Measurements of Momentum and Sensible Heat Fluxes Over the Open Ocean[1]

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ABSTRACT

Vertical fluxes of momentum and sensible heat have been measured above the sea surface by the direct dissipation method. Measurements were made over the open ocean from the Scripps Floating Instrument Platform (*FLIP*) during the Barbados Oceanographic and Meteorological Experiment (BOMEX). The results are compared with simultaneous measurements of the fluxes by the profile, dissipation, and eddy correlation methods.

The momentum flux was inferred from the rate of viscous dissipation ϵ above the sea surface. The dissipation was determined by integrating the velocity derivative spectra after correcting the spectra for filter response. The friction velocity (u_*) corrected for diabatic effects was 17.4 cm sec^{-1}, corresponding to a shear stress $\tau = 0.35$ dyn cm^{-2}. Profile measurements by the University of Washington gave the same value of u_* in agreement with the present results. Measurements of momentum flux by Oregon State University (OSU) and the University of British Columbia using dissipation and eddy correlation methods gave somewhat higher values. Correction of the Kolmogoroff inertial subrange constant used in the OSU dissipation calculations gives fluxes in good agreement with the present work.

The sensible heat flux was inferred from the rate of dissipation χ of temperature variance. The temperature derivative spectra were corrected for instrument response and integrated to obtain values of χ. The average value of the sensible heat flux was 0.74 mW cm^{-2}, in reasonable agreement with the profile and eddy correlation measurements. A value of sensible heat flux of 2.8 mW cm^{-2} has been reported by OSU using the dissipation technique. Correction of the temperature inertial subrange constant used by OSU lowered their heat flux to 1.1 mW cm^{-2}.

1. Introduction

The transfer of energy and moisture across the sea-air interface plays an important role in determining atmospheric and oceanic circulations. BOMEX was designed to test methods for obtaining estimates of this transport (Holland, 1972). During BOMEX the fluxes of momentum, heat and moisture were measured from a variety of platforms including satellites, airplanes and ships. One of these platforms, the *R/V FLIP*, was used to make measurements in the near surface layer, and provided a "ground truth" for the other systems.

The measurements reported here were made from *FLIP* during the first BOMEX alert period, May 1969. Simultaneous measurements were made by investigators from the University of Washington (UW), University of British Columbia (UBC), Oregon State University (OSU), and the University of California-San Diego (UCSD). The cooperative nature of the program provided a rare opportunity to make direct comparison of flux measurements made by the profile, eddy correlation, dissipation, and direct dissipation techniques. The results using the first three techniques have been reported by Paulson *et al.* (1972) and Pond *et al.* (1971). This paper presents measurements of the vertical transport of momentum and sensible heat using the direct dissipation technique.

The terminology "dissipation technique" is ambiguous since in fact there are three variants of this method. Taylor (1961) demonstrated that by measuring the rates of dissipation of velocity and temperature fluctuations, ϵ and χ, one could infer the fluxes of momentum and sensible heat by balancing the dissipation against production. The variations in technique occur in implementing this simple concept, particularly in estimating the dissipation. The dissipation may either be inferred from measurements in the inertial subrange or it may be measured directly.

Kolmogoroff's (1941) second universal similarity hypothesis relates the velocity structure function to ϵ and the separation distance $\mathbf{r}$ for values of $\mathbf{r}$ within the inertial subrange. Obukhov (1949) extended this result

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to express the temperature structure function in the inertial subrange in terms of χ, ϵ and **r**. Taylor (1961) used measurements of the velocity and temperature structure functions to determine ϵ and χ, and thus the fluxes. Pond *et al.* (1971) have extended the structure function technique to the measurement of moisture flux.

Kolmogoroff's similarity hypothesis can also be formulated in energy-wavenumber space. Using these relations the dissipation can be determined from the measured energy spectrum. This method, called the spectral or Φ_{11} technique, has been used by Miyake *et al.* (1970) to measure the momentum flux. The structure function and spectral techniques are equivalent, and therefore have the same deficiencies. In particular, both require a precise knowledge of the inertial subrange constants for velocity (α_1) and temperature (β_1). Uncertainty in the value of these constants reduces the confidence in results based on this method.

