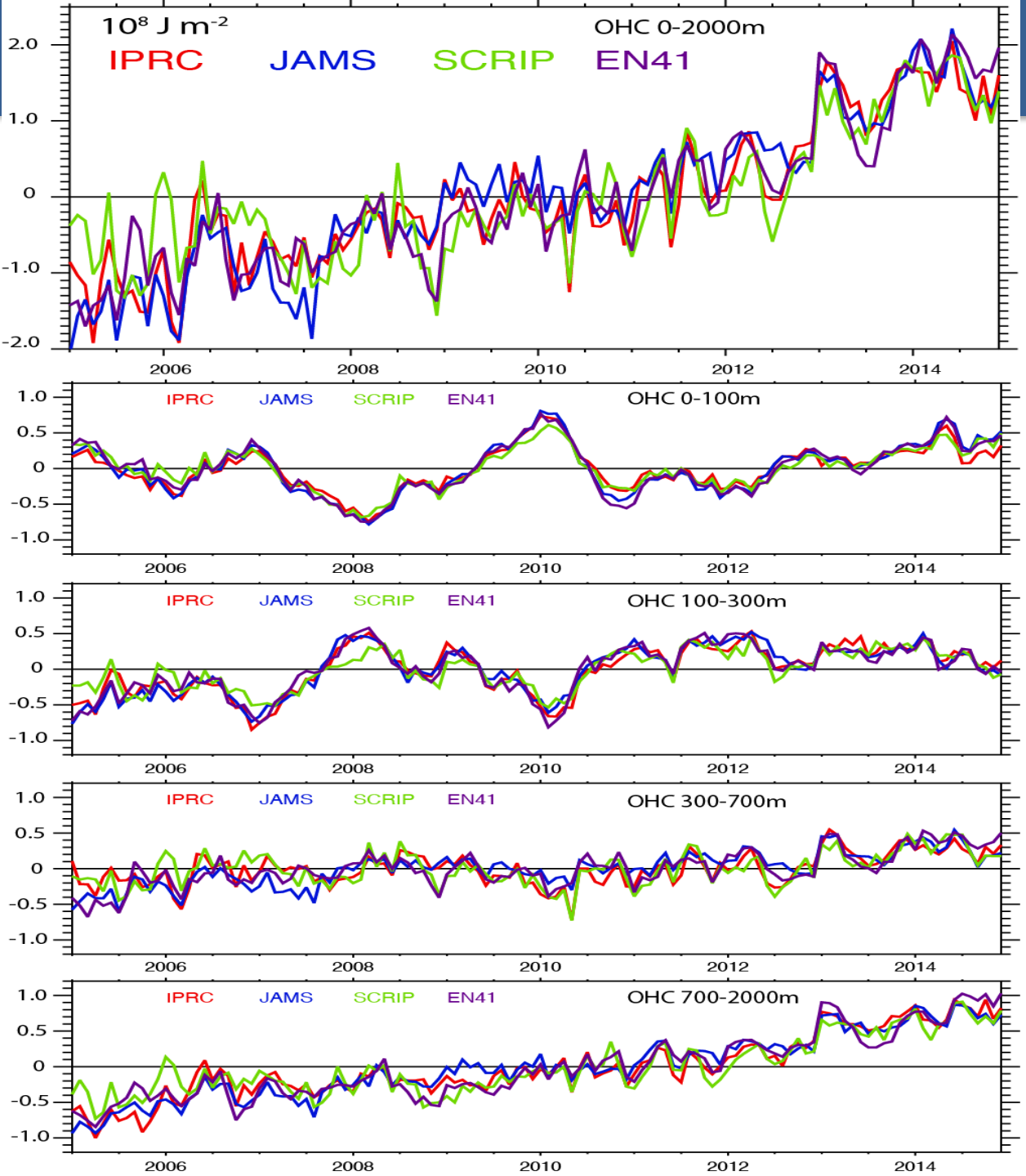
Intercomparison of independent observing systems to check “jump”



➔ “jump” seems to be not spourious and appears below thermocline depth

… BUT: work in progress …

OHC 2005-14
Courtesy: K. Trenberth

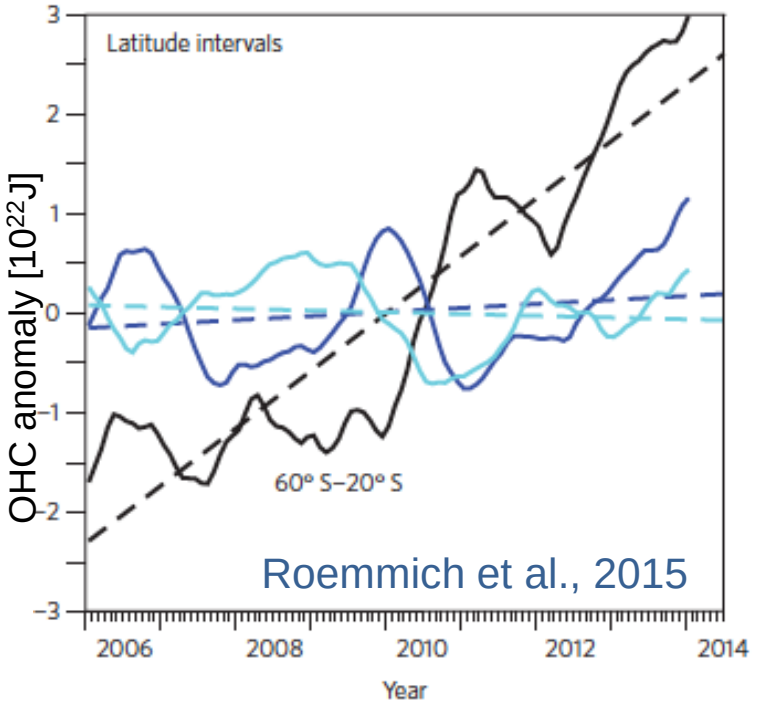


56% of trend 0-700m

… BUT: Southern Ocean signal accumulated in the 700-2000m depth layer.

Other reasons for observed discrepancies between Argo products?

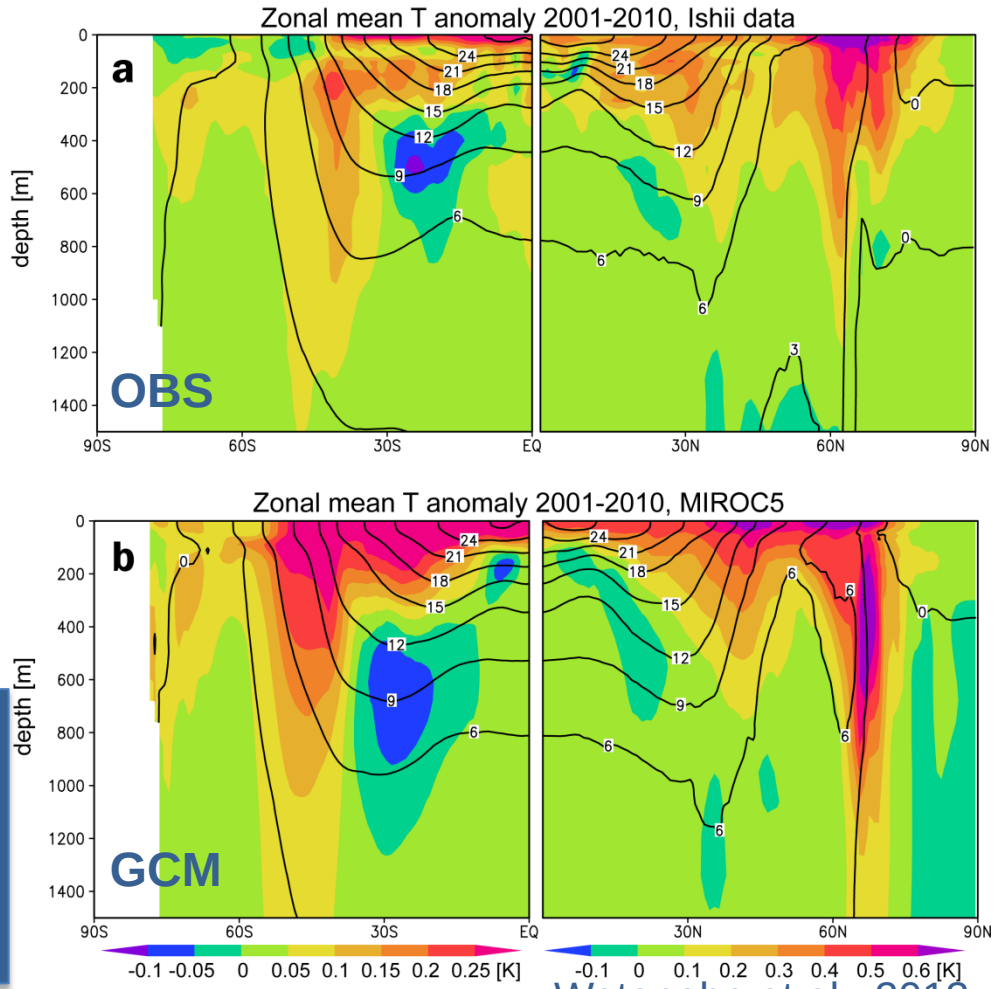
Most of the heat gain (67 to 98%) occurred in the Southern Hemisphere extratropical ocean.



