Climate Variability in Ocean Surface Turbulent Fluxes

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1. Project Summary

FSU produces fields of surface turbulent air-sea fluxes and the flux related variables (winds, SST, near surface air temperature, near surface humidity, and surface pressure) for use in global climate studies. Surface fluxes are by definition rates of exchange, per unit surface area, between the ocean and the atmosphere. Stress is the flux of horizontal momentum (imparted by the wind on the ocean). The evaporative moisture flux would be the rate, per unit area, at which moisture is transferred from the ocean to the air. The latent heat flux (LHF) is related to the moisture flux: it is the rate (per unit area) at which energy associated with the phase change of water is transferred from the ocean to the atmosphere. Similarly, the sensible heat flux (SHF) is the rate at which thermal energy (associated with heating, but without a phase change) is transferred from the ocean to the atmosphere. In the tropics, the latent heat flux is typically an order of magnitude greater than the sensible heat flux; however, in the polar regions the SHF can dominate.

We examine these fluxes on the basis of in situ data (funded solely by NOAA) and satellite data (leveraged from several NASA projects and from the PI being the NASA Ocean Vector Winds Science Team Leader). The in situ product is well suited for long time scale studies, and comparisons to reanalyses[1]. We find that the variability between flux products is far greater than

[1] **Smith, S.**, P. Hughes, and **M. Bourassa**, 2011: A comparison of nine monthly air-sea flux products. *Int. J. Climatology*, **31**, 1002-1027, doi: 10.1002/joc.2225.

the accuracy need to resolve climate variability[2], indicating that a great deal more work is needed to make products that are well suited to ocean process studies where the processes are sensitive to the fluxes (as is often the case). We have also found that it is very important to consider high frequency variability[3] (e.g., finer scale synoptic variability) in the calculation of longer-term average fluxes (particularly the ocean uptake of CO_2), and in the case of the Gulf of Mexico's West Florida Shelf, for correctly modeling the regional ocean climate[4]. This is very important for the local ecosystem including some important finfish and shellfish. We maintained our website on variability in northern hemisphere tropical cyclone activity through most of the year; however, it is now moved to the website of the former student that did the work and maintained the site. These studies add to the evidence demonstrating the importance of consider the ocean and the atmosphere as coupled for climate applications.

The FSU activity is motivated by a need to better understand interactions between the ocean and atmosphere on weekly to interdecadal time scales. Air-sea exchanges (fluxes) are sensitive indicators of changes in the climate, with links to floods and droughts[5] and East Coast storm intensity and storm tracks[6]. On smaller spatial and temporal scales they can be related to the storm surge[7], and tropical storm intensity. On longer temporal scales, several well-known climate variations (e.g., El Niño/Southern Oscillation (ENSO); North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO)) have been identified as having direct impact on the U.S. economy and its citizens. Improved predictions of ENSO phase and associated impact on regional weather patterns could be extremely useful to the agricultural community. Agricultural decisions in the southeast U.S. sector based on ENSO predictions could benefit the U.S. economy by over $100 million annually[8]. A similar, more recent estimate for the entire U.S. agricultural production suggests economic value of non-perfect ENSO predictions to be over $240 million annually[9]. These impacts could easily be extended to other economic sectors, adding further economic value. Moreover, similar economic value could be foreseen in other world economies, making the present study valuable to the global meteorological community.

ENSO, PDO, and NAO (AO) each have atmospheric and oceanic components that are linked through the surface of the ocean. Changes in the upper ocean circulation result in modifications to the SST and near surface wind patterns. Variations in SSTs can be related to ENSO and other climate patterns; however, it is the fluxes of heat and radiation near the ocean surface that transfer energy across the air-sea interface. It is an improved understanding of these turbulent

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[2] **Bourassa, M. A.**, S. Gille, D. L. Jackson, B. J. Roberts, and G. A. Wick: Ocean Winds and Turbulent Air-Sea Fluxes Inferred From Remote Sensing. *Oceanography*, **23**, 36-51.

