A fifty-year analysis of global ocean surface heat flux to improve the understanding of the role of the ocean in climate

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1. Project summary

The ocean and the atmosphere exchange heat at their interface via a number of processes: solar radiation, longwave radiation, sensible heat transfer by conduction and convection, and latent heat transfer by evaporation of sea surface water. The amount of heat being exchanged is called heat flux. The distribution of heat flux over the global oceans is a key element for climate studies, as it is required to establish air-sea feedback mechanisms, to provide guidance and motivation for modeling studies, to verify individual or coupled atmosphere-ocean general circulation model simulations, and to serve as forcing functions for ocean model exercises. However, direct flux measurements are sparse. Our present knowledge of the global air-sea heat flux distribution stems primarily from the bulk parameterizations of air-sea fluxes as functions of surface meteorological variables (e.g., wind speed, temperature, humidity, cloud cover, etc). The source of observations for those flux-related variables includes marine surface weather reports from Voluntary Observing Ships (VOS) collected by Comprehensive Ocean-Atmosphere Data Set (COADS) and satellite remote sensing from various platforms. Atmospheric reanalyses from numerical weather prediction (NWP) centers such as National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) provide additional model-based database. Nonetheless, none of the three data sources are perfect as each suffers from at least one of the four deficiencies: (1) incomplete global coverage, (2) relatively short time series, (3) systematic bias, and (4) random error.

While improving the quality of each data source is a necessary step toward improving the estimates of surface heat fluxes, this project takes an alternative approach, i.e., to improve the quality of the flux estimates through objectively synthesizing the advantages of the three data sources. Synthesis denotes the process of using an advanced objective analysis approach to combine several kinds of individual data sources with different characteristics. Such a process reduces the errors in data and produces an estimate that has the minimum error variance at the solution. This type of approach has been applied successfully to generate gridded products surface vector wind, SST, and precipitation. This project, which is termed "Objectively Analyzed air-sea heat Fluxes (OAFlux)", is to develop an equivalent global synthesis product for surface heat fluxes by utilizing the methodology developed and experience learnt from a previous pilot study for the Atlantic Ocean.

The project has two main objectives. The first objective is to produce a 50-year (from the mid 1950s onward) analysis of surface latent, sensible, net shortwave and net longwave radiation fluxes over the global oceans with improved accuracy. This is to be achieved by an appropriate combination of COADS data, NWP reanalysis outputs, and satellite retrievals using advanced objective analysis. The target resolution is 1° longitude by 1° latitude and monthly. Daily flux fields will be produced when satellite data are available. The second objective is to use the data to study the heat flux variability on seasonal, annual, interannual, decadal and longer timescales and their relation to global climate change. The scientific investigation helps to assess the quality and reliability of the dataset in depicting the multi-decade climate record since 1950s and to provide physical insights into the dataset.

The end product, multi-decade, gridded global fields of surface latent, sensible, fluxes with monthly and/or daily resolutions is freely available to the community via the project website (http://oaflux.whoi.edu). The proposed study contributes to CLIVAR programs including CLIVAR Atlantic, Pacific and PACS, and benefits the CLIVAR and other research communities on studies of climate variability and predictability.

2. Accomplishments

Two major tasks, with one on the product development and the other on the analysis study of climate variability of global heat fluxes, have been undertaken in response to the two main objectives stated in the project summary.

(i) Task 1: Product development

The data development efforts in FY2006 have been placed on the production of the 50-year time series of global latent and sensible heat fluxes from the mid 1950s to present. This is achieved by applying a synthesis approach to each of the flux-related variables (i.e., wind speed, air and sea surface temperatures, and specific air humidity) and then computing the estimates of latent and sensible heat fluxes using the state-of-the-art bulk flux algorithm version 3.0, which was developed from the Coupled Ocean Atmosphere Response Experiment (COARE) (Fairall et al. 2003). The input data for the synthesis include satellite observations and NCEP and ECMWF model reanalyses and operational analyses. However, no satellite observations were available before 1981. A two-phase development process is, therefore, carried out and discussed below.

