OBJECTIVELY DERIVED IN SITU TURBULENT FLUX CLIMATOLOGY: APPLICATION TO SEA SURFACE TEMPERATURE VARIABILITY

Paul J. Hughes [(1)], Mark A. Bourassa [(2)], Jeremy Rolph [(3)], Shawn R. Smith[(4)]

[(1)] Center for Ocean-Atmosphere Prediction Studies, and Department of Meteorology, Florida State University, Tallahassee, FL 32306-2840 USA, phughes@met.fsu.edu
[(2)] Center for Ocean-Atmosphere Prediction Studies, and Department of Meteorology, Florida State University, Tallahassee, FL 32306-2840 USA, bourassa@coaps.fsu.edu
[(3)] Center for Ocean-Atmosphere Prediction Studies, Florida State University, Tallahassee, FL 32306-2840 USA, rolph@coaps.fsu.edu
[(4)] Center for Ocean-Atmosphere Prediction Studies, Florida State University, Tallahassee, FL 32306-2840 USA, smith@coaps.fsu.edu

ABSTRACT

This study highlights the third generation Florida State University (FSU3) monthly mean gridded wind and surface flux product and examines the consequences of formulating the monthly mean via the “classical” time-averaging method. The classical monthly mean flux is obtained by applying the bulk flux aerodynamic formulas to the monthly averaged meteorological variables. This approach implicitly neglects the effects of variability on time scales shorter than the averaging period. The error in the FSU3 monthly mean latent heat flux estimate due to applying the classical method is estimated using six-hourly ECMWF data for the period 1978 through 2001. The largest errors were found in the midlatitudes during the winter where differences can exceed 90 W m^{-2}. In the tropics the bias is substantially smaller (< 10 W m^{-2}), but can still be physically significant. Improperly accounting for the submonthly effects on the monthly mean latent and sensible heat flux estimates can cause aliasing into lower frequencies and adversely impact the results of mixed layer heat balance and temperature variability studies. The inherent bias, based on the ECMWF data, is robust; thus, the opportunity exists to estimate the covariance terms and apply a correction to the FSU3 fluxes.

1. INTRODUCTION

Accurate knowledge of air-sea fluxes on a wide range of spatiotemporal scales is vital to improving our understanding of the Earth’s coupled climate system. The exchange of heat, moisture, momentum, gases, and particulate matter across the air-sea interface plays a major role in directing both regional and global climate variability. Direct air-sea flux measurements, however, are spatially and temporally sparse and thus woefully inadequate for climate variability studies. Consequently, air-sea fluxes of latent heat, sensible heat, and momentum are frequently estimated by applying the bulk formulas to ship and buoy (moored and drifting) data. In situ based turbulent flux climatologies are limited by uncertainties inherent in the observations, parameterizations, and the methodology used to derive the flux fields [1,2].

This study highlights the third generation Florida State University (FSU3) monthly mean 1°x1° gridded wind and surface flux product (section 2) and examines the consequences of formulating the monthly mean via the “classical” time-averaging method [3-9]. The classical monthly mean flux estimate is obtained by applying the bulk flux aerodynamic formulas to the monthly averaged meteorological variables. This method does not require simultaneous observations of the meteorological variables needed to calculate the fluxes, allowing more data to be utilized, but implicitly neglects the effects of variability on time scales shorter than the averaging period. The inherent bias in the FSU3 monthly latent heat flux associated with applying the classical method is estimated using six-hourly ECMWF data (section 3). The results show that the largest estimated errors in the monthly mean latent heat flux occurs in the midlatitudes (especially over the western boundary currents); however, the impacts in the tropics are not negligible. The physical implications on ocean mixed layer temperature are examined in section 4. The findings are summarized in section 5.

