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Workshop Report

Towards achieving global closure of ocean heat and freshwater budgets: Recommendations for advancing research in air-sea fluxes through collaborative activities

Report of the CLIVAR/GSOP/WHOI Workshop on Ocean Syntheses and Surface Flux Evaluation

Woods Hole, Massachusetts, 27-30 November 2012

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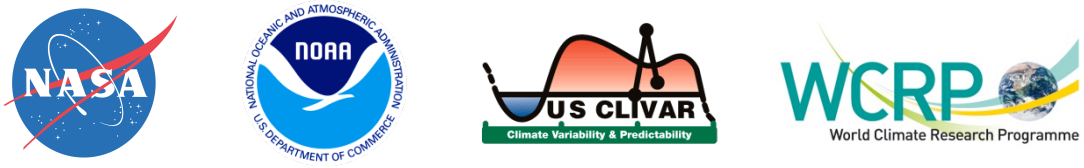

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1. Workshop background and objectives

The oceans have the largest heat capacity in the climate system and therefore control the rate of climate change (Levitus et al. 2005; Lyman et al., 2010; Trenberth and Fasullo 2010; Loeb et al. 2012). Ocean circulation redistributes heat and regulates air–sea fluxes, thus influencing climate variability and change. The distribution and rate of change of ocean heat content is one of key observational metrics for the IPCC and serves as a benchmark reference both for calibrating and evaluating climate models such as CMIP5 and for the emerging decadal climate prediction effort (Hansen et al., 2005; Meehl et al. 2011; Palmer et al. 2011). Improving the quantification of air–sea fluxes is identified as a critical research area for advancing our understanding of atmosphere–ocean interactions related to Earth's climate variability and change, and for improving our ability to account for ocean signals in short- and long-term climate fluctuations due to modes of natural variability and human influence.

Air–sea fluxes provide the fundamental links in virtually every atmosphere–ocean feedback process. Any persistent changes to the energy balance will cause global and regional temperature distributions to change, leading to changes in evaporation and precipitation that will then cause changes in ocean salinity (and thus density). Both the atmosphere and oceans will respond with circulation changes, if the air temperatures or ocean densities are altered, and with wind stress changes that lead to further feedbacks on ocean circulation. There are many pathways by which regional energy and freshwater budgets may be altered. Interactions between surface fluxes and atmospheric and ocean transport variations are therefore complex and depend on the time scales of externally induced changes (e.g., Bjerknes 1964; Shaffrey and Sutton 2006) driven by anthropogenic greenhouse gases, by fluctuations in natural forcings (e.g., volcanic aerosols and solar output), and by internal variability of the Earth's coupled climate system (e.g., various modes of climate variability). Knowing how local energy and freshwater budgets vary and contribute to both climate variability and change is deemed

critically important toward evaluating the consequences of climate change on the energy and water cycle (Trenberth et al., 2009).

Gridded air–sea flux products on basin and global scales are now produced by (i) atmospheric reanalyses, (ii) ocean syntheses, and (iii) parameterized flux analyses using empirical bulk formulae and available surface meteorological variables from satellite and ship observations and, in some products, combined with atmospheric reanalyses (WCRP 1989; Fairall et al. 2010). One seemingly unavoidable obstacle in air–sea flux estimation is the lack of sufficient direct flux measurements to quantify the errors in the products and to assess climate-related signals with certainty. All flux products suffer from uncertainties arising primarily from sampling issues, subgrid-scale parameterizations, empirical estimates of parameters, and changes related to the observational systems (e.g., changes in satellite sampling, aging of satellite sensors (e.g. Shie 2012)), transition from an in situ-dominated observing system to a satellite-dominated observing system, etc). The errors involved in deriving these products can accumulate and have major impacts on the accuracy of the flux products. This could lead to, for example, large imbalances in the energy and freshwater budgets over the global oceans. The uncertainties in existing gridded flux products preclude reliable estimates and assessment of the sensitivity of air–sea exchange processes to long-term climate signals.

Air–sea variables and flux measurements by moored buoys and research vessels (Bradley and Fairall 2007) are important benchmarks in evaluating basin- and global-scale parameterized flux products (Josey and Smith 2006). However, they are available only at selected locations. These in situ flux measurements alone are insufficient for addressing the imbalance problem in the global energy and freshwater budget because of two limitations. The first is that in situ measurements are too limited in both spatial and temporal sampling. Figure 1 shows the locations of ~120 archived and active moored buoys that provide measurements of partial or full-flux components useful for evaluating air–sea heat fluxes. More than 85% of these buoys are located in the tropical oceans within 25 degrees north and

south. The midlatitudes are covered by only a few long-term buoys, and the high latitudes have barely any long-term stations. The geographic distribution of moored buoys is sparse and highly uneven, which is particularly so for buoy longwave radiation measurements. There are currently only ~20 active buoys that are equipped with a pyrgeometer (longwave radiation sensor) over the global oceans. Since the net air–sea heat flux is the sum of latent heat, sensible heat, and longwave and shortwave radiation, this sets the limit for the number of full-flux buoy sites that can be used to validate global net heat flux products. The ~20 "full-flux" sites are far from sufficient to quality-check the global accuracy of the gridded products, let alone to address the imbalance problem in the global energy budget and the freshwater budget. Even fewer buoys measure wave and current characteristics that are important for accurate determination of turbulent fluxes.

The second limitation is that buoys do not have direct measurements of all flux components. Buoy latent and sensible heat fluxes are computed from bulk flux algorithms, such as the COARE algorithm by Fairall et al. (2003), using buoy measurements of air–sea variables (e.g., wind speed and direction, near-surface air temperature/humidity, sea surface temperature, barometric pressure, precipitation, incoming longwave and shortwave radiation). Since the same bulk flux algorithm is used in constructing global gridded flux products, the buoy fluxes may not be completely independent of the flux products being evaluated—although buoy air–sea observations are independent provided they are not assimilated/synthesized. In recent years, direct measurements of latent heat, sensible heat, and momentum flux components have been made possible by eddy-covariance methods (Edson et al. 1998), thus providing parallel sampling that helps to improve bulk flux algorithms. These direct and indirect in situ flux time series datasets are both important benchmarks. When used together, they can be beneficial to both algorithm improvement and flux product evaluation.

