# WIND PROFILES OVER THE SEA AND THE DRAG AT THE SEA SURFACE

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*Summary*

Wind speeds were measured at heights up to 13 m over the sea by means of anemometers mounted on a mast attached to the jib-boom of a small vessel and another on the foremast cross-trees. The vertical temperature gradient and air/sea temperature differences were also observed. On some occasions wind and temperature structures were explored up to 80–100 m by kite balloon.

A method of observation was devised whereby the effect of the ship's hull on the wind speeds was eliminated and from the corrected profiles surface drag coefficients were calculated. For neutral conditions and fetch of wind over the sea of 20–40 km it is found that the drag coefficient (for 10 m reference height) is about 0·0010 in light winds rising to about 0·0021 at wind speeds from 10 to 15 m/sec.

The drag coefficient is probably rather sensitive to stability variations, increasing particularly in the direction of instability, but the effects of variation in fetch of the wind over water are much less evident. In proximity to shallow water the drag coefficient increases appreciably.

## I. INTRODUCTION

The importance to both meteorology and oceanography of a proper knowledge of the friction between atmosphere and ocean is evident, but observational difficulties have made progress slow and much uncertainty remains (see, for example, Francis 1954). Work over land surfaces has shown that the Prandtl logarithmic wind profile provides a secure basis for the estimation of the surface shearing stress under neutral conditions of stability but accurate measurement of wind profiles at representative exposures over the sea is no easy task. Fixed installations are normally limited to comparatively shallow water and the results are therefore not necessarily representative of the open ocean. Some studies of wind profiles over the sea are of doubtful significance for this reason and others have been vitiated by faulty exposure of the anemometers, as shown by Roll (1949). Erections in deeper water have to be so massive to resist storms that the disturbance to the wind field is considerable and to mount the anemometers beyond the perturbed region, when known, is still difficult. A ship also obstructs the flow to some considerable extent and its motion in a rough sea is a complicating factor but the advantage of being able to make observations in deep water away from the land is so great that it seemed worth while to try to find means of overcoming these difficulties. That this has been

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largely achieved it is hoped to show in the following account of observations of wind profiles made at sea in October 1955.

On some occasions wind and temperature observations were extended up to 80–100 m using a kite balloon and these results are presented here. Records were also taken of the turbulent fluctuations of wind and temperature using quick-response elements mounted at 13 m height but the analysis of these will be dealt with elsewhere.

## II. Observational Procedure

The observations were made on the Fishery Research Vessel *Derwent Hunter*, a 70 ft Diesel-schooner of the Division of Fisheries and Oceanography, C.S.I.R.O., which for the duration of the trials (Oct. 6–26, 1955) was based on Portsea in Port Phillip Bay close inside the entrance (see Fig. 1). After an

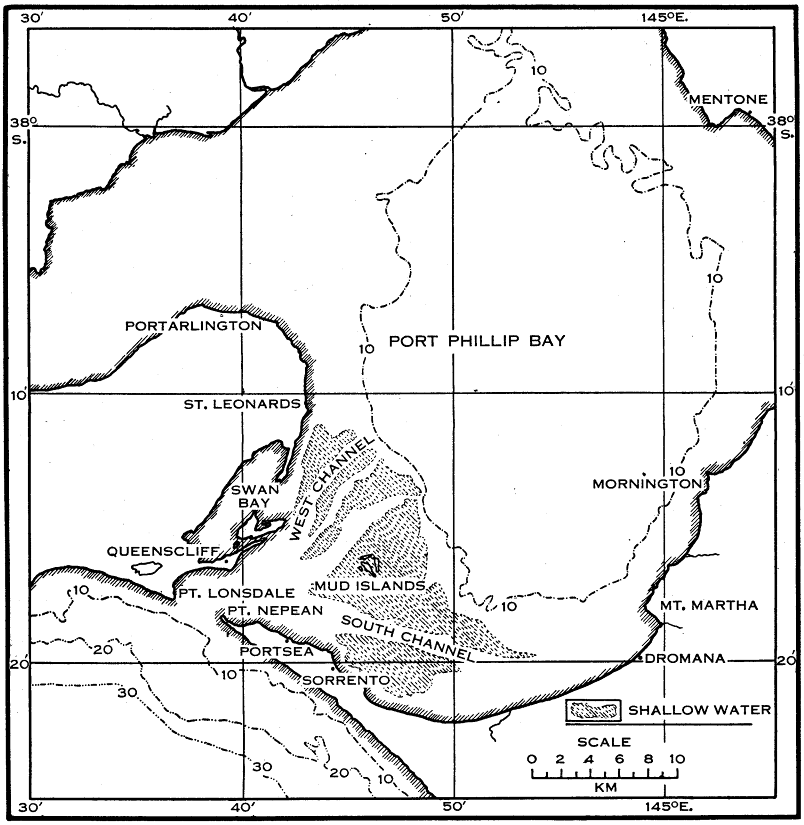


Fig. 1.—Area of observations. Depth contour lines are marked in fathoms.

initial exploratory period in Port Phillip Bay observations were made in Bass Strait a few miles out from Port Phillip Heads whenever the wind had a southerly component. With northerly winds a suitable station in Port Phillip Bay permitted observations to be made with fetches of the wind over water of up to

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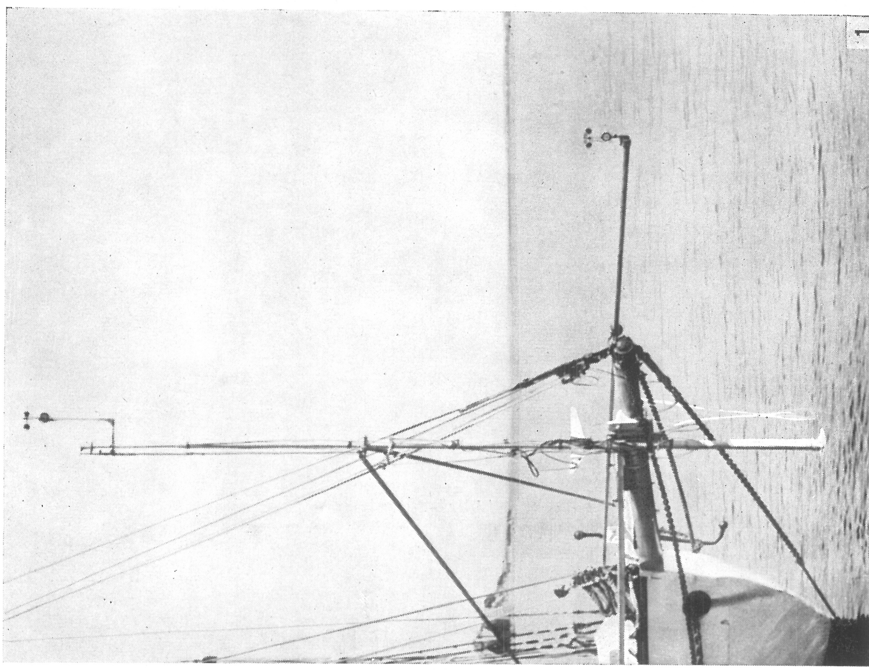

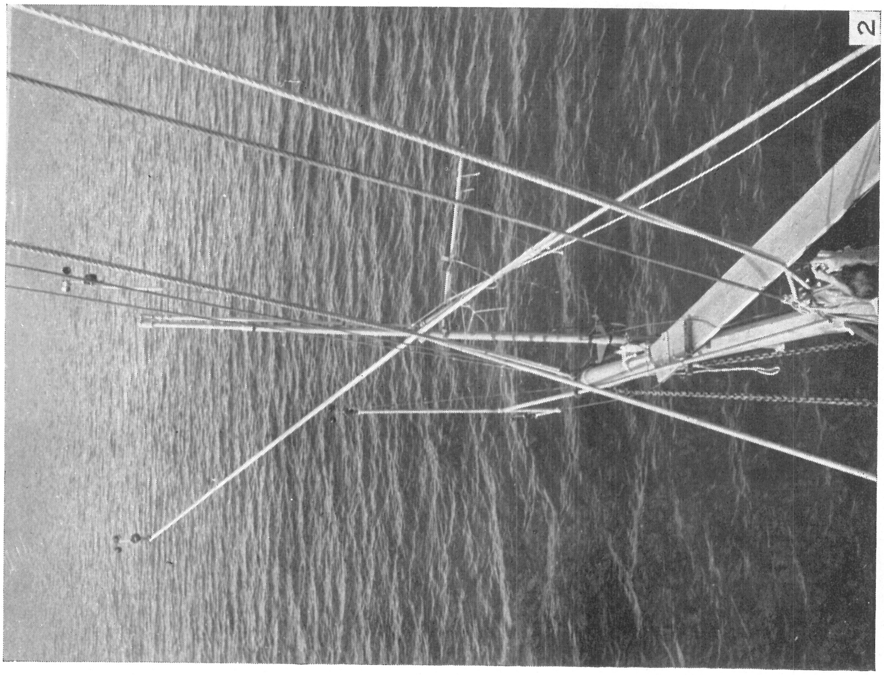

Fig. 1.—Bows of F.R.V. *Derwent Hunter* with anemometer mast fitted on the jib-boom.

