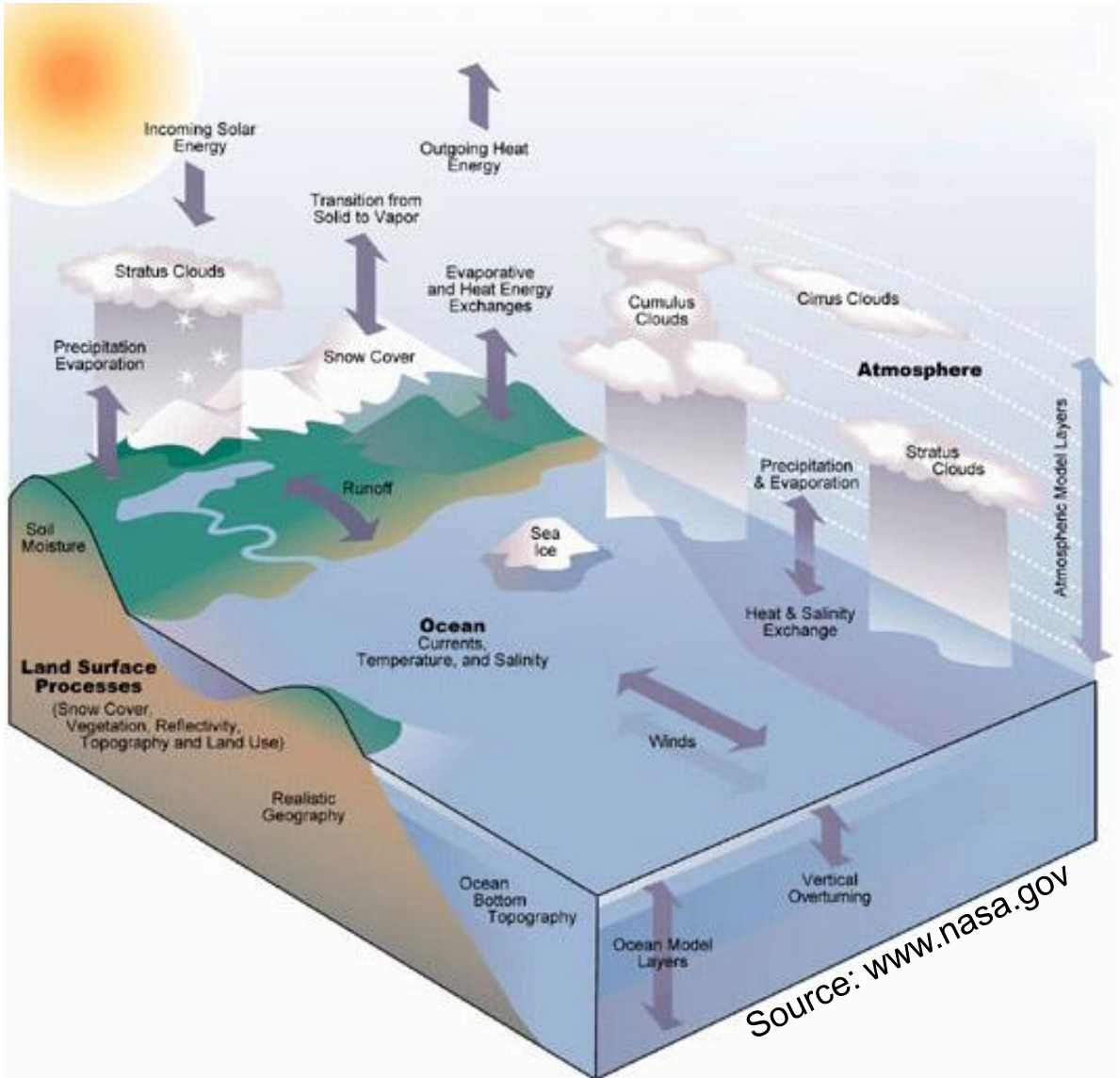
The concept of physical budget constraints

ESA-OHF meeting, 07.12.2017

EARTH CLIMATE.

A practical way to monitor climate variations at different time scales is to continually assess the transfer of energy in the Earth system.



INTERNATIONAL SPACE SCIENCE INSTITUTE

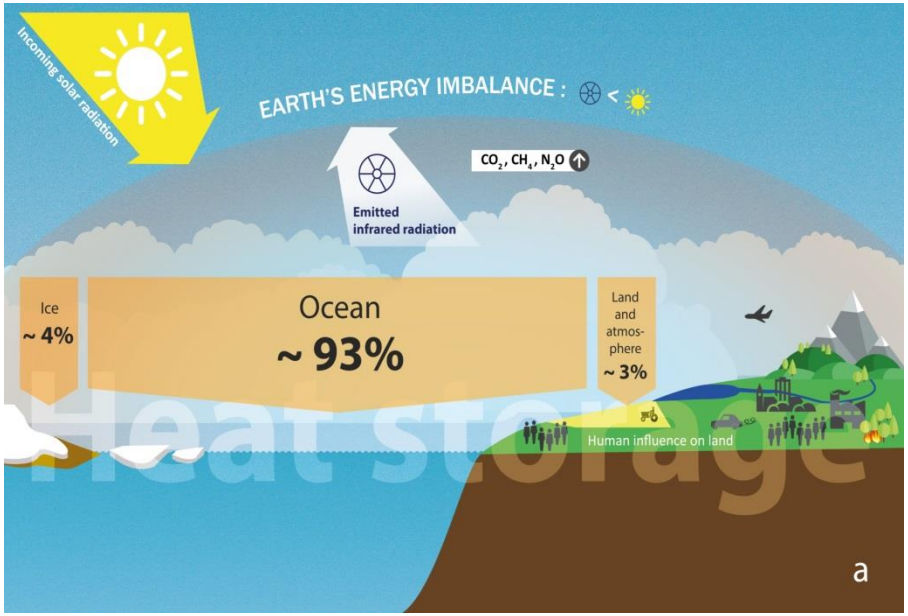
ISSI working group: “Consistency of Integrated Observing Systems monitoring the energy flows in the Earth System”

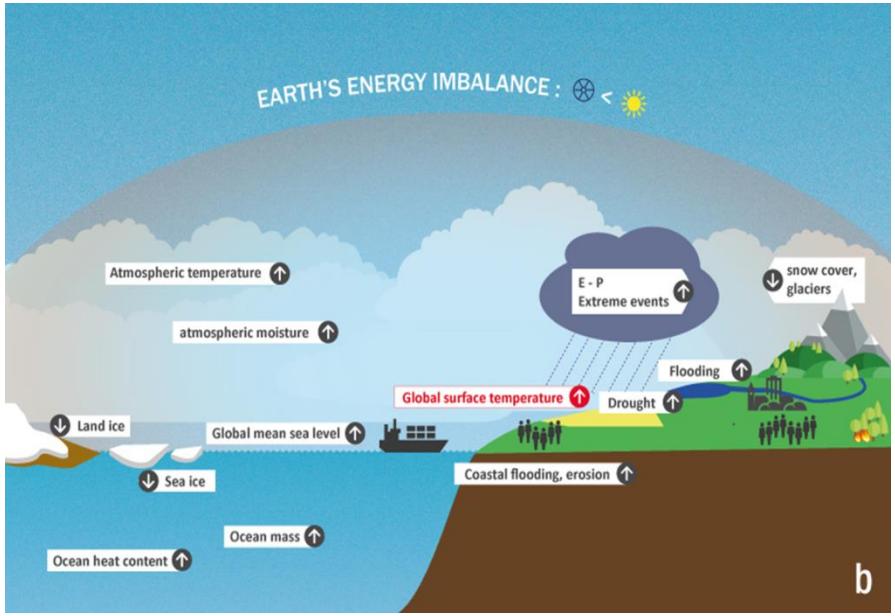
“The absolute measure of the Earth Energy Imbalance and its changes over time are vital pieces of information related to climate change as this is the single quantity defining the status of global climate change and expectations for continued global warming. “

PERSPECTIVE
PUBLISHED ONLINE: 27 JANUARY 2016 | DOI: 10.1038/NCLIMATE2876
nature climate change

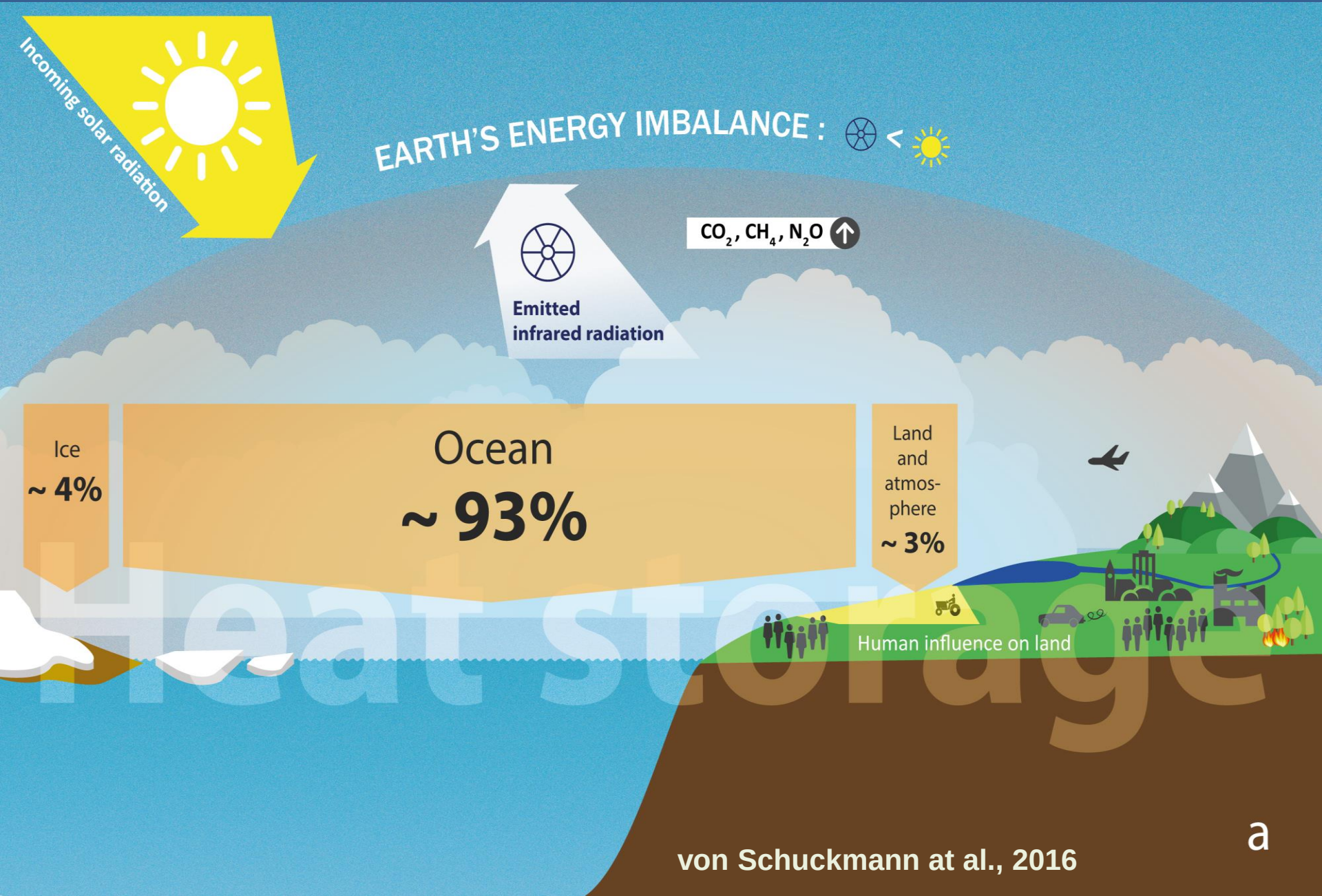
An imperative to monitor Earth's energy imbalance