Roemmich et al., 2015

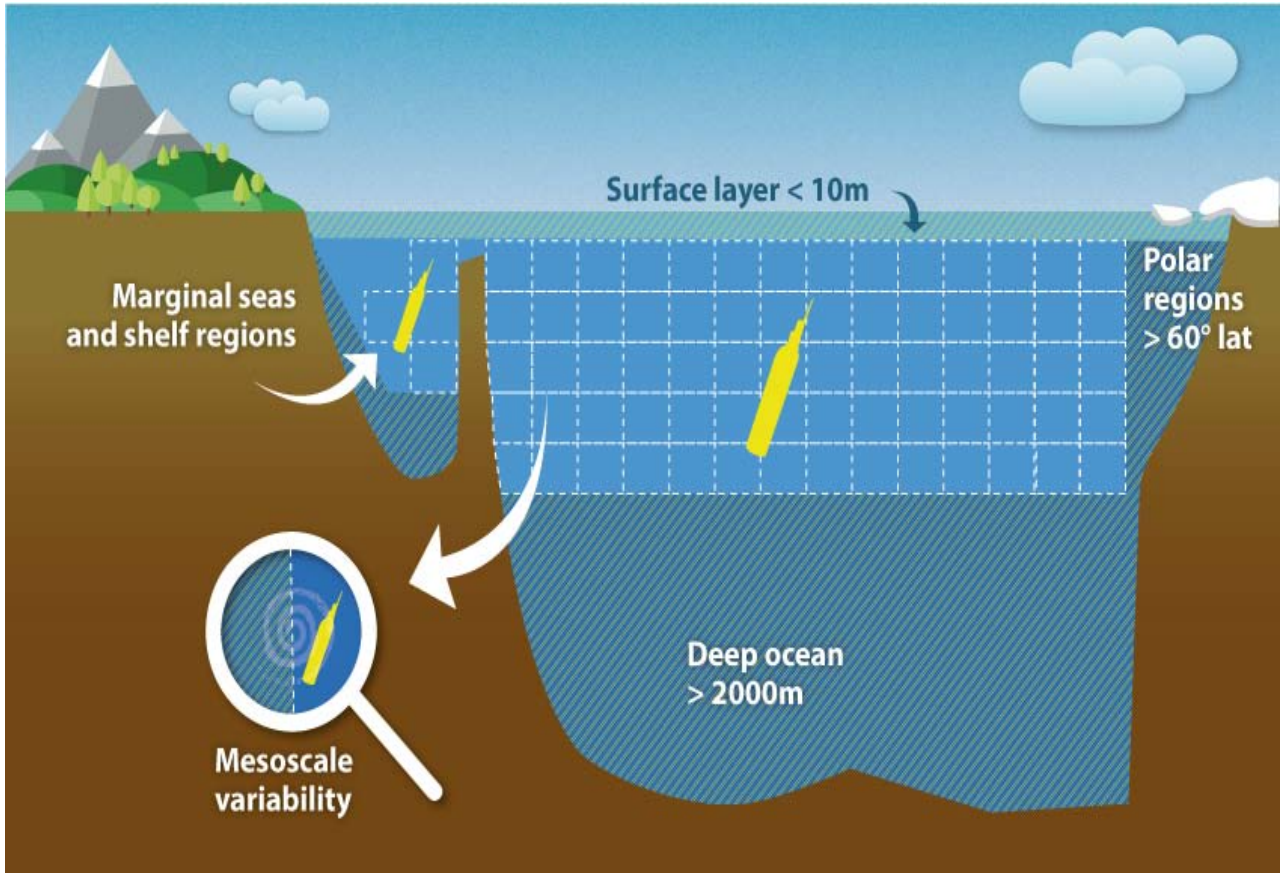
Interplay between steadily increasing greenhouse gas forcing and internally generated climate variability?

Surface heat appears to penetrate at around 50 S, where the wind-induced Ekman down-welling may have intensified in recent decades



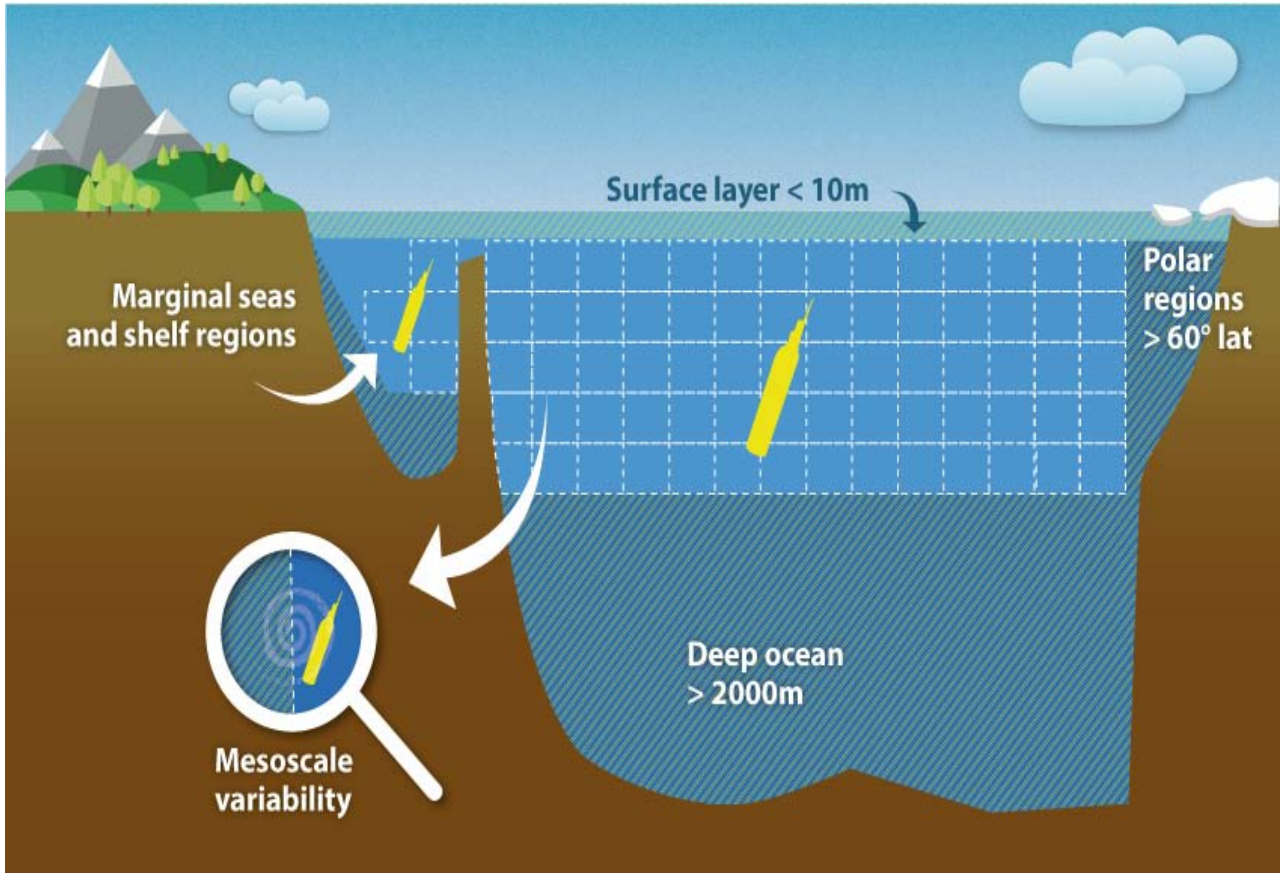
Watanabe et al., 2013

Argo –a comment



Argo's greatest contributions to observing the global oceans are still in the future, but its global span is clearly transforming the capability to observe climate-related changes.

