IS AN OBSERVED WIND-SPEED DEPENDENCE OF AMTEX '75 HEAT-TRANSFER COEFFICIENTS REAL?

R. J. FRANCEY and J. R. GARRATT
CSIRO Division of Atmospheric Physics, Aspendale, Vic., Australia

(Received 12 October, 1978)

Abstract. An extensive set of direct eddy flux measurements over the ocean in conditions of strong cold air advection during AMTEX '75 yield surface-layer sensible heat-transfer coefficients which, like the drag coefficients but unlike latent heat-transfer coefficients, correlate positively and significantly with mean wind speed. No satisfactory explanation for this behaviour emerges from a search for possible systematic errors in instruments, or due to sampling or coral reef effects. The results are not in strong conflict with previous field measurements. However, to explain the differences between sensible and latent heat transfer coefficients, a subtle contamination of four independent heat flux measurements, or a preferential enhancement of sensible heat flux (e.g., in conditions of spray) is required.

1. Introduction

Francey and Garratt (1978) compared three sets of eddy fluxes measured at two island sites in the East China Sea during AMTEX 1975. Instruments were mounted at a nominal height of 10 m on towers located on exposed northern shores of the islands Tarama and Miyako. These data sets were obtained from the measurements after careful consideration of sensor calibration, frequency response and local mean flow distortion. Averages of the edited data sets were assumed to represent open ocean conditions and were used to obtain boundary-layer transfer coefficients. In addition, sufficient data were available to obtain surface-layer transfer coefficients at Tarama, yielding the unexpected result of a neutral heat transfer coefficient, C_{HN}, falling off significantly at low wind speeds and consequently being, on average, 30% lower than the analogous coefficients for momentum and latent heat transfer.

Prompted by concern over the surface layer heat transfer behaviour, this note explores in more detail possible systematic errors, including reef effects.

2. Site Details and Data Selection

A coral reef extended some 500 m or so upwind of the instrument mast at Tarama, the site providing two independent sets of flux data from instruments at 7 to 10 m above sea level. The extremes of tide differed by about 1.5 m with the reef completely submerged at high tide with uniformly scattered exposed rock (typically comprising 10–20% of the surface area, in water of average depth 1–2 m) at low tide. Reef temperatures (AMTEX '75 Data Report No. 4) show deviations of up to 10 °C below the relatively constant value outside and upwind of the reef.

Boundary Layer Meteorology **16** (1979) 249–260. 0006–8314/79/0163–0249$01.80.

At the Miyako site, there was one set of instruments at about 12 m height. The reef was less evident, extending only 100 to 200 m upwind and falling away rapidly. Water depth was always several meters and water temperature observations near the shore line showed considerably less deviation (1–2 °C) from the ocean temperature.

The data sets used in the following analyses have been selected according to the following criteria:

(1) Only occasions of mean hourly wind speeds greater than 5 m s^{-1}, with mean wind directions in the north-east quadrant, were considered. Included are all occasions of well-defined 'cold-air outbreak'. Errors due to propellor inertia in the flux instrumentation (Hicks, 1972) and sea surface temperature skin effects (Katsaros, 1977) at these wind speeds are negligible. The near-constant wind direction minimized possible influences of local topography and sensor orientation on the flux measurements.

(2) Two occasions of gross non-stationarity have been rejected. These 5 h periods surround the onset of major cold air outbreaks on 18 and 20 February, in which the wind speed changed by a factor of two.

(3) The possibility of systematic errors of up to 0.5 °C in the temperature sensors has led to the selection of only those occasions when the magnitude of the measured air–sea temperature difference, $\Delta\theta$, exceeds 4.5 °C. This is particularly important since $\Delta\theta$ appears in the denominator of the expression defining the heat transfer coefficient. In practice, only a small fraction of data is rejected by this criterion. (With relatively large values of Δq, the air-surface difference in specific humidity, no such criterion is necessary in the description of latent heat transfer.)

(4) All flux measurements, provided there was no obvious instrument malfunction, have been accepted. The possibility of systematic bias in these measurements is discussed below.

The heat transfer data surviving these selection criteria are summarized in Figure 1, showing the heat transfer coefficient:

$$C_{HN} = \frac{H}{\rho c_p u \, \Delta\theta \, f(z/L)} = \frac{C_H}{f(z/L)} \tag{1}$$

for measured heat flux H, air density ρ and specific heat at constant pressure c_p, mean wind speed u at $z = 10$ m, and stability correction $f(z/L)$, with the Monin–Obukhov length L obtained from the virtual heat flux. Open circles represent 89 hourly observations at Miyako, the closed circles 159 Tarama values, using the mean of independent measurements when both exist. Linear regressions on the data from each station are indicated. In Figure 2 similar results are presented for the latent heat transfer coefficient C_{EN}. In both figures the empirical drag coefficient of Garratt (1977), which accurately represents our direct measurements, is included for comparison.