Fig. 2.—The anemometer arrangement on October 13, 1955: looking down on the jib-boom from the foremast rigging.

50 km. Apart from an area of shallow water at the south-west end of the bay, which was avoided as far as possible, the general depth of water is 15–25 m.

An anemometer mast with arms was rigged on the jib-boom of the vessel at 2·3 m forward of the stem and carried several (up to five) anemometers at heights above mean water level from 1·5 to 6·4 m. The arrangement, which varied in detail during the course of the trials, is shown in Plate 1, Figure 1. A thermometer element was also carried on this mast generally at a height of 4 m except for the first 2 days, when the height was 3 m. Another anemometer was mounted on the foremast cross-trees at a height of 12·95 m together with a thermometer element at 12·6 m. This upper anemometer level is hereafter referred to as 13 m although 12·95 m has been used in the calculations. At various times anemometers were carried at positions mainly about 2·7 m forward of the anemometer mast by means of booms of $1\frac{1}{2}$ in. steel pipe. These were used to get some information on the extent to which wind speeds at the anemometer mast were influenced by the presence of the ship's hull. Plate 1, Figure 2, a photograph from the foremast rigging looking down on the bow, shows the arrangement on October 13. The highest anemometer (6·4 m) in this figure is on a sub-mast mounted alongside the anemometer mast proper using a spring-loaded catch device, a design which greatly facilitated removing the instrument. An anemometer at 5·8 m is to be seen on a slanting boom projecting forward and to the port side. Two more anemometers (1·95 and 3·95 m) are carried by the L-shaped piece on the end of a boom extending the jib-boom. The 4 m arm on the anemometer mast is projecting to starboard ; when an anemometer was mounted on this it was swung forward to be at 30° to the fore-and-aft line.

During observation periods the ship steamed slowly into wind at the lowest speed for sufficient steerage way to be maintained. The relative wind direction was generally within 10° of the fore-and-aft line and was but rarely as much as 15° on the bow. The anemometer readings together with measurement of the speed of the ship relative to the water enabled wind speeds relative to the sea surface to be found. The ship's speed, usually around 1–2 knots, was found by timing the passage of floating objects (orange peel) between two points along the ship's side. Orange peel floats nearly totally submerged and the colour makes it easy to observe. The peel was flung about 20 ft out from the ship's side to avoid effects of the propeller intake, etc. An average of 7 determinations were made per 30 min run. Nearly all runs were of 30 min duration after the first 4 days during which the observation period was mostly 10 min.

To investigate the effect of the ship's hull on the wind profile some runs (" speed runs ") were made at full speed ($7\frac{1}{2}$ knots) into wind for comparison with normal runs. These were made on occasions of moderate to low wind speed.

Sea and air temperatures, the latter at about 1·5 m above deck level, were observed during each run and the temperature difference between 4 and 12·6 m was recorded on most days. On some days the wind and temperature structure for greater heights (up to about 100 m) was observed using an instrument lifted by a " Kytoon ".

## III. Instrumental

### (a) *The Anemometers*

The Sheppard type sensitive cup anemometers employed an electric contacting arrangement similar to that described by Crawford (1951) but the contacting rate was only half as great (100 counts/min$\sim$10 m/sec). Telephone message registers (6 V) were used for counting. The anemometers were calibrated in a wind-tunnel immediately before and after the trials and were also checked on October 19, about half-way through. Only one anemometer showed any significant change, about 1·5 per cent., and for this the initial calibration was used up to October 19 and the final thereafter.

The anemometers were taken down at the end of each day's work and checked over. When replaced at the beginning of the next day, interchanges were made so as, in the mean, to minimize errors from calibration inaccuracies.

### (b) *Temperature Recording System*

Temperatures were recorded using thermistor elements (S.T.C. type F2311/300) in a Wheatstone bridge circuit, the output of which was applied to an Evershed & Vignoles recording milliammeter (2 mA full scale, 1250 $\Omega$) via a Sunvic D.C. amplifier. The thermistors were switched in turn into the circuit to give samples, for a minute or two each, of temperatures in the sea and at 4 m, 12·6 m, and " Kytoon " height. The bridge was approximately balanced each time by the resistance box in one arm of the bridge. The average of the recorded trace, estimated by eye, provided simply a small correction to the resistance box reading. Once each day the thermistors were calibrated at a bath temperature equal to about the mean temperature for the day's runs. The 4 and 12·6 m elements were calibrated together in the same bath to enable the temperature difference between these heights to be obtained with the minimum error.

To improve the accuracy of determining the 12·6 : 4 m temperature differences, the circuit was changed to the differential type on October 17 and, by omitting the sea element, the sensitivity could be increased to $2\frac{1}{2}$ °F full scale. The slight change of zero with temperature due to imperfect matching of thermistors was determined each day with pairs of elements in the same bath at several temperatures spaced about 1 °F.

For air temperature measurement each thermistor was mounted in a radiation shield consisting of a pair of concentric chromium-plated cylinders. The shield was open at both ends and pointed forwards so that ventilation was automatically provided when the ship was headed into wind. The sea temperature element was placed in a sealed metal tube mounted on a weighted metal frame hung in the sea at a depth of about 0·5 m. In addition to the thermistor measurements, sea and air temperatures were taken on all occasions using mercury-in-glass thermometers. Except on rough days Assmann psychrometer readings were taken with the instrument suspended from the forestay. On rough days a whirling psychrometer was used amidships with the instrument held out to give as good an exposure as possible. Sea temperatures were taken with a bucket consisting of a large, wide-mouthed Dewar flask mounted in sponge rubber in a protective cylinder.

### (c) *The Captive Balloon-sonde*

A combined anemometer and temperature element was made for the balloon work. The construction, mainly in bright anodized aluminium, is sufficiently clear from Figure 2. The vane-wheel, 6·7 cm in diameter, operated an electric contact through a worm and wheel reduction gearing. The thermistor was housed in a lighter version of the double-tubular shield used on the ship. The instrument was inserted in the balloon cord some 15 m below the balloon—

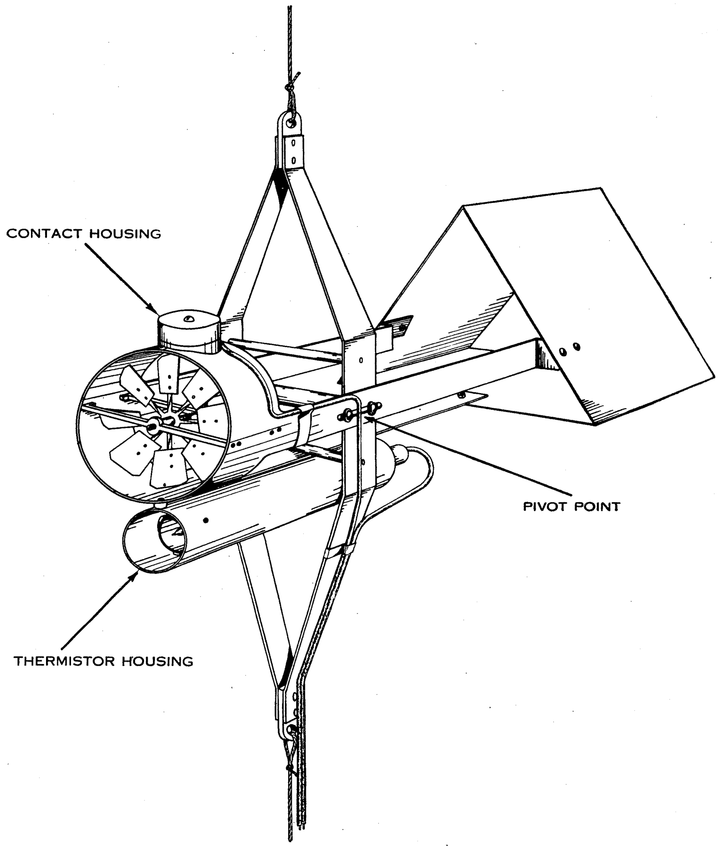


Fig. 2.—The captive balloon-sonde.

a Darex " Kytoon "—and electrical connection was by means of four P.V.C. covered copper wires, 0·038 cm diameter, twisted together and tied at 2 m intervals to the nylon cord. Weights were 7 g/m for the combined cable and 350 g for the instrument.