K. von Schuckmann[1,2*], M. D. Palmer[3], K. E. Trenberth[4], A. Cazenave[5,6], D. Chambers[7], N. Champollion[6], J. Hansen[8], S. A. Josey[9], N. Loeb[10], P.-P. Mathieu[11], B. Meyssignac[5] and M. Wild[12]





EARTH ENERGY IMBALANCE



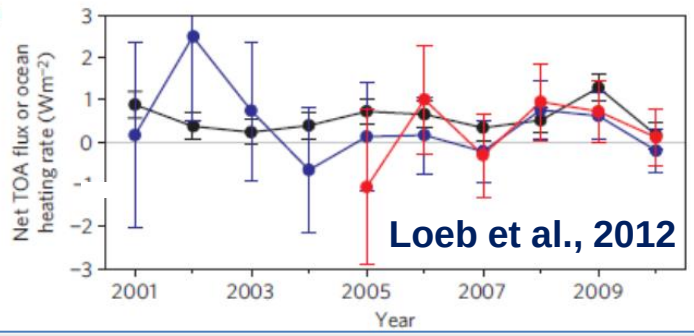
von Schuckmann at al., 2016

a

Determining Earth's energy imbalance: Three methods

METHOD I

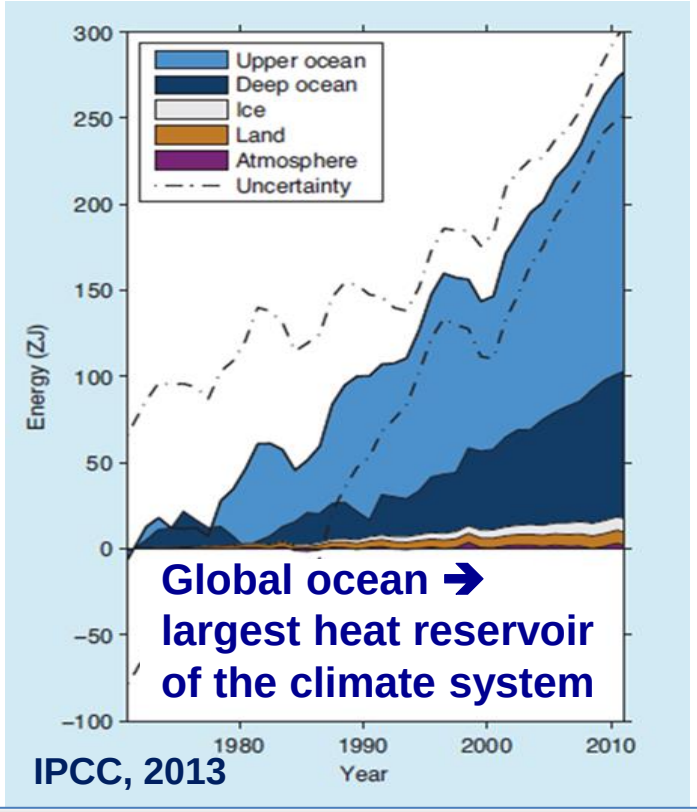
Radiation at TOA



Loeb et al., 2012

METHOD II

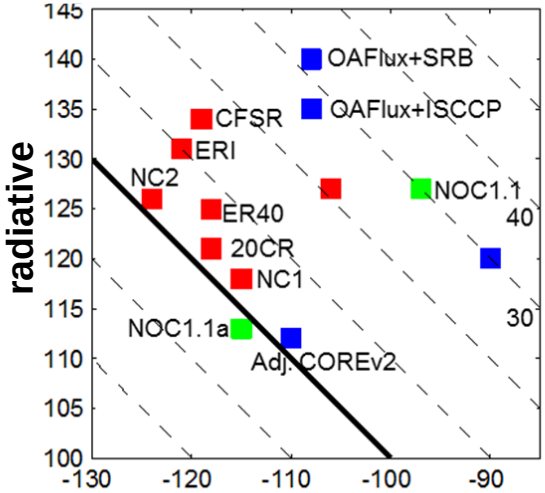
Ocean Heat Content



IPCC, 2013

METHOD III

Air-Sea fluxes

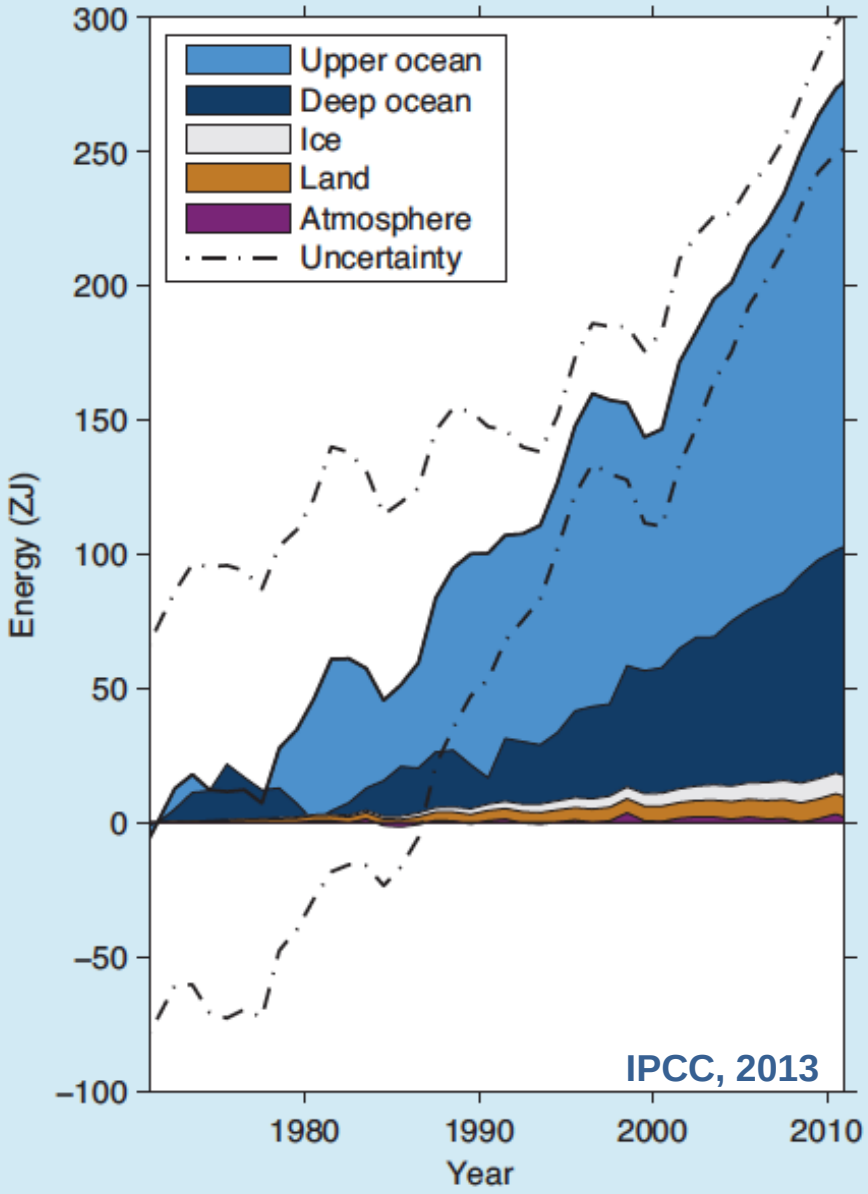


Josey et al., 2015

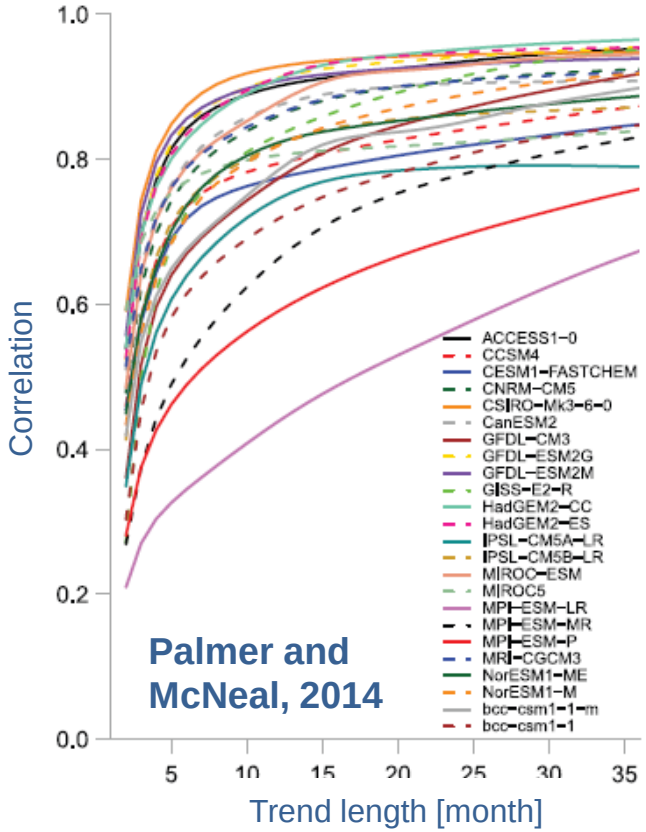
The Earth energy imbalance can best be estimated from changes in ocean heat content, complemented by radiation measurements from space

(von Schuckmann et al., 2016, NCC)