The stability correction was derived using empirical flux-profile relationships as described by Deardorff (1968). There is no universal agreement on flux-profile forms but in the AMTEX conditions, no significant difference in correction factor resulted

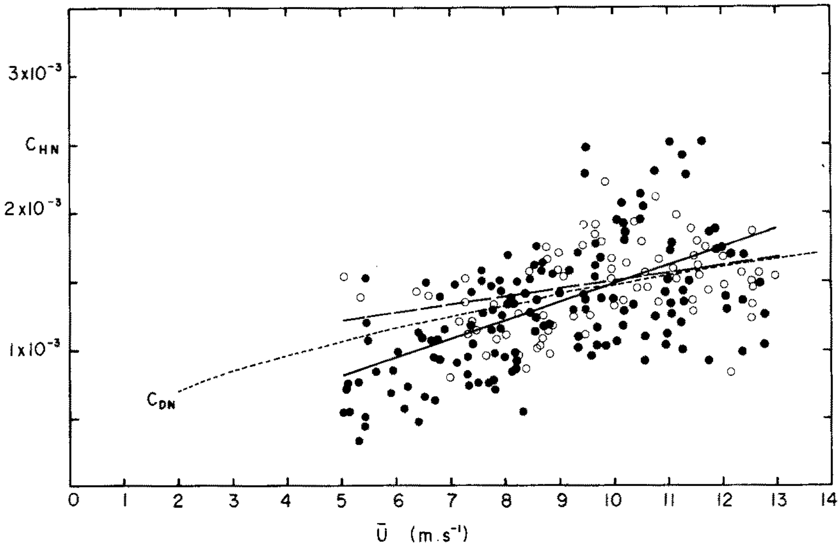

Fig. 1. Hourly average values of the neutral sensible heat transfer coefficient C_{HN} based on eddy correlation heat flux measurements at Tarama (closed symbols) and Miyako (open symbols). Linear regressions for each station are indicated. For comparison the empirical curve of C_{DN} versus wind speed of Garratt (1977) is included.

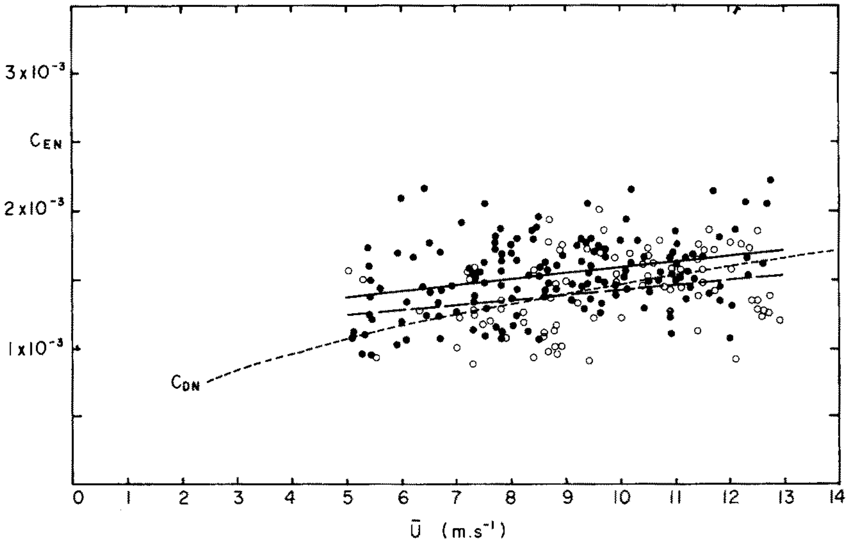

Fig. 2. As for Figure 1 but describing the latent heat transfer coefficient C_{EN}.

from the Businger *et al.* (1971) formulation or the Dyer and Hicks (1970) formulation. For example, typical values of $f(z/L)$ were 1.22, 1.19, respectively.

The use of a scaling length L rather than an L_T (derived from the sensible heat flux only) for temperature, and L_q (derived from the latent heat flux only) for moisture, represents an upper limit on the size of the corrections, with typical values of L, L_T, L_q being -24 m, -33 m, -84 m, respectively.

In the range of conditions experienced at AMTEX, the wind-speed dependence introduced by the stability corrections is negligible, as can be inferred from discussions below involving both neutral and uncorrected coefficients.

3. Systematic Measurement Errors

The main purpose of this note is to explore the possibility that the behaviour of C_{HN} with wind speed (and thus its difference from C_{EN}) is the result of systematic errors in measurement. The measurements of mean wind speed and wet- and dry-bulb temperatures at 10 m were routine, continuous and, in the present context, considered reliable. (Independent mean wind speed measurements at Tarama were in good agreement.) This focuses attention on the sensible and latent heat flux measurements, H or L_wE, and on surface temperature θ_0 from which surface specific humidity q_0 is calculated. We can first dispense with the latter as a likely source of the wind-speed dependence in C_{HN}.