Argo – a comment

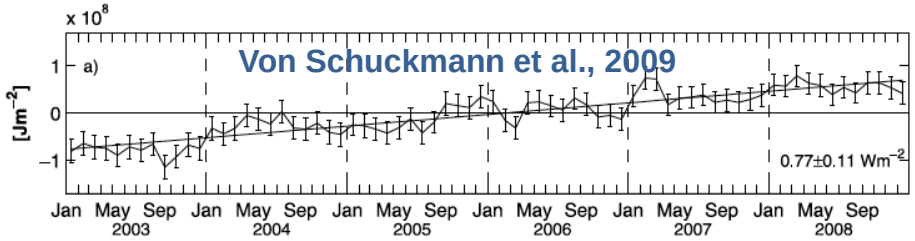


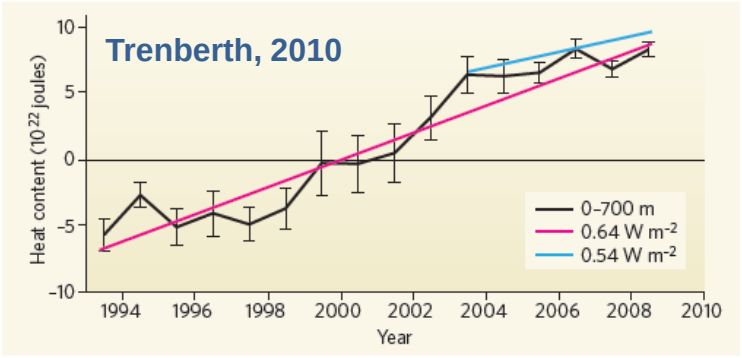
Argo's greatest contributions to observing the global oceans are still in the future, but its global span is clearly transforming the capability to observe climate-related changes.

Argo – a comment

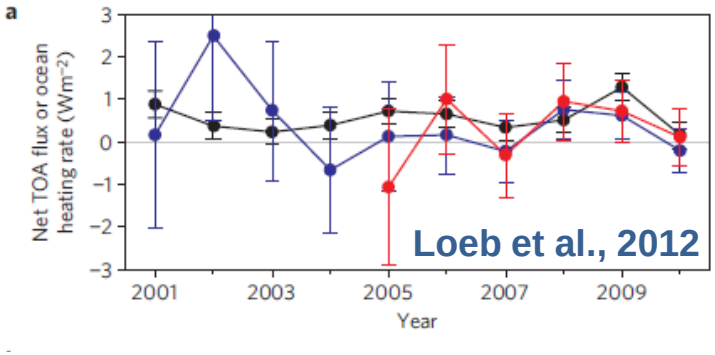
Argo is already the principal base for climate research …

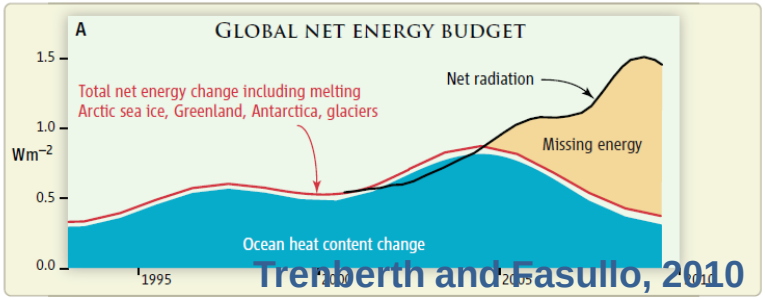
… first link to heat storage in the deep ocean



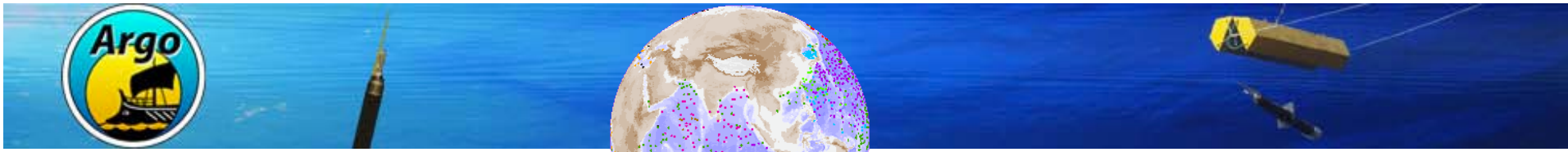


… intense discussions and improvements on energy inventory





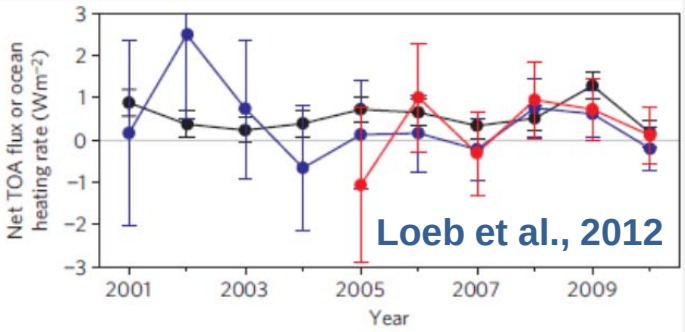
… fundamental basis to optimize our global ocean in situ observing system in the future



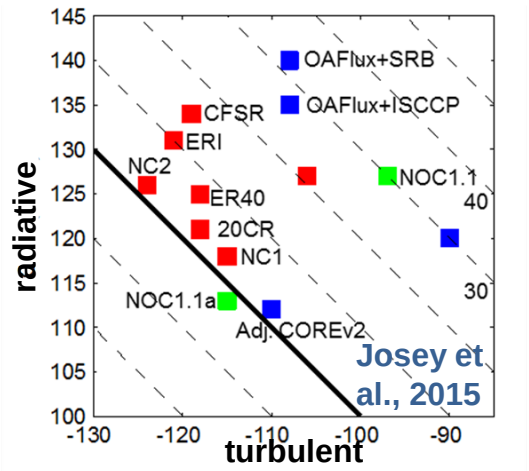
… sea level budget, reanalysis systems, …