METHOD II



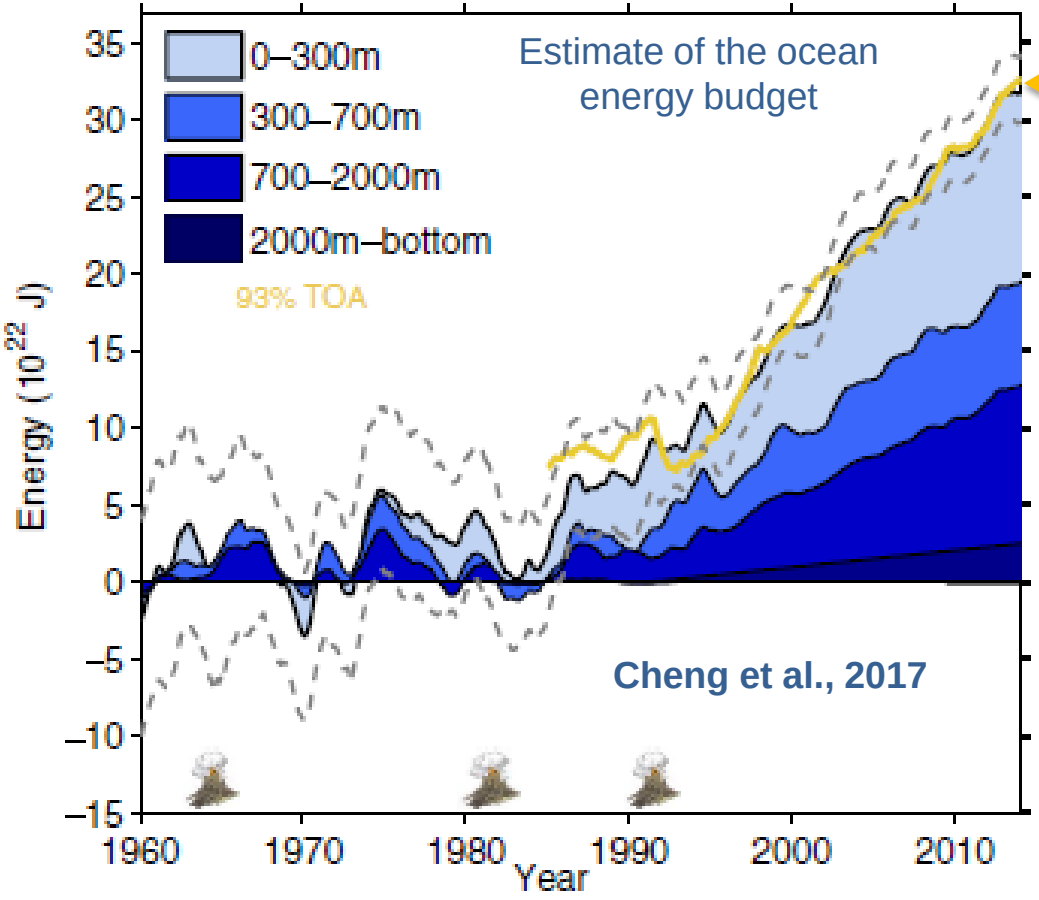
Correlation in total system energy & ocean heat content as a function of trend length



Climate models suggest that the global ocean becomes the dominant term in the Earth's energy budget on **timescales longer than about 1 year**

METHOD II: Close correspondence: Rate of ocean heat content change and net flux at TOA

Change in **TOA net radiation** and **rate of global ocean heat storage** from independent global climate observing systems should be **in phase** and of the **same magnitude** on annual and longer time scales (e.g. Loeb et al., 2012)

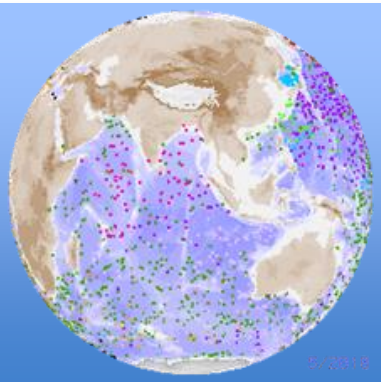


All other forms of heat storage are **factors of 10 smaller** at that time scale (Trenberth et al., 2009; Loeb et al., 2012, Palmer and Mc Neal 2014, von Schuckmann et al., 2016).

Methods for global **Ocean Heat Content** (OHC) estimates

1

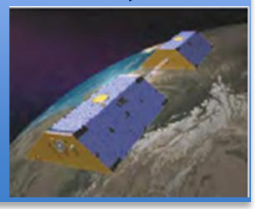
DIRECT ESTIMATES



2

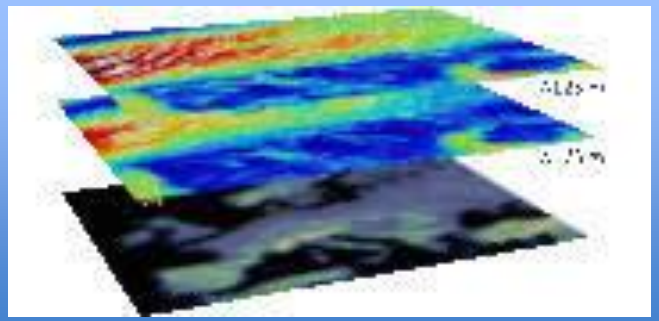
INDIRECT ESTIMATES

$$SL_{steric} = SL_{total} - SL_{mass}$$



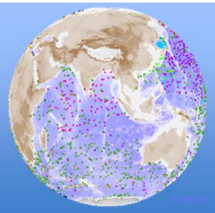
3

OCEAN REANALYSES



Methods for global **Ocean Heat Content** (OHC) estimates

1 DIRECT ESTIMATES



2 INDIRECT ESTIMATES

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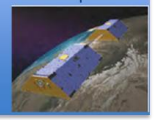
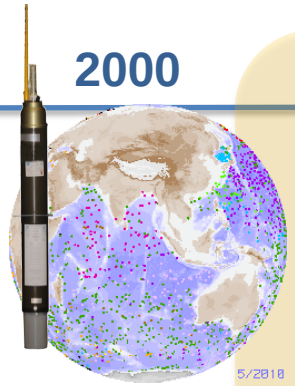


< 1950

In situ

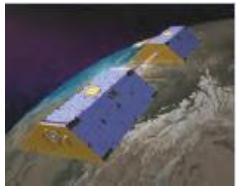
2000



Altimetry **1993 onwards**

TOA net flux **2000 onwards**

Ocean mass **2002 onwards**



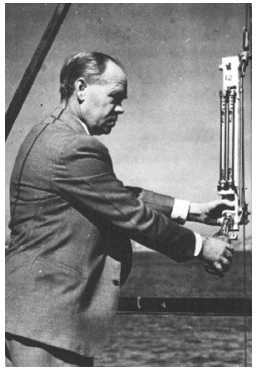
Golden period

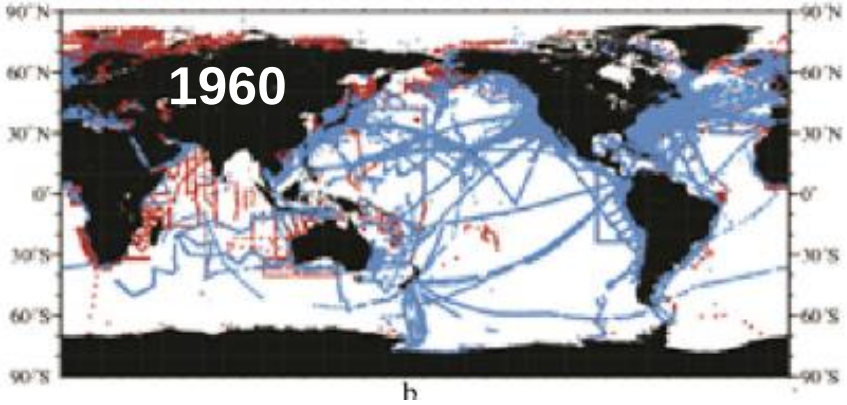
OHC: Historical in situ measurements

< 1950 **2000**

In situ

Era of historical measurements





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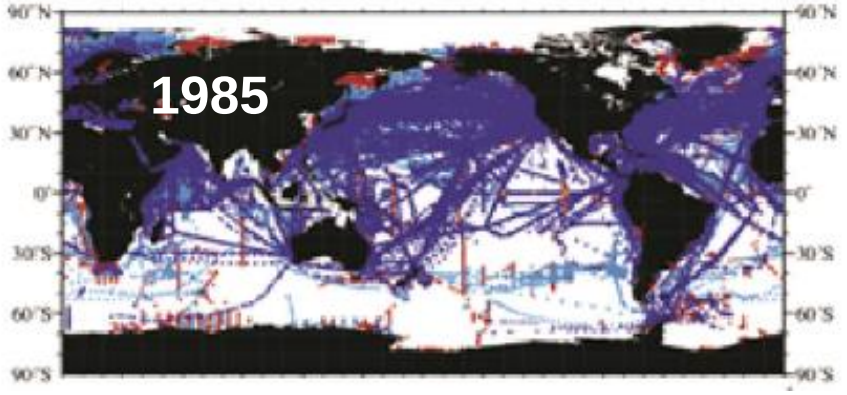
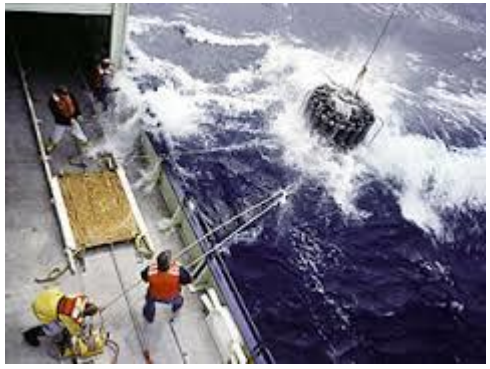
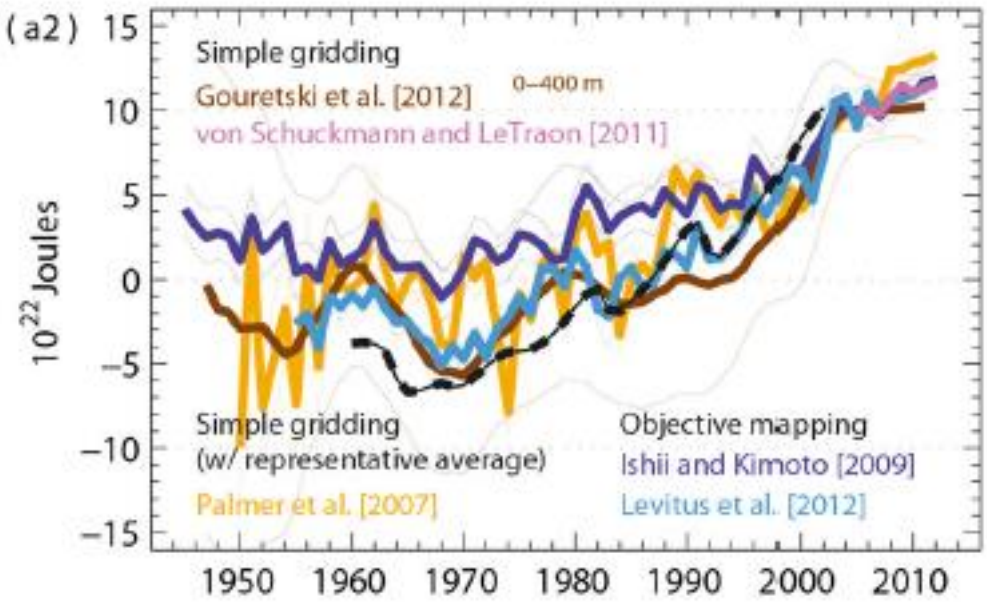
Abraham et al., 2013

