Report of the International Space Science Institute Working Group on

“ Consistency of Integrated Observing Systems Monitoring the Energy Flows in the Earth System ”

Members: 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], M. Wild[12]

1. Mediterranean Institute of Oceanography, Toulon, France
2. Mercator Océan, Ramonville St Agne, France, karina.von.schuckmann@mercator-ocean.fr
3. Met Office Hadley Centre, Exeter, UK
4. National Center for Atmospheric Research, Boulder, USA
5. Laboratoire d’Études en Géophysique et Océanographie Spatiales, Toulouse, France
6. International Space Science Institute, Bern, Switzerland
7. University of South Florida, College of Marine Science, Saint-Petersburg, USA
8. Earth Institute, Columbia University, New York, USA
9. National Oceanography Centre, Southampton, UK
10. NASA Langley Research Center, Hampton, USA
11. European Space Agency, Frascati, Italy
12. ETH Zurich, Zurich, Switzerland

Participants of the first meeting (June 2014) of this working group (from left to right): K. Trenberth, J. Hansen, A. Cazenave, K. von Schuckmann, M. Palmer, D. Chambers, B. Meyssignac, S. Josey (Missing persons: N Champollion, N Loeb, P.-P. Mathieu, M. Wild)

Website link: http://www.issibern.ch/workinggroups/monitorenergyflow/

Table of contents

A. Summary & Schedule

Climate Change is very much related to an energy disturbance. Over the last decades, increased emissions of GreenHouse Gases (GHG) induced by human activities have significantly impacted our climate, forcing a net flux imbalance of up to a few W m^{-2} at the Top-Of-the-Atmosphere (TOA), which is responsible for global warming (Hansen et al., 2005). This Earth's energy imbalance constrains that Earth is absorbing more energy from the Sun than it is radiating to space as heat and it is the portion of the climate forcing the Earth has not yet responded to.

Quantifying how much extra heat related to this imbalance has been generated by human activities, and how it affects our climate system is one of the key challenges faced by the climate research community (IPCC, 2013). It is estimated that about 90% of the excess energy is absorbed in the ocean, while the rest goes into melting sea and land ice and heating the land surface and atmosphere (see the Figure below, Hansen et al., 2011; Church et al., 2011). As the energy imbalance is shaping our current and future climate, it is imperative to accurately measure it and the factors that are affecting it.

The issue of the energy budget closure has now become one of the hot topics in climate science following the emerging climate debate regarding the issue of an apparent "plateau" in global surface temperature over approximately the last 15 years (Easterling and Wehner, 2009; Foster and Rahmstorf, 2011). The issue is that over this so-called "hiatus" period (Meehl et al., 2011), the global Earth surface temperature has fluctuated more or less around the same level, while the Greenhouse Gas emissions (not at about 400ppm concentration), the energy imbalance at TOA, the global "Ocean Heat Content" (OHC, von Schuckmann and Le Traon, 2011, Abraham et al., 2013) and the sea level (Cazenave and Llovel, 2010) have all continued to rise steadily, accompanied by a significant acceleration in ice melting (Steffen et al., 2010), thereby raising the question of "Where the extra heat building up in the system is going?", and "How did Earth's energy imbalance and ocean heating rate change?".

Developing the knowledge, and observational capability, necessary to "track" the energy flows through the climate system is therefore critical to better understand the relationships between climate forcing, response, variability and future changes. Each approach has its own strengths and drawbacks. There is therefore merit in pursuing all methods, trying to reconcile the different measurements sources to gain better confidence and insight into the energy budget.

The initiative capitalizes on previous seminal work, partly discussed within a recent International Space Science Institute (ISSI) publication (Bengtsson et al., 2012), bringing together leading scientists from multiple disciplines - across observations (space and in situ) and modeling (Earth system, remote sensing) - to tackle the new developments in the energy closure challenges highlighted by the new observations from satellites and in-situ networks. This activity will bring a new integrated perspective on uncertainties in, and consistencies across, both the energy–sea-level budgets focusing on a golden period, thereby complementing previous studies. It will also focus on observing systems, and in particular the space missions, needed to track energy flows in the Earth System.

