50 Year Global Ocean Surface Heat Flux Analysis

Lisan Yu and Robert A. Weller
Woods Hole Oceanographic Institution

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1. Project Summary

The Objectively Analyzed air-sea Fluxes (OAFlux) project is a research and development project focusing on global air-sea heat, moisture, and momentum fluxes. The project is committed to produce high-quality, long-term, global ocean surface forcing datasets from the late 1950s to the present to serve the needs of the ocean and climate communities on the characterization, attribution, modeling, and understanding of variability and long-term change in the atmosphere and the oceans.

The OAFlux project was established on the basis that quality global flux fields can be obtained only when data errors are properly treated. This is due to the fact that global air-sea flux fields are commonly constructed from flux bulk parameterizations that require surface meteorological observables (e.g., wind speed, temperature, humidity, cloud cover, etc.) as inputs. However, no surface meteorological observables are free from errors/biases regardless of whether they are ship-based measurements or space-born satellite retrievals. To take into account data errors, the OAFlux project developed an objective synthesis to include error information in the formulation and to improve the flux estimates through synthesizing measurements/estimates from various sources. The error information of input data is determined from air-sea measurements from surface moorings. The OAFlux established a validation database consisting of more 130 flux buoys from the ocean climate observing system, including the tropical moored array network in all three tropical oceans (i.e., the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) in the Pacific, the Prediction and Research Moored Array in the Atlantic (PIRATA), and the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) in the Indian Ocean), and the OceanSITES Ocean Reference Stations deployed and maintained by the Woods Hole Oceanographic Institution (WHOI) and by the National Oceanography and Atmospheric Administration (NOAA) Pacific Marine Environmental laboratory (PMEL).

The OAFlux project has produced the global 1° resolution, daily/monthly analysis (1958-to present) of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables. The products are distributed online through the project website at http://oaflux.whoi.edu/data.html and updated twice per year. The project continues in efforts to

develop a high-resolution (0.25°) global analysis of surface heat fluxes to improve the representation of the coupling between the atmosphere and ocean fronts/eddies, to develop surface radiative fluxes with improved accuracy, and to progress toward a net heat flux dataset.

The OAFlux project demonstrates the important role of integrating air-sea measurements from the global ocean climate observing system in constraining the global flux products. On the other hand, the OAFlux global products broaden, strengthen, and enrich the use of in situ flux measurements. The buoy-validated, completely global, gridded, and temporally homogeneous OAFlux products of several-decades long can help the ocean and climate diagnostic and modeling studies in many ways that the irregularly spaced and sparse buoy time series cannot do.

The OAFlux global products of 50-years continue to provide new insights into the fundamental changes in the global climate under warm conditions. The evidence yielded from the OAFlux products leads to a wide recognition on the intensification of ocean evaporation since the late 1970s, providing observational support for the Intergovernmental Panel on Climate Change (ICPP) 5th assessment report (AR5) on the acceleration of the global hydrological cycle in the past warm decades. The OAFlux products lead to the finding of the important role of the strengthening ocean surface wind speed in increasing ocean evaporation, providing a thought-provoking addition to the theory based on the Clausius-Clapeyron equation. The OAFlux datasets lead to the identification of the non-negligible contribution of high-latitude sensible heat flux (i.e. the thermal exchange at the air-sea interface due to air-sea temperature differences) to the global energy balance. The OAFlux global products have demonstrated in many ways their value in stimulating advances in our understanding of the role of the ocean in the global energy budget, the global hydrological cycle, and the change and variability of the Earth's climate.

The OAFlux products have gained wide recognition and appreciation in the community and the OAFlux data user base is growing rapidly. Users of the OAFlux products include but are not limited to: 1) global reanalysis projects, climate modeling groups and centers, including the Coupled Forecast System Reanalysis (CFSR) by NOAA National Centers for Environmental Prediction (NCEP), the Modern Era Retrospective-Analysis for Research and Applications (MERRA) by the National Aeronautics and Space Administration (NASA), the Coupled Model Intercomparison Project (CMIP), and the consortium for the Estimating the Circulation & Climate of the Ocean (ECCO),using the global OAFlux fields as a base reference for validating the performance of the models; 2) investigators and researchers working under the NASA SAC-D Aquarius salinity mission, the European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission, and the NASA field experiment of the Salinity Processes in the Upper Ocean Regional Study (SPURS), using OAFlux evaporation together with the precipitation from the NASA Global Precipitation Climatology Project (GPCP) as freshwater flux forcing for studying ocean salinity change; 3) The satellite surface radiation projects including Global Energy and Water Cycle Experiment – Surface Radiation Budget (GEWEX-SRB) and NASA Clouds and Earth's Radiant Energy Systems (CERES) , who collaborate with OAFlux to produce net heat flux products to investigate the global energy balance; 4) researchers and investigators working to understand the global hydrological change under climate warming, using OAFlux time series to study the intensification of the global ocean cycle in the past three decades; 5) investigators under targeted field programs, including CLIVAR (Climate Variability research program), Mode Water Dynamic Experiment (CLIMODE), and Dynamics of the Madden-Julian Oscillation (DYNAMO), using OAFlux products to identify key air-sea interaction processes and feedback mechanisms; 6) those working on the ocean carbon cycle, using OAFlux products to