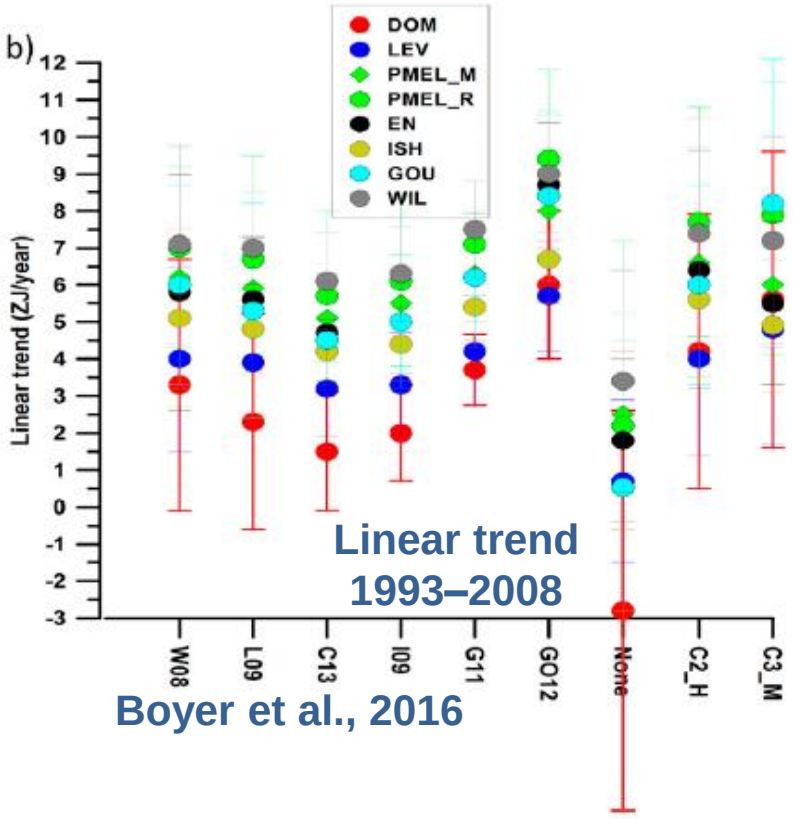




Global Ocean Heat Content: Historical & Argo era



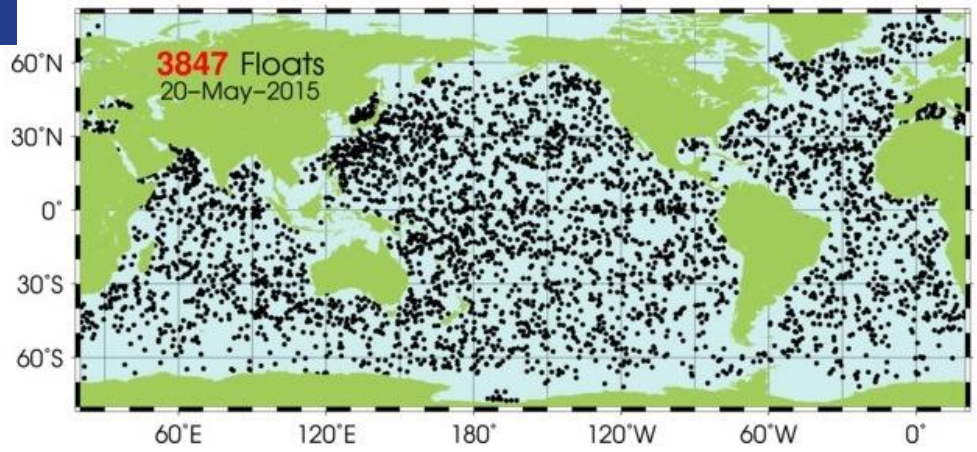
Abraham et al., 2013

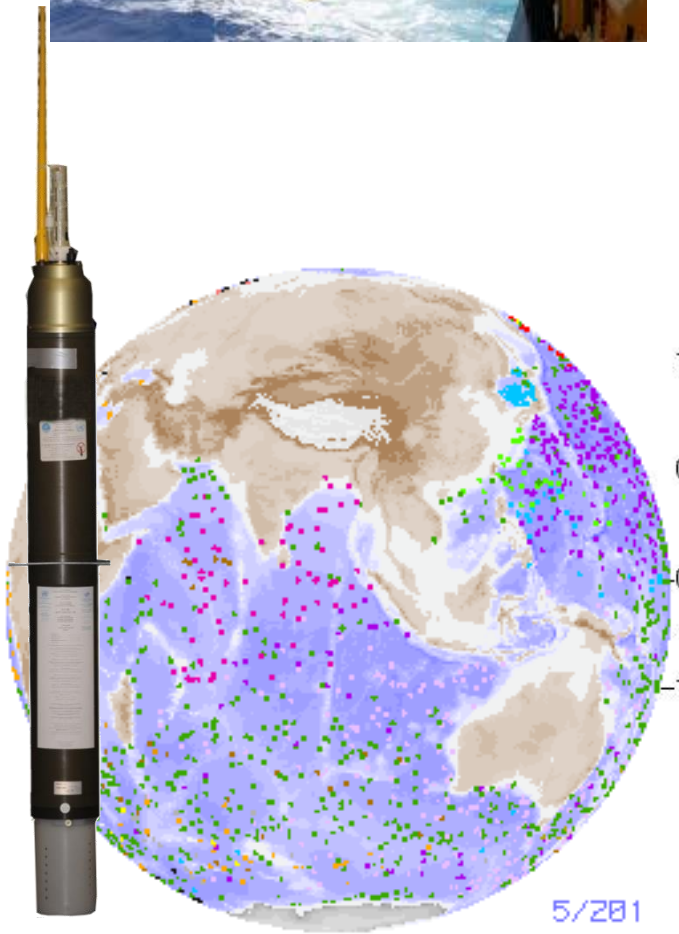


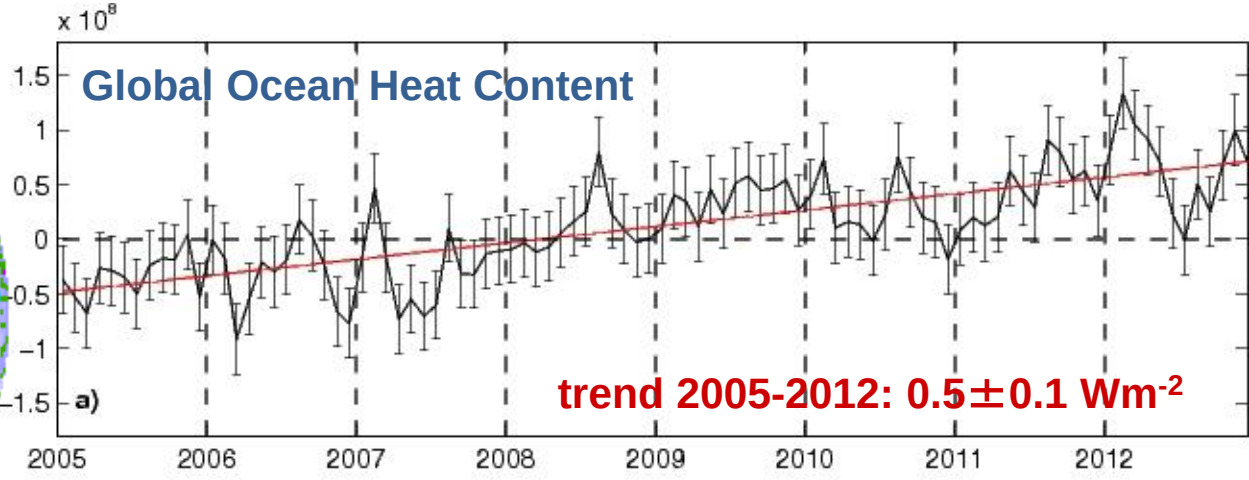
Boyer et al., 2016

- Differences in upper-ocean heat storage between analyses due to mapping, bias correction, baseline climatology & data quality (➔ www.iquod.org)
- Differences in “interannual to decadal variability” between analyses.
- All estimates show a multi-decadal increase in OHC in both, upper and deep ocean regions.

OHC: ARGO ERA







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

1. A reference estimates of box mean temporal changes for OHC

OHC method validation through physical budget constraint

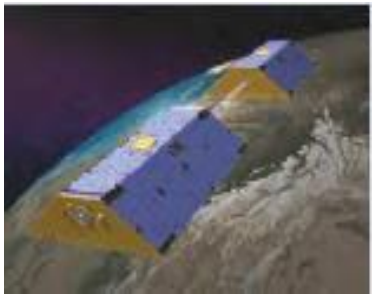
(von Schuckmann et al., 2014)

