11B.2 DIRECT MEASUREMENTS OF MOMENTUM AND LATENT HEAT TRANSFER COEFFICIENTS DURING THE GASEXIII 2008 FIELD PROGRAM: COMPARISONS WITH THE COARE3.0 BULK FLUX ALGORITHM

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1. INTRODUCTION

In 2008 a six-week research expedition aboard the NOAA Ship Ronald H. Brown was conducted with sponsorship from NASA, NOAA, and NSF. The Southern Ocean Gas Exchange Experiment departed Feb. 28 from Punta Arenas, Chile, and spent most of its time in the storm track east of the Southern tip of S. America (51 S 36 W). Scientists from dozens of universities and research institutions were on board to measure turbulence, waves, bubbles, temperature, ocean chemistry and biology, and investigate how these factors relate to the air-sea exchange of carbon dioxide and other climate-relevant gases. A consortium of researchers from NOAA/ESRL - U. Colorado, U. Connecticut, Columbia U., and U. Hawaii cooperated on comprehensive suite of instruments to make direct motion-corrected covariance and inertial-dissipation flux measurements and associated forcing variables such as near-surface bulk meteorology, surface waves and whitecap fraction. In this paper we report on analysis of the turbulent fluxes of momentum and water vapor and a comparison of the bulk transfer coefficients with the COARE algorithm (version 3.0).

2. THEORY

So-called bulk algorithms to estimate surface air-sea fluxes are widely used in numerical modeling and other important applications. According to this approach, the turbulent fluxes are represented in terms of the bulk meteorological variables of mean wind speed, air and sea surface temperature, and air humidity:

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

where *x* can be *u*, *v* wind components, the potential temperature, θ, the water vapor specific humidity, *q*, or some atmospheric trace species mixing ratio. Here c_x is the bulk transfer coefficient for the variable *x* (*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 (relative to the ocean surface), which is composed of a magnitude of the mean wind vector part *U* and a gustiness part U_g:

$$\Delta X = X_{sea} - X(z); \qquad S = \sqrt{U^2 + U_g^2} \equiv U\,G . \qquad (2)$$

In [2] *z* is the height of measurements of the mean quantity *X*(*z*) above the sea surface (usually 10 m) and $G = \sqrt{1+(U_g/U)^2}$ is the gustiness factor. The gustiness term in [2] represents the near-surface wind induced by the BL-scale.

Properly scaled dimensionless characteristics of the turbulence at reference height *z* are universal functions of a stability parameter, $\zeta \equiv z/L$, defined as the ratio of the reference height *z* and the Obukhov length scale, *L*. Thus, the transfer coefficients in [1] have a dependence on surface stability prescribed by MOST:

$$c_x^{1/2}(\zeta) = \frac{c_{xn}^{1/2}}{1-(c_{xn}^{1/2}/\kappa)\Psi_x(\zeta)}, \qquad c_{xn}^{1/2} = \frac{\kappa}{\ln(z/z_{ox})}, \qquad (3)$$

where the subscript *n* refers to neutral ($\zeta = 0$) stability, Ψ_x is an empirical function describing the stability dependence of the mean profile, and z_{ox} is a parameter called the roughness length that characterizes the neutral transfer properties of the surface for the quantity, *x* (see also *Fairall et al*. [2003] for details).

3. INSTRUMENTATION

The fluxes and mean variables used in this analysis were obtained from the ESRL/PSD system (recently described in Fairall et al. 2003, 2006). Velocity turbulence and fast temperature were obtained from a sonic anemometer, fast humidity from LI-7500 IR-absorption hygrometers, and ship motion corrections from the PSD motion package. Fig. 1 shows the collection of three sonic anemometers and 5 Li-7500's mounted on the jackstaff for GASEX-3 by different research groups. A mini-workshop was held in Boulder in July 2008 to compare instruments and motion corrections from the various systems. The results shown here use the PSD sonic and motion corrections and mean of two open-path and one sleeved-ventilated LI-7500 for fast humidity.

