Can measurements of sea level and Earth's gravity field constrain estimates of the global water/energy cycle fluxes ?

Benoit Meyssignac, Remy Roca, A.Blazquez (LEGOS) with inputs from T.L'Ecuyer (U. of Wisconsin), S.Fleury (LEGOS), A.Couhert, J.M.Lemoine, F.Mercier (CNES), B.Picard, M.Ablain, P.Prandi, L.Zawadski (CLS)

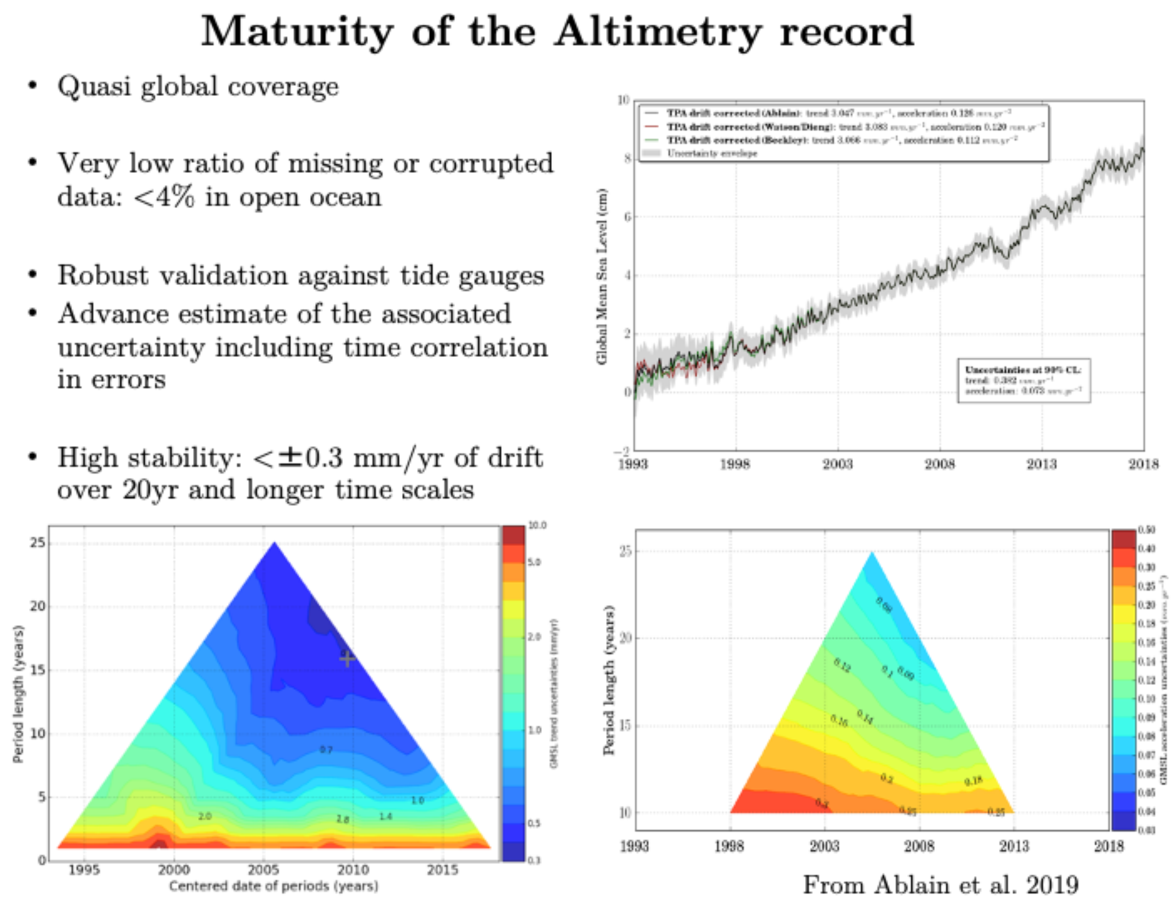
(benoit.meyssignac@legos.obs-mip.fr)

Welcome all to this presentation!

First I want to acknowledge my co-authors, Remy Roca and Alejandro Blazquez from LEGOS , and I want to thank all other co-authors who provided some inputs for this study.

In this presentation, I propose to show you recent developments where sea level data and gravimetry data retrieved from satellite is used to constrain the changes in the global water-energy cycle

Some of you are already aware of this work. But this is the opportunity here to tell you where we stand for now on this topic and the challenges to come



As you all know the sea level data has reached an unprecedented level of maturity over the last decade.

The sea level dataset shows a quasi-global coverage of the ocean with a high spatial resolution (<1/4°) and a high temporal repeatability (global products are produced now on a daily basis). There is a very low ratio of missing or corrupted data in the dataset.

The sea level data is validated against independent in situ data from tide gauges. And the product is delivered with an estimate of the uncertainty at global scale which includes the temporal correlation in the errors.

