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Evaluating CFSR Air-Sea Heat, Freshwater, and Momentum Fluxes in the context of the Global Energy and Freshwater Budgets

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Progress report for 09/01/2013-08/31/2018 – Final Report

1. Overview

The primary objectives of the project are: (i) to identify the strengths and weaknesses of the CFSR surface flux components by comparison with in situ flux measurement, satellite-based analyses and other reanalyses products and understand the sources of biases; (ii) to investigate the effect of spatial resolution in improving the accuracy and spatial structure of CFSR fluxes on regional and global scales, and (iii) to investigate the use of physical constraints together with ocean state variables to diagnose and understand the uncertainties in CFSR air-sea fluxes.

This is the project summary report for the period from 09/01/2013 to 08/31/2018. During the period, we have carried out all the tasks outlined in the project's workplan and have accomplished all we set out to do. Major results and accomplishments are summarized below.

2. Results and Accomplishments

(1) Regional biases in tropical Pacific surface fluxes from atmospheric reanalysis

The Tropical Pacific mooring array has been a key component of the climate observing system since the early 1990s. However, if not used correctly, these air-sea measurements may a source of errors for numerical weather prediction models and surface flux estimates. In this study, we identified a pattern of strong near surface humidity anomalies, collocated with the array, in the widely used European Center for Medium Range Weather Forecasting Interim atmospheric reanalysis. The pattern generates large, previously unrecognized latent and net air□sea heat flux anomalies, up to 50 Wm^{-2} in the annual mean, in reanalysis derived data sets employed for climate studies and ocean model forcing. 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}. Furthermore, these results have major implications for the dual use of air□sea flux buoys as reference sites and sources of assimilation data. The study, entitled "Unexpected

Impacts of the Tropical Pacific Ocean Array on Atmospheric Reanalysis Surface Meteorology and Heat Fluxes", is published in Geophys. Res. Lett. (Josey et al. 2014).

(2) The global ocean water cycle in atmospheric reanalysis and observations.

This study provides an assessment of the uncertainty in ocean-surface freshwater budgets and variability using evaporation (E) and precipitation (P) from 10 atmospheric reanalyses, 2 combined satellite-based E-P products, and 2 observation-based salinity products. Three issues are examined: the uncertainty level in the surface freshwater budget in atmospheric reanalyses, the uncertainty structure and association with the global ocean wet/dry zones, and the potential of salinity in ascribing the uncertainty in E-P. The products agree on the global mean pattern but differ considerably in magnitude. The ocean-surface freshwater budgets are 129±10 (8%) cm yr-1 for E, 118±11 (9%) cm yr-1 for P, and 11±4 (36%) cm yr-1 for E-P, where the mean and error represent the ensemble mean and one standard deviation of the ensemble spread. The E-P uncertainty exceeds the uncertainty in E and P by a factor of four or more. The large uncertainty is attributed to P in the tropical wet zone. Most reanalyses tend to produce a wider tropical rain band when compared to satellite products, with the exception of two recent reanalyses that implement an observation-based correction for the model-generated P over land. The disparity in the width and the extent of seasonal migrations of the tropical wet zone causes large spread in P, implying that the tropical moist physics and the realism of tropical rainfall remain a key challenge. Satellite salinity appears feasible to evaluate the fidelity of E-P variability in three tropical areas, where the uncertainty diagnosis has a global indication. The research findings are presented in a paper, entitled "The global ocean water cycle in atmospheric reanalysis, satellite, and ocean salinity" and published in J. Climate (Yu et al. 2017).

(3) Surface energy balance in atmospheric reanalysis and its consistency with ocean heat storage