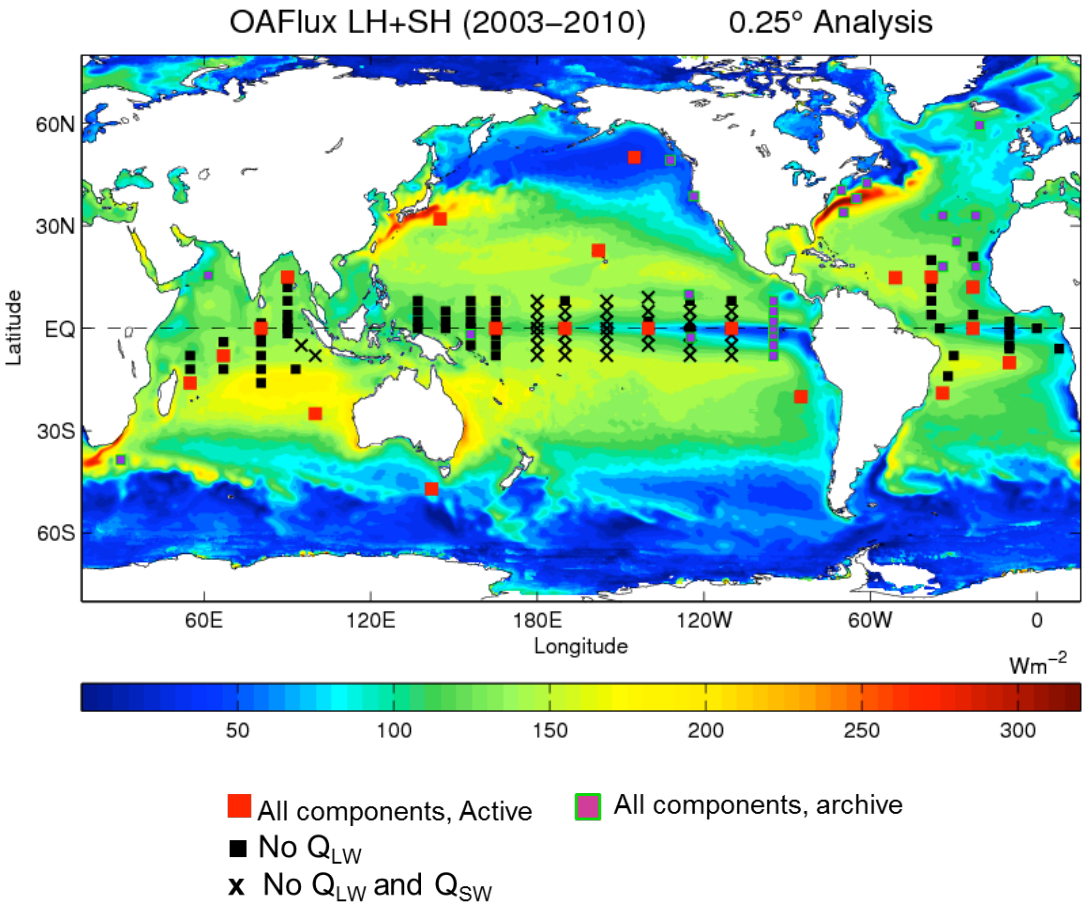

Fig. 1. Moored buoy locations over the global oceans superimposed onto the 0.25-degree OAFlux analysis of surface latent and sensible heat fluxes (colored background). Red squares denote full-flux buoy sites that provide all flux components (shortwave, longwave, latent and sensible heat fluxes, winds). Black squares denote the buoy sites that provide all flux components except longwave radiation. Crosses denote the sites that provide air–sea variables and winds for computing latent and sensible heat fluxes and wind stress only (adapted from Yu and Jin 2012 and Kato et al. 2012).

There is no doubt that in situ air–sea measurements, though limited in space, are indispensible for establishing benchmark accuracy for gridded flux products, as well as for maintaining long-term stability. They have been and will always be central to improving estimates of surface fluxes and ensuring the quality of the products (Josey and Smith 2006). On the other hand, the limitations in current in situ air–sea observing capability suggest the need to include ocean observations and ocean data-model syntheses to achieve greater consistency by balancing the regional/global heat/freshwater

budgets. Studies by Wunsch and Heimbach (2009) and Douglass et al. (2010) are examples of the applications of ocean observations and ocean synthesis to analyze regional and global heat and freshwater budgets. The ENSO region is another example of where regional heat content is sufficient to test models. Climate models have difficulty in correctly capturing air–sea fluxes of energy and momentum, as demonstrated in an examination of El Nino–Southern Oscillation (ENSO) characteristics found in the recent CMIP5 climate model comparison (Michael et al. 2013). In the eastern tropical Pacific, thermocline depth is a proxy for heat content. Figure 2 shows that the CMIP5 model's thermocline feedback (as described by the regression slope of SST anomalies to thermocline depth anomalies) is too active in comparison with observations, which affect the air–sea fluxes associated with ENSO. More work is required to provide observation-based fluxes for model evaluation.

The Argo program over the past 10 years has grown into a near-global observing system for the subsurface ocean with more than 3000 free-drifting, profiling floats monitoring the upper 2000 m of the open oceans (Roemmich et al. 2009). The Argo subsurface temperature and salinity observations, together with surface temperature and salinity observations from satellites (Lagerloef et al. 2008), provide a new means to direct estimates of the total integrated air–sea fluxes of heat and freshwater averaged on some spatial and temporal scales (Willis et al. 2004;

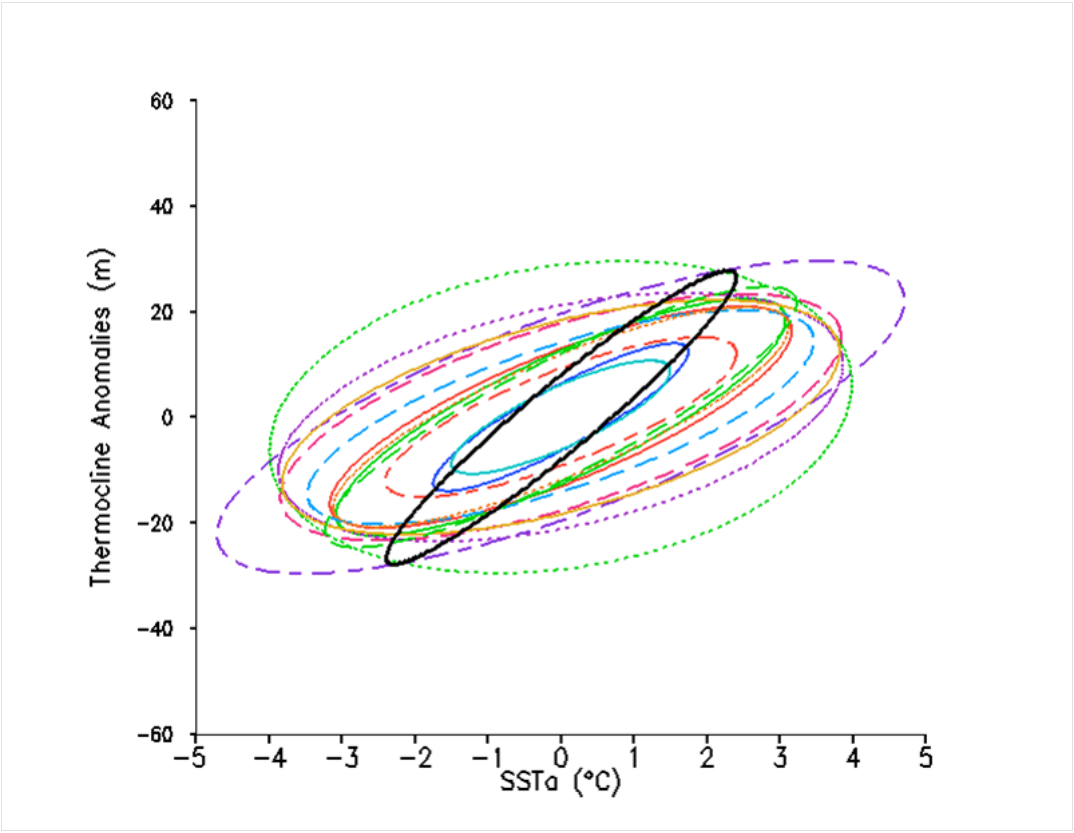

Fig. 2. Comparison of two related ENSO characteristics as determined from ocean observations and the CMIP5 output. The ovals represent the best fit to anomalies in the eastern equatorial Pacific sea surface temperature (SSTa) and the thermocline depth as seen in observations (black ellipse) and 17 model runs (where only the first member of ensemble runs is examined). All the models have an exaggerated change in SST associated with changes in thermocline depth, suggesting that thermocline feedback associated with ENSO could be too strong, thus leading to errors in surface fluxes (from Michael et al. 2013)

von Schuckmann and Traon 2011). These ocean data potentially offer important regional references for calibration of air–sea flux estimates in a way similar to flux buoy and ship measurements for pointwise calibration information. However, they represent an integration, and they lack the sampling needed for short-lived strong events that have large contributions to regional air–sea fluxes. Recent improvements in satellite observations of stress, air temperature, and humidity are also expected to contribute to improved accuracy of such exchanges.

Air–sea fluxes represent an important crosscut area within WCRP that link the interests of different core projects, including CLIVAR, GEWEX, and CLiC for the high-latitude areas including sea ice zones. The twin challenges of constraining global ocean heat and freshwater budgets using both models and observations, along with the importance of improving surface forcing functions for ocean and coupled climate modeling purposes, highlight the need for close collaboration between the observation (both in situ and remote sensing), modeling, and synthesis communities. The recent WCRP action plan on Surface Fluxes published in January 2012, specifically states that "The evaluation of model-based fluxes (NWP, atmospheric and ocean reanalysis) should be seen as an aspect of the evaluation of global surface flux datasets, and handled through the establishment of specific task groups." In recognizing the challenges and opportunities ahead, the Global Synthesis and Observational Panel (GSOP) of International CLIVAR worked closely with the air–sea flux and ocean synthesis communities to organize a joint workshop to address the pressing challenges and needs through collaboration. The workshop was held 27-30 November 2012, at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, and was sponsored jointly by NASA Physical Oceanography, NOAA Ocean Climate Observations, US CLIVAR, and WCRP.