The stability of the sea level record is high with drifts below ±0.4mm.yr^{-1} at global scale over periods >20 years (see the figures above)

Maturity of the GRACE record

- Global coverage
- low ratio of missing data (except at the end of GRACE mission)
- Robust validation against altimetry (laser radar) and in situ measurements
- estimate of the associated uncertainty including time correlation in errors
- High stability: $< \pm 0.5$ mm/yr of drift over 15yr

(mmSLE/yr)	GOM	Greenland	Antarctica	Arctic islands	Glacier &TWS
Processing center	0.09	0.02	0.06	0.01	**0.12**
Geocenter motion	**0.21**	0.01	0.05	0.01	**0.23**
$C_{2,0}$	0.02	<0.01	0.02	<0.01	<0.01
Filtering	0.02	0.03	0.01	0.02	<0.01
Leakage correction	0.08	<0.01	<0.01	<0.01	0.09
GIA	**0.12(0.4)**	<0.01	**0.12(0.4)**	0.01	0.03
Total Uncertainty	0.27(**0.5**)	0.04	0.15	0.04	0.27
RMS Uncertainties	0.27	0.04	0.15	0.04	0.27
Interaction	<0.01	<0.01	<0.01	<0.01	0.08

From Blazquez et al. 2018

The GRACE record of the Global Ocean Mass (GOM) and land ice loss has also reached an unprecedented level of maturity over the last decade.

It shows a global coverage with low ration of missing or corrupted data (except at the end of the GRACE mission and at the beginning of the GRACE-FO mission).

GRACE estimates of ice mass loss are validated against independent data from laser and radar altimetry and also in situ data.

The GRACE product come with an estimate of the uncertainty derived from an ensemble approach (see the table above for example) which includes the time correlation in errors.

The GRACE estimate of the ocean mass shows a high stability $<\pm0.5 mm.yr^{-1}$ over periods >15 years (see the table above).

Maturity of the Argo record

- Coverage down to 2000m depth
- Robust validation against in situ measurements (CTD)
- High stability: $< \pm 0.4$ mm/yr of drift over 10yr

The Argo record is less mature somehow as it has not yet reached the global coverage (few measurements below 2000 m depth, below sea ice and in marginal seas).

But it provides robust measurements validated against independent data from CTD and XBT with a very high stability.

The stability of the globally averaged thermosteric sea level derived from Argo is below $\pm 0.2 mm.yr^{-1}$ where data is regularly available and below $\pm 0.4 mm.yr^{-1}$ over the whole ocean when we include the regions that are sparsely sampled (deep ocean, sea under sea ice and marginal seas).

Maturity of the Argo record

·	Uncertainty due to quality control	Uncertainty due to errors in the bias corrections	Uncertainty due to the choice of climatology	Uncertainty due to the mapping method	Uncertainty due to the time correlation of the measurements	Uncertainty due to data distribution	Uncertainty due to the formal error of the optimal procedure (e.g. least square)	Time Period (years)	Depth range (m)	Trend Wm^{-2}	Uncertainty Wm^{-2}
Cheng et al. (2019)	no	no	no	no	yes but the method shows problems when applied over the period 2005-2017.[a] This method is not mature yet and is subject to further adjustments.	no	yes (ordinary least square)	2005-2017	0-2000	0.54	±0.02
Cheng et al. (2017)	no	no	no	no	no	no	yes (ordinary least square)	1992-2015	0-700 700-2000 0-2000	0.38 0.23 0.61[b]	±0.03 ±0.02 ±0.036[c]
Johnson et al (2018)	no (except in range of estimates)	no (except in range of estimates)	no (except in range of estimates)	no (except in range of estimates)	yes (autocorrelation analysis)	no	yes (ordinary least square)	1993-2017	0-700 700-2000 0-2000	0.36 to 0.40 0.19 to 0.35 0.48 to 0.70[b]	±0.06 to ±0.18 ±0.01 to ±0.07 ±0.06 to ±0.16[c]
Lyman and Johnson (2008)	no	no	no	no	no	yes	no	2000-2005	0-750	n/a	±0.06 to ±0.18[d]
Lyman et al. (2010)	yes	yes	yes	yes	yes (autocorrelation analysis)	no	yes (weighted least square)	1993-2008	0-700	0.64	±0.11
Johnson et al. (2016)	no	no	no	no	yes (autocorrelation analysis)	no	yes (ordinary least squares)	2005-2015	0-bottom	0.68	±0.10
Levitus et al. (2009)	no	no	yes	yes	no	no	yes	2005-2017	0-2000	0.51	±0.15
Palmer et al. 2007; Palmer and Brohan., (2011)	no	no (except in range of estimates)	no (except in range of estimates)	yes	no	no	no	1993-2017	0-700	0.40	±0.18
Domingues et al. (2008)	yes	no	no but remove a trend to reduce biases from historical climatologies (space, time, location data)	yes	no	no	yes	1993-2018	0-700	0.64	±0.03
Ishii et al. (2017)[a]	no no	no no	yes no	yes no	yes yes	yes yes	yes no	1993-2018	0 - 700 0 - 2000 0 - 700 0 - 2000	0.36 0.61 0.36 0.53	±0.07 ±0.08 ±0.01 ±0.05

From Meyssignac et al. 2019

Different estimates of the uncertainty in Argo products are available. They differ in the method used to estimate the uncertainty and in the physics that is accounted for in the uncertainty computation (see the table above).

Combining these estimates together lead to an estimate of the stability of the globally averaged ocean heat content derived from Argo to ~ ±0.1W.m^{-2} where data is regularly available and ~ ±0.2W.m^{-2} over the whole ocean when we include the regions that are sparsely sampled (deep ocean, sea under sea ice and marginal seas).