Surface fluxes from atmosphere reanalyses have large biases that vary both spatially and temporally, In situ measurements are limited, which challenge any attempt that tries to characterize the magnitude and scope of these biases. Throughout the course of the project, we have experimented the use of the energy conservation in enclosed regions and ocean observations to evaluate the physical consistency of the surface fluxes from atmospheric reanalyses. One experiment focused on the Mediterranean Sea, where the semienclosed basin is a constrained basin and the annual energy budgets into and out of the basin have been well observed. The hydrographic observations in the basin provide a strong physical constraint in evaluating the consistency of surface heat flux products. In this study, nine surface heat flux climatologies are analyzed. The ensemble mean estimation shows that the net downward shortwave radiation is balanced primarily by latent heat flux, followed by net longwave radiation and sensible heat flux. The resulting net heat budget (Qnet) is 2 ± 12 W m^{-2} into the ocean, which appears to be warm biased. The annual-mean Qnet should be -5.6 ± 1.6 W m^{-2} when estimated from the observed net transport through the Strait of Gibraltar. To diagnose the uncertainty in nine Qnet climatologies, we constructed Qnet from the heat budget equation by using historic hydrological observations to determine the heat content changes and advective heat flux. We also used the Qnet from a data-assimilated global ocean state estimation as an additional reference. By comparing with the two reference Qnet estimates, we found that seven products (NCEP 1, NCEP 2, CFSR, ERA-Interim, MERRA, NOCSv2.0, and OAFlux1ISCCP) overestimate Qnet, with magnitude ranging from 6 to 27 W m^{-2}, while two products underestimate Qnet by –6 W m^{-2} (JRA55) and –14 W m^{-2} (CORE.2). Together with the previous warm pool work of Song and Yu (2013), we show that CFSR, MERRA, NOCSv2.0, and OAFlux1ISCCP are warm-biased not only in the western Pacific warm pool but also in the Mediterranean Sea, while CORE.2 is cold-biased in both regions. The NCEP 1, 2, and ERA-Interim are cold-biased over the warm pool but warm-biased in the Mediterranean Sea. The study, entitled "Air-Sea heat flux climatologies in the Mediterranean Sea: Surface energy balance and its consistency with ocean heat storage", is published in J. Geophys. Res. Oceans (Song and Yu 2017).

(4) Evaluation of atmospheric reanalysis flux products using ocean models

We have pursued the use of ocean models to evaluate the uncertainty in atmospheric reanalysis flux products. We have two publications on this research topic. The first study was an assessment the global net air-sea heat flux, Q_{net}, from atmospheric reanalysis (ERA-Interim and NCEP1), satellite products (OAFlux and CERES) using the ocean data assimilation mdoel from the Estimating the Circulation & Climate of the Ocean (ECCO) project. For the 10-year "hiatus" period (2001-2010), all products agree on an overall net heat gain over the global ice-free ocean, but the magnitude varies from 1.7 to 9.5 Wm^{-2}. The differences among products are particularly large in the Southern Ocean, where they cannot even agree on whether the region gains or loses heat on the annual mean basis. Decadal trends of Q_{net} differ significantly between products. ECCO and OAFlux/CERES show almost no trend, whereas ERA-Interim suggests a downward trend and NCEP1 shows an upward trend. Therefore, numerical simulations utilizing different surface flux forcing products will likely produce diverged trends of the ocean heat content during this period. The downward trend in ERA-Interim started from 2006, driven by a peculiar pattern change in the tropical regions. ECCO, which used ERA-Interim as initial surface forcings and is constrained by ocean dynamics and ocean observations, corrected the pattern. Among the four products, ECCO and OAFlux/CERES show great similarities in the examined spatial and temporal patterns. Given that the two estimates were obtained using different approaches and based on largely independent observations, these similarities are encouraging and instructive. It is more likely that the global net air-sea heat flux does not change much during the "hiatus" period. The study, entitled "Variations of the global net air-sea heat flux during the "hiatus" period (2001-2010)", is published in J. Climate (Liang and Yu 2016).

The second study was to examine the fidelity of NCEP/DOE reanalysis (NCEP 2) and Climate Forecast System Reanalysis (CFSR) surface fluxes when used as forcing to drive ocean models. In particular, we identify two large discrepancies in these two products, including (1) stronger trade winds in CFSR than in R2 over the tropical Pacific prior 2000; (2) excessive net heat fluxes input into ocean in CFSR than in R2 with an increase in difference after 2000. We designed experiments to examine the sensitivity of ocean simulations to discrepancies between CFSR and NCEP 2 surface fluxes, and to assess the fidelity of the two products. A set of experiments, where an ocean model was driven by a combination of surface flux component from NCEP 2 and CFSR, were carried out. The model simulations were contrasted to identify sensitivity to different component of the surface fluxes in NCEP 2 and CFSR. The accuracy of the model simulations was validated against the tropical moorings data, altimetry SSH and SST reanalysis products. Sensitivity of ocean simulations showed that temperature bias difference in the upper 100m is mostly sensitive to the differences in surface heat fluxes, while D20 bias difference is mainly determined by the discrepancies in momentum fluxes. D20 simulations with CFSR winds agree with observation well in the western equatorial Pacific prior 2000, but have similar large negative bias with those with NCEP 2 winds after 2000, because easterly winds over the central Pacific were underestimated in both CFSR and NCEP 2. On the other hand, the observed temperature variability is well reproduced in the Pacific by simulations with both NCEP 2 and CFSR fluxes. The findings are presented in a paper, entitled "How do uncertainties in NCEP R2 and CFSR surface fluxes impact tropical ocean simulations?" and published in Climate Dynamics (Wen et al. 2017).