At first " Kytoons " of 2·3 m$^3$ capacity were used and, with the better of the two available,* heights of over 100 m were attainable. After this was lost in a strong wind, a smaller " Kytoon " (1·1 m$^3$ capacity) was used at heights

* Few balloon results were obtained in the first half of the trials owing to the first large " Kytoon " flying badly, probably owing to some asymmetry.

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up to some 80 m. Readings were taken at each of several heights in turn and, assuming a catenary form for the cable, these heights were subsequently calculated from the cable length, the elevation angle of the instrument, and angle of the cable to the horizontal where it left the winch drum, the last two being averaged over several clinometer readings for each recording.

The cable proved to be a weak feature of this equipment as the wires were rather delicate and the smallest crack in the insulation is serious in the presence of a salt film. The insulation was easily damaged at the points of attachment to the nylon cord.

## IV. Effects of the Ship on the Wind Profiles

### (a) *Obstruction of the Air Flow by the Ship's Hull*

The ship influences the wind field in its vicinity and, despite the fact that the anemometers were rigged well forward on a small ship with moderately fine lines and no raised forecastle, it was considered likely that there would still be an effect too large to be neglected.* This was found to be the case during the trials, when anemometers on booms were rigged forward of those on the anemometer mast. For example, 31 runs were made with an anemometer at 5·85 m carried 2·5 m forward of the 6·4 m anemometer. Using the final wind profiles to correct for the small height difference, it is found that the wind velocity at the forward position was $1 \cdot 2 \pm 0 \cdot 3$ per cent. greater than at the same level on the anemometer mast. A similar difference (0·9 per cent., mean of 7 runs) is found at the 4 m level.

The comparison of results of normal and speed runs is used to derive corrections for hull effect in the following manner. It is assumed that the relative wind speed at an anemometer position at height $z$ is increased due to the presence of the hull by a factor $f_z$ which is taken to be independent of relative wind speed. For simplicity the 13 m value of $f$ is taken as unity. This gives corrections relative to 13 m, which is all that is required.

For a standard run at ship speed $S_1$ we find the recorded wind ratio, $R_1$ ($z$ : 13 m) to be related to the true wind speed relative to the surface, $u_1(z)$, as follows:

$$R_1 = \frac{f_z\{u_1(z)+S_1\}-S_1}{u_1(13)}.$$

For a speed run at ship speed $S_2 > S_1$

$$R_2 = \frac{f_z\{u_2(z)+S_2\}-S_2}{u_2(13)},$$

and the difference of these ratios gives

$$R_2 - R_1 = f_z\left\{\frac{u_2(z)}{u_2(13)} - \frac{u_1(z)}{u_1(13)}\right\} + (f_z - 1)\left\{\frac{S_2}{u_2(13)} - \frac{S_1}{u_1(13)}\right\}.$$

* Sails were not set at any time in the trials.

The first term on the right-hand side will be zero if no changes in drag coefficient of the sea surface or in stability have taken place between the runs. Assuming this to be so, then

$$f_z=1+\frac{R_2-R_1}{S_2/u_2(13)-S_1/u_1(13)}. \qquad \ldots\ldots\ldots\ldots\ldots \quad (\mathbf{1})$$

If there is but a small change in wind speed between the runs compared, then equation (**1**) is approximated by

$$f_z=1+\frac{(R_2-R_1)u(13)}{S_2-S_1},$$

which shows that for accurate evaluation of $f_z$ by this method the change in ship speed between the runs must be of reasonable magnitude compared with the 13 m wind speed. Very light winds, however, are not generally favourable as they are too often variable in strength and direction.

The values of $f$ calculated from equation (**1**) give moderately consistent results, as may be seen from the following percentage effects, $100(f_z-1)$, for the 6·4 m position as a result of 10 speed runs on different occasions:

−0·3, −3·0, −3·6, −1·6, −2·8, −3·2, −4·3, −3·0, −3·9, −0·8

Mean −2·65 per cent. with standard error 0·42 per cent.

The corresponding mean for the 5·85 m boom anemometer from four speed runs is −1·2 per cent. so these results are in agreement, within the limits of observational error, with the fact that this boom anemometer registered a wind speed 1·2±0·3 per cent. higher than found for the same level at the anemometer mast position.

In this way the corrections for hull effect given in Table 1 were compiled.

TABLE 1

HULL EFFECT CORRECTIONS TO OBSERVED RELATIVE WIND SPEEDS

| Anemometer Position | No. of Speed Run Comparisons | Positive Correction (%) |
|---|---|---|
| 6·4 m mast .. .. .. | 10 | 2·7±0·4 |
| 5·85 m boom .. .. | 4 | 1·4 |
| 4 m mast (on 0·6 m arm) .. | 2 | 4·0 |
| 4 m mast (on 1·5 m arm) .. | 9 | 3·4±0·6 |
| 3·95 and 3·68 m boom .. | 4 | 2·5 |
| 3 m mast (0·6 m arm) .. | 1 | 7·5 |
| 2·67 m and 1·95 m boom .. | 6 | 3·9±0·7 |
| 1·5 m mast (0·6 m arm) .. | 3 | 12·5 |
| 1·5 m mast (1·5 m arm) .. | 4 | 9·5 |

It is interesting to note that even 5 m forward of the stem of the vessel the effect of the hull is felt to the extent of 2 or 3 per cent. Neglect of this effect would lead to vertical wind gradients seriously in error. Had the rather large magnitude of the hull effect been fully appreciated early in the trials more speed runs would have been made with a consequent gain in precision of the corrections.

The wind speeds shown in the table of results (Appendix I, Table 5) are those found after adding the above corrections to the observed relative wind speeds and then subtracting the ship speed $S$.

### (b) *The Effect of Rolling*

The lateral wind component caused by rolling results in the recorded wind speed ($U_r$) being greater than the relative wind speed which it is desired to measure. Here wind speeds relative to the ship are being considered. When the ship is running head to wind we have, for a harmonic rolling motion,

$$U_r^2 = U^2 + (2\pi h\alpha/T)^2 \sin^2 \omega t,$$

where $U$=actual relative wind velocity (assumed constant),
$h$=height of anemometer above axis of roll,
$\alpha$=rolling amplitude, radians,
$T$=rolling period,
$\omega = 2\pi/T$,
$t$=time.

Taking mean values over an extended period (i.e. $t \gg T$)

$$\bar{U}_r/U = (2/\pi)\int_0^{\frac{1}{2}\pi} \sqrt{(1+b^2 \sin^2 \omega t)}\,\mathrm{d}(\omega t),$$

where $b = 2\pi h\alpha/TU$. For the present purpose we are only concerned with solutions for $b<0\cdot3$ so, expanding in series before integration and neglecting terms containing the fourth and higher powers of $b$, we find

$$\bar{U}_r/U = 1 + \tfrac{1}{4}b^2. \qquad \ldots\ldots\ldots\ldots \quad (2)$$

Precise observations of mean rolling amplitude were not made on these trials but it was rarely as much as 7° and the higher values were confined to some runs in Bass Strait when the direction of the swell was different from that of the wind. Values of drag coefficient have not been evaluated for such occasions whenever the wind speed was less than 8 m/sec (i.e. October 10 and 26) as the rolling effect would then be rather large.

For a relative wind speed of 10 m/sec and a rolling amplitude of 7° with the observed period of 4 sec, we find that the observed 13 : 4 m winds ratio is larger than the true value by 1·2 per cent. and this may be shown to correspond to an error of about 17 per cent. in the calculated shearing stress. The drag coefficients for Bass Strait presented later are therefore up to some 10 or 15 per cent. too large but those for Port Phillip Bay should be in error by less than 5 per cent. as rolling there was in general quite slight, when head to wind, owing to the absence of swell.

Fore-and-aft motions of the anemometers caused by pitching and surging do not give rise to error in the wind profiles but there will be an effect of the varying attitude of the anemometers caused by pitching. This has been neglected as the angle of pitch is small and the attitude effect should not vary much with height.

