A prospectus for the CLIVAR research focus

"**Con**sisten**c**y b**e**tween **p**lane**t**ary energy balance and ocean **heat** storage **(CONCEPT-HEAT)"**

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1. Science priorities and objectives

As one of the four core projects of WCRP, CLIVAR's (Climate and Ocean: Variability, Predictability and Change, http://www.clivar.org/) mission is to understand the dynamics, the interaction, and the predictability of the coupled ocean-atmosphere system. The CLIVAR community has identified a number of scientific imperatives to better understand climate variability and dynamics, as well as predictability and change on various time-scales, through the collection and analysis of observations and the development and application of data sets and models of the coupled climate system to the benefit of society and the environment in which we live.

To achieve the overall CLIVAR objectives, the WCRP core project is working in cooperation with other relevant climate-research and observing activities and is developing seven research foci to work on specific challenges over the next 3-5 years. ***An overarching scientific challenge faced by the whole climate science community is related to achieving accuracy in the changes in storage and flows of energy throughout the climate system necessary for climate state and variability studies***. For this purpose, CLIVAR is developing the research focus "Consistency between planetary energy balance and ocean heat storage (CONCEPT-HEAT)". Developing the knowledge, and observational capability, necessary to "track" the energy flows through the climate system is critical for better understanding relationships between climate forcing, response, variability and future changes. ***An ongoing accounting of where heat goes and its manifestations is a great need and has implications for interpreting the recent past and immediate future.*** Improved knowledge and understanding of the climate system will be translated into improved climate assessments and more reliable climate models, synthesizing the observations, performing attribution of what is happening and why, and in making predictions and projections on all space and time scales.

The only practical way to monitor climate change across time scales is to continually assess the energy, mainly in the form of heat, in the climate system. Quantifying these exchanges, and in particular how much heat has resulted from human activities (including feedbacks), and how it affects our climate system is one of the key challenges faced by the climate research community (IPCC, 2013, Figure 1). Many studies based both on models and observations have been performed, leading to significant advances in our understanding of Earth's energy exchanges (Hansen et al., 2005; Hansen et al., 2011; Church et al., 2011; Trenberth and Fasullo, 2011; Loeb et al., 2012; Stephens et al., 2012, Balmaseda et al., 2013, Trenberth et al., 2014; Palmer et al., 2011; Palmer and McNeall, 2014; Allan et al. 2014; Katsman and van Oldenborgh, 2011), while highlighting at the same time large uncertainties in the estimates of the energy flows (Trenberth, 2009; 2010, Trenberth et al., 2011, Abraham et al., 2013, Trenberth and Fasullo, 2013 ; Trenberth et al., 2014). ***However, they all agree that 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.***

Large uncertainties challenge our ability to infer the absolute measure of the Earth Energy Imbalance and its changes over time. ***An ongoing accounting of where heat goes and its manifestations is a great need and has implications for interpreting the recent past and immediate future.*** Improved knowledge and understanding of the climate system will be translated into improved climate assessments and more reliable climate models, synthesizing the observations, performing attribution of what is happening and why, and in making predictions and projections on all space and time scales.

An overall goal of CONCEPT-HEAT is to bring together six 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
- Air-sea-fluxes
- Ocean Heat Content
- Ocean reanalysis
- Atmospheric reanalyses and NWP
- Climate models.
- Global sea level

This will increase our capabilities to answer pressing issues of climate related research. 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.

2) 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).

2. Key scientific issues and recommendations

2.1 General context

Climate dynamics is very much about exchanges of energy in the Earth System, in particular in the form of heat. To understand how the Earth's climate system balances the energy budget, we have to consider processes occurring at three levels: the surface of the Earth, where most solar heating takes place; the Top of the Atmosphere (TOA), where sunlight enters the system; and the atmosphere in between (Figure 1). At each level, the amount of incoming and outgoing energy, or net flux must, on average, be equal on longer time scales in an unchanging climate. Under the influence of external and/or internal climate forcing energy is not balanced anymore, and can hence, lead to a temporal positive or negative Earth's Energy Imbalance (EEI).

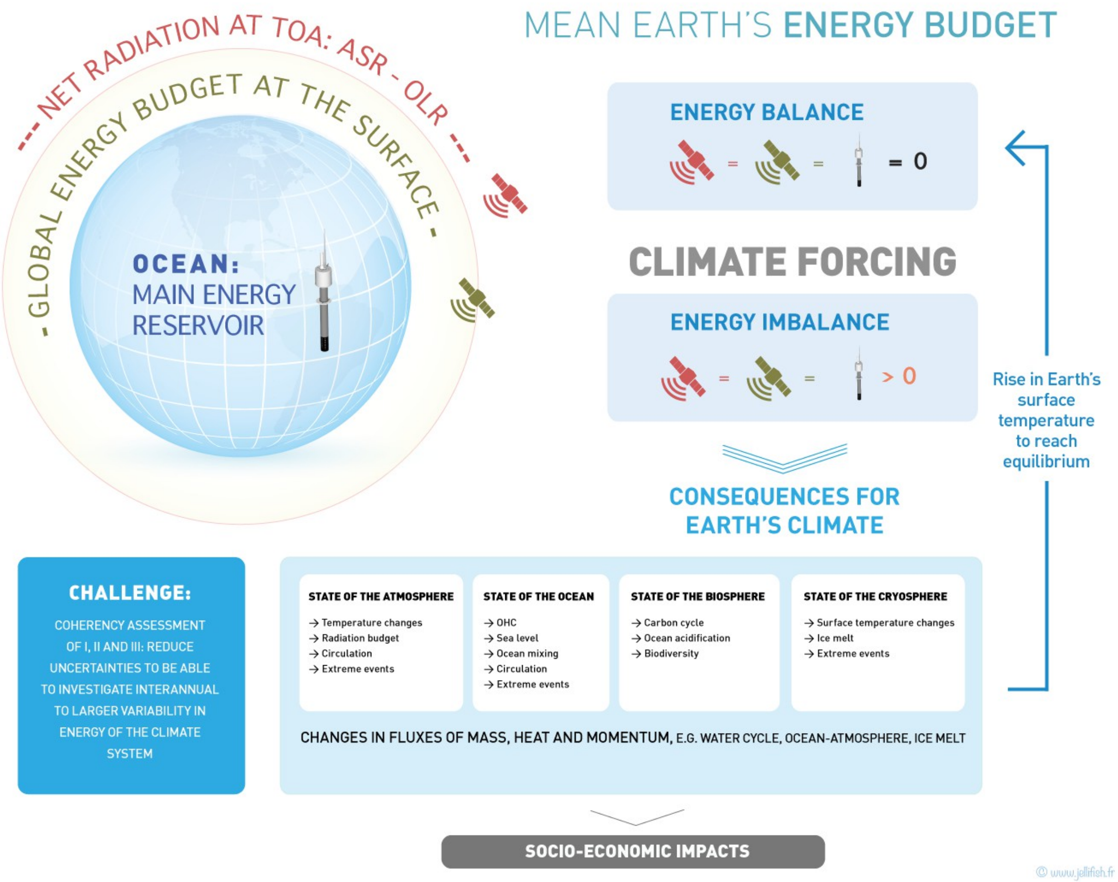

Figure 1 *Overview graphic summarizing the CLIVAR research focus "Consistency between planetary energy balance and ocean heat storage".*

Temporary variations of EEI can occur naturally due to internal variability as well as external forcing. On short time-scales (months), natural fluctuations in clouds and atmospheric dynamics associated with synoptic and low-frequency variability can create a temporary EEI.

Internal climate variations, in particular the El Niño Southern Oscillation (ENSO) can also lead to interannual fluctuations of EEI (e.g., Trenberth et al. 2014a; Allan et al., 2014; Palmer and McNeall, 2014; Brown et al, 2014). External forcing such as volcanic eruptions and variations of the sunspot cycle can also create such changes. All these influences occur superposed on the climate change signals associated with changes in atmospheric composition (Trenberth et al., 2014a).

