A prospectus for the CLIVAR research focus « Consistency between planetary heat balance and ocean heat storage”

June 2014, Version 05

1/ Defining the research priorities: what is the state of the art, what are the factors limiting progress, recommendations for a 5-10 year strategy to make significant progress.

1.1 Science questions, priorities and their broader impact

The CLIVAR community has identified a number of scientific imperatives and is developing a small number of focused global research foci that help to describe and understand climate variability and predictability 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, in cooperation with other relevant climate-research and observing activities. An overarching scientific challenge facing the whole climate science community is related to achieve accuracy in the changes in storage and flows of energy throughout the climate system necessary for climate state and variability studies, thus dealing with the detection and decrease of uncertainties of the global climate observing systems and related data and information products.

Climate is very much about exchanges of energy in the Earth System, and in particular in the form of heat. Over the last decades, increased emissions of Greenhouse Gases induced by human activities have significantly impacted our climate, forcing a net flux imbalance ranging from 0.5 to 1 Wm^{-2} at the Top Of the Atmosphere (TOA) during the last decade (Hansen et al., 2011; IPCC, 2013; Trenberth et al., 2014). 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). Many studies based on both 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; Katsman and van Oldenborgh, 2011), while highlighting at the same time large uncertainties in the estimate of the energy flows (Trenberth, 2009; 2010, Trenberth et al., 2011, Abraham et al., 2013, Trenberth and Fasullo, 2013 ; Trenberth et al., 2014).

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. To understand how the Earth’s climate system balances the energy budget, we have to consider processes occurring at the three levels (Figure 1): the surface of the Earth, where most solar heating takes place; TOA, where sunlight enters the system; and the atmosphere in between. At each level, the amount of incoming and outgoing energy, or net flux, must be equal in an unchanging climate. On short time-scales (months), natural fluctuations in clouds associated with weather systems can create a temporary energy imbalance. However, on longer time scales, 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 remaining extra heat has penetrated into the ocean forced through air-sea interactions, leading to an observed increase of the Ocean Heat

Content (OHC, Abraham et al., 2013). The rest of the extra heat is mostly used to melt continental ice and warm the atmosphere and land surface (Trenberth, 2009; Hansen et al., 2011; Church et al., 2011; 2013a). CMIP5 model simulations suggest that the full depth ocean becomes the dominant term in Earth's energy budget on a timescale of about 12 months (Palmer and McNeall, 2014).