### (c) *Effect of Variation in Height of Anemometers above the Water Surface*

In the course of an observation the height of the anemometers above the water fluctuates considerably about the mean owing to the waves and the pitching of the vessel and, as the variation of wind speed with height is not linear, an error is introduced in attributing the mean wind speed indicated by a given anemometer to the mean height of that instrument. The form of the wind profiles is such that the error will be larger at the lower levels. Even were data available for the amplitude of the fluctuation in height, a precise calculation of this error would require knowledge of the variations in wind speed over the waves as between the crests and troughs. It is useful, however, to make an estimate of the error on the basis of the mean wind profile. The neutral profile is

$$u=(u_*/k)\ \ln\ (z/z_0),$$

where $u_*$=the friction velocity,
$z_0$=roughness parameter,
$k$=the Kármán constant,

and the anemometer is assumed to be subject to a harmonic variation in height $A \sin \Phi t$. The mean wind speed recorded by the anemometer ($\bar{u}_r$) is therefore

$$\bar{u}_r=\overline{(u_*/k)\ \ln\ [(z+A\ \sin\ \Phi t)/z_0]}.$$

Provided that the period of the vertical oscillation is small compared with the observation period and $A<z$, this can be approximated by

$$\bar{u}_r=(u_*/k)[\ln\ (z/z_0)-\tfrac{1}{4}A^2/z^2]. \qquad (3)$$

From this it follows that

$$\bar{u}_r(z_2)-\bar{u}_r(z_1)=\left(\frac{u_*}{k}\right)\ln\ (z_2/z_1)\left[1-\frac{A^2(z_2^{-2}-z_1^{-2})}{4\ \ln\ (z_2/z_1)}\right].$$

In the present work $u_*$ was evaluated from the wind speed difference between 4 and 13 m, and it follows that the error in $u_*$ is then $1{\cdot}20A^2$ per cent. ($A$ measured in metres), the sense of the error being such that the observed values are too great. It was noted during the runs made in the rougher conditions that the foot of the anemometer mast (0·9 m above mean water level) was fairly frequently submerged in the wave crests but the average value of $A$ in these runs was generally rather less than 0·9 m. On a very few runs $A$ may have been rather more than 1 m but 1·3 m is an upper limit so the maximum error in $u_*$ on this score is about 2 per cent. corresponding to a 4 per cent. error in drag coefficient. It is likely that the above treatment based on the *mean* wind profile gives an overestimate of this effect, as any tendency for the wind over the wave crests to be greater than that in the troughs would entail smaller errors.

## V. Calculation of the Shearing Stress from the Wind Profile

The wind speeds given in the table of results (Appendix I, Table 5) were plotted against the logarithm of height and from these graphs the values of $u_{13}-u_4$ were approximately evaluated and used with the corresponding potential temperature difference† $\theta_{13}-\theta_4$ to give layer Richardson numbers $Ri\,(13:4)$ for each run from

$$Ri\,(13:4)=\frac{g}{\theta_4}\,\frac{\Delta\theta\Delta z}{(\Delta u)^2},$$

where the differences are for the height interval 4–13 m. In the following $Ri$ should be understood to be $Ri\,(13:4)$ unless stated otherwise. On two days potential temperature differences were not observed and values have been estimated from the air/sea temperature differences in the light of the rest of the data (see Section VII). It was immediately apparent that for many of the runs the value of $Ri$ was significantly different from zero and that stability effects on the form of the profiles would have to be taken into account.

The observations could not all be treated in uniform fashion over the whole stability range; it was found necessary to adopt two systems, one for the range $Ri$ $-0{\cdot}025$ to $+0{\cdot}10$ and the other for the observations at greater instability. A few profiles for $Ri>0{\cdot}10$ have not been used to evaluate shearing stresses as no reliable method is available.

For $Ri$ between $-0{\cdot}025$ and $+0{\cdot}10$ it is considered in the light of other observational work (Sverdrup 1936; Pasquill 1949; Deacon 1953, 1955; Rider 1954) that the Rossby-Montgomery (1935) formulation of the effect of stability provides the most acceptable basis for the estimation of surface shearing stress ($\tau_0$) but a considerable element of uncertainty remains. The relationship is

$$\frac{u_*}{z\partial u/\partial z}=\frac{k}{\sqrt{\{1+\sigma Ri(z)\}}}, \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where $u_*=(\tau_0/\rho)^{\frac{1}{2}}$,
$\rho$=air density,
$k$=the Kármán constant (taken to be $0{\cdot}40$),
$\sigma$=the Rossby stability constant.

The reason why some wind-profile observations (e.g. Deacon 1953) under moderately strong stability ($0{\cdot}05<Ri<0{\cdot}10$) have indicated a failure of equation (4) is now considered to be a consequence of the shearing stress having been estimated on the assumption that it is proportional to the square of the wind velocity close above the surface roughness elements. This is only true if the Reynolds number of the flow is sufficiently large and there is evidence now that this is often not the case (on land) under these conditions. This matter is dealt with in a note to be published by one of us (E.L.D.) elsewhere.

The value of $\sigma$ to be used in (4) is not yet known with accuracy. Sverdrup (1936) found $\sigma\sim 11$ and Deacon (1953) about 6 or 7, but in both these studies $\tau_0$ was not measured but estimated using the roughness parameter $z_0$ indicated by the neutral wind profiles. The values of $\sigma$ found in this way are very sensitive to errors in $z_0$; the above difference between 7 and 11 corresponds to the small change in $z_0$ from $0{\cdot}25$ to $0{\cdot}30$ cm. Rider's (1954) direct measurements of $\tau_0$

† The upper temperature element was at a height of $12{\cdot}6$ m but this has been taken to be close enough to 13 m for the difference to be neglected.

together with wind and temperature profiles provide, at present, the best material for an evaluation of $\sigma$. Using the values of $\partial u/\partial z$, $Ri$, and $\tau_0$ given by Rider (op. cit., Tables 2 and 3) the value of $\sigma=8\cdot 8$ was found from the least squares fit of equation (4) to the data in the range $-0\cdot 025<Ri<0\cdot 10$. In the reduction of the present data the value $\sigma=9$ is employed but it is apparent that this value is still uncertain by 1 or 2 units.

The application of equation (4) to our data in order to obtain $u_*$ presents some difficulty. The equation has no established integral form, while the scatter of points in the wind profiles and the absence of detailed temperature profiles make a direct application of equation (4) impossible. We have proceeded as follows:

(i) The wind and temperature profiles between 4 and 13 m were assumed similar in form and to be representable by the interpolation formulae

$$\frac{\partial u}{\partial z}, \frac{\partial \theta}{\partial z} \propto z^{-\beta}. \qquad (5)$$

(ii) The assumptions (i) enable equation (4) to be integrated and lead to

$$\beta=\frac{1+\sigma Ri(z)}{1+1\cdot 5\sigma Ri(z)}, \qquad (6)$$

and

$$u_*^2=F_1(u_{13}-u_4)^2, \qquad (7)$$

where $F_1$ is a function of $Ri(13:4)$ which has been calculated and is given in Table 2. The detailed procedure leading to Table 2 is given in Appendix II.

TABLE 2

VALUES OF $F_1$ FOR USE IN CALCULATING $u_*^2$ FROM THE 13 M—4 M WIND SPEED DIFFERENCE USING EQUATION (7)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $Ri$ (13 : 4) .. .. .. | $-0\cdot 02$ | $-0\cdot 01$ | 0 | $+0\cdot 02$ | $+0\cdot 04$ | $+0\cdot 06$ | $+0\cdot 08$ | $+0\cdot 10$ |
| $F_1\times 10^3$ .. .. .. | $1\cdot 42$ | $1\cdot 27$ | $1\cdot 16$ | $0\cdot 98$ | $0\cdot 86$ | $0\cdot 78$ | $0\cdot 68$ | $0\cdot 62$ |

The problem is now to find the best value of $u_{13}-u_4$ from the wind data and so also of $F_1$ in order to obtain $u_*$ from equation (7). The following steps were taken to this end.

(iii) Initial estimates of $u_{13}-u_4$ and hence of $Ri(13:4)$ were made (as already mentioned) and $\beta$ calculated from equation (6). A theoretical profile was then prepared passing through the observed $u_{13}$ and the value of $u_4$ corresponding to the wind difference.

(iv) This theoretical curve was slightly adjusted on the $u:\log z$ diagram until, maintaining the curvature unchanged, it gave a good fit to the observations and still ran through the 13 m point.

(v) A revised value of $u_{13}-u_4$ was then available from which was obtained a revised $Ri(13:4)$. The appropriate value of $F_1$ together with the wind difference then gave $u_*^2$ from equation (7).

(vi) From $u_*^2$ and $u_{10}$ read from the fitted wind profile the drag coefficient $c_{10}=u_*^2/u_{10}^2$ was obtained. The values of $c_{10}$ so derived are given in Table 5 of Appendix I.

It will be noted from step (iv) that, for each profile, the 13 m observation was accepted as correct and the lower level observations were utilized in obtaining an estimate of $u_4$. They were therefore given less individual weight than the 13 m value. This system was adopted, partly in order that the profile fitting should be as objective a process as possible, but also because it was appropriate to give rather less weight to the low-level observations in view of the much bigger hull effect at low levels. As all six anemometers took turns at 13 m systematic calibration errors at this height were excluded.