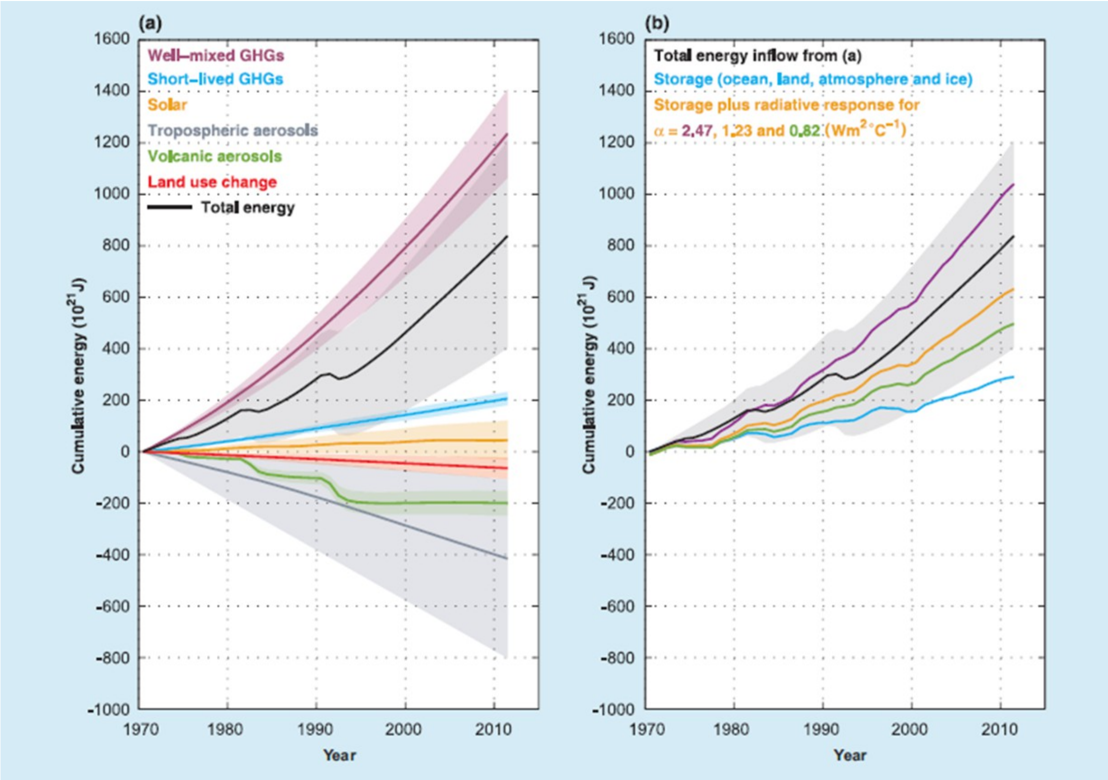

Figure 2 *(From IPCC, 2013): Since the accelerated increased concentration of greenhouse gases from human activities (a), energy at the top of the atmosphere is not balanced, leading to an accumulation of heat in the climate system (b). The total cumulative energy flow into the Earth System (ES, black line in a and b) is going into warming of ES and results in increase of outgoing radiation inferred from changes in Earth's global surface temperature (colored lines in b; blue shows amount of stored energy in the climate system, and other colors show stored plus radiative responses for different climate feedback scenarios which trigger climate response).*

Over the last few decades, increased emissions of Greenhouse Gases induced by human activities have significantly impacted our climate (Figure 2a), forcing a positive net flux imbalance ranging from 0.5 to 1 Wm^{-2} at TOA during the last decade with considerable interannual variability (Earth's Energy Imbalance, Hansen et al., 2011; IPCC, 2013; Loeb et al., 2012; Trenberth et al., 2014a). The apportioning of this energy in the atmosphere, oceans, land and ice (Figure 2b), and the exchanges among them along with the phase changes of water, on various time-scales are at the core of climate dynamics and how the climate system evolves. ***The global ocean plays a critical role in regulating these energy flows, being by far the most important heat reservoir due to its enormous heat storage and transport capacity.***
Over the last 50 years, it is estimated that a large share (about 90%) of the accumulating heat at the ocean surface has penetrated into the top 700m (and deeper) layers through subduction and mixing processes, leading to an observed increase of upper Ocean Heat Content (OHC, Abraham et al., 2013; IPCC, 2013; Figure 3). CMIP5 model simulations suggest that full-

depth global ocean heat content becomes the dominant term in Earth's energy budget on timescales of about 1 year (Palmer and McNeall, 2014). The remaining excess heat from planetary warming goes into melting of both terrestrial and and sea ice, warming the atmosphere, and the land surface (Trenberth, 2009; Hansen et al., 2011; Church et al., 2011; 2013a, Figure 3).

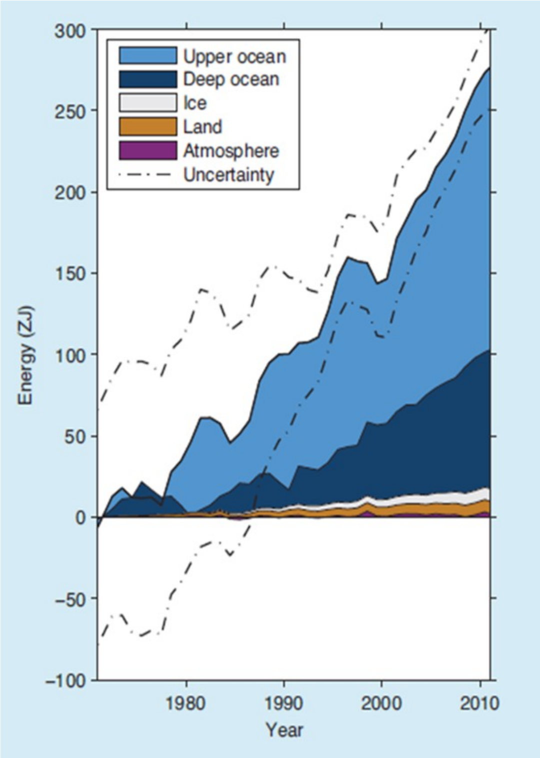

Figure 3 *(from IPCC, 2013): The largest amount of energy accumulated in the climate system is stored in the global ocean (~ 93%). The rest goes into melting of land and sea ice (~ 4%) and warming of the atmosphere and land (~ 3%). The prevailing increase of stored energy in the global ocean (blue shadings) as measured by Global Ocean Heat Content (see Abraham et al., 2013 for a review on observed GOHC) is a clear indicator for a warming climate.*

The positive energy imbalance apparent in both observations and climate model simulations suggests an ongoing accumulation of energy in the Earth climate system manifested primarily as a warming of the global ocean (Figure 3). ***Multiple studies show that there has been a multi-decadal increase in OHC*** of the ocean layer going down to at least 3000 meters (Figure 3), although the confidence in these estimates is higher for the upper ocean (700 meters) and decreases below due to the differences in measurement methods, input observations, and analyses techniques (Abraham et al., 2013). This clearly reflects the impact of anthropogenic warming on the Earth's climate system.

Despite this, Earth's surface temperature trends have slowed substantially over the last 15 years and the observed trends are very much at the lower end of model simulations (Smith, 2014; Forster and Rahmsdorf, 2011; Easterling and Wehner, 2009). This ***observed hiatus*** in global warming is challenging the prevailing view that anthropogenic forcing causes global surface warming. Various mechanisms have been proposed for this hiatus in global surface warming highlighting the role of ***internal climate variability forcing a redistribution of heat in the oceans*** (Meehl et al. 2011; Guemas et al., 2013; Watanabe et al., 2013; Trenberth and Fasullo 2013; Trenberth et al., 2014a; Yu and Xie, 2013; England et al., 2013; Meehl et al. 2013, 2014; see also Nature Geoscience special issue: www.nature.com/ngeo/focus/slowdown-global-warm/index.html).