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

Argo: 2000-2012

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

Altimetrie: 1993-2012



GRACE: 2002-2012

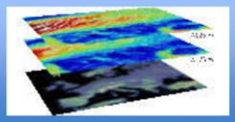
Overlapping time window for global and re-qualified data 2005-2010: Methods developed for global estimations

von Schuckmann and Le Traon, 2011

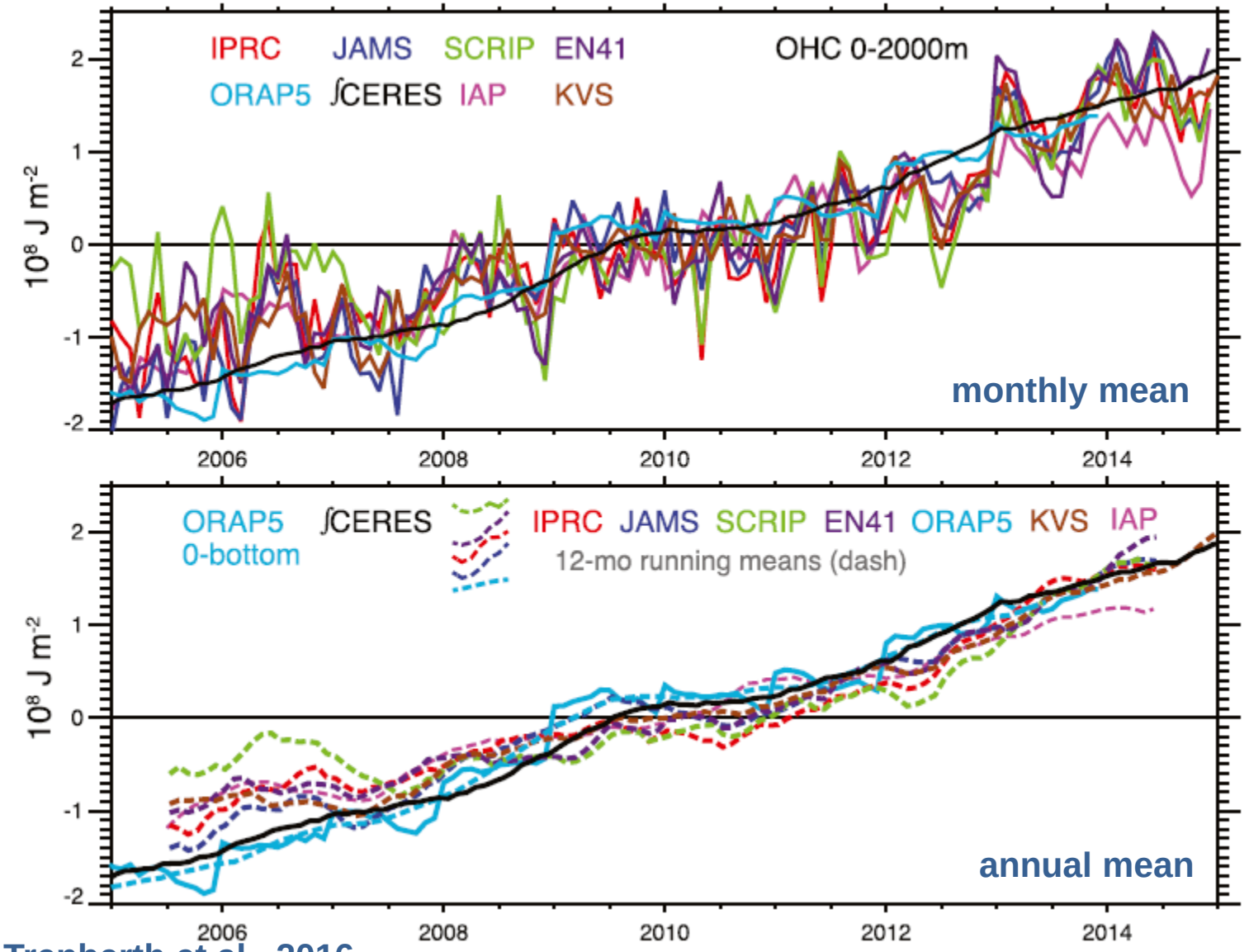
Averaged DM gridded product, AVISO

Chambers and Schröter, 2011

Ocean heat content estimates from reanalyses

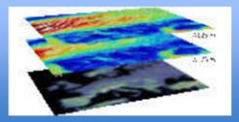


Comparison to net flux at TOA & Argo based estimates

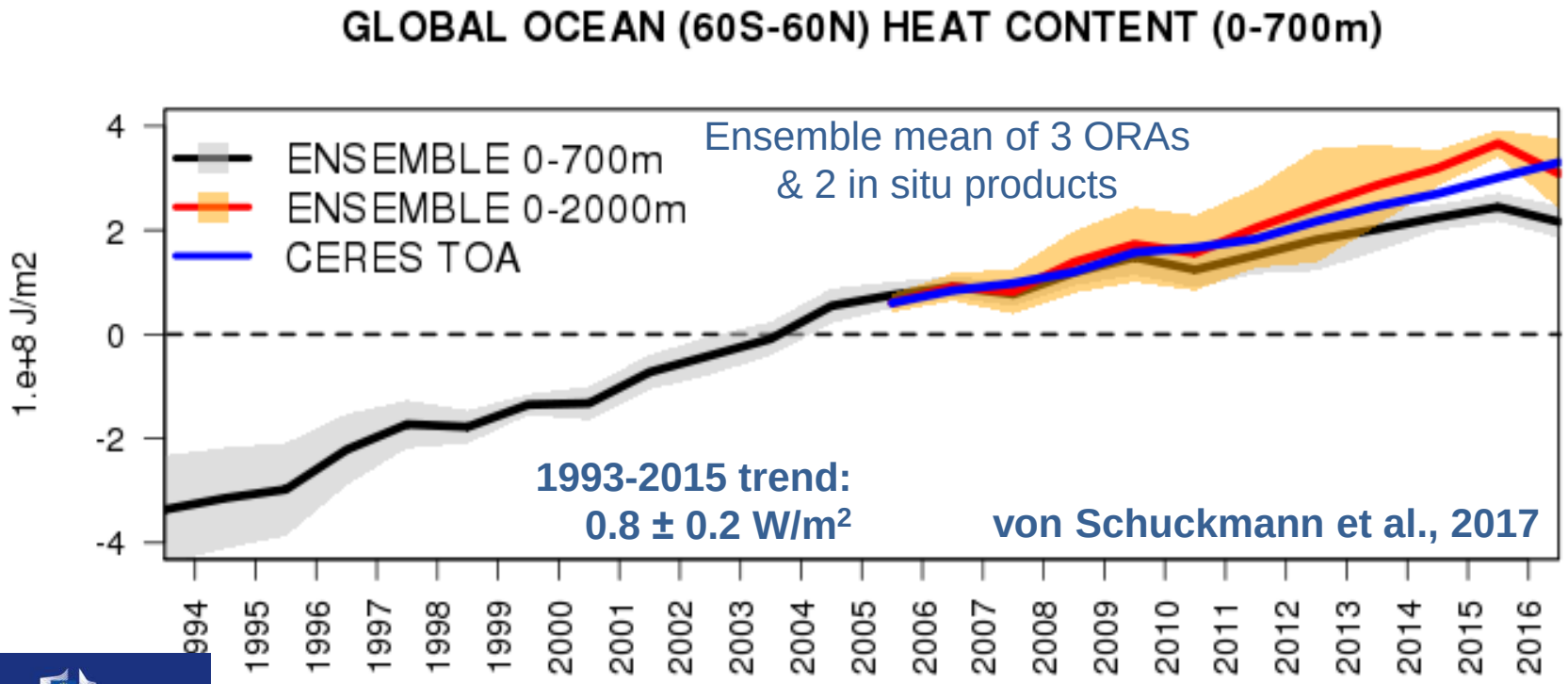


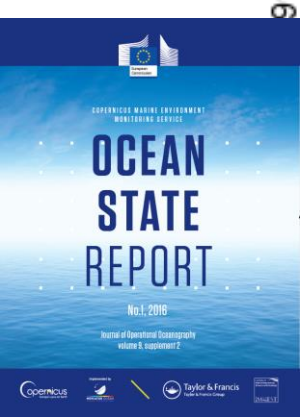
Trenberth et al., 2016

Ocean heat content estimates from reanalyses



Further evaluation under the physical budget constraint of the Earth energy imbalance



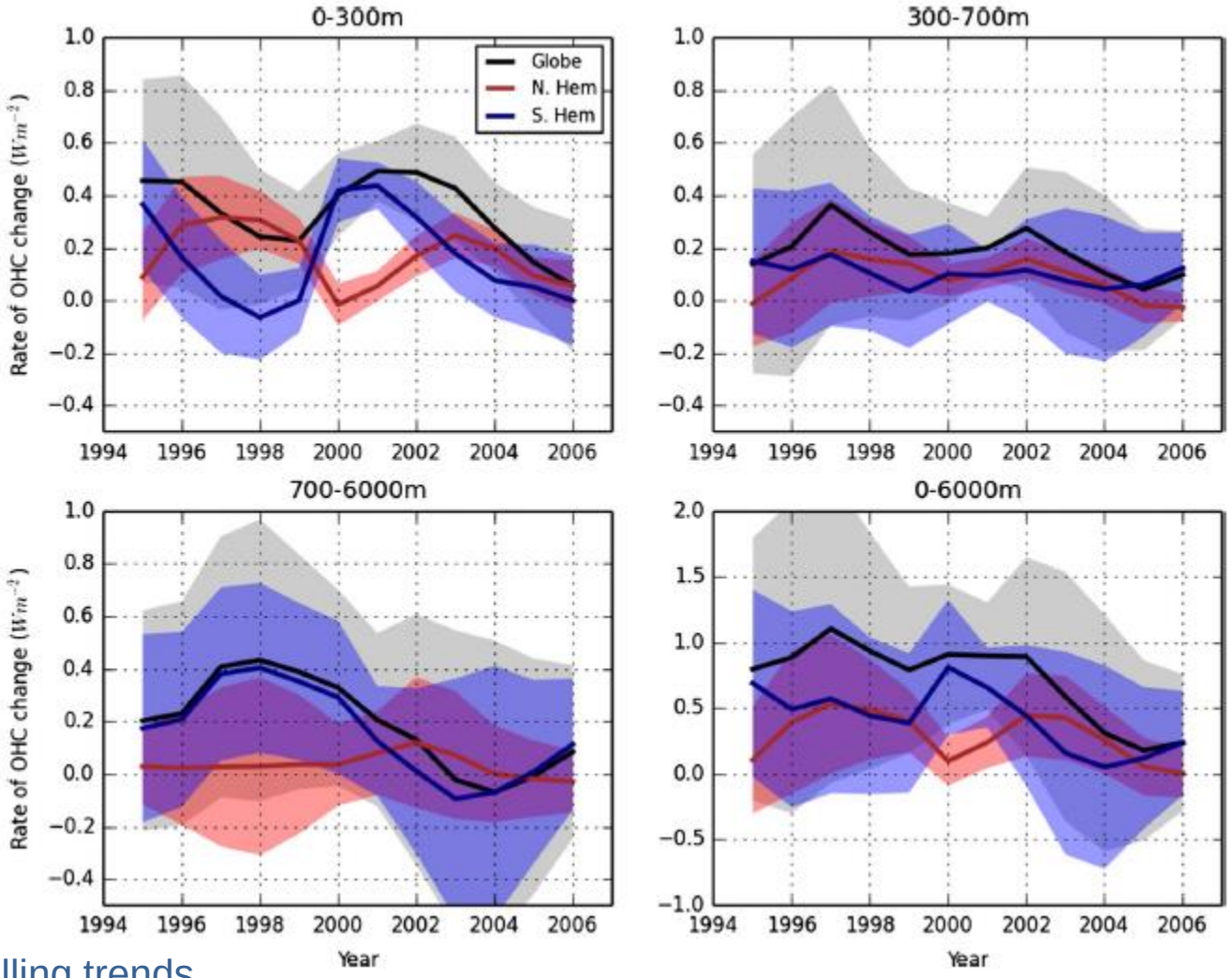


Improved budget constraint closure when changes in the 700-2000m depth are taken into account.