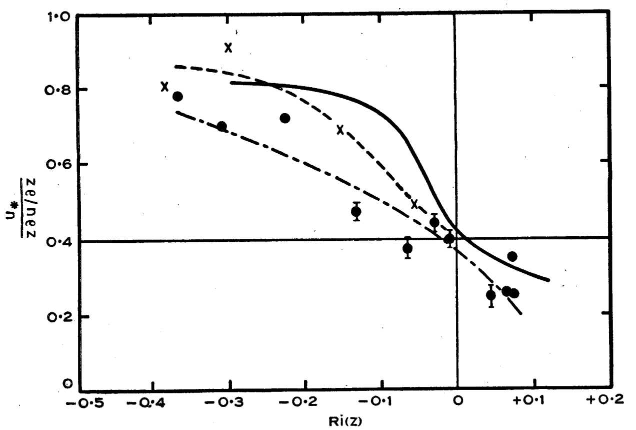


Fig. 3.—Variation of $\dfrac{u_*}{(z\partial u/\partial z)}$ with Richardson number.

——— Rider's (1954) mean curve.

●—·—· Observations by eddy correlation method (Deacon 1955).

× - - - - From wind profile data given by Deacon (1953) with $k=0\cdot40$.

The Rossby equation fails under unstable conditions when the instability exceeds a relatively small amount owing to the onset at about $Ri=-0\cdot03$ of a regime of effectively free convection (Priestley 1955). The observational evidence on the behaviour of $\overset{*}{K}\equiv u_*/(z\partial u/\partial z)$ at negative Richardson numbers is summarized in Figure 3, from which it is apparent that knowledge is still very imperfect in this range. There is some measure of agreement that $\overset{*}{K}$ tends to a value of about $0\cdot8$ at very large instability but in the neighbourhood of $Ri=-0\cdot1$ there is much uncertainty. It is considered that Rider's data are probably the most reliable of those at present available and accordingly they are employed in the reduction of our data for $Ri<-0\cdot025$, but the uncertainty in this reduction should be borne in mind. Rider's observations of $u_*$ and of wind speed and temperature at heights of 50 and 150 cm are used to give the factor $F_2$ (see Table 3) as a function of $Ri(3a:a)$ in

$$u_*^2=F_2(u_{3a}-u_a)^2, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

and on grounds of profile similarity it is assumed that this may be applied to our data with $a=4$ m.

The factors of Table 3 are applied to the wind speed differences $u_{12}-u_4$ read from the faired profiles.

TABLE 3

FACTORS FOR THE EVALUATION OF $u_*^2$ FROM WIND PROFILES AT MODERATE TO STRONG INSTABILITY USING EQUATION (8)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $Ri$ $(3a:a)$ .. .. | —0·025 | —0·04 | —0·06 | —0·08 | —0·10 | —0·15 | —0·20 | —0·25 |
| $F_2\times10^3$ .. .. | 1·97 | 2·7 | 3·3 | 3·7 | 3·9 | 4·5 | 5·0 | 5·4 |

## VI. The Wind Profile Results and Discussion

### (a) *The Wind Profiles and Drag Coefficients*

The wind velocities after correction for hull effects and ship speed are given in the table of results (Appendix I, Table 5) together with other relevant data and values of the drag coefficient $c_{10}\equiv u_*^2/u_{10}^2$ calculated as indicated in Section V.

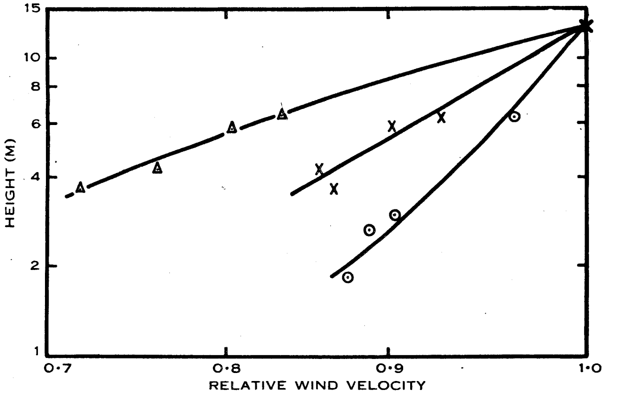


Fig. 4.—Specimen wind profiles. These examples are rather better than average but a greater part of the material is of similar quality.
⊙ run No. 17*a*, $Ri(13:4)=-0\cdot07$; × run No. 106, $Ri(13:4)=0\cdot01$; △ run No. 103, $Ri(13:4)=0\cdot18$.

Some specimen profiles at various degrees of atmospheric stability are shown in Figure 4. Approximately 75 per cent. of the profiles can be classified as good or fairly good while the remainder show more scatter of the points but are still usable. There is no evidence of any systematic departure of the profiles from the expected forms, i.e. linear on the $u:\log z$ plotting under neutral conditions and somewhat curved, but in opposite senses, under stable and unstable conditions.

The drag coefficients $c_{10}$ are considered in relation to the 10 m wind speed in three groups: (i) the Bass Strait results, (ii) the Port Phillip Bay results, (iii) the observations for neutral and near-neutral conditions for both locations.

(i) *Bass Strait Results.*—These results are shown in Figure 5. The fetch of the wind over sea was from 20 to 40 km (average 27 km) for the observations at wind speeds above 8 m/sec and very large for the remainder. No great weight can be attached to the squares for which $Ri(13:4) < -0 \cdot 04$, owing to uncertainties in the calculation of $u_*$ under such conditions.

The full line in Figure 5 has been drawn to represent, rather tentatively, the variation of $c_{10}$ with wind speed under neutral conditions. There are no near-neutral results between 6 and 10 m/sec so here the curve has been drawn below the points for unstable conditions and mainly above those for stable stratification.

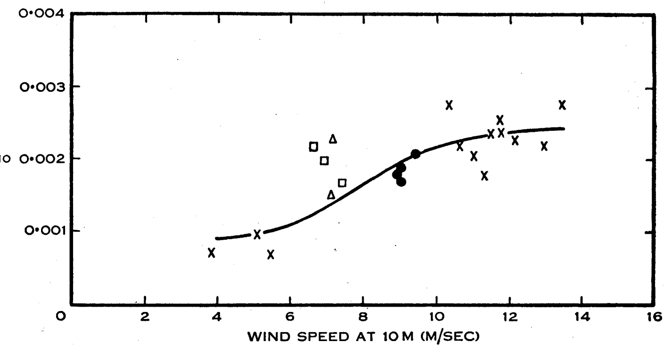


Fig. 5.—Drag coefficient related to wind speed; Bass Strait observations. The curve is drawn for neutral conditions. Range of $Ri(13:4)$: □ $<-0 \cdot 04$; △ $-0 \cdot 02$ to $-0 \cdot 04$; × $-0 \cdot 019$ to $+0 \cdot 029$; ● $+0 \cdot 03$ to $+0 \cdot 06$.

The three points for near-neutral conditions and $u_{10} < 6$ m/sec (runs 15–17) were obtained on an occasion when the sea and air temperatures differed by only a fraction of 1 °F and $\theta_{13} - \theta_3$ was zero within the limits of observational error. The three profiles are shown in Figure 6 with straight lines fitted to the values by least squares. There appears to be little doubt that on this occasion the drag coefficient was distinctly low as compared with other occasions of neutral stability but strong wind. The value of $c_{10}$ for an aerodynamically smooth surface is expected from laboratory investigations to be about $0 \cdot 0009$ at 5 m/sec, a value close to that given, on a larger scale, by Van Dorn's (1953) measurements on a pond which had detergent applied to the surface to reduce wave formation.

The 10 near-neutral observations at wind speeds between 10 and 14 m/sec give a mean $c_{10} = 0 \cdot 00235$ with a standard error of $0 \cdot 00010$. But the motion of the ship under these conditions was such that this mean value is probably about 10 per cent. too large, mostly because of rolling but partly owing to oscillation in height of the anemometers, so the true value of $c_{10}$ should be fairly close to $0 \cdot 0021$; the corresponding value of the roughness parameter is $0 \cdot 15$ cm.