The first development phase is for the satellite era from 1981 onward. For this period, most flux-related variables (e.g., wind speed, sea surface temperature (SST), humidity) can be derived from passive and active satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR), Advanced Microwave Scanning Radiometer (AMSR), NSCAT and Quikscat scatterometers, TRMM Microwave Imager (TMI), and the Special Sensor Miscrowave Imager (SSM/I). Nevertheless, not all flux-related variables are satellite retrievable. To fill the data gap, the surface meteorology outputs from ECMWF operational forecast, ECMWF ReAnalysis-40 (ERA40), and NCEP-1 and NCEP-2 reanalyses are incorporated. COADS ship observations are not a direct input data source; but they, together with in situ buoy measurements, serve as the base data to provide the estimates for error properties of each input dataset and to validate flux estimates at the buoy sites. The analysis of daily global latent and sensible heat flux fields on a 1-degree grid from 1981 to 2002 has been made online since December 2005 via the project website http://oaflux.whoi.edu/.

The second phase is for the pre-satellite era from the mid 1950s to 1980, the period that there are only limited ship reports of surface meteorology. In absence of sufficient observations, NWP reanalyses play a major role in the development. Extensive efforts are made to compare NWP surface meteorology against available COAD in situ observations, from which error statistics are computed and included as weighting information during synthesis to control the actual contribution of each dataset. That is, data with poor quality are given a small weight so that their impact on the solution is minimized. To date, we have completed the analysis and validation of the dataset, and are in preparation for the release of the entire dataset in the coming months. Only monthly-mean data fields are to be distributed for this period, as the dataset may not be sufficient to resolve the spatial and temporal evolution of synoptic variability due to the lack of observations.

(ii) Task II: Analysis study

A series of the analysis study has been conducted to utilize the newly developed flux dataset to investigate climate variations of global heat flux fields, their relation to SST, and their implications for regional and global climate change. As a result, six papers have been submitted/accepted/published in peer-review journals during FY2006. The major findings are highlighted and discussed below.

(1) The manuscript on “Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global ice-free oceans” (Yu and Weller, 2006) introduced the newly developed 25-year (1981-2005) time series of daily latent and sensible heat fluxes and also presented variability of the global ocean heat flux fields on seasonal, interannual, decadal and longer timescales suggested by the new dataset. The paper showed that among all the climate signals in study the most striking is a long-term increase in latent heat flux that dominates the 25-year data record. Positive linear trends occur on a global scale, being most significant over the tropical Indian and western Pacific warm pool and the boundary current regions. The increase in latent heat flux is found to be in concert with the rise of sea surface temperature (SST), suggesting a response of the atmosphere to oceanic forcing (Figures 1a-b).

(a) (b)

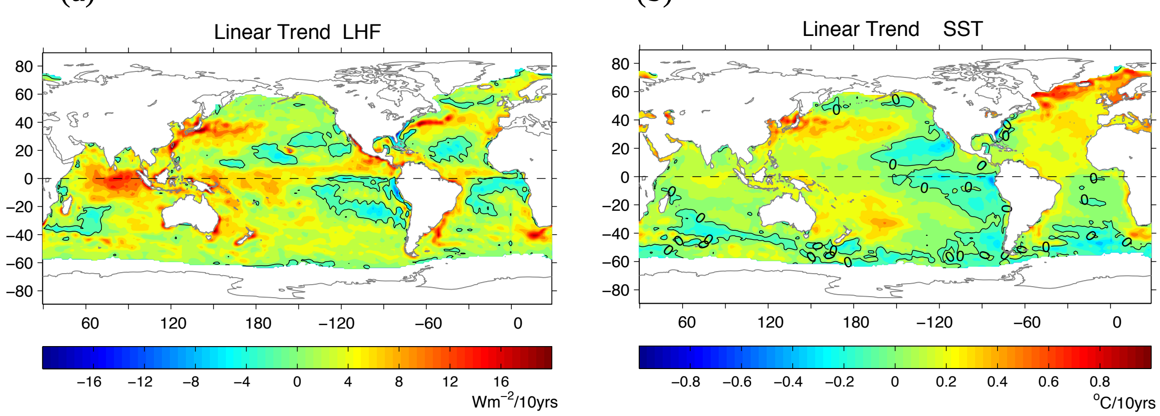

Figure 1 Linear trends in yearly-mean (a) latent heat flux (LHF) and (b) SST derived from the period from 1981 to 2005. Zero contours are highlighted.