Marine Environment Monitoring

Ocean heat content estimates from reanalyses

The ORA-IP intercomparison project: OHC



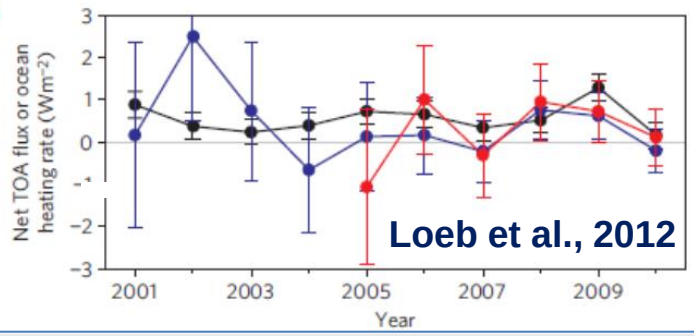
5-year rolling trends
Ensemble mean of 15 ORAs

Palmer et al., 2015

Determining Earth's energy imbalance: Three methods

METHOD I

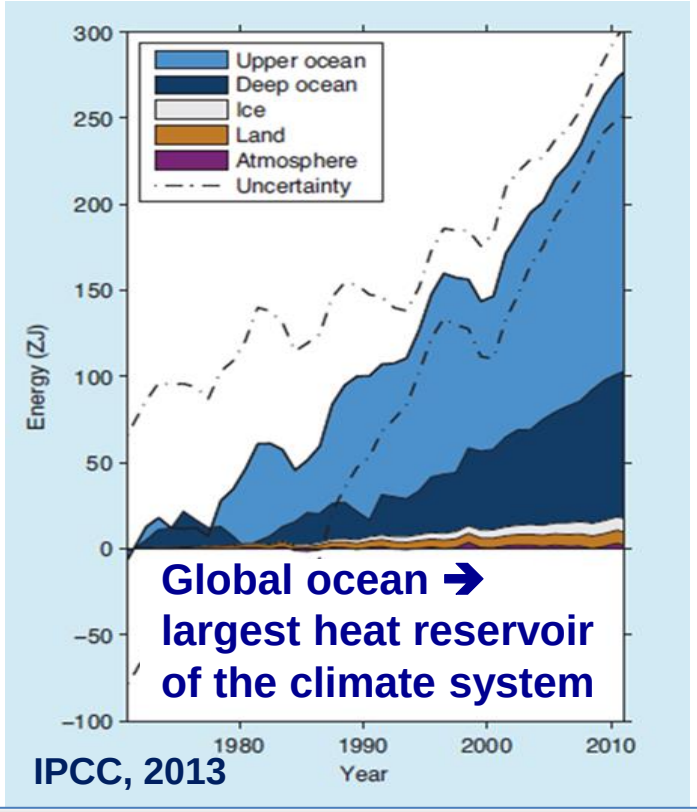
Radiation at TOA



Loeb et al., 2012

METHOD II

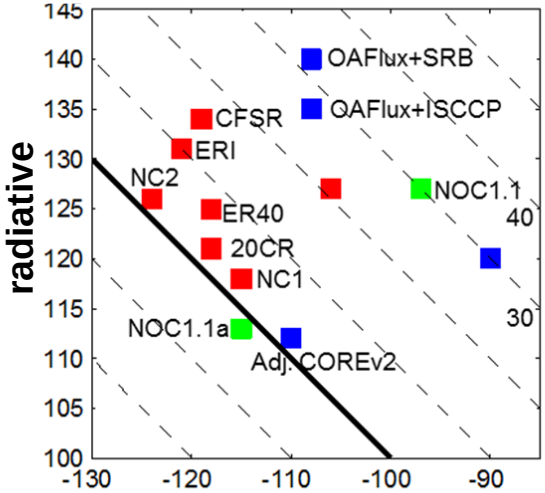
Ocean Heat Content



IPCC, 2013

METHOD III

Air-Sea fluxes



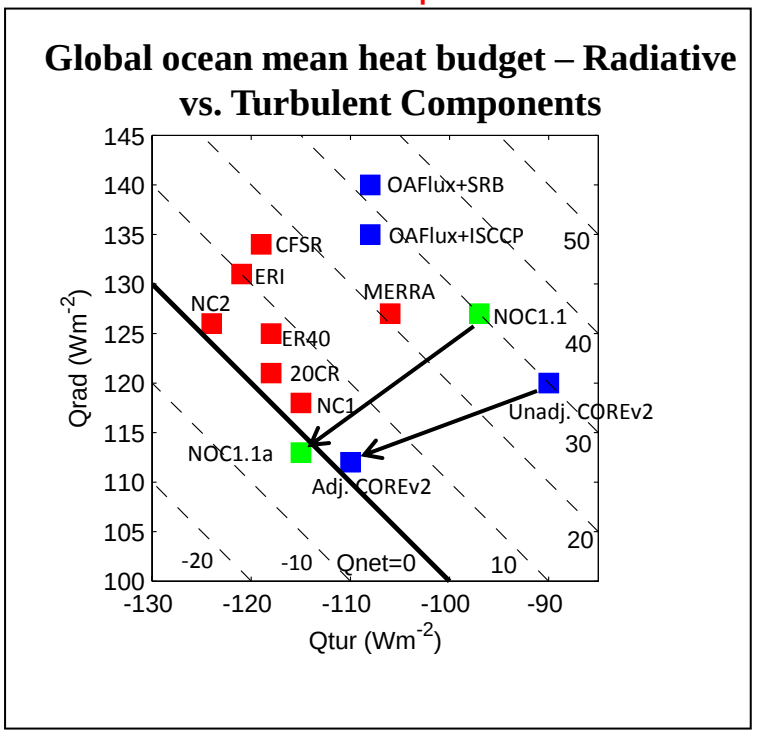
Josey et al., 2015

Courtesy: S. Josey

Global Heat Budget Closure : Overview

- Wide spread of products ➔ heat budget closure remains a significant problem.
- Satellite net radiative fluxes typically exceed those of other products by 10-20 Wm^{-2}.

Example showing the wide spread of different products



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

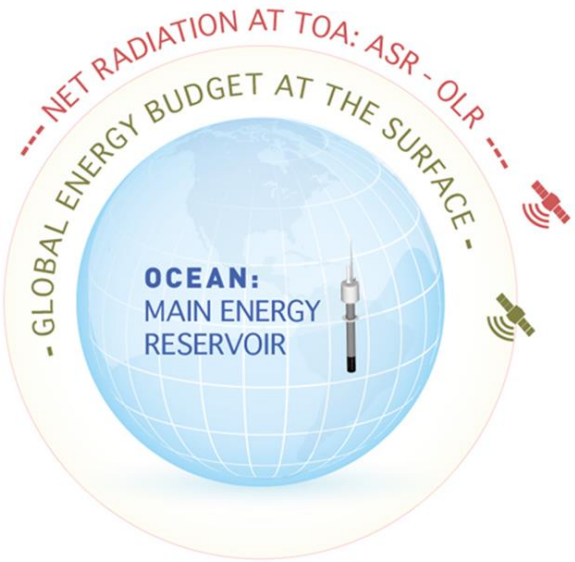
CONCEPT of REGIONAL BUDGET CONSTRAINTS

Characterizing the uncertainty and biases in fluxes is essential to address scientific challenges related to the Earth Energy budget, energy flows, and understanding the observed shorter-term interannual to decadal fluctuations (e.g., recent “hiatus” period) superimposed on the centennial-scale warming of the global ocean surface

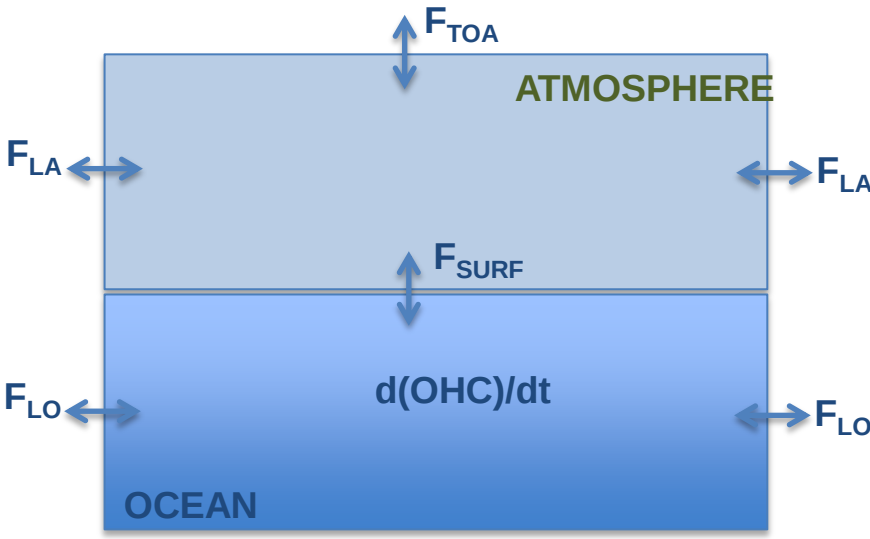
Recommendation to step from “local validation” to “regional validation”
CONCEPT of CAGES (Bretherton et al., 1982; Yu et al., 2012; WCRP, 2013)

➔ independent climate observing systems and tools are compared and set into the constraint of the physical budget for each defined ocean box.

