JP3.1 THE AIR-SEA MOISTURE TRANSFER COEFFICIENT FOR WIND SPEED FROM 0 TO 20 MS^{-1}

C. W. Fairall [*], J. E. Hare, and A. A. Grachev
NOAA Environmental Technology Laboratory (ETL)
Boulder, CO

E. F. Bradley
CSIRO Land and Water
Canberra, Australia

J. B. Edson
Woods Hole Oceanographic Insitution
Woods Hole, MA

1. INTRODUCTION

The world's oceans are the dominant source of moisture in the global hydrological cycle. Simplified representations of oceanic evaporation (referred to as *bulk parameterizations*) are used with near-surface meteorological data, numerical models, and satellite data for estimating air-sea moisture transfer, oceanic heat budgets, or to constrain models. In this paper we describe an analysis of the moisture transfer coefficient with a large data base of direct measurements made over the ocean. These new results are based on both previously published field results and 2777 one-hour covariance and inertial-dissipation moisture flux measurements in the ETL inventory plus 4439 new values from field experiments between 1997 and 1999. The results are incorporated into a state-of-the-art in bulk models of evaporation in the form of a new version (3.0) of the COARE algorithm. The COARE algorithm uses a combination of physically-based submodels of interfacial processes to relate the evaporation to bulk parameters. The average (mean and median) model results agreed with the measurements to within about 5% for moisture from 0 to 20 ms^{-1}. In the paper we will discuss some measurement issues, how these results compare with classic results from other field programs and models, and prospects for extending well beyond 20 ms^{-1}.

2. BACKGROUND

Bulk algorithms to estimate surface fluxes are widely used in numerical models and in applications (e.g., satellite retrievals) where highly detailed local information is not available. These are based upon Monin - Obukhov similarity (MOS) representations of the fluxes in terms of mean quantities (Smith et al. 1996)

$$\overline{w'x'} = c_x^{1/2} c_d^{1/2} S \Delta X = C_x S \Delta X \ , \qquad (1)$$

where x can be the u, v wind components, the potential temperature, θ, the water vapor mixing ratio, q, or some atmospheric trace species mixing ratio. Here c_x is the bulk transfer coefficient for the variable x (the d being used for wind speed) and C_x is the total transfer coefficient. ΔX is the sea-air difference in the mean value of x and S is the mean wind speed which is composed of a mean vector part (U and V components) and a gustiness part (U_g) to account for subgridscale variability

$$\Delta X = X_s - X(z) \ ; \ S = (U^2 + V^2 + U_g^2)^{1/2} \ . \qquad (2)$$

The transfer coefficients have a dependence on surface stability prescribed by MOS

$$c_x^{1/2}(\xi) = c_{xn}^{1/2} / [1 - \frac{c_{xn}^{1/2}}{\kappa} \psi_x(\xi)] \ ; \ c_{xn}^{1/2} = \frac{\kappa}{\ln(z/z_{ox})} \ , \qquad (3)$$

where ξ is the MOS stability parameter, the subscript n refers to neutral (ξ = 0) stability, z is the height of measurement of the mean quantity [$X(z)$], ψ an empirical function describing the stability dependence of the mean profile, κ is von Karman's constant, and z_{ox} parameter called the roughness length that characterizes the neutral transfer properties of the surface for the quantity, x. The MOS stability parameter is given by

$$\xi = - \frac{\kappa g z}{T} \frac{(\overline{w'\theta'} + 0.61 T \overline{w'q'})}{(-\overline{w'u'})^{3/2}} \ . \qquad (4)$$

The essence of the bulk model is contained in (1), (2), and (4) plus the representations (parameterizations) of the roughness lengths (or, equivalently the transfer coefficients) and the stability functions (ψ_x). While there are many algorithms available today and these will be considered in this work, for purposes of brevity we will restrict our comments in this paper to the TOGA COARE bulk algorithm (Fairall et al. 1996a). The velocity roughness length is specified via a Charnock plus a smooth flow limit

$$z_o = \frac{\alpha u_*^2}{g} + \frac{0.11 \nu}{u_*} \ , \qquad (5)$$

---

[*] *Corresponding author address*: C. W. Fairall, NOAA/ETL, 325 Broadway, Boulder, CO 80305-3328; e-mail: Chris.Fairall@noaa.gov

Table 1. Summary of ETL air-sea flux and bulk meteorological data cruises used in the analysis.