Meeting I: 11 – 13 June 2014, ISSI, Bern, Switzerland
Meeting II: 18 – 19 June, 2015, ISSI, Bern, Switzerland

B. Summary of Meeting I

A first working group meeting took place from 11.06.-13.06.2014 at ISSI in Bern (Switzerland). The purpose of this first meeting was to review and discuss challenges of investigating the global Earth's energy budget by using and confronting different and independent measurement approaches of the energy fluxes. In particular the discussions were aiming to:

- Develop a scientific framework on consistency between planetary heat balance and ocean heat storage,
- Foster international partnerships and efforts to support inter-comparison of data sets,
- Evaluate existing data sets and information products and their consistency, focusing on a data-rich "golden" period to be identified, i.e. overlap amongst the highest quality data sets,
- Explore the requirements for an integrated observing system to track the flow of Energy in the Earth System,
- Recommend best practices for filling in gaps in space and time between observations.

The working group has addressed several questions during the 3-day meeting:

1. Why do we want to measure the Earth energy budget ?

Earth's energy imbalance, the excess of absorbed solar energy over emitted heat energy, is the single quantity defining the status of current global climate change and expectations for continued global warming. Hence, this quantity and its changes over time are vital pieces of information related to understanding and prediction of climate change. With increased GEG from human activities we expect that these heat-trapping gases will increase the heat content of the Earth until it reaches a stage where it can radiate more energy back to space and equilibrate. This straight-forward concept is complicated by the Earth system response and feedbacks.

The only practical way to measure the energy imbalance is to continually assess the energy in the climate system, mainly in the form of heat, and over 90% is stored in the ocean. Approximately 4% goes into melting ice, both sea ice and ice on land. The latter contributes significantly to sea level rise. The remaining percentage (~3%) contributes to warming of the atmosphere and land. Energy flows also alter clouds, while weather and internal climate modes like El Ninõ Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) can temporarily alter the energy balance for periods of days to a several decades. Understanding and attribution of the changes is necessary to enable reliable future projections on multiple time scales.

Increased heat in the ocean and adding water mass to the ocean from melting ice both contribute to sea level rise. Thus measurements of sea level rise and these two components (ocean thermal expansion and ocean mass change) can help constrain this problem and add to understanding temporal variations and relative magnitudes, as well as being of interest in their own right.

2. How can we best measure the Earth energy imbalance and its changes (sub-annual to decadal) ?

Currently, there are three ways being used to estimate year to year changes in the global energy balance: TOA residuals of incoming short-wave and outgoing long-wave radiation, integration of atmospheric and air-sea energy fluxes estimates from a combination of models and observations, and the time-derivative of Global OHC (GOHC).

An Argo-like global ocean observing system of 3D temperature and salinity is the only presently feasible approach to adequately quantify GOHC and, with accounting for the other smaller components, this is the only way the Earth's energy imbalance can be estimated as an absolute value. It is essential to maintain high quality ocean observations from Argo, reference high precision ship-board CTD casts and moored arrays and to develop high quality controlled datasets. In turn these must be analyzed into global gridded fields and incorporated into ocean reanalysis models. It has only become possible to measure the Earth's energy imbalance with sufficient accuracy over the last decade with the full deployment of the Argo ocean monitoring system. Continuation and improvement of this system is crucial for assessing the status of global climate change and the effectiveness of mitigation actions.

Supplementary data, such as satellite measurements of gravity, sea level, and regional scale radiation budget are essential adjuncts. Sea level measurements contain information on both the thermal expansion and mass gain from melting ice, while gravity data provide the best direct measure of mass losses over ice sheets and mass gains over the ocean. Satellite radiation measurements are useful for understanding climate processes internal to the Earth system.

Temporal variation of the energy balance and the 3-D distribution of ocean temperature and salinity will provide crucial data for understanding climate variations and improving global ocean and climate models. The temporal variations also provide the necessary fodder for analyzing natural variability, such as that caused by ENSO, as well as the effect of changes in climate forcings, including natural forcings such as volcanoes and solar variations, and human-made forcings such as tropospheric aerosols and increasing GEG. An extended Argo era, when appropriate key measurements are continued, would provide a basis for understanding climate change in ways that has been impossible over the past century because of the inadequacy of essential data.

Polar regions require special attention, because changes of ice shelves and ice sheets, with their resulting effect on sea level, constitute a major threat to humanity. Some of the largest climate feedbacks are largely polar processes. This includes “fast” feedbacks such as changes of sea ice and “slow” feedbacks such as ice sheet changes. As sea ice melts, more heat is absorbed by the ocean and this needs to be measured. This warming of polar waters can the have a large impact on the ice shelf, melting them from below and leading to destabilization of ice sheets. Thus, measurements under ice are critical in the polar regions.