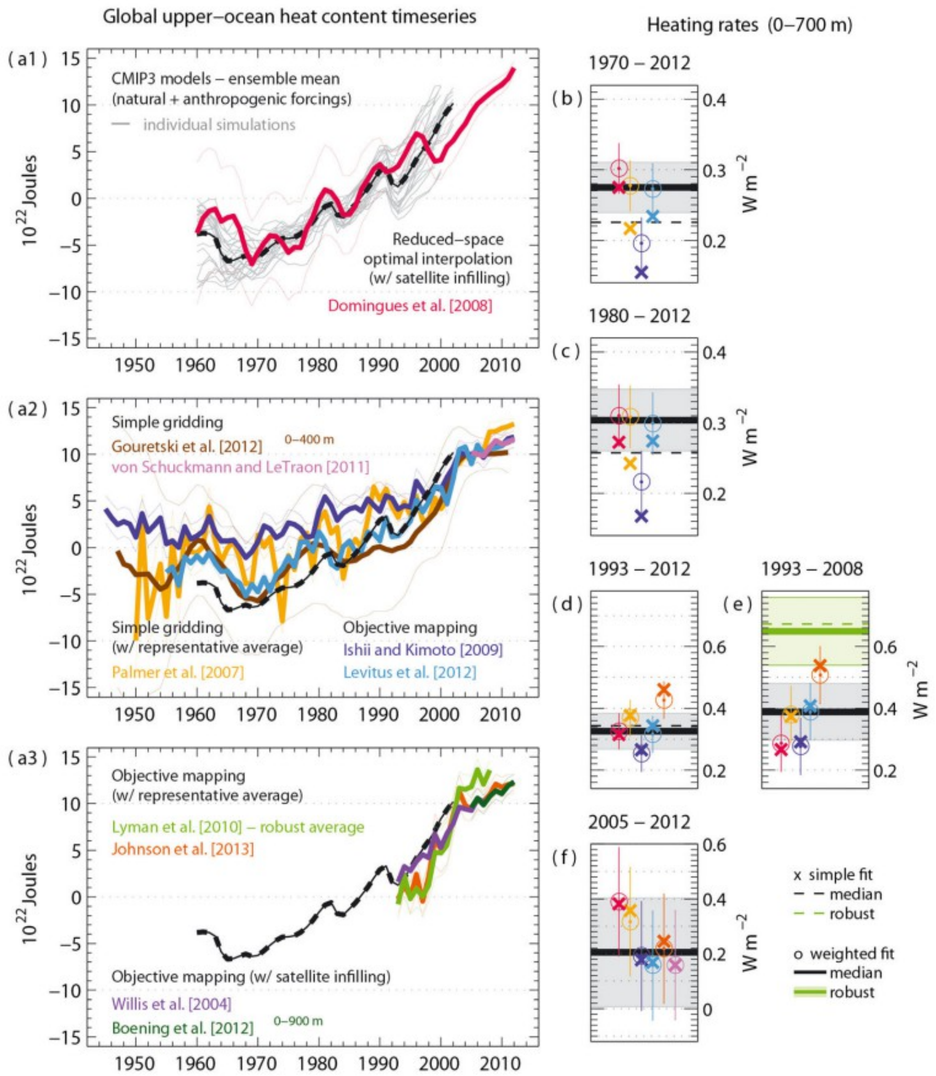

Figure 4 *(from Abraham et al., 2013): Time series of ocean heat content change from a number of different statistical estimates (a1-3) and equivalent planetary heating rates for various periods (b-f).*

Periods with little or no surface warming trend have occurred before in observations (Knight et al., 2009; Easterling and Wehner, 2009), and are seen as well in climate-model simulations (Santer et al., 2011; Meehl et al. 2011, 2014). Trenberth et al. (2014a) show in their estimates that the net energy imbalance at TOA varies naturally in response to weather and climate variations, the most distinctive of which is ENSO. It also varies with the sunspot cycle, affecting 15% of the climate change signal on decadal time scales. Moreover, the net TOA energy flux, as well as OHC is profoundly influenced by volcanic eruptions (Palmer et al., 2007; Domingues et al., 2008; Balmaseda et al., 2013). On multidecadal time scales strong intrinsic variability of the ocean affecting the Pacific (Meehl et al 2011; Kosaka and Xie 2013; Trenberth and Fasullo 2013; Trenberth et al. 2014a), and Atlantic (Latif et al. 2004, Knight et al. 2005; Chen and Tung 2014) may produce multidecadal signals in air-sea heat fluxes (Gulev et al. 2013). All of these ***influences occur superposed on the climate change signals*** (e.g. Cazenave et al., 2014) associated with changes in atmospheric composition. While heating continues during the recent upper-ocean-warming hiatus (Figure 3), but the heat is absorbed in the deeper ocean below 300-700m (e.g. IPCC 2013; Abraham et al., 2013; Balmaseda et al., 2013). So the plateau in surface warming is not because heating from rising greenhourse gas concentrations has ceased. The evidence supports continued heating of the climate system as manifested by melting of Arctic sea ice and glaciers, as well as Greenland, but most of the heat is penetrating below the ocean mixed layers which influence surface temperature (e.g. Balmaseda et al. 2013; England et al., 2013; Chen and Tung, 2014), and thus contribute to observed increasing global mean sea level rise (e.g., Church et al., 2013b).

Some studies have shown that the closure of the observed energy budget over the hiatus period remains elusive for interannual variations pointing to an amount of “missing energy” in the system (Trenberth, 2009; Trenberth and Fasullo, 2010; Trenberth et al. 2014). Although some of this previously “missing energy” is accounted for within the substantial observational uncertainty range (e.g. Hansen et al., 2011; Loeb et al., 2012), the large inconsistencies between independent observations of Earth's energy flows points to the need for improved understanding of the error sources and of the strengths and weaknesses of the different analysis methods, as well as further development and maintenance of measurement systems to track more accurately Earth's energy imbalance on annual timescales (Trenberth et al., 2014; Loeb et al., 2012). A particular key science question of this research focus is concerned with the range of substantially different heating rates that have shown to be large (Figure 4).

Energy balance can also be estimated from climate models, which in turn require validation to provide confidence in their results (Hansen et al., 2011; Trenberth et al., 2014), but can play an important role in informing the observational requirements for improved estimates of Earth’s energy budget (Meehl et al., 2011; Meehl et al., 2013, Katsman and van Oldenborgh, 2011; Palmer et al., 2011; Palmer and McNeall 2014). The key issues in this case relate to 1) how realistic the model is, 2) the external forcings that are specified, and 3) the integrity of the model in terms of internal variability. The external forcings are quite incomplete, especially in the 2000s in all CMIP5 model simulations (Santer et al 2013; Trenberth et al 2014; Allan et al 2014). Small volcanic eruptions are missed altogether, solar variability, especially as a function of wavelength is inadequate, and aerosols are generally poorly dealt with whether specified in concentrations or as emissions that are then interactively evolved within the model. The model must in turn represent realistic energy budgets regionally and the simulations of clouds remain a key issue (e.g. Trenberth and Fasullo 2010b). The internal variability in CMIP5 models remains inadequate, whether in terms of ENSO or multidecadal variability (such as NAO, SAM etc). All of these outstanding issues require the development of metrics for evaluating models and homogeneous datasets.

2.2 Key Science Questions and recommendations

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?

Advances made on this key science question are most fundamental for climate research as ***EEI is the single quantity defining the status of global climate change and expectations for continued global warming.*** We are able to obtain this information from current global observing systems, ocean reanalysis and climate models, but fundamental work is urgently needed to understand existing inconsistencies and unsolved issues of different products and estimates of EEI. This is necessary in order to adequately track where the energy is currently accumulating, how our climate is changing and what are the implications for the future. A proper accounting is needed of the absolute mean value, the temporal variability as well as the uncertainties in the EEI and we need to identify what is required to further reduce the uncertainties.

Recommended activities:

i) To benchmark our ability to monitor OHC changes at sub-annual time scales during the Argo era by using an agreed delayed-mode Argo input data set. Initially using statistical methods but this could be extended to ocean reanalyses later. This gives us a starting point from which to move forward.

ii) Carry out a comparison of mapping methods using “pseudo profiles” in a “perfect model” experiment (including both high-resolution ocean model coupled climate model simulations). This would give insights into the pros and cons of the different mapping methods and assumptions in a known system (current intercomparison efforts can reveal important differences, but not which product/mapping is most like reality). In addition, perform test of gap filling in space and time from ocean reanalyses (by using ocean heat transport) which in principle should be better than any statistics-only method for developing OHC estimates

iii) To utilize massively available SST (and potentially SSS) data along with mean sea level gauge records for the further cross-validation of estimates based upon data from different underwater systems. In addition, use of mean sea level from satellite altimetry corrected for ocean mass variations deduced from GRACE to analyze current biases from in situ sampling (including undersampled regions such as marginal seas and deep ocean below 2000m depth).

iv) To achieve advancements in data quality control issues: for the historical in situ database: joint activity with CLIVAR-GSOP Coordinated Quality-Control of Global Subsurface Ocean Climate Observations – the IQuOD initiative [www.iquod.org]; but also for the Argo era, in joint collaboration with the international Argo program. This also includes to manage and coordinate support for data and metadata archaeology (joint activity with IQuQD).

v) Liaise with climate modelling community to define suitable OHC patterns/metrics for testing climate variability hypotheses emerging from climate modelling simulations.

vi) Evaluate OHC changes from the ensemble of current ocean reanalyses and work with the OHC in situ community to identify and understand differences, coming from different observations or coming from the gap filling or data assimilation methodologies. This includes continued performance of multi-analysis ensemble approach to study the uncertainties as successfully performed during the GSOP initiative (Clivar exchanges No.64) and to quantify and reduce model biases by using recent well observed periods and built in to any reanalysis estimates.

vii) Develop a community review paper on all components of EEI

Question B: Can consistency between planetary heat balance and ocean heat storage achieved and what are the major limitations?