(2) The ocean, being the source of 86% of the global evaporation and the receiver of 78% of global precipitation, is a key component of the global water cycle. A good understanding of the change of oceanic evaporation can lead to improved understanding of the climate behavior of the water cycle in the context of global climate change. Evaporation (*Evp*) is related to latent heat flux (LHF) by $Evp = LHF/\rho_w L_e$. Hence, time series of global evaporation fields is derived as a by-product of the OAFlux project (Figure 2a). The manuscript on “Global variations in oceanic evaporation (1958-2005)” (Yu, 2006) showed that the decadal change of the global oceanic evaporation (*Evp*) is marked by a distinct transition from a downward trend to an upward trend around 1977-78. Since the transition the global oceanic *Evp* has been up about 12 cm yr^{-1}

(~11%), from a low at 115 cm yr^{-1} in 1977 to a peak at 127 cm yr^{-1} in 2002 (Figure 2b). The increase in *Evp* is most significant during the decade of the 1990s. The analysis of the cause of the *Evp* change suggested a dominant role of the wind forcing. It is hypothesized that wind impacts *Evp* by two ways. The first way is direct: the greater wind speed induces more evaporation by carrying water vapor away from the evaporating surface to allow the sea-air humidity gradients to be reestablished at a faster pace. The second way is indirect: the enhanced surface wind strengthens the wind-driven subtropical gyre, which in turn drives a greater heat transport by the western boundary currents, warms up SST along the paths of the currents and extensions, and causes more evaporation by enlarging the sea-air humidity gradients. Although the trend in *Evp* can be traced directly to changes in surface wind forcing and its effects on sea-air humidities, the long-term trend in SST is, nevertheless, the ultimate cause of the change.

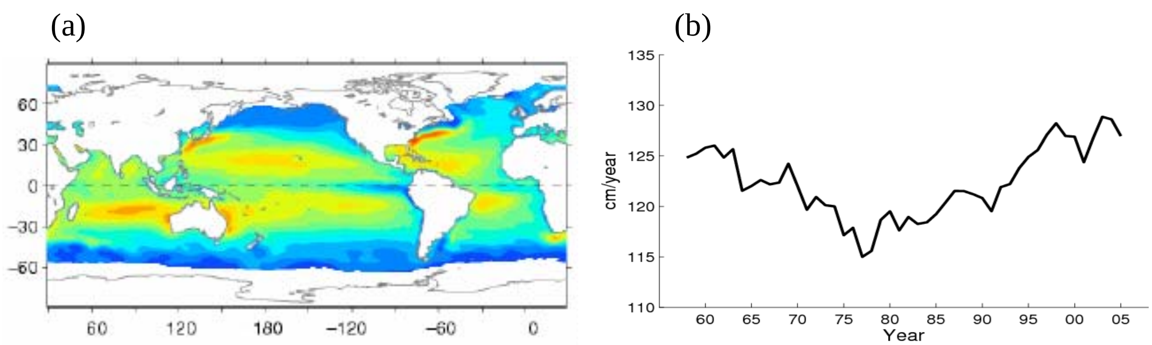

Figure 2 (a) Mean global evaporation pattern averaged over the 1958-2005 period. (b) Time series of the yearly-mean evaporation averaged over the global ice-free regions.

(3) In situ flux measurements made by buoys and ships provide benchmark time series for evaluation the accuracy of various heat flux products. The manuscript on “Annual, Seasonal, and interannual variability of air-sea heat fluxes in the Indian Ocean” (Yu et al. 2006a) presented an evaluation study for six net heat flux products, including the latent and sensible fluxes from OAFlux plus net shortwave and longwave radiation from the International Satellite Cloud Climatology Project (ISCCP), the heat flux analysis from Southampton Oceanography Centre (SOC), NCEP1, and NCEP2, ECMWF operational (ECMWF-OP) and ERA40. The study showed that the net heat flux into the northern Indian Ocean is considerably underestimated by the four NWP model flux products; sometimes, even the sign is wrong. At the two in situ measurements sites, NCEP1 net heat flux is 52 – 69 Wm^{-2} lower, and ERA40 is about 26 Wm^{-2} lower – the magnitude of the bias is larger than the mean itself. On the other hand, the OAFlux+ISCCP has the best comparison at both measurement sites, differing from buoy/ship flux measurements by about 5% on average.