Cruise Name	Dates	Hours	Vessel	Latitude	Longitude
TIWE	11/21-12/13/91	460	Moana Wave	0	140 W
ASTEX	6/06-6/28/92	390	M. Baldrige	30 N	25 W
COARE-1	11/11/-12/03/92	589	Moana Wave	2S	156 E
COARE-2	12/17/-1/11/93	648	Moana Wave	2S	156 E
COARE-3	1/28/-2/16/93	385	Moana Wave	2S	156 E
SCOPE	9/17/-9/28/93	305	FLIP	33 N	118 W
FASTEX	12/23-1/24/97	730	Ron Brown	45 N	10-60 W
JASMINE	5/5-5/31/99	654	Ron Brown	8 N	89 E
Nauru99	6/15-7/18/99	794	Ron Brown	0.5 S	167 E
KWAJEX	7/28-9/12/99	875	Ron Brown	8 N	167.5 E
Moorings	9/14-10/21/99	746	Ron Brown	52 N	140 W
PACSF99	11/11-12/2/99	640	Ron Brown	±10 N	100 W

where $u_* = \sqrt{-\overline{w'u'}}$ is the friction velocity. The scalar roughness lengths are parameterized in terms of the roughness Reynolds number, $R_r = u_* z_o / \nu$.

The stability functions are a blend of conventional well-determined overland functions near neutral stability with a form that obeys the theoretical scaling limit in highly convective conditions (Fairall et al. 1996a).

In typical execution of a bulk algorithm, the atmospheric variables (U, V, T, q) at reference height z are provided through measurement or model output; the surface properties (surface current vector, water temperature) are also provided. Usually the water temperature at some depth, $T_w(D)$, is given while the surface value is required by (1); the surface value for specific humidity is computed from the surface temperature and the vapor pressure of seawater (0.98 times the vapor pressure of pure water). If the true interface water temperature is not provided, then some method of estimating T_s from T_w must be used. In the COARE model this is accomplished through submodels that represent the millimeter-scale cool skin near the interface and the diurnal (solar) warm layer in the upper few meters of the ocean (Fairall et al. 1996b). Finally, in the COARE algorithm, the gustiness is represented as boundary-layer scale large eddies using the convective velocity scale

$$U_g = \beta W_* , \qquad (6)$$

where β is a parameter presently set to 1.20.

3. IMPROVEMENTS IN COARE ALGORITHM

The COARE 2.5 algorithm (Fairall et al. 1996a) was developed for the Coupled Ocean Atmosphere Response Experiment (COARE) program (Webster and Lukas 1992) and has been evaluated against several sets of tropical data. It performs well, as do several other algorithms (Zeng et al. 1998). The published version (2.5b) of the COARE algorithm is in widespread use but the Flux Working Group has continued to pursue improvements in the various components of the model. A new version of the model (3.0) has been made public; the changes are summarized in Fairall et al. (2002). Aside from various structural improvements, the neutral transfer coefficients have been ajdusted slightly. The Liu et al. (1979) scalar roughness relationship [$f_x(R_r)$] has been replaced with a much simpler one that fits both the COARE and HEXMAX data bases and the Charnock parameter has been given a slight wind speed dependence for winds between 10 and 18 ms^{-1}. These changes were intended to extend the algorithm's region of applicability from a maximum wind speed of 10 ms^{-1} to 20 ms^{-1}.

4. THE FLUX DATABASE

The results given here were based on fits to ETL flux data from six cruises in the early 1990's plus published results on fluxes at high wind speeds (DeCosmo et al. 1998; Yelland and Taylor 1996). Six new cruises obtained with the ETL seagoing flux system (Fairall et al. 1997) recently became available and were combined with the original six cruises (see Table 1). The measurement system is based on motion-corrected high-speed turbulence sensors and very high quality bulk variable measurements. The structure of the system has remained essentially the same (sonic anemometers and

IR fast hygrometers) although the data acquisition and processing hardware has evolved considerably.