[3] Hughes, P., and **M. A. Bourassa**, J. Rolph, and **S. R. Smith**, 2011: An examination of FSU3 turbulent heat flux methodology. *J. Clim.*, (submitted).

[4] Morey, S. L., D. S. Dukhovskoy, and **M. A. Bourassa**, 2009: Connectivity between variability of the Apalachicola River flow and the biophysical oceanic properties of the northern West Florida Shelf. *Continental Shelf Research*, doi:10.1016/j.csr.2009.02.003.

[5] Enfield, D. B., A. M. Metas-Nuñez, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophy. Res. Let*., **28**, 2077-2080.

[6] Hurrell, J.W., and R.R. Dickson, 2004: Climate variability over the North Atlantic. Marine Ecosystems and Climate Variation - the North Atlantic. N.C. Stenseth, G. Ottersen, J.W. Hurrell, and A. Belgrano, Eds. Oxford University Press, 2004.

[7] Morey, S. L., S. Baig, **M. A. Bourassa**, D. S. Dukhovskoy, and J. J. O'Brien, 2006: Remote forcing contribution to storm-induced sea level rise during Hurricane Dennis. *Geophys. Res. Letts.*, 33, L19603–19607, doi:10.1029/2006GL027021.

[8] Adams, R. M., K. J. Bryant, B. A. McCarl, D. M. Legler, J. O'Brien, A. Solow, and R. Weiler, 1995: Value of improved long-range weather information. *Contemporary Economic Policy*, **13**, 10-19.

[9] Solow, A. R., R. F. Adams, K. J. Bryant, D. M. Legler, J. J. O'Brien, B. A. McCarl, W. Nayda, and R. Weiler, 1998: The value of improved ENSO prediction to U. S. agriculture. *Climate Change*, **39**, 47-60.

fluxes and their variability that motivates our research (radiative fluxes are difficult to accurately estimate from in situ data; however, satellite-based estimates are available). By constructing high quality fields of surface fluxes we provide the research community the improved capabilities to investigate the energy exchange at the ocean surface.

FSU produces both monthly in-situ based (the FSU3) and hybrid satellite/numerical weather prediction (NWP) fields of fluxes and the flux-related variables. Our long-term monthly fields are well suited for seasonal to decadal studies, and our hybrid satellite/NWP fields will be ideal for daily to inter- annual variability and quality assessment of the monthly products. The flux-related variables are useful for ocean forcing in models, testing coupled ocean/atmospheric models, ENSO forecasts, and for understanding climate related variability (e.g., the monthly Atlantic surface pressure is a good indicator of extreme monthly air temperatures over Florida).

The flux project at FSU targets the data assimilation milestones within the Program Plan. Our assimilation efforts combine ocean surface data from multiple Ocean Observing System networks (e.g., VOS, moored and drifting buoys, and satellites). One set of performance measures targeted in the Program Plan is the **Air-Sea Exchange of Heat, Momentum, and Fresh Water**. These fluxes can be related to **Sea Surface Temperature** and **Ocean Heat Content**. Additional targets are **Ocean Transport** and **Thermohaline Circulation.** Surface winds (stress) contribute to upper ocean and deep ocean transport. The heat and moisture fluxes also contribution to the thermohaline circulation. **Ocean Carbon Uptake** is highly dependent on wind speed. We have recently worked with other members NOAA climate observing team to estimate the importance of using six hourly winds vs. monthly averaged winds on estimates of **Ocean Carbon Uptake**. The FSU flux project also focuses on the task of evaluating operational assimilation systems[10,11] (e.g., NCEP and ECMWF reanalyses) and continues to provide timely data products that are used for a wide range of ENSO forecast systems. The FSU fluxes support a broad user community. Our web data portal currently shows 169 registered users from 16 countries. Fifty-seven users are from academic institutions, 35 at governmental agencies, four from public/non-profit entities, and one from the military. Although we do not track the users applications, we know that many are using the FSU winds and fluxes to support tropical SST forecast models (e.g., LDEO model; http://rainbow.ldeo.columbia.edu/~dchen/forecast.html).