(4) The manuscript on “Role of net surface heat flux in the seasonal evolution of sea surface temperature in the Atlantic Ocean” provided an example that the better fluxes can lead to a better understanding of SST variability (Yu et al. 2006b). Ocean observations indicate that the seasonal SST increase in the tropical Atlantic Ocean is associated with a shallow thermocline, suggesting that the major contributor to the surface mixed layer heat budget is the net surface heat flux through the air-sea interface. By combining the OA latent and sensible heat fluxes with

ISCCP surface radiation, the role of surface heat fluxes was clearly depicted. In consistent with ocean subsurface observations, surface heat fluxes are the forcing for the seasonal SST cycle over most of the tropical Atlantic basin except for the equatorial cold tongue and the region under the Intertropical Convergence Zone (ITCZ) (Figure 3a). Such depiction cannot be established using NWP flux products from NCEP and ERA40. The seasonal evolution of *dSST* can be well simulated by the OAFlux+ISCCP heat fluxes outside of the two zonal belts (Figure 3b).

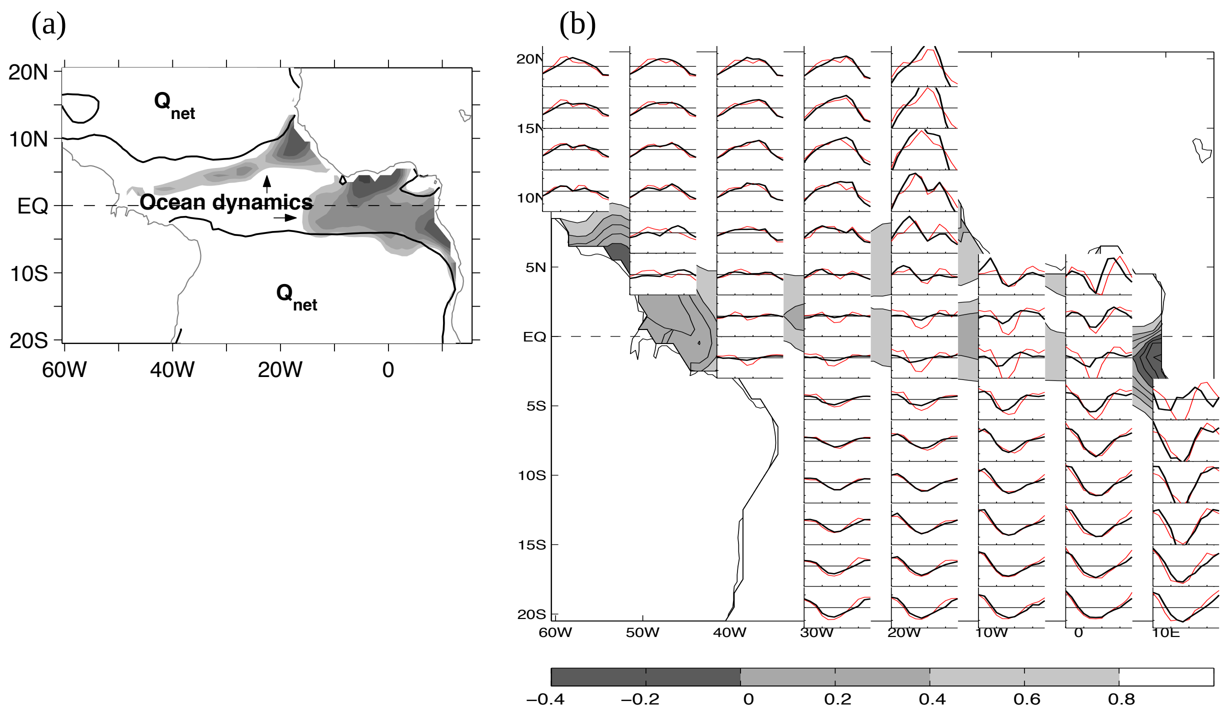

Figure 3 (a) Schematic diagram of the dominant influence of net heat flux (Q_{net}) and ocean dynamic processes in seasonal variations of SST of the tropical Atlantic Ocean. The pattern is based on the 0.9 correlation coefficient of <Q_{net}, *dSST*> derived from the OAFlux product. *dSST* denotes the monthly increment in SST. The role of oceanic process is deemed important in the two zonal belts (gray color shaded). (b) Model predicted (black) versus observed (red) *dSST*. The individual plots are drawn at every 10° in longitude and every 3° in latitude starting from the grid location (60.5°W, 18.5°S). The x-axis is Month and the y-axis ranges between -1.6 to 1.6°C.

(5) In addition to heat flux products, the OAFlux project also delivers daily/monthly estimates of the flux-related variables including SST, wind speed, sea/air temperatures and humidities since the mid 1950s. The study on "Dependence of hurricane formation on sea surface temperature anomaly fields in the Atlantic Ocean" (Saotome and Yu, 2006) provided one example of the use of the supplemental OAFlux datasets in climate studies. In this study, the daily SST dataset from the OAFlux product was taken to analyze the relationship between SST and hurricane formation locations using singular value decomposition. The study yielded two interesting results. The first is that between the positive SST anomaly pattern to the East of Florida in the first mode and the positive SST anomaly pattern in the Gulf of Mexico, Gulf Stream, and MDR in the second mode, almost all the hurricane formation locations from 1981-