The workshop convened 60 researchers working on ocean observations, ocean syntheses, and air–sea fluxes to (1) review achievements we have made collectively in recent decades in improving air–sea flux observations and estimates; (2) discuss gaps and current limitations in global air–sea flux products, with particular reference to constraining (even balancing) ocean heat and freshwater budgets; (3) discuss challenges and advantages we have in planning our activities in the coming years; (4) propose areas of collaboration with the ocean observation (in situ and satellite) community, the flux modeling community, and the ocean data assimilation community that benefit air–sea flux activities; and (5) develop recommendations and requirements for the areas of research that we could demonstrate benefits through collaboration on both a 2-year and a 5-year timescale.

NASA sponsor, Eric Lindstrom, put forth the following questions for the workshop attendees to address and react to. (1) Reducing large uncertainties in air–sea flux products needs help from ocean reanalysis. It seems that the advent of scatterometers, Argo, GHRSST, and Aquarius/SMOS should have helped reduce uncertainty. Why hasn't uncertainty been reduced more? (2) Is there a set of principles and standards for generating flux products so that they all can be compared and contrasted easily? (3) What is the best way to define "truth" against which flux products are judged? (4) What are the key areas of research for which individual PI efforts or stove-piped efforts by individual agencies fall short? What kind(s) of team effort can you imagine that CLIVAR could spearhead? NOAA sponsor, David Legler, expanded the list with additional questions. What mechanisms are in place and what evidence is there to indicate that flux fields are improving (e.g., uncertainties are better characterized, and errors or error spread is reduced)? How do you know (or how do you not know)?

The 3.5-day meeting covered seven main themes, including (1) review of the present state of air–sea flux estimation, (2) topical issues in air–sea flux estimation techniques, (3) topical issues in regional air–sea flux estimation, (4) integrating air–sea fluxes with temperature and salinity observations, (5) fluxes in coupled models and synthesis products, (6) synthesis evaluation and intercomparison, and (7) synthesis applications and the way forward. The workshop evaluated flux production activities and recommended flux-oriented comparisons based on essential ocean variable metrics. These activities are highly relevant to the interests of the WOAP, WGSF, and the WCRP Data Council. There were 58 oral/poster presentations. The workshop agenda, which contains the list of presentations, is included in Appendix A.

2. Workshop recommendations

Given the gaps in present-day knowledge and understanding, a consensus was reached during the workshop that achieving globally balanced energy and freshwater budgets is a long- term challenge,

and should be broken down into incremental steps with achievable targets at each stage. Guided by the NASA and NOAA perspectives and objectives, the workshop discussions were directed toward seeking areas of collaborative research by maximizing the use of existing observations made at the ocean surface and subsurface, and by integrating regional budget analysis with direct pointwise comparison with in situ buoy/ship measurements. The following recommendations are developed and generalized from the stimulating and productive discussion sessions during the workshop.

2.1) Collaborative activities

2.1.1) Regional heat/salt budget analysis

The advent of the complete Argo program is allowing upper ocean heat and salinity content to be monitored both regionally and near globally (excluding polar areas and marginal seas). This monitoring should be regarded as a means of providing direct estimates of the total integrated air–sea fluxes of heat and freshwater averaged on some spatial and temporal scale, against which, in the future, parameterized air–sea flux products may be calibrated. Rates of change in these integrated results can be used to evaluate air–sea fluxes and local transport. These budgets, if estimates of uncertainty included, can be examined for a wide variety of regions and on various time scales to provide insights into the probability distribution of temporally averaged surface fluxes. Thus ocean data should be capable of providing regional references for calibration of temporally integrated air–sea flux estimates in the same way that flux buoy and ship measurements have previously provided pointwise calibration information. Extending the calibration of air–sea flux products using regional scale constraints provided by ocean data should greatly help to resolve the issues of regional biases and global imbalance that currently affect almost all flux products constructed from satellites, ships, and atmospheric reanalyses.

However, there are several important caveats to achieving these goals. Regional ocean heat budgets can provide information on the integrated heat flux but not the components, although the regional freshwater budgets do provide a separate constraint on the latent heat flux through evaporation. In addition, advective convergence and divergence of heat may be important in the regional heat budgets, and if they cannot be sufficiently constrained these transport terms may dominate the error estimate on the regional air–sea flux budgets.

Two solutions to this problem are proposed from the workshop.

a. Using ocean synthesis and reanalysis products, the advective convergence of heat and freshwater can be constrained. In principle, the ocean transports ought to be well constrained geostrophically by the assimilation of Argo and other in situ data. In practice, the synthesis results have probably yet to attain the needed consistency in transports, and need to be properly assessed.
b. Select budget study regions from which advective transports and their variability are likely to be small to minimize the errors introduced into assessments of the surface fluxes.

A number of suggestions were made at the workshop to help in the selection of ocean regions for flux budget studies. These included

a. Seek areas away from boundary currents where advective convergence is minimal. It is possible that ocean synthesis or other modeling products could be used to assess the likely transports in or out of such regions. Areas could include enclosed and semi-enclosed basins such as the Mediterranean and the Red and Black seas.
b. Seek areas that include within them one or more flux buoys (e.g., the OceanSITES flux buoys or an ongoing field program such as SPURS, particularly buoys associated with process study data (e.g., STRATUS and PAPA) to allow for a direct regionalization and cross-referencing. It was

also recommended that satellite data and other in situ data (ships and drifters) be used to observe and/or assess the regional variability around the buoys.

c. Analyze areas of particular interest for ocean processes (e.g., other areas of water formation).

d. Choose areas with the best Argo sampling over the longest period.

These cross-reference studies would be a joint effort between the flux analysis, Argo, ocean syntheses, and process study communities. **It is recommended that a working group should be set up to define regional flux budget areas that have good sampling of ocean properties and to define the needed intercomparison studies.** This activity would be closely allied to the development of a buoy and research vessel flux database infrastructure where calibrated time series products could be used for intercomparison with regional or global products on different time scales.

2.1.2) Direct pointwise comparison with selected OceanSITES

In situ air–sea flux measurements set the accuracy standard for gridded flux products. **It is recommended to proceed with regional heat/salt budget analyses in conjunction with direct pointwise comparisons of different ocean synthesis products using air–sea buoy measurements at selected full-flux sites (OceanSITES).** Preliminary effort has been initiated for this workshop, and it is recommended that these comparisons should be carried out for all global flux products, including atmospheric reanalyses, ocean syntheses, and parameterized flux products. The analysis of the heat and freshwater budgets from the different products around the calibration sites should yield insight into synthesis product consistency, distributions and scaling effects, and areas of common biases, as well as enable flux component comparisons. It is also suggested that these observations be compared to satellite data for appropriate variables, with the goal of determining the importance of spatial and

temporal variability (e.g., May and Bourassa 2011) in the unavoidable random errors associated with comparison to the individual buoys.

There are ~20 full-flux buoy sites currently operating (Fig. 1). The OceanSITES buoys at the following key climate locations are recommended.

a. The Tropical Oceans (20°S-20°N, 9 buoys)

The tropical moored buoy arrays of TAO, PIRATA, and RAMA (http://www.pmel.noaa.gov/tao/oceansites/flux/main.html) deliver real-time measurements of air–sea conditions for improved detection, description, understanding, and prediction of regional climate variability on seasonal, intraseasonal, interannual, and longer time scales, that include but are not limited to regional phenomena such as ENSO, monsoons, the Madden-Julian oscillation, the Indian Ocean dipole, and tropical Atlantic variability. The selected buoys include (i) two TAO buoys, one located in the eastern equatorial Pacific cold tongue at EQ, 110ºW and the other in the western equatorial Pacific warm pool at EQ, 165ºE; (ii) two RAMA buoys, one in the central equatorial Indian Ocean at EQ, 80ºE, and the other in the Bay of Bengal warm water pool at 15ºN, 90ºE; and (iii) three PIRATA buoys, one in the central equatorial Atlantic at EQ, 23ºW, one in the tropical southwest Atlantic at 10ºS, 10ºW, and one in the tropical northwest Atlantic at 15ºN, 38ºW.