The derivation of sea-surface temperature has been described fully in Garratt and Francey (1978). By using a spatial variation given by a 5-year mean February isotherm, a linear temporal variation given by a least-square fit to continuous temperature records from 3 ships within 500-1000 km of the flux measurement sites during Amtex 1975, and absolute values given by isolated direct measurements at the sites, areal average sea surface temperatures were obtained to an accuracy shown to be better than 1 °C. In the present context, the emphasis is not so much on areal averaging but more on the individual values upwind of the sites. It is relevant that each ship station recorded surface temperature deviations of up to 2 °C from the linear trend, and although deviations persisted for several days, they were not correlated from one ship to the next. A bias of the type necessary to explain Figure 1 could only arise as a result of an extremely unlikely coincidence of, for example, cold 'pools' (deviating some 2–3 °C below the linear trend) enveloping both Tarama and Miyako (60 km away) at times of low windspeed.

That the flux measurements hold a more likely explanation for a wind-speed dependence can be seen in Figure 3 which plots hourly values of the Bowen ratio H/L_wE against u. It can be seen that the behaviour of C_{HN}/C_{EN} can almost certainly be explained in terms of H/L_wE and that a surface temperature effect is not required. In passing, it may also be relevant that the value at the lowest wind speeds more closely corresponds to the empirical 'universal' value for θ_0 of 22–23 °C, i.e., $H/L_wE \simeq 0.1$, suggested by Priestley and Taylor (1972). The reliability of the flux measurements is now investigated in terms of previous experience with the instrumentation, their operation in a marine atmosphere and the consistency between independent observations at AMTEX. To conclude the section, two additional possible sources of systematic bias are considered, the influence of the coral reefs and the onset of mesoscale cellular convection.

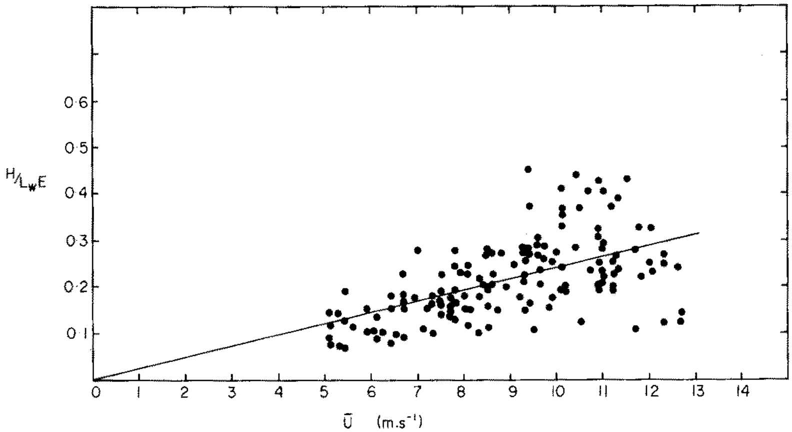

Fig. 3. Hourly values of the Bowen ratio (H/L_wE) as a function of a wind speed, showing the line of best fit.

A. LABORATORY AND LAND-BASED FIELD EXPERIENCE

Laboratory calibrations of the Fluxatron signal processors (e.g., Dyer *et al.*, 1967) are reproducible over their whole range to an accuracy equivalent to 1 to 2 Wm^{-2}. Calibration of the w-propellor and thermistor are relatively straightforward and introduce no further uncertainty with the ranges of wind and temperature encountered. However calibration of the infrared hygrometer (Hyson and Hicks, 1975), requiring *changes* in humidity, is more difficult, and in light of recent experiments (International Turbulence Comparison Experiment, ITCE, Deniliquin, Australia, 1976, to be published) must, along with all types of hygrometer represented there, be accepted with some reserve.

Experience with the instruments in a *turbulent* atmosphere over land is typified by the following:

(i) In conjunction with ITCE, two of the Fluxatrons were operated alongside two sonic anemometer/thermistor systems (E. F. Bradley, CSIRO Division of Environmental Mechanics, private communication). The difference between mean sonic and Fluxatron heat fluxes for 15 unstable half-hourly runs with $\bar{H} < 200\ \mathrm{Wm}^{-2}$ was $(8 \pm 20)\ \mathrm{Wm}^{-2}$, similar to the difference between the two sonics $(14 \pm 23)\ \mathrm{Wm}^{-2}$.