Gibson and Williams (1969) demonstrated that in the atmospheric boundary layer ϵ can be measured directly. With the assumption of local isotropy and Taylor's hypothesis of frozen turbulence ($Ud/dx \approx -d/dt$), ϵ can be determined from the time derivative of the longitudinal velocity u by

$$\epsilon = \frac{15\nu}{U^2}\overline{\left(\frac{du}{dt}\right)^2}. \tag{1}$$

Similarly for χ we find

$$\chi = \frac{6D}{U^2}\overline{\left(\frac{d\theta}{dt}\right)^2}. \tag{2}$$

This approach has come to be known as the direct dissipation technique. Measurement of the mean-square values of the time derivatives is, however, not a trivial task. Sensors with small space resolution ($\sim$1 mm), high-frequency response ($\sim$2000 Hz), and very high signal-to-noise ratios are required. If these criteria are met, this method offers the advantage of being less sensitive to sensor tilting or flow distortion effects than other methods.

2. Instrumentation and data analysis

The velocity and temperature sensors were mounted on the UW roving probe 30 and 35 cm, respectively, above the UW cup anemometer. The roving probe continuously cycled between measurement stations nominally 2, 4, 7 and 12 m above the mean sea surface. The usual UW sampling period of 20 sec at each height was increased to 45 sec to provide adequate time for sampling of the velocity and temperature fluctuations. The average spectra were calculated using data taken during five cycles of the roving probe.

The profiler was located about 15 m to the side of *FLIP* at a location where the flow distortions due to *FLIP* were assumed small. The true distortions are really unknown; however, wind tunnel studies by Mollo-Christensen (1968) indicate that at the chosen measurement location, distortion of the mean speed of 2% could be expected. During BOMEX the conditions were less than ideal. *FLIP* was anchored to the attending tug *Salish* by a bridle and 800 m of line. With the tug steaming slowly downwind, the bridle kept the main deck facing into the wind, and the boom perpendicular to the wind. In spite of this precaution, changing wind and sea conditions caused *FLIP* to rotate about its vertical axis with amplitudes as high as 30°. These oscillations caused serious difficulties in the measurement of fluxes by the profile and eddy correlation techniques. Both of these techniques require long averaging times and are orientation sensitive. Fortunately, the direct dissipation technique is not very sensitive to these effects. The short sampling period ($\sim$15 min) required for this method meant that measurements could be made during the intervals when the rotations of *FLIP* were small. In addition, the velocity and temperature sensors were insensitive to wind direction, provided there was no direct structural interference. The velocity and temperature measurements as discussed by Gibson *et al.* (1970) are summarized below.

a. *Velocity and temperature measurements*

The streamwise velocity was measured with a linearized constant resistance hot-wire anemometer (Thermo-Systems 1054A). The anemometer sensor was a tungsten wire 3.75 μ in diameter and 1.25 mm long, small enough to resolve the viscous dissipation scale without needing to apply wire length corrections. The time derivative of the velocity was obtained simultaneously by analog filtering and differentiation of the velocity signal.

Continuous *in situ* calibration of the hot-wire anemometer against the UW precision cup anemometer showed no signs of drift due to temperature variation or salt contamination. Izumi and Barad (1970) in a comparison of sonic and cup anemometers have shown overspeeding of the cup anemometer can result in 10% errors in the mean speed. A distinct advantage of the direct dissipation technique is that the measured dissipation is independent of the absolute anemometer calibration (Gibson and Williams, 1969).

Temperature fluctuations were measured with a "cold" wire resistance technique. The sensor was a fine platinum wire (0.62 μ diameter, 1.5 mm long) soldered to a hot-wire probe support. Resistance changes of the temperature sensor were detected by using the probe in an ac Wheatstone bridge circuit operating with 1 mA maximum probe current. On-site temperature calibration was obtained by unbalancing the bridge with a known resistance change and using 0.003(°C)$^{-1}$ for the temperature coefficient of platinum. The time derivative of the temperature was measured simultaneously by analog filtering and differentiation of the temperature signal.