(5) Air-sea interaction regimes in the sub-Antarctic southern ocean and Antarctic marginal ice zone

We obtained shipboard air-sea measurements from the icebreaker *Aurora Australis* that traversed the water between Hobart, Tasmania and the Antarctic continent during off-winter (October – April) seasons. A total of 22 ship tracks for the period of December 2010 – May 2012 were analyzed. These measurements provide valuable in situ insight into two dynamically important, yet poorly sampled, regimes: the sub-Antarctic Southern Ocean and the Antarctic marginal ice zone (MIZ) in the Indian Ocean sector.

Part 1 of the study focused on (i) obtaining the estimates of the air-sea fluxes using shipboard measurements of surface meteorology and (ii) understanding the differences in air-sea interaction between the open water and the MIZ. The transition from the open water in the sub-Antarctic to the ice-covered surface in the MIZ creates sharp changes in albedo, surface roughness, and air temperature, leading to consequential effects on air-sea variables and fluxes. We successfully implemented flux algorithms that are tuned for the sea-ice effects in the MIZ, while computed the fluxes over the sub-Antarctic section using the COARE3.0 algorithm. The study found strong sea-ice modulations on winds, with the southerly airflow showing deceleration (convergence) in the MIZ and acceleration (divergence) when moving away from the MIZ. Marked seasonal variations in heat exchanges between the atmosphere and the ice margin were noted. The monotonic increase in turbulent latent and sensible heat fluxes after summer turned the MIZ quickly into a heat loss regime, while at the same time the sub-Antarctic surface water continued to receive heat from the atmosphere. The drastic increase in turbulent heat loss in the MIZ contrasted sharply to the non-significant and seasonally invariant turbulent heat loss over the sub-Antarctic open water. The results were published in *J. Geophys. Res. Oceans,* entitled "Air-sea interaction regimes in the sub-Antarctic southern ocean and Antarctic marginal ice zone revealed by icebreaker measurements" (Yu et al. 2017).

Part 2 of the study is to make use of the findings from Part 1 to examine the representation of surface heat fluxes from four atmospheric reanalyses in the sub-Antarctic Southern Ocean (58-42°S) and the eastern Antarctic MIZ (68-58°S). Four reanalyses (CFSR, ERA-interim, JRA55, MERRA2) are analyzed, which all show a high-level agreement among themselves. However, our results show that the agreement does not mean that reanalyzed fluxes are converged to a "truth"; rather it reveals a consistent bias when compared to ship-based fluxes. The net solar heating (SW) and longwave radiative cooling (LW) are overestimated in reanalyses. In the MIZ, the two biases are able to cancel out each other, leaving the total surface heat budget (Qnet) to be dictated by the underestimation bias in sensible heat loss (SH). The reanalyzed Qnet is warm biased by 10 - 36 Wm^{-2} (depending on the product), about 80-220% of the ship-based Qnet value. Over the sub-Antarctic open water, the LW bias is too large to be offset and it affects the Qnet estimate. The reanalyzed Qnet is cold biased in the open ocean by 6 – 20 Wm^{-2}, accounting for 7 – 25% of the ship-based Qnet value. Overall, the LW bias is the leading source of bias in the reanalyzed surface heat budget in the sub-Antarctic. In the MIZ, the SH bias is predominant as the result of the bias compensation between SW and LW. The findings are presented in a manuscript, entitled "Surface Heat Budget in the Southern Ocean from 42°S to the Antarctic Marginal Ice Zone: Four Atmospheric Reanalyses versus Icebreaker Aurora Measurements" by Yu et al. (2018). It is currently under review in the journal of *Polar Research*.