In addition to the buoys from the tropical moored arrays, two OceanSITES buoys deployed by WHOI Upper Ocean Process Group (http://uop.whoi.edu/) are selected to provide vital air–sea measurements in regions that are not covered by the tropical arrays. The two WHOI buoys are from (i) the STRATUS (20ºS, 85ºW) project that studies long-term evolution and coupling of the boundary layers in the STRATUS deck regions of the eastern tropical Pacific, and (ii) the Northwest Tropical Atlantic Station (NTAS) (15ºN, 51ºW), both of which

are well suited for investigations of surface forcing and oceanographic response in a region of strong SST anomalies and significant local air–sea interactions.

b. The subtropical region (20–40 degrees north and south, 6 buoys)

The subtropics are regions of relatively large latent heat flux due to strong evaporation, with maximum latent heat loss occurring over the western boundary currents (WBC) and extensions during fall and winter seasons. Six buoys in these regions can be used to evaluate the performance of gridded flux products; three are located in the open oceans and three are in the regime of the WBC. The three buoys in the open oceans are (i) the RAMA buoy in the Indian Ocean southeast trade wind regime at 20ºS, 100ºE (http://www.pmel.noaa.gov/tao/oceansites/flux/main.html), (ii) the WHOI Hawaii Ocean Time-series Station (WHOTS) in the north Pacific at 22.5ºN, 158ºW (http://uop.whoi.edu/), and (iii) the Salinity Processes in the Upper Ocean Regional Study (SPURS) buoy in the north Atlantic deployed by WHOI at 24.5ºN, 38ºW (http://uop.whoi.edu/). The three WBC-related buoys are (i) the Kuroshio Extension Observatory (KEO) buoy located in the recirculation gyre south of the Kuroshio Extension at 144.6°E, 32.4°N (http://www.pmel.noaa.gov/keo/), (ii) the JAMSTEC Kuroshio Extension Observatory (JKEO) in the north Kuroshio Extension region at 38ºN, 146.5ºE (http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/), and (iii) the CLIVAR Mode Water Dynamic Experiment (CLIMODE) buoy deployed by WHOI in the core of the mean Gulf Stream at 38.5ºN, 65ºW (http://uop.whoi.edu/).

c. Higher latitudes (poleward of 40 degrees north and south, 2 buoys)

Higher latitude surface fluxes differ markedly from those in temperate regions because of changes of several key air–sea variables, such as strong seasonality, very low winter air temperatures, frequent extreme weather events with high wind speeds, large local variability associated with mesoscale eddies and ocean fronts, etc. Uncertainties in gridded flux products

are large at higher latitudes and in situ validation datasets are sparse. Two reference stations are recommended, including (i) Ocean Station PAPA (http://www.pmel.noaa.gov/stnP/index.html) located at 50ºN, 145ºW to monitor air–sea interaction for the harsh conditions of the North Pacific region, and (ii) the Southern Ocean Flux Station (SOFS; http://imos.org.au/SOTS.html) located in the sub-Antarctic Zone near 47ºS, 140ºE, the site critical for studying air–sea interaction that affects regional climate variability on a wide range of time scales. The site is particularly vulnerable to the extreme weather events that typify the area, including very large waves, strong currents, and severe storms.

It is recommended that, to obtain independent comparisons, reference station data (identified by an "84" in its WMO number) be withheld from assimilation in reanalyses to provide an independent verification of these products and their parameterization schemes. Likewise, **it is recommended that the WMO numbers of data that are assimilated into NWP be listed and made available.**

It is also recommended that, to facilitate the comparisons between different products, ocean synthesis and reanalysis groups separately archive the components of the air–sea heat flux, i.e., short and longwave radiation and sensible and latent heat fluxes, in addition to the other variables needed for net budget studies. This is not commonly done and these components need to be separately compared with observations to improve understanding of the flux exchange processes.

Importantly, the point comparisons should be supported with scaling analysis and estimation of the uncertainties imposed by spatial/temporal variations in surface fluxes and flux-related variables when point measurements are co-located with the gridded products or/and grid cell averages.

2.2) Metrics for surface flux evaluation and improvements

A white paper on "Guidelines for Evaluation of Air-Sea Heat, Freshwater and Momentum Flux Datasets" was developed previously under GSOP (Josey and Smith 2006). It provides a basis for flux evaluation using global, regional, and local metrics as summarized below.

2.2.1) Global:

Metrics should include global mean Qnet and means for individual flux components along with characteristics of the statistical distributions of surface fluxes presented as climate maps and zonal means.

2.2.2) Regional:

Metrics should include the following two sets of computation.

a. Comparison of integrated net surface heat flux estimates for regions bound by reliable oceanographic heat transport estimates with the corresponding heat transport implied value.

b. Integrated surface flux estimates of individual flux components for selected regions with reasonably good coverage by in-situ observations and likely small impact of ocean dynamics and lateral advection, heat and freshwater budgets of selected semi-enclosed seas (Red, Mediterranean, Black, Baltic—with a caveat on the Gulf of Bothnia and the Great Lakes). The time series of these statistics is also highly desirable. Care needs to be taken here as conclusions reached for enclosed seas may not be valid for the open ocean.

2.2.3) Local:

Metrics should include time series analysis along with probability and spectral characteristics of fluxes in the buoy and OWS locations.

2.2.4) Transport information from observations

It is important that relevant metrics should be combined wherever possible as this will help avoid biases developing in surface flux products derived through parameterization over

large scales, for which nonlinearities make parameter estimation problematic. Ocean transports, whether determined traditionally from hydrographic sections, or monitored continuously (e. g. as in the RAPID array (Cunningham et al 2007)), or using sections adjusted by inverse modeling (e. g. Lumpkin and Speer 2007), or through transports evaluated from ocean syntheses or reanalyses, can provide valuable constraints for evaluating regional air-sea fluxes.

One of the drawbacks of using such data in the past has been the asynoptic sampling and therefore the need to assume a steady state to infer surface flux information. However, the RAPID array is providing continuous monitoring of flow across an entire ocean section, and synthesis or reanalysis studies allow transports to be derived from asynoptic ocean observations without assuming steady state conditions. A number of studies are currently underway to use the RAPID data as a constraint on the heat budget changes in the North Atlantic and similarly for the freshwater budgets. Although still in their early stages, results are promising.

It is recommended that using ocean transport monitoring across key ocean sections including RAPID would be of considerable benefit to the reduction in uncertainty of surface fluxes and would contribute to proper closure of regional budgets, which are of great importance for understanding regional climate change.

2.3) Accuracy and resolution requirements

The accuracy goals for net surface heat flux measurement were set at ±10 Wm^{-2} on annual time scales during the WOCE observing program (WCRP 1989) and the TOGA-COARE process study (Webster and Lukas 1992; Weller et al. 2004). However, accuracy and resolution requirements for air–sea fluxes are highly dependent on the spatial and temporal scales of the specific process studied. The

need for imposing an accuracy standard that is better than 10Wm^{-2} has been articulated by many applications. Figure 3 summarizes the accuracies for net heat flux and surface winds desired by applications to key processes in meteorology, oceanography, and climate. In particular, the flux products would be required to be as accurate as 0.1Wm^{-2} (averaged over large space and time scales) when used for detecting long-term climate change signals.