The velocity and temperature signals and their time derivatives were recorded simultaneously on an FM magnetic tape recorder (Ampex SP-300). At UCSD the analog signals were played back and converted to digital form for further analysis.

b. Data analysis

The data presented here are the average values from three separate digital runs. Two slightly different sections of the time series were analyzed on a CDC 3600, while a third section was analyzed on an IBM 1130 laboratory data processing system. The spectra of the derivative signals were calculated using a fast-Fourier transform technique. The one-dimensional velocity and temperature derivative spectra measured at 2 m are shown in Figs. 1 and 2. The energy and wavenumber scales have been normalized with the Kolmogoroff length and time scales. These figures demonstrate that the signal bandwidth was sufficient to measure the mean square value of the derivatives. The spectra shown were corrected for 60-Hz noise ($\sim$1%) and for the transfer function of the analog filter used in digitizing. The derivative spectra were integrated both numerically and graphically to obtain the mean square values.

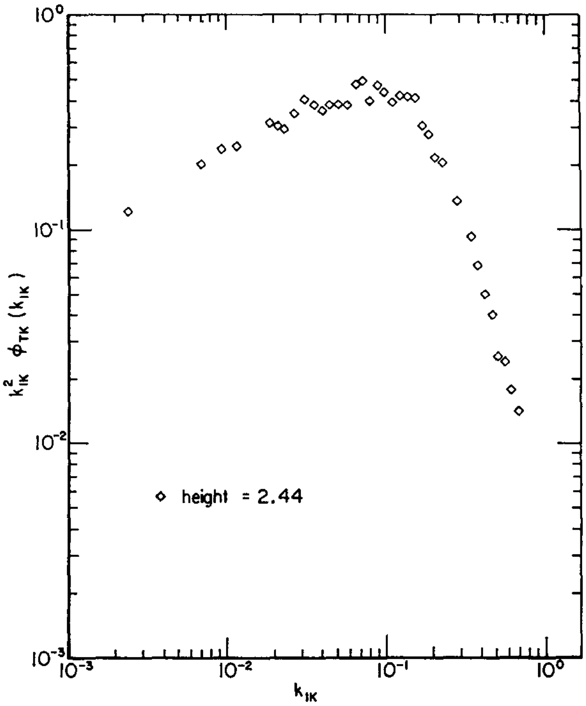

FIG. 2. Temperature derivative spectra (normalized with Kolmogoroff length and time scales) measured at 2.44 m above the mean sea surface.

3. Direct dissipation technique

a. Momentum flux

The direct dissipation technique for momentum flux measurements has been discussed by Gibson and Williams (1969) for the case of unstratified flow. The derivation is repeated here in the context of recent experimental results to elucidate the influence of stratification on the basic assumptions and results. For an equilibrium turbulent boundary layer with horizontal homogeneity, the kinetic energy budget can be written as

$$\overline{uw}\frac{\partial U}{\partial z}-\frac{g}{T}\overline{w\theta}+\epsilon+\frac{1}{2}\frac{\partial\overline{wq^2}}{\partial z}+\frac{1}{\rho}\frac{\partial\overline{pw}}{\partial z}=0, \qquad (3)$$