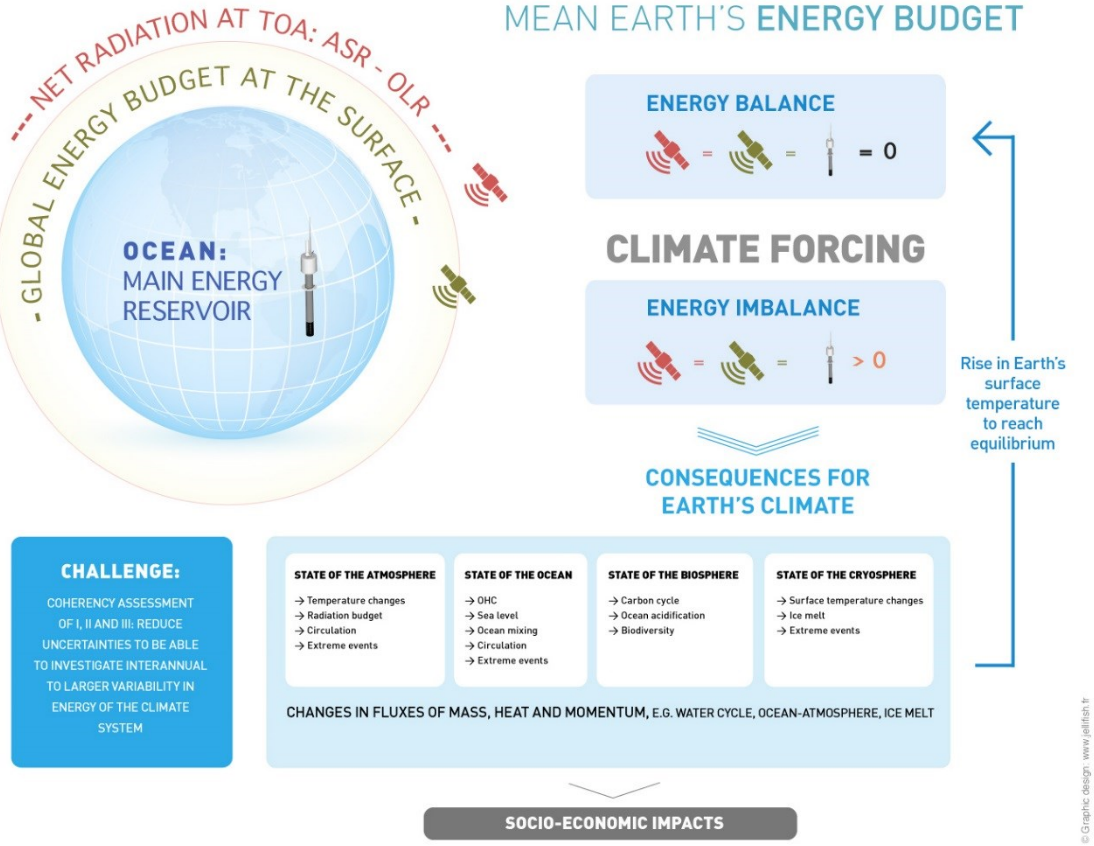

***Figure 1**: Overview graphic summarizing the CLIVAR research focus "Consistency between planetary heat balance and ocean heat storage".*

The role of the ocean in energy uptake has now become one of the hot topics in climate science following the emerging climate debate regarding an observed "plateau" in global surface temperature rise over approximately the last 15 years (Easterling and Wehner, 2009; Foster and Rahmstorf, 2011, trenberth and Fasullo, 2014). The issue is that over this so-called "hiatus" period (Meehl et al., 2011), the globally averaged surface temperature has remained more-or-less constant, while the Greenhouse Gas emissions, the energy imbalance at TOA (Loeb et al., 2012), 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?*"**.

This puzzle of the so-called "missing energy" (Trenberth and Fasullo, 2010, Figure 2) or "recent pause in warming" has now reached the public sphere (The Economist, 2013, Climate science: a sensitive matter – see also Nature Geoscience special issue: www.nature.com/ngeo/focus/slowdown-global-warm/index.html) and is also exploited by climate deniers as a sign of global warming slow down. Intensive research efforts using data and model experiments are currently ongoing to explore the possible causes of the plateau, indicating that a hiatus period is a relatively common climate phenomenon (Easterling and Wehner, 2009; Knight et al., 2009; Meehl et al., 2011; Palmer and McNeall, 2014). More precisely, non-data-assimilation runs suggest a role for changes in the winddriven upper circulation and associated sequestration of ocean heat, in support of recent observation and modeling studies (Kosaka and Xie, 2013; England et al., 2014; Meehl et al., 2011).

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). Trenberth et al. (2014) 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). All of these influences occur superposed on the climate change signals associated with changes in atmospheric composition. In particular, these events are identified as sharp cooling events punctuating a long-term ocean warming trend, while heating continues during the recent upper-ocean-warming hiatus, but the heat is absorbed in the deeper ocean. In the last decade, about 30% of the warming has occurred below 700 m, contributing significantly to an acceleration of the warming trend (Balmaseda et al., 2013). So the plateau in warming is not because global warming 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 going into the oceans and increasingly into the deep ocean, and thus contributes to sea level rise (e.g., Church et al., 2013b).