Translated in terms of globally averaged thermosteric sea level, this stability is below ±0.2mm.yr^{-1} where data is regularly available and below ±0.4mm.yr^{-1} over the whole ocean when we include the regions that are sparsely sampled (deep ocean, sea under sea ice and marginal seas).

Closure of the sea level budget:

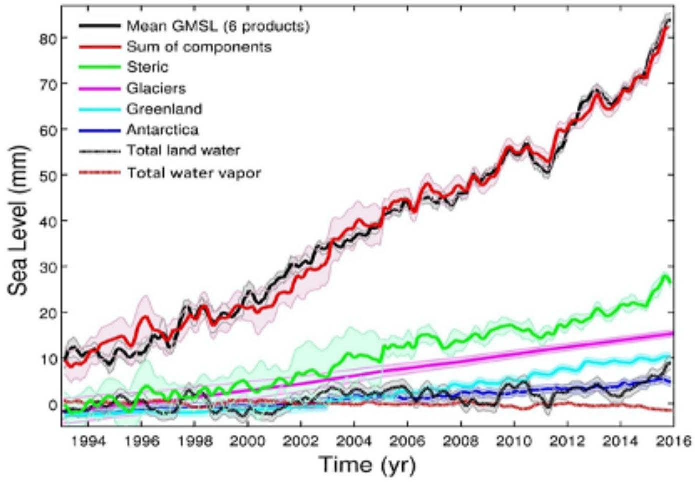
Trend uncertainty over 2005-2015 (90%CL)

Altimetry: 3.4±0.4 mm.yr^{-1}

Argo: 1.3±0.4 mm.yr^{-1}

OM: 1.9±0.5 mm.yr^{-1}

Closure: 0.2±0.5 mm.yr^{-1}

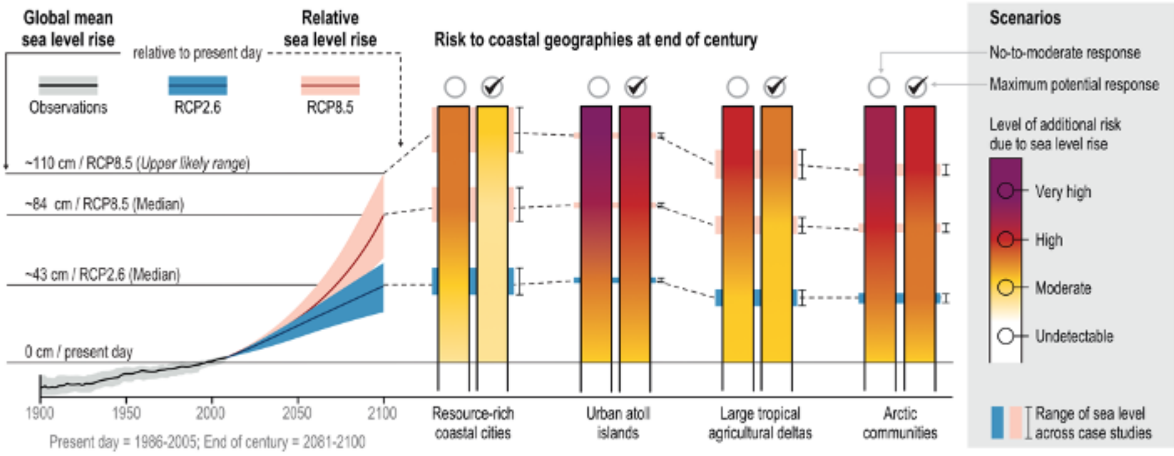


From Dieng et al. 2017 and The WCRP sea level budget group et al. 2018

This maturity of the sea level observing system (by which I mean satellite altimetry, space gravimetry and in situ ocean temperature) has allowed to close the sea level budget with an unprecedented accuracy of <±0.5mm.yr^{-1} over periods >20years. (see the figure above)

This is a very important achievement that enables to …

Constructing robust past, present and future sea level record for impact studies and risk assessment

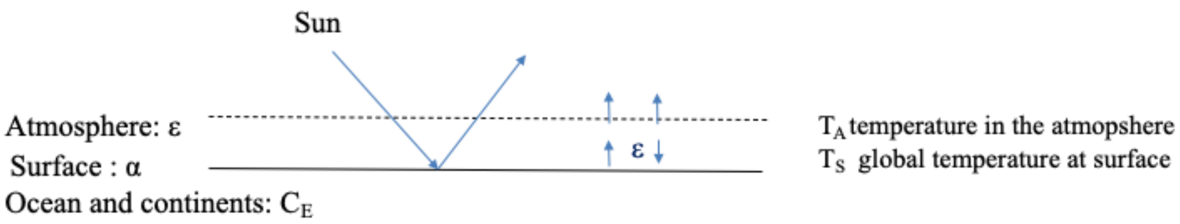


From the SROCC report

… construct a robust past and present sea level record which is essential for the assessment of the impact of sea level rise and the risks for coastal communities and ecosystems (see the figure above)

Causes for climate change?

idealized planet with an isothermal atmosphere transparent to solar radiation and behaving as a grey body in the longwave (emissivity ε) and with surface albedo α



$$C_E \frac{\partial T_S}{\partial t} = \frac{S_0}{4}(1 - \propto) + \varepsilon\sigma {T_A}^4 + (1-\varepsilon)\sigma T_S^4$$

The assessment of the impacts of sea level rise and associated risks is certainly a most important question. But here I want to address another question:

Can we use such a mature observing system as the sea level observing system to understand the causes for climate change and not only the impacts?