Also changes in the deep ocean are of special importance. Floats currently go to only 2000 m depth; the deep OHC is not routinely measured. It is currently impossible to validate ocean model states for the deepest layers, except in a few regions and for limited times. Having deep measurements will help validate models and improve data-assimilated state estimates. An implication is that Argo data need to be expanded to include deep ocean and under sea ice measurements.

In addition to the energy imbalance then we must know more about the distribution of the heat and the changes. The radiation budget at TOA can be measured to sufficient accuracy to track changes over time (but not absolute amounts). The surface energy budget is more of challenge but also more relevant for regional effects, e.g. land versus ocean, tropics versus polar regions, etc. The surface energy budget involves radiative fluxes (solar and longwave, up and down), and turbulent fluxes (sensible and latent heat). The latter relates to the water cycle and precipitation in particular.

Accordingly, as well as global estimates, the spatial distribution of energy, heat and water are important, and they must be consistent in time to produce reliable rates of change. The latter has not been a focus of OHC for the most part until recently. In addition, to fully understand the energy imbalance we must track the external influences from the sun and volcanoes, in particular. With Argo, the Energy Imbalance can be computed on monthly time-scales since 2005. This is critical to enable resolution of sudden effects of aerosols from volcanic eruptions on the global energy imbalance, and also ENSO.

The other two methods of measuring the Earth's Energy Imbalance have significant issues. The global ocean mean net air-sea heat flux, and its components, have uncertainties up to 20 W m^{-2}. It is currently impossible to detect an imbalance of order 1 W m^{-2}. Studies applying this method have generally fixed an imbalance value from other means, and solved for at least one of the terms to enforce balance. Constraints on OHC from Argo measurements are a useful tool to contribute to the understanding of these uncertainties as recommended by CLIVAR/GSOP (CLImate and ocean – VARiability, Predictability and Change / Global Synthesis and Observations Panel). TOA measurements of the residual energy imbalance give biases (order 6 W m^{-2}), but the stability of the measurements is believed to be order 0.3 W m^{-2} per decade, and thus these measurements should provide useful information on variability. However, at present, there remain discrepancies between the two approaches: from changes in heat content versus TOA radiation that remain to be resolved.

In summary, measurements in order of importance for understanding the ocean's heat imbalance and the relationship to sea level:

- OHC - Argo, moored arrays, XBTs (eXpendable BathyThermographs), reference (for Argo) ship-board CTD (Conductivity, Temperature, Depth) casts etc; a data assimilation system/analysis system that is comprehensive; desirably layers: 0-100-300-700-2000-bottom; total depth,
- Sea level-altimetry with calibration from ground stations,
- Time-variable satellite gravity,
- Sea surface temperature,
- TOA satellite radiation measurements,
- Atmospheric reanalysis,
- Precipitation,
- Surface fields; temperatures, winds, humidity, surface radiation budget, bulk fluxes.

3 How can we best measure the regional impact and changes of the Earth energy imbalance, as well as the single components ?

Assessment of the importance of deep vs under-ice vs marginal seas in heat budget