Determining Earth's energy imbalance: 4 different approaches

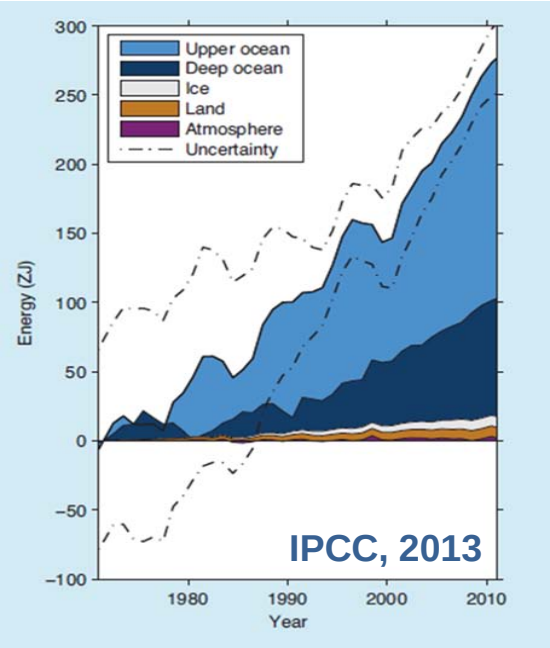
Radiation at TOA



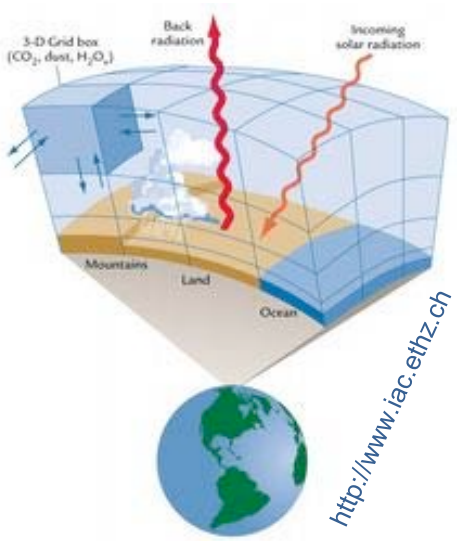
Surface flux



Ocean heat content



Climate models

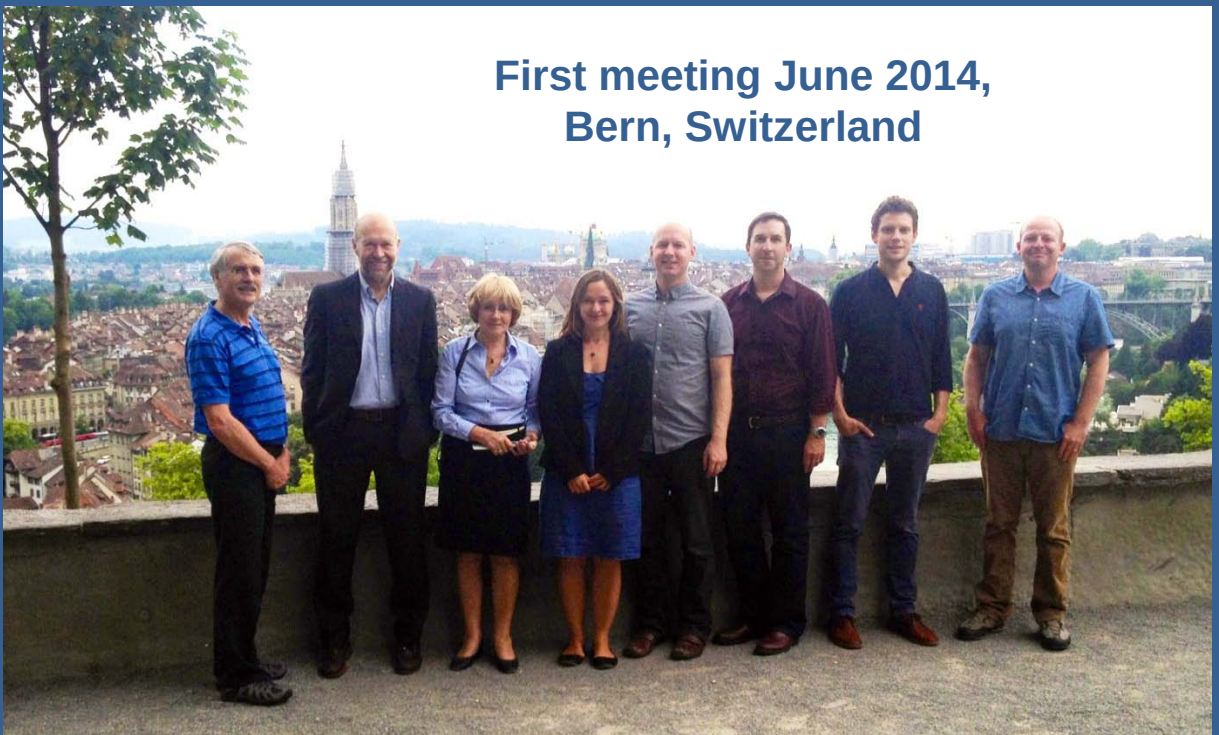


Earth's Energy Imbalance.

Currently +0.5 to 1 Wm^{-2}

The absolute measure of the Earth Energy Imbalance and its changes over time are vital pieces of information related to climate change as this is the single quantity defining the status of global climate change and expectations for continued global warming.

ISSI working group: "Consistency of Integrated Observing Systems monitoring the energy flows in the Earth System"



First meeting June 2014, Bern, Switzerland

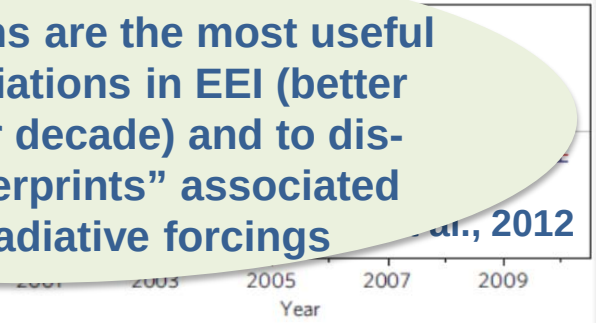
K. von Schuckmann
A. Cazenave, D. Chambers, J. Hansen, S. Josey, Y. Kosaka, N. Loeb, P.P. Mathieu, B. Meyssignac, M. Palmer, K. Trenberth, M. Wild

Perspective paper NCC, in press
(von Schuckmann et al., 2015)

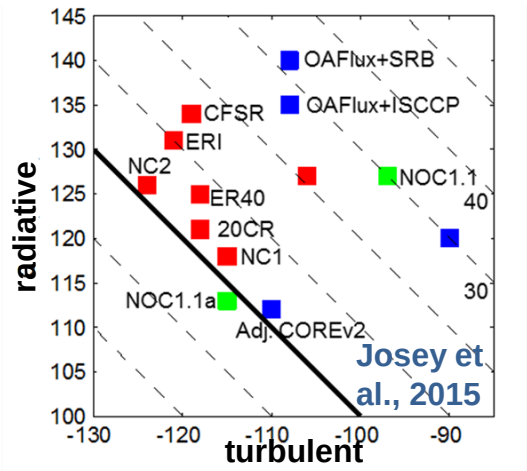
Detect changes in EEI with an accuracy of < 0.1 Wm-2 on multiannual-to-decadal timescales and < 0.5 Wm-2 on subannual-to-interannual timescales

von Schuckmann et al., 2015, under review

Satellite observations are the most useful means to track variations in EEI (better than 0.3 W m-2 per decade) and to dis-entangle the "fingerprints" associated with different radiative forcings



Surface flux



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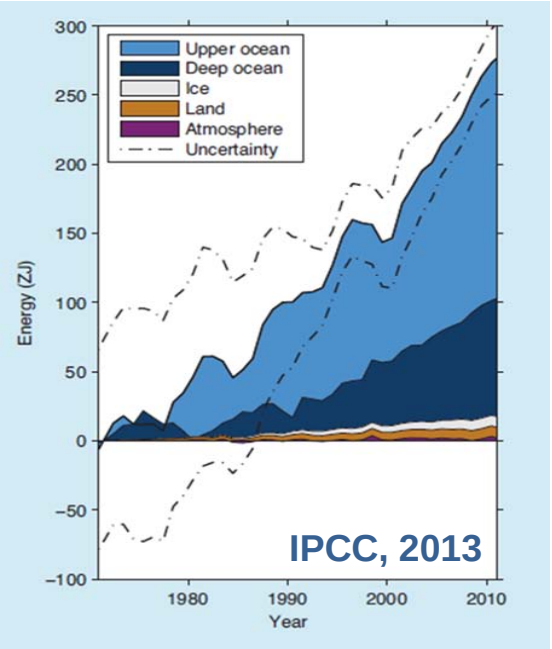
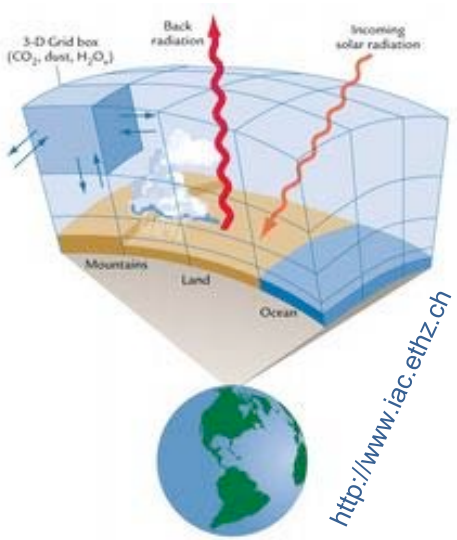


Climate models



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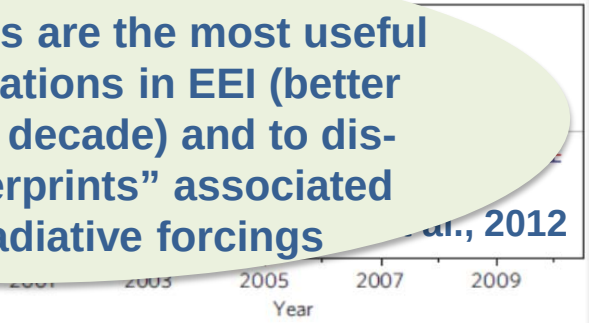
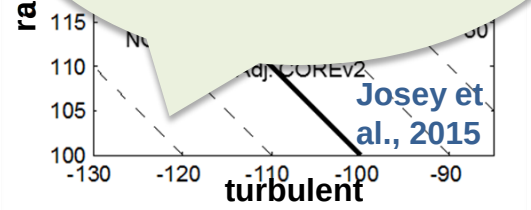


Surface flux

Still large uncertainties, but... improvements under the way through regional budget constraints



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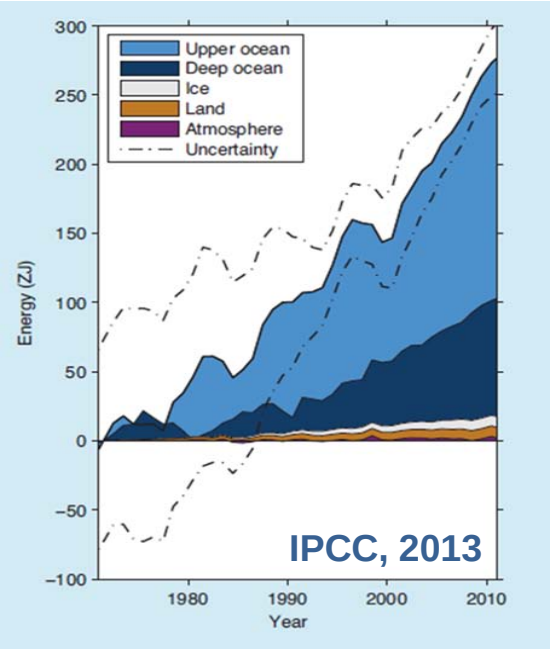