where

$$q^2=u^2+v^2+w^2.$$

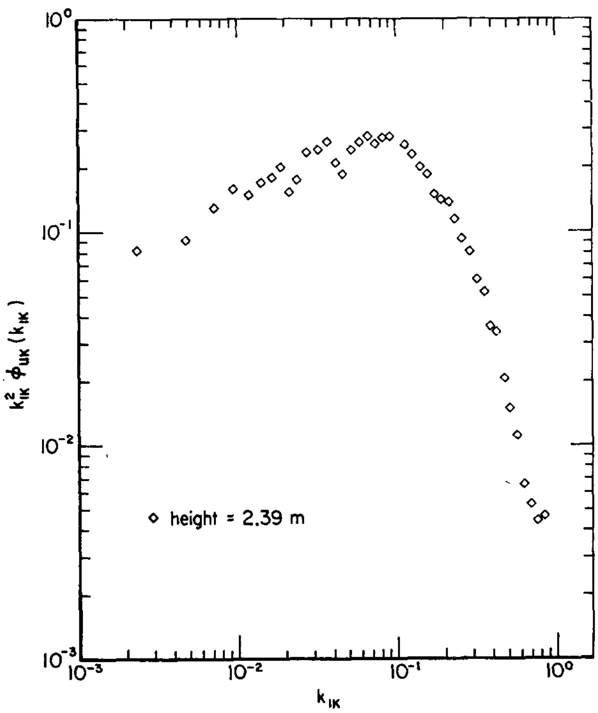

FIG. 1. Velocity derivative spectra (normalized with Kolmogoroff length and time scales) measured at 2.39 m above the mean sea surface.

The first three terms are the rates of shear production, buoyant production, and viscous dissipation. The last two terms are flux divergences due to turbulent and pressure transport, respectively. Wyngaard and Coté (1971) have provided extensive analysis of this budget for the boundary layer over land. While perhaps not strictly applicable to the boundary layer over the open ocean, their results provide insight into the difficulties inherent in measuring the terms in the kinetic energy budget. Aside from the expected measurement errors, they indicate that horizontal inhomogeneity, nonstationarity, and vertical pressure gradients can cause an imbalance in the budget. Their results show that under unstable conditions shear production plus buoyancy production is approximately balanced by dissipation. For neutral conditions the buoyancy production goes to zero, leaving a balance between shear production

TABLE 1. Results of momentum flux calculations.

Height (m)	$kz\bar{\epsilon}$ (cm^3 sec^{-3})	u_* (cm sec^{-1})	u_* [corrected] (cm sec^{-1})
11.69	4.02×10^3	15.9	14.0
6.70	6.86×10^3	19.0	17.3
3.89	6.36×10^3	18.5	17.4
2.39	6.03×10^3	18.2	17.4

and dissipation. In this case the velocity profile is logarithmic and the dissipation is given by

$$\epsilon=u_*^3/(kz), \tag{4}$$

where u_* is the friction velocity and k is von Kármán's constant. For the more general case of stratified flow, stability theory leads to the result

$$kz\epsilon/u_*^3=F(z/L), \tag{5}$$

where L is the Monin-Obukhov length and $F(z/L)$ is a universal function describing the stability effects with a value of 1.0 at neutral conditions ($z/L=0$). Several analytical models for $F(z/L)$ have been suggested in the literature (see Paulson, 1970).

In their formulation of the direct dissipation technique, Gibson and Williams (1969) used (4) to estimate u_*. From (5) we see that neglecting diabatic effects introduces a bias into the data. The averaged values of $kz\epsilon$ are shown in Table 1, along with the values of u_* calculated at each height using Eq. (4). The lower three stations show a 12% increase in $kz\epsilon$ with height, and a corresponding 4% increase in u_*. The anomalously low value of u_* at 11.69 m will be discussed later.

From Wyngaard and Coté (1971) we find a possible analytical form for $F(z/L)$ is

$$F(z/L)=(1.0+0.5|z/L|^{\frac{2}{3}})^{\frac{3}{2}}. \tag{6}$$

From the UW measurements (Paulson *et al.*, 1970), the Monin-Obukhov length was found to be $\sim$25 m. Using this value for L, the corrected u_*'s listed in Table 1 were calculated from (5) and (6). The corrected u_*'s at the first three heights have a value of 17.4 cm sec^{-1}, the absolute value having decreased 5%. In Fig. 3 the measured values of ϵ are shown along with the averaged values corrected for stability effects. This figure gives an indication of the observed variability[3] in ϵ. The essential point is that the corrections for diabatic effects are small relative to the measurement errors usually encountered in flux measurements. By confining the measurements to the first 10 m above the surface, the influence of stability can be ignored for sufficiently large values of the Monin-Obukhov length. Stability corrections can be made later based upon the initial estimates of the fluxes.

b. Sensible heat flux

In the past the direct dissipation technique has only been applied to measurements of the momentum flux. The reason for this has been the difficulty of measuring temperature fluctuations at the dissipation scale. The present results are the first to use the directly measured rate of dissipation of temperature variance in estimating the flux of sensible heat.