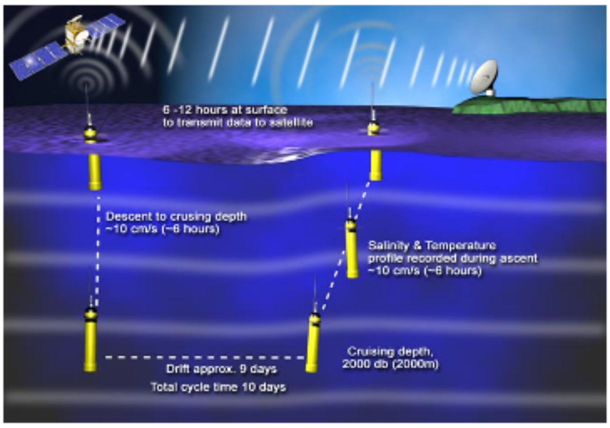
The essential question in climate change science is to understand the radiative response of the Earth under increasing GHG emissions because this radiative response is the primary cause of climate change. To illustrate this, I write here an idealised version of the energy budget of the Earth. In this equation we see that the incoming **solar radiation** is compensated by the **radiative response of the Earth**. And when this radiative response is modified by GHG emissions then an **Energy Imbalance** (EEI) appears at the top of the atmosphere and the climate system start to store energy which make climate change.

So, the question I want to address here is: can we use the mature sea level observing system to evaluate (or at least constrain) the radiative response of the Earth?

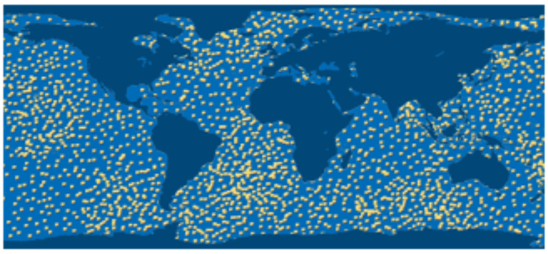
As the sea level observing system comprises only ocean observations and because the radiative response of the Earth is essentially dominated by surface and atmospheric processes, it seems difficult to constrain directly the radiative response of the Earth.

Another option is to constrain the energy imbalance and provide an indirect constraint on the radiative response through the equation above. This is possible because >90% of the energy stored in the climate system in response to the energy imbalance is stored in the ocean. By estimating the changes in the Ocean Heat Content (OHC) precisely with the sea level observing system we should be able to derive a constraint on the radiative response of the Earth. In the next slides I propose an approach to do so.

OHC estimation from Argo since the 2000s



Global coverage on the 4th of May 2018

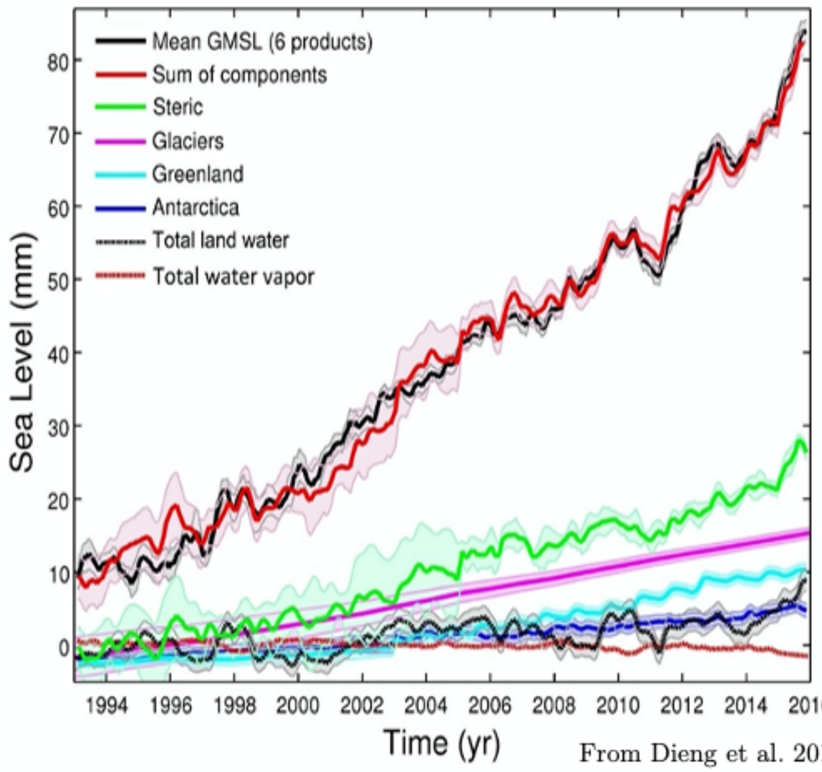


global OHC from Argo 0.66 ± 0.22W.m^{-2} (1.65 σ, i.e. 90% CL)

Down to 2000m depth, no measures in marginal seas or under sea ice

The classical approach to estimate the OHC changes is to use the Argo measurements of the ocean temperature and salinity.
This is possible on a quasi-global basis since 2005 with the deployment of the Argo profiling floats (see Figures above).
When accounting for the different sources of uncertainty (including the uneven sampling of the global ocean) we find a global Ocean heat uptake (OHU which is the derivative of the OHC) of 0.66±0.22 W.m^{-2}.
The problem with Argo is that it has a limited sampling of the ocean: the deep ocean, the marginal seas and the sea under sea ice are poorly sampled.