THE OCEANS'ROLE AS EARTH SYSTEM REGULATOR: RESEARCH ACTIVITIES: NEXT STEPS…



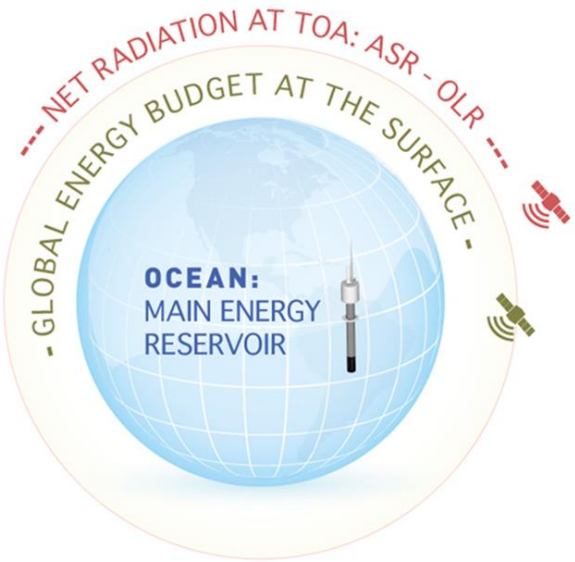
REGIONAL



Example: The net surface heat flux can be evaluated through the rate of change in ocean heat content and ocean divergence

$$F_s = -\mathrm{dOHC}/\mathrm{d}t - \nabla \cdot \mathbf{F_O}$$

THE OCEANS'ROLE AS EARTH SYSTEM REGULATOR: RESEARCH ACTIVITIES: NEXT STEPS…



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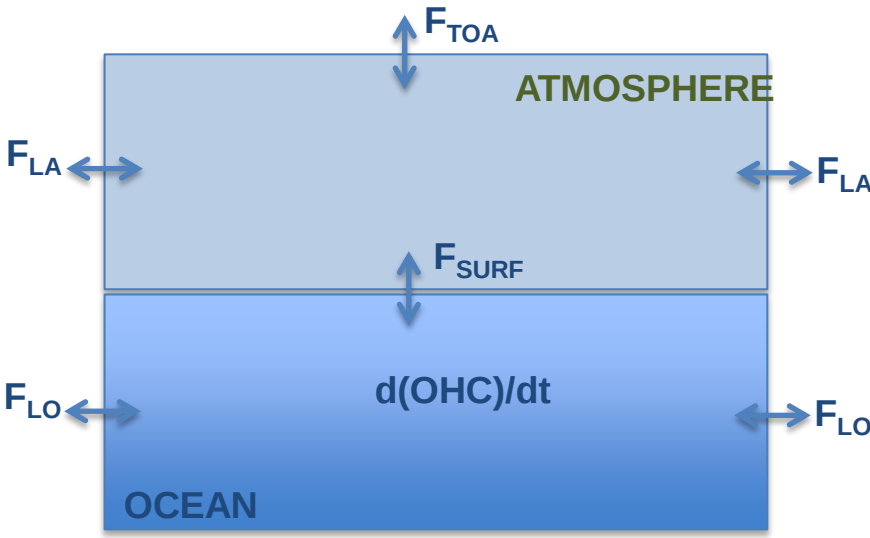
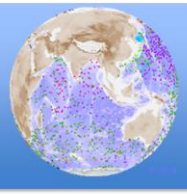


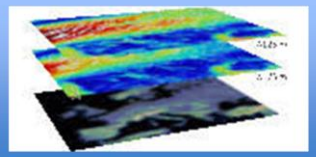
1 DIRECT ESTIMATES

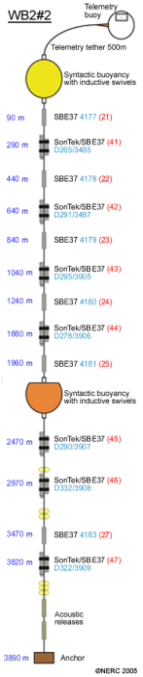


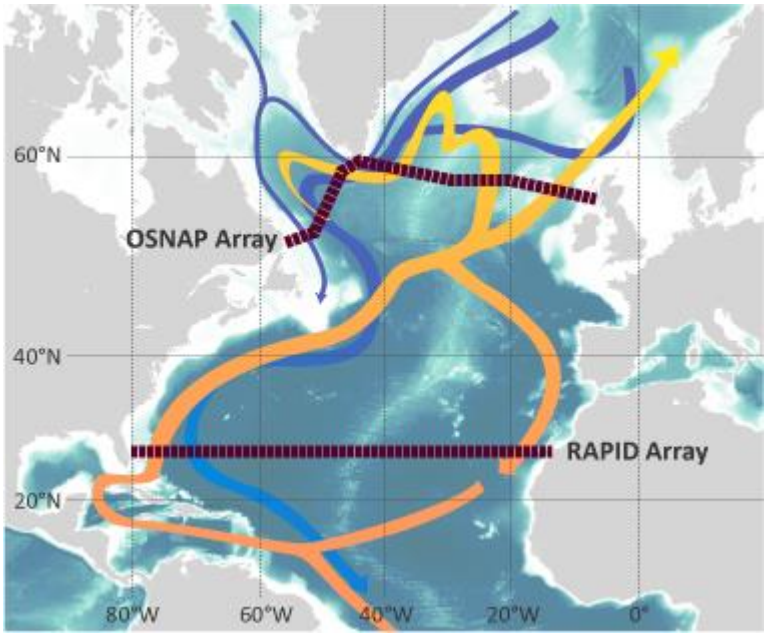
2 INDIRECT ESTIMATES

$SL_{steric} = SL_{total} - SL_{mass}$

3 OCEAN REANALYSES

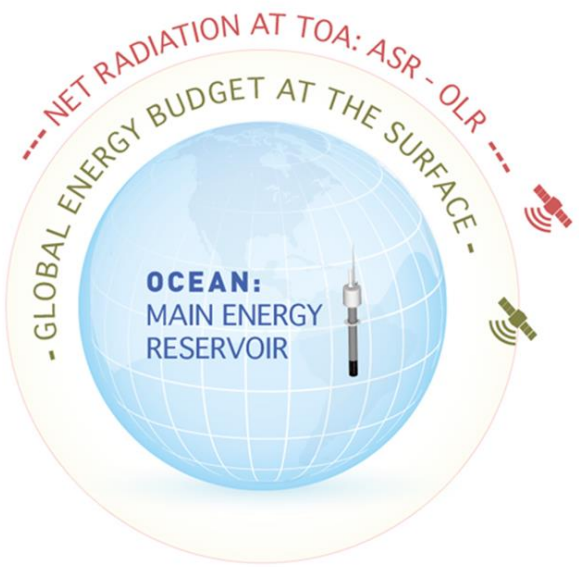






http://www.rapid.ac.uk/

THE OCEANS'ROLE AS EARTH SYSTEM REGULATOR: RESEARCH ACTIVITIES: NEXT STEPS…



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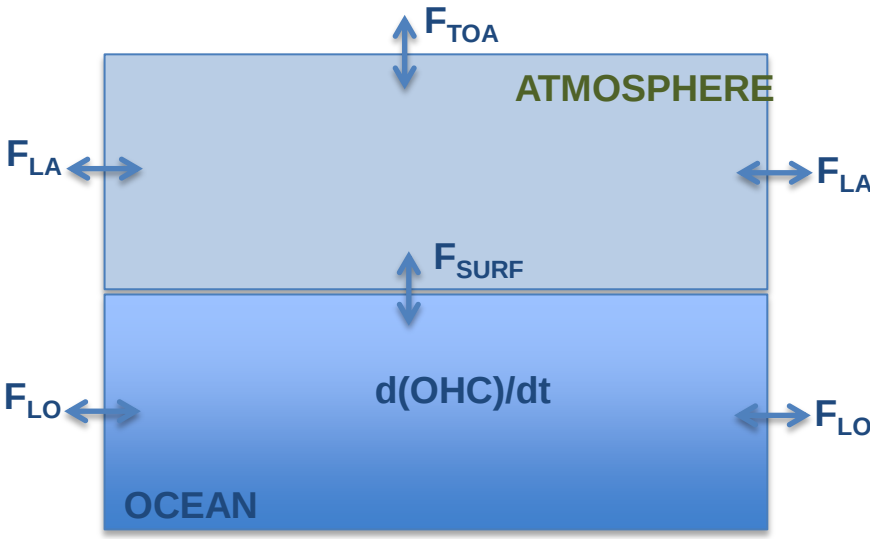
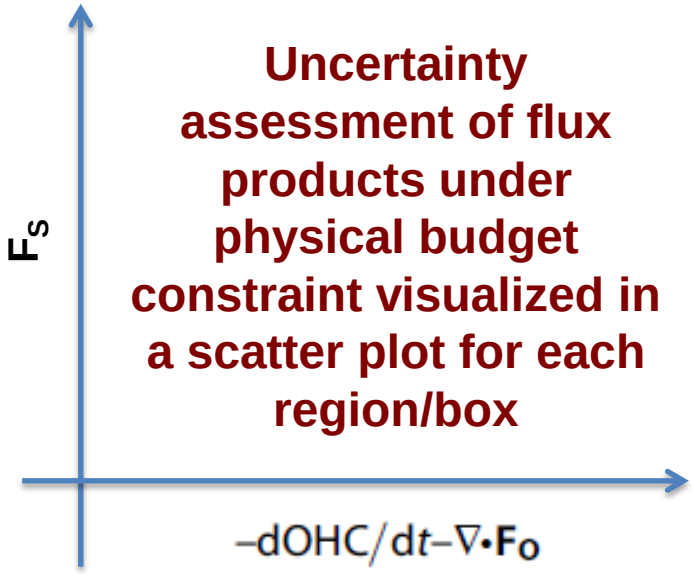


$$F_s = -\mathrm{dOHC}/\mathrm{d}t - \nabla \cdot \mathbf{F_O}$$



Uncertainty assessment of flux products under physical budget constraint visualized in a scatter plot for each region/box

Apply this to the global ocean

- Division global ocean into boxes (60°S-60°N)
- Temporal resolution: decadal trend (e.g. 2005-2010), and annual averages

Expected outcome:

- Assessment plots (scatter) of flux products for each region and for different temporal resolution

CONCEPT of CAGES: what is needed

Estimates of physical budget components to implement the approach:

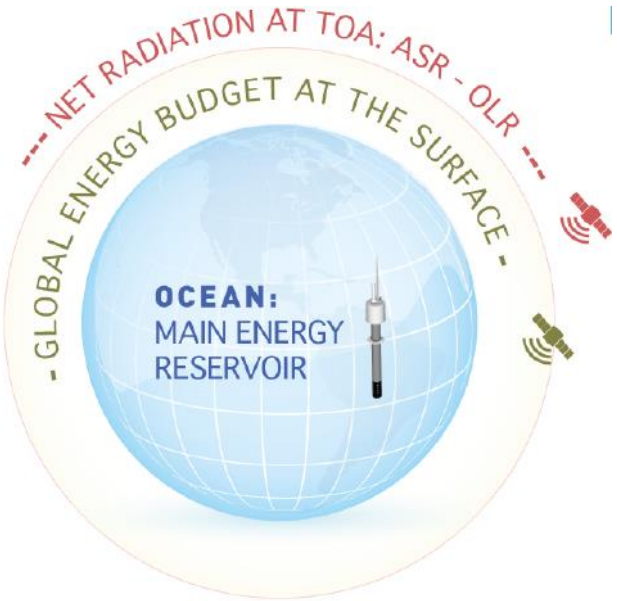
1. **a reference estimates of box mean temporal changes for OHC: K. von Schuckmann (MIO): software & datasets developped**

