50 Year Global Ocean Surface Heat Flux Analysis

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1. Project Summary

The Objectively Analyzed air-sea Fluxes (OAFlux) is a research and data 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 than 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 the 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 its 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. At the same time, the OAFlux global products broaden, strengthen, and enrich the use of in situ flux measurements. The buoy-validated, completely global, gridded, and temporally homogeneous 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 user base has been growing rapidly. Since the access counter was installed on 01 May 2013, the project home page has been accessed 8,482 times and the data download page 7,901 times. The products were a base dataset in 670 publications since they were released in 2007. There were 141 citations in peer-reviewed journals in FY2014, compared to 149 citations in FY2013. A new recent trend shows that OAFlux is a leading source of verification and validation for climate models and data assimilation models, and a key evaporation product used in the two satellite salinity missions, the NASA Aquarius/SAC-D and the Soil Moisture and Ocean Salinity (SMOS) of the European Space Agency (ESA).

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.

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 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

2.1 Enhancing the OAFlux project deliverables to address the program’s priorities

The Objectively Analyzed air-sea Fluxes (OAFlux) project is committed to produce high-quality, long-term, global analysis of ocean surface heat, moisture, and momentum fluxes from the late 1950s to the present. Since the online dissemination in 2007, the OAFlux products have established a reputation for quality, reliability, near-realtime updates, and easy access. OAFlux is being used in a broad range of applications, including characterization, attribution, modeling, and understanding of the variability and long-term change in the atmosphere and ocean.

For the OAFlux project, the quality of the flux analysis is attained by three ways: (1) buoy-based validation at 130+ sites, (2) constant development of innovative statistical approaches, and (3) as a user of our own products. All of these three areas have been worked on during FY2014. The progress and accomplishments are highlighted below.

(1) Important lessons learned from buoy validation of reanalysis products
We issued two online updates of the OAFlux products in FY2014, one in May and the other in October, to bring the time series from 1958 to the present (up to September 2014 as of this report). Ensuring the quality and continuity of data products is the top priority for each update. The OAFlux methodology is based on the objective synthesis of multiple data sources from satellites and reanalyses. There are more than 30 input datasets used in constructing the OAFlux time series, and the data sources have been constantly changing and updating. Hence, the updates cannot be taken lightly. We need to check the changes of data versions and formats during each update. For instance, the NCEP/NCAR (hereafter referred to as NCEP1) air temperature serves as one good substitute input dataset in our near-realtime update to accommodate the delayed release of some reanalyses (such as European Center for Medium Range Weather Forecasting Interim atmospheric reanalysis (ERAinterim) and NCEP Coupled Forecast Reanalysis System (CFSR)). However, the transition of the NCEP output files from netCDF3 to the netCDF4-classic format on October 20th 2014 failed all our existing computing programs due to the lack of the netCDF4 support on our computing facilities. As a result, we spent more than one week to upgrade the computers to adapt the latest netCDF library and another week to rewrite the codes and test the consistency with the previous experiments. Changes of data versions, particularly for satellite products, present even more serious challenges to the update. The upgrade of a data version usually means a jump in the global mean average. Decision has to be made on whether we correct the mean or embrace the newer version by updating the entire OAFlux time series to avoid spurious jumps. In FY2014, the OAFlux time series from 1987 onward was rerun to accommodate the newly released version 7 wind speed products of the Remote Sensing System that include not only SSMI and SSMIS, but also AMSRE and WindSat; we implemented QuikSCAT rain-corrected wind speed and vector products developed by the Jet Propulsion Laboratory to recover the wind speed values under rain conditions; and we introduced OSCAT, ASCAT-A and ASCAT-B to compensate for the loss of QuikSCAT after November 2009.