One of the Bradley sonic systems incorporated a Hyson hygrometer and comparison with a Fluxatron at similar height over 17 runs gave a difference of $(7 \pm 40)\ \mathrm{Wm}^{-2}$ in L_wE, a relatively larger scatter.

(ii) At the KOORIN expedition, Daly Waters July/August 1974 (e.g., Garratt, 1978) a 30-day daytime average of sensible plus latent heat flux, $(\overline{H + L_wE}) = 277\ \mathrm{Wm}^{-2}$, was in excellent balance with net radiation minus ground heat flux $(\overline{R - G}) = 270\ \mathrm{Wm}^{-2}$. In specific reference to a possible systematic error in heat flux calibration, seven hourly runs with comparable stability to AMTEX and $H < 150\ \mathrm{Wm}^{-2}$ gave $C_{HN} = (4.91 \pm 0.50) \times 10^{-3}$, indistinguishable from twelve hourly runs with $H > 250\ \mathrm{Wm}^{-2}$ having $C_{HN} = (4.84 \pm 0.50) \times 10^{-3}$.

B. THE MARINE ATMOSPHERE

The marine atmosphere, in particular the salt spray, has been shown to influence eddy correlation measurements of heat flux owing to a humidity sensitivity of contaminated thermistors (Schmitt *et al.*, 1978). Frequent observation of the electrical output from our relatively large thermistors (STC Type P glazed bead, with measured response time 0.1 to 0.2 s) has shown no evidence of the spikes characterising this particular behaviour. However an influence of salt spray contamination *was* observed mainly at the lowest levels (Tarama), easily recognisable by comparison of a mean temperature inferred from these thermistors with the dry-bulb measurements. Any surviving influence might be expected to show up in a comparison of results from different levels.

C. INDEPENDENT AMTEX MEASUREMENTS

The operation of neighbouring instruments at Tamara provides an unusual opportunity for direct comment on instrument performance. The operation of a sonic anemometer/thermistor eddy correlation system on the same mast by Okayama University (Sahashi, Amtex Data Report No. 4) plus the third Fluxatron at Miyako, strengthens this aspect.

Overall comparisons between Fluxatrons given in Francey and Garratt (1978) showed satisfactory agreement between instruments. One disturbing feature, a large scatter between hourly Tamara heat flux measurements, has since been associated with the use of an electronic compensator (Hyson *et al.*, 1977) which was used intermittantly on one instrument at a time. The affected data have been corrected. (Similar adverse effects are not evident on momentum or latent heat flux measurements.)

All of these data have been reviewed with specific attention to factors which might simulate the observed C_{HN} increase with wind speed coupled with a lack of similar behaviour in C_{EN}. In Table I, the wind-speed dependence of the uncorrected C_H values in a linear regression, is compared for a variety of subsets of the Tarama data, selected to expose systematic influences due to thermistor, instrument level, signal processor and compensator. In all cases the wind-speed dependence (a_1) is highly significant at 4 to 5 standard errors. (The effect of the compensator malfunction is to mask the dependence.) When coupled with a similar result for the Miyako C_H data set ($a_1/s_1 = 4.3$) and for Okayama University C_H data (at times corresponding to our data, implying $u > 5\ \mathrm{ms}^{-1}$, $|\Delta\theta| > 4.5\ ^\circ\mathrm{C}$), $a_1\ (\pm s_1) = 0.145\ (\pm 0.030)$, it is extremely difficult to attribute the slope to an instrumental bias.

While the scatter between L_wE measurements at Tarama is tolerable, there is evidence for systematic differences which may be combinations of the influences of hygrometer calibration, compensator and instrument level but are not dominated by any one. However, for C_E to behave similarly to C_H requires both Tarama instruments plus the Miyako instrument to over-estimate at low L_wE values (in the range most frequently encountered over land and where H/L_wE is in best agreement

TABLE I

Wind speed dependence in subsets of Tarama C_H

$C_H = a_0(\pm s_0) + a_1(\pm s_1)u, \quad u$ in m s^{-1}.

Subset	n	$\overline{C_H} \times 10^3$	$\overline{a_0} \times 10^3$	$\overline{a_1} \times 10^3$	$\overline{s_1} \times 10^3$
Signal Processor:					
$(A+B)/2$*	100	1.47	0.31	0.128	0.023
A	137	1.39	0.55	0.095	0.023
B	117	1.55	0.42	0.126	0.021
$(A+B)/2$, A, B†	154	1.47	0.59	0.098	0.019
Level:					
10 m	112	1.46	0.32	0.129	0.023
9 m	32	1.14	0.61	0.055	0.025
7 m	101	1.50	0.47	0.117	0.026
Thermistor:					
No. 10 only	78	1.44	0.10	0.161	0.030
Compensator:					
Not connected	135	1.55	0.40	0.127	0.022
Connected (uncorrected)	98	1.29	0.58	0.080	0.022

* Average hourly values, both A and B instruments in operation.