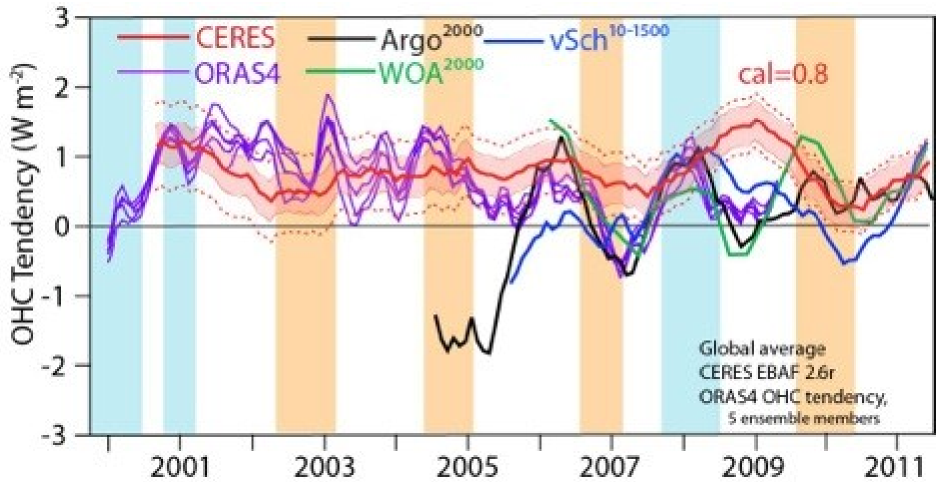

Figure 2: *A 12-month running mean tendency from the ocean reanalysis ORAS4 full depth ocean OHC tendencies are given in purple for all 5 ensemble members along with updated estimates from the World Ocean Atlas (WOA ; Levitus et al. 2012) and from Argo as analyzed by Roemmich and Gilson (2009, 2011) and von Schuckmann and Le Traon (2011). Also shown is an estimate of the TOA imbalance based on CERES estimates (red solid lines) with 1 standard error uncertainty bounds (pink shading) for random errors based on Loeb et al. (2012) and drift (dot lines) under an assumption of net radiative imbalance at TOA of 0.8 W m*$^{-2}$*. Vertical orange bars indicate El Nino events and blue bars La Nina events as given by NOAA's ONI index. From Trenberth et al. (2014).*

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. Some studies have shown that the closure of the observed energy budget over the hiatus period remains largely elusive for interannual variations pointing to an amount of "missing energy" in the system (Trenberth 2009; Trenberth and Fasullo, 2010). Although some of this previously "missing energy" is accounted for (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 on the range of different heating rates that have shown to be large (Figure 3). In particular, largest inconsistencies occur during the transition period in the global in situ observing system (years 2000 to 2005) from historical in situ ocean temperature data (predominantly XBT and CTD) to the Argo observing system (starting in 2000, but achieving global coverage in 2005). After 2005, inconsistencies decrease, but uncertainties are still large and care has of be taken when using Argo data for OHC comparison estimates (quality control issues, mapping techniques, etc.).

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 play also 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).