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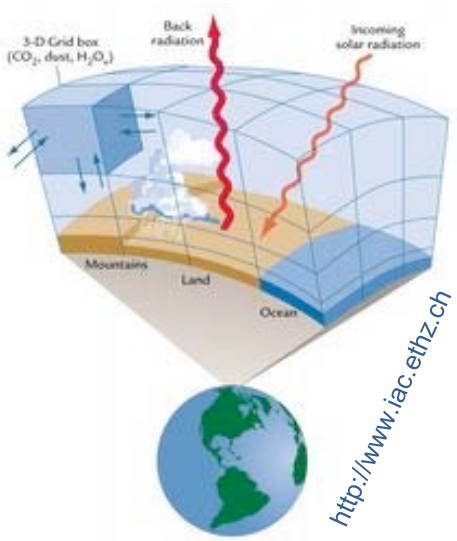
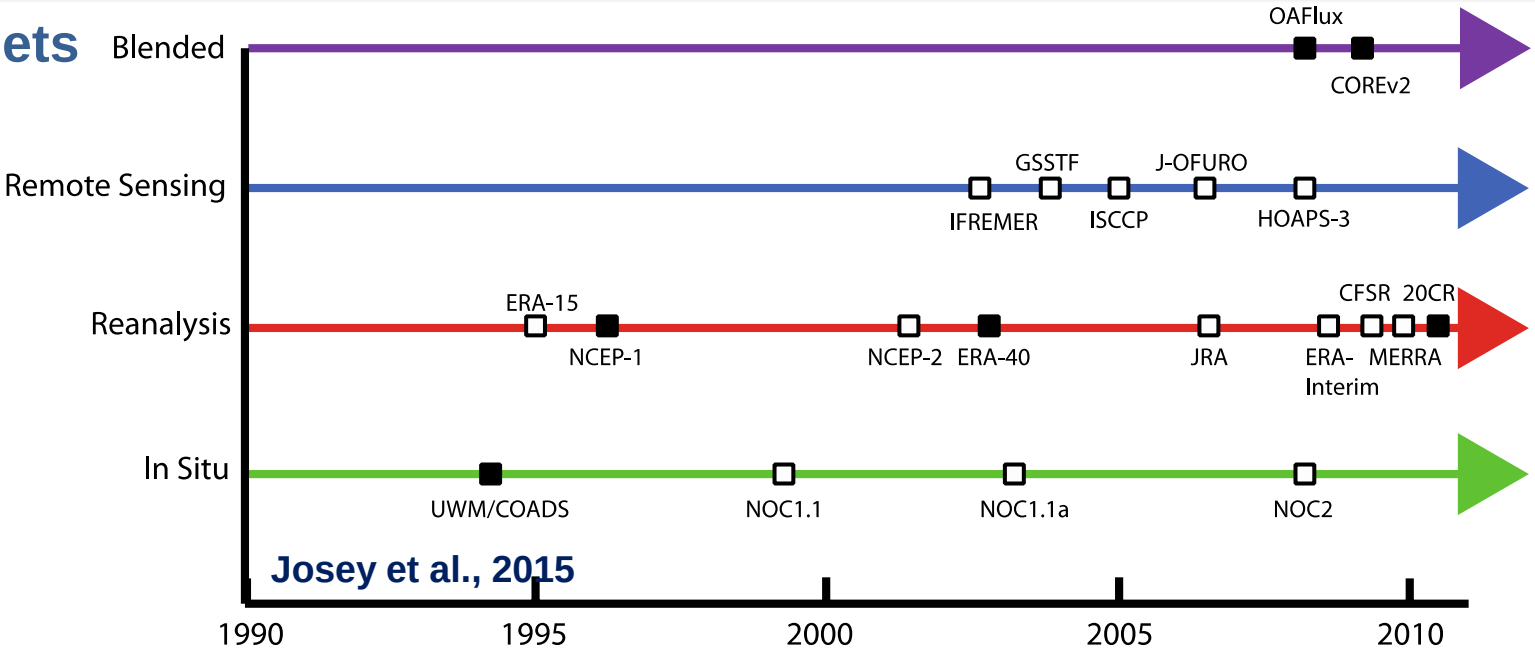


Air-Sea fluxes

Courtesy: S. Josey

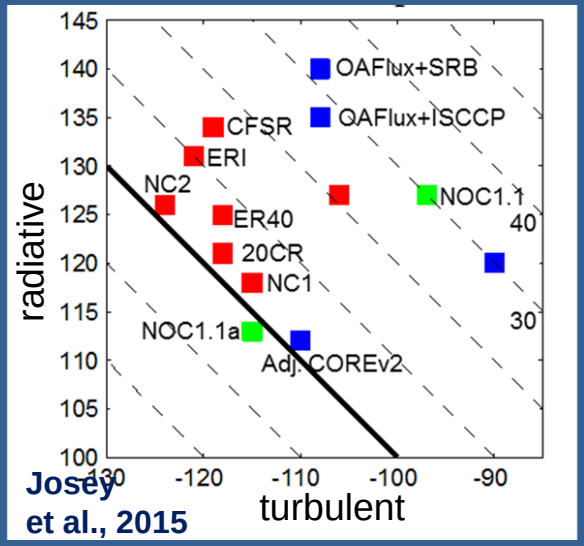
Flux Datasets



Global ocean heat budget closure.

Still a long way from obtaining well-based closure of the budget, products tend to be biased warm by 10-25 Wm^{-2}. Bias is probably due to multiple sources of error at the 2-5 Wm^{-2} level.

Flux product assessment



Towards Improved Estimates of Ocean Heat Flux (ESA-OHF): OBJECTIVES

- Establishing a reference input dataset (ensemble of daily and monthly global ocean heat turbulent flux products, 0.5deg x 0.5deg in space, 10 years)
- Developing a Flux Data Portal to access, share and foster the use of the reference data set and flux products with the scientific community, and to enable easy inter-comparison between products and observations.
- Perform a feasibility study to evaluate the quality, consistency, accuracies and sources of uncertainties of the various flux products.
- Coordinating with relevant partners, activities and international programs, such as CLIVAR, GSOP, GEWEX and SeaFlux.

www.oceanheatflux.org

esa Ifremer PML REMOTE SENSING GROUP

mio Mediterranean Institute of Oceanography

University of Reading

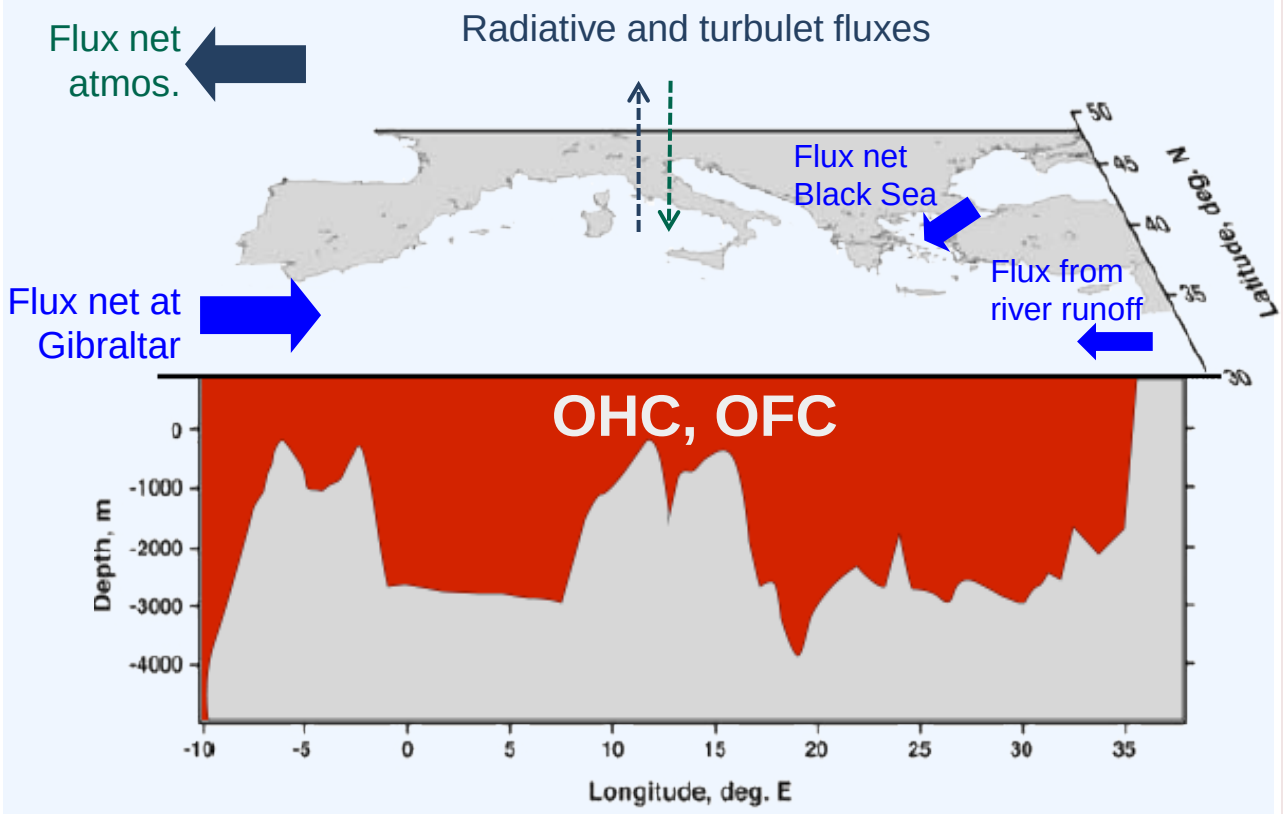
UNIVERSITY OF MARYLAND 18 56

DWD

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

NERSC

Recommendation to step from “local validation” to “regional validation” CONCEPT of CAGES (Bretherton et al., 1982; Yu et al., 2012; WCRP, 2013)