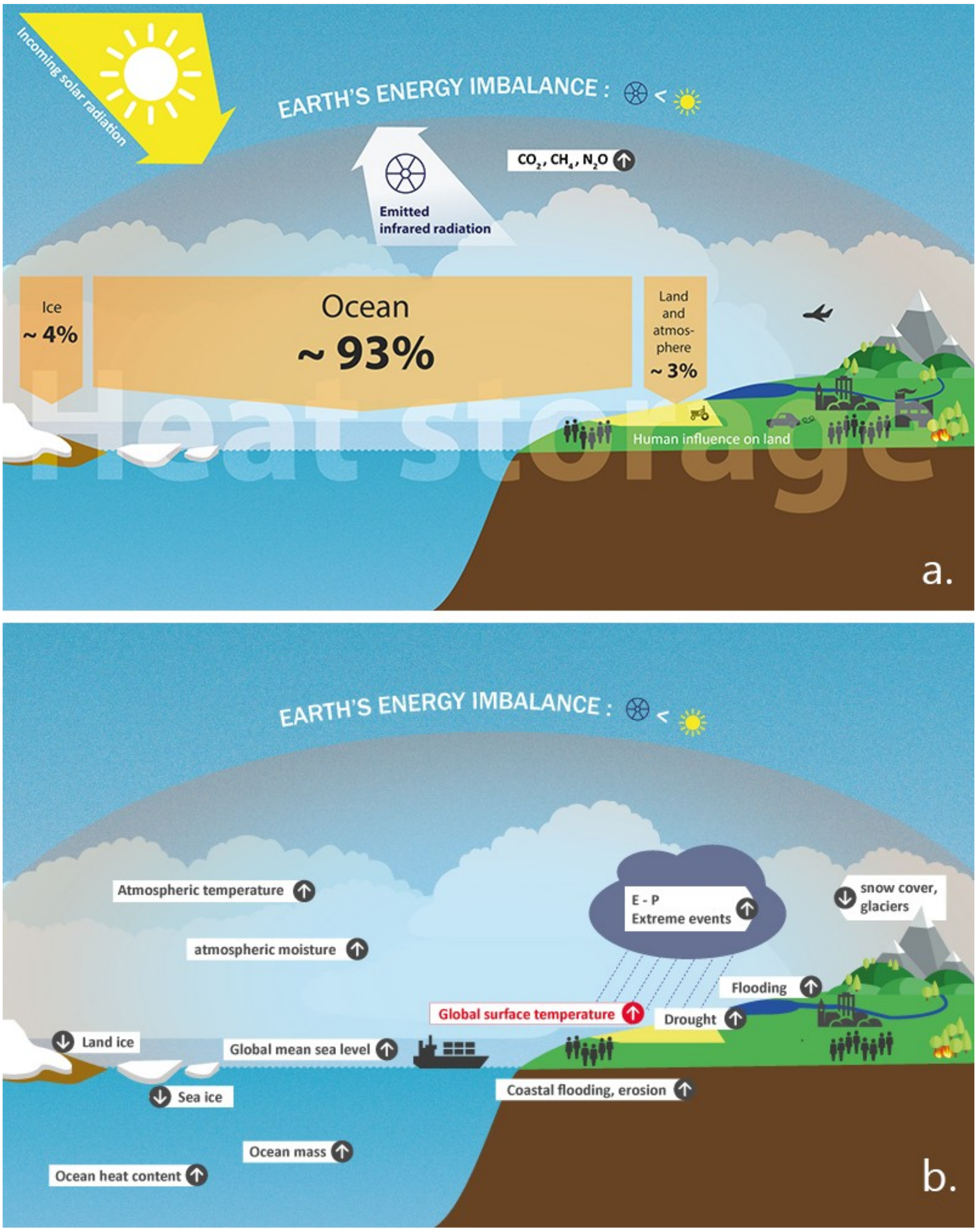
4 What accuracy do we need for global averaged measurements, and for regional and single components ? => assessment how good we do now, for the period 2005-2012, what can we do to get the derivative of OHC (resolution of the seasonal time scale) ? Accuracy of surface fluxes for average estimate.

- Establish the accuracy we need from global OHC measurements to resolve/monitor external forcings (volcanoes, anthropogenic aerosols etc). High frequency variability in net TOA sets an upper limit on this (?)
- Need to "benchmark" the range of estimates of d(OHC)/dt during the Argo period using delayed mode data (how well can we do ?)
- Methodological improvements: e.g. consideration of alternative vertical coordinate or heat budget above an isopycnal ? (attempt to reduce sampling noise). More focus on the temporal mapping of OHC ?
- Investigate mapping approaches using model data (advantage of using climate models with known net TOA ?)
- More work to help inform future observations by considering the change signals ?

- Estimate sampling uncertainty associate with CERES-like (Clouds and the Earth's Radiant Energy System) observations ? (perfect model experiments ?)
- Estimate "quality" of the GOHC estimate by inter-comparison of independent observing systems via physical constraints (e.g. sea level budget)
- Determination and inter-comparison of air-sea flux dataset global mean net heat and freshwater flux time series for the period 2005-12 for all available datasets (reanalysis, satellite, in situ, blended, hybrid). To also include component terms (shortwave, longwave, latent, sensible, evaporation, precipitation). It is anticipated that this inter-comparison will reveal unphysical trends and strong inter-annual variability at the level of 5-10 W m^{-2} over the period in many of these datasets. This information is not at present readily available and is required to clearly establish that surface flux datasets are not currently suitable for assessing variability at the 0.5 Wm^{-2} level in the global mean ocean heat budget.

