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EVALUATION OF AIR-SEA BULK FORMULA

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1. INTRODUCTION

Reliable formulation of air-sea fluxes of momentum, sensible heat and latent heat is critical for accurate forecasts of the marine boundary layer. The surface flux is commonly parameterized in large-scale models using a bulk flux formulation in terms of exchange coefficients that depend on stability and roughness lengths (e.g., Fairall et al., 2003; Mahrt et al., 2003).

The bulk flux model assumes stationarity and homogeneity such that: a) the drag coefficient only depends on z/L and z/z_{om} as described by Monin-Obukhov similarity theory, b) z_{om} is proportional to the momentum transport from the atmosphere to the ocean (e.g., Charnock formulation), and c) the observations are taken in the surface layer.

Despite these requirements, large-scale models must apply the bulk flux formulation in all conditions, as there is no viable alternative. This contributes to discrepancies between modelled and observed fluxes.

In this study, eddy-correlation fluxes from aircraft and tower measurements over the ocean are compared to flux estimates from a widely used bulk flux model without wave-state information. Similar bulk models without wave-state effects are used to parameterize the air-sea fluxes in most large-scale atmospheric models.

2. DATA

Data collected by the NOAA LongEZ (N3R) aircraft during two field experiments: 1) the pilot program of the Coupled Boundary Layers Air Sea Transfer experiment (CBLAST Weak Wind) conducted over the Atlantic Ocean south of Martha's Vineyard Island, MA, during July-August 2001, and 2) the Shoaling Waves experiment (SHOWEX) in November and December 1999 over the Atlantic off the Outer Banks near Duck, NC, are used in the analysis.

Eddy-correlation fluxes were calculated from data collected during low altitude (10 to 20 m) flight segments where aircraft altitude, roll, pitch and heading fluctuations remained within prescribed limits and where the flight track was either primarily into or following the mean wind. The latter criteria enables a better estimate of the SST in the flux footprint, but significantly reduces the size of the data sets. An accurate SST estimate is critical for evaluating fluxes with the bulk model. The SHOWEX dataset includes 190 flight segments on 21 different days, while the CBLAST pilot dataset includes 74 flight segments on 9 different flight days.

The LongEZ fluxes compare favorably with fluxes measured with eddy-correlation instrumentation on two different buoys and from sonic anemometers deployed on the Duck pier for limited intercomparisons (Mahrt et al., 2001).

We adjusted the skin temperature measurements from the radiometer for both the SHOWEX and CBLAST pilot experiments by applying one constant offset temperature for each flight day derived from comparisons with SST measurements from buoys, and by assuming that the heat flux should be directed down the mean temperature gradient.

Additional data from the Air-Sea Interaction Tower (ASIT) collected during the CBLAST experiment in late summer of 2003 are analyzed. Jim Edson supplied the fast response time series data. The offshore tower is located 3 km south of Martha's Vineyard in 15 m of water. Turbulence measurements at approximately 5 m above the sea surface are used to calculate eddy-correlation fluxes. We retain ASIT data for analysis only for periods with the wind direction inside the sector from 160 to 250 degrees (flow from the SSW) to avoid influences from nearby land to the north and shallow water to the east and west. The dataset includes 383 1-h averages between 16 July and 2 October 2003.

We briefly examine data collected by the Naval Postgraduate School's CIRPAS (Center of Inter-Disciplinary Remotely Piloted Aircraft Studies) Pelican aircraft in the CBLAST experiment during August 2003. The nominal Pelican altitude for flux measurements was 30 m above the surface. These fluxes are shown in Section 4, but are not discussed further.

3. FLUX CALCULATIONS

An algorithm is used to identify the averaging time scale τ for each individual flight segment (and each 1-h

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record from the tower) that captures the turbulence while excluding most of the mesoscale motions (Vickers and Mahrt, 2006). Once the perturbation quantities are computed based on the averaging scale τ, the fluxes are averaged over a larger window λ of 4 km for the aircraft and 1 hour for the tower.

For stable conditions ($z/L > 0.1$), the flux at aircraft level is extrapolated to the surface by assuming a linear flux profile between the surface and the top of the boundary layer, where the flux is zero. Stable boundary-layer depth is formulated in terms of u_* following Vickers and Mahrt (2004). 30% of the CBLAST pilot experiment fluxes are corrected by an average of 18%. The corresponding numbers for the SHOWEX data are 14% of the fluxes with an average correction factor of 32%. While this adjustment to the flux is admitably crude, it should account for first-order systematic effects due to shallow stable-boundary layers. No correction is applied when $z/L < 0.1$.