To review briefly, the budget for temperature variance under stationary horizontally homogeneous conditions can be written as

$$\overline{w\theta}\frac{\partial\Theta}{\partial z}+\frac{1}{2}\frac{\partial\overline{w\theta^2}}{\partial z}+\tfrac{1}{2}\chi=0, \tag{7}$$

where Θ is the potential temperature and χ the rate of dissipation of temperature variance. The first term is the rate of production of temperature variance by the interaction of the mean vertical temperature gradient and the vertical flux of sensible heat; the second is the turbulent transport of temperature variance.

The present data are insufficient to allow the evaluation of the transport term. Referring again to Wyngaard and Coté (1971), we find that in the stability range $-0.5<z/L<0$, the transport term is typically 10% of the total budget. If the transport term is neglected, the production and dissipation terms balance to give

$$\chi=-2\overline{w\theta}\frac{\partial\Theta}{\partial z}. \tag{8}$$

At neutral conditions, (8) can be written as

$$\chi=2T_*^2u_*/\alpha kz, \tag{9}$$

where $T_*=-\overline{w\theta}/u_*$, a scaling temperature; and

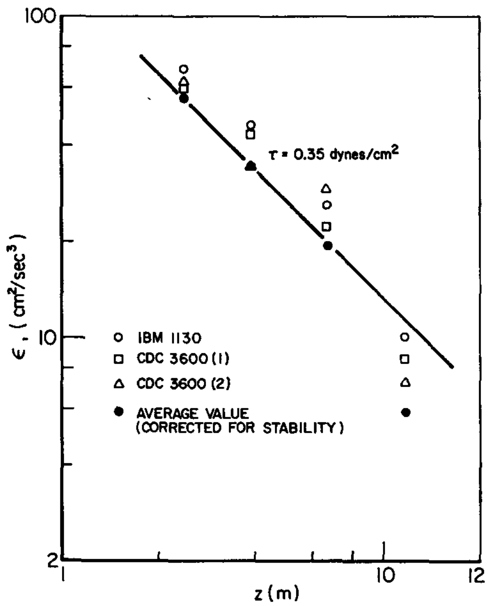

FIG. 3. Measured values of ϵ vs z, the height above the mean sea surface. The solid line has a slope of -1, and corresponds to $\tau=0.35$ dyn cm^{-2} at neutral conditions.

[3] The statistical reliability of the estimates of ϵ will be discussed in a forthcoming paper.

TABLE 2. Results of sensible heat flux calculations.

Height (m)	$kz\bar{\chi}/2$ [(°C)^2 cm sec^{-1}]	T_*[a] (°C)	H_s (mW cm^{-2})
11.74	1.38×10^{-2}	−0.028	0.56
6.75	2.71×10^{-2}	−0.040	0.79
3.94	1.78×10^{-2}	−0.032	0.64
2.44	2.62×10^{-2}	−0.039	0.78

[a] The sign of T_* has been determined from the profile measurements.

TABLE 3. Comparison of flux measurements.

	τ (dyn cm^{-2})	H_s (mW cm^{-2})
UCSD		
Direct dissipation	0.35	0.74
UW (tape 76)		
Profile	0.35	0.61
Corrected profile	0.56	0.61
OSU (run 11)		
Dissipation	0.43	2.8
Eddy correlation	0.44	1.0
UBC (run 3)		
Eddy correlation	0.49	1.3