Lateral flux

– d(OHC)/dt

Budget

$$OHC = \int_z \rho c_p T_0(z) dz$$

$$\frac{d(HB)}{dt} = \frac{d(OHC)}{dt} - HF_{lateral}$$

Estimates of physical budget components to implement the approach:

1. a reference estimates of box mean temporal changes for OHC
2. one reference of box mean radiative flux estimate
3. one reference estimate of lateral HF at the boundaries of each box
4. a set of box mean turbulent fluxes from the “OHF reference data set”

Detect changes in EEI with an accuracy of < 0.1 Wm-2 on multiannual-to-decadal timescales and < 0.5 Wm-2 on subannual-to-interannual timescales

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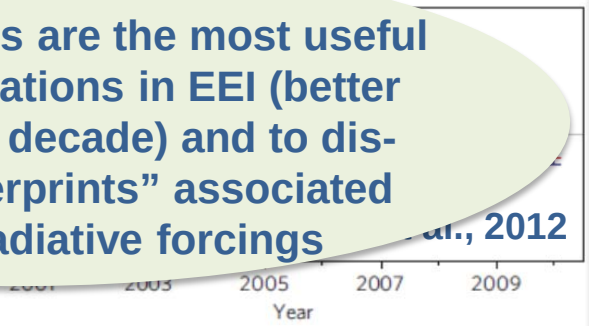

Surface flux

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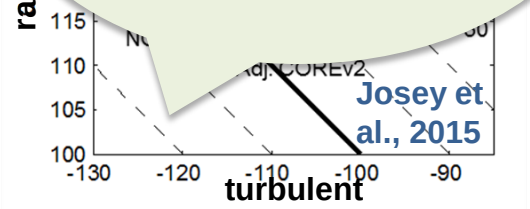
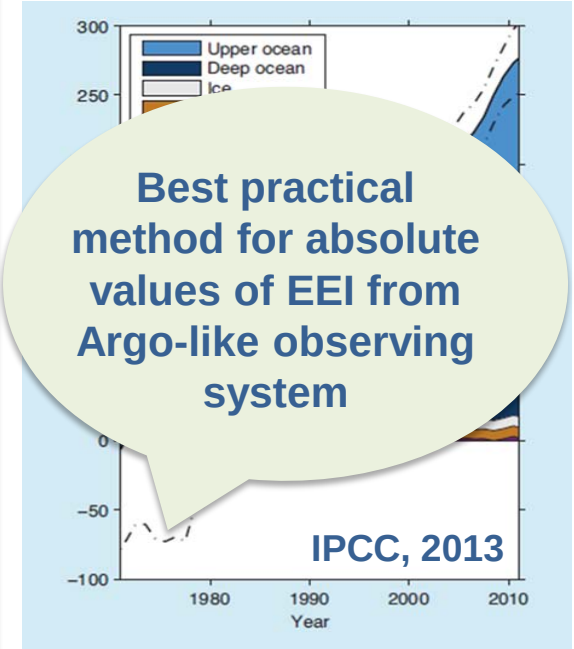
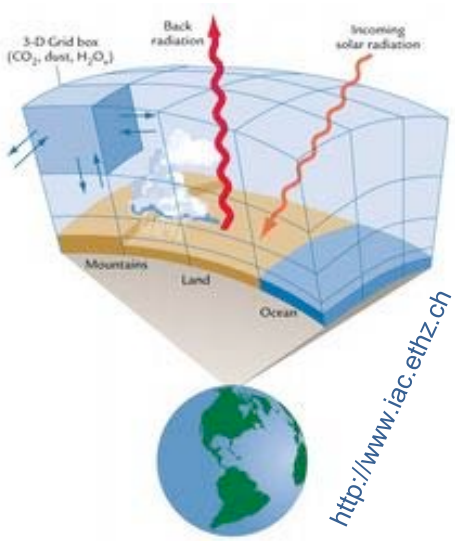


Ocean heat content

Best practical method for absolute values of EEI from Argo-like observing system



Climate models



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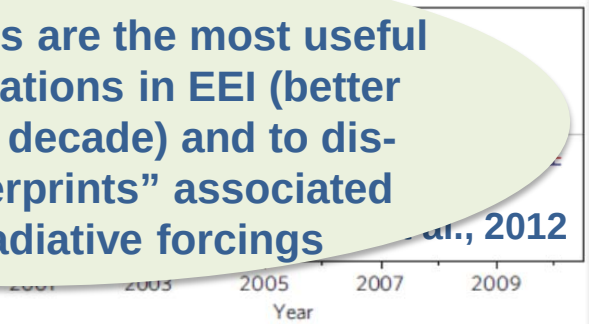

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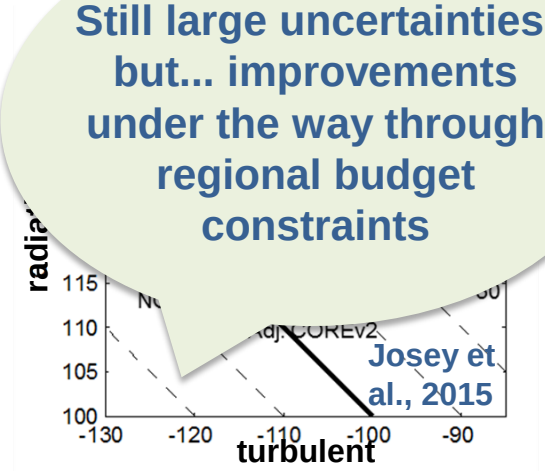

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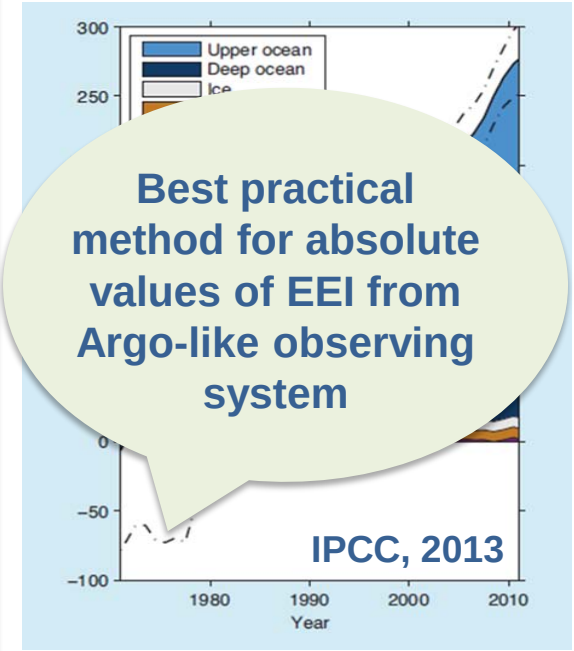


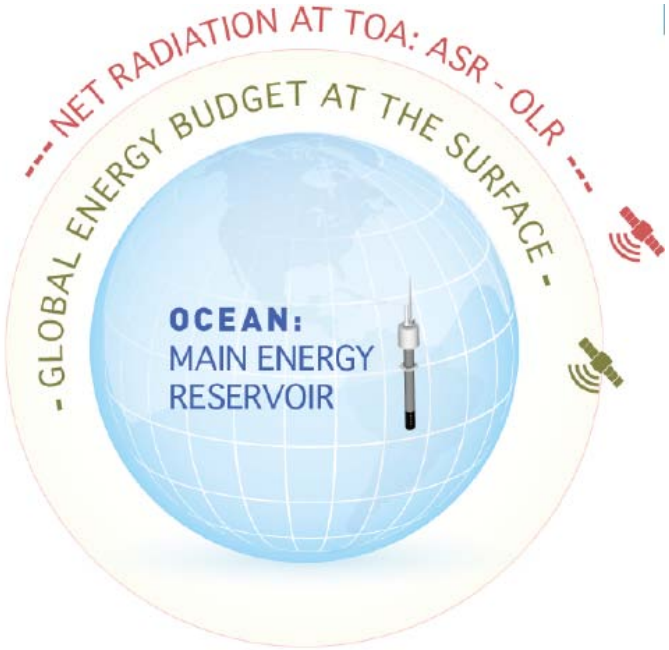
Climate models

Can provide greater insights into the underlying mechanisms, but implementation of radiative forcings needs to be improved