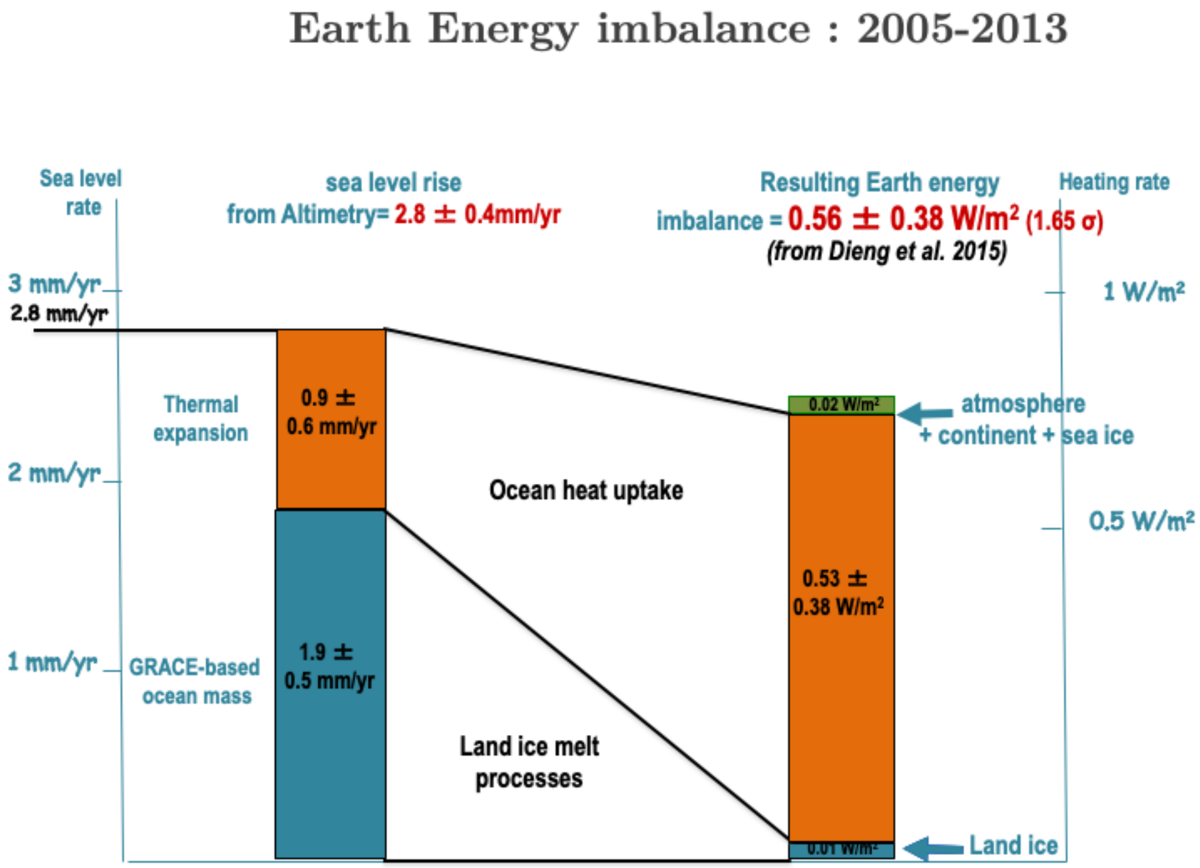
Alternative approach



From Dieng et al. 2017

There is an alternative approach that has a more global sampling. It is to estimate the OHU through the sea level budget (see Figure above).

By making the difference between sea level changes estimated by satellite altimetry and the ocean mass changes estimated by GRACE and GRACE-FO we can estimate the global steric sea level changes. Then , because the global steric sea level is linearly related to the global ocean heat content we can derive an independent estimate of the OHU. The constant that relates the global steric sea level to the global OHU is the Expansion efficiency of Heat.



Here is an example where we translate the sea level budget into an Earth energy budget to estimate the OHU and deduce the Earth energy Imbalance (EEI) over the period 2005-2013.

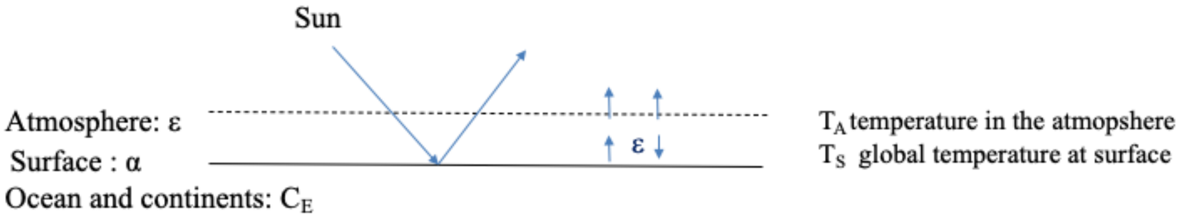
From the sea level budget on the left we derive an energy budget of the Earth on the right (see the figure above).