identify global "hot spots" where the ocean releases heat to the atmosphere and absorbs carbon dioxide from the atmosphere; 7) those working to quantify the role of the ocean in climate variability and change, using the OAFlux time series to evaluate the ocean's role as a source or sink of heat and freshwater; 8) those working with ocean models, who use the OAFlux product as the forcing fields for model runs; 9) those developing alternate air-sea flux fields from remote sensing and/or in situ data, who compare their products to the OAFlux fields; 10) those researching new and renewable energy sources, using OAFlux wind and near-surface meteorological parameters to estimate global offshore wind power potential; and 11) educators involved in the Education and Outreach programs, e.g., the education program of the NASA Aquarius mission, the NOAA National Weather Service (NWS) online weather school - JetStream, and the Cooperative Program for Operational Meteorology, Education and Training (COMET) established by the University Corporation for Atmospheric Research (UCAR) and NWS, using OAFlux climatology as course materials.

2. Scientific and Observing System Accomplishments

The three tasks proposed in the FY2012 work plan have been fully executed. Our project deliverables serve the observing system's program deliverables on "*Air-Sea Exchanges of Heat, Momentum, and Fresh Water*", and help "to identify changes in forcing functions driving ocean conditions and atmospheric conditions, and to elucidate oceanic influences on the global water cycle". Our project is on a global scale. We demonstrated through the work in FY2012 that our project deliverables also help the observing system's program deliverables on "*Sea Ice Thickness and Extent*", and help "to elucidate climate variability and rapidly changing climate at high latitudes". The accomplishments we have achieved in FY2012 are summarized below.

(1) Timely updating and maintaining the online OAFlux long-term time series

Two updates were issued in FY2012 to bring the OAFlux time series from 1958 to the near real time. As of today, the OAFlux time series is available up to the end of September 2012 and is accessed freely from our project website at http://oaflux.whoi.edu. The updates were validated with 130+ air-sea time series measurements from surface moored buoys of the ocean climate observing system (Figure 1) to ensure the quality and consistency of the time series.

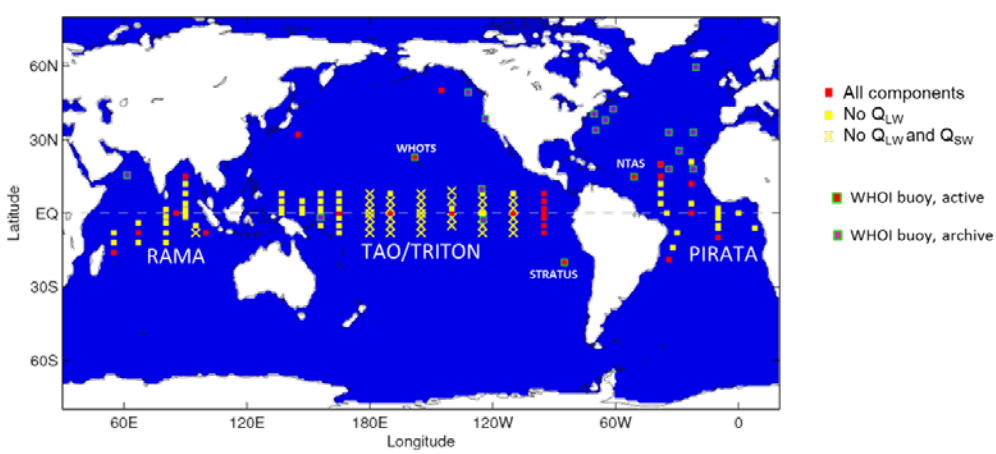

Figure 1. Surface buoys included in the OAFlux in situ validation database

One major factor affecting the stability and consistency of OAFlux time series is the spurious trends and jumps associated with the change of the observing system. The OAFlux products are constructed from multiple data sources, including atmospheric reanalyses and satellite products. For every OAFlux update, we validate each input data with in situ flux measurements to examine whether spurious jumps or mean drifts exist before using the dataset. Although the work is labor intensive and time consuming, it is a necessary step to ensure the high quality of the OAFlux products.

