PARAMETERIZATION OF SURFACE MOMENTUM FLUX DURING CONVECTIVE CONDITIONS

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Abstract

Parameterization of surface momentum flux estimates near-surface turbulent momentum fluxes from differences of mean wind speeds between the surface skin and the mid-mixed layer (ML). The rate of this turbulent transport is proportional to the product of a convective velocity times an empirical transport coefficient. To further investigate parameterization of surface momentum flux, some topics are discussed. New data from three different sites within Boundary Layer Experiment - 1996 (BLX96) are presented, and used to evaluate surface momentum flux parameterization. Old data from three other field programs (BLX83, Koorin, and TOGA-COARE) are re-analyzed to test this parameterization. Evidence from virtually all of these experiments indicates that the empirical transport coefficients for momentum fluxes depend on surface roughness.

Intisari

Fluks momentum turbulen dekat permukaan dapat diestimasi dari selisih antara kecepatan angin di batas permukaan (surface skin) dan di bagian tengah lapisan tercampur (mid-mixed layer). Kecepatan dari transpor turbulen ini sebanding dengan perkalian antara koefisien empiris transpor dengan kecepatan konvektif. Untuk pengamatan lebih lanjut akan didiskusikan beberapa hal. Data baru dari hasil pengukuran BLX96 pada 3 lokasi yang berbeda akan digunakan untuk mengevaluasi parameterisasi ini. Sementara data yang diperoleh dari yang pernah dilakukan sebelumnya (BLX83, Koorin, and TOGA-COARE) digunakan untuk menguji hasil parameterisasi ini. Hasil yang diperoleh mengindikasikan bahwa koefisien empiris transpor untuk fluks momentum tergantung pada kekasaran permukaan (surface roughness).

1. INTRODUCTION

During convective conditions with calm to light winds, most of the atmospheric boundary-layer turbulence is generated buoyantly by thermals rather than mechanically by wind shear (Stull 1997a). Thermal diameters are sufficiently large (order of 1 to 2 km) that the very large

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central core in each thermal is protected from small-eddy lateral entrainment (Crum et al. 1987). Within this core, air parcels from near the surface rise to the middle and the top of the convective boundary layer (BL) with virtually no dilution (Stull and Eloranta 1985). The vertical transport by thermals is not a small-eddy diffusion-like process, but a large-eddy vertical-advection-like process (Stull 1995) with a rate of transport proportional to the Deardorff velocity. Because buoyant thermals are anisotropic with greater energy in the vertical, they efficiently transport heat, momentum and moisture vertically from the surface.

Stull (1994, 1997b) utilized these characteristics of convection to show that during free convection the surface vertical turbulent flux $\overline{w'y'}_s$ of any mean variable $\overline{y}$ is proportional to the Deardorff velocity times the difference of $\overline{y}$ between the surface skin and the mid-mixed layer (ML). The term ML is used to represent the whole convective BL between the surface and the top of the BL (z_i). A subdomain within the interior of the ML is called the uniform layer (UL, Santoso and Stull 1998), because within that region wind speed and potential temperature are nearly uniform with height Below the UL is a radix layer (Santoso and Stull 1998), of which the classical surface layer is a subdomain.

Convective transport theory that was first suggested by Stull (1994) parameterized surface momentum flux for convective conditions (analogous to drag coefficient in traditional surface drag formulation). It was originally calibrated with data from Boundary Layer Experiment-1983 (BLX83) in Oklahoma (Stull and Eloranta 1984), and was independently validated using data from the Koorin experiment in Australia (Clarke and Brook 1979). By using surface skin and the UL values in the formulation, Stull (1994) proposed that surface momentum flux parameterization should be independent of roughness length for free convection, an hypothesis that will be tested here.

The empirical parameter has been tested over a variety of sites by Lundquist (1997, 1998), Greischar and Stull (1998), and Chang & Grossman (1998). These sites include the Tropical Ocean-Global Atmosphere - Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE) conducted in western Pacific (Bond and Alexander 1994), and the 1997 Cooperative Atmospheric-Surface Exchange Study (CASES97) conducted in Kansas (LeMone et al. 1998, LeMone and Grossman 1998).

Greischar and Stull (1998), and Chang and Grossman (1998), found the surface flux parameterization to work over the Pacific Ocean warm pool, but with slightly different values of the empirical parameter. Lundquist also found parameter values to vary by site (rangeland/pasture vs. winter wheat). Beljaars (1995) and Sorbjan (1995, 1997) argue that the parameter should also depend on the surface roughness, based on the success of roughness-based surface-layer and micro-layer similarity theories.

A new BL field experiment (BLX96) was conducted in Oklahoma and Kansas over three sites with different aerodynamic roughness (Stull et al. 1997) to test the parameterization and its empirical parameter. One goal of this paper is to present in details of BLX96. In brief, The University of Wyoming King Air aircraft collected turbulence measurements in the bottom half of the convective BL. The aircraft measured standard BL parameters including: mean (line averaged) variables, turbulent deviations, and turbulent fluxes of temperature, moisture, and momentum. Portions of each flight included slant soundings and near-surface horizontal flights to determine radiometric surface skin temperature and ML scaling variables such as ML depth, Deardorff velocity. While the ML during BLX96 was shallower and the ground wetter than anticipated based on climatology, a high-quality data set was obtained.