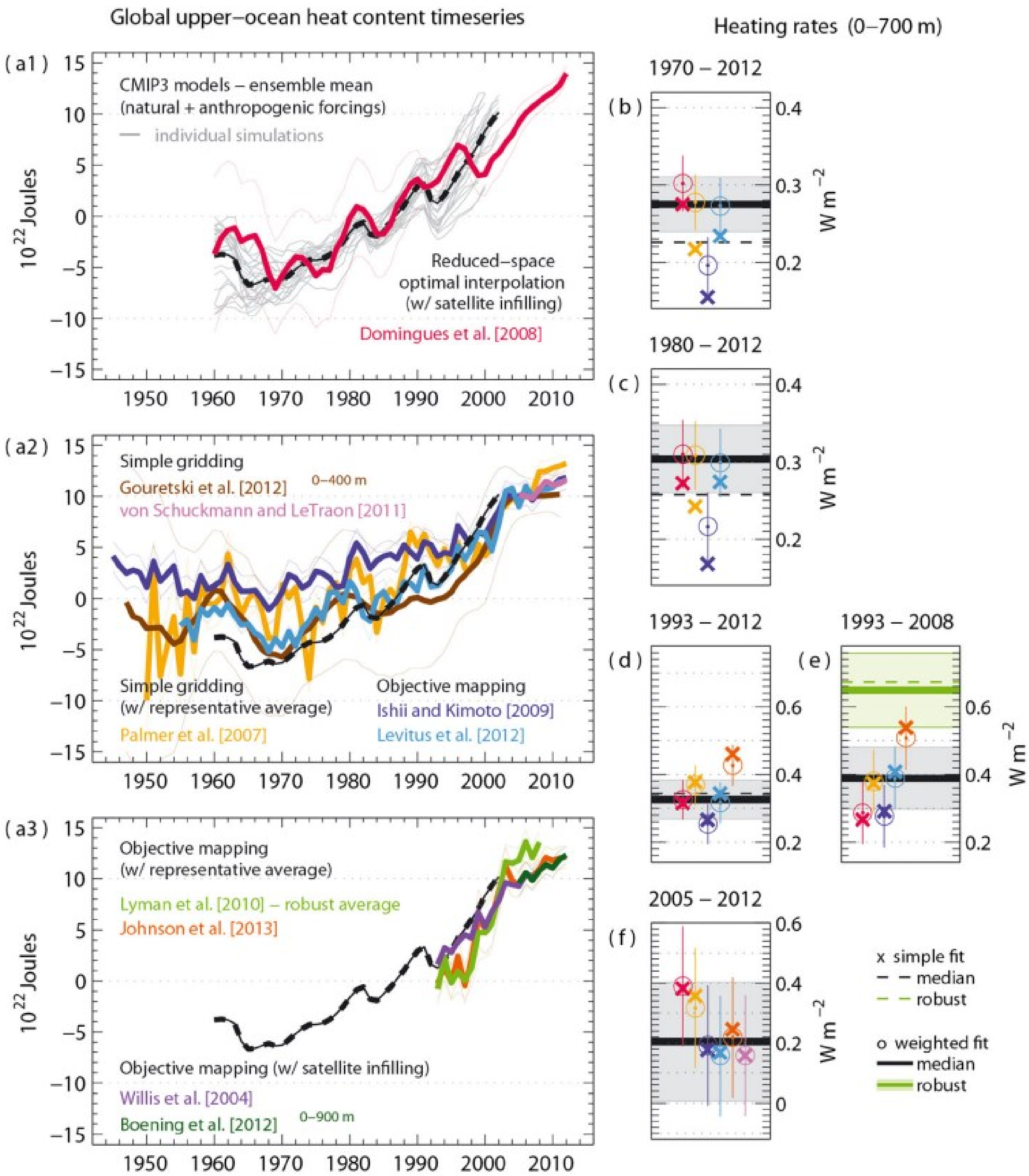

Figure 3: Time series of ocean heat content change from a number of different statistical estimates (a1-3) and equivalent planetary heating rates for various periods (b-f). Source: Abraham et al. (2013).

1.2 Objective:

The main objective of the activity is to analyze the consistency between planetary heat balance and ocean heat storage estimates, data sets and information products based on different parts of the global observing systems (remote sensing (ESA/EO) and in situ) and ocean reanalysis. The proposed initiative is envisaged to contain *three foci:*

1) Earth Observation Measurement Constraints on Ocean Heat Budget

2) In situ observations of ocean heat content changes

3) Ocean reanalysis for atmosphere-ocean heat exchange and ocean heat content estimate

Key science question:

1) How can we reduce uncertainties and refine the scientific framework on the consistency between planetary heat balance and ocean heat storage? More work is needed to define on what timescale TOA observations and OHC change should be in balance.

2) How can we use conservation and physical principles to reconcile independent measurements and syntheses to advance our understanding of Earth's state and flux changes ?

3) How can we use observations and reanalyses to critically evaluate ocean heat content changes in global climate models, to better understand the limitations of the observing systems, and to obtain information on uncertainties ?

4) How can data gaps in space and time be optimally filled and is there a "best practices" for synthesis of ocean data? Can the discrepancies among datasets be substantially reduced?

5) How can models be exploited to sort out the forced versus internal variability in the climate record? This question also relates to the knowledge and completeness of the external forcing (which is quite idealized in CMIP5), and whether the natural variability in models is adequate on multiple time scales.

Expected outcomes:

- Refinement of a scientific framework on consistency between planetary heat balance and ocean heat storage
- Evaluation of existing data sets and information products and their consistency.
- Recommendations on how to improve the observing systems and derived information products, assimilation methods, ocean and climate models and surface fluxes and development of new data sets, analyses and diagnostics that can be used to assess energy flows in models.
- Contributing insights to the understanding of interannual-to-decadal climate variability in Earth's Energy Budget and thus the climate system, linking to initiatives on predictability and detection of anthropogenic climate change.

1.3 Recommendations toward the activities and implementation of the focused research including next steps

Each of these independent approaches to determine exact 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 of budget imbalance is a key emerging research topic in climate science. Errors involved in deriving the single components can accumulate and have major impacts on the accuracy of climate indicators, leading to large imbalances differences in estimates of global Earth's climate budgets. There is merit in pursuing all methods, because confidence in the result will become high only when they agree or at least the reasons that they differ are understood. Reconciling the different approaches remains a challenge. Only by using conservation and physical principles can we infer the likely resolution.