2. FSU3 WIND AND SURFACE FLUX PRODUCT

2.1. Data and methodology

The FSU3 product is objectively constructed from in situ ship and buoy observations obtained from release 2.2 of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) [10,11] and the National Meteorological Center’s (NMC) blended sea surface temperature analysis (referred to as Reynolds SSTs hereafter) [12]. Reynolds SSTs are used due to the fact that bias corrections for ship based SSTs are not well understood and vary greatly on a ship to ship basis. The gridded fields are derived via a variational method where a cost function based on weighted constraints is minimized using a conjugate-gradient minimization scheme [13]. The constraints help to maximize the similarity of the solution fields to the observations and minimize unrealistic spatial features [14,15]. The resulting fields are available for the Atlantic, Pacific, and Indian oceans from 1978 through 2004 and include: wind stress, latent heat flux, sensible heat flux, pseudostress, wind speed, air temperature, and specific humidity.

2.2. Flux calculations

The wind stress (τ), sensible heat flux (H), and latent heat flux (E) are estimated via the bulk aerodynamic formulas

$$\boldsymbol{\tau} = \rho C_D \boldsymbol{\Psi}, \tag{1}$$

$$H = \rho c_p C_H \left(SST - AT \right) w, \tag{2}$$

$$E = \rho L_v C_E \left(q_{sfc} - q \right) w, \tag{3}$$

where ρ is the density of moist air, c_p is the specific heat of air, L_v is the latent heat of vaporization, C_D is the drag coefficient, C_H is the heat transfer coefficient, and C_E is the moisture transfer coefficient. The transfer coefficients are adapted from [16]. The variables w, AT, and q are the scalar wind speed, temperature, and specific humidity of the air at a height of 10 m. The variables SST and q_{sfc} are the sea surface temperature (Reynolds SSTs) and 98% of the saturation specific humidity corresponding to the SST. The variable Ψ is the vector pseudostress. The zonal (Ψ_x) and meridional (Ψ_y) components of the pseudostress are defined as:

$$\Psi_x = uw, \tag{4}$$

$$\Psi_y = vw, \tag{5}$$

where u and v represent the zonal and meridional components of the wind vector. The bulk flux formulas (Eqs. 1-3) are applied to the monthly averaged meteorological variables. Formulating the monthly mean flux in this manner implicitly excludes the effects of the covariance between the bulk flux variables. This can be seen by decomposing the variables on the right hand side of Eq. 3 into mean and time varying perturbation components:

$$\bar{E} = \bar{\rho} L_v \left(\begin{array}{l} \bar{C}_E \bar{w}\left(\bar{q}_{sfc} - \bar{q}\right) - \bar{C}_E \overline{w'\left(q'_{sfc} - q'\right)} - \\ \bar{w}\overline{C'_E\left(q'_{sfc} - q'\right)} + \overline{C'_E w'}\left(\bar{q}_{sfc} - \bar{q}\right) - \\ \overline{C'_E w'\left(q'_{sfc} - q'\right)} \end{array} \right) \tag{6}$$

In deriving Eq. 6, it is assumed that the average of the perturbation is zero, L_v is approximately constant, and the perturbation in density is negligible. If the latent heat flux is computed using monthly averaged variables then only the first term on the right hand side of Eq. 6 is retained, making it equal to Eq. 3: the classical approach. The influence of the covariance terms (i.e., submonthly variability) is an error in this approach.

3. SUBMONTHLY VARIABILITY

The error in the FSU3 monthly latent heat flux estimate due to neglecting the covariance terms is estimated using six-hourly ECMWF data for the period 1978 through 2001. The monthly mean latent heat flux is calculated by both averaging over individual six-hour estimates for a given month (sampling method; Eq. 6) and using monthly averaged meteorological data (classical method, Eq. 3). The difference between the two monthly mean estimates is taken to be the bias in the FSU3 latent heat fluxes (Fig. 1). Generally, the classical method is found to underestimate the sampling mean values. In the tropics, this bias is usually less than 10 W m^{-2}, which can still be physically substantial compared to the 5 W m^{-2} desired accuracy specified from TOGA-COARE [17, 18]. In the midlatitudes, the bias can be substantially larger, especially over the western boundary currents during the winter where values can exceed 100 W m^{-2}.