Another goal of the present paper is to test, refine, and better understand the capabilities and limitations of surface momentum flux parameterization. Detailed results from BLX96 will be given along with re-analyses of six other published data sets. It will be shown that there is a dependence of the coefficients on the surface roughness.

2. REVIEW OF SURFACE MOMENTUM FLUX PARAMETERIZATION

Surface-momentum-flux bulk-transfer relationship (Stull 1994) is shown as follows:

$$u_*^2 = C_{*D} \cdot w_* \cdot \overline{M}_{UL} \qquad (1)$$

where C_{*D} is the dimensionless, empirical ML coefficients for momentum, and w_* is the Deardorff velocity that is shown in the following equation:

$$w_* = \left[(g / T_v) \cdot z_i \cdot \overline{w'\theta_v'}_s \right]^{1/3} \qquad (2)$$

where g is gravitational acceleration, T_v is virtual absolute temperature, z_i is the convective BL depth, $\overline{w'\theta_v'}_s$ is vertical virtual temperature flux near the surface, and subscript s denotes near-surface characteristics

The last factor in (1) is a difference between the surface skin condition and the value in the UL, for wind speed $\Delta\overline{M} = \overline{M}_{skin} - \overline{M}_{UL} = -\overline{M}_{UL}$ where the wind is zero at the ground by definition. The negative sign on the UL wind speed disappears in (1) because friction velocity squared (u_*^2, a positive number) is used in place of the surface momentum flux (a negative number for westerly winds) in the left-hand side. In other words, (1) relates the magnitude of the surface stress to the magnitude of the wind speed, with the understanding that surface drag (momentum flux) acts in a direction opposite to the wind vector.

Eq. (1) is in implicit form, because the surface momentum flux on the left side is a function of surface heat and moisture fluxes hidden in w_* on the right side. This is because w_* is a function of

$$\overline{w'\theta_v'}_s \approx \overline{w'\theta'}_s \cdot (1 + 0.61 \cdot \bar{r}) + 0.61 \cdot \bar{\theta} \cdot \overline{w'r'}_s$$

Fortunately, that equation is easy to manipulate into explicit form (Stull 1994), yielding:

$$u_*^2 = b_D \cdot w_B \cdot \overline{M}_{UL} \qquad (3)$$

where b_D is the dimensionless empirical convective transport coefficient for surface momentum flux, and w_B is buoyancy velocity that is shown by following equation:

$$w_B = \left[(g / T_v) \cdot z_i \cdot \Delta\theta_B \right]^{1/2} \qquad (4)$$

Stull (1994) showed theoretically and empirically to get a relationship between w_* and w_B :

$$w_* = b_H^{1/3} \cdot w_B \qquad (5)$$

where b_H the dimensionless empirical convective transport coefficient for surface heat flux (see Stull 1994, Santoso 1999). Stull (1994) also defined a dimensionless ML Richardson number R_* to indicate the ratio between buoyant and mechanical turbulence production mechanisms:

$$R_* = \left(w_B / \overline{M}_{UL} \right)^2 \qquad (6)$$

Free convection is approached as R_* increases.

3. REVIEW OF PREVIOUS ESTIMATES OF EMPIRICAL TRANSPORT COEFFICIENT VALUES

Stull (1994) used data from the BLX83 field experiment near Chikasha, in an agricultural region in Oklahoma (Stull and Eloranta 1984), to evaluate the empirical ML transport coefficient for surface momentum flux. The region was generally flat with local height variations on the order of 15 m and gentle average slope toward the east with gradient 1/1000. The average aerodynamic roughness length was on the order of z_o = 0.05 m. He found that the mean non-dimension ML transport coefficient and its standard deviations to be: C_{*D} = 0.023 (± 0.007). The associated convective transport coefficient was: b_D = 0.0018 (± 0.0006). He found that a value of R_* > 3 indicated free convection. Both the theory and the parameter values were found to work well when tested with independent data from the Koorin experiment (Clarke and Brook 1979) conducted in a semiarid, forested area with a grass understory in northern Australia, with average roughness of z_o = 0.4 m.

Greischar and Stull (1998) used data from the TOGA-COARE field experiment in the Western Pacific to test and validate the applicability of the surface momentum flux parameterization for a tropical marine BL. The momentum flux values during this field campaign was an order of magnitude smaller than those of the BLX83 experiment. They found the dimensionless ML coefficient and it standard deviation C_{*D} = 0.0053 (± 0.0023) and the related convective transport coefficient to be: b_D = 0.0004 (± 0.0002). They also used value of R_* > 3 to indicate free convection. The parameter value for momentum was much larger, perhaps indicating that surface wind-wave characteristics were important. Aerodynamic roughness length was roughly z_o = 0.00003 to 0.0004 m.

Lundquist (1997) used data from two Kansas sites obtained during the 22 April to 22 May 1997 field period of CASES97. The Beaumont, KS, site was mostly rangeland/pasture with some rolling hills and a large escarpment to the east. The Oxford, KS, site was mostly winter wheat, with patches of trees. Aerodynamic roughness in the rangeland/pasture was roughly z_o = 0.01 m, and in the winter wheat was roughly z_o = 0.05 m. Values of the surface momentum flux were found using sonic anemometers at 4 m height on instrumented masts, and a cross-chain loran sounding system (CLASS) was used to get mid-ML characteristics. She found C_{*D} = 0.013 ± 0.01 at Beaumont, based on 22 data points. For the Oxford site, she found C_{*D} = 0.011 ± 0.011 based on 10 data points.