The thermal expansion of the ocean is translated into OHU with the expansion efficiency of heat
The ice mass loss is converted in ice heat uptake with the enthalpy of fusion

To complete the Earth energy budget we add on top the energy stored in continents and the energy used to melt sea ice. The total energy represents the EEI
You can verify here that the EEI is actually largely dominated by the OHU. In this sense the OHU provide a precise proxy of EEI (at annual and longer time scales).

Causes for climate change?

idealized planet with an isothermal atmosphere transparent to solar radiation and behaving as a grey body in the longwave (emissivity ε) and with surface albedo α



$$C_E \frac{\partial T_S}{\partial t} = \frac{S_0}{4}(1 - \alpha) + \varepsilon \sigma {T_A}^4 + (1 - \varepsilon)\sigma T_S^4$$

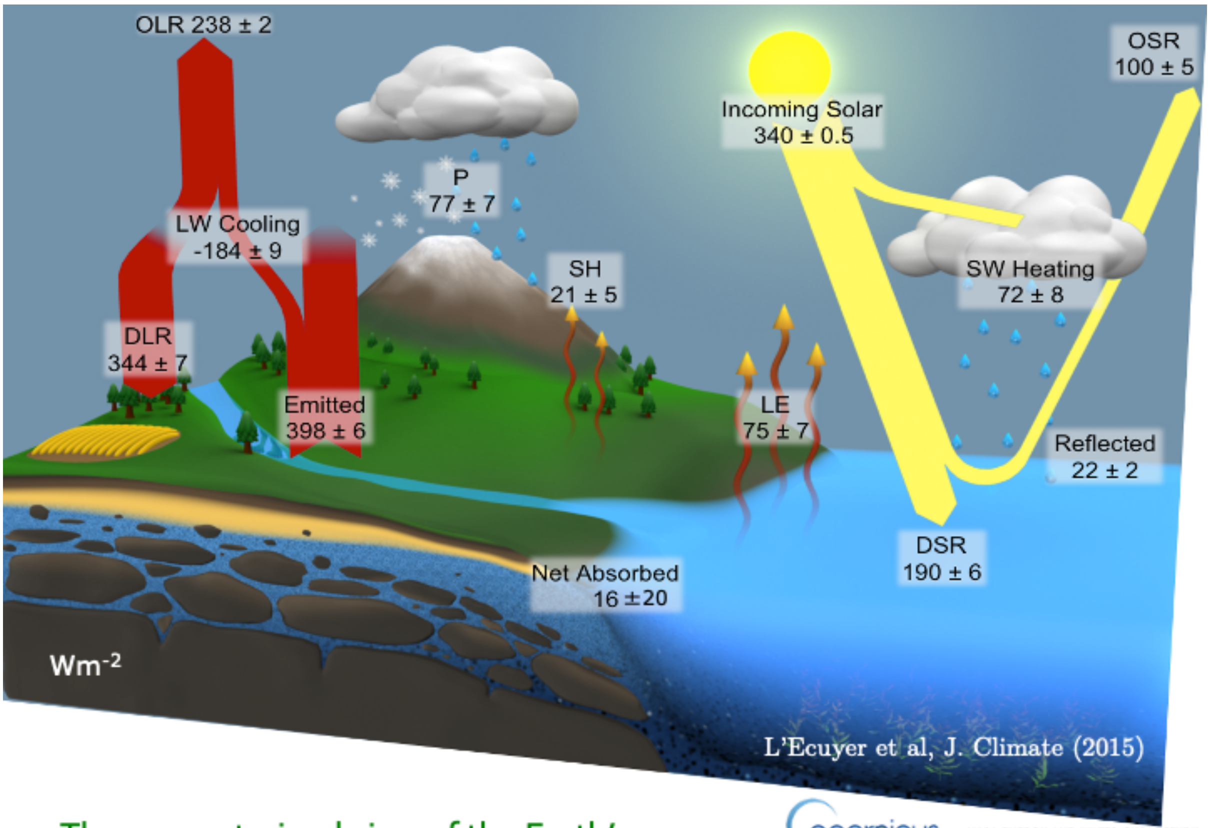
Resulting Earth energy imbalance = **0.56 ± 0.38 W/m²** (1.65 σ)

We have now a constraint on the EEI with the sea level observing system (see the equation above)

The next question is : how do we constrain the radiative response of the Earth with this constraint on the EEI?

To do so we use the variational approach of the NASA NEWSTex project (L'Ecuyer et al. 2015) in which we are involved with our American colleagues.

In the next slides I describe this variational approach and I show how the EEI derived from the sea level observing system helps to adjust the water energy fluxes that compose the radiative response of the Earth.



The unconstrained view of the Earth's energy budget does not balance

Copernicus Europe's eyes on Earth
Climate Change Service
NASA ENERGY AND WATER CYCLE STUDY NEWS

This figure is the depiction of global energy balance of the Earth. The different fluxes and storages of this energy budget can be estimated with different sources of space and in situ observations

The problem in present day, is that when primarily observation or observation-integrating datasets are used to estimate the Earth water/energy budgets (with no other adjustment) then the surface and atmospheric energy budgets of the planet do not balance!