(ii) *Port Phillip Bay Results.*—Altogether 58 values of drag coefficient are available for Port Phillip Bay. For these the fetch over water varied from 11 to 50 km, but in a considerable number of cases the first part of the fetch was over the shallow water above the sand banks in the south-western part of the Bay (see Fig. 1) where the character of the sea surface was observed to be very different from that over the deeper parts of the Bay (15–25 m). In view of this, fetch over the deeper water is also given in Table 5 of Appendix 1. Fortunately, the transition from shallow to deep water is sharp, so there was no difficulty in assigning values to the fetch over deep water. The correlation coefficient between drag coefficient and the logarithm of fetch over deep water is $-0{\cdot}37$ (58 values) while the partial coefficient after eliminating $Ri(13:4)$ is $-0{\cdot}34$, a value significant at the 1 per cent. level. The 39 observations for

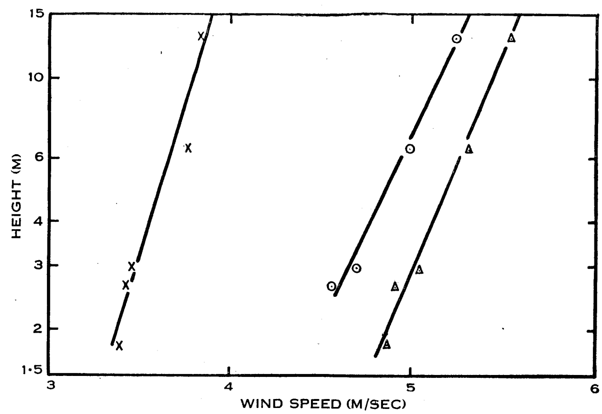


Fig. 6.—Wind profiles for conditions of neutral stability and light wind; Bass Strait.
⊙ Run 14. × Run 15. △ Run 16.

$u_{10} > 7$ m/sec give a similar result. In Figure 7 mean values after grouping for fetch are shown plotted against fetch over deep water. It seems from this that the drag coefficient may be relatively independent of fetch if this exceeds about 3 km over deep water but at smaller fetches (all to leeward of shallow water) where the surface is marked by short rather steep waves in a confused pattern, the drag coefficient rises to a rather higher value.

The results for fetches over deep water of 5 km or more are shown in Figure 8. The observations are too few, considering the extensive range of stability and the uncertainty in interpretation of profiles under extreme conditions, for much more to be said than that the general level of the Bay values is much the same as for Bass Strait.

(iii) *Neutral Conditions*; *Both Locations.*—As the near-neutral results are the most reliable they provide the best material for a comparison of the drag coefficients for Port Phillip Bay and Bass Strait. They are shown for both locations plotted together in Figure 9 in which the line drawn is from Figure 5. For the Bay observations the least fetch over deep water is 6 km. The two sets of results appear to accord reasonably well bearing in mind that the Strait values for high winds are about 10 per cent. too high owing to ship motion, whereas the Bay values are much less affected by these factors.

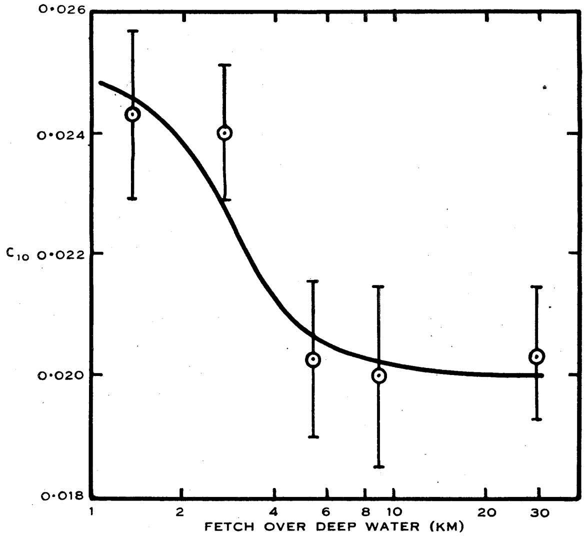


Fig. 7.—The rise in drag coefficient in proximity to shoal water. Observations in Port Phillip Bay.

Two near-neutral observations for Port Phillip Bay (runs 86 and 87—not shown in Fig. 9) are worthy of separate mention as they were made in a

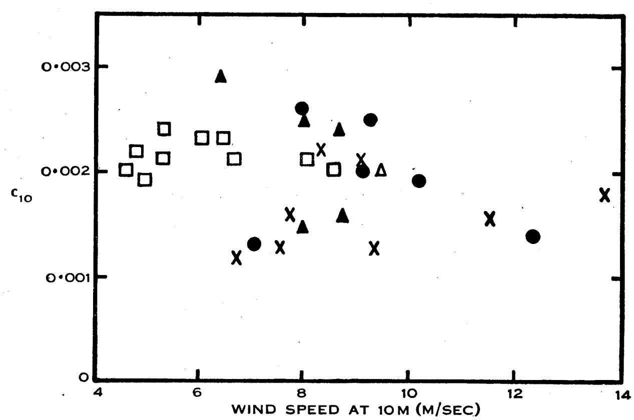


Fig. 8.—Drag coefficients from observations in Port Phillip Bay when the fetch of wind over deep water was 5 km or more. □ *Ri* <—0·04 ; △ *Ri* —0·02 to —0·04 ; × *Ri* —0·019 to +0·029 ; ● *Ri* +0·030 to +0·059 ; ▲ *Ri* +0·06 to +0·10.

confused sea at a time when the wind was still changing direction appreciably after a thunder squall. The drag coefficients of 0·0021 and 0·0017 for 10 m wind speeds of 5·7 and 6·7 m/sec respectively are some 50 per cent. above the values indicated by the line in Figure 9, for a sea more nearly in equilibrium with the wind.

### (*b*) *Comparison of the Drag Coefficients with Published Values*

The values of drag coefficient for neutral stability from the Bass Strait observations (Fig. 5) may now be compared with the results of previous work. Charnock (1951) has given a diagram conveniently summarizing the state of knowledge at that time and Francis (1954) has collected together the results of some more recent studies.

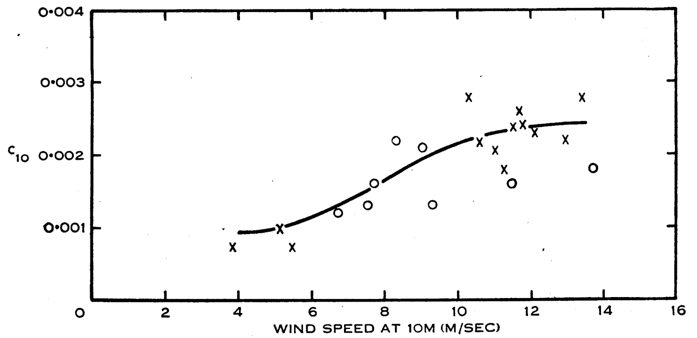


Fig. 9.—Drag coefficient related to wind speed; near-neutral observations; $-0 \cdot 02 < Ri(13:4) < 0 \cdot 03$.

○ Bay observations; × Bass Strait observations.

Observation of the wind-induced surface tilt of lakes or arms of the sea has given in the wind speed range 10–15 m/sec (for which our information in Figure 5 is most definite) values of $c_7$ scattered between 0·0015 and 0·0033 but averaging about 0·0025 as compared with $c_{10} = 0 \cdot 0021$ given by the present work after allowing for motion of the vessel. The difference is less than 20 per cent. when the difference in wind speed reference level (rather uncertain in the tilt observations) is taken into account. At lower wind speeds we may doubt with Francis (1954) whether the tilt method is capable of giving results of much value owing to the smallness of the slopes, the interference of surges, and probably also the lack of homogeneity of the water.

A preliminary study (Sheppard and Omar 1952) by the geostrophic departure method using pilot balloon data for the Trades has given a mean value of $c$ of about 0·0013 over the range 4–10 m/sec. This is a little lower than indicated by Figure 5 but not by a significant amount in view of the large observational scatter.

The evidence from profile studies is rather conflicting. Roll (1949) finds cogent reasons to suppose that inadequate exposure of anemometers has vitiated the results of some studies and Brocks (1955) shows, as is also evident from the present work, that more attention must be paid to atmospheric stability conditions than has been customary in much of the earlier work. This is particularly important in the light wind and large height range.

Rossby and Montgomery (1936) inferred that in light winds the sea behaves as a hydrodynamically smooth surface, $c \sim 0 \cdot 0009$, while at higher wind speeds the value of $c_{10}$ is about $0 \cdot 0029$. Sverdrup (1946) put forward evidence from humidity gradient observations over the sea suggesting that the corresponding increase in evaporation coefficient occurs rather abruptly at about 6–7 m/sec and Munk (1947) attributed this to a marked change at that speed in the nature of the sea surface associated with the appearance of white caps. With the accumulation of further evidence it now seems doubtful if the change is as sudden as Sverdrup and Munk then supposed. Brocks (1955) in a careful study of the available data on water vapour profiles finds that the weight of evidence is in favour of the sea surface behaving as hydrodynamically smooth in light winds but that with increasing wind the evaporation and drag coefficients increase to higher values rather gradually—a conclusion in accordance with the present observations. Some wind profile observations by Hay (1955) give a similar indication; he finds that $c_{10}$ rises from about $0 \cdot 0015$ at $6 \cdot 5$ m/sec to $0 \cdot 0023$ at 11 m/sec, a variation paralleling fairly closely that of our curve in Figure 5. Hay's observations were, however, made with a short fetch (800 m) of the wind over the sea and to leeward of steep cliffs.