All of the field programs above used the same method to find mean and standard deviation values of C_{*D}. Namely, first the C_{*D} value was found using (1) from each individual run or sub-experiment, and then the resulting set of C_{*D} values were combined to yield the reported statistics for each field program. In this research a different approach will be taken, using regression to estimate the best C_{*D} coefficients for the whole field program. This approach yields new insights into the systematic variation of coefficient values.

4. BLX 96 OBSERVATIONS AND DATA ANALYSIS PROCEDURE

Data from the Boundary Layer Experiment - 1996 (BLX96) field experiment over Oklahoma and Kansas are used here as an additional test of CTT for heat and momentum fluxes. Relatively flat topography, large areas of uniform land use, and frequent fair weather motivated the selection of this region. The University of Wyoming King Air aircraft was flown over three different sites having different land use and surface roughness within this region, in order to determine if the empirical coefficients for momentum flux are indeed independent of surface roughness. The three flight tracks were named after nearby villages, with each track length of order 70 km.

The Lamont track, in Oklahoma, was primarily over crop land, and was the least rough. Terrain under the track was quite flat, but gently rising to the west, with elevations ranging from 320 to 425 m MSL (mean sea level). Vegetation coverage consisted of 60 - 80% wheat fields, 20 - 40% pasture, and a small number of trees less than 10 m tall. The average aerodynamic roughness was z_o = 0.1 m, based on direct calculations using Monin-Obukhov similarity theory for the surface layer, and using tables of roughness classifications (Smedman-Hogstrom and Hogstrom 1978; Stull 1988; Wieringa 1980, 1986).

The Winfield track, in Kansas, was over predominantly pasture land. Small hills near the center of the track ranged from 70 to 100 m in height. Terrain was rising to the west, with elevations ranging from 250 to 400 m MSL. Vegetation coverage consisted of 30 - 60% pasture, 10 - 50% forested areas (more wooded at the east end) with trees less than 10 m tall, and the remaining area was cultivated. The average aerodynamic roughness length was z_o = 0.9 m.

The Meeker track, in Oklahoma, was over a region mainly covered by forest, and was the most rough. It had more small rolling hills that ranged from 40 to 60 m in height. Otherwise, the terrain was relatively flat, with elevations from east to west ranging from 250 to 280 m MSL. Vegetation coverage consisted of 40 - 50% pasture, 40 - 60% wooded areas with trees less than 10 m tall, and 10 - 30% cropland. The average aerodynamic roughness length was z_o = 1.4 m. A more detailed description of the goals, sites, instruments and experimental procedures of BLX96 can be found in Stull et al. (1997) and Berg et al. (1997).

Flight patterns were designed by first “flying” a virtual aircraft along several candidate flight patterns through a hypothetical boundary layer (Santoso and Stull 1999), and then analyzing the synthetic data collected for robustness using the criteria of Lenschow and Stankov (1986). Based on the resulting experimental design, 34 low-altitude horizontal flight legs were actually flown, each 68 to 75 km long, during 12 flights of the King Air flown between 15 July and 13 August 1996. Average heights of the low-altitude legs varied between 30 m and 75 m AGL (above ground level). Also flown at the beginning, middle, and end of the flight each day were slant ascent/descent soundings from 5 m AGL to top altitudes well above the top of the ML (top altitudes were on the order of 3 to 4 km AGL, but varied from day to day depending on the weather).

Flight conditions varied from clear to partly cloudy, with UL winds ranging from near calm to 13 ms^{-1}. There was no moisture flux data during 21 July 1996, so for that one day we use $\overline{w'q'}_s$ as an estimate of $\overline{w'\theta_v'}_s$.

Fast rate data, sampled at 50 Hz for the three wind components, mixing ratio and temperature, were used in the eddy-correlation flux calculation for each leg. The aircraft speed was roughly 100 ms^{-1}. Sun et al.’s (1996) recommendations with slight modification were followed in calculating fluxes, considering that the low-altitude horizontal legs were flown almost following the gently-rolling surface terrain. The following criteria were used to identify the acceptable portions of the horizontall legs: aircraft pitch value of less than ± 5° with a difference of less than 2.5° for two any consecutive points, roll values of less than ± 10° with a difference of less than 5° for two any consecutive points, and no sudden changes in height (based on the two radar altimeters). In some cases there were data points in the leg that did not fulfill the above criteria. These data points were removed and replaced with missing-data flags during the post-experiment data analysis.

Before calculating fluxes, the data series were detrended, and were despiked by removing data points that were more than five standard deviations from the mean and replacing them with a linear interpolation between neighboring good data values. In order to remove the inadequately-sampled mesoscale features larger than 2.5 km (equivalent to a wavelength of 5 km), Fourier analysis (Stull 1988; Press et al. 1992) was used to filter out those wavelengths greater than 5 km. The highest frequencies (wavelengths less than 20 m) were removed, because the sensors used to measure wind, mixing ratio and temperature were mounted on different parts of the aircraft, with separation distances of up to 4 - 5 m. These filtered fluxes differed by less than 1% from the unfiltered fluxes, based on filtering experiments we conducted.