C. Summary of Meeting II

The second meeting took place one year later at ISSI (18.06. – 19.06.2015). The fundamental outcome of this ISSI working group was to develop a perspective paper on the Earth's Energy Imbalance including all different expertises of this working group. During the year between the first and second meeting, extensive collaborations had been achieved, and the perspective piece had been developed and finally submitted before the second meeting to Nature Climate Change. This positive development had precised the objective of the second meeting, i.e. to further re-fine the perspective, and to fully address and discuss the comments of the 2 reviewers. The result is that this perspective piece is now published in Nature Climate Change, and precisely summarizes and visualizes all issues raised during the 2 years of this ISSI working group.



Caption: **a**, EEI as a result of human activities. **b**, 'Symptoms' of positive EEI (*Source: Karina et al., 2016*)

D. Outcomes & Acknowledgments

A perspective paper has been published by Nature Climate Change journal:

Von Schuckmann, K., Palmer, M. D., Trenberth, K. E., Cazenave, A., Chambers, D., Champollion, N., Hansen, J., Josey, S. A., Loeb, N., Matthieu P.-P., Meyssignac, B. and Wild, M., 2016: An imperative to monitor Earth's energy imbalance. *Nat. Climate Change*, Volume 6, pp 138–141. Doi: 10.1038/nclimate2876

A report has been written covering all Working Group activities.

All members of the Working Group thank the International Space Science Institute for its financial support & facilities, as well as its staff members for their logistic & administrative support.

E. References

Bengtsson, L., Koumoutsaris, S., Bonnet, R.-M., Allan, R. P., Frahlich, C., Heintzenberg, J., Ingmann, P., Kandel, R., Loeb, N. G., Soden, B. and K. E. Trenberth, 2012: Observing and Modeling Earth's Energy Flows. *Space Sciences Series of ISSI*, Volume 41, Springer, ISBN 9789400743267.

Cazenave, A. and W. Llovel, 2010: Contemporary Sea Level Rise, *Annual Review of Marine Science*, Volume 2, pp 145–173, doi:10.1146/annurevmarine-120308-081105.

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., van den Broeke, M. R., Monaghan, A. J. and I. Velicogna, 2011: Revisiting the Earth's sea-level and energy budgets from 1961 to 2008, *Geophysical Research Letters*, Volume 38, pp L18601, doi:10.1029/2011GL048794.

Easterling, D. R. and M. F. Wehner, 2009: Is the climate warming or cooling ? *Geophysical Research Letters,* Volume 36, pp L08706, doi:10.1029/2009GL037810.

Foster, G. and S. Rahmstorf, 2011: Global temperature evolution 1979–2010, *Environmental Research Letters,* Volume 6, pp 044022-044030, doi:10.1088/1748-9326/6/4/044022.

Hansen, J., Nazarenko, L., Ruedy, R., Sato, M., Willis, J., Del Genio, A., Koch, D., Lacis, A., Lo, K., Menon, S., Novakov, T., Perlwitz, J., Russell, G., Schmidt, G. A., and Tausnev, N.: Earth's energy imbalance: Confirmation and implications, *Science*, Volume 308, pp 1431–1435, doi:10.1126/science.1110252, 2005.

Hansen, J., M. Sato, P. Kharecha and K. von Schuckmann, 2011: Earth's energy imbalance and implications, *Atmos. Chem. Phys.*, Volume 11, pp 13421-13449, doi: 10.5194/acp-11-13421-2011.

IPCC 5th Assessment Report, 2013: Climate Change 2013: The Physical Science Basis. (*eds. Stocker, T. F., et al.*). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, doi:10.1017/ CBO9781107415324.018.

Meehl, G. A., Arblaster, J. M., Fasullo, J. T., Hu, A., and Trenberth, K. E., 2011: Model based evidence of deep-ocean heat uptake during surface-temperature hiatus periods, *Nature Climate Change*, Volume 1, pp 360–364, doi:10.1038/NCLIMATE1229.

Von Schuckmann, K. and Le Traon, P.-Y.: How well can we derive Global Ocean Indicators from Argo data ?, *Ocean Sci.*, Volume 7, pp 783–791, doi:10.5194/os-7-7.

Date: March 22, 2016

INTERNATIONAL SPACE SCIENCE INSTITUTE