Each of the existing independent approaches (satellite measurements at TOA, in-situ observations and reanalysis outputs for ocean heat content, estimates of EEI from climate models) to determine values for energy flows in the Earth's system has its own advantages and drawbacks in terms of sampling capability and accuracy, leading to different estimates, and associated uncertainties. In addition different communities are involved in delivering these estimates and as yet these communities have not worked closely together to allow different assumptions to be compared and for some of the uncertainties to be reduced. Thus ***evaluating and reconciling the resulting budget imbalance is a key emerging research topic in climate***

science which has the potential to bring 6 different communities together to make a major contribution to reducing climate change uncertainties. Errors involved in deriving single components without a coupled context can accumulate and have major impacts on the accuracy of climate indicators, leading to large imbalances differences in estimates of Earth's budgets and climate. Reconciling the different approaches remains a challenge. Only by using conservation and physical principles can we infer the likely resolution.

Recommended activities:

i) Improve accessibility and information content of products to evaluate the different components of EEI (ocean reanalysis products, in situ OHC, net flux at TOA, climate models) for use by wider community. Develop improved evaluation of these products to quantify strengths and weaknesses to provide advice to a wider range of potential users.
ii) Strengthen collaboration of interdisciplinary climate community by building up a synergy community. This requires funded collaboration initiatives (network funding for workshops, working visits at laboratories, etc.., e.g. started with ISSI working group, MISTRALS ENVIMED, COST Action ES1402).
iii) Assessment of consistency between planetary heat balance and ocean heat storage as a multi-analysis approach from the synergy community to investigate uncertainties, quantify inconsistencies and understand their causes.
iv) Develop a community review paper on all components of EEI

Question C: How are TOA net radiation and ocean heating rate distributed in space and time?

Observed climate variations such as the current hiatus or unresolved inconsistencies of climate observations (e.g. "missing energy" in the climate system) underpin the need for fundamental research activities on the regional distribution of TOA and OHC (including vertical distribution), as well as their implication for their global estimates. Continued assessment and attribution studies of ***regional natural climate variability are essential to improve our estimates of global changes***. There is also an urgent need to ***evaluate the relative importance of currently under-sampled regions of ocean heat content change*** (ice-covered ocean, marginal seas and deep ocean) ***and to understand how heat is transferred vertically***. We have to evaluate how regional patterns change in time and if regional OHC tendency patterns can, along with other patterns e.g. regional sea level, be ***used to test/falsify model hypotheses***. We need to further understand ***the role of resolution of climate models and reanalysis models*** in resolving natural climate variability and providing accurate error estimates, as well as to understand which are the relevant model physics and parameterizations that need further improvements.

Recommended activities:

i) Evaluate the relative importance of the ice-covered ocean, marginal seas and deep ocean (> 2000m) of ocean heat content change and to understand how heat is transferred vertically, with the objective to develop recommendations for observing system design (GOOS).
ii) Evaluate how regional patterns change in time
iii) Use of ocean reanalyses to analyze physical processes for exchanging OHC with the deep ocean through mechanisms of diffusion and deep water formation.
iv) Use of ocean reanalyses to analyze processes and forcing (momentum and buoyancy) of regional natural climate variability and their impact on the global budget
v) Analyze if regional OHC tendency patterns can, along with other patterns e.g. regional sea level, be used to test/falsify model hypotheses.

Question D: How can we improve validation requirements for and from coupled climate models to improve estimates of EEI?

Models are self-consistent and accounting for any drifts and biases may therefore be useful in identifying inhomogeneity in observational datasets or in providing transfer functions between measurements and physical variable. Consideration of models in conjunction with observations is therefore essential in evaluating climate change processes. Addressing the energy budget in climate models is a powerful method for understanding future climate projections. A prerequisite thereby is an adequate representation of the energy budget in climate models, which requires a careful validation process and adequate reference datasets. They can be used to evaluate the main drivers for understanding the energy budget, more precisely to analyze the transient climate response and the role played by ocean heat uptake (i.e. ocean heat uptake efficiency). This can be achieved by focusing on the net energy accumulated in the Earth's system and how that energy is redistributed in space and time. A large part of this energy will be found in the deep ocean heat uptake, and particular emphasizes should be given to projected OHC and accompanied uncertainties, including the uncertainty of projections of global thermal expansion, which is a large term in projections of sea level (of order 50% of the projected signal).

More work is needed to understand biases in specific terms of energy budgets in the models as derived from climate model energy imbalances. These biases depend on the way how the different models balance the terms, and their understanding in turn will shed light on biases in forcing terms from observations (e.g. surface fluxes). Here the effort is needed for understanding the role of eddy resolved ocean in forming new mechanisms of coupling and, thus, changing the picture of surface fluxes diagnosed by models. Moreover, more work is needed to assess the response of climate models to the radiative forcing, and a combined study of satellite observations with climate models will be particularly valuable to advance on this issues.

Recommended activities:

i) Characterize range of model simulations of ocean heat uptake and mechanisms.

ii) Assess the representation of the energy budgets in climate models with adequate reference datasets.

ii) Use of self-consistent models in assessing and improving dataset homogeneity and perform signal (from emergent patterns of OHC change) to noise (from internal variability) analysis to reveal fundamental information on the extension of the in situ observing system (e.g. test the importance of ice-covered ocean vs. shelf seas vs. deep ocean (> 2000m depth) and examine the role of mesoscale noise).

iii) Develop observational constrains on future sea level rise and transient surface temperature rise, and develop process-based relationships between observable quantities and the emergent signals of change, the net energy gain and the re-arrangement of energy within the system for an assessment of future climate projections.

iv) Providing controlled experiments to assess attribution of different processes on EEI and perform inter-comparison of coupled climate model response to radiative forcings and observed changes in different components of the TOA radiation budget (satellite, in situ) to evaluate and reduce uncertainties, and analysis on the spatial patterns of change.

v) Utilize the experiments with coupled climate models with eddy resolving ocean blocks, including those done at regional level. A close, careful look is needed on the role of atmospheric synoptic and mesoscale processes in forming surface fluxes to assess further the extent to that these phenomena are undercounted (poorly counted) in the existing climate models. The first pilot results can be generated at regional level (for key-areas), while in the future global assessment is necessary.

Question E: How can we better constrain the surface energy fluxes and their spatio-temporal variations at regional scale?

Characterizing the uncertainty and biases in surface 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 superimposed on the centennial-scale warming of the global ocean surface. Quantifying sea surface heat fluxes to the required level of accuracy needed to support the various applications is a very challenging task. The current level of uncertainties in global ocean mean and trends of heat and moisture fluxes remain higher than is required by many applications and improvements to these estimates are required for further progress. Many of the current global ocean products use local measurements for determination of methodologies and/or uncertainties. Given the relative paucity of local measurements, sampling issues and errors in flux algorithms and satellite retrievals under extreme wind or wave conditions between differing data sets cannot be resolved by comparisons with these in situ data alone. Also, a further critical issue is the scaling of surface fluxes because in-situ measurements of the fluxes and state variables are scale dependent. Regional and global energy budget assessments may help provide further constraints for the surface flux datasets to aim towards. Using constraints on energy budget considerations, and hence, inter-comparisons to other independent observing systems as well as to re-enforce interdisciplinary collaborations for climate research application will contribute to advances urgently needed for estimates of surface energy fluxes.