The calculated kinematic momentum fluxes for the low-altitude (z of order of 10 m) legs were assumed equal to their respective surface values (i.e., at z = 0), and were combined to yield the square of the surface friction velocity, u_*^2. The kinematic heat-flux values for these low-level legs were extrapolated to the surface following Stull (1994) using $\overline{w'\theta}_s = \overline{w'\theta}(z) / \left[1 - 1.2 \cdot (z / z_i)\right]$. The same method was applied to calculate surface kinematic fluxes of virtual potential temperature, $\overline{w'\theta'_v}_s$, used later to calculate the Deardorff velocity w_*.

From vertical profiles of virtual potential temperature, mixing ratio and winds measured during the aircraft slant ascent and descent soundings, the average mixed layer depths, z_i, were estimated. Then using polynomial interpolation in time to account for the nonstationarity of ML depth during the whole day's flight, z_i for each low-altitude leg at its midtime was calculated, and this z_i value was used in the calculations of w_* for that flight leg.

The next step was to calculate values of wind in the UL. First, the raw slant ascent/descent sounding data were sorted into bins of 2 m height, and an average was computed for the center of each bin. An example of these bin-averaged values are plotted in Fig. 1 for 15 July 96. Bin-averaged winds had significantly more scatter (Fig. 1).

To improve the robustness of the $\overline{M}_{UL}$ estimate, data from the slant soundings and the horizontal flight legs were combined. Fig. 2 shows a comparison of $\overline{M}_{UL}$ computed from the slant ascent/descent sounding averaged between 200 and 600 m, versus $\overline{M}_{UL}$ computed from the near-surface and mid-ML horizontal flight legs immediately before and after (at most 24 minutes difference in mid-times). Because of the relatively close agreement (with average difference of order 0.5 ms^{-1}) between $\overline{M}_{UL}$ found by these methods, we averaged them together to give a final estimate of $\overline{M}_{UL}$, with sampling error of ± 0.550 ms^{-1} standard error of the mean. More details about BLX96 observations and data analysis procedure can be found in Santoso (1999)

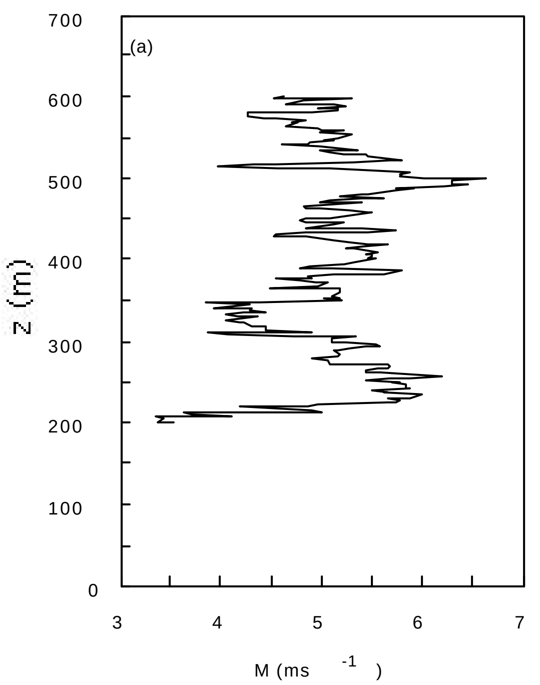

Fig. 1.Example of wind speed, *M,* profiles at 1157 CDT (=UTC – 5 h) during 15 July 96, for flight leg ABA (the first of three deep soundings on this day during BLX96) showing data after averaging into 2 m vertical bins (roughly 15 data per bin). Plotted here are only the portions of the soundings that were within the uniform layer (UL).

5. RESULTS

To find the ML transport coefficients using (1), u_*^2 was linearly regressed against the product $w_* \cdot \overline{M}_{UL}$. The slope of the resulting least-squares best fit gives the desired coefficients, C_{*D}. Plot of this regression allow us to identify other characteristics of the data set that would have been hidden if we had utilized the traditional approach of finding the C_{*D} coefficient separately for each data point using (1), and then averaging the results.

Some of the observations in BLX96 and in the three other data sets were made during conditions that do not satisfy the requirement of free convection. Namely, they were obtained on days when winds and surface stress were great enough to produce a substantial non-buoyant production of turbulence. These are usually discernible as outlier points, for which we identify the wind speed $\overline{M}_{UL}$, surface stress u_*^2, and/or convective Richardson number R_* that best explain their characteristics. It will be suggested later which of these three criteria provide the best overall estimate of non-free-convective conditions.