† As above, plus additional single instrument values. These are the data represented in Figure 1.

with the Priestley and Taylor (1972) value). A consistent underestimate at the extremely high L_wE values encountered at AMTEX is not as firmly excluded by past experience but would tend to emphasize the ratio of mean values C_{EN}/C_{HN}, already approaching a significant difference from unity at 1.3.

The scatter observed between L_wE instruments and the limited times of sampling a full range of wind speeds prevent a meaningful subdivision of the data into smaller periods. The overall agreement with the AMTEX 1974 results (Garratt and Hyson, 1975) is good, as discussed in Francey and Garratt (1978). One apparent conflict arises from the Garratt and Hyson comment that 'taken as a whole no significant correlation of β (Bowen ratio) with wind speed is found'. In actual fact a linear regression of H/L_wE *versus* wind speed (for times of $|\Delta\theta| \geqslant 3$ °C) gives a slope of similar sign and magnitude to that of Figure 3. The far greater scatter (and thus lack of significance) possibly arises through the somewhat less rigid selection criteria applied to the 1974 results.

D. THE INFLUENCE OF CORAL REEFS ON THE FLUX MEASUREMENTS

Two independent methods of investigation have been employed. The first applies theoretical models of local advection (Philip, 1959 and E. K. Webb, in preparation for publication). The second uses multiple regressions of the transfer coefficients against wind speed and a reef-dependent parameter.

The Webb model, similar to that of de Vries (1959) and explicitly incorporating effects of molecular diffusion near the surface, predicts a larger reef influence than that of Philip, and is quoted here. For typical Tarama conditions with $z/L \simeq -0.27$, friction velocity $u_* = 0.34\ \mathrm{m\,s^{-1}}$, $H_{\mathrm{meas}} = 105\ \mathrm{Wm^{-2}}$ and a reef-ocean temperature difference $\overline{\theta_1 - \theta_0} = -2.5\ °\mathrm{C}$,

$$H_{\mathrm{meas}}/H_0 = 0.92$$

whilst for water vapour with $\overline{q_1 - q_0} = -0.0022\ g\,Kg^{-1}$ and $L_w E_{\mathrm{meas}} = 583\ \mathrm{Wm^{-2}}$

$$E_{\mathrm{meas}}/E_0 = 0.97\ .$$

At Miyako, for $u_* = 0.37\ \mathrm{m\,s^{-1}}$, $H_{\mathrm{meas}} \simeq 123\ \mathrm{Wm^{-2}}$, $\overline{\theta_1 - \theta_0} = -1.5\ °\mathrm{C}$, $\overline{q_1 - q_0} = -0.0014\ \mathrm{g\,Kg^{-1}}$ and $L_w E_{\mathrm{meas}} \simeq 542\ \mathrm{W\,m^{-2}}$

$$H_{\mathrm{meas}}/H_0 \simeq E_{\mathrm{meas}}/E_0 = 0.99\ .$$

The model predicts a wind-speed dependence of H_{meas}/H_0 which is small and *decreasing* ($H_{\mathrm{meas}}/H_0 \rightarrow 1$) with increasing wind speed. Neither the magnitude (particularly at Miyako) nor sense of the predicted effect supports the view that the coral reefs are an important influence.

Multiple regressions of the neutral transfer coefficients against wind speed and a normalised reef-ocean concentration difference were obtained for sensible and latent heat measurements at both stations. Similar regressions for momentum used tide height as crudely representing surface roughness through the area of reef uncovered. The results can be summarized as follows:

(i) The wind-speed dependences in C_{HN}, C_{DN}, at both stations remain highly significant (at 5 to 6 standard errors in the regression coefficient) and of similar magnitude. The corresponding C_{EN} coefficients are smaller by a factor of 2 or more and only marginally significant at 1 to 2 standard errors.

(ii) The reef-dependent regression coefficients are all consistent with a cooler and rougher reef, but *in all cases are barely significant* at 1 to 2 standard errors. (The magnitudes of the Tarama reef-dependent coefficients are in good agreement with the model predictions; however, the more uncertain Miyako ones are somewhat larger despite the less pronounced reef).

E. MESOSCALE CELLULAR CONVECTION

Sheu and Agee (1977) discuss evidence for the onset of mesoscale cellular convection within limited ranges of u and $\Delta\theta$ at AMTEX. It is feasible that this represents a switching between modes of differing heat transfer rates. Regressions of C_H against $\Delta\theta$ in limited wind-speed ranges show no evidence for a systematic effect.