Although the budget cut in FY2012 forced us to focus our effort on developing high quality flux products while limiting the scope of research applications in the work plan, we have worked diligently to keep our research activities going by means of leveraging available resources and establishing collaborations with international colleagues. The research activities benefit us greatly on assessing the quality of the OAFlux products. One lesson we have learned from the applications of OAFlux products to high latitudes (*Song and Yu, 2012; Song was a visiting Ph.D. student at WHOI) is that we need to pay special attention to flux estimates at high latitudes where few buoys are available. We found that the OAFlux latent and sensible heat fluxes over the Arctic/Antarctic open seas have a peculiarly large increase after 2004 (Figures 2a-b, black curve), with the rate of the change far exceeding our expectation. Our investigation led to the identification of a mean shift in the sea ice concentration in the OISST 0.25° daily product. OISST is a widely used community SST product, and is a base data set for producing the OAFlux products. OISSTs are generated for sea-ice concentrations above 50% and the associated ice mask has been used by OAFlux to define the global ice-free areas. However, sea ice data are not from the same source. The sea ice for 1985-2004 is from the National Snow and Ice Data Center (NSIDC), and the sea ice from 2005 to present is from the Polar and Great Lakes Ice group of NCEP. The problem is that the latter sea ice data set is not consistent with the former (NSIDC) and the merge causes a mean drift in the time series after 2004 (Figures 2c-d). The OISST sea ice failed to show the drastic decrease of the Arctic sea ice extent since 2004. It also depicts erroneously a large increase of the Antarctic sea ice concentration. The effect on the OAFlux in the polar open seas is significant (Figures 2a-b). To correct the spurious effect induced by OISST sea ice, we downloaded and processed the sea ice concentration from NSIDC, recomputed the fluxes, and revised the online OAFlux time series from 2005 onward.

We believe that data developers should be the users of their own data, because one can only learn the limitations of a dataset through research applications. We have been doing the best we could within our ability to reduce the impact of the budget cut on our research application studies of OAFlux products, and trying our best effort to continue producing high-quality OAFlux products.

The OAFlux user base has increased rapidly in recent years. During 2011-2012, the OAFlux products were a base dataset in 82 referred publications according to Google Scholar.

(2) Developing high-resolution analysis of turbulent latent and sensible heat fluxes

The development of the OAFlux high-resolution (HR, 0.25°) analysis benefits from the recent availability of three datasets: (i) the 0.25° global ocean vector wind analysis constructed from passive microwave radiometers and scatterometers (1987-, Yu and Jin 2012), (ii) the 0.5° air