This larger database has more high-latitude measurements and includes about 800 hrs of data at wind speed greater than 10 ms^{-1}. Because the initial ETL database of six cruises had only 67 hrs of data at wind speed greater than 10 ms^{-1}, this new data allows us to test the in the wind speed range of 10 - 20 ms^{-1}.

5. FLUX AND TRANSFER COEFFICIENT EVALUATION

The first step in evaluating the moisture transfer coefficient is to select a subset of the data that pass a set of criteria to reject invalid points. Such criteria include experimental aspects (such as the relative wind must fall within a certain range to eliminate obvious contamination by the ship's structure), instrument performance indicators, ship motion-correction errors associated with ship maneuvers, and requirements that certain variables (e.g., variances) fall within physically reasonable limits. The criteria are arbitrary but the results are only weakly affected by modest criteria changes. Both direct covariance and inertial-dissipation (ID) flux estimates are used in our analysis. The 3226 1-hr points that pass the criteria above are shown in a scatter plot in Fig. 1.

We are interested in both computing the mean 10-m neutral moisture transfer coefficient as a function of wind speed and in comparing it to the COARE algorithm. The next step is to compare the values of fluxes obtained from the bulk algorithm with the measurements in some rational fashion. Usually we are interested in the *average* performance of the bulk algorithm plus some information on its statistical scatter about the observations. One can compute mean and standard deviations of differences, linear regressions, etc.

Because of the noisy nature of flux data and the difficulties of making very accurate bulk meteorological measurements, the experimental evaluation of transfer coefficients is problematical. Using (1) we can compute a transfer coefficient for each observation and average in wind speed bins (method 1). Or, we can average the fluxes and bulk variables in wind speed bins, compute 'effective' transfer coefficients that deliver the correct average flux (method 2). Another approach is to compute an average transfer coefficient that is the mean bulk coefficient times the ratio of the mean measured flux to the mean computed bulk flux (method 3). We have experimented with these (and other) approaches; at the moment we weakly favor method 3. Our results are shown for moisture flux (Fig. 2). Compared to the COARE algorithm, the data show a tendency for slightly lower transfer coefficients for wind speeds below 8 ms^{-1} and greater transfer coefficients for greater wind speeds. Surprisingly, the COARE moisture roughness length parameterization is in good agreement with the data; the difference in transfer coefficient for moisture is caused by the velocity contribution (i.e., the $c_d^{1/2}$ part of Eq. 1). To remove the velocity contribution, we show the data in the form of moisture roughness length vs R_r. (Fig. 3). The COARE 2.5 and 3.0 parameterizations are shown with some other models for comparison (Garratt 1992).

Another way to look at this is to examine mean moisture flux comparisons averaged in bins of 10-m neutral wind speed. Fig.4 shows a comparison of the mean latent heat flux computed in wind speed bins from 0 to 22 ms^{-1}. The width of the bins is increased slightly at higher wind speeds where the density of data decreases. The turbulence values are the average of covariance and ID values; the bulk values (x's) are COARE3.0. We have used both medians and means to indicate skewed distributions or effects of outliers. Fig. 5 shows these same values plotted on a linear scale as flux vs flux.

Our results show a mean 10-m neutral moisture transfer coefficient of 1.13 X 10^{-3} but our measurements are consistent with about a 10% increase in transfer coefficient from 5 to 20 ms^{-1}. The COARE algorithm fits the windspeed bin-averaged data to about 5%.

ACKNOWLEDGMENTS

This work is directly supported by the Office of Naval Research, the NSF Office of Climate Dynamics, The Department of Energy ARM program, and the NOAA Office of Global Programs.

REFERENCES

DeCosmo, J., K. B. Katsaros, S. D. Smith, R. J. Anderson, W. A. Oost, K. Bumke, and H. Chadwick, 1996: Air-sea exchange of water vapor and sensible heat: The Humidity Exchange Over the Sea (HEXOS) results. *J. Geophys. Res.*, **101**, 12001-12016.