4. RESULTS

The reduction of an ensemble of observations of turbulent fluxes and near-surface bulk meteorological variables to estimates of the mean 10-m neutral transfer coefficient is a problem of some subtlety. The straightforward approach is to convert each observation to C_{x10n}

$$C_{x10n} = \frac{\overline{w'x'}}{U_{10n}\Delta X_{10n} G} = \frac{\kappa}{\ln(10/z_o)}\frac{\kappa}{\ln(10/z_{ox})}, \qquad (4)$$

then average to obtain

$$< C_{x10n} > = < \frac{\overline{w'x'}}{U_{10n}\Delta X_{10n} G} > . \qquad (5)$$

The 10-m neutral values of the mean profile are computed as

$$U_{10n} = \frac{u_*}{\kappa}\ln(\frac{10}{z_o}) = U(z) - \frac{u_*}{\kappa}[\ln(\frac{z}{10}) - \Psi_u(z/L)] \qquad (6a)$$

$$\Delta X_{10n} = -\frac{x_*}{\kappa}\ln(\frac{10}{z_{ox}}) = \Delta X(z) + \frac{x_*}{\kappa}[\ln(\frac{z}{10}) - \Psi_q(z/L)] , \qquad (6b)$$

where x_* can be θ_* or q_*. Note, the sign difference between [6a] and [6b] follows from ΔX being defined as $X_s - X(z)$ in Equation [1]. An example of the comparison for flux measurements versus bulk variables is shown for latent heat flux in Fig. 2. We can also average flux estimates in wind speed bins and plot mean observed fluxes versus mean fluxes computed via the bulk algorithm. An example for covariance and inertial dissipation (ID) stress estimates is shown in Fig. 3. Note in this case that the covariance values are significantly larger than the ID values at higher wind speeds. This has been observed previously (Persson et al. 2005) and may be caused by unresolved transfer of some kinetic energy to the wave field (Edson and Fairall 1998).

Because artificial correlation may confuse attempts to compute the mean transfer coefficients via [5], we use the approach of *Fairall et al*. [2003] to compute estimates of mean transfer coefficients as a function of wind speed. Here the fluxes are averaged in wind speed bins and the mean transfer coefficient is the one that correctly returns the mean or median flux

$$< C_{x10n} > = \frac{< \overline{w'x'} >}{< \overline{w'x'} >_b} < C_{x10nb} >, \qquad (7)$$

where the subscript *b* refers to values computed with the bulk algorithm. The data used in the analysis are filtered for acceptable relative wind direction and other data quality criteria described by *Fairall et al*. [2003].The results for momentum and sensible heat flux are shown in Figures 4a and 4b.

For GASEX-3, the momentum transfer is uniformly about 10% greater than estimates from the COARE3.0 algorithm. This is significantly greater than expected measurement bias (about 5%), but we cannot rule out an experimental problem at this preliminary stage. The latent heat flux is well-represented by COARE3.0 except at wind speeds exceeding 16 m/s. This represents a fairly small fraction of the data, so the significance is difficult to evaluate. Because the sea-air temperature differences were small, sensible heat flux observations were not sufficiently greater than the noise/bias uncertainty, so no sensible heat transfer coefficient evaluations were made. On balance, it appears that air-sea transfer for conventional meteorological fluxes at wind speeds in the 5-15 m/s range during GASEX-3 were ‘normal’ for the open ocean but there is evidence of enhanced transfers for wind speeds exceeding 15 m/s.

5. REFERENCES

Edson, J. B. and C. W. Fairall, 1998: Similarity relationships in the marine atmospheric surface layer for terms in the TKE and scalar variance budgets. *J. Atmos. Sci.*, **55**, 2311-2338.

Fairall, C. W., E. F. Bradley, J. E. Hare, A. A. Grachev, and J. B. Edson, 2003: Bulk parameterization of air-sea fluxes: Updates and verification for the COARE algorithm. *J. Clim.*, **16**, 571-591.

Fairall, C. W., Ludovic Bariteau, A.A. Grachev, R. J. Hill, D.E. Wolfe, W. Brewer, S. Tucker, J. E. Hare, and W. Angevine 2006: Coastal effects on turbulent bulk transfer coefficients and ozone deposition velocity in ICARTT. *J. Geophys. Res.*, **111**, D23S20, doi:1029/2006JD007597.

Persson, P. O. G., J. E. Hare, C. W. Fairall, W. D. Otto, 2005: Air-sea interaction processes in warm and cold sectors of extratropical cyclonic storms observed during FASTEX. Q. *J. Roy. Met. Soc.*, **131**, 877-912.