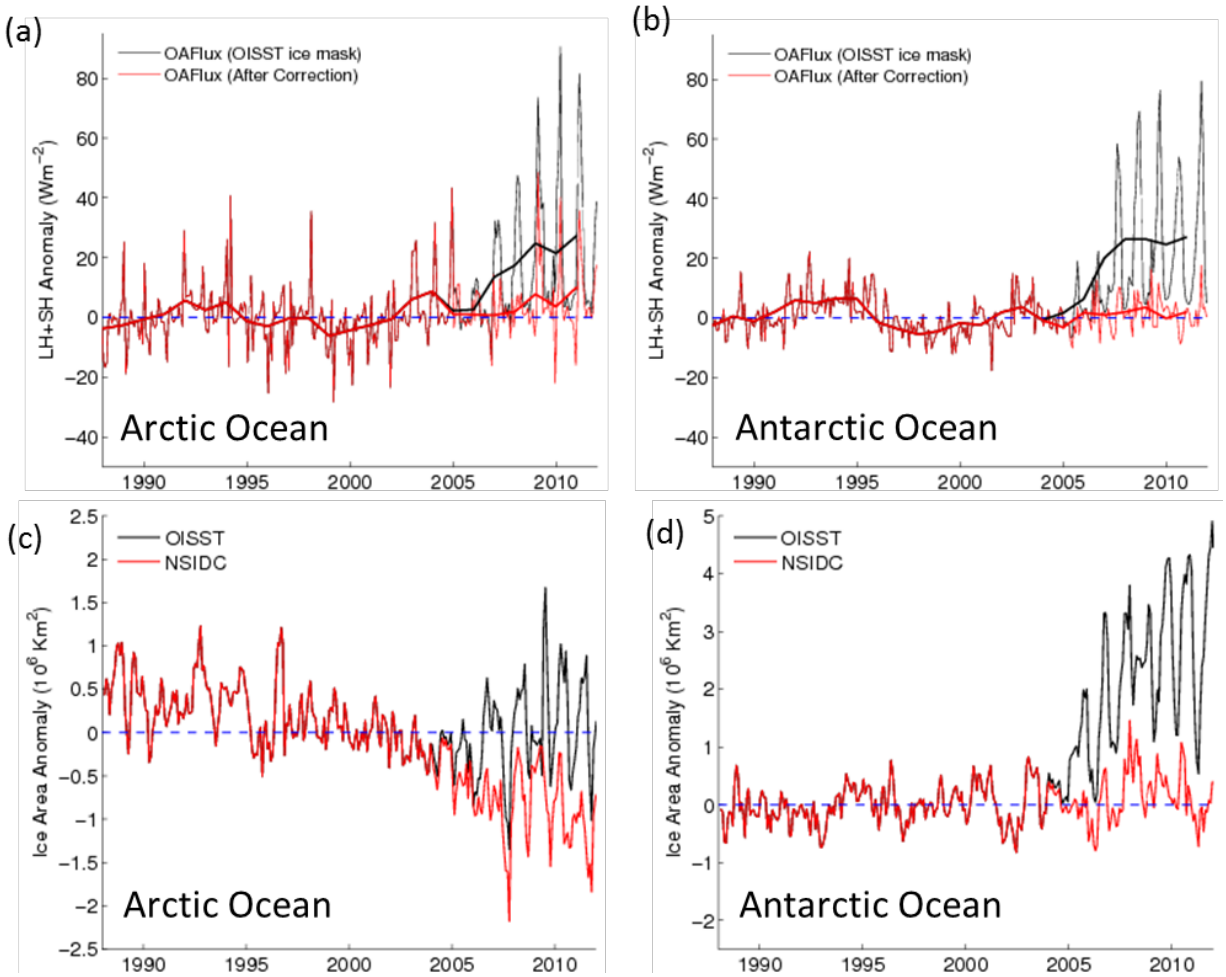

Figure 2. Top panels: Time series of monthly-mean area-averaged turbulent latent and sensible heat flux anomalies released from the open seas in the (a) Arctic and (b) Antarctic to the atmosphere (1988-2011). The superimposed thicker, smoother lines denote the annual mean time series. Bottom panels: Time series of monthly-mean area-averaged sea ice extent anomalies in the (a) Arctic and (b) Antarctic (1988-2011).

humidity/temperature (qa/ta) dataset derived from satellites by Jackson and Wick (2010) of NOAA Earth System Research Laboratory (1999-; hereafter ESRL), and (iii) a 4-km multi-scale SST analysis (2003-, Chin et al. 2010). Because of the constraint of the SST time series, the OAFlux HR analysis starts from 2003.

The satellite-derived ESRL qa/ta are not bias free. In FY2011, we found that the ESRL qa/ta estimates improved the spatial variability of the OAFlux 1° analyzed qa/ta, but need to be de-biased before they can be used (Figure 3a). In FY2012, major efforts were devoted to correct the biases and to validate the accuracy of the resulting OAFlux analysis. We identified the difference between ESRL and OAFlux qa (Figure 3b) that ERSL qa is considerably wetter in the tropical oceans but drier at higher latitudes when compared to OAFlux 1°. Our exiting buoy validation data (Figure 1) has difficulty evaluating the sign reversal in the ERSL qa bias due to the lack of

sufficient buoy sites beyond 30°N/S. Thus, we invested considerable effort in FY2012 to search the NDBC database for buoys outside of the tropics. We were able to identify 8 NDBC weather buoys in the Gulf of Alaska and 5 NDBC buoys in the vicinity of the Gulf Stream (Figure 3c). The augmented validation database depicts clearly that the sign of the bias in ERSL qa changes with latitude bands. Similar bias pattern is also found in ESRL ta, with a warm bias in the tropics and a cold bias at high latitudes. In other words, compared to buoy measurements, the OAFlux 1° qa/ta analysis based on buoy-adjusted atmospheric reanalyses has a better mean state than the satellite-derived qa.