Nevertheless, data products, particularly those from reanalyses, have biases. One effective way to identify the biases in input variables proves to be the validation against buoy time series measurements at 130+ buoy sites (this number has been down in recent years due to the lack of service for TAO buoys) (Figure 1). Although the work is labor intensive and time consuming, it is a necessary step to ensure the high quality of the OAFlux products. In FY2014, we narrowed down the sources of bias in two reanalyzed variables that are related to the use of the Tropical Pacific mooring array: one is the near-surface air humidity in ERAinterim (Josey et al. 2014) and the other is the surface wind in NCEP/DOE (referred to as NCEP2 thereafter). We identified a pattern of strong near surface humidity anomalies in ERAinterim that is collocated with the array (Figure 2). These bulls-eye anomalies generate large, previously unrecognized latent and net air-sea heat flux anomalies, up to 50 Wm$^{-2}$ in the annual mean. As a consequence, uncertainty in Tropical Pacific ocean heat uptake between the 1990s and early 2000s at the mooring sites is significant with mooring collocated differences in decadally averaged ocean heat uptake as large as 20 Wm$^{-2}$.
Figure 1. Global buoy locations superimposed onto the mean net heat flux (Qnet) field merged from OAFlux ocean turbulent heat flux estimates and NASA CERES surface radiation estimates. The buoy locations are marked by different symbols, indicating that not all flux variable measurements can be obtained at all locations. While ocean turbulent latent and sensible flux measurements are available at all locations, shortwave radiation (marked by black squares) is measured at ~80 locations and longwave radiation (marked by red squares) is available at only about ~20 locations.

Figure 2. ERA-Interim 2 m specific humidity (colored field). (a) 1994 annual mean (mooring locations,
black crosses) and (b) 1994 annual anomaly (relative to 1979–2012, wind velocity anomaly shown by arrows), (c) equatorial section of 1994 mean specific humidity for Drakkar Forcing Set (DFS) (dashed blue), ERA-Interim (red), ERA40 (magenta), Modern Era Reanalysis for Research and Applications (MERRA) (black dash-dot), NCEP1 (green), CFSR (black dash), Objectively Analyzed Air-Sea heat flux (OAFlux) (black), and TropFlux (blue), and (d) as in Figure 1b but for ERA-Interim 2012 anomaly (from Josey et al. 2014). It is important to note from (c) that OAFlux is not affected. We have been aware of the bias in the ERAInterim humidity and did not include it in the synthesis.

Another example of the impact of the buoy on the reanalysis is revealed in our analysis of NCEP2 surface winds. The investigation was conducted in the spring of 2014 at the request of Dr. Yan Xue at the NCEP Climate Prediction Center, who at that time experienced difficulties in making an ENSO prediction in line with the predictions from other weather prediction centers, as the central equatorial Pacific was anomalously cold in the NCEP ocean model. We identified the cold SST anomalies were caused by peculiarly strong easterlies (negative anomalies in Figure 3a) in the NCEP2 winds that were used in forcing the NCEP prediction model, after the examination with CFSR and our satellite wind products (Figure 3b). The stronger westward

Degradation of TAO reporting has an impact on NCEP ENSO prediction

Figure 3. Our analysis of the source of the NCEP2 wind anomalies in the tropical Pacific to help correct the anomalously cold SST conditions produced by the NCEP seasonal-to-interannual prediction model. (a) NCEP2 winds show peculiarly strong easterly anomalies (negative anomalies) in the central Pacific. (b) The NCEP2 easterly anomalies are related to an anomalous local enhancement at 170W, which is not seen in the CFSR. (c) We suspect that the NCEP wind anomalies along the meridional section at 170W is caused by the poor TAO returns in the central Pacific (solid red squares denote active TAO returns), which makes NCEP2 work extremely hard to adjust to the remaining 1-2 buoys (From Yu’s presentation at the US CLIVAR summit in Denver, CO. July 2014).
winds produced stronger equatorial upwelling that cooled down the surface temperatures and inhibited the generation of the warming conditions as seen in other prediction models. Our investigation also suggested that the NCEP2 easterly anomalies were centered at 170W, due perhaps to the poor TAO returns in recent years (Figure 3c). Unlike CFSR that assimilates satellite WindSat observations, NCEP2 assimilates only TAO buoy, making it extremely vulnerable to the reduction of the TAO buoy reports. Our analysis helped the CPC in understanding the surface wind conditions in the spring of 2014 and the oceanic consequences during the CPC Monthly Ocean Briefing in June/July.

The two studies (Figures 2-3) raise major questions regarding the dual use of flux mooring observations as (i) data assimilation input to reanalyses and (ii) a reference for the subsequent evaluation of reanalysis product air-sea exchange data sets. An evaluation of ERA-interim and NCEP2 products against the Tropical Pacific buoys may reveal reasonable local agreement with buoy measurements given their potential to locally correct biases in the reanalyzed fields. However, it would be misleading to interpret such results as being indicative of the accuracy of the reanalysis fields across the Tropical Pacific as a whole given the strong variations away from the buoy sites.