$\alpha=(\overline{w\theta}\partial U/\partial z)/(\overline{wu}\partial\Theta/\partial z)$, the ratio of eddy transfer coefficients for heat and momentum. The equation is written in this form to show that α and k only appear as a product. In the past, α has been taken to have a value of 1.0 at neutral conditions. However, Businger *et al.* (1971) have suggested that at neutral stability $\alpha=1.35$ is a more appropriate value. They further find a value of von Kármán's constant $k=0.35$ compared to the usual value of 0.4. In the present analysis only the product αk is significant. Using Businger's results, the value of αk increases from 0.4 to 0.47. The resulting increase in T_* is only 8%, indicating the relative insensitivity of this formulation to uncertainties in α and k. Eq. (9) can be rewritten in a form similar to (5) as

$$kz\chi/2T_*^2u_*=G(z/L). \tag{10}$$

The function $G(z/L)$ includes the dependence of α on stability. At neutral conditions $G=1.0$, and we have a simple expression for the flux of sensible heat (expressed as T_*) in terms of the dissipation χ. The averaged values of $kz\chi/2$ are tabulated as a function of height in Table 2. The values of T_* calculated for neutral conditions are given at each height, along with the corresponding value of sensible heat flux H_s. Fig. 4 shows the individual measurements of χ along with the averaged values used in Table 2. The average χ's have not been corrected for diabatic effects, since the variability of χ is considerably greater than the errors introduced by neglecting stability effects. The average value of H_s at the three lower heights is 0.74 mW cm^{-2}.

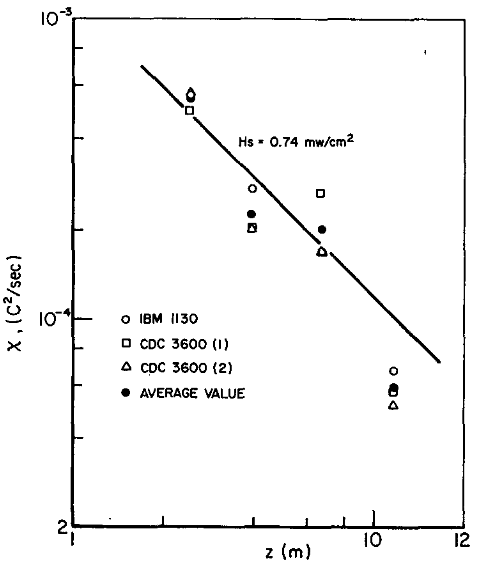

FIG. 4. Measured values of χ vs z, the height above the mean sea surface. The solid line has a slope of −1, and corresponds to $H_s=0.74$ mW cm^{-2} at neutral conditions.

4. Comparison of flux measurements

Data for this study were chosen to be simultaneous with flux measurements by the other investigators onboard *FLIP*. The various independent measurements of momentum and sensible heat flux corresponding to the present work are summarized in Table 3. One is immediately struck by the wide variability in the reported flux values. Each of the investigators has pointed out that the flow distortions due to *FLIP* might account for the discrepancies; however, some basic difficulties of the various techniques warrant further discussion.

a. *Momentum flux*

The profile measurements of mean wind speed by UW have been discussed by Paulson *et al.* (1972). In Table 3, two values of shear stress reported by UW are given: 0.35 and 0.56 dyn cm^{-2}. The higher value is based upon empirical corrections for the structural interference of *FLIP*. This value is clearly too high, as was pointed out by Paulson (private communication). There is a plausible explanation for this result which illustrates an interesting difference between the direct dissipation and the profile techniques for flux measurements. The profile data were corrected by holding the velocity at 12 m fixed, and applying an average correction to the data at lower heights. The high value of the stress suggests that the measured velocity at 12 m was too large. This could be caused by a downdraft convecting fluid characteristic of a higher height down to the 12 m level. If the fluid packet being measured is characteristic of a higher level, the measured dissipation would be lower than expected. This would result in a low value for the stress using the direct dissipation technique. In fact, at the upper level, $u_*\doteq14.0$ cm sec^{-1}, 20% below the true value. We therefore see how a downdraft at the upper level could cause the profile method to indicate a high value of the flux, while the direct dissipation technique would give a low value. However, it is also possible that this low value is simply due to statistical variations in ϵ.