(6) "Global Air-Sea Fluxes of Heat, Freshwater, and Momentum: Energy Budget Closure and Unanswered Questions" by Yu, 2018. Invited review article in Annual Review of Marine Science.

This study is a culmination of the 5-year project research combined with the PI's decade long experience in developing satellite based air-sea flux products. The air-sea fluxes are important venue for the ocean to interact with the atmosphere. These fluxes constitute the ocean-surface energy and water budgets and define the ocean's role in the Earth's climate and its variability on both short and long time scales. Because direct flux measurements are available only at limited locations, air-sea fluxes are commonly estimated from bulk flux parameterization using flux-related near-surface meteorological variables (i.e., winds, sea and air temperatures, humidity) that are available from buoys, ships, satellite remote sensing, numerical weather prediction models, and/or a combination of any of these sources. Uncertainties in parameterization-based flux estimates are large, which, when integrated over the ocean basins, cause large imbalance in the global-ocean budgets. Despite many processes that have been made in quantifying surface fluxes in past 30 years, achieving a global closure of ocean-surface energy and water budgets remains a challenge for flux products constructed from all data sources. This review provides a personal perspective on three questions: First, to what extent can time-series measurements from air–sea buoys be used as benchmarks for accuracy and reliability in the context of the budget closures? Second, what is the dominant source of uncertainties for surface flux products, the flux-related variables or bulk flux algorithms? And third, given the coupling between the energy and water cycles, precipitation and surface radiation can act as twin budget constraints. Are the community-standard precipitation and surface radiation products pairwise compatible?

3. Refereed Journal Publications

Josey S. A., L. Yu, S. Gulev, X. Jin, N. Tilinina, B. Barnier, L. Brodeau, 2014: Unexpected Impacts of the Tropical Pacific Ocean Array on Atmospheric Reanalysis Surface Meteorology and Heat Fluxes. *Geophys. Res. Lett., **41**, 6213-6220, doi:10.1002/2014GL061302.*

Yu, L., X. Jin, P. W. Stackhouse, A. C. Wilber, S. A. Josey, Y. Xue, and A. Kumar, 2015: Ocean surface heat and momentum fluxes. In "State of the Climate in 2014". *Bull. Amer. Meteor. Soc.*, **96**(7), S68-S71. Issue published online: July 16, 2015

Liang, X., and L. Yu, 2016: Variations of the global net air-sea heat flux during the "hiatus" period (2001-2010). *J. Climate.* 29, 3647–3660, doi: http://dx.doi.org/10.1175/JCLI-D-15-0626.1.

Yu, L., X. Jin, S.A. Josey, T. Lee, A. Kumar, C. Wen, and X. Yan, 2017: The global ocean water cycle in atmospheric reanalysis, satellite, and ocean salinity. *J. Climate*, **30**, 3829–3852, http://dx.doi.org/10.1175/JCLI-D-16-0479.1.

Wen, C., Y. Xue, A. Kumar, D. Behringer, and L. Yu, 2017: How do uncertainties in NCEP R2 and CFSR surface fluxes impact tropical ocean simulations? *Climate Dynamics*, 49(9), 3327-3344. doi:10.1007/s00382-016-3516-6.

Song, X. and Yu, L. 2017: Air-Sea heat flux climatologies in the Mediterranean Sea: Surface energy balance and its consistency with ocean heat storage. Special issue on "Dense water formations in the North Western Mediterranean: from the physical forcings to the biogeochemical consequences", *J. Geophys. Res. Oceans,* 112, doi: 10.1002/2016JC012254.

Yu, L., X. Jin, E. Schulz, and S. A. Josey, 2017: Air-sea interaction regimes in the sub-Antarctic southern ocean and Antarctic marginal ice zone revealed by icebreaker measurements. *J. Geophys. Res. Oceans.* 122, doi:10.1002/2016JC012281.

Yu, L. 2018: Global Air-Sea Fluxes of Heat, Freshwater, and Momentum: Energy Budget Closure and Unanswered Questions. *Annual Review of Marine Science.* https://doi.org/10.1146/annurev-marine-010816-060704.

Yu, L., X. Jin, and E. Schulz, 2018: Surface Heat Budget in the Southern Ocean from 42°S to the Antarctic Marginal Ice Zone: Four Atmospheric Reanalyses versus Icebreaker Aurora Measurements. *Polar Research*. Under review.

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