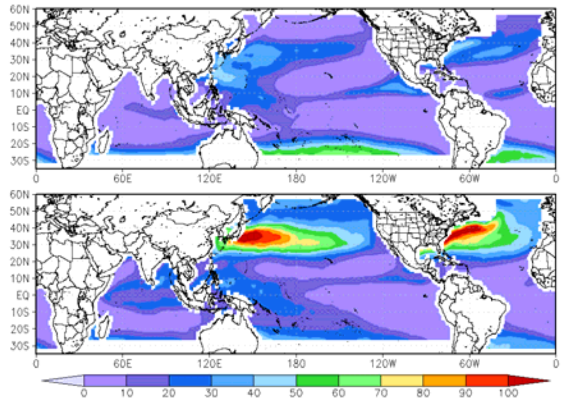

Figure 1. Estimated monthly bias (W m^{-2}) in the FSU3 latent heat fluxes for August (top) and November (bottom) due to implementing the classical time-averaging method. Error calculated by subtracting ECMWF classical mean from the sampling mean.

4. IMPLICATIONS ON MIXED LAYER TEMPERATURE

A simple one-dimensional mixed layer ocean model is used to examine the effects of omitting the covariance terms in Eq. 6 on the mixed layer temperature tendency. The change in temperature is determined by

$$\frac{\partial T}{\partial t} = \frac{\left(Q_{sfc} + Q_{pen}\right)}{\rho_w C_p h}, \tag{7}$$

where ρ_w is the density of seawater, C_p is the heat capacity, and h is the climatological mixed layer depth [19]. The effects of horizontal temperature advection, turbulent mixing, and entrainment from below the mixed layer on the mixed layer temperature are neglected, so the temperature change is solely forced by the net surface heat flux:

$$Q_{sfc} = Q_{sw} - Q_{lw} - E - H \; . \qquad (8)$$

Here Q_{sw} and Q_{lw} are the net shortwave and longwave radiation respectively [20]. Q_{pen} is the amount of shortwave radiation that penetrates through the mixed layer [21-23] and is represented by

$$Q_{pen} = -0.47 Q_{sw} \exp\left(-\gamma h\right). \qquad (9)$$

If the covariance terms in (6) are considered, then the mixed layer temperature change is estimated using

$$\frac{\partial T_{adjust}}{\partial t} = \frac{\left(Q_{sfc\_adjust} - Q_{pen}\right)}{\rho C_p h}, \qquad (10)$$

where Q_{sfc_adjust} is defined by

$$Q_{sfc\_adjust} = Q_{sw} - Q_{lw} - E_{adjust} - H \; . \qquad (11)$$

Here E_{adjust} represents the bias corrected latent heat flux and is computed by adding the estimated climatological bias (Fig. 1) to the FSU3 latent heat flux. The bias correction was positive in all cases, resulting in a greater amount of heat being removed from the ocean. Computing the difference between Eq. 7 and Eq. 10 reveals the impact of neglecting the submonthly variability when computing the latent heat flux on the change in mixed layer temperature. Differences of greater than 0.4 °C month^{-1} consistently occur in the midlatitudes and western boundary current regions; however, the greatest differences in these regions occur during the summer months when the bias correction is a minimum (Fig. 2). The amplified response of the mixed layer depth temperature to the bias corrected latent heat flux is likely due to the fact that the mixed layer depth is shallower during the summer months and requires a smaller amount of energy to change the temperature. In addition, a greater amount of solar radiation penetrates through the base of the mixed layer and is lost for heating.