In the profile method the measured flux depends critically on the accuracy of the measurements at each location. Any distortion of the profile at a single location will invalidate the measurements. Neglecting the small stability corrections, the direct dissipation method gives independent measurements of the flux at each location. By making measurements at several heights, anomalous results are immediately obvious.

The shear stresses measured by OSU and UBC using the eddy correlation technique are 15% higher than the present results. The eddy correlation technique has great appeal, since it is a direct measure of the vertical transport of momentum ($\overline{uw}$). However, several difficulties are encountered in trying to obtain a good estimate of the average product. The first problem is that the fluxes occur in a very wide band ($3\frac{1}{2}$ decades) extending to quite low frequencies ($\sim$0.001 Hz). Proper estimation of such low frequencies requires long averaging periods. However, the fluxes over the ocean are highly variable, having significant changes during such intervals (Paulson *et al.*, 1972). Any short-period results using this technique will be biased by the low-frequency fluctuations of the fluxes.

The second problem is simply how to measure u and w in this frequency range. During BOMEX, OSU and UBC used a three-dimensional sonic anemometer (Miyake *et al.*, 1970) to measure velocities. This device gives velocity components in three perpendicular directions which must be transformed to obtain u, v and w. The implementation of the transformation is somewhat empirical. For example, the important rotation in the u,w plane relies on making the correlation coefficient $R_{uw}\approx 0.5$ in the frequency band $0.01<fz/U<0.1$. This correction is applied to the averaged results, when in fact the orientation of the array was continuously varying due to the motion of *FLIP*. This problem was recognized by Pond *et al.* (1971) and is reflected in the 15–25% error band established for the momentum flux.

The shear stress measurements by OSU using the dissipation technique (structure function method) are in apparent agreement with the values obtained using the eddy correlation technique. As indicated earlier, there is a large uncertainty in the value of α_1 used in these measurements. Pond *et al.* (1971) have used a value $\alpha_1=0.55$, while McBean *et al.* (1971) have suggested a value $\alpha_1=0.60$. Adjusting the OSU results for the higher value of α_1 gives a shear stress of 0.39 dyn cm^{-2} in agreement with the present results.

Momentum flux is usually reported in terms of the drag coefficient C_D evaluated at a reference height of 10 m. The calculation of C_D requires both a good estimate of the momentum flux, and a reliable estimate of the mean speed U at 10 m under neutrally stable conditions. The mean speed estimate is almost as difficult to make as the flux measurement. As indicated by Izumi and Barad (1970), overspeeding in cup anemometers can result in mean speeds as much as 10% too high. Corrections to the velocity profile for diabatic effects and sampling errors can account for an additional 5–15% change in the mean speed. Even under the best conditions, 40% errors in C_D are not unusual. For example, the measured mean speed for this study was $U_{10}=5.12$ m sec^{-1} resulting in a drag coefficient $C_D=1.15\times10^{-3}$. Correcting the mean speed for sampling errors and diabatic effects gives $U_{10}=5.77$ m sec^{-1} and $C_D=0.91\times10^{-3}$.

b. *Sensible heat flux*

The average sensible heat flux of 0.74 mW cm^{-2} measured by the direct dissipation method is in reasonable agreement with values measured by the profile and eddy correlation methods. The large scatter is representative of the measurement errors encountered. The comments regarding the momentum flux measurements apply equally well to the measurements of sensible heat flux.

The OSU heat flux measurement using the dissipation technique is about three times larger than the other measurements. This technique is similar to the dissipation technique for momentum flux, and suffers from the same deficiencies. Of particular concern is the uncertainty in the temperature inertial subrange constant β_1. Examination of the OSU results indicates that the dissipation measurements are systematically higher than the eddy correlation measurements by a factor of 2.1. In their calculations Pond *et al.* (1971) used a value $\beta_1=0.4$ based on the results of Paquin and Pond[4] (1971). In contrast, Gibson *et al.* (1970) and Boston (1971) have reported values of β_1 in the range 0.8–1.2. Adjusting the OSU results for a value $\beta_1=1.0$ removes most of the systematic bias between the dissipation and eddy correlation measurements. The corrected value of sensible heat flux is 1.1 mW cm^{-2}, in better agreement with the other measurements. From this brief example it is apparent that additional measurements of β_1 are needed.