<u>1) Earth Observation Measurement Constraints on Ocean Heat Budget</u>

Air-sea fluxes are considered central to climate research given their key role in exchanges of energy. As such, air-sea fluxes have long been a strategic focus of the WCRP activities leading to the creation of several working groups, reviews, and publications. Also characterizing the uncertainty and biases in fluxes is essential to address the big scientific challenges related to the Earth Energy budget, energy flows and understanding the observed shorter term fluctuations (e.g., recent "hiatus" period) superimposed on the multi-decadal warming of the global ocean surface (e.g., Trenberth et al., 2010, Loeb et al., 2012, Cazenave et al., 2014).

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 Ocean Atmosphere Panel (WOAP, 2012). Air-sea fluxes have also been addressed through the CLIVAR Global Synthesis and Observations Panel (GSOP) panel. Within 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). 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 programmes, such as the Surface Ocean Lower Atmosphere Study (SOLAS) for biogeochemical fluxes, and the Global Energy & Water Exchange Project (GEWEX) for LandFlux, as well as the long standing SeaFlux efforts. Radiative fluxes are also considered by the GEWEX Data Assessment Panel (GDAP).

Quantifying heat fluxes to the required level of accuracy needed to support the various applications identified by WGASF is a very challenging task. For example, climate studies are one of the most demanding and challenging applications in terms of accuracy, as the global Net Heat Flux should be quantified within a few W/m2 in order to close the energy budget (e.g. the IPCC (2007) estimated a global Radiative Forcing at the TOA of about +1.6 W/m2 , between 0.6 and 2.4 W/m2), while the magnitude of the component fluxes is much larger (e.g. order a few 100 W/m2), and can vary significantly in space and time. Hence, estimating global fluxes poses formidable challenges. It is therefore not surprising that most of the flux data sets available today suffer from systematic biases and fail to satisfy energy constraints.

In order to better define the scope of the ESA/STSE activity, ESA and the CLIVAR Project Office held a workshop on 3-4th July 2013 at the University of Reading in the UK. The workshop led to a series of recommendations by the community regarding the EO component of the new CLIVAR research focus:

- (R1) Quantify the different types of uncertainties of EO-based surface fluxes, their correlation structure, and sensitivity to uncertain parameters (e.g. input data, transfer coefficients) and algorithms (e.g. 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,
- (R2) Develop an innovative ensemble approach to generate multiple realisations of EO based flux products (as illustrated in Fig 2), 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 EO data sets of climate quality (e.g. ESA CCI). The idea is that a well-designed ensemble of multiple realisations of fluxes would sample some of the uncertainties related to the flux product, in a similar way as is done for SST within the HadSST3 data set.
- (R3) Exploit integral constraints as suggested by GSOP to check consistency of the Net Heat Flux product components, and in particular by use of Argo data on a series of Cages of interest, such as enclosed seas (e.g. Mediterranean Sea, Pacific Warm Pool).
- (R4) 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 (e.g. meteorologists, oceanographers, climatologists, observationalists and modelers), as well as new ways of combining in situ measurements and EO data. Such a platform was regarded as a very useful tool to achieve R1, R2 and R3, and organize a global effort to coordinate the evaluation of flux products, improve their inter-operability and encourage their use.
- (R5) Complement the GSOP inventory 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 users (in particular non-experts) in selecting the best product for their application across the multitude of flux products available on the web (Schneider et al, 2013).

Perhaps the most reliable total surface flux values have come from an indirect residual approach of using TOA radiation combined with the vertically integrated atmospheric energy divergence from atmospheric reanalyses (Trenberth et al. 2001; Trenberth and Caron 2002; Fasullo and Trenberth 2008; Trenberth and Fasullo 2013).

In this context, ESA is considering these recommendations to initiate a potential new dedicated activity, capitalizing on the latest knowledge in algorithms and data sets from independent observing systems (e.g. satellites, Argo), with strong focus on ESA missions and related datasets. By doing so, the project would contribute to the new CLIVAR focus while complementing GEWEX, SeaFlux and ESA flux activities, such as the Water Cycle Multimission Observation Strategy - Evapotranspiration (WACMOS-ET) project for land fluxes, SOLAS OceanFlux GHG, and Upwelling projects for CO2 ocean fluxes .

2) In situ observations of ocean heat content changes

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 status of ocean variability and change, and interactions with other components of the climate. Indeed, analysis of the rate at which the ocean is gaining heat is the most precise approach that is most accurate, and perhaps the only practical way, to determine the state of Earth's energy imbalance.