2005 can be accounted for. The second is that the principle component time series shows an increasing trend in the second mode and a decreasing trend in the first mode since 1995, which coincides with the time point at which hurricane activity in the North Atlantic has dramatically increased. These two results strongly suggest that SST anomaly patterns and hurricane formation locations are linked.

3. Publications and reports

Yu, L., R. A. Weller, 2006: Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global ice-free oceans. *Bull. Amer. Meteor. Soc*. Accepted.

Yu, L., 2006: Global variations in oceanic evaporation (1958-2005). *J. Climate*. Accepted.

Yu, L., X. Jin, and R. A. Weller, 2006a: Annual, Seasonal, and interannual variability of air-sea heat fluxes in the Indian Ocean. *J. Climate*. In press.

Yu, L., X. Jin, and R. A. Weller, 2006a: Role of net surface heat flux in the seasonal evolution of sea surface temperature in the Atlantic Ocean. *J. Climate*, **19**, 6153–6169.

Saotome, R., and L. Yu, 2006: Dependence of hurricane formation on sea surface temperature anomaly fields in the Atlantic Ocean. *J. Climate.* Submitted.

Schein, K.A. et al, 2006: The state of the climate 2005. *Bull. Am. Meteorol. Soc., 87,* S1-S102.

Yu, L., 2006: Objectively analyzed air-sea fluxes (OAFlux) for the global oceans. Proceeding of the 86th American Meteorological Society Annual Meeting. Atlanta, Georgia. January, 2006.

Helber, B., F. Bonjean, R. H. Weisberg, E. S. Johnson, and L. Yu, 2006: Heat transport analyses of the tropical Atlantic Ocean mixed layer. Proceeding of the 86th American Meteorological Society Annual Meeting. Atlanta, Georgia. January, 2006.

Yu, L., Xiangze Jin, and R. A. Weller, 2006: Objectively analyzed air-sea fluxes (OAFlux) for the Indian Ocean climate studies. Proceeding of the 13th AGU Ocean Sciences meeting. Honolulu, Hawaii.

Jin, X., L. Yu, and R. A. Weller, 2006: Global daily air-sea heat fluxes from the WHOI OAFlux Project. Proceeding of the 13th AGU Ocean Sciences meeting. Honolulu, Hawaii.

Helber, B., F. Bonjean, R. H. Weisberg, E. S. Johnson, and L. Yu, 2006: Heat transport analyses of the tropical Atlantic Ocean mixed layer. Proceeding of the 13th AGU Ocean Sciences meeting. Honolulu, Hawaii.