2. one reference of box mean radiative flux estimate: data base available

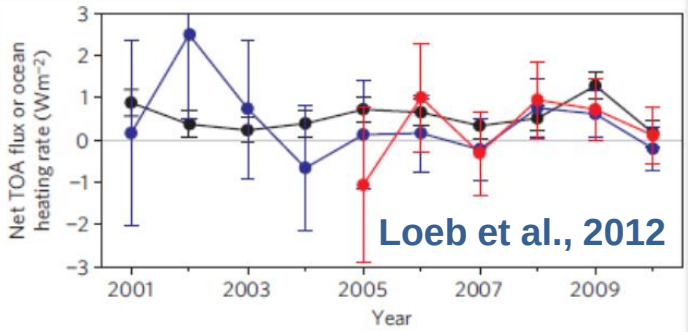
3. one reference estimate of lateral HF at the boundaries of each box: Availability through reanalyses products, and scientific framework developped

4. a set of box mean turbulent fluxes from the "OHF reference data set: Data base available from OHF

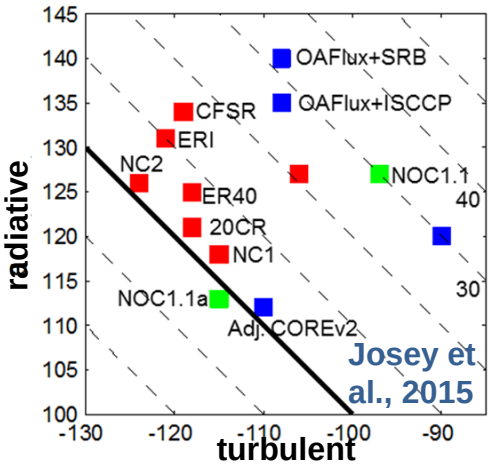
Determining the Earth energy imbalance…



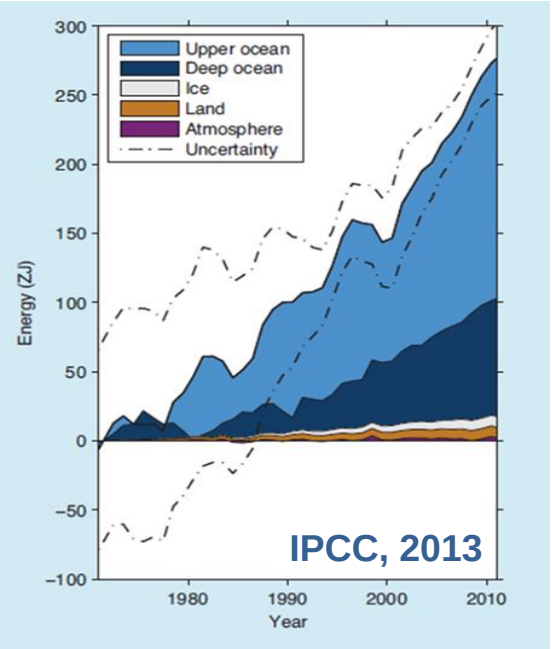
Radiation at TOA



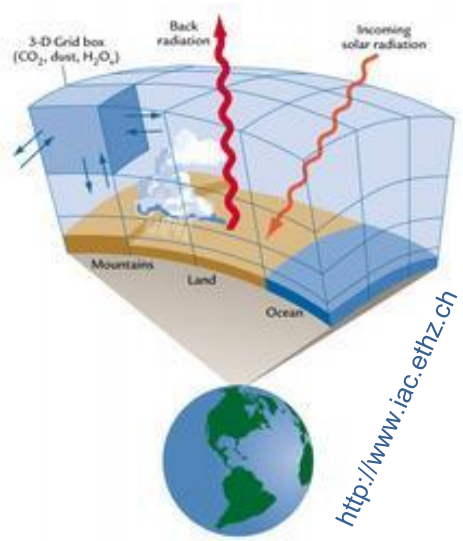
Surface flux



Storage inventory (OHC)



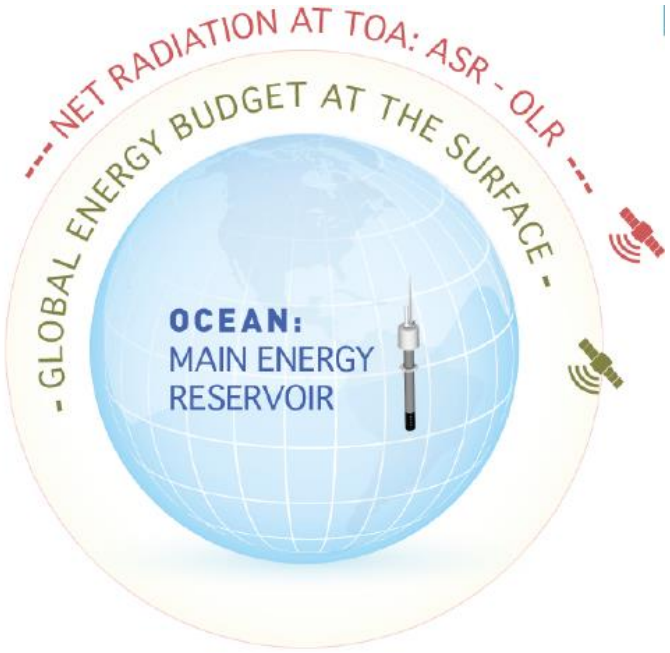
Hindcast and climate projection



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 system to advance on the **understanding of the uncertainties through physical 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

More precisely, this **CLIVAR research focus CONCEPT-HEAT has the main objective to build up a pluri-disciplinary synergy community for climate research** aiming to work on two different issues:

1. Quantify Earth's energy imbalance, the ocean heat budget, and atmosphere-ocean turbulent and radiative heat fluxes, their observational uncertainty, and their variability for a range of time and space scales using different observing strategies (e.g., in-situ ocean, satellite), reanalysis systems, and climate models.

1. Analyze the consistency between the satellite-based planetary heat balance and ocean heat storage estimates, using data sets and information products from global observing systems (remote sensing and in situ) and ocean reanalysis, and compare these results to outputs from climate models to obtain validation requirements (for model and observations).

CONCEPT-HEAT: Consistency between planetary energy balance and ocean heat storage

Name	Institute	Role	Country
Karina von Schuckmann	Mercator Ocean	Co-chair	France
Tristan L'Ecuyer	University of Wisconsin-Madison	Co-chair	USA
Kevin Trenberth	NCAR	Member	USA
Carol Anne Clayson	WHOI	Member	USA
Catia Domingues	IMAS/ACE-CRC	Member	Australia
Sergey Gulev	IORAS	Member	Russia
Keith Haines	UR	Member	UK
Norman Loeb	NASA	Member	USA
Matt Palmer	Met Office	Member	UK
Martin Wild	ETH	Member	Switzerland
Pierre-Philippe Mathieu	ESA	Member	Italy
Robert Weller	WHOI	Member	USA

CONCEPT-HEAT: OUTCOMES so far…

Workshops

2013: CLIVAR-ESA
2014: 1st ISSI meeting
2014: Pan-CLIVAR session
2015: 2nd ISSI meeting
2015: CLIVAR C-H
2017: C-H/GDAP workshop
2018: CLIVAR/GEWEX workshop

Scientific collaborations

2014-2015: ISSI working group
2014-2016 ESA project OHF
2016-current: global sea level budget
2016-current: Transport constraints
2016-current: synthetic profile experiments
Future: C-H/GDAP collaboration

Fundraising

CLIVAR
WCRP World Climate Research Programme
NCAR
University of Reading
US CLIVAR
INTERNATIONAL SPACE SCIENCE INSTITUTE
esa
EUMETSAT
Met Office

Sessions

- Pre-COP21: Our common future under climate change
- AGU 2016 & 2017
- Ocean Science 2017
- GEWEX international science conference (MAY 2017)

WORKSHOPS

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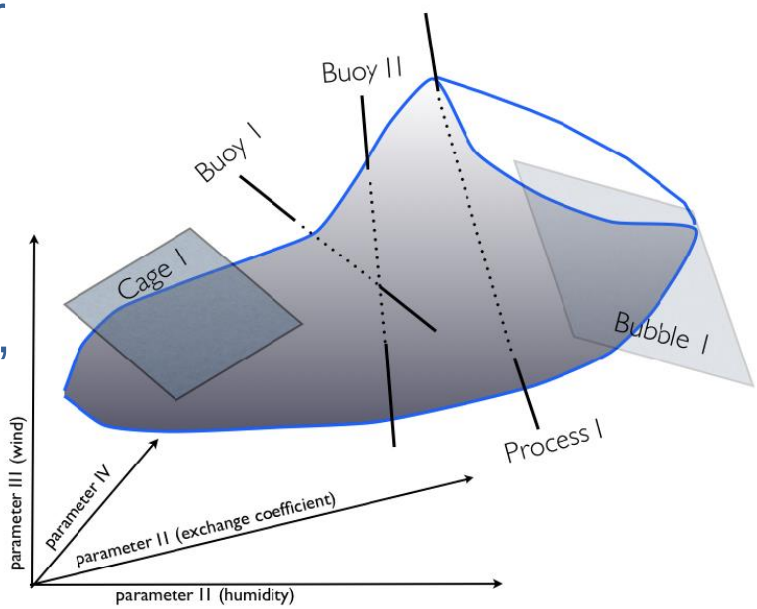
2015: 2nd ISSI meeting
2015: CLIVAR C-H
2017: C-H/GDAP workshop
2018: CLIVAR/GEWEX workshop

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



WORKSHOPS

Workshops

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2018: CLIVAR/GEWEX workshop

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

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)

EEI

most fundamental measure for climate change

FINDINGS

Estimate EEI locally and as a function of time

The estimation of OHC plays a key role for climate science

Studies of energy flows in climate modes

Concept of Cages:
- TOA 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
- Horizontal redistribution of heat in the oceans

- Development of recommendation letters from CONCEPT-HEAT to different research and operational instituions and structurations
- Webpage, summer school, conference session, …

WORKSHOPS

Workshops

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Joint WCRP/CLIVAR/GEWEX:
« Synergy community on the Earth energy imbalance »
Fall 2018, Toulouse, France

Overall goal:

Strengthen and extend the synergy community on the Earth's energy imbalance aiming to discuss cross-links between the different WCRP core programs, in particular between CLIVAR and GEWEX, but also including CliC.

Expected outcomes:

The workshop will identify research goals and opportunities on the Earth's energy imbalance and global &regional physical budget constraints, and synthesize and focus the various aspects across WCRP. A main outcome may include the discussion and reporting on how the C-H topic could evolve into a WCRP topic.

NEXT STEPS… CLIVAR CONCEPT-HEAT

- Common CLIVAR / GEWEX workshop in 2018 (Toulouse, France)
- GEWEX (GDAP)/CLIVAR(C-H) in-depth assessment of the Earth Energy Imbalance (to be further discussed during 2018 workshop)
- Regional budget constraint activity (to be further discussed during 2018 workshop)
- Scientific paper on energy storage
- Continued interaction with ongoing initiatives (e.g. OOPC, University of Reading/National Center for Earth Observations)
- Continued interaction with CLIVAR GSOP & DCVP

Thank you.