The current datasets agree well with commonly used flux-variance similarity relationships for σ_w/u_*, σ_T/T_* and σ_q/q_* as a function of z/L, suggesting that atmospheric surface layer similarity applies. However, satisfying flux-variance similarity does not necessarily imply that the data satisfy flux-gradient similarity.

4. BULK MODEL

The stability functions follow the Businger-Dyer-Paulson formulations. We use the usual value of $\alpha = 0.011$ in the Charnock formulation of z_{om}. The roughness lengths are identical to those in the COARE algorithm version 2.5, where z_{om} has rough and smooth flow terms, and z_{oh} approximately equals z_{oq}.

Differences between fluxes calculated with the bulk formulation used here and those calculated using the COARE algorithm version 2.5 are negligible. In COARE version 3.0 (Fairall et al., 2003), the roughness lengths are slightly greater for wind speeds exceeding 10 m s^{-1}, thus slightly increasing the fluxes in strong winds, and the roughness lengths for heat and moisture are equated.

5. BULK AND OBSERVED FLUXES

Figures 1 and 2 contrast bulk and observed fluxes. Some of the scatter in Figures 1 and 2 is presumably due to: a) random flux sampling errors, b) flux divergence associated with advection below the measurement height, c) non-equilibrium conditions due to flow over SST heterogeneity, and d) wave-state effects.

The bulk model momentum fluxes are generally larger than the observed for the LongEZ data and smaller than observed for ASIT data. Consequently, the roughness length for momentum is larger based on the ASIT data compared to the aircraft data (Figure 3). The scatter in the roughness lengths (not shown) is enormous, as found in most studies. The dependence of z_{om} on $u_*^2\ g^{-1}$ for the current aircraft datasets (Figure 3) is similar to the relationship found by Mahrt et al. (2003, Figure 1) using offshore tower and buoy data from six different field programs.

In near-collapsed turbulence, defined as $u_* < 0.05$ m s^{-1}, the bulk momentum flux exceeds the observed momentum flux for all datasets. The bulk model generally fails to predict these near-collapsed cases observed by both the tower and the aircraft possibly due to wave-state effects not included in the model. For example, the wind stress is reduced relative to the bulk prediction for conditions with weak wind following swell (Grachev and Fairall, 2001).

Reasonable agreement is found between modelled and observed sensible heat flux, however, the good agreement for weak winds is due to cancellation of two errors, where z_{om} is overpredicted and z_{oh} is underpredicted, with the result that C_h agrees reasonably well with the observations.

The bulk latent heat flux clearly exceeds the observed for $LE < 300$ W m^{-2} for both the aircraft and tower data, however, for the largest $LE > 300$ W m^{-2} observed during SHOWEX, the bulk latent heat flux is less than the observed. Excluding the periods with the largest LE and the strongest wind speeds observed by the aircraft in SHOWEX, the observed z_{oq} is significantly smaller than specified in the bulk model for both the aircraft and tower datasets (Figure 3).

6. SCALAR ROUGHNESS

In contrast to the bulk model formulation, both the aircraft and tower data indicate that the scalar roughness length ratio (z_{oh}/z_{oq}) is significantly greater than unity with the exception of the strongest wind-speed cases (discussed below). The result that $z_{oh} > z_{oq}$ is consistent with other observational evidence that the dimensionless variance of moisture tends to be larger than that of temperature, or equivalently, that R_{wT} exceeds R_{wq}, where R is the correlation coefficient.

The more efficient transport of heat for these data could be associated with the domination of buoyancy generation of turbulence by temperature fluctuations instead of moisture fluctuations. In this sense, moisture acts more like a passive scalar than does temperature. The current datasets indicate that the scalar roughness length ratio is strongly coupled to the transport efficiency ratio.

In the strongest observed winds, the scalar roughness length ratio (Figure 4) becomes less than unity due to the combination of a precipitous decrease in z_{oh} coupled with a large increase in z_{oq} (Figure 3). The decrease in z_{oh} could be due to wave sheltering while the increase in z_{oq} could be related to wave breaking. Donelan (1990) postulated that at high wind speeds the decrease in moisture flux due to sheltering may be offset by an increase due to a disruption of the surface microlayer by breaking waves. The observations here indicate no clear dependence of the scalar roughness length ratio on wind speed until a threshold wind speed (about 12 m s^{-1}) is reached, wherein the ratio plummets by a factor of nearly 200. This behavior is consistent with a threshold wind speed required for initiation of wave breaking.