For example, with the particular combination of datasets used in this figure above, we find that there is a net imbalance of 16 Wm^{-2} at the surface which is greater by an order of magnitude than can be explained by changes in ocean heat content or continental and ice heat uptake.

This result is largely independent of the choice of datasets used. While there isn't time to show them, similar imbalances ranging from 10 to more than 20 Wm^{-2} are obtained when any combinations of widely used flux datasets are used.

The reason for this is the fact that most of the flux datasets are derived independently – and, therefore, in the absence of any balance constraints. This independent development allows structural biases to remain between products that give rise to imbalances when they are recombined.

“Soft” Balance Constraints

General budget equation: $R = \sum_{i=1}^{M} F_i - \sum_{o=1}^{N} F_o$

Surface Energy Budget: $S = F_{LW}^{\downarrow} + F_{SW}^{\downarrow} - F_{LW}^{\uparrow} - F_{SW}^{\uparrow} - LH - SH$

Surface Water Budget: $Q = P - \underset{(E)}{LH}$

- Equations are valid for all continents on annual time-scales.
- Similar equations apply to the world oceans (cannot separate basins since transports are not known).
- Additional constraints: $\sum_{continents} Q_L = \sum_{basins} Q_O$
  - S = 0 for all continents
  - S = 0.53 for world oceans based on ocean heat content measurements

This problem of imbalances is addressed in the NEWSTex project by imposing balance constraints that are missing when fluxes are estimated in isolation.

All fluxes are combined together in the general energy budget equation and water budget equation. Both equations being coupled by the Evaporation flux (see equations above) Then the conservation laws are ensured through a variational framework that seek to adjust fluxes within their error bars in order to simultaneously satisfy all relevant energy and water conservation constraints.The equations are derived at regional scale and annual scale.

For the energy storage term that characterizes the EEI, some simple constraints are added. It is assumed that the continents do not store any energy while the ocean stores $0.53 W.m^{-2}$ (our old estimate of the OHU from Altimetry and space gravimetry)
Key points:

(1) This approach establishes a link between the energy fluxes and the storage of energy in the ocean. The estimates of OHC changes from altimetry + gravimetry (or analyses of buoy-based heat content measurements) provide essential constraints for resolving the biases between the different energy fluxes .
(2) Optimizing the energy and water cycles simultaneously adds significant value by introducing several additional independent constraints.

Variational Optimization

- If errors are assumed to be Gaussian and random, balance can be objectively imposed by minimizing the cost function:

$$J = (F - F_{obs})^T S_{obs}^{-1} (F - F_{obs}) + (R - R_{obs})^T S_R^{-1} (R - R_{obs})$$

Minimum occurs when:

$$F = F_{obs} - S_F K^T S_y^{-1} (R_{obs} - K F_{obs}) \qquad S_F = \left(K^T S_y^{-1} K + S_{obs}^{-1}\right)^{-1}$$

- Energy and water cycle constraints are satisfied simultaneously (linked through ET → LH)
- "Goodness of Fit" (χ^2) helps answer 'can balance be achieved within current uncertainties?'

$$\chi^2 = (\mathbf{F} - \mathbf{F}_{obs})^T \mathbf{S}_{obs}^{-1} (\mathbf{F} - \mathbf{F}_{obs}) + (\mathbf{R} - \mathbf{R}_{obs})^T \mathbf{S}_R^{-1} (\mathbf{R} - \mathbf{R}_{obs})$$

In the variational framework the conservation of water and energy is included as a soft constraint through the cost function J (see equation above).
In addition, each individual observation is weighted by its corresponding uncertainty
This gives us an objective way of imposing balance constraints that explicitly accounts for the relative uncertainties in the component fluxes