Fairall, C. W., E. F. Bradley, D.P. Rogers, J. B. Edson, and G. S Young, 1996a: Bulk parameterization of air-sea fluxes in TOGA COARE. *J. Geophys. Res.*, **101**, 3747-3767.

Fairall, C. W., E. F. Bradley, J. S. Godfrey, G.A. Wick, J. B. Edson, and G. S. Young, 1996b: Cool skin and warm layer effects on the sea surface temperature. *J. Geophys. Res.*, **101**, 1295-1308.

Fairall, C.W., A.B. White, J.B. Edson, and J.E. Hare, 1997: Integrated shipboard measurements of the marine boundary layer. *J. Atmos. Oceanic Tech.,* **14**, 338-359.

Fairall, C.W., E. F. Bradley, J.E. Hare, A. A. Grachev, and J.B. Edson, 2003: Bulk parameterization of air-sea fluxes: Updats and verification for the COARE algorithm. *J. Clim.,* in press.

Garratt, J. R., 1992: *The Atmospheric Boundary Layer*. Cambridge University Press, Cambridge, MA, 316 pp.

Liu, W. T., K. B. Katsaros, and J. A. Businger, 1979: Bulk parameterization of the air-sea exchange of heat and water vapor including the molecular constraints at the interface. *J. Atmos. Sci.*, **36**, 2052-2062.

Smith, S. D., C. W. Fairall, G. L. Geernaert, and L. Hasse, 1996: Air-sea fluxes: 25 years of progress. *Bound.-Layer Meteorol.*, **78**, 247-290.

Yelland, M. and P. K. Taylor, 1996: Wind stress measurements from the open ocean. *J. Phys. Oceanogr.*, **26**, 541-558.

Webster, P. J., and R. Lukas, 1992: The Coupled Ocean Atmosphere Response Experiment. *Bull. Am. Met. Soc.*, **73**, 1377-1416.

Zeng, X., M. Zhao, and R. E. Dickinson, 1998: Comparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using the TOGA COARE and TAO data. *J. Clim.*, **11**, 2628-2644.

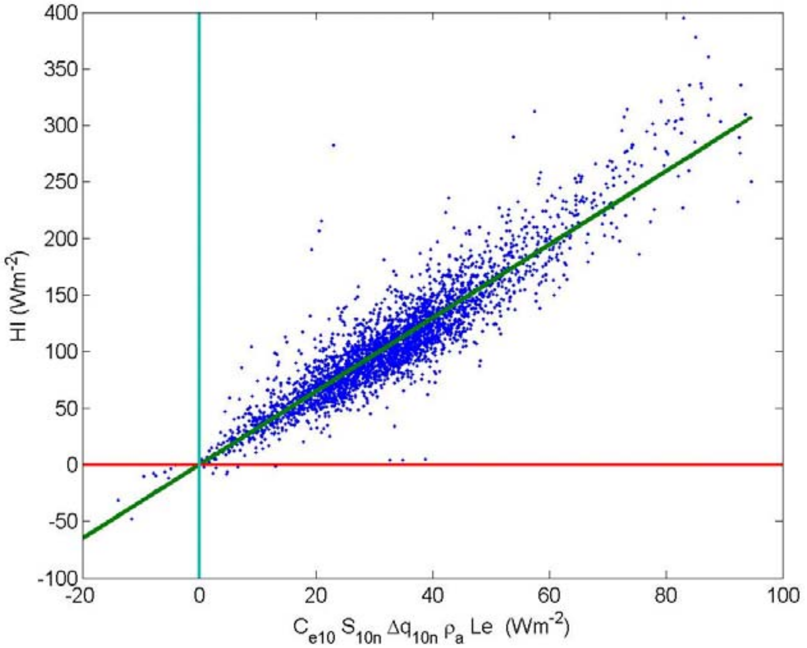

Figure 1 Individual latent heat flux data points passing the data selection criteria versus the basic bulk scaling relationship: C_{e10n} is given the value 1.13 E-3; S_{10n} is the 10-m neutral wind speed, and Δq_{10n} the 10-m neutral moisture sea-air difference.