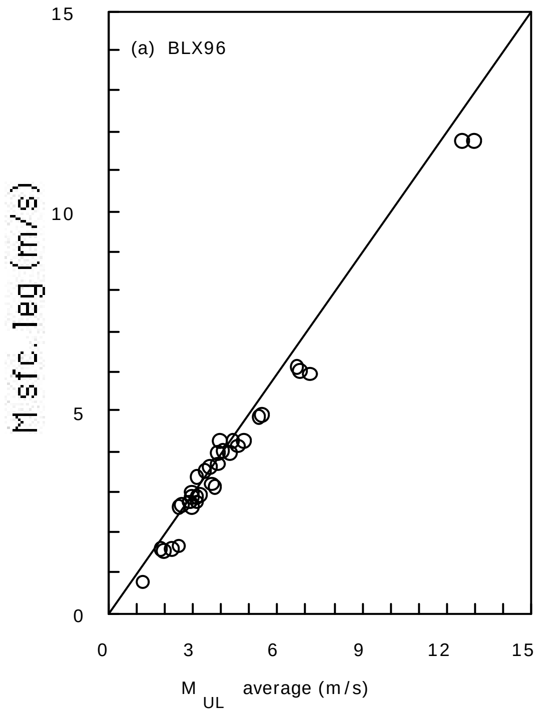

Fig. 2. Comparison of uniform-layer winds, M_{UL}, found from near-surface flight legs vs. averages over all horizontal flight legs and vertical soundings flown at neighboring times, based on all flights during the two month BLX96 field experiment.

5.1 Empirical Transport Coefficients for BLX96

Fig. 3 shows the method of estimated the transport coefficients C_{*D}, using different plotting symbols for the three field sites. There is significant natural segregation of the data by sites for momentum fluxes. For this reason, the Lamont, Meeker, and Winfield momentum fluxes are analyzed separately.

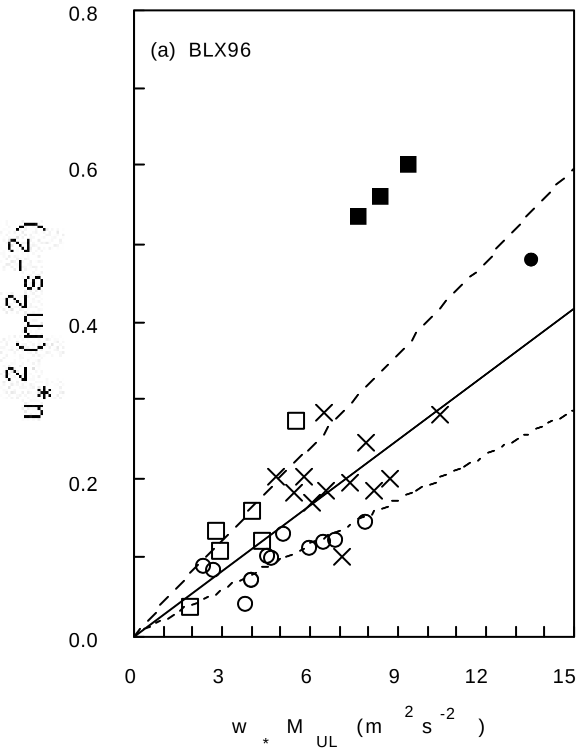

Fig. 3. Friction velocity squared, u_*^2, as a measure of the magnitude of momentum flux is regressed (straight line) against the product of Deardorff velocity w_* times magnitude of the wind-speed difference $\left|\Delta\overline{M}\right| = \left|\overline{M}_{skin} - \overline{M}_{UL}\right| = \left|0 - \overline{M}_{UL}\right| = \overline{M}_{UL}$, for BLX96 field experiment data [Winfield (crosses and solid line), Meeker (open squares and dashed line), Lamont (open circles and dotted line), and the non-free-convective cases (Meeker: filled square and Lamont: filled circle)]. The regression is forced to pass through the origin.

For the Lamont, Meeker and Winfield data, plots of (u_*^2) versus ($w_* \cdot \overline{M}_{UL}$) are shown in Fig. 3, where the slope of the best-fit lines represent C_{*D}. One of the Lamont data points and 3 of the Meeker data points in this figure are identified as non-free-convection cases based on their large u_*^2 values, and were associated with windy days of $\overline{M}_{UL}$ > 6.8 ms^{-1}, u_*^2 > 0.48 m^{2}s^2 and R_* < 6.0. Excluding the non-free convection data points, we then regress a straight line through the data from each site, with the constraint that the line must pass through the origin. The resulting least-squares best fit ML transport coefficients for momentum are C_{*D} = 0.019 (± 0.007) for Lamont, C_{*D} = 0.028 (± 0.008) for Winfield and C_{*D} = 0.040 (± 0.011) for Meeker, where the plus/minus error is given as a standard deviation. The differences of ML transport coefficients between the three sites are statistically significant, with a significance level of better than 0.03 based on a two-sided t-test.

5.2. *Comparison with Other Field Programs*

To compare with surface momentum flux coefficients from other field programs, we use the same linear-regression approach to reanalyze data from BLX83, Koorin, and TOGA - COARE. For these analyses, we initially constrain the best-fit line to pass through the origin, and also identify non-free convection cases.

The BLX83 data were measured by instrumented aircraft in Oklahoma over rangeland and some crops. Estimated surface roughness lengths for this site were z_o = 0.05 m (Stull 1994) based on the roughness classification tables, and z_o = 0.34 m (Beljaars 1995) based on traditional surface-layer flux-profile relationships. Typical flight leg lengths were about 20 km, which are too short for statistically-robust statistics according to the criteria of Lenschow and Stankov (1986).