4. Discussion

The drag coefficients obtained at AMTEX, not specifically discussed above, are in good agreement with the empirical relation of Garratt (1977),

$$C_{DN}(10)\times 10^3 = 0.51\, u^{0.46}\,,$$

with u in m s^{-1}, where C_{DN} is related to a surface roughness scale height z_0 by

$$C_{DN}(z) = \left[\frac{k}{(\ln(z/z_0))}\right]^2$$

(k = von Kármán constant), and z_0 over the ocean is related to friction velocity u_* by Charnock's (1955) relation,

$$z_0 = \text{const.}\times u_*^{\,2}\,.$$

The behaviour of the sensible and latent heat coefficients (C_{PN}, $P = H, E$ resp.) can be described in terms of appropriate scaling heights z_P where

$$C_{PN}(z) = k^2[\ln(z/z_P)\ln(z/z_0)]^{-1}\,.$$

Previous evidence for a range of roughness Reynolds numbers ($\mathrm{Re} = u_* z_0/\nu$, ν = kinematic viscosity of air) appropriate to the ocean suggests

$$C_{EN} > C_{DN}\,,\qquad (\ln(z_0/z_P) < 0),\qquad \text{at low Re}$$

$$C_{EN} < C_{DN}\,,\qquad (\ln(z_0/z_P) > 0),\qquad \text{at high Re}\,,$$

not incompatible with the results in Figure 2 (Garratt and Hicks, 1973; Kitaygorodskiy *et al.*, 1973). Recent very direct evidence on the intrinsic relative transfer rates of water vapour and momentum (but not sensible heat) at an air water interface uses isotopic tracers (Merlivat, 1978). Her wind-tunnel results can be summarised in terms of 10 m transfer coefficients such that C_D is well described by Charnock's relation and C_E/C_D decreases from 1.31 to 0.84 for u increasing from 2 to 13 m s^{-1}. The sense and magnitude of the variation is again in good accord with Figure 2.

No such direct information exists for C_H; from wind tunnel results, however, Mangarella *et al.* (1973) conclude equal energy and mass neutral transfer coefficients, except in cases involving spray. The influence of spray, while appearing capable of significantly contributing to energy transfer in field conditions, is thought to enhance latent rather than sensible heat transfer, as required by Figure 1 (Wang and Street, 1978).

It is often assumed in the literature that $C_{HN} = C_{EN}$ (e.g., Kitaygorodskiy *et al.*, 1973) and Garratt and Hicks (1973) quote limited evidence to this effect. This is consistent with additive eddy and molecular diffusivities (e.g., Sheppard, 1958), resulting in $z_P \propto u_*^{\,-1}$. In conditions pertaining to AMTEX, i.e., with temperature and humidity gradients of similar sign and heat and moisture both contributing to buoyancy, a recent model of Warhaft (1976) predicts $C_{HN} = C_{EN}$. Warhaft quotes support for his model in the measurements over the ocean of Pond *et al.* (1971) and Phelps and Pond (1971).

A comparison of our C_H measurements with other previous observations over the ocean is made in Figure 4 which plots $\overline{w'\theta'} = H/\rho c_p$ against $u\ \Delta\theta$ for the Tarama data, and includes data from a recent comprehensive review by Friehe and Schmitt (1976). The line is a best fit to all data considered by them, with the slope $C_H = 1.41 \times 10^{-3}$, almost solely determined by the Smith and Banke (1975) data represented by inverted open triangle symbols.

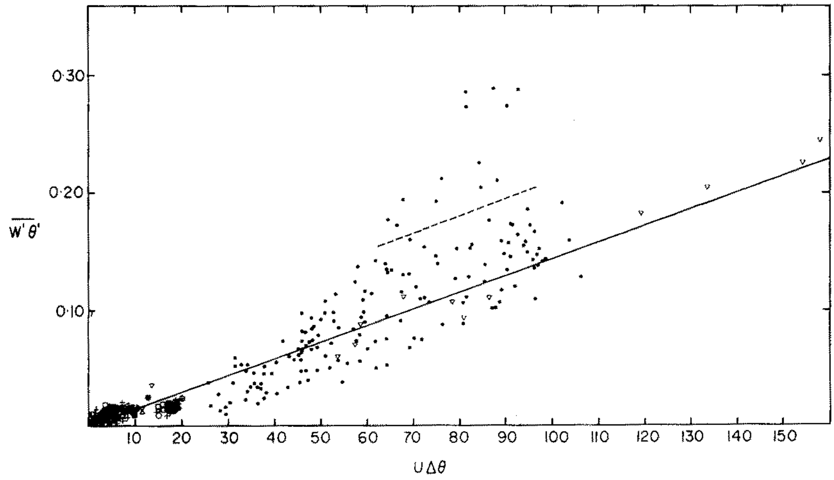

Fig. 4. Comparison of Tarama hourly heat flux measurements ($H = \rho c_P \overline{w'\theta'}$) with previous results reviewed by Friehe and Schmitt (1975).