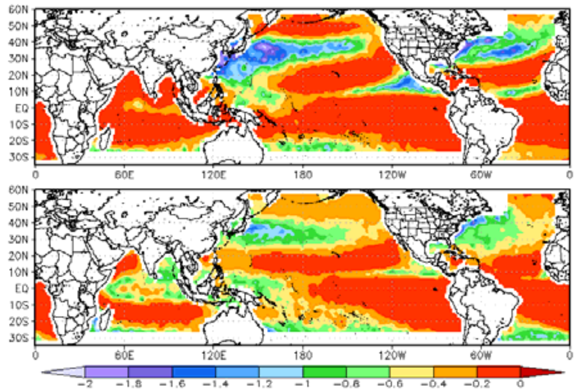

Figure 2. Monthly mean difference (1984-2003) in mixed layer temperature tendency (°C month^{-1}) for August (top) and November (bottom). Difference is calculated by subtracting the temperature tendency forced with the FSU3 latent heat flux (E) from the temperature tendency forced with the bias corrected latent heat (E_{adjust}).

5. SUMMARY AND DISCUSSION

The results suggest that the FSU3 monthly mean fluxes (at least for the latent heat) contain errors associated with the implementation of the classical method and implicitly neglecting the effects of submonthly variability. The inherent bias is most prominent in the midlatitudes (especially over the warm western boundary currents) during the winter where a tremendous amount of heat can be removed from the ocean through the latent and sensible heat fluxes associated with transient cyclones. Improperly accounting for the submonthly (e.g., synoptic scale) effects on the monthly mean latent and sensible heat flux estimates can cause aliasing into lower frequencies. This aliasing can adversely impact the results of mixed layer heat balance and temperature variability studies. Based on the ECMWF data, the inherent bias is robust; thus, the opportunity exists to estimate the covariance terms and apply a correction to the FSU3 fluxes.

Employing the sampling method, which implicitly includes the effects of the covariance between the bulk flux variables, would improve the accuracy of the flux estimates in regions that are relatively well sampled (e.g., moored buoy arrays and major shipping lanes). However, even in these regions a large portion of the total submonthly variability can be missed. In situ based flux climatologies can be improved through more detailed meta data and bias corrections; however, over vast regions the overall accuracy is limited by the inadequate sampling of synoptic variability. In order to overcome this inherent deficiency additional data sources (e.g., satellites) need to be utilized.

6. REFERENCES

1. Gulev, S., Jung, T., & Ruprecht, E. (2007). Estimation of the Impact of Sampling Errors in the VOS Observations on Air-sea Fluxes. Part I: Uncertainties in Climate Means. *J. Climate* **20**, 279-301.

2. Thomas, B.R., Kent, E.C., Swail, V.R., & Berry, D.I. (2008). Trends in Ship Wind Speeds Adjusted for Observation Method and Height. *Int. J. Climatology* **28**, 747-763.

3. Esbensen, S.K. & Reynolds, R.W. (1981). Estimating Monthly Averaged Air-sea Transfers of Heat and Momentum Using the Bulk Aerodynamic Method. *J. Phys. Oceanogr.* **11**, 457-465.

4. Simmonds, I. & Dix, M. (1989). The Use of Mean Atmospheric Parameters in the Calculation of Modeled Mean Surface Heat Fluxes Over the World's Oceans. *J. Phys. Oceanogr*. **19**, 205-215.

5. Gulev, S.K. (1994). Influence of Space-time Averaging on the Ocean-atmosphere Exchange Estimates in the North Atlantic Midlatitudes. *J. Phys. Oceanogr.* **24**, 1236-1255.

6. Josey, S.A., Kent, E.C., & Taylor, P.K. (1995). Seasonal Variations Between Sampling and Classical Mean Turbulent Heat Flux Estimates in the Eastern North Atlantic. *Ann. Geophysicae* **13**, 1054-1064.

7. Zhang, G.J. (1995). Use of Monthly Mean Data to Compute Surface Turbulent Fluxes in the Tropical Pacific. *J. Climate* **8**, 3084-3090.