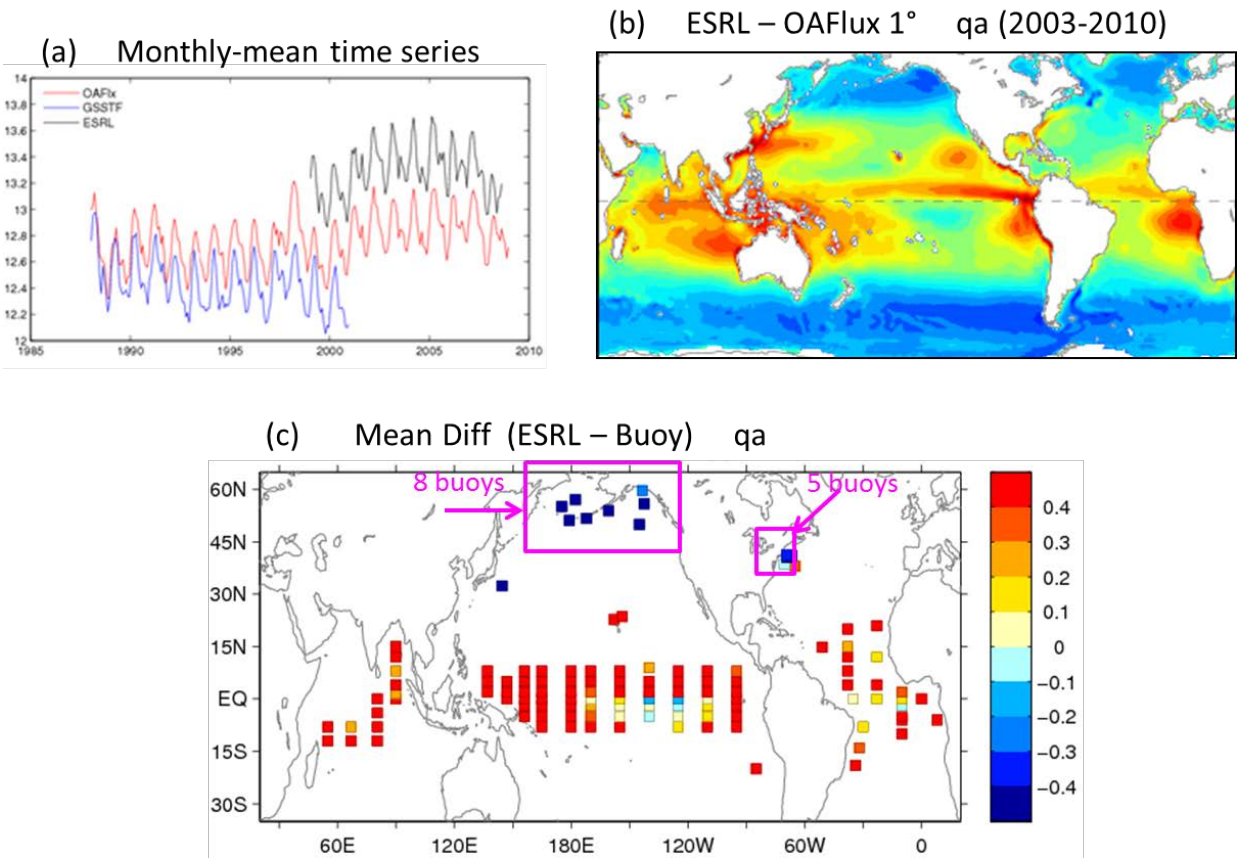

Figure 3. (a) Monthly mean time series of qa from three datasets: OAFlux 1° analysis (red), ESRL (black), and GSSTF (blue). (b) Mean difference in qa between OAFlux 1° analysis and ESRL satellite-derived. (c) Mean difference between ESRL and buoy shows the ESRL qa is biased wet in the tropics but biased dry at higher latitudes. The two magenta boxes denote the new addition of NDBC buoys to the OAFlux validation database.

We have experimented ways to correct the biases in ESRL qa/ta estimates while retaining the spatial variability of the dataset. We found that the best solution was to apply the objective analysis approach developed for the OAFlux 1° analysis, i.e. to obtain an optimal estimate by synthesizing ESRL with ERAinterim and MERRA qa/ta fields. The resulting HR latent and sensible fluxes were fully validated with buoy flux time series (Figure 3), showing that, for 164,600 collocations, OAFlux HR latent heat flux (LH) has a mean difference from buoy by 4.56

W/m^2 and a daily standard deviation by 21.96W/m^2, while sensible heat flux (SH) has a mean difference by 0.93 W/m^2 and a daily standard deviation by 5.43W/m^2.

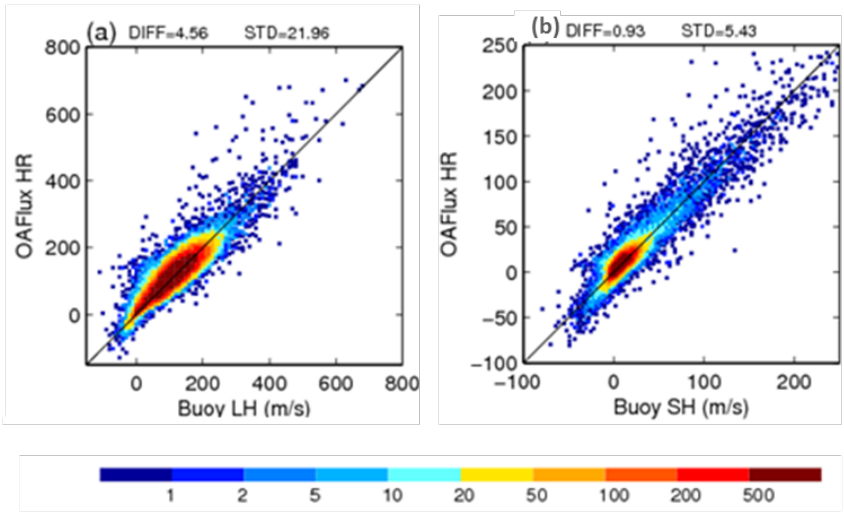

Figure 4. Scatter plot of (a) HR LH versus buoy, and (b) HR SH versus buoy based on 164,600 collocations between daily OAFlux HR and daily-mean buoy measurements during 2003-2010.

The HR analysis can better resolve the fine spatial structures associated with ocean fronts and eddies, and represents a major improvement over the OAFlux 1° analysis in the Western Boundary Currents (WBCs) where the large latent and sensible heat release from the ocean to the atmosphere have far-reaching impacts on global climate change and variability. We presented the study of the OAFlux HR analysis in the Gulf Stream region at the AMS 18th conference on air-sea interaction, July 2012, Boston, Massachusetts (Jin and Yu, 2012). We plan to further evaluate the OAFlux HR analysis, particularly at high latitudes, and to fully document the analysis procedure and dataset in FY 2013, with an objective to disseminate the entire dataset online for free public access in late 2013. This HR dataset will be a valuable addition to the ocean and climate community.