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[4] The definition of β_1 has been chosen consistent with Gibson *et al.* (1970). The subrange constant B_T' used by Paquin and Pond (1971) is related to β_1 by $B_T'=2\beta_1$.

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REFERENCES

Boston, N., 1971: An investigation of high wave-number temperature and velocity spectra in air. Ph.D. thesis, University of British Columbia.

Businger, J. A., C. C. Wyngaard, Y. Izumi and E. F. Bradley, 1971: Flux-profile relationships in the atmospheric surface layer. *J. Atmos. Sci.*, **28**, 181–189.

Gibson, C. H., and R. B. Williams, 1969: *Proc. AGARD Spec. Symp. on the Aerodynamics of Atmospheric Shear Flows.* AGARD CP No. 48.

——, G. R. Stegen and R. B. Williams, 1970: Statistics of the fine structure of turbulent velocity and temperature fields measured at high Reynolds number. *J. Fluid Mech.*, **41**, 153–167.

Holland, J. Z., 1972: Comparative evaluation of some BOMEX measurements of sea surface evaporation, energy flux and stress. *J. Phys. Oceanogr.*, **2**, 476–486.

Izumi, Y., and M. L. Barad, 1970: Wind speeds as measured by cup and sonic anemometers and influenced by tower structure. *J. Appl. Meteor.*, **9**, 851–856.

Kolmogoroff, A. N., 1941: The local structure of turbulence in an incompressible viscous fluid for very large Reynolds number. *Akad. Nauk SSSR, Compt. Rend.*, **30**, 301–305.

McBean, G. A., R. W. Stewart and M. Miyake, 1971: The turbulent energy budget near the surface. *J. Geophys. Res.*, **76**, 6540–6549.

Miyake, M., M. Donelan, G. McBean, C. Paulson, F. Badgley and E. Leavitt, 1970: Comparison of turbulent fluxes over water determined by profile and eddy correlation techniques. *Quart. J. Roy. Meteor. Soc.*, **96**, 132–137.

Mollo-Christensen, E., 1968: Wind tunnel test of the superstructure of the *R/V FLIP* for assessment of wind field distortion. Rept. Dept. of Meteorology, MIT (AD 847286).

Obukhov, A. M., 1949: Structure of the temperature field in a turbulent current. *Izv. Akad Nauk SSSR, Ser. Geogr. Geofiz.*, **13**, No. 1, 58 pp.

Paquin, J. F., and S. Pond, 1971: The determination of the Kolmogoroff constants for velocity, temperature and humidity fluctuations from second- and third-order structure functions. *J. Fluid Mech.*, **50**, 257–269.

Paulson, C. A., 1970: The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer. *J. Appl. Meteor.*, **9**, 857–861.

——, E. Leavitt and R. G. Fleagle, 1970: Tabulation of mean profiles of wind speed, temperature and specific humidity for BOMEX, May 2 to 13, 1969. Sci. Rept., Dept. of Atmos. Sci., University of Washington, Seattle.

——, ——, and ——, 1972: Air-sea transfer of momentum, heat and water determined from profile observations during BOMEX. *J. Phys. Oceangr.*, **2**, 487–497.

Pond, S., G. T. Phelps, J. E. Paquin, G. McBean and R. W. Stewart, 1971: Measurements of the turbulent fluxes of momentum, moisture and sensible heat over the ocean. *J. Atmos. Sci.*, **28**, 901–917.

Taylor, R. J., 1961: A new approach to the measurement of turbulent fluxes in the lower atmosphere. *J. Fluid Mech.*, **10**, 449–458.

Wyngaard, J. C., and O. R. Coté, 1971: The budgets of turbulent kinetic energy and temperature variance in the atmospheric surface layer. *J. Atmos. Sci.*, **28**, 190–201.