8. Esbensen, S.K. & McPhaden, M.J. (1996). Enhancement of Tropical Ocean Evaporation and Sensible Heat Flux by Atmospheric Mesoscale Systems. *J. Climate* **9**, 2307-2325.

9. Gulev, S.K. (1997). Climatologically Significant Effects of Space-time Averaging in the North Atlantic Sea-air Heat Flux Fields. *J. Climate* **10**, 2743-2763.

10. Woodruff, S.D., Slutz, R.J., Jenne, R.L., & Steurer, P.M. (1987). A Comprehensive Ocean-atmosphere Data Set. *Bull. Amer. Meteor. Soc.* **68**, 1239-1250.

11, Worley, S.J., Woodruff, S.D., Reynolds, R.W., Lubker, S.J., & Lott, N. (2005). ICOADS release 2.1 Data and Products. *Int. J. Climatol.* **25**, 823-842.

12. Reynolds, R.W. (1988). A Real-time Global Sea Surface Temperature Analysis. *J. Climate* **1**, 75-86.

13. Shanno, D.F. & Phua, K.H. (1980). Remark on Algorithm 500-A Variable Method Subroutine for Unconstrained Nonlinear Minimization. *ACM Trans. Math. Software* **6**, 618-622.

14. Pegion, P.J., Bourassa, M.A., Legler, D.M., & O'Brien, J.J. (2000). Objectively Derived Daily "Winds" from Satellite Scatterometer Data. *Mon. Wea. Rev.* **128**, 3150-3168.

15. Bourassa, M.A., Romero, A.R., Smith, S.R., & O'Brien, J.J. (2005). A New FSU Winds Climatology. *J. Climate* **18**, 3686-3698.

16. Bourassa, M.A. (2006). Satellite-based Observations of Surface Turbulent Stress During Severe Weather. *Atmosphere-ocean Interactions* **2**, W. Perrie, Wessex Institute of Technology, 35-52.

17. Webster, P.J. & Lukas, R. (1992). TOGA COARE: The Coupled Ocean-atmosphere Response Experiment. *Bull. Amer. Meteor. Soc.* **73**, 1377-1416.

18. Weller, R.A., Bradley, F., & Lukas, R. (2004). The Interface or Air-sea Flux Component of the TOGA Coupled Ocean-atmosphere Response Experiment and its Impact on Subsequent Air-sea Interaction Studies. *J. Atmos. Oceanic Technol.* **21**, 223-257.

19. de Boyer Montegut, C., Madec, G., Fischer, A.S., Lazar, A., & Iudicone, D. (2004). Mixed Layer Depth Over the Global Ocean: An Examination of Profile Data and a Profile-based Climatology. *J. Geophys. Res.* **109**, C12003, doi:10.1029/2004JC002378.

20. Zhang, Y., Rossow, W.B., Lacis, A.A., Oinas, V., & Mishchenko, M.I. (2004). Calculation of Radiative Fluxes from the Surface to Top of Atmosphere Based on ISCCP and Other Global Data Sets: Refinements of the Radiative Transfer Model and the Input data. *J. Geophys. Res.* **109**, D19105, doi:10.1029/2003JD004457.

21. Ohlmann, J.C., Siegel, D.A., & Gautier, C. (1996). Ocean Mixed Layer Radiant Heating and Solar Penetration: A Global Analysis. *J. Climate* **9**, 2265-2280.

22. Wang, W. & McPhaden, M.J. (1999). The Surface-layer Heat Balance in the Equatorial Pacific Ocean. Part I: Mean Seasonal Cycle. *J. Phys. Oceanogr.* **29**, 1812-1831.

23. Foltz, G.R. & McPhaden, M.J. (2006). The role of Oceanic Heat Advection in the Evolution of Tropical North and South Atlantic SST Anomalies. *J. Climate* **19**, 6122-6138.