A NOTE ON BULK AERODYNAMIC COEFFICIENTS FOR SENSIBLE HEAT AND MOISTURE FLUXES

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Abstract. Values are presented for bulk aerodynamic coefficients which were calculated from two rather extensive sets of estimates of sensible heat and moisture fluxes based on profile measurements. These results are compared with a number of other results mainly based on fluxes estimated from eddy-correlation measurements.

1. Introduction

In the last decade or so, considerable effort has been expended in attempts to make direct estimates of the exchanges of momentum, moisture (and thus latent heat), and sensible heat between the atmosphere and the ocean. Such measurements are very useful in increasing our understanding of the exchange processes. However, for larger scale studies of the oceanic and atmospheric circulations, values of the exchanges are needed over wide areas and long periods of time; it is not feasible to obtain these values by direct measurements. Attempts must be made to parameterize the exchanges in terms of variables that are, or are likely to be, more readily available.

The bulk aerodynamic method provides one approach to parameterization. The parameterization formulae are:

$$\begin{aligned}&\text{stress, } \tau = \varrho C_D U^2\\ &\text{sensible heat flux, } H_s = (\varrho c_p)\, C_T U \Delta\theta\\ &\text{moisture flux, } E = C_q U \Delta q\end{aligned} \tag{1}$$

where ϱ is air density, U is mean wind speed, c_p is specific heat of air at constant pressure, $\Delta\theta$ is the potential temperature difference [sea surface temperature $(T_s)-$ air temperature $(T_a)-\gamma Z$] (γ is the adiabatic lapse rate, 0.01 °C m^{-1}, and Z is height in meters), and Δq is the humidity difference (sea surface absolute humidity (saturation value at T_s)$-$air absolute humidity (q_a)). Some reference level in the atmospheric surface layer (commonly 10 m) is chosen for U, T_a and q_a. C_D, C_T and C_q are non-dimensional bulk aerodynamic coefficients and are sometimes referred to as the drag coefficient, Stanton number and Dalton number, respectively. Roll (1965) discusses the derivation of these equations and suggests that $C_D \approx C_T \approx C_q$ over the sea for near-neutral stability. Perhaps it is best to regard these equations as simple, dimensionally correct formulae which need to be tested by as direct means as possible.

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A good deal of work has been done on the momentum exchange and it appears that the drag coefficient is a useful parameter and is reasonably well established for wind speeds up to about 15 m s^{-1}, as noted by a number of authors (Hidy, 1972; Phillips, 1972; Pond, 1972). The value of C_D appears to be about 1.5×10^{-3} with an uncertainty of perhaps 20%; its dependence on stability, over the range usually encountered, wind speed and other parameters seems to be rather weak. The reader is referred to the cited papers for further discussion.

Rather less work has been done on the sensible heat and moisture exchanges due to greater experimental difficulties and perhaps in part because many of the investigators have been oceanographically oriented and hence more interested in the momentum exchange. Our knowledge of the coefficients C_T and C_q is rather limited (see, for example, Phillips, 1972). However, interest in them has increased because of their importance in estimating energy inputs to the atmosphere for such things as GARP (Global Atmospheric Research Program) and modeling of the general circulation. Clearly any data which could be used to provide measurements of C_T and C_q should be examined.

Recently a number of estimates of C_q and C_T have been made (Hasse 1970; Hicks 1972; Pond *et al.*, 1971). In addition, estimates of the heat and moisture fluxes based on two rather extensive sets of profile measurements have recently been published (Badgley *et al.*, 1972; Paulson *et al.*, 1972). In view of the limited knowledge of C_T and C_q, we felt it worthwhile to compute the values from these data sets and make comparisons with other estimates.

In addition, the C_T results from Pond *et al.* (1971) appear to be anomalous. The statistically more reliable air temperatures from the profile analysis of Paulson *et al.* (1972) can be used to re-examine these apparently anomalous results.

2. Data

The data reported in Badgley *et al.* (1972) were collected over the Arabian Sea. The results are based on a very careful analysis of 110 profile observations (each based on about a 40-min average) measured on a buoy upwind of the ship. Corrections were made for stability effects on the profiles and then fluxes of momentum, moisture and sensible heat were estimated. The top level of the profiles was about 8 m and these values are used as reference level value for calculating C_D, C_T and C_q from Equations (1).

The data reported in Paulson *et al.* (1972), were collected from FLIP (Floating Instrument Platform) situated in the tropical Atlantic near Barbados during BOMEX (Barbados Oceanographic and Meteorological Experiment). Again the results are based on a careful analysis of profile observations (141 runs each based on about a 48-min average). Corrections were made for stability effects and also for structural interference from FLIP (by comparison of the momentum flux estimates with those of Pond *et al.* (1971) based on eddy-flux and dissipation measurements). The top level of the profiles, again used for the reference values, was about 11 m for these data.