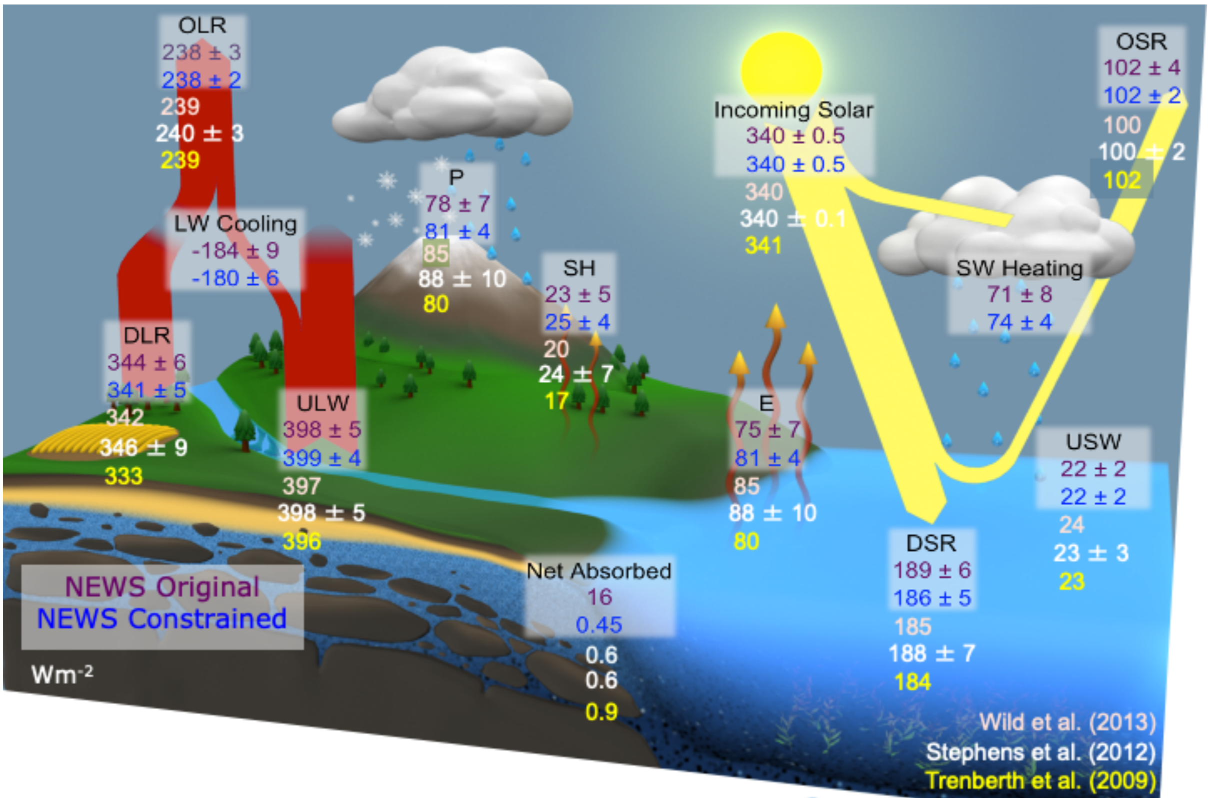
There are two nice benefits of such an approach – it allows energy and water cycle constraints to be imposed simultaneously and provides metrics of "goodness of fit". These metrics allow us to answer the questions "can balance be achieved within current best estimates of uncertainties?" and "Are the energy fluxes consistent (within error bars) with the current OHU estimate and thus with the current sea level rise estimate".

UNCERTAINTY ESTIMATES

- ❑ Validation
- ❑ Product Inter-comparisons
- ❑ Sensitivity Studies

As in data assimilation or optimal estimation retrievals, the key element to this method is accurate specification of the uncertainties in all component products.
Unfortunately we don't have time to cover the uncertainty analysis in detail but I want to emphasize that they are the result of years of research from the expert developers of all of the component flux datasets that are involved in the NASA NEWSTex project. The flux uncertainties derive from a combination of comparison against in situ observations, product inter-comparisons, and sensitivity studies.

The same is true for the estimate of the OHU estimate derived from satellite altimetry and space gravimetry that serves as a constraint. The OHU uncertainty derives from a combination of comparison against in situ observations, product inter-comparisons, and sensitivity studies. But we have been able to do this only at global scale so far.
In the future we will need to develop the OHU uncertainties at regional scale. (To derive uncertainties at regional scale we will need to estimate the space correlation in sea level errors from satellite altimetry   and in ocean mass errors from GRACCE and GRACE-FO. This is still to be done and it is not an easy task).



Earth's energy budget with balance constraints imposed.

Here is the optimized energy budget reconstruction that results after all available energy and water cycle constraints have been introduced and after the introduction of the OHU constraint from satellite altimetry and GRACE and GRACE-FO.

Notice that the surface energy imbalance more closely resembles recent estimates of changes in ocean heat content that were imposed as a soft constraint on the system (0.45W.m^{-2} is now very close to our constraint from satellite altimetry and GRACE at 0.53W.m^{-2}).

Also included are the values from prior reconstructions by Trenberth et al and Stephens et al as well as the reconstruction by Martin Wild et al. (2013) that was largely based on surface observations for comparison. The agreement is actually quite good especially considering how different the methodologies are but there are some differences. Estimates of SH, for example, are larger than reported in Wild et al. which seems to be compensated for by their larger evaporation estimates.

Conclusion

- EEI can be estimated from space from sea level and ocean mass data (or land ice loss or sea ice combined with ocean salinity)

- Satellite flux datasets that are generated in isolation yield significant imbalances in the energy budget reconstructions. These imbalances are too large to provide any accurate tracking of the excess of energy due to climate change

- Closure constraints including EEI estimates can be objectively reintroduced to the energy budget while respecting error bounds (not at al spatial scales)

- It is an objective method that provides a framework for broader integrated consistency studies. It provides a regional view of the water energy fluxes that is consistent with water and energy conservation and with the EEI estimates.

Perspective

- Objective optimization methods provide a pathway to blending the Earth surface budget and the EEI estimates approaches. ΔOHC provides the best way to access EEI but optimized budgets provides break down into component fluxes
- With sea level and ocean mass from space we could provide a regional constraint on the water-energy cycle
- The same is under way for the ocean mass to constrain the global water cycle. Other variables could provide new independent constraints on the energy/water cycle

- Imbalances reveal systematic biases in component fluxes that may be traceable to specific fluxes by examining covariances between residuals when approach is applied on monthly/regional scales

- NEWS/C3S plans to extend this analysis to monthly scales to quantify variability and trends and to 'statistically downscale' regional residuals to the underlying daily, gridded data to reduce structural biases