Fig. 4 shows the plots of kinematic surface stress (u_*^2) vs. ($w_* \cdot \overline{M}_{UL}$) for all BLX83 data, where the fluxes were found using the eddy-correlation method. The new ML transport coefficient for momentum for BLX83 is C_{*D} = 0.024 (± 0.007). Non-free convection cases (4 points, based on large u_* values) that are excluded from analysis occurred on windy days with $\overline{M}_{UL}$ > 11.8 ms^{-1}, u_*^2 > 0.59 m^{2}s^{-2} and R_* < 1.2.

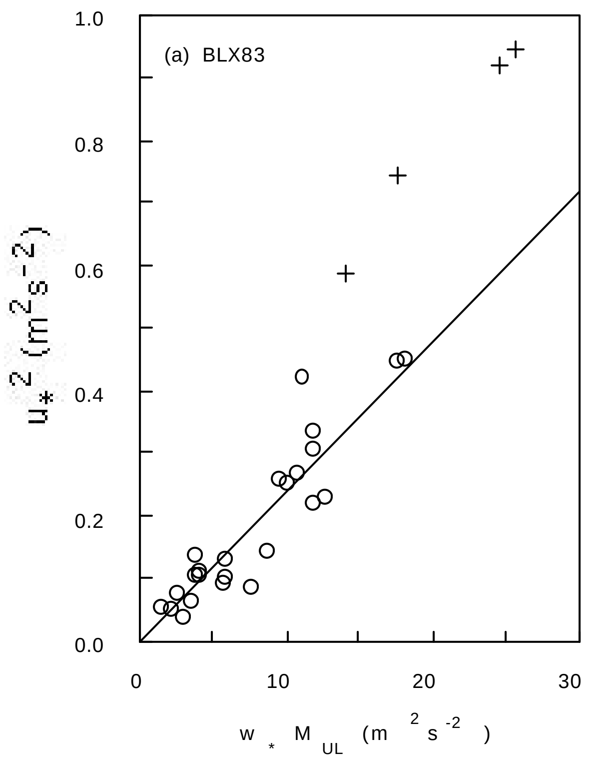

Fig. 4. Similar to Fig 3, but for BLX83. Non-free convection points are indicated with (+) symbols.

In the Koorin experiment, the ABL and UL data were measured by radiosondings in northeast Australia over a sparse forest. Estimated surface roughness lengths were z_o = 0.4 m at site 1 and z_o = 0.9 m at site 2 (Clarke and Brook 1979). The data analyzed for this paper were mainly from observations at site 1. Fluxes were calculated by tower-based eddy correlation. Surface skin temperatures were based on a near surface "black ball" radiometric approach (Clarke and Brook 1979, Stull 1994). Fig. 5 shows the new regression for the Koorin data. The new ML coefficients are C_{*D} = 0.022 (± 0.026). For momentum, the non-free convection cases (17 points) are related to moderately windy days with u_*^2 > 0.48 m^{2}s^{-2}. There is no significant relationship between these outlying values and wind speeds or R_*. Plots from Greischar and Stull (1988) also show that the data behaved less like free convection when R_* < 10, although those authors continued to use the earlier recommendation of R_* < 3 in their discussion. After excluding the cases with large u_*^2, the winds associated with the remaining points vary from moderately windy to nearly calm, with R_* in the range of 3 to over 1000.

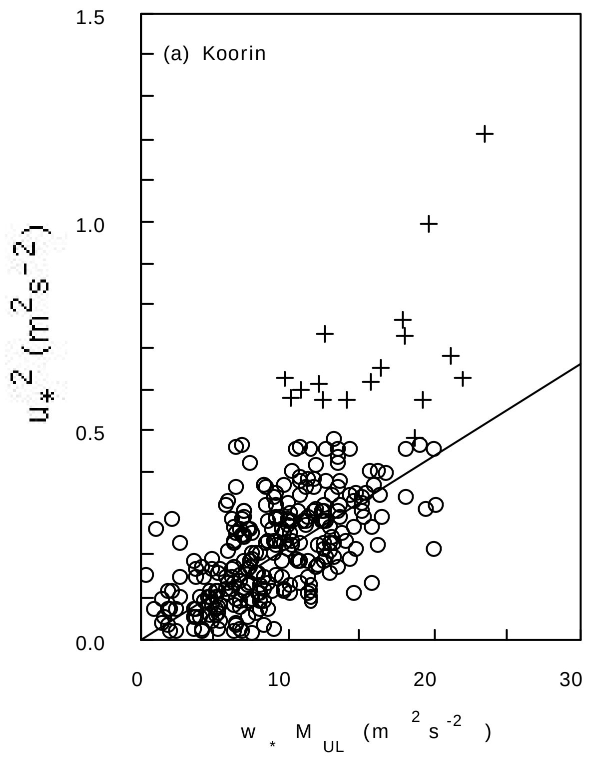

Fig. 5.Similar to Fig 3, but for Koorin. Non-free convection points are indicated with (+) symbols.

TOGA - COARE data were measured by instrumented aircraft over the western tropical Pacific Ocean. The estimated surface roughness length was z_o = 0.0004 m based on surface-layer flux-profile relationships, which was within the range of values found from roughness classification tables. Typical flight legs were longer than 60 km. We neglected possible effects of ocean currents causing nonzero wind at the surface, based on the discussion of Greischar and

Stull (1998). Fig. 6 shows the regressions of kinematic surface stress (u_*^2) vs. ($w_* \cdot \overline{M}_{UL}$). The new ML coefficient for momentum is C_{*D} = 0.0084 (± 0.0030), about an order of magnitude smaller than values over land sites. Winds vary from calm to moderate, values of u_*^2 are relatively small (< 0.05 m^2s^{-2}), and R_* ranges from smaller than 1 to about 75.