(3) Characterizing and quantifying errors in surface short and longwave radiation products

Efforts made in characterizing and quantifying surface shortwave and longwave radiation fluxes from satellites in FY 2012 led to a close collaboration with the NASA CERES science team and a joint publication with the CERES surface radiation group at NASA Langley (Kato et al. 2012).

The OAFlux products currently developed include air-sea turbulent latent and sensible heat fluxes. To obtain a net heat flux at the ocean surface, we need to take into account the surface shortwave and longwave radiation. There are three surface radiation data products derived from satellites: ISCCP (International Satellite Cloud Climatology Project), GEWEX-SRB (Global Energy and Water Cycle Experiment – Surface Radiation Budget), and CERES-EBAF (Clouds and Earth's Radiant Energy Systems - Energy Balanced and Filled). The last product is derived from CERES and Moderate Resolution Imaging Spectrometer (MODIS) measurements.

However, the net heat flux from combining OAFlux with these surface radiation products does not yield a balanced budget over the global oceans, with a residual ranging from 33 W/m2 for SRB+OAFlux 1°, 29W/m2 for ISCCP+OAFlux 1°, 23W/m2 for CERES+OAFlux 1°, and 18 W/m2 for CERES+OAFlux 0.25° (Figure 5). Improvement in the global net heat imbalance is clearly seen with CERES EBAF and OAFlux HR analysis, suggesting the better accuracy of these two products. When compared with the net heat budget constructed from other datasets (Figure 5), it is clear that the existing data sets have a greater uncertainty in closing the global ocean heat budget. In fact, the global budget balance has been a challenging issue for the flux community for the past three decades.

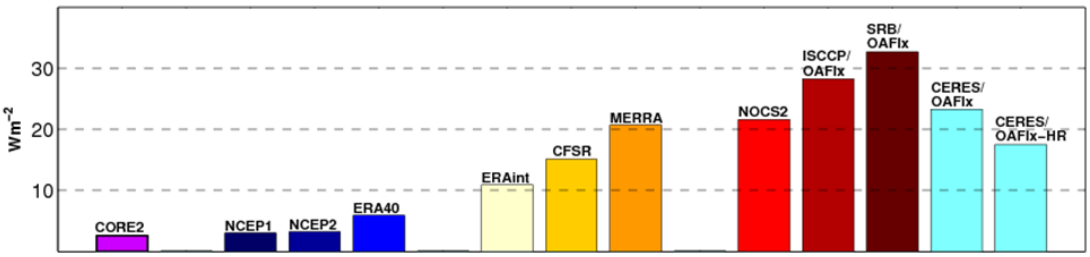

Figure 5. Mean net heat flux averaged over the global ice-free oceans constructed from earlier reanalyses (NCEP1, NCEP2, ERA40), latest reanalyses (ERAinterim, CFSR, and MERRA), ship-based NOCS2, blended CORE2, and the combined satellite-based products (ISCCP+OAFlux 1°, SRB+OAFlux 1°, CERES+OAFlux 1°, and CERES+OAFlux 0.25°.

Our work in FY 2012 was best summarized by PI (L.Yu) in her invited 45-min science presentation on "Toward a Balanced Net Heat Flux at the Ocean Surface" at the NASA CERES Science Team Meeting, May 2012, Newport News, Virginia. A key result is that the surface radiation from ISCCP and SRB overestimate the downward solar radiation by about 10-12 W/m^2 (Figure 6) when compared with the OAFlux in situ validation database (Figure 1). The bias is largest in the tropical oceans where the buoys are primarily located.

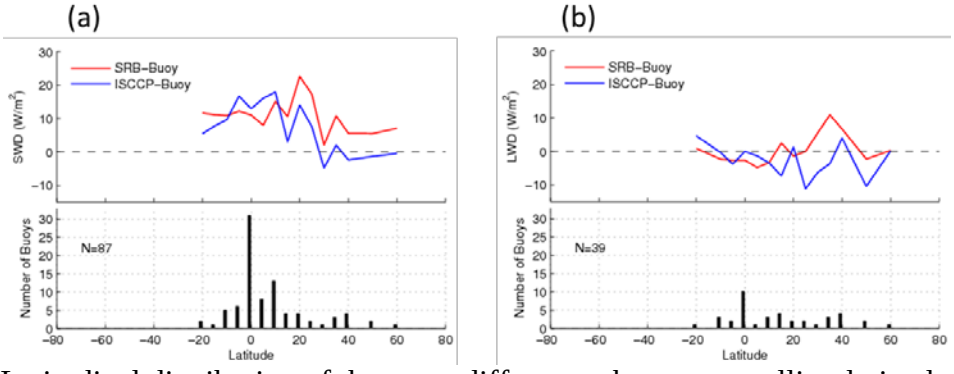

Figure 6. Latitudinal distribution of the mean differences between satellite-derived surface radiation estimates and buoys for (a) downward shortwave component and (b) downward longwave component. The lower panels in (a) and (b) show the number of buoys included in the analysis for each 5° latitude band. There are a total of 87 buoys in (a) and 39 buoys in (b) for the period of 1991-2009.