Recommended activities:

i) Quantify the different types of uncertainties of surface fluxes, their correlation structure, and sensitivity to uncertain parameters (e.g. input data, bulk algorithms) and satellite retrieval schemes in order to improve the usefulness of global flux products, and make them more suitable to support scientific studies of climate variability, trends, and the global ocean heat budget closure

ii) Develop an innovative ensemble approach to generate multiple realisations of flux surface products, combining the individual strengths of existing data sets, the latest knowledge in bulk formulations and associated input data, and the most recent efforts in re-processing flux data sets of climate quality (e.g. ESA CCI). The idea is that a well-designed ensemble of multiple realisations of surface fluxes would sample some of the uncertainties related to the flux products, in a similar way as is done for SST within, for example, the HadSST3 data set.

iii) Exploit integral constraints as suggested by Yu et al (2012) along with statistical approaches using reconstruction of probability density functions for surface fluxes (Gulev and Belyaev 2012) to check consistency of the Net Heat Flux product components, and in particular by use of Argo data on a series of regional "Cages" of interest (e.g. Pacific Warm Pool, the North Atlantic and enclosed seas such as Mediterranean and Red Seas). Include use of ocean reanalyses for regionalizing OHC budgets by providing estimates of ocean heat transports and transport convergences and their temporal variability in different regions of the ocean based on the full range of available ocean observations.

iv) Develop a community-led Flux Platform to share, access and inter-compare easily 6 different sets of flux climatologies, and their input data (e.g. different SSM/I data streams), thereby fostering close collaboration between different communities, as well as new ways of combining in situ measurements and flux data. Such a platform was regarded as a very useful tool to organize a global effort to coordinate the evaluation of flux products, improve their inter-operability and encourage their use.

v) Complement the GSOP inventory of surface flux products with “assessment”-type

information regarding the strengths and weaknesses of the various flux products, in an effort analogous to the "Climate Data Guide" (NCAR/UCAR, USA), to guide the in selecting the best product for their application across the multitude of flux products available on the web.
vi) Evaluate potential for improving surface heat flux estimates based on ocean or coupled reanalysis products.
vii) Ensure continuation and foster expansion of high quality in situ measurements in remote locations, such as on ocean platforms and small islands, as anchor sites for the assessment of modelling and remote sensing products.

2.3 Expected outcomes:

The main expected outcome of this initiative is to achieve refinement of a scientific framework on consistency between planetary heat balance and ocean heat storage aiming to build up a pluri-disciplinary synergy community for climate research (see 1.2).

- Evaluation of existing data sets and information products and the assessment of their consistency.
- Recommendations on how to improve the observing systems, methods to derive surface flux products, data assimilation methods, ocean and climate models and development of new data sets, analyses and diagnostics that can be used to assess storage terms and energy flows in models, as well as future climate projections.
- Contributing insights to the understanding of interannual-to-decadal climate variability in Earth's Energy Budget as well as associated changes in the ocean heat storage and surface fluxes, thus, assessing changes in the climate system, and linking them to initiatives on predictability and detection of anthropogenic climate change.
- Quantitative constraints for climate models on heat budget imbalances at TOA, the air-sea interface as well as regional and depth limited accumulation rates of OHC.

3. Governance and international coordination

3.1 Scientific steering team

Name	Affiliation/ Country	Partner organization	Expertise
Karina von Schuckmann (co-chair)	MOI, University of Toulon, France		In situ ocean observations (Argo OHC and sea level)
Kevin Trenberth	NCAR/UCAR, Boulder, USA	GEWEX SSG	Earth's climate, datasets and reanalyses
Carol Anne Clayson	WHOI, Woods Hole, USA	SeaFlux (chair)	Surface fluxes, remote sensing
Catia M. Domingues	IMAS/ACE CRC, Univ. Tasmania, Australia	CLIVAR GSOP GC sea level (scoping team co-chair)	In situ ocean observations (OHC and sea level)
Sergey Gulev	IORAS, Moscow, Russia	SeaFlux	Surface Flux, Ocean general circulation modeling
Keith Haines	University of Reading,	CLIVAR GSOP	Coupeled and Ocean

	UK		Reanalysis for Climate Analysis and Forecasting Climate data
Norman Loeb	NASA, Hampton, USA	GEWEX GDAP, CERES Science Team Leader	TOA radiation flux
Pierre-Philippe Mathieu	ESA, Frascati, Italy	CLIVAR GSOP	remote sensing, environmental modelling, weather risk management
Matthew Palmer	MetOffice,	CLIVAR GSOP co-chair, Argo UK expert team	Climate models, ocean in situ observations
Bob Weller	WHOI, Woods Hole, USA	US CLIVAR SSC Chair	Ocean in situ observations
Martin Wild	ETH, Zurich, Switzerland	IAMAS-IRC-GEB (co-chair)	Earth's Climate, Global climate modelling, surface flux
Yan Xue	NCEP/NOAA, USA	CLIVAR GSOP	Ocean Synthesis

3.2 International coordination

The CONCEPT-HEAT research focus involves an interdisciplinary team, with significant expertise to address the key scientific issues proposed in Section 2.2. Members are part of a number of WCRP core-projects and cross-cutting initiatives (Figure 4). This will help to coordinate close collaboration between a mix of relevant communities and integration of scientific outcomes. It is anticipated that the research outcomes from CONCEPT-HEAT will directly contribute to these 10-year WCRP Grand Challenge initiatives:

- “Clouds, circulation and climate sensitivity”
- “Change in water availability”
- “Regional sea level change and coastal impacts”

In addition, of particular importance to CONCEPT-HEAT, is the connection between two WCRP core-projects: CLIVAR and GEWEX. GEWEX has projects on the radiation budgets at TOA and the surface, as well as surface flux estimates over land (LANDFLUX) and ocean (SEAFLUX), with a strong focus on atmospheric radiation budgets and atmospheric energy transports as constraints on the Earth’s energy imbalance.

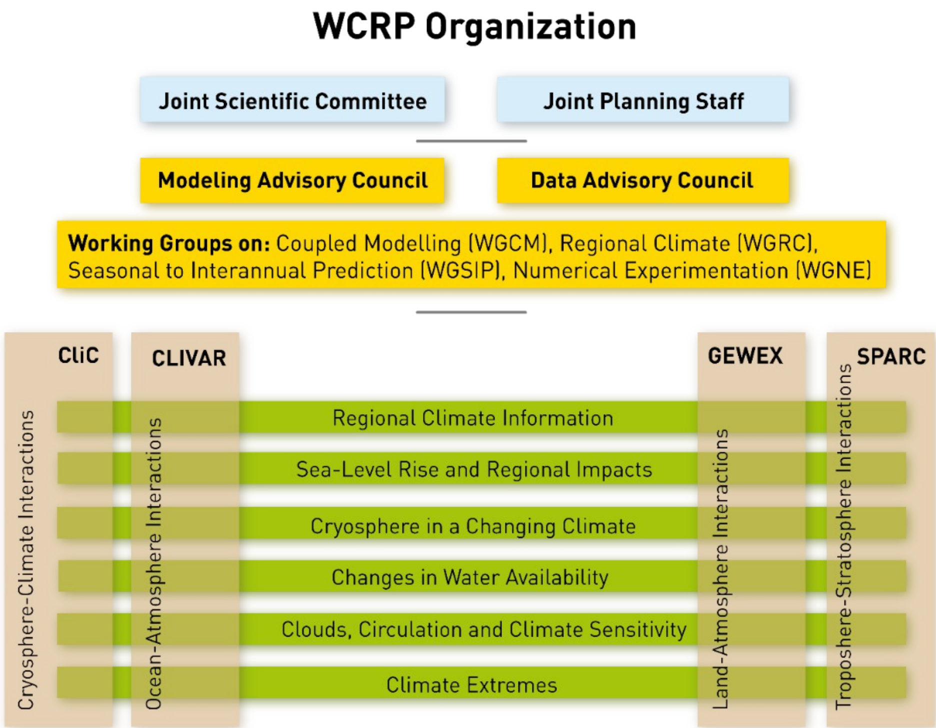

***Figure 4**: The implementation of WCRP with its four core projects: CliC, CLIVAR, GEWEX and SPARC (Source: www.wcrp-climate.org)*

The HEAT-CONCEPT initiative should also benefit from achievements made during the past years in the frame of the international GODAE OceanView programme. GODAE was based on the hypothesis that data assimilation into high resolution ocean models could succeed in constraining the evolution of the global ocean circulation at eddying resolution. Building on the success of the GODAE, since its inception in 2008 the GOVST international program has been been created, with the mission to define, monitor, and promote actions aimed at coordinating and integrating research associated with multi-scale and multidisciplinary ocean analysis and forecasting systems (Schiller et al., 2014). Global modelling and data assimilation systems have been progressively developed, implemented and inter-compared, taking advantage of increased computing power and enhanced model resolution (Martin et al., 2014). The same data assimilation systems are also used to produce reanalyses covering many years for various purposes including the calibration of coupled seasonal forecasts, and for understanding how the ocean has changed over the past decades. In-situ and remote sensing data are now routinely assimilated in global and regional ocean models to provide an integrated description of the ocean state, allowing for reanalyses of the ocean's variability from the mesoscale to global variability. In the future, cooperation between CLIVAR and GOV should be engaged along the objectives of HEAT-CONCEPT, i.e. by ensuring that data assimilation systems will be improved in a way to produce more accurate estimates of heat content diagnostics in ocean reanalyses.