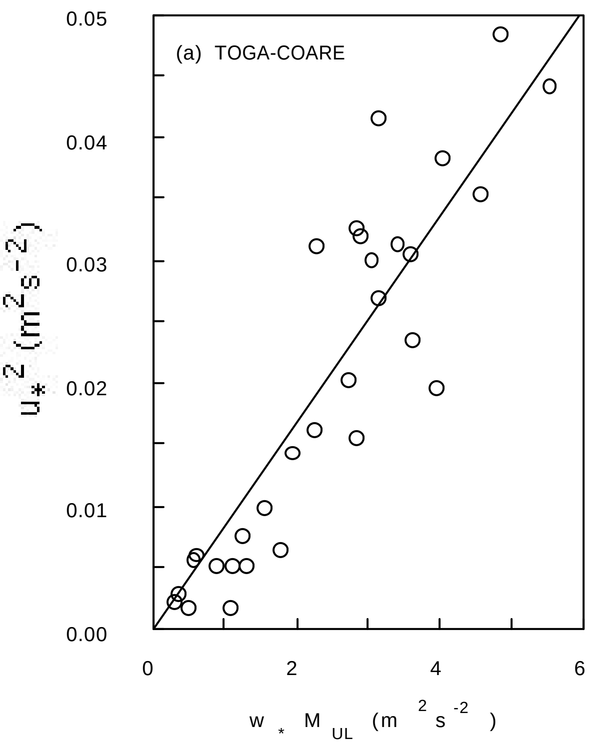

Fig. 6. Similar to Fig 3, but for TOGA - COARE.

5.3. *Dependence of C_{*D} on z_o:*

Based on these comparisons, the ML coefficients for momentum C_{*D} appear to vary with surface roughness z_o. The ML transport coefficients for momentum for BLX83 and Koorin are quite similar, probably due to the similar magnitudes of z_o from both experiments (Beljaars 1995, Clarke and Brook 1979). A linear regression between C_{*D} and z_o based on all six data sets having stress data (three from BLX96, and one each from BLX83, Koorin, and TOGA-COARE) is:

$$C_{*D} = a + b \cdot z_o \qquad (7)$$

where a = 0.014 and b = 0.018 m^{-1}, with correlation coefficient r = 0.94. If we consider the land sites only, the best relation is found using nonlinear-regression to be:

$$C_{*D} = a \cdot \exp(b \cdot z_o) \qquad (8)$$

where a = 0.018 and b = 0.53 m^{-1}, with correlation coefficient r = 0.98. This relationship is plotted in Fig 7.

For the data sets re-analyzed here, the friction velocity squared (u_*^2) was the best indicator of non-free convection situations. The data show that for momentum, the non-free-convection cases generally occur when u_*^2 > 0.47 m^2s^{-2}. For future data analyses, it is recommended that this criterion be used to identify the non-free-convection data, which should be excluded from the analyses of C_{*D}. If one does not exclude such cases with larger observed values of u_*^2, then there will be a tendency to underestimate C_{*D} because of the significant contribution of shear-generation of turbulence.

6. CONCLUSIONS

New data from the BLX96 field experiment were analyzed, and old data from BLX83, Koorin, and TOGA-COARE were re-analyzed to test surface momentum flux parameterization. In summary the following was found:

1) The surface momentum flux parameterization can be used to estimate surface stress if C_{*D} is recognized to be dependent on z_o. This differs from the original suggestion by Stull (1994) that C_{*D} should be roughness independent.
2) There is significant correlation of the ML transport coefficient for momentum C_{*D} with z_o. The best empirical relation for land sites is $C_{*D} = a \cdot \exp(b \cdot z_o)$, where a = 0.018 and b = 0.53 m^{-1}, with correlation coefficient r = 0.98.
3) The empirical coefficient value for the surface momentum over ocean was an order of magnitude smaller than that over land.
4) On the plots of u_*^2 for all sites, although the data are quite scattered, they are distributed reasonably well around best fit lines that are forced to pass through the origin. In other words, zero momentum flux occurs with zero wind speed, as expected.

REFERENCES

Beljaars, A. C. M., 1995: The parameterization of surface fluxes in large scale models under free convection. *Quart. J. Roy. Meteor. Soc.*, **121**, 255 - 270.

Berg, L. K., R. B. Stull, E. Santoso, J. P. Hacker, 1997: *Boundary Layer Experiment - 1996 (BLX96) Airborne Scientist Flight Log*. Boundary Layer Research Team Technical Note BLRT- 97-1. 116 pp. (Available from corresponding author, Stull).

Bond, G. and D. Alexander, 1994 : *TOGA COARE Meteorology Atlas*. TOGA - COARE International Project Office. 336 pp

Chang, H.-R. and R.L. Grossman, 1998: Evaluation of bulk surface flux algorithms for light wind conditions using data from the Coupled Atmosphere-Ocean Response Experiment (COARE). *Quart. J. Roy. Meteor. Soc.* (in press).