The study is the first full buoy-based evaluation ever provided for satellite-derived surface radiation products. It is evident that the net heat imbalance with ISCCP and SRB is partially attributable to the bias in the downward solar radiation component, an important input to the surface radiation community for improving the transform functions. CERES appears to have a better comparison with buoys (Kato et al. 2012). Work is ongoing in collaboration with CERES product PIs using buoys to evaluate CERES, and to investigate its combination with OAFlux for a net heat flux.

2.1. Outreach and Education

Lisan Yu

Dr. Yu routinely presents research results at national and international scientific meetings. She serves on the NOAA Ocean Observing System Team of Experts and has led the analysis of global ocean surface flux for the NOAA State of Climate annual assessment report since 2005. She serves on the CLIVAR Global Synthesis and Observations Panel. She is a member of the NASA Sea Surface Temperature Science Team, NASA Ocean Surface Salinity Science Team, and NASA Ocean Vector Wind Science Team. She served as the advisor for Samantha Whitmore, a 2012 WHOI Summer Student Fellow from Harvard University. She was a doctoral thesis advisor for Xiangzhou Song, a visiting Ph.D. student at WHOI. She is currently a committee member for Julian Schanze, a Ph.D. student of the WHOI/MIT joint program.

Robert A. Weller

Dr. Weller's outreach and education on air-sea fluxes is closely linked to these same activities on the Ocean Reference Station project that provides some of the high quality validation of the OAFlux. The cruises to the moorings invite participation by the NOAA Teacher at Sea program, and an important teaching topic is air-sea flux. Ten Teachers at Sea have been hosted. A video of one of these cruises and the work to collect air-sea fluxes from surface moorings was produced by volunteer Diane Suhm. This video was recently provided to the Climate Observation Division. A shorter version has run on cable TV in Massachusetts and will be used at public lectures in Woods Hole. These cruises, whenever possible, offer space to undergraduate and graduate students to provide hands on experience at sea and about air-sea fluxes. Weller has used opportunities derived from sailing from different Central and South American ports for regional outreach. Staff from INOCAR (Institute of Naval Oceanography) in Ecuador, the Hydrographic Division of the Peruvian Navy (DHN), the Institute of Marine Sciences of Peru (IMARPE), and the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) have joined Stratus cruises. Weller now advises 1 postdoctoral investigator.

3. Publications and Reports

3.1. Publications by Principal Investigators

- Published

Yu, L., and M. J. McPhaden, 2011. Ocean pre-conditioning of Cyclone Nargis in the Bay of Bengal: Interaction between Rossby waves, surface fresh waters, and sea surface temperatures. *J. Phys. Oceanogr*., **41**(9), 1741-1755, doi:10.1175/2011JPO4437.1.

Yu, L., 2011. A global relationship between the ocean water cycle and near-surface salinity. *J. Geophys. Res.*, **116**, C10025, doi:10.1029/2010JC006937.

Song, X., and L. Yu, 2012. High latitude contribution to global variability of sensible heat flux at the air-sea interface. *J. Climate*, special collection on "CLIVAR/SeaFlux High Latitude Surface Fluxes", **25**, 3515-3531, DOI: 10.1175/JCLI-D-11-00028.1.

Yu, L., P. W. Stackhouse, and R.A. Weller. 2012. Global ocean heat fluxes [in "State of the Climate in 2011"]. *Bull. Ameri. Meteor. Soc*., **93**(7), S65-S68.

- In press

Gimeno, L., A. Stohl, R. Trigo, F. Dominguez , K. Yoshimura, L. Yu, A. Drumond, A. Duran-Quesada, and R. Nieto, 2012: Oceanic and Terrestrial Sources of Continental Precipitation. *Rev. Geophys*., doi:10.1029/2012RG000389. In press.

Kato, S, N. G. Loeb, F. G. Rose, D. R. Doelling, D. A. Rutan, T. E. Caldwell, L. Yu, and 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. In press.

Weller, R.A., S. P. Bigorre, J. Lord, J. D. Ware, and J. B. Edson, 2012. A surface mooring for air-sea interaction research in the Gulf Stream. Part 1: Mooring design and instrumentation. *J. Atmos. Oceanic. Tech.*, in press.

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.*, doi:10.1029/2012JC008069. In press.

- In revision

Bigorre, S. P., R.A. Weller, and J. B. Edson, 2012. A surface mooring for air-sea interaction research in the Gulf Stream. Part 2: Analysis of the observations and their accuracies. *J. Atmos. Oceanic Tech.*, in review.

Josey, S., S. Gulev, and L. Yu, 2012: Exchanges through the ocean surface. In "Ocean Circulation and Climate", 2nd Edition. G. Siedler, J. Church, J. Could, and S. Griffies. Eds. In revision.

- Submitted

Edson, J., V. Jampana, R. Weller, S. Bigorre, A. Plueddemann, S. Miller, L. Mahrt, D. Vickers, and H. Hersbach, 2012. On the exchange of momentum over the open ocean. *Jrnl. Phys. Oceanogr.*, submitted.