Despite the importance of accurately measuring the thermal energy of the ocean, it remains a challenging problem for climate scientists. Measurements covering extensive spatial and temporal scales are required for a determination of the energy changes over time. While there have been significant advancements in the quantity and quality of ocean temperature measurements, coverage is not yet truly global (e.g., Abraham et al., 2013; Gould et al., 2013, von Schuckmann et al., 2014). Past eras of ocean monitoring have provided extensive data but variable spatial coverage. Changes in measurement techniques and instrumentation have resulted in biases, many of which have been discovered with some account made (e.g., Abraham et al., 2013; Church et al., 2013b, Trenberth et al., 2014).

Since its inception, the World Climate Research Program (WCRP) has taken international leadership with the Tropical Ocean-Global Atmosphere project which focused on observation in the equatorial region in the 1980s, including initiating the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) moored array and the World Ocean Circulation Experiment (WOCE) which took a truly global set of oceanographic coast-to-coast full-depth sections and expanded the XBT network in the 1990s (Roemmich et al., 2012). The WOCE provides a global-scale benchmark against which change can be assessed. Following TOGA, the WCRP formulated the Climate Variability and Predictability project (CLIVAR) that begun in 1995, further fostering the Argo float array 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 global ocean observing system and encouraged contribution to it, particularly through the OceanObs workshops in 1999 and 2009 (e.g. Palmer et al., 2009). Argo has now become the major contributor to the global ocean in situ observing system, and challenges are to sustain the network, but also to extend it (marginal seas, shallow and ice-covered areas, deep ocean; e.g. Church et al., 2013b).

Several key historical and modern subsurface measurement instruments exists 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 and the Ocean Buoy Network, drifting boys and Gliders complement the global ocean in situ observing system.

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., 2014) and best practices do not exist for how to interpolate in space and time when ocean reanalyses/syntheses (Section 3) are not used. Largest challenges remain for the historical data the large gaps and the correction method for XBT data (e.g. Domingues et al., 2008). During the Argo era, systematic biases represent the largest challenge which have shown to induce important biases in global OHC estimates (Willis et al., 2009; Barker et al., 2011; von Schuckmann et al., 2014).

Spread among bias-corrected estimates of ocean heat content change (thermosteric sea level), however, remains large (e.g. Abraham et al., 2013; Church et al., 2013; Palmer et al., 2014). There are ongoing efforts to better quantify the origins of these discrepancies (Lyman et al., 2010; Boyer et al., pers comm.). One serious limitation in our ability to more properly account for instrumental biases, for example, is lack of necessary information to identify XBT probe types and manufacturer (Abraham et al., 2013). Without support for data archaeology activities, much of this crucial information (e.g., metadata and full-resolution data) cannot be recovered and used to refine corrections for systematic errors in the historical record.

With the inception of the Argo array of autonomous profiling floats (http://www.argo.ucsd.edu/), our ability to monitor global and regional ocean heat content (steric sea level) variability and change significantly increased. In comparison to previous hydrographic data, Argo floats have better instrumental accuracy and sampling coverage. These floats return a profile of both temperature and salinity of the upper 2 km of the ocean with a 10-day repeat cycle. Caution, however, is still needed, as instrumental problems have been found and corrected to the extent possible (e.g., Willis et al., 2007; Barker et al., 2011). High-quality shipboard CTD programmes are critical to maintain high accuracy and minimal systematic errors in the Argo array (and in other instrument types) (Freeland et al., 2010).

Recommendations: A core activity of CLIVAR should be a quantitative estimation of global and regional changes in the Ocean Heat Content, more precisely to foster international partnerships and coordinated efforts:

i) to reduce uncertainties in estimates of OHC at monthly time scales for the period of the last several decades using the most accurate in situ observations, results from ocean re-analyses, data assimilation, and surface flux products. This includes methods of filling gaps in space and time, e.g., using physical and statistical models and other fields such as SST.

ii) to set up an inter-comparison module of the different OHC estimates in order to assess potential of different sources for quantifying changes in OHC and associated uncertainties and develop constraints and recommendations (e.g. sampling strategy) to reduce them (e.g. deep ocean, marginal seas and their linkage between major oceans, boundary current systems).