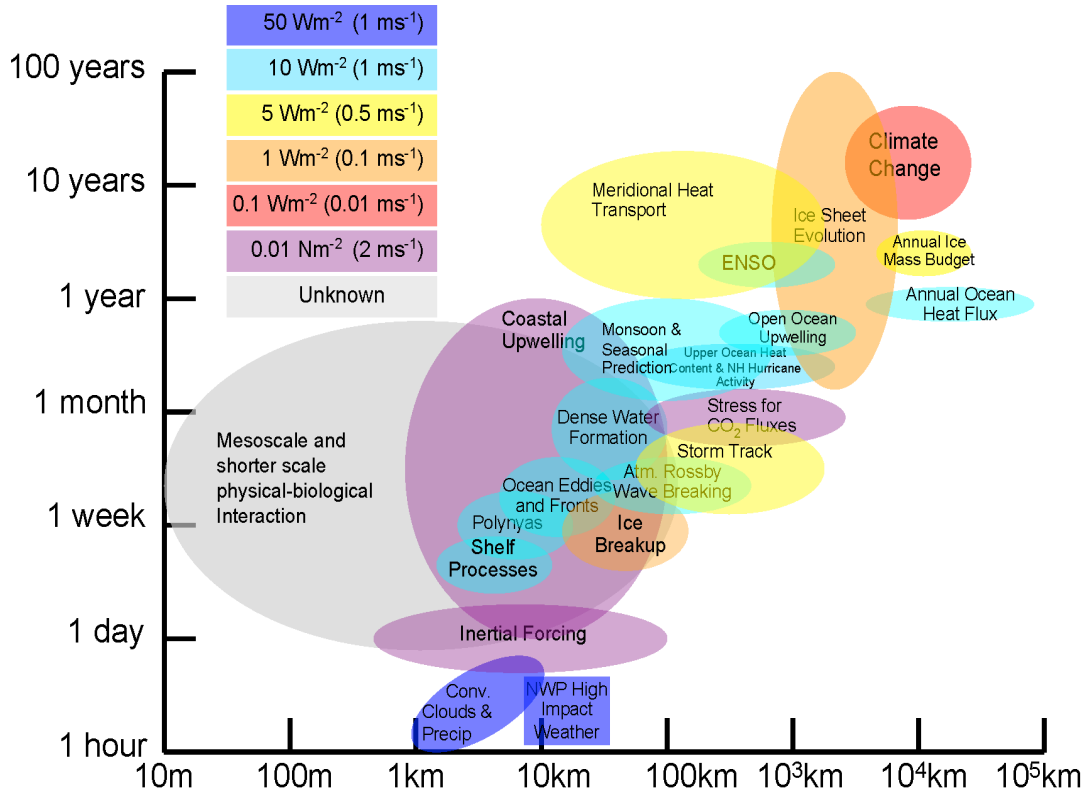

Fig. 3. A first-order estimation of flux and wind accuracies desired for various applications (Adapted from Bourassa et al. 2013). Fluxes expressed in W m^{-2} refer to total heat fluxes (including radiative and turbulent processes). Wind speeds expressed in ms^{-1} refer to surface winds. On short time scales, inaccuracies are usually dominated by random errors. On long time scales, the averaging is so great that random errors are small compared to biases.

At present, the global imbalance in the gridded products ranges between 2 Wm^{-2} and 30 Wm^{-2}, which is far from meeting the accuracy requirements for many applications. One difficulty is the lack

of precision in knowing the net downward flux of energy associated with global warming, although we know this cannot be large, likely no more than a few tenths of 1 Wm^{-2} on decadal time scales as indicated from ocean temperature observations. Even atmospheric reanalyses and ocean syntheses each use fixed surface boundary conditions and therefore lack consistent feedbacks that would allow air-sea fluxes to be properly constrained against local observations. The newly developing field of coupled data assimilation and coupled reanalysis should start to overcome this problem in future, but the parameterized flux products which will be available for comparison are still usually a combination of products from very different groups. While surface turbulent latent and sensible heat fluxes are constructed by both meteorologists and oceanographers, and surface shortwave and longwave radiation products are usually constructed by atmospheric scientists. Inconsistency in input surface data used in turbulent and radiative flux products, and the lack of common platforms to compare and cross-validate the flux components estimated by oceanographers and atmospheric scientists contribute to the errors in the net surface heat flux product. Surface net flux evaluation and uncertainty estimate, therefore, must be done in collaborative work by two communities. For example, observations of radiative flux at moored buoys are particularly useful in evaluating radiative flux products over the oceans, which is demonstrated by Kato et al. (2012). In addition, collaborations in estimating surface net flux over time periods and regions where some components are observed with small errors could identify net flux components that have larger uncertainties. Furthermore, evaluating turbulent and radiative flux products together is useful to identify bias errors because the global mean net surface flux averaged over a sufficiently long time (e.g. annual) must balance with ocean heating.

In seeking solutions through integrating regional budget analysis with direct pointwise buoy/ship measurements, the workshop recommended that we should identify those applications for which the required flux accuracy is met with the present observations, and those applications for which the required flux accuracy is not met. Altogether, these analyses should contribute to define the flux

accuracy that gridded flux products should aim at, to provide insights into the underrepresented processes that may hold keys to global imbalance, and to articulate a stepwise approach to achieving the long-term goals for air–sea flux improvements over the coming years.

2.4) Data requirements and infrastructure to be enhanced

The need to standardize and increase the availability and presentation of existing in situ flux datasets has been articulated by many as one primary means to improve their value as evaluation standards for large-scale flux products.

2.4.1) Mooring flux database

It is recommended that a simple table with ftp links should be created to facilitate access to daily averaged and higher resolution net heat flux, components, and meteorological state variables from each mooring site (initially those listed above, subsequently all 130 sites). This archive can be enriched by addition of datasets from OWSs (covering the period from the late 1940s to the mid-1970s and selected stations continued to the 1990s) as well as high-resolution data from field programs (like SECTIONS [Gulev 1999] covering more than 10-year periods). Ideally, the flux files should reside on the OceanSITES data product server. It is recommended that GSOP/CLIVAR communicate this need to the OceanSITES group and follow up to ensure that action is taken. In the midterm this regularly updated table should become an online catalogue.

2.4.2) Research vessel flux database

a. Bulk Flux Estimates. Most RVs do not measure direct fluxes, but with appropriate caution they can be used to determine good bulk fluxes. **We recommend that fluxes should be calculated on the time resolution at which the data are available. The algorithm(s) used in the**

calculation should be clearly stated with references to published literature. The assumptions that are not clear in these publications should be identified and articulated.

b. Direct Flux Data. A great deal of direct flux data were made available on the Seaflux Web site. **We recommend that this Web site (recently revitalized, http://seaflux.org) be updated with recent data (since roughly 1999) as well as other missing datasets. We further recommend that at least modest metadata accompany the data files.** Experience has shown that the metadata in the NOAA Environmental Technology Laboratory (ETL) datasets have been quite effective. We recommend that the datasets include sufficient information to distinguish direct flux estimates from bulk estimates, label the units, explain quality assurance data, and provide accuracy estimates. We further recommend that datasets with fluxes calculated only with bulk methods (e.g., PACS) be separated from datasets containing direct fluxes.

2.5) Perspective of CAGE experiments

The proposed integration of regional budget analyses, coupled with direct pointwise comparison with in situ buoy measurements to improve surface flux estimates, has much in common with the CAGE concept envisaged in the early 1980s (Bretherton et al. 1982). The design of a CAGE experiment recognized (i) the importance of meridional heat transport in Earth's climate, (ii) the need for obtaining an accurate estimate of the mean state of the world climate and of the ocean's role in maintaining that state, and (iii) uncertainties in existing surface flux products and ocean observations that preclude realistic assessment of the changes in ocean heat transport and storage. Three approaches for computing meridional heat transport by the oceans were proposed, including using the ocean temperature and velocity observations, air–sea heat fluxes, and the net radiation at the top of the atmosphere coupled with the atmospheric flux divergence. The CAGE experiment was designed to

intercompare the three types of product in a single basin under favorable circumstances to establish the random and systematic errors associated with each approach, and hence to determine the changes in ocean heat storage. The region of the north Atlantic 20ºN–60ºN was recommended to attempt the use of the Bryden and Hall (1980) assumption on long coast-to-coast zonal sections every 5-degrees from 24 to 60ºN.

