P6A.10 AN OLD AND IMPROVED BULK ALGORITHM FOR AIR-SEA FLUXES: COARE2.6A

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

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

1. INTRODUCTION

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). None of the new algorithms have been extensively tested against a large and latitudinally diverse data base. A joint CSIRO/ETL effort has been underway to use new data to evaluate the algorithm, continue improvements, and add better physics.

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 MOS representations of the fluxes in terms of mean quantities (Smith et al., 1996)

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

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

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

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

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

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} a 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

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

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

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

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

$$z_{ox} = \frac{\nu}{u_*} f_x(R_r) \quad (6)$$

The stability functions are a blend of conventional well-determined overland functions near neutral stability with a form

Corresponding author address: C. Fairall, NOAA/ETL, 325 Broadway, Boulder, CO 80304; cfairall@etl.noaa.gov.

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

$$U_g = \beta W_* \tag{7}$$

where β is a parameter presently set to 1.25.

3. IMPROVEMENTS IN COARE ALGORITHM

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 (2.6a) has been made public; the changes are summarized as follows:

1. The empirical constants in the convective portion of the profile functions have been changed for improved matching to direct profile observations (Grachev et al., 2000).
2. The Kansas stable profile functions have been replaced by those from Beljaars and Holtslag (1991) based on new profile data taken over the Arctic ice cap.
3. A fixed value of the Charnock parameter (α=0.011) has been replaced by a formulation with a simple wind-speed dependence above 12 m/s based on data from Yelland and Taylor (1996) and Hare et al. (1999).
4. 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.
5. The stability iteration loop has been reduced from 20 to 3 using bulk Richardson number parameterization for an improved first guess (Grachev and Fairall, 1997).
6. The latent heat flux has been reformulated in terms of mixing ratio instead of water vapor density to eliminate the need for a Webb et al. (1980) correction.
7. A few minor adjustments have been made in constants and algorithm structure to make the model more globally applicable.

The first two changes tend to increase the fluxes in light winds. The second two lead to substantial changes in the fluxes primarily for wind speeds above 10 m/s (see Figs. 1 and 2). These are essentially empirical adjustments based on evaluation of a few high wind speed data sets. The fifth change speeds up the calculations while the sixth casts the moisture transfer in the more conservative quantity (mixing ratio) rather than that which is actually measured by most flux systems.

4. SOURCE CODE AVAILABILITY

Matlab and Fortran versions of both COARE 2.5b and 2.6a have been made publically available at the ftp site at ETL: ftp://ftp.etl.noaa.gov/pub/et7/users/cwf/bulkalg/. Included is a description of the codes and a test data set file. The programs are set up to read the test file and output the results; output files and graphs of results are also provided. Figs. 3 and 4 show the test data time series for both versions. A few data sets obtained with the ETL seagoing flux system (Fairall et al., 1997) are also available at this site.

5. IMPROVEMENTS CONTEMPLATED FOR COARE 3.0

Several options are being considered to make the COARE algorithm more useful for applications to more limited data sets and for implementation in numerical models. The first is the addition of simple parameterizations to furnish downward IR and/or solar radiative fluxes for those cases where they are not available by direct measurement (e.g., COADS data). These would be standard parameterizations available in the literature (see Josey et al. 1999 for examples). The second is the addition of a parameterized form of the warm layer effect, probably using Webster et al. (1996). This would have the advantage that the fluxes would be a pure function of a single line of data, rather than an integral of the previous time series. We are also considering an expansion of the gustiness velocity to include the effects of mesoscale variability associated with convective precipitation using the approach of Jabouille et al. (1995) or Redelsberger et al. (1998). A major addition is being considered to account for the effects of waves on the fluxes. This would allow the algorithm to be applied in coastal/shallow water areas such as much of the Gulf of Mexico. The new model from Taylor and Yelland (2000) is the primary candidate. Here the surface roughness is parameterized in terms of the significant wave height and the peak wavelength (or, equivalently the wave period); both of these variables are observable from satellites.

Acknowledgments

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

REFERENCES

Beljaars, A. C. M., and A. A. M. Holtslag, 1991: Flux parameterization over land surfaces for atmospheric models. *J. Appl. Meteor.*, **30**, 327-341.

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.

Grachev, A.A., and C.W. Fairall, 1997: Dependence of the Monin-Obukhov stability parameter on the bulk Richardson number for unstable conditions over the ocean. *J. Appl. Meteorol.*, **36**, 406-414.

Grachev, A. A., C. W. Fairall, and E. F. Bradley, 2000: Convective profile constants revisited. *Bound.-Layer Meteorol*., to appear.

Hare, J. E., P. O. G. Persson, C. W. Fairall, and J. B. Edson, 1999: Behavior of Charnock's relationship for high wind conditions. Proc. 13th Symposium of Boundary Layers and Turbulence. AMS. Dallas, TX, Jan. 15-20, paper 5B.8.

Jabouille, P., J. L. Redelsperger, and J. P. Lafore, 1995: Modification of surface fluxes by atmospheric convection in the TOGA COARE region. *Mon. Wea. Rev*., **124**, 816-837.

Josey, S. A., E. C. Kent, and P. K. Taylor, 1999: New insights into the ocean heat budget closure problem from analysis of the SOC air-sea flux climatology. *J. Clim.*, **12**, 2856-2880.

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.

Redelsberger, J. L. F. Guichard, and S. Mondon, 1998: Parameterization of mesoscale enhancement of surface fluxes for regional and large scale models. *J. Atmos. Sci*., to appear.