4. Implementation

CLIVAR can help to adapt to support implementation activities by supporting the development of a cross-panel and cross-collaboration between this RF and CLIVAR GSOP and GEWEX, in particular by supporting working groups and network development. A joint GSOP/HEAT-CONCEPT meeting is discussed to be held at MET-Office, Exeter, UK in fall 2015. In addition, further development on implementation targeted activities and timeline need to be further discussed during a first meeting, as well as during several teleconferences (and CLIVAR could help by setting up these teleconferences). However, travel budgets generally seem pretty tight these days and some travel expenses to facilitate workshops and meetings in support of the proposed activities would be needed. Moreover, potentially hosting some of the model data required for "perfect model" experiments, if that option is pursued.

4.1 Targeted activities

In section 2.2, recommendations have been defined, and further development is needed to refine targeted activities based on these recommendations. Proposals for targeted activities should be encouraged from the community and discussed and leaders identified as well as timeline for implementation. A meeting planned (joint with GSOP in fall 2015) will help to further develop these potential targeted activities. However, some initial targeted activities have already been identified:

(i) Systematic intercomparisons

- The Ocean Reanalyses Intercomparison Project (ORA-IP)
  http://www.clivar.org/sites/default/files/documents/Exchanges64.pdf
  Carry out a "perfect model" experiment with a number of groups providing statistiacal estimates of OHC (documented in Abraham et al., 2013). This could, in principal, be extended to a number of ocean reanalysis centres (solution for computational and real costs is needed)

- To coordinate a protocol of experiments for intercomparison of in situ OHC estimates (e.g. building on from Boyer et al. and Cheng et al. intercomparison paper (in preparation), and taking advantage of the material already generated by the various groups involved (NODC, ACE CRC/CSIRO, UK Met Office, PMEL/JPL, KlimaCampus, Coriolis/Ifremer) for both periods, Argo and pre-Argo (two different targeted activities)

- Systematic intercomparison of existing turbulent surface flux products, and uncertainty evaluation using the concept of "cages" (ESA Tender, funding 2014/2015); as well as of existing radiative surface flux products.

(ii) Assessment studies of energy budget

- To coordinate a community review paper (decision ISSI working group 2013)

- To coordinate a systematic assessment study of all components of the energy budget (cross-activity with targets in (i)).

(iii) Develop cross-links with GEWEX

- Coordinate the systematic assessment of the components of the energy budget (ii above) with the satellite datasets that GEWEX has already developed (atmospheric and oceanic)

- Ensure that representation of the GEWEX flux, precipitation, and radiation data set development groups are invited and participate in the planned meeting for fall 2015

- Determine a joint co-chair from the GEWEX Data and Assessments Panel for this research focus

4.2 Timeline

Scoping activities to this date

Date	Event/Location	Purpose/Outcomes
3-4 July 2013	CLIVAR ESA Scientific Consultation Workshop on Ocean Heat Flux University of Reading, UK	http://www.clivar.org/events/clivar-esa-scientific-consultation-workshop-2013
February, 2014	Informal meeting during the AGU Ocean Science meeting, Honolulu Hawaii, USA	
April 2014	Informal meeting with some members during the EGU General Assembly, Vienna, Austria	
17. July 2014	Breakout session during Pan-Clivar meeting	
November 2014	report to CLIVAR/SSG	

Planned activities

Dec. 2014	Telephone conference to discuss feedback from CLIVAR SSG meeting in Nov.	
July 2014	Telephone conference to discuss issues on the upcoming workshop	
Sept. or Oct. 2015	Joint meeting GSOP/CONCEPT-HEAT	
End of 2015	Telephone conference	
2016	RF meeting (maybe joint with GEWEX and/or CLIVAR panels)	

4.3 Deliverables, outreach and capacity building

The following is envisioned:

- Integration of interdisciplinary community
- Spawning of systematic intercomparison analyses (obs/models)
- Development of best standard practices
- Improved estimates and uncertainties (public/easy access/guidance for users)
- High-impact publications
- Design recommendations for sustained observing systems (eg, impact on space/in situ agencies) and model development
- Workshop reports
- Web outreach through WCRP and social media
- FLUXNEWS issue and development of brochure/handout
- TbD at meeting: Potential summer schools/training for young scientists and capacity building in developing countries

5. Funding opportunities (meetings/projects)

Past:

- ISSI Workshop on Observing and Modeling Earth's Energy Flows (Bengsston, 2012).
- ISSI Working group on "Consistency of Integrated Observing Systems monitoring the energy flows in the Earth System": Duration: 2014-2015; first meeting 11.-13.06.2014 (ISSI, Bern, Switzerland)
- MISTRALS/ENVIMED (national funding France): The Mediterranean Sea mass

and heat budget: Understanding its forcing, uncertainties and time evolution. MED-MaHb: Duration: 2014-2015; first meeting 9.-10.10.2014 (IMEDEA, Mallorca, Spain)

- ESA (European funding): Towards Improved Estimates of Ocean Heat Flux (TIE-OHF): : Improvement and Calculation of Global Long Time Series of Ocean Heat Fluxes from Satellite Remotely Sensed Data, In response to ESA ITT ESRIN/AO/1-7712/13/I_AM

Future:

- new COST Action designated as COST Action ES1402: Evaluation of Ocean Syntheses
- Perspective: Program at MetOffice Hadley center for testing mapping strategies
- Australian Research Council: Discovery Projects (http://www.arc.gov.au/ncgp/dp)
- ISSI Working group on "Consistency of Integrated Observing Systems monitoring the energy flows in the Earth System": Duration: 2014-2015; second meeting July 2015 (ISSI, Bern, Switzerland)

6. Appendix: Estimates of EEI from global climate observing systems and its uncertainties

6.1 Estimates at TOA

Monthly observations of TOA radiation from Earth Radiation Budget Satellite (ERBS) wide field of view (WFOV) for the period 1985-1999 (Wong et al., 2006) and the Clouds and the Earth's Radiant Energy System (CERES, Loeb et al., 2012) can be used to evaluate estimates for EEI. While the absolute accuracy of satellite TOA net radiative flux is insufficient to provide EEI to better than a few Wm^{-2}, the measurements provide a useful estimate of temporal changes in EEI. For example, CERES observations provide a precision in global mean net TOA flux to better than 0.5 Wm^{-2} (95% confidence; Loeb et al., 2012). However, ERBS observations suffer from discontinuities in temporal coverage, and therefore long-term temporal variability is more uncertain. Allan et al. (2014) have attempted to derive EEI estimates over the entire period with the help of a model, and discuss the issues. The changes of energy anomalies can be compared with other methods, including OHC (observations and reanalysis) and from climate models.

However, intercomparisons and inter-validation schemes have shown that unresolved inconsistencies occur at interannual time scales (Trenberth et al., 2014a), but generally fall within the uncertainties of the interannual OHC tendencies. The error bars in OHC tendencies are too large to assess interannual variability in EEI for climate research in the early 2000s, a period of transition from XBT to Argo observing systems, although they can bear within large error bars (Loeb et al., 2012). An agreement is better after 2006 owing to a much greater number of available Argo floats. However, there is still room for improvement, as there remain significant differences amongst independent analyses of the same Argo which are still too large to account for the accuracy needed for climate research (Trenberth et al., 2014a). In particular, the combination of Argo and TOA estimates to further improve and understand these inconsistencies at interannual timescales has been done before (e.g. Loeb et al., 2012; Trenberth et al., 2014a; Allen et al., 2014), and needs to be improved in the future.

6.2 Estimates of GOHC from the in situ observing system

The ocean is the principal source of the climate system's inertia, the “pacemaker” in the response to natural and anthropogenic forcings. It is thus essential that we improve our understanding of the role of the ocean in the climate system, monitor the observed ocean variability and change, and interactions with other components of the climate system. Indeed, analysis of the rate at which the ocean is gaining heat is the most natural and accurate approach and perhaps the only practical way, when added to other much smaller components, to determine the state of Earth's energy imbalance.

To evaluate heat stored by the climate system, global OHC can be derived from the global ocean in situ observing system. Several key historical and modern subsurface measurement instruments exist for assessing ocean temperatures globally as required for climate assessment, i.e. the expendable bathythermograph (XBT), shipboard CTD measurements, the Argo floats and seal data for the Southern Ocean (see Roemmich et al., 2012 and Abraham et al., 2013 for an overview). Other measurement techniques such as mooring arrays from TAO, RAMA and PIRATA and the Ocean Buoy Network, drifting boys and Gliders complement the global ocean in situ observing system.