Uncertainties in air–sea heat fluxes and wind stress were recognized as a major difficulty for the CAGE concept, and validating surface flux estimates in the context of a heat budget that can be completely balanced was proposed. In particular, two questions were posed with regard to surface flux (radiation) parameterization. One was how well the available surface measurements validate the flux climatology, and the other was how to design a sampling network to do a proper validation. The CAGE feasibility study included careful analysis of observational strategies at various levels of effort, assessing likely scientific returns in terms of the probable errors in estimating regional heat budget terms in both the ocean and the atmosphere. The CAGE experiment would have mainly relied upon the World Ocean Circulation Experiment (WOCE), as well as on satellite measurements including scatterometer, altimeter, and the international satellite cloud climatology project (ISCCP). However, the global ocean observational network has progressed significantly in recent decades. Today, Argo has more than 3000 free-drifting, profiling floats that provide global monitoring of subsurface temperature and salinity fields, one section, 26.5ºN in the Atlantic, is continuously monitored by the RAPID array (Cunningham et al. 2007), and satellites now provide real-time monitoring of ocean surface temperature, salinity, winds, and the solar irradiance at the top of the atmosphere along with cloud vertical profiles. The Argo data in particular would potentially allow much greater flexibility in choice of CAGE regions, including the possibility to avoid near-coast regions with strong currents. In conclusion, the concept that was envisioned 30 years ago during the CAGE experiment is still highly valuable and may be much more feasible today.

2.6) Argo's current status and future enhancement plan

The Argo 3000-float target was achieved in late 2007, and so there are only 5 years so far of "complete" global Argo coverage, maybe 7 years with "reasonable" coverage. The quality of delayed-mode Argo profile data continues to improve, and the Argo (trajectory) velocity data is also improving and becoming more accessible for users. The recommendations of regional and global studies outlined in subsections 2.1) "collaborative activities" and 2.2) "Metrics for surface flux evaluation and improvements" are dependant on Argo for heat and freshwater storage estimates as well as for advective corrections. The time-scales of interest for these studies are seasonal, interannual, decadal, and multi-decadal. With ~7 years of Argo data, the seasonal variability is fairly well-sampled, and interannual variability is beginning to be seen in the dataset. However, addressing variability on decadal and longer timescales requires a time series of 20 years and longer. The present Argo time series may not be able to allow us to answer the regional-to-global scale questions to the full extent; nonetheless, it provides sufficient means to start addressing integrated approaches on combining air-sea fluxes/storage/advection.

There is a broad community consensus (e.g. OceanObs09 (Freeland et al. 2010)) that the Argo array needs to be enhanced and improved in a number of ways. They include:

a. Western boundary regions in each ocean will have increased float density (at least 2x the original design). Enhanced sampling in the Kuroshio region (by KESS, OKMC, and Argo) has provided strong arguments in favor of this.

b. Argo coverage will be extended through the seasonal ice zones, especially in the Southern Ocean. Present sampling in the ACC and farther south is not sufficient.

c. Coverage will be extended into the marginal seas that are not presently sampled. Some of these have significant impacts on global integrals of heat and freshwater (e.g. Indonesian seas).

d. Argo coverage in the equatorial wave guide will be increased for better estimation of storage and zonally-propagating signals down to intra-seasonal timescales.

e. Deep Argo: prototype floats are now being deployed that eventually will extend Argo profiling to the ocean bottom (6000 m). This will enable heat content estimates to be extended to full water column.

f. Parallel programs (e.g. Bio-Argo) are beginning to deploy float arrays with additional sensors.

The coverage enhancements a-d will require that the original Argo array of 3000 floats be increased to 4000 or more. A summary map and document is being prepared by the Argo Information Centre (draft at http://www.argo.ucsd.edu/Argo_Enhancements.pdf). These recommended enhancements will increase substantially Argo's value for understanding air-sea fluxes either through extended spatial domains or higher signal-to-noise ratio.

3. Summary of recommendations and future planning

In summary, the group of 60 researchers from the surface fluxes, ocean observations (both in situ and satellite), atmospheric reanalysis, and ocean synthesis communities attending the workshop reviewed the recent progress in surface fluxes research, identified gaps, and made recommendations for the way forward. The recommendations can be summarized into the following:

1) Establish a working group to develop the strategy for regional heat/salt budget analysis and regional flux assessment (as described in "2.1) Collaborative activities: 2.1.1) Regional heat/salt budget analysis", and 2.2) "Metrics for surface flux evaluation and improvements"). The working group will draw from surface flux, observation, atmospheric modeling, and synthesis communities to identify the CAGE regions where such regional study and assessment are suitable and potentially reliable. These regions include areas with abundant ocean- and surface-flux-related observations for an extended period of time, as well as areas bounded by lands and

sections or channels that have reliable estimates of heat/salt transports derived from observations or synthesis products with known accuracy, or sections or channels that are known to have little heat/salt transport. A smaller task team of the working group will then select a region or regions ("CAGE" or "CAGEs") to perform an analysis as a pilot project. It is envisioned that the working group and subtask team will form in 2013 to begin implementation of the recommended work. The working groups and the task team should co-operate with the other interested WCRP activities under, for example, GEWEX SEAFLUX and WGNE. The working group and subtask team can report directly to either CLIVAR SSG or GSOP.

2) Proceed with further direct pointwise comparisons of different ocean synthesis and atmospheric reanalysis products with flux buoy and OceanSITES measurements, including scaling analysis to estimate uncertainties from spatial/temporal variability (as described under 2.1) "Collaborative activities", 2.1.2) "Direct pointwise comparison with selected OceanSITES" and 2.3) "Accuracy and resolution requirements").
3) Ocean synthesis and reanalysis groups should separately archive the components of the air–sea heat flux i.e., short- and longwave radiation and sensible and latent heat fluxes, to facilitate comparisons with the flux observation sites.
4) A simple Web-based table with ftp links should be created to facilitate access to daily averaged and higher resolution net heat flux, components, and meteorological state variables from each mooring site (as described under "2.4) Data requirements and infrastructure needing to be enhanced").
5) Reference station data (indicated by WMO "84") should be withheld from reanalyses. Furthermore, WMO numbers of all data that are assimilated into NWP should be listed and made available.

6) The Seaflux Web site (recently revitalized, http://seaflux.org) should be updated with recent data (since roughly 1999) as well as other missing datasets, and appropriate metadata should accompany the data files. Ideally, a common set of variable names and self-describing formats would be chosen and applied across platforms to facilitate the use of these datasets. It is recognized that the metadata and quality assessment information are dependent on the instruments. It would also be timely to revive the Fluxnews Letter, as an electronic review of surface flux research, coordinated experiments, and relevant dataset publication.
7) GSOP should continue the evaluation of surface fluxes and ocean transports inferred from ocean syntheses and identify regions that are suitable for regional heat/salt budget study and flux evaluation as described in recommendation (1). An ESF COST (European Science Foundation Cooperation in Science and Technology) proposal is being prepared as part of the effort to sustain the intercomparisons of CLIVAR ocean syntheses.
8) The workshop also recommended that the surface fluxes and synthesis communities continue to enhance the interaction with relevant programs funded by different agencies (e.g., NASA and ESA Science Teams, NOAA program activities) in performing the activities summarized above, especially 1), 2), and 7).

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References

Bjerknes, J.,1964: Atlantic air-sea interaction. *Adv. Geophys.*, **10**, 1–82.

Bourassa, M. A, S. Gille, C. Bitz, D. Carlson, I. Cerovecki, M. Cronin, W. Drennan, C. Fairall, R. Hoffman, G. Magnusdottir, R. Pinker, I. Renfrew, M. Serreze, K. Speer, L. Talley, and G. Wick, 2013: High-latitude ocean and sea ice surface fluxes: requirements and challenges for climate research. *Bull. Amer. Meteor. Soc.* **94**, 403-423.

Bradley, E. F., C. W. Fairall, 2007: A Guide to Making Climate Quality Meteorological and Flux Measurements at Sea. NOAA Technical Memorandum OAR PSD-311, NOAA/ESRL/PSD, Boulder, CO, 108 pp.

Bretherton, F. P., D. M. Burridge, J. Crease, F. W. Dobson, E. B. Kraus, and T. H. Vonder Haar, 1982: The 'CAGE' experiment: A feasibility study. Final report, January 1982, Commissioned by the JSC/CCCO Liaison Panel, 134 pp.

Bryden, H. L., and M. H. Hall, 1980: Heat transport by currents across 25°N in the Atlantic Ocean. *Science*, **207**, 884–886.

Cunningham, S. A., Kanzow, T., Rayner, D., Baringer, M. O., Johns, W. E. and co-authors. 2007. Temporal variability of the Atlantic meridional overturning circulation at 26.5°N. *Science*, **317**(5840), 935–938.