Observations by Cox and Munk (1954) on the mean square slope of the water surface measured from aerial photographs of the Sun's glitter on the sea, suggest a gradual rather than a sudden increase in $c$ with wind speed. We find, however, that the data for slope in the direction of the wind indicate a rate of increase of mean square slope with wind speed which is significantly greater above 7 or 8 m/sec (at $12 \cdot 5$ m height) than below. Munk (1955), assuming a linear variation between slope and wind speed over the whole range, has inferred that the drag coefficient probably increases with wind speed, but rather less rapidly than linearly.

Little is to be found in the literature on the variation of drag coefficient with stability. Tilt observations on Lough Neagh (Darbyshire and Darbyshire 1955) suggest that the effect is quite large, but this may be due to the use of wind observations at a nearby land station instead of over the Lough. So the variation displayed in Figure 5 remains to be more fully investigated.

## VII. The Observations of Vertical Temperature Gradient

The relationship between the vertical temperature gradient in the air and the difference in temperature between sea and air is of interest, not least in order to be able to estimate the vertical temperature gradient, which is not an easily measurable quantity, from simple observations of air and sea temperatures. Furthermore, much information on the air-sea temperature difference is available from ships' routine observations; to be able to interpret these in terms of the temperature gradient in the air is of value in studies of heat transfer between sea and atmosphere, smoke diffusion, radio wave propagation, and so on.

The observations of potential temperature difference ($\Delta\theta$) between $12 \cdot 6$ and 4 m are plotted against the air-sea temperature difference in Figure 10;

various ranges of 10 m wind speed are distinguished, as a unique relationship between the temperature differences is not to be expected. For wind speeds above 5·5 m/sec any variation of the dependence is too small to be detected in the presence of considerable observational scatter and the line in Figure 10

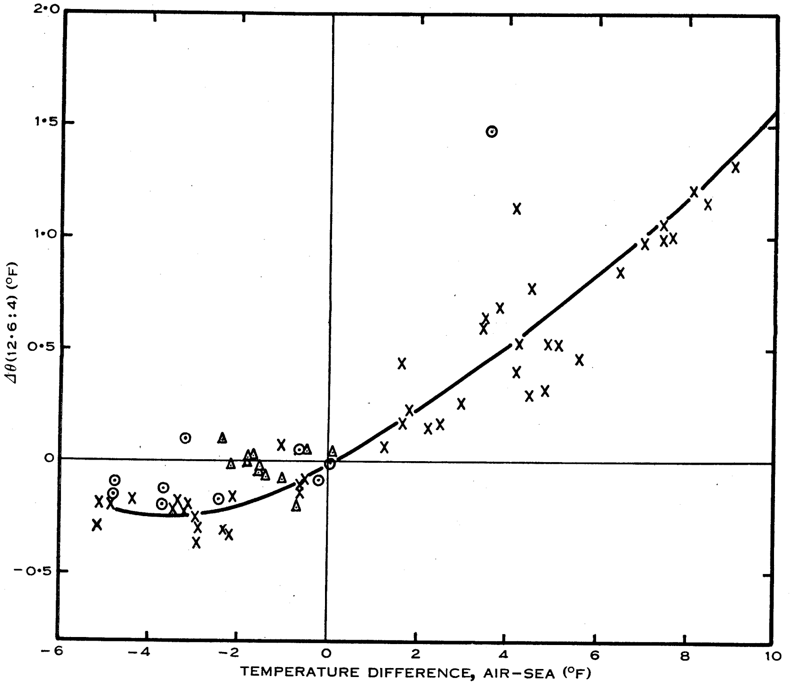


Fig. 10.—Potential temperature difference between 12·6 and 4 m in relation to the difference in temperature between sea and air.

× $u_{10}>5\cdot5$ m/sec ; ⊙ $u_{10}$ 4·5 to 5·5 m/sec ; △ $u_{10}$ 2·5 to 4·5 m/sec.
The line is drawn to represent the variation for $u_{10}>5\cdot5$ m/sec.

is drawn to represent this range. This is sufficiently closely approximated by the following equations :

$$\left.\begin{aligned}\Delta\theta(12\cdot6:4)&=0\cdot005(T_a-T_s)^2+0\cdot105(T_a-T_s)\,; \quad 0<(T_a-T_s)<10\ {}^\circ\mathrm{F},\\ \Delta\theta(12\cdot6:4)&=0\cdot02(T_a-T_s)^2+0\cdot14(T_a-T_s)\,; \quad -5<(T_a-T_s)<0\ {}^\circ\mathrm{F},\end{aligned}\right\} \qquad (9)$$

where $T_a$=air temperature at about 3 m height,
$T_s$=sea surface temperature,

and temperatures are in degrees Fahrenheit. These relationships were used to estimate values of Δθ for some of the runs for which measured values were not available.

For the sea warmer than the air and wind speed less than 5·5 m/sec the evidence in Figure 10 is for a progressive decrease of Δθ such that in the lighest wind range, 2·5–4·5 m/sec, Δθ is not significantly different from zero. A change in this sense is to be expected from the well-established variation in the form of profiles from the logarithmic form at high wind speeds to forms at lower speeds in which a greater part of the temperature difference occurs near the boundary surface. But the magnitude of the effect is rather surprising and some doubt might be felt as to the adequacy of

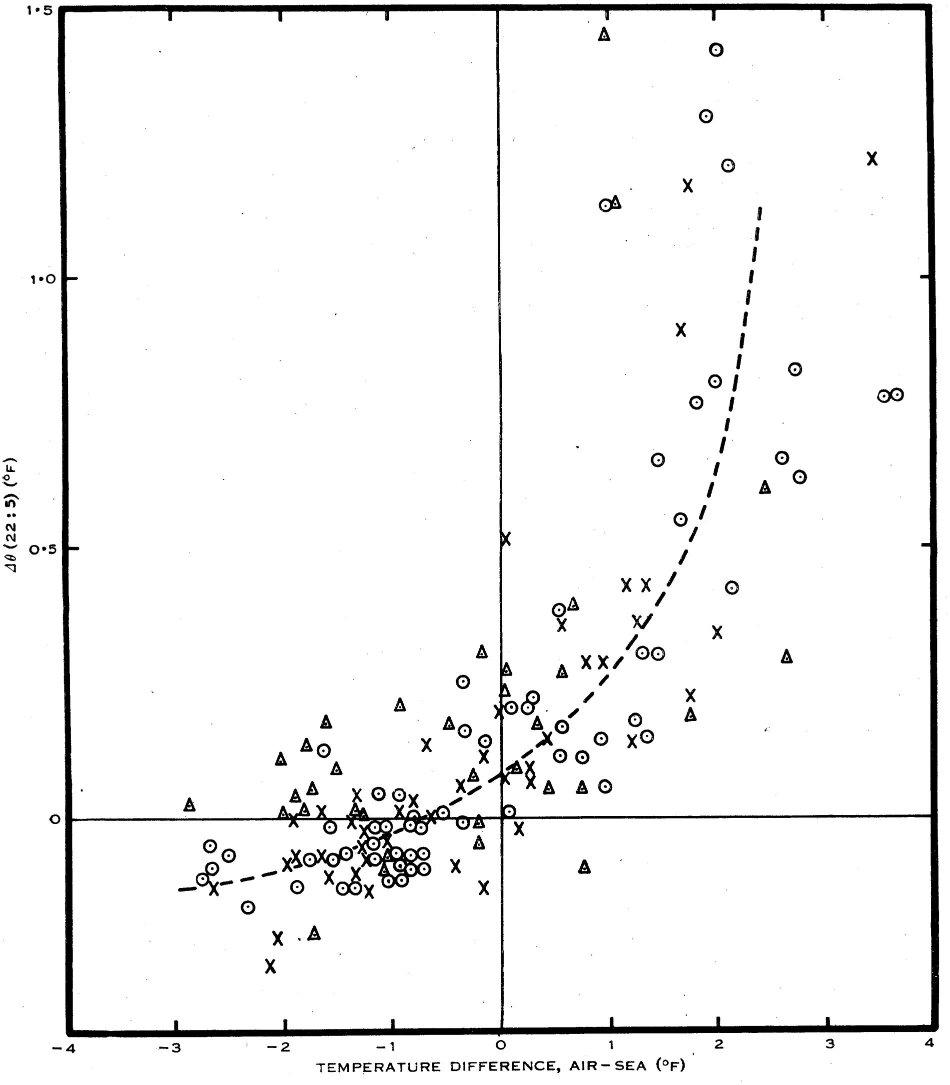


Fig. 11.—The potential temperature difference between 22 and 5 m in relation to the difference in temperature between sea and air (after Johnson and Meredith).
△ Wind speed 0–2 m/sec ; ⊙ 3–5 m/sec ; × above 5 m/sec.