Since its inception, the World Climate Research Program (WCRP) has taken international leadership with the Tropical Ocean-Global Atmosphere project in the 1980s, including initiating the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) moored array focusing on the tropical Pacific heat budget and OHC redistribution via ENSO. Also the World Ocean Circulation Experiment (WOCE) was a part of WCRP which used resources from nearly 30 countries to make unprecedented in-situ observations (full-depth sections and expanded XBT network, see e.g. Roemmich et al., 2012 for an overview) of the global ocean between 1990 and 1998 in order to determine poorly-understood but important physical processes and focus on ocean circulation and hence, energy transports within the global ocean. The latter are still a big challenge for regionalizing the energy budget.

Following TOGA, the WCRP formulated CLIVAR that begun in 1995, further fostering the Argo float array capable of monitoring OHC directly in the upper 2 km with a 10-day repeat cycle, and reoccupation of some of the full-depth WOCE hydrographic sections under the auspices of the Global Oceanographic Ship-Based Hydrographic Investigations Program. The Global Climate Observing System (GCOS), in partnership with WCRP, has formulated a concept for the Global Ocean Observing System (GOOS) and encouraged contribution to it, particularly through the OceanObs workshops in 1999 and 2009 (e.g. Palmer et al., 2009).

With the inception of the Argo array of autonomous profiling floats (http://www.argo.ucsd.edu/) in 2000, our ability to monitor global and regional ocean heat content (steric sea level) variability and change significantly increased, owing predominantly to increased sampling density. Argo has now become the major contributor to the global ocean in situ observing system. Estimates for GOHC from today’s Argo sampling, were it truly global, could be derived with an accuracy of about 0.1 Wm^{-2}, and uncertainties will rapidly decrease with a longer time series (up to 0.02 W/m^{-2} after 15 years of today’s Argo sampling, von Schuckmann and Le Traon, 2011).

But these uncertainties do not reflect current limitations of the Argo observing system for GOHC estimates. Since Argo does not sample below 2000m and sampling is limited for shallow oceans (shelf areas, marginal seas, e.g. von Schuckmann et al., 2014) and areas polewards of 60° latitude, methodologies for accurate estimation of sampling errors and their minimization through the data-infilling strategies are required to improve the accuracy of the

estimates in the deep ocean and poorly sampled areas (Abraham et al., 2013). Hence, an Argo-like observing system has the large potential to deliver accurate estimates of GOHC, but needs to be maintained in the future and with efforts made to fill in existing sampling gaps. Moreover, caution is still needed, as instrumental problems have been found and must be corrected to the extent possible (e.g., Willis et al., 2007, 2011; Barker et al., 2011). High-quality shipboard CTD programs are critical to maintain high accuracy and minimize systematic errors in the Argo array (and in other instrument types) (Freeland et al., 2010).
The collection, assembly, and quality control of a comprehensive data set as done by oceanographic data centers are invaluable for global analyses of heat content. An additional quality control in delayed mode is indispensable when using the data base from the data centers (Coriolis, UK Met Office, US NODC) for OHC analyses, (coherence analyses to check for platform drifts, exclude black-listed Argo profiles and others, check for systematic biases, application of corrections (XBT, MBT, etc)). Most of the analyses of OHC are done by individuals or small groups of investigators, using their own delayed-mode quality control and mapping strategy. Large differences exist among currently available products (e.g., Abraham et al., 2013; Church et al., 2013b, Trenberth et al., 2014a) and best standardized practices do not exist yet for statistical interpolation and objective analysis to be applied when dynamical ocean reanalyses/syntheses are not used. Largest challenges remain for the historical data, including the large gaps and the correction method for XBT data (e.g. Domingues et al., 2008). Despite independent efforts over the past few decades by a number of research organizations who have attempted to assemble, rescue and quality-control (QC) subsurface ocean profiles, the global historical profile database still contains a relatively large fraction of biased, duplicated and substandard quality data and metadata that can confound climate-related applications. The IQuOD (International Quality-controlled Ocean Database, http://www.iquod.org/) effort is being organized by the oceanographic community, and includes experts in data quality and management, climate modellers and the broader climate-related community. The primary focus of IQuOD is to produce and freely distribute the highest quality and complete single ocean profile repository along with (intelligent) metadata and assigned uncertainties for use in ocean climate research applications. This goal will be achieved by developing and implementing an internationally-agreed framework. Although of less impact compared to the historical database, systematic biases represent also during the Argo era a challenge which has shown to induce biases in GOHC estimates (Willis et al., 2009; Barker et al., 2011; von Schuckmann et al., 2014).
By correcting sea level rise estimates (obtained from satellite altimetry) for ocean mass changes (obtained from GRACE) estimates it is possible to get an estimate of the thermal expansion of the ocean. Assuming a reasonable climatology of the deep ocean it is further possible to deduce an alternative estimates of the GOHC. This method has the advantage to give a direct estimate of the total GOHC including the deep ocean and the marginal seas. However this estimates cumulates the uncertainties coming from satellite altimeter systems, the GRACE system and the assumed climatology of the deep ocean. Today it is unclear whether these uncertainties enable to get precise estimates of the GOHC compared to a potential extended (below 2000m depth) ARGO network (von Schuckmann et al., 2014). Some analysis give first indication that this method can provide at least interesting upper bounds on total GOHC (Llovel et al. 2014). With improved error estimates of GRACE and satellite altimetry this method should give very valuable constraints on the total GOHC estimates for the time being as long as ARGO network is still limited.

6.3 Ocean reanalysis

The production of ocean reanalyses is now an established activity in several research and operational centers, with new versions produced at intervals when improvements in ocean models, data assimilation methods, forcing fluxes or ocean observations are available. The key benefits to be gained from using ocean reanalyses for OHC and earth energy budget studies are as follows.

For global estimation ocean reanalyses can provide dynamical gap filling in space and time which should be better than any statistics-only method for developing OHC estimates directly from in situ data. In particular, reanalysis systems can provide dynamically consistent reconstructions of the evolving ocean and associated uncertainties, taking into account the whole spectrum of scales (from mesoscale to large scales) that contribute to the ocean climate variability. In addition to in situ T/A data, they also utilize additional ocean observations, e.g. satellite SST, SSS and altimetric data, and bring in the longer record of atmospheric observations through use of atmospheric reanalyses to help improve surface momentum and buoyancy forcing functions. Ocean reanalyses provide estimates of air sea fluxes as well as OHC, and also provide a direct physical representation for exchanging OHC with the deep ocean through mechanisms of diffusion and deep water formation, which otherwise can only be estimated as a budget residual. Finally ocean reanalyses provide a mechanism for regionalizing OHC budgets by providing estimates of ocean heat transports and transport convergences and their temporal variability in different regions of the ocean based on the full range of available ocean observations.

The weakness of ocean reanalyses lies in the models being used, the data assimilation methods applied, the ocean observing system that only captures a limited portion of the space-time variability spectrum, and the prior error statistics that must be specified to weight the relative importance of model and data information. All models have biases which may be imposed to a greater or lesser extent upon the reanalysis results, and the more these are understood, quantified, and reduced e.g. through bias correction methods, the more useful ocean reanalysis results will become. Recent well observed periods can be used to characterize these biases, and then corrections made to earlier reanalysis periods when the lack of observations leave reanalysis results more prone to showing model biases. Bias corrections are typically also necessary for the atmospheric reanalysis based forcing fields, especially surface fluxes, but these too can be bias corrected based on well observed fields like SSTs. Regarding observations, the lack of in situ and remotely-sensed observed information at high latitudes and in the deep ocean yield increased uncertainties in the corresponding regions, making accurate estimates of the global ocean heat content still challenging.

Atmospheric reanalyses have in the past used SST as a lower boundary condition, which does not allow for any flux feedbacks. However, they do represent much of the high amplitude synoptic to inter-monthly and even longer variability reasonably well; something that is often problematic for other surface flux estimates. Most ocean reanalyses similarly use pre-defined atmospheric boundary conditions thus also cutting out feedbacks. Despite these drawbacks atmospheric and ocean reanalysis products usually produce much more balanced global surface flux estimates than any of the direct observation based methods (REFS). New approaches that use coupled data assimilation methods may provide a better way forward in future by allowing feedbacks between the upper ocean and lower atmosphere as part of the reanalysis process which should allow one of the most relevant and best observational records, that of SSTs, to be assimilated much more rigorously and effectively.

CLIVAR GSOP has taken an overview of ocean reanalysis activities. A first review of the state of the art on ocean reanalyses was produced around 2006 and reported for OceanObs09 in Stammer et al (2010) and Lee et al. (2009), among others. Carton and Santorelli (2008) provided a first look at OHC from these early reanalyses. A new intercomparison of ocean reanalyses is now underway based on the availability of new surface forcing, from atmospheric reanalyses, and improved quality controlled ocean datasets, (e.g., Willis et al., 2007; Barker et al., 2011; Cowley et al., 2013). First results have been presented in CLIVAR Exchanges No 64, with a summary paper in press Balmaseda et al (2014), with further publications underway.