The majority of the data indicating enhanced moisture transport ($z_{oq} > z_{oh}$) occur on 30 November in SHOWEX, with isolated cases also occurring on 16 and 28 November. All three of these days are characterized by breaking waves and cold, dry air advection from land located 50 km or more to the northwest of the study area. These are large-scale cold air outbreaks leading to strong instability and roll circulations.

Previous studies by Andreas and Monahan (2000) and DeCosmo et al. (1996) did not find enhanced moisture transport over breaking waves and proposed that the cause was rapid saturation of the near-surface air which reduces further moisture transport. However, for these three days in SHOWEX, a strong supply of cold dry air is available due to advection from land. We speculate that the occurrence of enhanced moisture flux ($z_{oq} > z_{oh}$) over breaking waves may be confined to coastal regions with strong offshore advection of dry air, however, the erratic behaviour of the bin-averaged z_{oq} from both the tower and aircraft data suggests that we need more data to make more definitive conclusions. In addition, organization of the turbulence by the roll circulations probably leads to large spatial variability of the turbulence flux and cross-wind flight tracks would be more useful.

While we cannot rule out the possibility that the measurements underestimate surface fluxes, the systematic differences between bulk and observed latent heat fluxes appear to be too large to be fully explained by measurement problems.

7. ACKNOWLEDGMENTS

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REFERENCES

Andreas,E.L., and E.C.Monahan, 2000, The role of whitecap bubbles in air-sea heat and moisture exchange. *J. Phy. Oc.*, 30, 433-442.

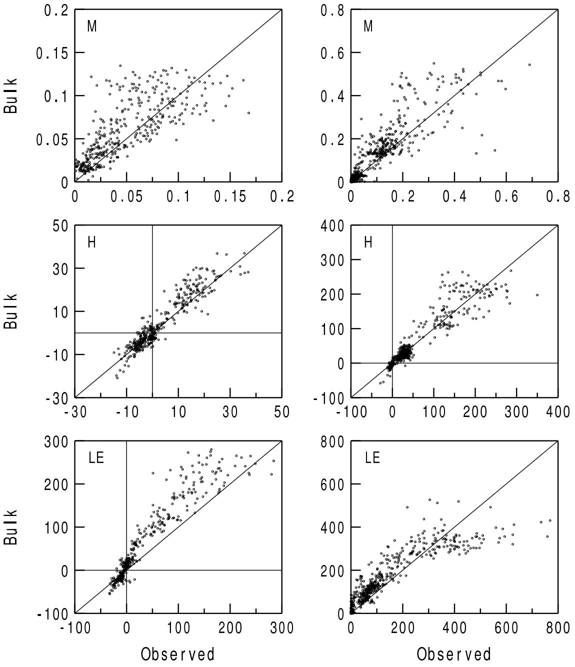

Figure 1: Bulk fluxes of momentum (M) (N m^{-2}), sensible heat (H) (W m^{-2}) and latent heat (LE) (W m^{-2}) as a function of the observed fluxes for LongEZ CBLAST (left column) and SHOWEX (right column).

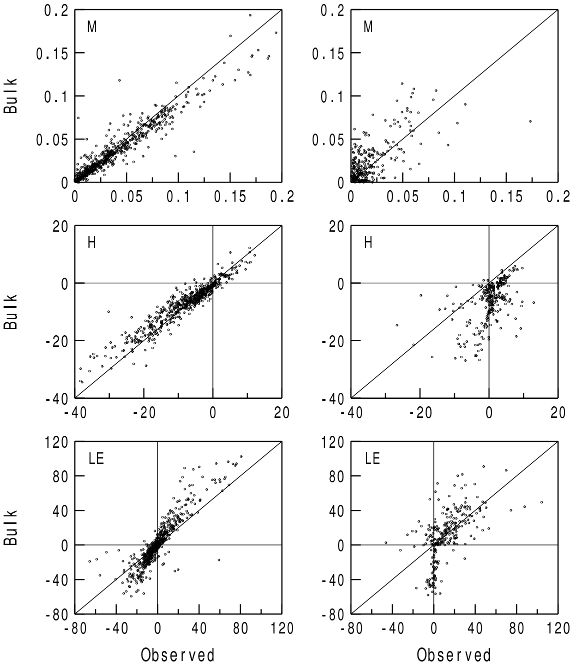

Figure 2: Same as Figure 1 but for ASIT CBLAST data (left column) and Pelican CBLAST (right column).