iii) to achieve advancements in mapping strategies and data quality control issues, in particular for the historical temperature database (joint activity with CLIVAR-GSOP Coordinated Quality-Control of Global Subsurface Ocean Climate Observations – the IQuOD initiative [www.iquod.org]), but also for this decade (complete Argo era from 2005 onwards, more on mapping strategies).

iv) to manage and coordinate support for data archaeology

3) Ocean reanalysis for atmosphere-ocean heat exchange and ocean heat content estimate

The combination of ocean models, atmospheric forcing fluxes and ocean observations via data assimilation methods has the potential to provide more accurate information than observation-only or model-only estimations. The production of ocean reanalyses is now an established activity in several research and operational centres. Ocean reanalyses are revisited every so often, and new 'vintages' are produced at intervals of about five years, when improvements in ocean models, data assimilation methods, forcing fluxes or ocean observations are available. A review of the state of the art on ocean reanalysis produced around 2006 is given by Stammer et al (2010) and Lee et al. (2009), among others. A new vintage has recently been generated, which has come about through the availability of new surface forcing fluxes (from new atmospheric reanalyses), improved quality controlled ocean datasets, which include important corrections to observations (e.g., Willis et al., 2007; Barker et al., 2011; Cowley et al., 2013), as well as the steady improvement in the ocean models and data assimilation methods. There are low resolution reanalyses (1 degree), spanning a long time period (typically 50 years), as well as higher resolution products (about ¼ of degree), which exhibit eddy permitting capabilities and are available for shorter records (usually the altimeter period 1993-onwards).

In spite of the continuous improvements in methodology, the robust estimation of the ocean history with reliable error bars is a major challenge. In addition to the three dimensional estimation of the ocean state at a given time (the analysis problem), the estimation of the time evolution is also required in a reanalysis. The time evolution represented by an ocean reanalysis will be sensitive to the time variations of the observing system, to the errors of the ocean model, atmospheric fluxes and assimilation system, which are often flow-dependent, and not easy to estimate. Estimates of effects of the changing observing system can be made using observing system experiments (OSEs) in which some data are withheld (e.g. Balmaseda et al. 2013). An ad hoc but pragmatic way of measuring the current uncertainty of the reanalyses products is to conduct an intercomparison leading to a multi-reanalysis approach. The multi-analysis ensemble approach has been already used successfully to study of the ocean heat content (Xue et al 2012, Zhu et al 2012), and to the initialization of seasonal (Zhu et al 2012, 2013) and decadal forecast (Pohlmann et al 2013)

- ⇨ Comment: Brief discussion of Coupled Data Assimilation, which ensures that the surface fluxes are meaningful.

- ⇨ Comment: Another approach is modeling based. In any case experiments need to be done, such as OSEs to determine effects of the changing observing system. The modeling approach can say, given the forcings, what the forced signal ought to be?

2/ Terms of Reference, organizational needs (coordination panel/WGs, etc).

1. To focus, limit and prioritize research questions/activities to be addressed through consultation with broader climate science community. Relevant activities include WCRP core projects (CLIVAR, GEWEX, CliC, SPARC) and their relevant programmes GSOP, PAGES, CCI/CLIVAR/JCOMM, WGCM, WCRP grand challenges, major ocean observing programmes/initiatives (OOPC, AOPC, GOOS including Argo), sectorial science communities (Global Framework for Climate Services, *SPECIFY, Euro-Argo ERIC*), funding bodies (e.g. ESA, ISSI, MISTRAL/ENVIMED). This will include teleconference, workshops/groups or other means of consultation.

Relevant objectives could be to:

i) Perform a core activity on the heat budget based on a comprehensive inter-comparison module to improve estimates of Ocean Heat Content (OHC) by using in situ observations, results from ocean reanalyses, data assimilation, and surface flux products, as well as climate model simulations to test infilling methods and gain some knowledge about unobserved parts of the system. Space-time scaling issues of flux estimates need to be considered in order to achieve a comprehensive and potentially useful inter-comparison and validation procedures for OHC.

ii) Close interaction with related WCRP activities, in particular surface fluxes over land (GEWEX/LANDFLUX and land surface modeling); surface and biogeochemical fluxes in SOLAS (WCRP/IGBP); physical fluxes under CLIVAR/GSOP; sea-air interaction developed under GEWEX/SEAflux with focus on satellite born surface flux estimates; Top Of the Atmosphere (TOA) energy budgets, nominally measured by CERES under GEWEX/GDAP (SRB, GPCP, ISCCP).

iii) Develop a strategy using coupled models and coupled data assimilation as surface fluxes only become well posed in the context of the coupled system, where the flux is the exchange of some quantity that is lost from the ocean as it is gained from the atmosphere (or vice versa).