There is still considerable diversity in the reanalysis products with low resolution reanalyses (1°), spanning a long time period (typically 50 years), as well as higher resolution products (~¼°), which exhibit eddy permitting capabilities and are so far available only for shorter records (usually the altimeter period 1993-onwards). Some coupled atmosphere ocean reanalyses have also been included for the first time. The suitability of the different approaches for use in OHC and Earth energy budget studies now needs to be carefully assessed. Values for OHC obtained from a selection of ocean reanalyses are described Palmer et al., (2014). An ad hoc but pragmatic way of measuring the current uncertainty of the reanalyses is to develop multi-reanalysis ensemble products. This has been used to study ocean heat content (Xue et al. 2012, Zhu et al. 2012), air-sea fluxes (Valdivieso et al 2014), and for the initialization of seasonal (Zhu et al 2012, 2013) and decadal forecasts (Pohlmann et al 2013). In addition, more advanced approaches (e.g. based on fully probabilistic or ensemble methods) are needed to include self-consistent estimates of uncertainties in the reanalysis products (Candille et al., 2014). These approaches, however, require very significant computer resources that are still challenging to secure by individual reanalysis groups. Further coordinated studies are required to achieve the full potential of ocean reanalyses for OHC studies.

6.4 The surface energy budget

Because the atmosphere has very small heat capacity, on annual and longer time scales the surface fluxes should match the TOA values to within about 0.1 W m^{-2} globally.

The surface energy budget consists of radiative fluxes (net shortwave, SW, and net longwave, LW, radiation), and turbulent fluxes (sensible and latent heat, the latter being related to the water cycle). Improving our estimates of the global surface energy budget, and producing reliable uncertainty estimates, is currently a significant challenge of the air-sea/land interaction community.

Air-sea net heat fluxes have on average local systematic uncertainties of the order of 10 Wm^{-2}, but these errors can vary significantly in space and time. Errors in extreme conditions such as hurricanes, or in regions with strong SST gradients, such as the Gulf Stream, can be much larger. Global and regional integration of surface heat fluxes leads to mean errors on the order of 20 Wm^{-2} (Josey et al. 2013). Hence, it is currently impossible to detect an imbalance equivalent to 1 Wm^{-2} via estimation of the surface energy budget. However, 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 (e.g., Trenberth et al., 2010, Loeb et al., 2012, Cazenave et al., 2014; Trenberth and Fasullo 2013).

Air-sea fluxes have long been a strategic focus of the WCRP activities leading to the creation of several working groups, reviews, and publications. The Joint WCRP/SCOR Working Group on Air-Sea Fluxes (WGASF, www.noc.soton.ac.uk/ooc/WGASF) performed a comprehensive review of the various flux data sets that were then available (WGASF, 2000), and a research action plan regarding fluxes has been developed by the WCRP WGSF in 2003-2008 and by WCRP Ocean Atmosphere Panel (WOAP, 2012). Within CLIVAR/GSOP, a set of guidelines for evaluation of air-sea flux datasets was developed (Josey and Smith, 2006) and discussed further in Yu et al. (2012). US-CLIVAR has also set-up a dedicated “Working Group on High Latitude Surface Fluxes” (Bourassa et al., 2013). Air-sea interaction research addresses multiple international scientific programs, such as the Surface Ocean Lower

Atmosphere Study (SOLAS) for physical and biogeochemical fluxes, and the Global Energy & Water Exchanges Project (GEWEX) for LandFlux, as well as the long standing SeaFlux efforts (e.g. Curry et al., 2004; Clayson et al, 2014). Radiative fluxes are also considered by the GEWEX Data Assessment Panel (GDAP) and from CERES (http://ceres.larc.nasa.gov/science_information.php?page=computed-fluxes).

Quantifying sea surface heat fluxes to the required level of accuracy needed to support the various applications identified by WGASF and later by WGSF is a very challenging task. Furthermore, it is still unclear which of the components of surface net heat flux contributes mostly to our uncertainties and where regionally these contributions are most significant. Also, we know only tentatively the relative role of sampling errors, uncertainties in the measurement of surface state variables, and the inaccuracy of bulk algorithms to the total uncertainty of surface fluxes (Gulev et al. 2010). Both in situ and satellite-derived data sets that rely on the bulk algorithms are dependent on errors in the flux parameterization, which appear to be relatively small outside of extreme winds or wave states (Bourassa et al. 2013). In-situ data sets generally have larger sampling errors than the satellite-derived products. The largest errors in the satellite products are errors associated with retrievals of the surface state variables (e.g. Clayson et al. 2014, Prytherch et al. 2014). Compared to the sea surface fluxes, land surface flux products can be better constrained by direct observations, due to the availability of high quality land-based reference stations such as for example obtained from the Baseline Surface Radiation Network (BSRN).

Many biases in surface air-sea heat flux products are associated with inadequate capturing of synoptic and mesoscale patterns of air-sea fluxes and, thus, surface flux extremes by different data sets (e.g Gulev and Belyaev 2012). However rapidly changing on meso- and synoptic scales sea surface conditions are now amenable to direct satellite measurements which has led to a considerable number of satellite-based surface turbulent heat flux products being developed (Curry et al. 2004; Clayson et al, 2014). Much as with the radiative flux satellite products, many of the satellite turbulent flux data sets use in situ data for development of the physics of the retrieval methodologies, but do not assimilate these same in situ data into the final product. As such, there are multiple different methodologies currently in use, with varying local and global results and uncertainties. None of these data sets are tuned to provide values constrained by global energy budgets, in part because there is no general consensus of what the other components of the budgets themselves are. A number of globally constrained estimates of TOA and surface fluxes are becoming available (Trenberth et al 2009, Wild et al 2013a, b; L'Ecuyer et al 2014, Roddell et all 2014, Curry et al 2014) all of which require multiple sensors and assumptions, although they have different methods and results for balancing the surface energy budget, and not all of which then compare well with ocean-based surface flux constraints (e.g. Large and Yeager, 2009).

In July 2013 ESA and CLIVAR sponsored a workshop at the University of Reading in the UK under the framework of this research focus, aimed at scoping a Support for Science Element (STSE) project to improve satellite based air-sea flux products to make them more useful in OHC and Earth energy budget applications. The workshop also led to a series of recommendations by the community regarding the EO component of the new CLIVAR research focus (see section 2.3).

6.5 Climate models

Climate models are an essential tool for understanding and making predictions about the evolution of the climate system. Observations of Earth's energy budget, and the mean pathways of energy through the climate system (e.g. Trenberth et al., 2009; Stephens et al., 2012; Wild et al., 2013a) provide a powerful framework for assessing climate model errors and thereby improving the next generation of models. Analysis of both global and local energy budgets can be used to understand the fidelity of model simulations over the historical period and the differences in how models respond to anthropogenic climate change. A prerequisite thereby is the availability of spatially and temporally representative in situ observations of adequate quality to be used in the assessment process. Regional analysis of surface fluxes, their variability, and impact on air-sea coupling, is an important area for future consideration (Gulev et al., 2013).

Model-based projections of near-surface temperature, precipitation and water availability and both global and regional sea level rise are of particular societal importance (e.g. IPCC AR5). All of these facets of global change are intimately linked to the representation of Earth's energy pathways and how these might change under future climate change. Climate model simulations have played a central role in our understanding of surface warming 'hiatus' events (e.g. Meehl et al., 2011; 2013; Katsman and van Oldenborgh, 2011; Kosaka and Xie, 2013; Maher et al 2014) and the potential for unforced variability in Earth's net radiation budget and ocean heat re-arrangements (Palmer et al., 2011; Palmer and McNeall, 2014; Brown et al, 2014).

A key question for development of the ocean observing system, as we strive for more accurate measurements of Earth's energy budget, concerns the emergent patterns of ocean heat uptake (e.g. Kuhlbrodt and Gregory, 2012). Both these long-term patterns of change and the unforced variability must be taken into account in order to aid the design of an optimal deep observing array. Models provide a dynamically consistent and conservative system in which we can test the effectiveness of 'virtual observing systems'. In addition, research into relationships between the emergent patterns of change and representation of key climate processes offer the potential to provide 'observational constraints' to reduce uncertainty in projections of global and regional climate change (Hegerl et al., 2007).

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