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.

Taylor, P. K., and M. A. Yelland, 2000: The dependence of sea surface roughness on the height and steepness of the waves. *J. Phys. Oceanogr*., submitted.

Webb, E. K., G. I. Pearman, and R. Leuning, 1980: Correction of flux measurements for density effects due to heat and water vapour transfer. *Q. J. Roy. Met. Soc.*, **106**, 85-100.

Webster, P. J., C. A. Clayson, and J. A. Curry, .1996: Clouds, radiation and the diurnal cycle of sea surface temperature in the tropical Western Pacific. *J. Clim*., **9**, 1712-1730.

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, Xubin, 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.

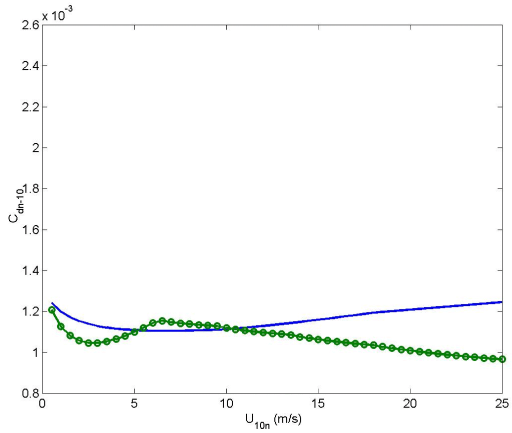

Figure 2 Neutral 10-m moisture transfer coefficient versus the 10-m wind speed for the COARE algorithm: dots: version 2.5b, line: version 2.6a

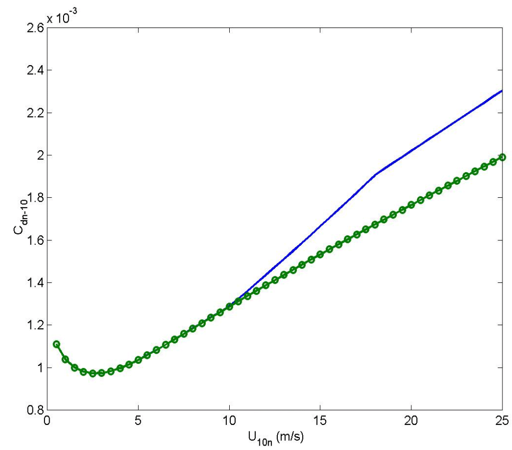

Figure 1 Neutral 10-m drag coefficient versus 10-m wind speed for the COARE algorithm: dots: version 2.5b, line: version 2.6a.

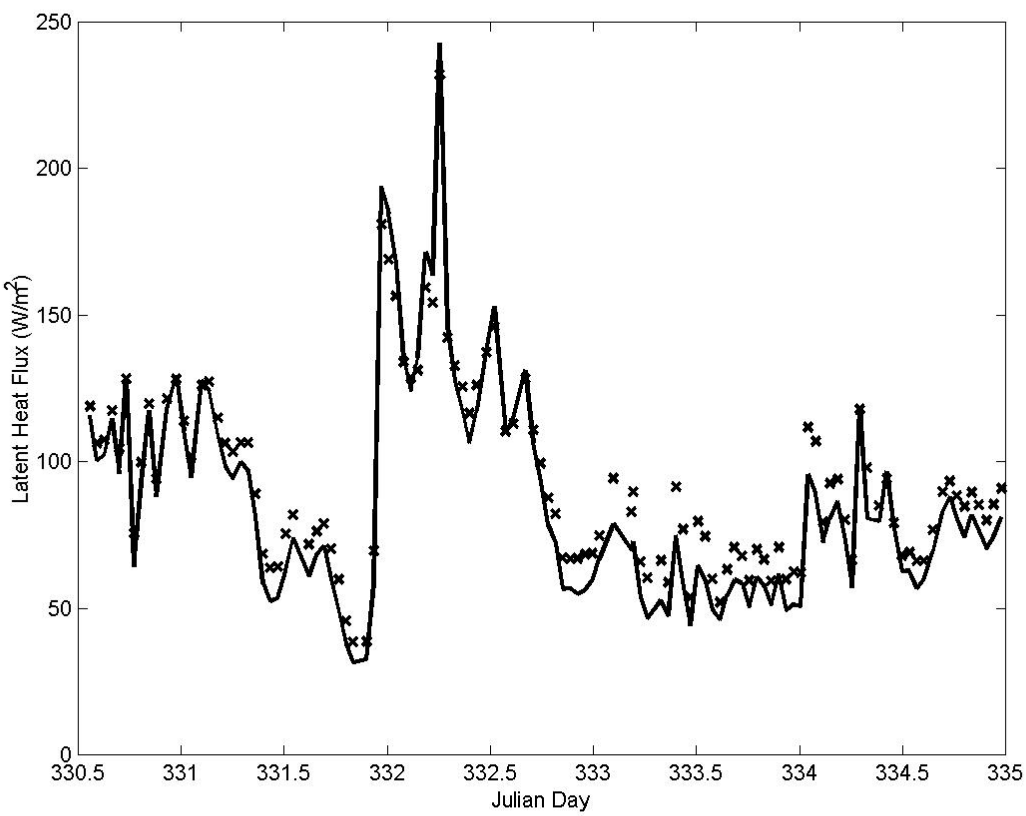

Figure 3 Time series of latent heat flux from the COARE test data set using the old and new versions of the COARE algorithm: line - 2.5b, x's 2.6a.