In both these sets of data, the air-sea temperature differences and sensible heat fluxes are rather small so one might expect considerable scatter in the values for C_T. On the other hand, both sets are from regions where the air-sea humidity differences and moisture fluxes are large so one might expect to get good results for C_q.

The reference heights differ in the two cases but the effect on the results is quite small compared to the scatter caused by statistical variability and observational errors (They differ from 10-m values by 2–4%.) The coefficients reported below are based on the observed values. For the Pond *et al.* (1971) C_T results, their values of wind speed are used (8 or $8\frac{1}{2}$ m) with the Paulson *et al.* (1972) values for $\Delta\theta$ (11 m); thus the C_T's should be representative of 10-m values within about 1%.

3. Results

3.1. Drag coefficients

Since the value of the drag coefficient is reasonably well known, the values for these data sets provide a check on their quality. For both sets, the authors report values reduced to a 10-m reference height and conditions of neutral stability. Badgley *et al.* (1972) give the value 1.4×10^{-3} and Paulson *et al.* (1972) give the value 1.3×10^{-3}.

We also calculated the values from the estimated stress and the observed values of U at the top of the profile; for the Arabian Sea, the value is $(1.55\pm0.28)\times10^{-3}$ (mean$\pm$standard deviation); for BOMEX the value is $(1.45\pm0.21)\times10^{-3}$. Extrapolated to 10 m, the values of $10^3\ C_D$ are 1.49 and 1.48, respectively. These values are somewhat larger than those reported, as might be expected because the measurements were made under somewhat unstable conditions. The values for C_D computed in either way are reasonable giving some confidence in the quality of the data.

3.2. Sensible heat-flux coefficients

Badgley *et al.* (1972) report that the values of the sea-air temperature differences for their data are not very accurate. An examination confirms that there is some systematic error, since there are small upward fluxes as estimated from the profiles in some cases with $\Delta\theta<0$. The best that one can hope to do is to show that their data are consistent with the representation $H_s/\varrho c_p=C_T U\Delta\theta$. The most likely problem is a more or less constant offset in their $\Delta\theta$'s due to an error voltage in the amplification of their thermocouple voltages. One should be able to find such an offset by examining their data for cases when $\Delta\theta$ might be expected to be small. We estimated an expected $\Delta\theta$ from $H_s/(\varrho c_p U C_T)$ using $C_T=1.5\times10^{-3}$. In order that the correction should not be too sensitive to the assumed value of C_T, we used only cases for $|\Delta\theta\ \text{estimated}|<0.5°\text{C}$ with typical values of about 0.3°C. We found that the correction required to make $\Delta\theta$ fit $\Delta\theta$ estimated for these runs (22 out of 110) was 0.85 ± 0.26°C (mean$\pm$ standard deviation). We then calculated C_T using $\Delta\theta$ observed $+0.85$°C. The result is $10^3\ C_T=1.91\pm2.2$. Clearly the results are rather scattered probably in part due to observational errors in both H_s and $\Delta\theta$ and also round-off in H_s which is reported to the nearest 0.1 mW cm^{-2}. To check this idea, we eliminated runs with $|\Delta\theta\ \text{corrected}|<$

$<0.5°C$ and $|H_s|<0.5$ mW cm^{-2}. For these runs (70 out of the original 110) 10^3 $C_T=1.67\pm0.69$. Thus it appears that these data are consistent with a bulk aerodynamic parameterization but with a lot of scatter due to observational errors because the values of H_s and $\Delta\theta$ are rather small.

For the Paulson *et al.* (1972) data from BOMEX, there do not appear to be any systematic errors although there is still quite a lot of scatter. For all the data (141 runs), 10^3 $C_T=1.64\pm1.06$. If runs with $|\Delta\theta|<0.5$ and $|H_s|<0.5$ are removed, then for the remaining runs (99), 10^3 $C_T=1.54\pm0.64$.

For the Pond *et al.* (1971) data, also measured on FLIP during BOMEX, the values for C_T based on eddy-flux measurements seem to be rather high. Using T_a from the profiles, one could get a more reliable estimate of $\Delta\theta$ than that using T_a from the deck psychrometer observations used in the original calculations. In addition, the one result which did not fit with the others (OSU run 12) was, as had been suspected, due to an error in the recorded value of T_a. The values reported in Pond *et al.* (1971) with run 12 corrected give: for all 16 runs, 10^3 $C_T=5.20\pm2.29$; for the 8 runs with $\Delta\theta>0.5$, 10^3 $C_T=3.11\pm0.60$. Using T_a from the profiles the results are: for all 16 runs, 10^3 $C_T=4.05\pm1.98$; for the 10 runs with $\Delta\theta>0.5$, 10^3 $C_T=2.74\pm0.63$. Clearly no matter how we sort the data, the C_T's based on the eddy-flux observations are larger than those based on the profile observations. Indeed, where the data were taken over about the same time periods, the eddy-flux estimates of H_s are nearly twice those estimated from the profiles.