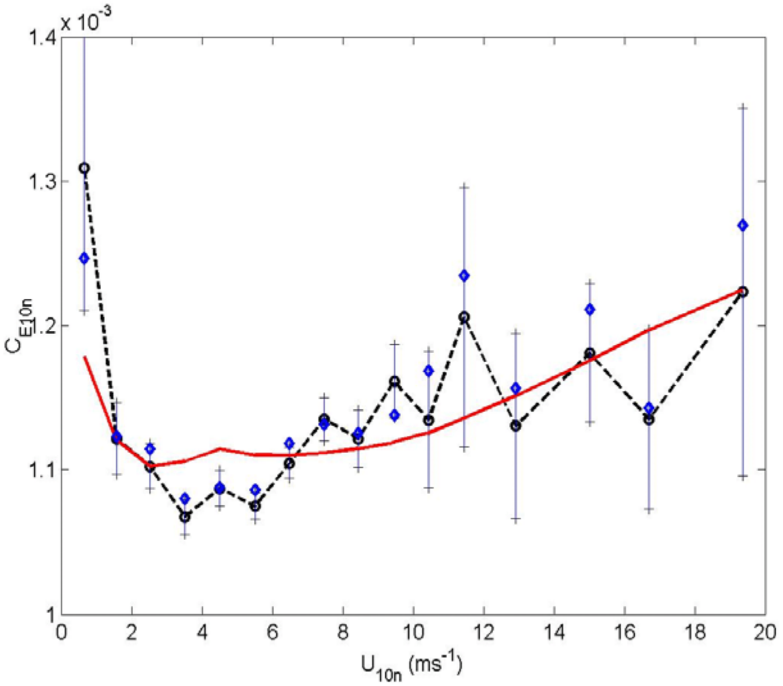

Figure 2 10-m neutral transfer coefficient for moisture as a function of 10-m neutral wind speed. Diamonds are method 1 and circles method 3, the red line is COARE 3.0; bars indicate uncertainty in the mean estimate.

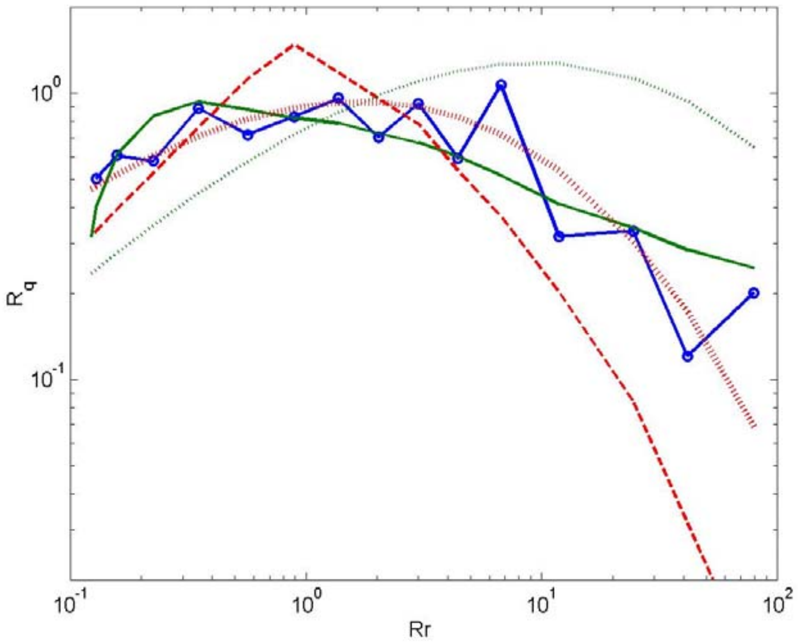

Figure 3 Moisture roughness Reynolds number vs velocity roughness Reynolds number: circles, ETL data set; solid line, COARE 3.0; dashed line, COARE 2.5 (Liu et al. 1970); dotted line, Garratt (1992); Heavy dotted line, R_r exp(3.4-3.5 $R_r^{-1/4}$).