We use reanalyzed flux-related variables in the OAFlux synthesis when there are no direct satellite retrievals, such as the near-surface air humidity and temperature. As seen in Figure 2c, OAFlux is not affected because we have been aware of the bias in ERAinterim humidity during validation with buoys and excluded it in the synthesis. All input datasets, whether from satellites or from reanalyses, are under strict quality control based on validation with buoy and cross-validation between products before they are used in the synthesis. Any data set that shows drifts in the means (due to drifts in sensors or changes in model platforms) or large departure from buoys is discarded. We use extensively the satellite wind observations and do not include any reanalysis winds.

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(2) Improving OAFlux products through research and implementation of innovative statistical approaches

The OAFlux datasets that are currently distributed online are on 1° grids. Improving the spatial resolution is a necessary next step to improve the OAFlux’s representation of the fine-detail air-sea exchanges associated with the ocean fronts (Jin and Yu 2013). We have been making major efforts in recent years to develop the 0.25° gridded latent and sensible heat flux analysis (Jin and Yu 2013; Jin et al. 2014) and the 0.25° vector wind analysis (Yu and Jin 2012; 2014a; 2014b). The latter project was funded by the NASA ocean vector wind science team activities to merge a time series from 1987 onward using 14 satellite sensors. The wind speed from the vector analysis is an important variable in constructing the high-resolution (HR) OAFlux heat flux products, and the other three key variables are SST, near surface air humidity (Qa), and temperature (Ta). We obtain SST from the Objective Interpolated (OI) SST 0.25° daily analysis produced by Reynolds et al. (2007), and are currently developing our own retrieval algorithm to derive Qa/Ta directly from satellite humidity/temperature sounding profiles from AMSU-A and AMSU-B and total integrated water vapor from SSMI and SSMIS (Figure 4). There are a few groups producing Qa/Ta products, but none of the products are satisfactory when compared to buoys – the bias is too large and shows a latitudinal dependence. We worked with one group to impose buoy-based
bias adjustment to the Multi-Instrument Microwave Regression (MIMR) Qa/Ta analysis (Jackson and Wick, 2010) and to use OA synthesis algorithm to reduce error size (Jin et al. 2014). However, the MIMR product is a research product for the period of 1999-2010 only, while our HR analysis is intended for the near-real time production. Thus, in FY2014, we decided to move forward with our plan to develop our own Qa/Ta regression algorithm by using buoys as training datasets. We have made good progress (Figure 4).

Figure 4. The OAFlux new satellite-derived high-resolution (HR, 0.25°) heat flux analysis. (a) The mean Qa in 2010 derived from the OAFlux retrieval algorithm, (b) The mean Qa in 2010 estimated by MIMR (Jackson et al 2010), and (c) the mean difference between (a) and (b). Buoy shows that MIMR Qa is wet biased in the tropics and dry biased at high latitudes. The OAFlux algorithm is capable of improving the mean Qa pattern. (d) OAFlux HR versus the online1° analysis, showing that the two time series have very similar decadal viability but the HR latent heat (LH) flux analysis is about 3 Wm⁻² higher than the 1° analysis, while the sensible heat (SH) flux has not changed.

(3) Benefits by being a user of our own products

We believe that data producers should be users of their own products to gain a better understanding of the physical meanings of the statistical signals in the products, and the understanding and knowledge would help to further improve the accuracy of the products. Over the years, we have been persistently working on the oceanic applications of OAFlux products and have a long publication track record. In FY2014, one of the research foci was placed on the use of OAFlux for the salinity and water cycle study (Yu 2014). The effort was primarily leveraged by the PI’s funding support from the NASA Aquarius salinity mission activities.
OAFlux evaporation is the product most consistent with the NASA TRMM precipitation among the evaporation products being tested (Ren et al., 2014), and the OAFlux/TRMM combination is widely used as the freshwater flux forcing by the Aquarius mission as well as the water mission SMOS of the European Space agency. The PI’s study is to investigate whether and how ocean salinity can serve as a rain gauge to monitor the change of the global water cycle. Presently, the existing surface freshwater (evaporation-minus-precipitation) products contain large uncertainty (Figure 5), and the differences between products are larger than the mean value. Most differences occur in the tropical ITCZ regions where precipitation is the most intensive. The global water cycle has a strong imprint on ocean salinity through evaporation and precipitation, and the fresh ocean surface waters in the tropical oceans is the direct consequence of the ITCZ rainfall. Work is underway to decipher the water cycle signals from the satellite salinity observations.