2. Scientific and Observing System Accomplishments

The tasks pertain to the continued development/production of products and the dissemination of scientific results. Results include a detailed comparison of nine freely available flux products, revealing many differing strengths as weaknesses. This has better enabled the PI to recommend flux products for specific applications.

Work Plan and Deliverables for FY 2010 include:

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[10] **Smith, S.**, P. Hughes, and **M. Bourassa**, 2010: A comparison of nine monthly air-sea flux products. *Internat. J. Climatol*., **30**, 26pp., DOI: 10.1002/joc.2225.

[11] **Bourassa, M**., 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, G. Wick, 2009: High-Latitude Ocean and Sea Ice Surface Fluxes: Requirements and Challenges for Climate Research. *Bull. Amer. Meteor. Soc*. (submitted).

1. Update Atlantic, Indian, and Pacific Oceans using new ICOADS releases (if available)
    - Subtask 1: Develop code for processing data from the new ICOADS format
2. Publish evaluation of practical applications of FSU3 fluxes
3. Develop quick look (near real time) monthly flux products
    - Subtask 1: Automate the data stream and processing for GTS data
    - Subtask 2: Simulate and test the quick look product for times that the science quality product is available. Tune quick look parameters to minimize the differences between the two versions.
4. Improve upon the capabilities of our satellite-based gridded flux product (proposed to NASA)
    - Subtask 1: Collaborate in testing of intercalibration of satellite retrievals of near surface atmospheric temperature and humidity
    - Subtask 2: revise moisture flux parameterization to account for biases identified by a current student, Josh Griffin
    - Subtask 3: Compare our new flux product to other flux products
5. Continue production of satellite and NWP hybrid wind fields for the Gulf of Mexico.
6. Continue updating the information on the tropical web page developed by Ryan Maue.

Progress on these deliverables specifically target the **program deliverables related to sea surface temperature, surface currents (via wind observations), and the air-sea exchanges of heat, momentum, and freshwater.** The DAC strives to make high-quality observations readily available to the research and operational marine climate community. Our FY2011 deliverables address the collection, quality evaluation, and distribution of surface marine observations to the community.

2.1 Update fluxes using new ICOADS release [deliverable 1]

Version 2.5 of ICOADS was released in mid-summer 2009. It uses a new format, the International Marine Meteorological Archive (IMMA), that required revisions to our data processing codes. These revisions were completed in FY2011, and we have processed wind and fluxes for the years 2005 through 2007. We also completed and extension of the wind fields for the Atlantic Ocean for the period 1968-1977.

2.2 Publish evaluation of practical applications of FSU3 fluxes [deliverable 2]

We found that piracy off the Somalia coast has severely altered the sampling from Volunteer Observing Ships[12]. The merchant marine traffic was moved further offshore to avoid pirates. Consequently, there are very few observations within 500km of the coast, which is an area that has several strong climate signals that are not well represented at the locations of current observations. Furthermore, the few observations that do occur within 500km of the shore are restricted to high wind conditions (poor conditions for the pirate's small boats) which are not representative of typical conditions. Piracy has severely impacted the climate record in this

[12] Smith, R.S., **M.A. Bourassa**, and M. Long, 2011: Pirate attacks affect Indian Ocean climate research. *Eos*, **92**, 225-226.

region. This research attracted a great deal of national and international attention (see outreach section).

A paper is in review. The subjects are the impact of sampling and averaging-related biases in the latent heat flux, and the consequences on biases in modeled sea surface temperature. Another paper (also in review) outlines the current state of high-latitude flux observations and modeling, and provides recommendations for improvements. A comparison of relative biases in existing flux products has also been published[1].