Douglass, E., D. Roemmich, and D. Stammer et al., 2010: Interannual variability of North Pacific heat and freshwater budgets. *Deep-Sea Res. Part II-Topical Studies in Oceanogr.*, **57**, 13–14, 1127–1140, doi:10.1016j.drs2.2010.01.001.

Edson, J. B., A. A. Hinton, K. E. Prada, J. E. Hare, and C.W. Fairall, 1998: Direct covariance flux estimates from mobile platforms at sea. *J. Atmos. Oceanic Technol.*, **15**, 547–562.

Fairall, C. W., E. F. Bradley, J. E. Hare, A. A. Grachev, and J. B. Edson, 2003: Bulk Parameterization of Air-Sea Fluxes: Updates and Verification for the COARE Algorithm, *J. Climate*, **16**, 571-591.

Fairall, C. & Co-Authors, 2010: Observations to Quantify Air-Sea Fluxes and their Role in Climate Variability and Predictability, in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2),* Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.27.

Freeland, H. & Co-Authors, 2010: Argo - A Decade of Progress, in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2)*, Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.32.

Gulev, S. K., 1999: Comparison of COADS Release 1a winds with instrumental measurements in the North-West Atlantic. *J. Atmos. Oceanic Technol.*, **16**, 133–145.

Hansen, J., et al., 2005: Earth's energy imbalance: Confirmation and implications. *Science*, **308**, 1431–1435, doi:10.1126/science.1110252.

Josey, S. A. and S. R. Smith, 2006: Guidelines for Evaluation of Air-Sea Heat, Freshwater and Momentum Flux Datasets, CLIVAR Global Synthesis and Observations Panel (GSOP) White Paper, July 2006, pp. 14. At http://www.clivar.org/sites/default/files/gsopfg.pdf.

Kato, S, N. G. Loeb, F. G. Rose, D. R. Doelling, D. A. Rutan, T. E. Caldwell, L. Yu, R. A. Weller, 2012: Surface irradiances consistent with CERES-derived top-of-atmosphere shortwave and longwave irradiances. *J. Climate*,. doi: http://dx.doi.org/10.1175/JCLI-D-12-00436.1.

Lagerloef, G., F. R. Colomb, D. Le Vine, F. Wentz, S. Yueh, C. Ruf, J. Lilly, J. Gunn, Y. Chao, A. deCharon, G. Feldman, and C. Swift, 2008: The Aquarius/SAC-D mission: Designed to meet the salinity remote-sensing challenge. *Oceanography*, 21, 68-81.

Levitus, S., J. I. Antonov, T. P. Boyer, 2005: Warming of the World Ocean, 1955-2003. *Geophys. Res. Lett.* , 32, L02604, doi:10.1029GL021592.

Loeb, N. G., J. M. Lyman, G. C. Johnson, D. R. Doelling, T. Wong, R. P. Allan, B. J. Soden, and G. L. Stephens. 2012. Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty. *Nature Geoscience*, 5, 110-113, doi:10.1038/ngeo1375.

Lumpkin, Rick, Kevin Speer, 2007: Global Ocean Meridional Overturning. *J. Phys. Oceanogr.*, **37**, 2550–2562. doi: http://dx.doi.org/10.1175/JPO3130.1.

Lyman, J. M., S. A. Good, V. V. Gouretski, M. Ishii, G. C. Johnson, M. D. Palmer, D. A. Smith, and J. K. Willis. 2010. Robust warming of the global upper ocean. *Nature,* 465, 334-337, doi:10.1038/nature09043.

May, J., and M. A. Bourassa, 2011: Quantifying variance due to temporal and spatial difference between ship and satellite winds. *J. Geophys. Res.*, **116**, doi:10.1029/2010JC006931.

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

J. -P. Michael, V. Misra, and E. P. Chassignet, 2013: The El Niño and Southern Oscillation in the historical centennial integrations of the new generation of climate models. *Regional Environmental Change*, doi:10.1007/s10113-013-0452-4

Palmer, M. D., D.J. McNeall, and N.J. Dunstone, 2011: Importance of the deep ocean for estimating decadal changes in Earth's radiation balance, *Geophys. Res. Let.*, 38, , L13707, doi:10.1029/2011GL047835.

Roemmich, D. and the Argo Steering Team, 2009: Argo: the challenge of continuing 10 years of progress, *Oceanography*, 22, 26–35.

Shaffrey, L. C. and R.T. Sutton, 2006: Bjerknes Compensation and the Decadal Variability of Energy Transports in a Coupled Climate Model. *J. Climate*, **19**, 1167–1181.

Shie, C.-L., 2012: Science background for the reprocessing and Goddard Satellite-based Surface Turbulent Fluxes (GSSTF3) Data Set for Global Water and Energy Cycle Research. Science Document for the Distributed GSSTF3 via Goddard Earth Sciences (GES) Data and Information Services Center (DISC), 21 pp. (Available online at: http://disc.sci.gsfc.nasa.gov/measures/documentation/Science_of_the_data.GSSTF3.pdf)

Trenberth, K. E., and J. T. Fasullo, 2010: Tracking Earth's Energy. *Science,* **328**(5976), 316-317.

Trenberth, Kevin E., John T. Fasullo, Jeffrey Kiehl, 2009: Earth's Global Energy Budget. *Bull. Amer. Meteor. Soc.*, **90**, 311–323.

von Schuckmann, K. and Le Traon, P.-Y., 2011: How well can we derive Global Ocean Indicators from Argo data?, *Ocean Sci. Discuss.*, **8**, 999-1024, doi:10.5194/osd-8-999-2011.

WCRP, 1989: WOCE Surface Flux Determinations – A strategy for *in situ* measurements. Working Group on *in situ* measurements for Fluxes WCRP-23 (WMO/TD No.304), WMO, Geneva.

Webster, P.J. and R. Lukas, 1992: The Coupled Ocean-Atmosphere Response Experiment. *Bull. Am. Met. Soc.*, **73**, 1377-1416.

Weller, R.A., E.F. Bradley, and R. Lukas, 2004: The interface or air-sea flux component of the TOGA Coupled Ocean-Atmosphere Response Experiment and its impact on subsequent air-sea interaction studies. *J. Atmos. Oceanic Tech.*, **21**, 223-257.

Willis, J. K., D. Roemmich, and B. Cornuelle, 2004: Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales, J. Geophys. Res., 109, C12036, doi:10.1029/2003JC002260.

Wunsch, C., and P. Heimbach, 2009: The global zonally integrated ocean circulation, 1992-2006: seasonal and decadal variability. *J. Phys. Oceanogr.*, **39**, 2, 351–368. Doi:10.1175/2008JPO4012.1.

Yu, L., X. Jin, and R. Weller, 2008: Multidecade Global Flux Datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: Latent and Sensible Heat Fluxes, Ocean Evaporation, and Related Surface Meteorological Variables, OAFlux Project Tech. Rep. OA-2008-01, 64 pp.

Yu, L. and X. Jin, 2012: Buoy perspective of a high-resolution global ocean vector wind analysis constructed from passive radiometers and active scatterometers (1987–present), *J. Geophys. Res.,* **117**, C11013, doi:10.1029/2012JC008069.