3.3. Moisture flux coefficients

The Arabian Sea data yield 10^3 $C_q=1.42\pm0.40$. If we accept that there is a systematic offset in $\Delta\theta$, then this offset will produce an error in the humidity differences as well, since the wet-bulb temperature is based on the observed air-sea and wet bulb-dry bulb differences. The effect of this possible error is to increase Δq by about 10% and thus reduce C_q by about 10% on the average.

The BOMEX profile data yield 10^3 $C_q=1.47\pm0.18$.

4. Comparison with Other Results

There are some other results with which these values may be compared. Kitaigorodski and Volkov (1965) examined a number of earlier results. There is a great deal of scatter in the C_T, C_q values. As Phillips (1972) notes, the data were not of very high quality. Perhaps much of the scatter is due to observational errors and some to the neglect of stability corrections in computing fluxes from profiles. Their results are rather reminiscent of the early drag coefficient results. However, it appears that $C_q \simeq C_T$ with a great deal of scatter about an average between 10^{-3} and 2×10^{-3} (with values ranging from 10^{-4} to 10^{-2}).

A number of other results along with those calculated as reported in the previous section are summarized in Table I. One should probably not read too much into the numerical value based on Wüst's work (Sverdrup, 1951) because of the problems of

TABLE I

Values of C_T and C_q from various sources

Source	Location	Method	Wind speed range (m s^{-1})	Value (mean $\pm$ standard deviation when available)
Sverdrup (1951) based on Wüst's measurements	Tropical and South Atlantic	evaporation pan	5–10[a]	$10^3\ C_q = 1.3$
Hasse (1970)	North Sea	eddy flux	4–11	$10^3\ C_T = 1$
Hicks (1972)	Lake Wyangan, Bass Strait, Lake Michigan	eddy flux	3–10	$\left.\begin{matrix}10^3\ C_T\\10^3\ C_q\end{matrix}\right\} = 1.4$
Pond *et al.* (1971)	BOMEX	eddy flux	4–7	$10^3 C_T = 2.7 \pm 0.6$
	San Diego	eddy flux		$10^3\ C_T = 1$
	BOMEX and San Diego	eddy flux		$10^3\ C_q = 1.23 \pm 0.17$[b]
		dissipation		$10^3\ C_q = 1.25 \pm 0.25$[b]
Calculated from Badgley *et al.* (1972)	Arabian Sea	profile	2–8	$10^3\ C_q = 1.42 \pm 0.40$
Calculated from Paulson *et al.* (1972)	BOMEX	profile	$2\frac{1}{2}$–8	$10^3\ C_T = 1.54 \pm 0.64$
				$10^3\ C_q = 1.47 \pm 0.18$

[a] long-term averages

[b] determined from the same data set

pan correction factors. However, the result does suggest that the bulk aerodynamic parameterization with $C_q \sim$ constant is reasonable. Hicks and Dyer (1970) point out that their value of C_T (1.4×10^{-3}) is consistent with estimates of C_q from large lakes $(\sim 1.5 \times 10^{-3})$. Deacon and Webb (1962) give values for C_q between 1×10^{-3} and 1.6×10^{-3} based on their formula for C_D and various hypotheses for the moisture exchange process.

Of the results in Table I, only the Pond *et al.* (1971) C_T result for the BOMEX data does not seem to fit with the others, being too large by a factor of about 2. It seems unlikely that this large discrepancy is an experimental error. Some recent calculations reported by Coantic and Seguin (1971) seem to provide a possible explanation. As they point out, it is not H_s which is constant with height in the surface or constant flux layer but $H_s +$ the long-wave radiation flux. In conditions of high humidity and low winds, the radiation flux divergence can lead to an appreciable increase of H_s at heights of a few meters. The results are only suggestive because many assumptions are made, in particular that the temperature profile is not much affected. However the results do seem to fit the observations; the eddy flux estimates of H_s seem too high for the observed values of $U\Delta\theta$ but the profile values are about as expected. Thus $C_T U \Delta\theta$ with a value of 10^3 C_T of about 1.5 serves to estimate the sensible heat flux from the surface but this flux increases somewhat with height. This situation is only likely to arise when H_s is a rather small term in the heat balance since sufficiently high humidities occur only in regions where the latent flux, H_L, dominates H_s.

5. Summary

From the limited number of results available, it seems that the bulk aerodynamic approach is useful for the sensible heat and moisture fluxes. It appears that the coefficient is about the same for both fluxes with a value of the order 1.5×10^{-3} for the moderately unstable conditions typical of the data and the usual conditions encountered over the ocean. (A coefficient corrected to neutral conditions would be somewhat smaller.) This value is also comparable to that of the drag coefficient although, because the details of the boundary layer near the surface are unknown, the prediction of equal drag and scalar coefficients should be regarded with caution. Clearly the number of results and the range of conditions are very limited so the suggested value should be regarded only as *tentative* and subject to revision as more results become available. Fortunately, several groups are making measurements so we may expect considerably more data in the near future.

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