2.3 Develop quick look (near real time) monthly flux products [deliverable 3]

This goal has been deferred in favor of developing our satellite product (which is partially supported by NASA NEWS). We have almost completed the revised winds portion of this work (also supported by NASA OVWST). We can now assimilated data from scalar winds, vector winds, and pressures in a physically consistent manner. This technique also assimilated SST gradients, which helps produce realistic small scale variability (i.e., similar to what is seen where wind data are available) in the gaps between wind observations. In the case of storms, we have found that product to product differences in winds dominate the differences in fluxes when a common flux algorithm is applied to all products[13].

It is also worth noting that if NOAA follows through with its termination of the ICOADS program, there will be no improved science quality data for the flux products, nor near real time products based on a quick release of ICOADS data.

2.4 Continue production of satellite and NWP hybrid products [deliverables 4 and 5]

We ceased producing this product when the SeaWinds scatterometer on QuikSCAT ceased to function. We are involved in reprocessing of the QuikSCAT data, and intercalibration with new satellites. If the intercalibration of the new satellites reaches sufficiently high quality we will consider a new product. Currently the greater efforts are being made in intercalibration among Ku-band instruments and a separate effort is being made on C-band instruments. These efforts have resulted in much smaller differences between Ku and C-band instruments; however, a better intercalibration is needed before these data sets can be merged for high wind applications.

We also produced a very high resolution surface wind data set for several hurricanes in the region of the Gulf of Mexico. Collaborators at COAPS are using these data set to simulate storm surge associated with these hurricanes. These fields are available upon request.

For subtask 1, we have collaborated with groups at NOAA/PSD and FSU on the intercalibration of satellite retrievals of near surface humidity and temperature. Our collaborators retuned the calibrations, which were published that year (Bourassa et al., 2010). The key difference in both intercalibrations is a relative bias, which is small compared to modeling related errors in adjusting the in situ observations to a standard height of 10m (see subtask 2). We agreed to adjust the NOAA/PSD product to better match the FSU product. In the last year, our SAMOS data has been used to validate and improve the NOAA/PSD retrievals.

[13] Scott, J. P., 2011: An intercomparison of numerically modeled flux data and satellite-derived flux data for warm seclusions. M.S. Thesis, Florida State University, Tallahassee, FL 32306.

For subtask 2, have improved our technique for estimating the bias in the moisture flux (and hence height adjustment) models. In short, noise in one of the key observations is very large, and propagates through several non-linear equations to cause large random errors as well as a substantial bias due to propagation of random errors through several non-linear equations.

Subtask 3, comparison to other flux products has been deferred until our flux product is ready for comparison.

2.5 Continue updating the information on the tropical web page developed by Ryan Maue [deliverable 6]

The web pages of one of our Ph.D. students Ryan Maue, particularly the pages related to the tropical work mentioned above, receive hundreds of thousands of hits each year. On two occasions in previous year, these pages received over 100,000 hits in a day. These pages are highly readable and contain a great deal of easily digested information (e.g., Fig. 1) in comparison to other tropical pages. This kind of outreach is highly visible and has been noticed by the researchers and the general public. We maintained this page through most of the funding year. However, Dr. Maue has now moved the site to his own site.

We are in the process is developing new climate-related metrics related to fluxes and winds. The winds portion is also supported by NASA's Climate Data Record program. We will post these on our web site when they are sufficiently mature.

3. Outreach and Education

The principle investigators collaborated on an EOS article that described the impact of piracy in the northwest Indian Ocean on our ability to collect marine climate observations. An article[12] resulted in several media requests. Mr. Smith conducted and interview with Nature News which resulted in a secondary media piece (the Nature News article also included comments from our NOAA colleague Mike McPhaden regarding the impact on Indian Ocean moorings). Mr. Smith also conducted a phone interview with the German Public Broadcasting Network focused on piracy and climate research.

From spring 2010 through now we have worked with an undergraduate honors student interested in how cold air outbreaks modify the temperature of the Gulf Stream waters passing through the Florida Straight. We continue to train graduate students in flux related activities.