2. Formulate major challenges for and coordinate and promote activities targeting the consistency between planetary heat balance and ocean heat storage estimates, data sets and information products based on different parts of the global observing systems (remote sensing EO, in situ measurements, NWP-atmospheric reanalyses and ocean reanalyses). The three key data sources to be assessed will be: i) Earth Observation Measurement Constraints on Ocean Heat Budget, ii) Air-sea flux products based on in situ observations of ocean heat content changes, iii) Ocean (or coupled) reanalysis for atmosphere-ocean heat exchange and consistency of regional heat budgets. The project aims at a:

- Refinement of a scientific framework on consistency between planetary heat balance and ocean heat storage
- Evaluation of existing surface flux data sets and metadata, quantifying their uncertainties and assessing their consistency, in strong collaboration with the IQuOD initiative.
- Recommendations on how to improve the observing systems and derived information products, assimilation methods, ocean and climate models and surface fluxes products for a better quantification of OHC and its variations.
- Contributing insights to related climate research topics such as anthropogenic climate change, seasonal climate prediction, decadal variability, predictability and prediction, as well as sea-level variability and change. In particular, (1) Promotion of process-based understanding of

Earth's energy flows to facilitate improvements in next generation climate models; (2) Derived data sets to underpin improved understanding of the historical climate record through attribution of key climate drivers; (3) Towards observational constraints for global and regional climate change and improved predictability through better understanding of Earth System variability and change;

3. To deliver four documents:

A) Refined list of science questions and priorities and their broader impact => *element of CLIVAR science plan. (4-6 pages including figures):*

B) Recommendations toward the activities and implementation of the focussed research including next steps
=> *contribution to CLIVAR and GEWEX implementation strategies. (2-4 pages); needs to be integrated with GEWEX*

C) Recommend governance arrangements for execution of Research Foci => *impact on CLIVAR organization. (2 pages, including TOR and list of potential names)*

D) Summary of regional and national Funding prospects
=> *critical for SSG approval* (1-4 pages)

4. To report to the CLIVAR community at the pan-CLIVAR 2014 meeting about progress and to the CLIVAR SSG (fall 2014 or later) for approval. And joint with pan-GEWEX: should be a plenary topic.

3/ Implementation activities

- Proposals for targeted activities should be encouraged from the community and discussed and leaders identified as well as timeline for implementation.
- Cross panel/project implementation issues
- 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 observational OHC estimates (e.g. building on from Boyer 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).

3.1 Timeline/Activities

- 3.-4. July 2013 CLIVAR ESA Scientific Consultation Workshop on Ocean Heat Flux University of Reading, UK

- February, 2014: small meeting with some members during the AGU Ocean Science meeting, Honolulu Hawaii, USA

- April 2014: small meeting with some members during the EGU General Assembly, Vienna, Austria

- May 2014: phone-meeting with all members

- 17. July 2014: Breakout session during Pan-Clivar meeting

- November 2014: report to CLIVAR/SSG

3.2 Publication and Outreach

* Workshop report
* Website – summarize activities, and present regularly news: currently under CLIVAR development of own webpage ??
* development of brochure/handout ???

3.3 Membership

Current members:

Karina von Schuckmann
Bernard Barnier
Carol Anne Clayson
Catia Domingues
Sergey Gulev
Keith Haines
Simon Josey
Norman Loeb
Pierre-Philippe Mathieu
Mathew Palmer
Anne-Marie Treguier
Kevin Trenberth
Maria Valdivieso
Martin Visbeck
Martin Wild

4/ Coordination and funding requirements

4.1 How CLIVAR needs to adapt to support implementation activities (eg supporting WGs, network development)

4.2 What network funding is required from WCRP (teleconferences, meetings, workshops)

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.

Potentially hosting some of the model data required for "perfect model" experiments, if that option is pursued.

4.3 Research funding needs

4.4 Funding opportunities (multinational, national, foundation)

- 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)
- Proposal under evaluation: 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
- OTHERS ??

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