- Abstract /Proceedings from meeting conferences

Yu, L., 2011: The WHOI OAFlux project: Objectively Analyzed Air-Sea Fluxes (OAFlux) for improved representation of short and long-term changes in global ocean

heat, freshwater, and momentum fluxes". WCRP Open Ocean Science Conference, 24-28 October 2011, Denver, Colorado.

Yu, L., 2011: "Observation for Climate: The WHOI OAFlux Project Sustained Air-sea Flux Buoy Observations for Improved Estimation of Global Ocean Surface Heat, Moisture, and Momentum Fluxes". WCRP Open Ocean Science Conference, 24-28 October 2011, Denver, Colorado.

Yu, L., 2011: "Satellite and RAMA observations of air-sea interaction in the Bay of Bengal". ONR workshop on the Role of the Bay of Bengal for Prediction of the Indian Monsoon, 16-18 November 2011, Woods Hole, MA.

Yu, L., 2012, "Toward a Balanced Net Heat Flux at the Ocean Surface". NASA CERES Science Team Meeting, May 1-3, 2012, Newport News, Virginia.

Yu, L., 2012, "Decadal trends in ocean evaporation". The Morss Colloquium on The Ocean and Earth's Changing Water Cycle: Past, Present, Future. 16-18 May 2012. Woods Hole, MA.

Yu, L., 2012 "OAFlux high-resolution flux analysis", CLIMODE PI meeting, 18-19 July 2012, Woods Hole, MA. Invited presentation.

Yu, L., 2012, "The WHOI OAFlux project: High-resolution analysis of global air-sea heat and momentum fluxes". NOAA Ocean Climate Observation 8th Annual PI meeting, 25-27 June 2012, Silver Spring, MD.

Jin, X., and L. Yu, 2012: "OAFLux high-resolution air-sea flux fluxes over the Gulf Stream". AMS 18th conference on air-sea interaction, 9-13 July 2012, Boston, MA.

3.2. Other Relevant Publications

The two publications on OAFlux products, Yu and Weller (2007, BAMS) and Yu et al. (2008, WHOI technical report) have received 386 citations by refereed publications. During 2011-2012, the OAFlux products were a base dataset in 82 referred publications that include the following most noted publications (an electronic copy for the two publications marked with * is attached in the package):

*Allen, R. J., S. C. Sherwood, J. R. Norris, and C. S. Zender, 2012. Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature*, **485**(7398), 350-354.

*Balaguru, K., P. Chang, R. Saravanan, L. R. Leung, Z. Xu, M. Li, and J. S. Hsieh, 2012. Ocean barrier layers' effect on tropical cyclone intensification. *Proceedings of the National Academy of Sciences*, **109**(36), 14343-14347.

Bosilovich, M. G., F. R. Robertson, and J. Chen, 2011. Global energy and water budgets in MERRA. *Journal of Climate*, **24**(22), 5721-5739.

Chang, Y. S., S. Zhang, A. Rosati, T. L. Delworth, and W. F. Stern, 2012. An assessment of oceanic variability for 1960–2010 from the GFDL ensemble coupled data assimilation. *Climate Dynamics*, 1-29.

Delcroix, T., G. Alory, S. Cravatte, T. Corrège, and M. J. McPhaden, 2011. A gridded sea surface salinity data set for the tropical Pacific with sample applications (1950–2008). *Deep Sea Research Part I: Oceanographic Research Papers*, **58**(1), 38-48.

Hansen, J., M. Sato, and R. Ruedy, 2012. Perception of climate change. *Proceedings of the National Academy of Sciences*, **109**(37), E2415-E2423.

Moore, G. W. K., I. A. Renfrew, and R. S. Pickart, 2012. Spatial distribution of air-sea heat fluxes over the sub-polar North Atlantic Ocean. *Geophysical Research Letters*, **39**(18), L18806.

Peterson, T. C., P. A. Stott, P and S. Herring, 2012. Explaining extreme events of 2011 from a climate perspective. *Bulletin of the American Meteorological Society*, **93**(7), 1041-1067.

Schulz, E. W., S. A. Josey, and R. Verein, 2012. First air-sea flux mooring measurements in the Southern Ocean. *Geophysical Research Letters*, **39**(16), L16606.

Séférian, R., L. Bopp, M. Gehlen, J. C. Orr, C. Ethé, P. Cadule, and G. Madec, 2012. Skill assessment of three earth system models with common marine biogeochemistry. *Climate Dynamics*, 1-25.

Trenberth, K. E., and J. T. Fasullo, 2012. Tracking Earth's energy: From El Niño to global warming. *Surveys in Geophysics*, 1-14.

Xue, Y., B. Huang, Z. Z. Hu, A. Kumar, C. Wen, D. Behringer, and S. Nadiga, 2011. An assessment of oceanic variability in the NCEP climate forecast system reanalysis. *Climate Dynamics*, **37**(11), 2511-2539.