Appendix A

CLIVAR GSOP WHOI Workshop Agenda

Meeting Room: WHOI Quissett Campus, Clark 507

Day 1 (Tuesday, November 27th)

7:30-8:30 Continental breakfast

Opening: Agencies and program perspectives on surface fluxes and synthesis

8:30-8:40 Lisan Yu and Keith
Co-chairs of the workshop

8:40-8:50 Antonio Caltabiano
ICPO perspectives

8:50-9:00 Mike Patterson
US CLIVAR perspectives

Theme I: Review of Present state of air-sea flux estimation (Chair: Lisan Yu)

9:00-9:20 Simon Josey
Air-Sea Fluxes: An Overview of Developments in the Past Decade

9:20-9:40 Chris Fairall
Synthesis of surface observations of turbulent flux transfer coefficients:
Updates on the COARE flux algorithms

9:40-10:00 Bob Weller
The present state of surface meteorological observations and sustained air-sea flux observations from moored buoys and plans for the future

10:00-10:20 Break

Theme II: Topical issues in air-sea flux estimation (Chair: Simon Josey)

10:20-10:40 Carl Wunsch
Data assimilation, reanalyses, state estimates, all that, and the problems of understanding the ocean

10:40-11:00 Bill Large
Flux variability and trends in nature versus the CESM Climate Model

11:00-11:20 Seiji Kato
Surface irradiances derived from NASA A-train observations:
CERES EBAF-surface product

11:20-11:40 Lisan Yu
On balancing heat and freshwater budgets at the ocean surface

11:40-12:20 Discussion with Rapporteur (Simon Josey and Lisan Yu lead)

12:20-14:00 Lunch (Box lunch provided)

Theme II continued: Topical issues in air-sea flux estimation (Chair: Mark Bourassa)

14:00-14:20 Arun Kumar
Comparison of air-sea interaction between different reanalyses

14:20-14:40 Sergey Gulev
Comparative assessment of air-sea turbulent fluxes in reanalyses and climate models

14:40-15:00 Gary Wick
The impact of uncertainties in the input parameters on the uncertainty of satellite-derived flux estimates

15:00-15:20 Carol Ann Clayson
Issues with satellite ocean evaporation budgets in the context of global water cycles

15:20-15:40 Tim Liu
Spacebased estimation of sea-air water flux and evaporation

15:40-16:00 Break

Theme II continued: Topical issues in air-sea flux estimation (Chair: Sergey Gulev)

16:00-16:20 Chung-Lin Shie
A Rice Cooker Theory -- the Equally Important Quality of Model/Algorithm (Rice Cooker) and Input Parameters (Rice) in Retrieving the Satellite-Based Air-Sea Turbulent Fluxes (the Cooked Rice!)

16:20-16:40 Masahisa Kubota
Topics related to construction of J-OFURO Ver.3

16:40-16:55 Arun Kumar
Summary of the Reanalysis workshop in May, Silver Spring, MD

16:55-17:40 Discussion with Rapporteur (Mark Bourassa and Sergey Gulev lead)

End of day

Day 2 (Wednesday, November 28th)

7:30-8:30 Continental breakfast

Theme III: Topical issues in regional air-sea flux estimation (Chair: Ivana Cerovecki)

8:30-8:50 Mark Bourassa
High-latitude Ocean Surface Fluxes

8:50-9:10 Praveen Kumar
TropFlux

9:10-9:30 Meghan Cronin
Reference time series from the Kuroshio Extension Observatory, Station Papa, and the Agulhas Return Current station

9:30-9:50 Jiping Liu
High-Resolution satellite surface latent heat fluxes in North Atlantic hurricanes

9:50-10:10 Break

Theme IV: Integrating air-sea fluxes with temperature/salinity observations (Chair: Meghan Cronin)

10:10-10:30 Dean Roemmich
Ocean heat storage observed by Argo:
Separating components due to air-sea flux and ocean dynamics

10:30-10:50 Gary Lagerloef/Hsun-Ying Kao
Global freshwater budgets from Aquarius satellite salinity measurements

10:50-11:10 Ray Schmitt
The ocean and the global water cycle

11:10-11:30 Ivana Cerovecki
Can oceanic data improve air-sea buoyancy flux estimates?
The Southern Ocean State Estimate example

11:30-11:50 Nadya Vinogradova
How good is surface salinity as a proxy for surface freshwater flux?

11:50-12:30 Discussion with Rapporteur (Ivana Cerovecki and Meghan Cronin lead)

12:30-14:00 Lunch (Box lunch provided)

Theme V: Fluxes in coupled models & synthesis products (joint with ocean synthesis)
(Chairs: Keith Haines/Tong Lee)

14:00-14:20 Tong Lee
How well do CMIP models represent momentum and heat fluxes climatology?

14:20-14:40 Keith Haines
Surface fluxes from ocean and/or coupled synthesis

14:40-15:00 Yan Xue
Air-sea coupled variability of tropical instability wave simulated by the NCEP CFSR

15:00-15:20 Magdalena Balmaseda
Budget analysis of global ocean heat content in ORAS4

15:20-15:40 Break

15:40-16:00 Introduction to the poster session
(A 3-min (2slides) presentation per poster presenter)

Maria Aleksandrova	New global short-wave radiation climatology from VOS based on highly accurate parameterization
Mike Brunke	Recent Work on Understanding the Uncertainties in Ocean Surface Turbulent Fluxes in Reanalysis, Satellite-Derived, and Combined Global Datasets
Masanori Konda	An evaluation of directly measured surface turbulent fluxes and their influence on the ocean mixing layer
Alison McDonald	The relationship between heat and carbon transports in Pacific
Xiangzhou Song	Sensitivity of high latitude water formation to the air-sea heat fluxes

16:00-17:00 Discussion with Rapporteur (Keith Haines lead)

17:00-18:30 Reception & Poster viewing

End of day

Day 3 (Thursday, November 29th)

7:30-8:30 Continental breakfast

8:30-8:40 Keith Haines
Metrics; collaboration with other program/panel (GODAE, OOPC);

8:40-8:50 Magdalena Balmaseda
Introduction to the synthesis products Intercomparisons

Theme V continued: Fluxes in global ocean synthesis products (chair: Tong Lee)

8:50-9:10 Maria Valdivieso
Surface fluxes intercomparison results

9:10-9:30 Veronica Nieves
Insight into the energy balance over the global oceans: a comparison of ECCO2 net heat flux estimates with other products

9:30-9:50 Dimitris Menemenlis
Comparison of surface wind stress from global, eddying ocean state estimation with QuikSCAT retrievals

9:50-10:00 Break

10:00-11:00 WHOI PO seminar by Simon Josey

11:00-11:20 Break

11:20-11:50 Outcomes and Further Actions: Surface fluxes and syntheses
(Lisan Yu and Keith Haines lead)

Theme VI: synthesis evaluation and Intercomparison (chair: Magdalena Balmaseda)

11:50-12:10 Takahiro Toyoda
Mixed-layer depth intercomparison results

12:10-12:30 Fabrice Hernandez
Sea level and D20 intercomparison results

12:30-2:00 Lunch (Box lunch provided)

Theme VI continued: Synthesis evaluation and Intercomparison (chair: Fabrice Hernandez)

14:00-14:20 Andrea Storto (or Magdalena Balmaseda)
Steric height intercomparison results

14:20-14:40 Matt Palmer
Heat content intercomparison results

14:40-15:00 Keith Haines

AMOC transports intercomparison

15:00-15:20 Greg Smith (presented by Hal Ritchie)
Sea ice intercomparison

15:20-15-40 Robin Wedd
Upper Ocean salinity intercomparison results

15:40 Break and Poster session

Poster Session:

Catia Domingues	Human-induced Global Ocean Warming on Multidecadal Timescales
Stephanie Guinehut	Monitoring the ocean from observations
Drew Peterson	The GloSea ocean analysis
Karina von Schuckmann	A new in situ database for global ocean reanalyses (CORA): validation and diagnostics of ocean temperature and salinity in situ measurements

16:40-17:40 Discussion with Rapporteur (synthesis evaluation and intercomparison focus, Magdalena Balmaseda leads)

End of day

Day 4 (Friday, November 30th)

7:30-8:30 Continental breakfast

Theme VII: Synthesis applications and the way forward (chair: Tony Lee)

8:30-8:50 Jim Carton
SODA and some alternative syntheses/reanalyses on longer time scales

8:50-9:10 Yosuke Fujii
Intercomparison of data-free and data-assimilated ocean simulations with a common ocean model forced by CORE II data

9:10-9:30 Guillaume Vernieres
The GMAO ocean sea ice synthesis

9:30-9:50 Magdalena Balmaseda
Coupled synthesis initiative at ECMWF and ECMWF Coupled Synthesis workshop summary

9:50-10:10 Jake Gebbie
Development of a Physically-consistent Coupled Ocean-Atmosphere Re-analysis

10:10-10:30 Break

10:30-11:30 Discussion with Rapporteur
(Synthesis applications and the way forward, Tony Lee leads)

11:30-12:30 Summary and discussion for all themes;
Workshop Recommendations (Lisan Yu and Keith Haines lead)

12:30 Workshop ends

Appendix B: Author Affiliations

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