Clark, R. H. and R. R. Brook, 1979: *The Koorin Expedition, Atmospheric Boundary Layer Data over Tropical Savannah Land*. Bureau of Meteorology, Australian Government Publishing Service, Canberra. ISBN-0-642-01484-1. 359 pp.

Crum, T. D., R. B. Stull and E. W. Eloranta, 1987: Coincident lidar and aircraft observations of entrainment into thermals and mixed layers. *J. Climate Appl. Meteor.* **26**, 774 - 788.

Greischar, L. and R. B. Stull, 1998: Convective transport theory for surface fluxes, tested over the western Pacific warm pool. *J. Atmos. Sci*. (in press).

LeMone, M. A., S. Oncley, T. Horst., R. L. Grossman, J. K. Lundquist, R. McMillen, B. Hicks, R. Coulter, and G. Klazura, 1998: CASES-97: Diurnal variation of the fair-weather PBL. *Proceedings, Special Session on Hydrology*, Amer. Meteor. Soc., 88 -92.

LeMone, M.A., and R.L. Grossman, 1998: Evolution of potential temperature and moisture during the morning: CASES-97. *Preprints, 13th Symposium. on Boundary Layers and Turbulence, Dallas, Texas. January 1999*. Amer. Meteor. Soc. (in press)

Lenschow, D. H. and B. B. Stankov, 1986: Length scale in the convective boundary layer. *J. Atmos. Sci*., **43**, 1198 - 1209.

Lundquist, J.K., 1997: *A Test of Convective Transport Theory*. Comprehensive Exam Thesis, Program in Atmospheric and Oceanic Science, Univ. of Colorado - Boulder. 32 pp. Available from the author: Julie Lundquist, Campus Box 311, Program in Atmospheric and Oceanic Sciences, Univ Colorado at Boulder, Boulder, CO, USA 80309-0311.

Lundquist, J.K., 1998: Testing Convective Transport Theory with CASES 97 data. Submitted to *J. Applied Meteor*.

Press, W. H., B. P. Flannery, S. A. Teukolsky and W. T. Vetterling, 1992 : *Numerical Recipes in FORTRAN: The Art of Scientific Computing*, Second Ed., Cambridge University Press 963 pp.

Santoso, E, 1999: *Surface Fluxes and Vertical Profiles in the Radix layer*. PhD Dissertation, University of British Columbia, 184pp.

Santoso, E. and R. B. Stull, 1998: Wind and temperature profiles in the radix layer, the bottom fifth of the convective boundary layer. *J. Appl. Meteor.*, **37**, 545 - 558.

Santoso, E. and R.B. Stull, 1999: Use of synthetic data to test flight patterns for a boundary-layer field experiment. *J. Atmos. and Ocean Tech.*, **16** (in press).

Smedman-Hogstrom, A. S. and U. Hogstrom, 1978: A practical method for determining wind frequency distributions for the lowest 200 m from routine meteorological data. *J. Appl. Meteor.*, **17**, 942 - 954.

Sorbjan, Z., 1995: Toward evaluation of heat fluxes in the convective boundary layer. *J. Appl. Meteor.*, **34**, 1092-1098.

Sorbjan, Z., 1997: Comments on "A convective transport theory for surface fluxes." *J. Atmos. Sci.*, **54**, 576-578.

Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers, Dordrecht, The Netherlands. 666 pp.

Stull, R.B., 1993: Review of nonlocal mixing in turbulent atmospheres: transilient turbulence theory. *Boundary-Layer Meteor.*, **62**, 21-96.

Stull, R. B., 1994: A convective transport theory for surface fluxes. *J. Atmos. Sci.*, **51**, 3 - 22.

Stull, R. B., 1995: *Meteorology Today for Scientists and Engineers*. Wadsworth (West) ITP, Belmont, California. 385 pp.

Stull, R. B., 1997a : Reply (to comments on "A convective transport theory for surface fluxes). *J. Atmos. Sci.*, **54**, 579.

Stull, R. B., 1997b: Convective transport theory and the radix layer. *NATO Advanced Study Institute Buoyant Convection in Geophysical Flows*. Pforzheim, Germany.

Stull, R.B. and E.W. Eloranta, 1984 : Boundary Layer experiment - 1983. *Bull. Amer. Meteor. Soc.*, **65**, 450 - 456.

Stull, R.B. and E.W. Eloranta, 1985: A case study of the accuracy of routine, fair-weather cloud-base reports. *National Weather Digest*, **10**, 19-24.

Stull, R. B., E. Santoso, L. Berg and J. Hacker, 1997: Boundary layer experiment - 1996 (BLX96). *Bull. Amer. Meteor. Soc.*, **78**, 1149-1158.

Sun, J. et al., 1996 : Scale dependence of air-sea fluxes over the western equatorial Pacific. *J. Atmos. Sci.*, **53**, 2997 - 3012.

Wieringa, J., 1980 : Representativeness of wind observations at airports. *Bull. Amer. Meteor. Soc.*, **61**, 962 - 971.

Wieringa, J., 1986 : Roughness-dependent geographical interpolation of surface wind speed averages. *Quart. J. Roy. Meteor. Soc.*, **112**, 867 - 889.

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