4. Publications and Reports

4.1 Refereed Manuscripts

Bourassa, M., S. Gille, C. Bitz, D. Carlson, I. Cerovecki, C. A. Clayson, M. Cronin, W. Drennan, C. Fairall, R. Hoffman, G. Magnusdottir, R. Pinker, I. Renfrew, M. Serreze, K. Speer, L. Talley, G. Wick, 2011: High-latitude ocean and sea ice surface fluxes: requirements and challenges for climate research. *Bull. Amer. Meteor. Soc*. (submitted).

DiNapoli, S. M., **M. A. Bourassa**, and M. D. Powell, 2011: Uncertainty and intercalibration analysis of H*Wind. *J. Atmos. Oceanic Technol*. (submitted).

Knapp K. R., S. Ansari, C. L. Bain, **M. A. Bourassa**, M. J. Dickinson, C. Funk, C. N. Helms, C. C. Hennon, C. D. Holmes, G. J. Huffman, J. P. Kossin, H.-T. Lee, A. Loew, and G. Magnusdottir, 2011: Globally gridded satellite (GridSat) observations for climate studies. *Bull. Amer. Meteor. Soc.* **92**, 893-907.

Liu, J., J. A. Curry, C. A. Clayson, and **M. A. Bourassa**, 2011: High-resolution satellite surface latent heat fluxes in North Atlantic hurricanes. *Mon. Wea. Rev*. **139**, 2735-2747.

Smith, S. R., 2011: Ten-year vision for marine climate research. *EOS, Trans Amer. Geophys. Union*, **92**(43), 376.

Smith, S.R., P.J. Hughes, and M. A. Bourassa, 2011: A comparison of nine monthly air-sea flux products. *Int. J. Climatology*, **31**, 1002-1027, doi: 10.1002/joc.2225.

Smith, R.S., **M.A. Bourassa**, and M. Long, 2011: Pirate attacks affect Indian Ocean climate research. *Eos*, **92**, 225-226.

4.2 Book Chapters

Katsaros, K. B., A. Bentamy, **M. Bourassa**, N. Ebuchi, J. Gower, W. T. Liu, and S. Vignudelli, 2011: Climate Data Issues from an Oceanographic Remote Sensing Perspective, Remote Sensing of the Changing Oceans, Springer-Verlag, Berlin, Germany, 7 – 32 pp, ISBN: 978-3-642-16540-5.

4.4 Conference Presentations

Bourassa, M. A., 2011: Scientific basis of climate change: role of observational and historical records. *Fellows Forum - Global Climate Change and North Florida: Facts, Perceptions, and Planning*, March, Tallahassee, Florida. (Invited)

Bourassa, M. A., 2011: Using CFOSAT to determine the role of swell in climate. Chinese-French Oceanographic Satellite (CFOSAT) Meeting. November, Brest, France (Invited)

Bourassa, M. A., and H. Holbach, 2011: OSCAT and IR-based early detection of tropical disturbances. Oceansat-2 International Announcement of Opportunity Science Meeting, March, Ahmedabad, India.

May, J. C., **M. A. Bourassa**, and **S. R. Smith**, 2011: Quantifying variance due to temporal and spatial difference between ship and satellite winds. Poster, *Third International Workshop on Advances in the Use of Historical Marine Climate Data (MARCDAT-III)*, Frascati, Italy, 2-6 May 2011.

Dukhovskoy, D., and **M. Bourassa**, 2011: Comparison of ocean surface wind products in the perspective of ocean modeling of the Nordic Sea. *MTS/IEEE OCEANS'2011*, Sept., Kona, Hawaii.

Dukhovskoy, D., **M. Bourassa** and P. Hughes, 2011: High-resolution satellite-derived ocean surface winds in the North Atlantic. *2011 International Ocean Vector Winds Science Team Meeting*, May, Annapolis, Maryland.

Scott, J. P., and **M. A. Bourassa**, 2011: Remotely sensed surface turbulent fluxes and validation with in situ observations. *Third International Workshop on Advances in the Use of Historical Marine Climate Data (MARCDAT-III)*, May, Frascati, Italy.