CLIVAR research focus CONCEPT-HEAT:

Consistency between planetary energy balance and ocean heat storage

An overall goal is to **bring together different climate research communities** all concerned with the energy flows in the Earth's System to advance on the **understanding of the uncertainties through budget constraints**:



- **Atmospheric radiation**
- **Ocean Heat Content**
- **Earth's surface fluxes**
- **Climate variability and change**
- **Data assimilation & operational services (R&D)**
- **Climate projection**
- **Global sea level**

Remote sensing	In situ	Reanalysis systems	Numerical model

CLIVAR research focus CONCEPT-HEAT:

Consistency between planetary energy balance and ocean heat storage

Key scientific questions

- Question A: **What is the magnitude and the uncertainties of our estimates of Earth's energy imbalance (EEI), and how does it vary over time?**
- Question B: **Can consistency between planetary heat balance and ocean heat storage achieved and what are the major limitations?**
- Question C: **How are TOA net radiation and ocean heating rate distributed in space and time?**
- Question D: **How can we improve validation requirements for and from coupled climate models to improve estimates of EEI?**
- Question E: **How can we better constrain the surface energy fluxes and their spatio-temporal variations at regional scale?**

Scientific steering team:

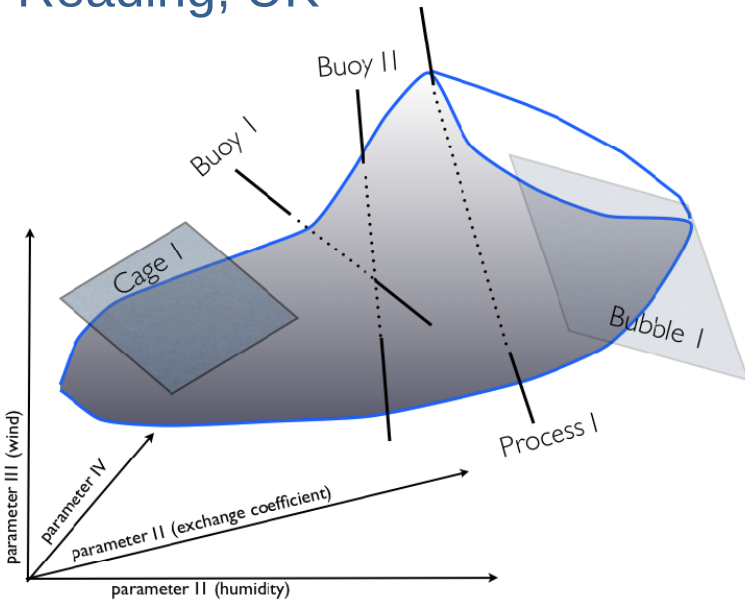
Co-Chairs: K. von Schuckmann, K. Trenberth

Members: C.-A. Clayson, S. Gulev, C. Domingues, K. Haines, N. Loeb, P.P. Mathieu, M. Palmer, M. Wild, B. Weller, Y. Xue

CLIVAR CONCEPT-HEAT: Development

Joint CLIVAR-ESA scientific consultation workshop on: Earth Observations Measurement Constraints on OHC 03.-04. July 2013, University of Reading, UK

Magdalena Balmaseda, Matthew Palmer, Roger Barry, Richard Allan, Keith Haines, Sergey Gulev, Christopher Merchant, Karina von Schuckmann, Tony Lee, Bernard Barnier, Norman Loeb, Anny Cazenave, Andrea Storto, Svetlana Jevrejeva, Liz Kent, Caroline Katsman, Rowan Sutton, Aida Alvera Azcarate, Rainer Hollmann, Bertrand Chapron, Carol Ann Clayson, Pierre-Philippe Mathieu, Diego Fernandez, Gabriel Jordà, Nico Caltabiano, Gregory Johnson, Josh Willis

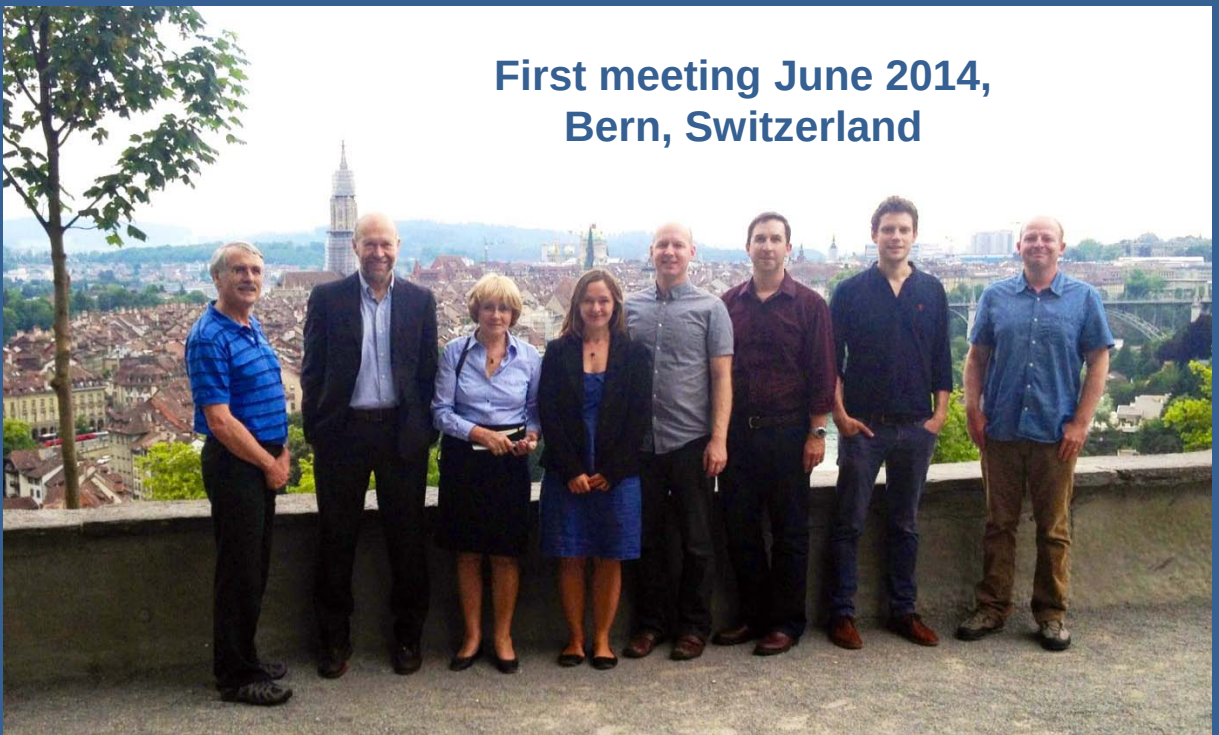


ESA – STSE
Ocean heat flux
www.oceanheatfluf.org

CLIVAR CONCEPT-HEAT: Development

The absolute measure of the Earth Energy Imbalance and its changes over time are vital pieces of information related to climate change as this is the single quantity defining the status of global climate change and expectations for continued global warming.

ISSI working group: "Consistency of Integrated Observing Systems monitoring the energy flows in the Earth System"



First meeting June 2014, Bern, Switzerland

K. von Schuckmann
A. Cazenave, D. Chambers, J. Hansen, S. Josey, Y. Kosaka, N. Loeb, P.P. Mathieu, B. Meyssignac, M. Palmer, K. Trenberth, M. Wild

Perspective paper NCC accepted
(von Schuckmann et al., 2015)

CLIVAR CONCEPT-HEAT: Development

Break-out session during Pan-CLIVAR meeting (July 2014)

.. and **SEVERAL** side-discussion in smaller groups

➔ Development of key scientific questions

➔ Basis for the development of the CONCEPT-HEAT white paper

CLIVAR research focus CONCEPT-HEAT:

Consistency between planetary energy balance and ocean heat storage

First CONCEPT-HEAT workshop, Met Office, Exeter (29.09.-01.10.2015)

CLIVAR research focus CONCEPT-HEAT:

First CONCEPT-HEAT workshop, Met Office, Exeter (29.09.-01.10.2015)

Earth's Energy Imbalance (EEI): most fundamental measure for climate change

FINDINGS

- Estimate EEI locally and as a function of time
- The estimation of Ocean Heat Content (OHC) plays a key role for climate science
- Studies of energy flows in climate modes

RECOMMENDATIONS

Concept of CAGEs:
- Radiation flux and atmos. energy transport divergence;
- ocean transport divergence & changes in OHC;
- directly computing air-sea fluxes.