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Figure 1. Cluster of sonic anemometers, fast humidity sensors, and mean T/RH sensors on the jackstaff of the NOAA Ship Ronald H. Brown for GASEX-3. The PSD sonic is in the center. The sleeved fast-sample LI-7500 is the unit on the right with the large blue ventilation tube. The two open path units are on the left. Each sonic is mounted to its own motion-measuring system.

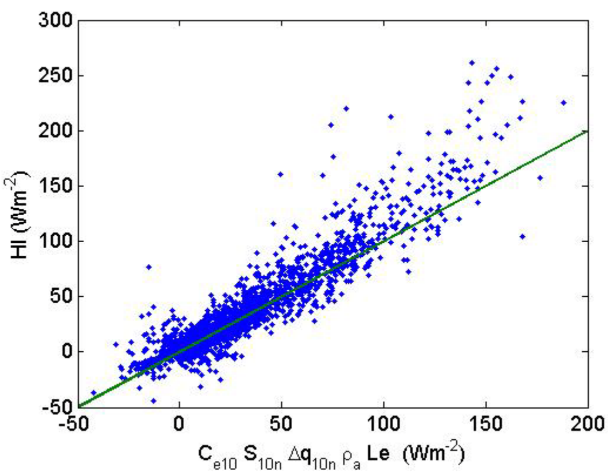

Figure 2. 10-min estimates of latent heat flux from GASEX-3 versus the fundamental bulk flux variable as represented by [4] using $C_{e10} = 1.1E-3$.

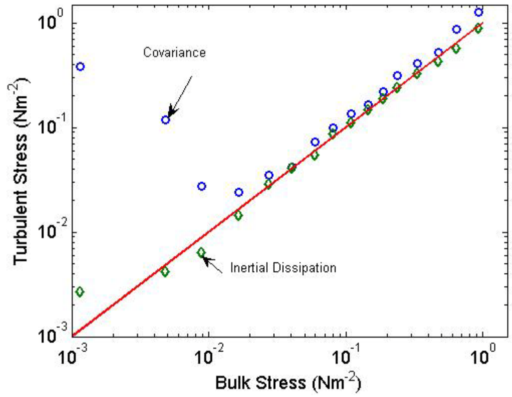

Figure 3. Wind-speed bin averaged stress values (covariance – circles; ID – diamonds) vs average values computed with COARE3.0 algorithm from GASEX-3.

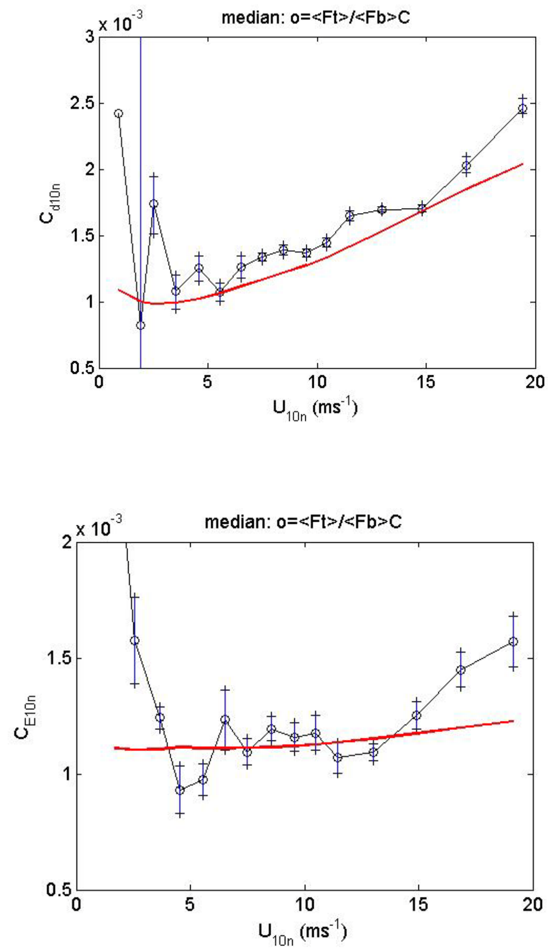

Figure 4. Turbulent transfer coefficients (using combined covariance and ID estimates) as a function of 10-m neutral wind speed. The solid red line is the COARE algorithm. The circles (with 1-sigma median limits) are the medians within wind-speed bins as described by Equation (7). Upper panel is the momentum coefficient; lower panel (is the sensible heat coefficient.