Several points become obvious:—

(1) the present data set is relatively large and covers a range of $u\Delta\theta$ not well represented in previous measurements.

(2) in this type of presentation, the wind-speed dependence is not marked and in general our results fit the other data well.

(3) our extreme heat fluxes 'appear anomolous' on this plot; however, arbitrary rejection of 13 hourly values above the dashed line in Figure 4 leaves a linear regression of C_{HN} against wind speed $C_{HN} \times 10^3 = 0.359(\pm 0.115) + 0.100(\pm 0.013)u$, $s_{y.x} = 0.304$, still significantly dependent ($a_1/s_1 = 7.8$). The only remaining conflict would appear to be with the 4 extreme $u\ \Delta\theta$ points of Smith and Banke.

5. Conclusions

The measurements discussed here, by comparison to previous data sets obtained over the ocean, are comprehensive, represent ranges of $u\Delta\theta$ and $u\Delta q$ not frequently monitored, and have an unusual degree of replication.

A wind-speed dependence of the 10 m sensible heat transfer coefficient C_{HN}, comparable to that in the drag coefficient C_{DN}, exists in data from 4 independent flux measurement systems, representing different sensor types, different levels above the surface and different locations (in particular different coral reef conditions). This result is *not* in strong conflict with previous measurements over the ocean. Previous experience with the instrumentation employed provides no evidence for systematic effects sufficient to explain the dependence. Neither is such evidence forthcoming from a consideration of other measured physical parameters, in particular those relating to a coral reef influence or the onset of mesoscale cellular convection.

The latent heat measurements described herein are of more questionable reliability (i.e., exhibit more scatter between 3 independent observations) but in all cases lead to a transfer coefficient C_{EN} whose dependence on wind speed is considerably less than that for sensible heat. The relation between C_{EN} and C_{DN} is in good accord with previous wind-tunnel and field data. That the difference between the sensible and latent heat coefficients stems from the flux measurements and not the air-surface profile measurements is strongly implied from the wind-speed dependence of the Bowen ratio H/L_wE.

It would appear that the difference in behaviour between C_{HN} and C_{EN} within this data set requires a subtle contamination of *all* vertical velocity–temperature covariances $(\overline{w'\theta'})$, practically independent of sensor type, height and exposure – or a relatively enhanced heat flux at high wind speeds. If it is the latter and is associated with surface structure or spray formation, new mechanisms for the enhancement of sensible rather than latent heat fluxes are required.

Acknowledgements

The advection model results provided by Mr. E. K. Webb, and his interest and advice, have been greatly appreciated.

References

AMTEX '75, *Data Report, Vol. 4, Boundary Layer and Radiation Observations*, Ed. by Y. Mitsuta, Disaster Prevention Research Institute, Kyoto, and T. Fujita, Meteorological Research Institute, Tokyo.

Businger, J. A., Wyngaard, J. C., Izumu, Y., and Bradley, E. F.: 1971, 'Flux Profile Relationships in the Atmospheric Surface Layer', *J. Atmos. Sci.* **28**, 181–189.

Charnock, H.: 1955, 'Wind Stress on a Water Surface', *Quart. J. Roy. Meteorol. Soc.* **81**, 639–640.

Deardorff, J. W.: 1968, 'Dependence of Air–Sea Transfer Coefficients on Bulk Stability', *J. Geophys. Res.* **73**, 2549–2559.

De Vries, D. A.: 1959, 'The Influence of Irrigation on the Energy Balance and Climate Near the Ground', *J. Meteorol.* **16**, 256–270.

Dyer, A. J.: 1963, 'The Adjustment of Profiles and Eddy Fluxes', *Quart. J. Roy. Meteorol. Soc.* **89**, 276–280.

Dyer, A. J., Hicks, B. B., and King, K. M.: 1967, 'The Fluxatron – a Revised Approach to the Measurement of Eddy Fluxes in the Lower Atmosphere', *J. Appl. Meteorol.* **6**, 408–413.

Dyer, A. J. and Hicks, B. B.: 1970, 'Flux–Gradient Relationships in the Constant Flux Layer', *Quart. J. Roy. Meteorol. Soc.* **96**, 715–721.

Friehe, C. A. and Schmitt, K. F.: 1976, 'Parameterization of Air–Sea Interface Fluxes of Sensible Heat and Moisture by the Bulk Aerodynamic Formulas', *J. Phys. Oceanog.* **6**, 801–809.

Francey, R. J. and Garratt, J. R.: 1978, 'Eddy Flux Measurements Over the Ocean and Related Transfer Coefficients', *Boundary-Layer Meteorol.*, **14**, 153–166.