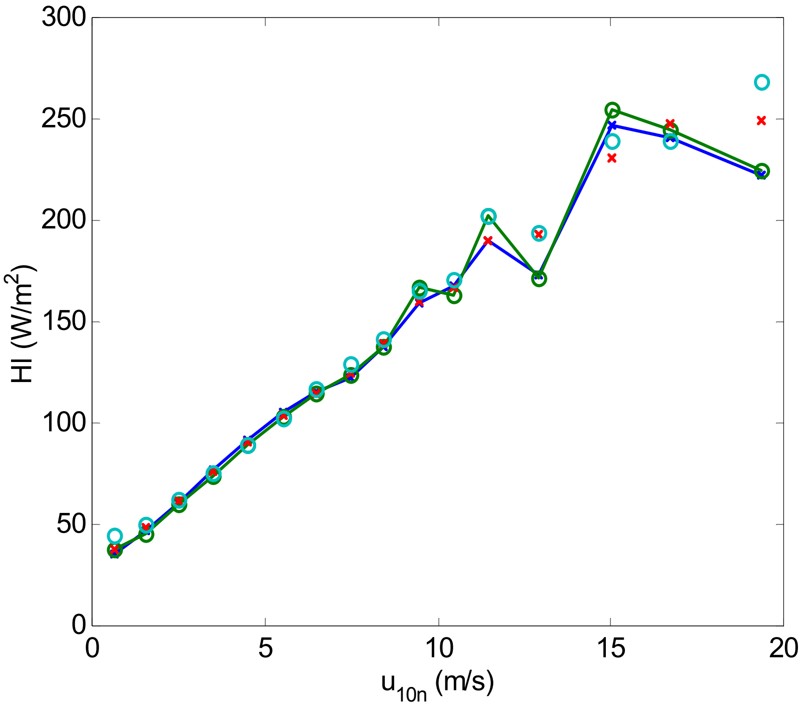

Figure 4 The average of covariance and inertial-dissipation latent heat fluxes computed in 10-m neutral wind speed bins. Mean values are shown by lines and medians by symbols; the solid lines are circles are measured fluxes and the broken lines and crosses are computed with COARE 3.0.

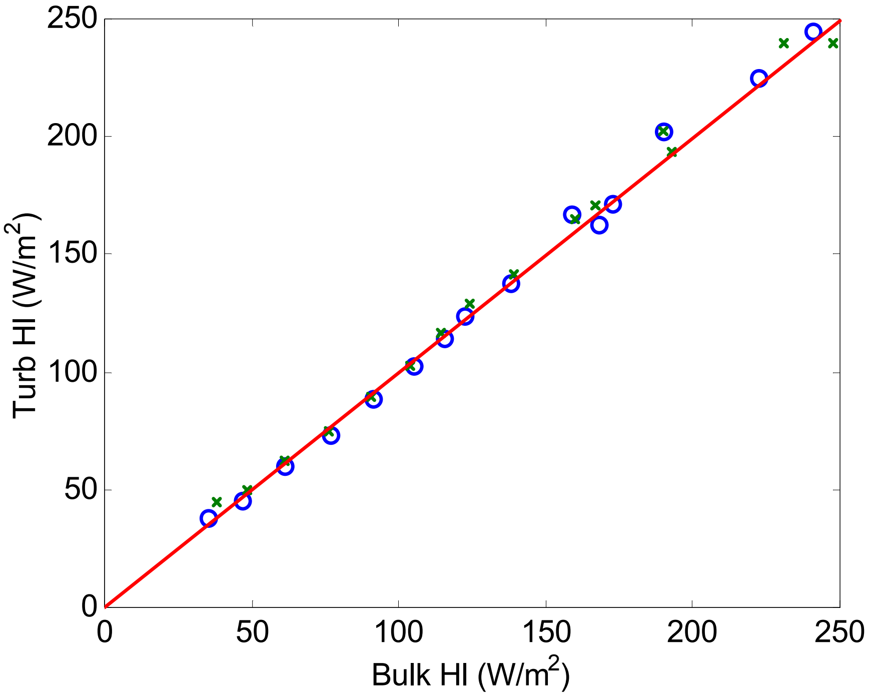

Figure 5 The same data points from Fig. 4, but plotted as bulk latent heat flux versus measured turbulent values. The x's are the means; the circles are medians.