Figure 5. (a) Estimates of the surface freshwater budget over the global oceans based on 11 evaporation/precipitation products. (b) The mean distribution of the surface freshwater fluxes. (c) The standard deviation (STD) between the means of the 11 products (from Yu’s presentation at the NASA Aquarius Salinity Science Team meeting, Seattle, WA. November 2014).

2.2 Primary achievements during FY 2014

Major achievements we have made during FY2014 are summarized as follows.

- We issued two online updates of the OAFlux product, which brings the time series from 1958 to the present (up to September 2014 as of this report).
- We provided the OAFlux-based analysis of the state of the global ocean surface heat flux in 2013 to the NOAA State of Climate annual assessment report. We have led the effort since 2005.

- We found that the assimilation of buoy observations in atmospheric reanalyses, if implemented improperly, could lead to erroneous patterns in the surface heat and momentum fluxes. The buoy-induced regional anomalies affect the ENSO prediction skills and the assessment of tropical climate variability. Our findings raise major questions regarding the dual use of flux mooring observations as (i) data assimilation input to reanalyses and (ii) a reference for the subsequent evaluation of reanalysis product air-sea exchange data sets.

- We designed and implemented an improved regression algorithm to derive near-surface air humidity and temperature from satellite humidity/temperature profiles. We are working toward the completion of satellite-based high-resolution heat flux products that cover the period from 1987 to the present.

- We authored and co-authored 8 manuscripts in refereed journals, with 7 published and one under minor revision.

### 2.3 Scientific advances made and/or facilitated through the OAFlux products and their significance

- The OAFlux products were used and cited in 141 refereed publications in FY2014, compared to 149 citations in FY2013.

- OAFlux products are known for quality, reliability, near-realtime updates, and easy access. They are being used in a broad range of applications, including characterization, attribution, modeling, and understanding of variability and long-term change in the atmosphere and ocean.

- Using OAFlux for evaluation and verification of climate models and data assimilation models is a recent trend that is growing in the modeling community.

- The OAFlux evaporation product is a major freshwater forcing dataset for studying the salinity observations from the two satellite missions, the NASA Aquarius/SAC-D mission, and the ESA’s water mission SMOS.

### 2.4 The website for the OAFlux project and related data-hosting sites

The OAFlux data products from 1958 to the present are freely available from our project website at [http://oaflux.whoi.edu](http://oaflux.whoi.edu). Since the access counter was installed on 01 May 2013, the project home page has been accessed 8,482 times, up from 2593 times in October 2013; and the project data download page has been accessed 7,901 times, up from 2,390 times.

The OAFlux data products are also disseminated through two other data centers:

- Asia-Pacific DATA-Research Center (ADPRC) at the University of Hawaii ([http://apdrc.soest.hawaii.edu/data/whoi_oaflux.php](http://apdrc.soest.hawaii.edu/data/whoi_oaflux.php))
3. Outreach and Education

The PI 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, and 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 is a member of NOAA Climate Reanalysis Task Force, and actively promotes the integration of the OAFlux products with NOAA climate observing and modeling activities.

4. Publications and Reports

4.1 Publications by Principal Investigators

Out:


**Under review:**

### 4.2 Other Relevant Publications

The OAFlux products described by Yu and Weller (2007, BAMS) and Yu et al. (2008, WHOI technical report) have received 670 citations by refereed publications through 11/15/2014. For the period from 1 October 2013 to 30 September 2014, the OAFlux products were used and cited in 141 referred publications, compared to 149 citations in last fiscal year.

The following list contains 70 publications assembled from the 141 citations in FY2014. These papers show that OAFlux datasets are used in a wide range of research topics, including the global water cycle, the ocean salinity change and variability, the basin-scale climate mode variability, the global energy transfer, the atmosphere-ocean feedback mechanisms, the subtropical mode water formation, climate model assessments, and verification of coupled data assimilation.


FY2014 Annual Report [50 Year Global Ocean Surface Heat Flux Analysis]


5. Slides
Three slides that highlight the OAFlux project’s progress are attached to this annual report.