Garratt, J. R.: 1977, 'Review of Drag Coefficients Over Oceans and Continents', *Mon. Wea. Rev.* **105**, 915–929.

Garratt, J. R.: 1978, 'Transfer Characteristics for a Heterogeneous Surface of Large Aerodynamic Roughness', *Quart. J. Roy. Meteorol. Soc.*, **104**, 491–502.

Garratt, J. R. and Francey, R. J.: 1978, 'Bulk Characteristics of Heat Transfer in the Unstable, Baroclinic Atmospheric Boundary Layer, *Boundary-Layer Meteorol.*, **15**, 399–421.

Garratt, J. R. and Hicks, B. B.: 1973, 'Momentum, Heat and Water Vapour Transfer from Natural and Artificial Surfaces', *Quart. J. Roy. Meteorol. Soc.* **99**, 680–687.

Garratt, J. R. and Hyson, P.: 1975, 'Vertical Fluxes of Momentum, Sensible Heat and Water Vapour During the Air Mass Transformation Experiment (AMTEX) 1974, *J. Meteorol. Soc. Japan* **53**, 149–160.

Hicks, B. B.: 1972, 'Propeller Anemometers as Sensors of Atmospheric Turbulence', *Boundary-Layer Meteorol.* **3**, 214–228.

Hyson, P., Garratt, J. R., and Francey, R. J.: 1977, 'Algebraic and Electronic Corrections of Measured *uw* Covariance in the Lower Atmosphere', *J. Appl. Meteorol.* **16**, 43–47.

Hyson, P. and Hicks, B. B.: 1975, 'A Single Beam Infrared Hygrometer for Evaporation Measurement', *J. Appl. Meteorol.* **14**, 301–307.

Katsaros, K. B.: 1977, 'The Sea Surface Temperature Deviation at Very Low Wind Speeds; Is There a Limit?', *Tellus* **29**, 229–239.

Kitaygorodskiy, S. A., Kuznetsov, O. A., and Panin, G. N.: 1973, 'Coefficients of Drag, Sensible Heat and Evaporation in the Atmosphere Over the Surface of the Sea', *Izv., Atmospheric and Oceanic Physics* **9**, 1135–1141.

Mangarella, P. A., Chambers, A. J., Street, R. L., and Hsu, E. Y.: 1973, 'Laboratory Studies of Evaporation and Energy Transfer Through a Wavy Air-Water Interface', *J. Phys. Oceanog.* **3**, 93–101.

Merlivat, L.: 1978, 'The Dependence of Bulk Evaporation Coefficients on Air–Water Interfacial Conditions as Determined by the Isotopic Method', *J. Geophys. Res.* **83**, 2977–2980.

Phelps, G. T. and Pond, S.: 1971, 'Spectra of the Temperature and Humidity Fluctuations and of the Fluxes of Moisture and Sensible Heat in the Marine Boundary-Layer', *J. Atmos. Sci.* **27**, 918–928.

Philip, J. R.: 1959, 'The Theory of Local Advection: 1', *J. Meteorol.* **16**, 535–547.

Pond, S., Phelps, G. T., Paquin, J. E., McBean, G., and Steward, R. W.: 1971, 'Measurements of the Turbulent Fluxes of Momentum, Moisture and Sensible Heat Over the Ocean', *J. Atmos. Sci.* **28**, 901–917.

Priestley, C. H. B. and Taylor, R. J.: 1972, 'On the Assessment of Surface Heat Flux and Evaporation Using Large Scale Parameters', *Mon, Wea. Rev.* **100**, 81–92.

Sheu, Pi-Jaw and Agee, E. M.: 1977, 'Kinematic Analysis and Air–Sea Heat Flux Associated with Mesoscale Cellular Convection During AMTEX '75', *J. Atmos. Sci.* **34**, 793–801.

Schmitt, K. F., Friehe, C. A., and Gibson, C. H.: 1979, 'Humidity Sensitivity of Atmospheric Temperature Sensors by Salt Contamination', *J. Phys. Oceanog.* **8**, 151–161.

Sheppard, P. A.: 1958, 'Transfer Across the Earth's Surface and Through the Air Above', *Quart. J. Roy. Meteorol. Soc.* **84**, 205–224.

Smith, S. D. and Banke, E. G.: 1975, 'Variation of the Sea Surface Drag Coefficient with Wind Speed', *Quart. J. Roy. Meteorol. Soc.* **101**, 665–674.

Wang, Chen Sheng and Street, R. L.: 1978, 'Transfers Across an Air–Water Interface at High Wind Speeds: The Effect of Spray', *J. Geophys. Res.* **83**, 2959–2969.

Warhaft, Z.: 1976, 'Heat and Moisture Flux in the Stratified Boundary Layer', *Quart. J. Roy. Meteorol. Soc.* **102**, 703–707.