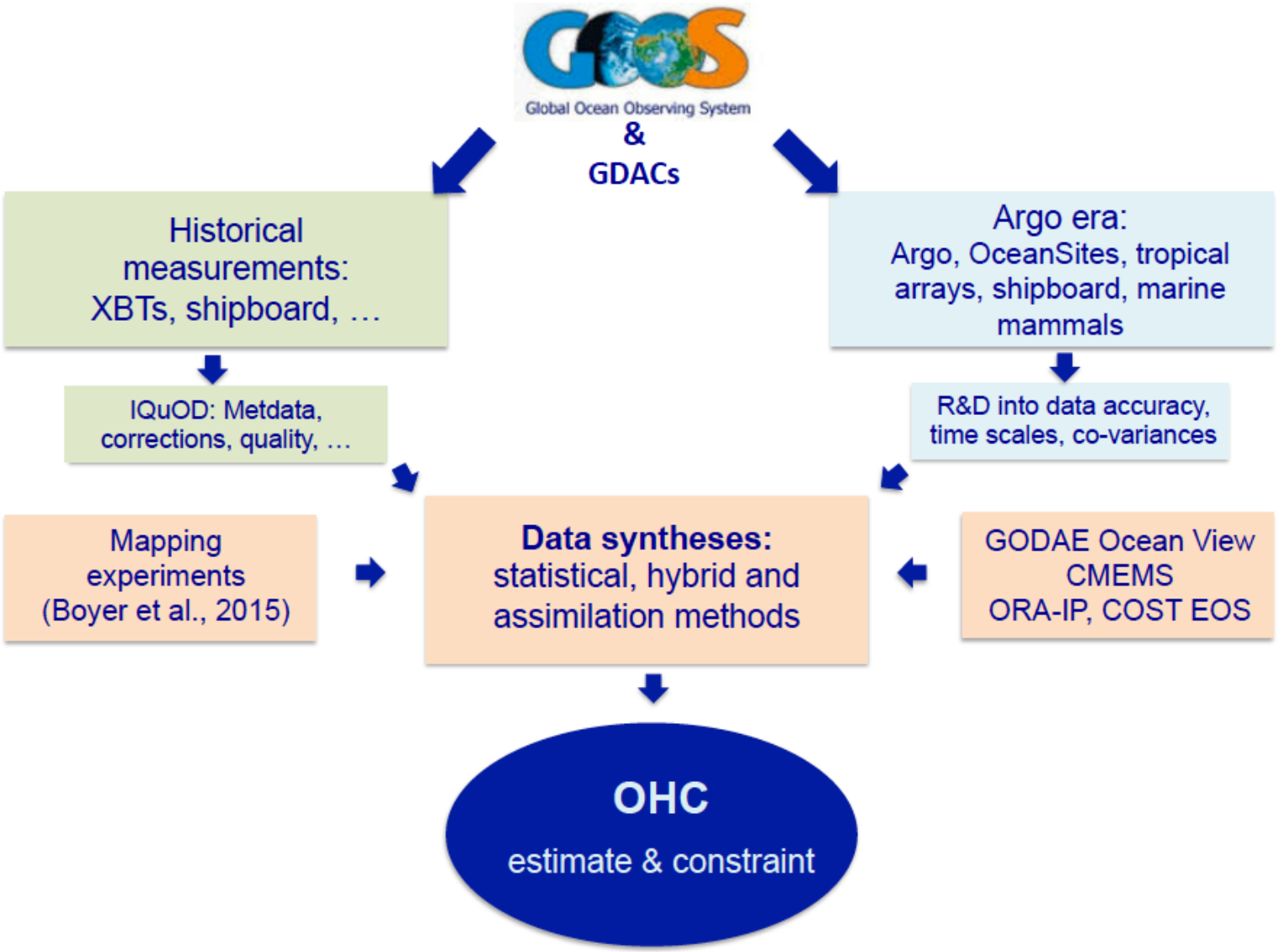
- Improved ocean observation system
- Improve OHC estimate capability

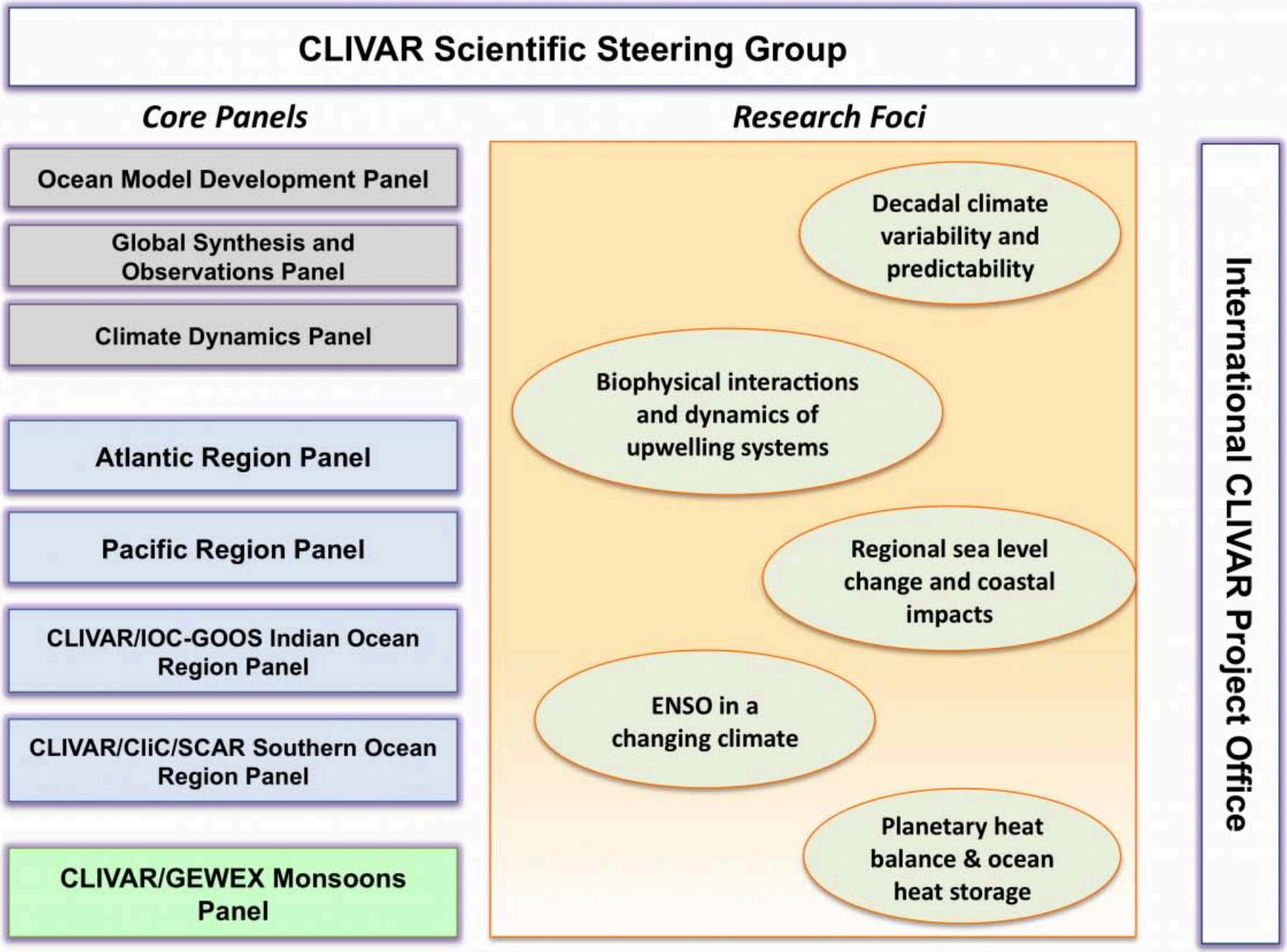
- Vertical disposition of heat in the oceans
- Spatial redistribution of heat in the oceans
- Atmospheric teleconnections

- Write letters concerning recommendations from the CONCEPT-HEAT community
- Foster the development of a CONCEPT-HEAT synergy community (web pages, conference sessions, summer schools, and a brochure)

CLIVAR research focus CONCEPT-HEAT:

First CONCEPT-HEAT workshop, Met Office, Exeter (29.09.-01.10.2015)




CLIVAR Scientific Steering Group
Core Panels
Ocean Model Development Panel
Global Synthesis and Observations Panel
Climate Dynamics Panel
Atlantic Region Panel
Pacific Region Panel
CLIVAR/IOC-GOOS Indian Ocean Region Panel
CLIVAR/CliC/SCAR Southern Ocean Region Panel
CLIVAR/GEWEX Monsoons Panel
Research Foci
Decadal climate variability and predictability
Biophysical interactions and dynamics of upwelling systems
Regional sea level change and coastal impacts
ENSO in a changing climate
Planetary heat balance & ocean heat storage
International CLIVAR Project Office

THANK YOU.