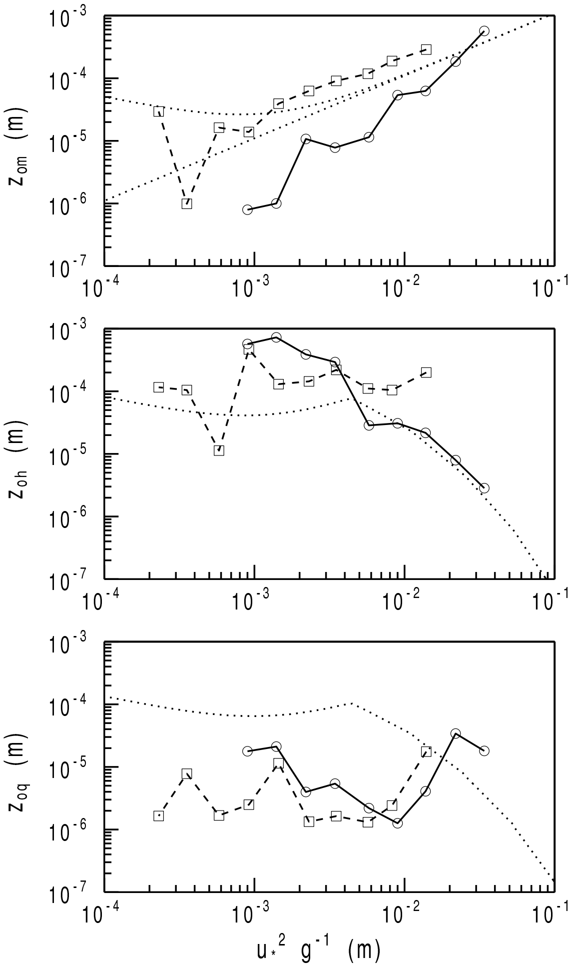

Figure 3: Bin-averaged roughness lengths (m) for combined LongEZ CBLAST and SHOWEX data as a function of $u_*^2\ g^{-1}$ (m). Dotted curves are the bulk model. Dotted straight line is the z_{om} rough flow term only. ASIT data is denoted by the dashed curves with squares.

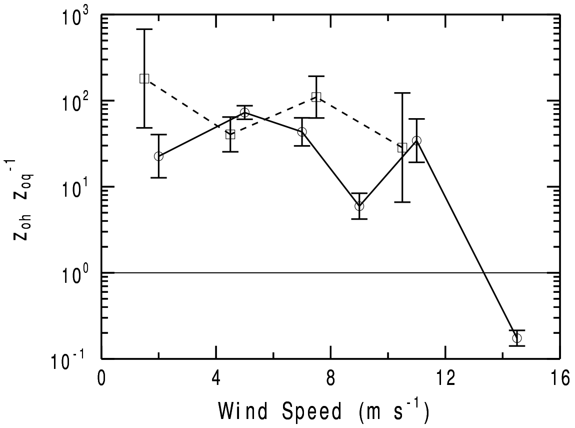

Figure 4: Observed scalar roughness length ratio (z_{oh} divided by z_{oq}) as a function of the 10-m wind speed (m s^{-1}) for combined LongEZ CBLAST and SHOWEX data. ASIT data is denoted by the dashed curve with squares.

DeCosmo,J., K.B.Katsaros, S.D.Smith, R.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.

Donelan,M.A., 1990, Air-sea interaction, in *Ocean Engineering Science*, B. LeMehaute and D. M. Hanes, Eds., John Wiley and Sons, New York, NY.

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

Grachev,A., and C.W.Fairall, 2001, Upward momentum transfer in the marine boundary layer. *J. Phy. Oc.*, 21, 1698-1711.

Mahrt,L., D.Vickers, J.Sun, T.Crawford, G.Crescenti and P.Frederickson, 2001, Surface stress in offshore flow and quasi-frictional decoupling. *J. Geophys. Res.*, 106, 20629-20639.

Mahrt,L., D.Vickers, P.Frederickson, K.Davidson and A.Smedman, 2003, Sea-surface aerodynamic roughness. *J. Geophys. Res.*, 3171, oi:10.1029/2002JC001383.

Vickers,D., and L.Mahrt, 2004, Evaluating formulations of stable boundary-layer height. *J. Appl. Meteor.*, 43, 1736-1749.

Vickers,D., and L.Mahrt, 2006, A solution for flux contamination by mesoscale motions with very weak turbulence. *Boundary-Layer Meteorol.*, in press.