ventilation of the temperature elements at low wind speeds were it not for the fact that observations by Johnson and Meredith (unpublished data 1927) on a ship in the Mediterranean show the same behaviour. They used aspirated and shielded platinum resistance elements as described by Johnson (1927) and they were of the opinion that their observations of the temperature difference 22 m—5 m were correct to within 0·1 °F. Their counterpart of Figure 10 is reproduced here as Figure 11 and it will be seen that, with light winds and sea

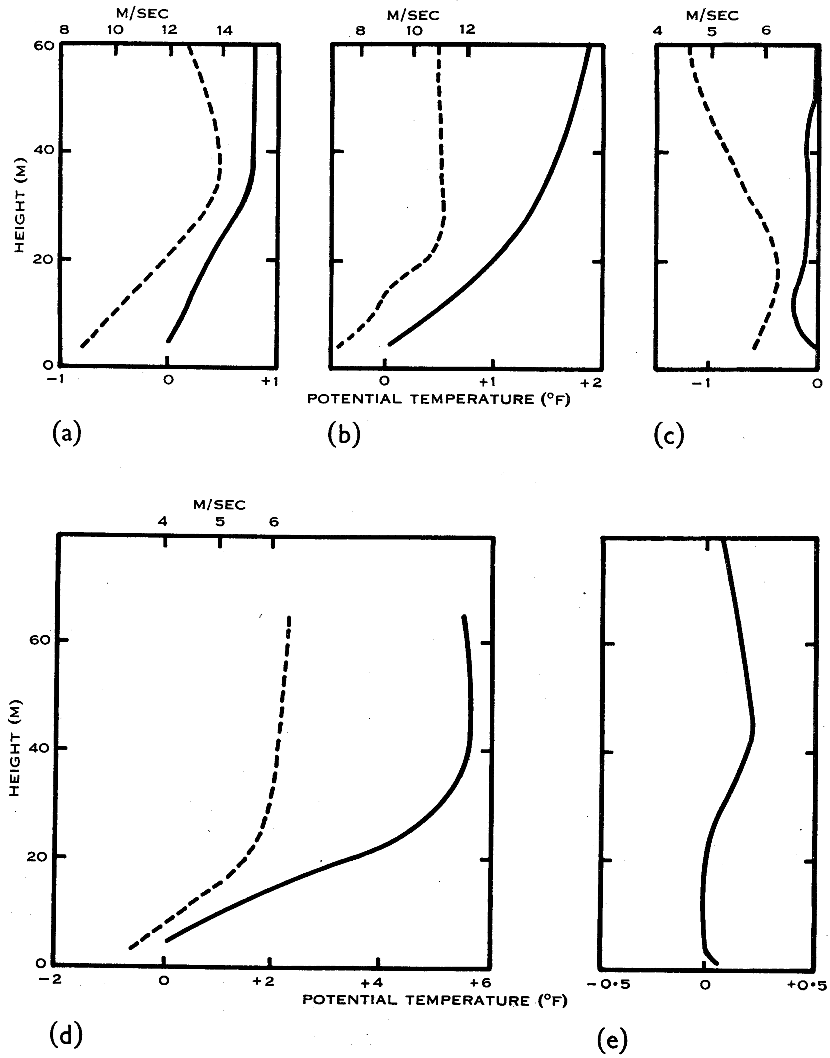


Fig. 12.—Profiles of wind speed (broken lines) and potential temperature, referred to 4 m level (full lines).

(*a*) 24.x.55, 10·50–13·00 E.S.T., Bass Strait, $T_a—T_s=4$ °F ;
(*b*) 24.x.55, 13·30–15·40 E.S.T., Bass Strait, $T_a—T_s=5$ °F ;
(*c*) 26.x.55, 08·40–10·30 E.S.T., Bass Strait, $T_a—T_s=—5$ °F ;
(*d*) 23.x.55, 14·20–15·20 E.S.T., Port Phillip Bay, $T_a—T_s=3·3$ °F ;
(*e*) 13.x.55, 12·30–15·40 E.S.T., Port Phillip Bay, $T_a—T_s=—1·7$ °F.

warmer than the air, the values of $\Delta\theta(22:5)$ are often zero or even somewhat positive. That this is by no means impossible is now becoming evident. Priestley (1954) in a study of free convection has shown how a mechanism of convective plumes is able to carry heat upwards through a layer of subadiabatic lapse rate and Bunker (1956) has observed upward heat fluxes through stably stratified air at heights from 100 to 500 m over the sea.

## VIII. The Kite Balloon Observations

Some wind and temperature profiles using the kite balloon equipment are shown in Figure 12 ; these are for the occasions when the most complete sets of data were secured. It had been hoped to obtain many more observations but troubles with balloon and cable were only surmounted a few days before the end of the trials. Each profile in Figure 12 is the mean of three sets of readings, i.e. three separate soundings, but even so the time spent by the instrument at any one level was rather small and sampling errors were probably rather large.

The temperature profiles show no very remarkable features but the tendency for the wind profiles to show maxima at low levels is unexpected. The low level maximum on October 26 (Fig. 12 (*c*)) under unstable conditions is, however, not significant as only two of the three profiles obtained on this occasion show it. The wind observations in Port Phillip Bay at the time of the temperature profiles of Figure 12 (*e*) were rather remarkable ; the 13 m anemometer gave wind speeds mainly between 2 and 4 m/sec yet at heights from 30 to 110 m no wind speed of more than 1 m/sec was observed. The wind profiles taken on the ship on this day have accordingly not been analysed for resistance coefficient.

On some occasions of strong stability in Port Phillip Bay there was evidence of marked changes of wind direction with height. In particular on October 17, around 15·00 E.S.T., when the 13 m wind speed was about 10 m/sec and the air 8–9 °F warmer than the water, a streamer on the balloon cable showed that at 70 m the wind direction was about 70–80° veered from that shown by a vane at 13 m on the cross-trees. Unfortunately the balloon cable parted before more observations could be secured on this interesting phenomenon.

## IX. Conclusions

The main conclusions drawn from this work may be summarized as follows :

(*a*) It is possible to obtain satisfactory observations of wind profiles on a ship despite some disturbance to the wind flow caused by the ship's hull if measurements are made both with the ship nearly stationary and also steaming into wind at moderate speeds. The interference effect may then be eliminated as shown in Section IV (*a*). It is also advisable to take records of ship motion, particularly roll, so that corrections may be made (see Section IV (*b*)).

(*b*) The tentative indication from the wind profiles is that the drag coefficient of the open sea under neutral conditions of atmospheric stability is close to 0·001 at low wind speeds but from about 5 m/sec upward to 12 m/sec there is a fairly gradual increase in resistance coefficient to a value of about 0·0021 (anemometer height 10 m). Further work is clearly needed to consolidate these findings.

(*c*) The need for atmospheric stability to be taken fully into account in all work on turbulent transfer between sea and atmosphere is evident from this work.

(*d*) The temperature gradient measurements show that with little wind and sea warmer than atmosphere the layer of appreciably superadiabatic lapse rate is very shallow, i.e. 10 m or less.

## X. Acknowledgments

Thanks are due to the Division of Fisheries and Oceanography, C.S.I.R.O., for making the Fishery Research Vessel *Derwent Hunter* available for this work despite a crowded programme and to the master, Capt. R. Downie, and crew for their ready cooperation.

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# APPENDIX I

## TABLE 4

GENERAL CONDITIONS OF OBSERVATIONS

| Date (Oct. 1955) | Location | Run Nos. | Times (E.S.T.) | Duration of Runs (min) | Clouds | Swell (ft) | Heights of Anemometers (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | *a* | *b* | *c* | *d* |
| 6 | Bay | 1–4 | 14·05–15·26 | 10 | As 8/8 | | 3·0 | 1·5 | — | — |
| 7 | Bay | 5–13 | 12·51–16·10 | 10 | Cu 1/8, Ac As 5/8–8/8 | | 3·0 | 2·67* | — | — |
| 8 | Strait | 14–18 | 11·15–14·46 | 10 or 15 | Cu Sc 6/8–8/8 | 3–4 | 3·0 | 2·67† | 1·85 | — |
| 9 | Bay | 19–25 | 15·14–17·16 | 10 | Cu Sc 7/8 | | 4·0 | 2·67† | 1·5 | 1·5‡ |
| 10 | Strait | 26, 27 | 12·08–12·52 | 10 | Cu Sc 3/8 | 4–5 | 4·15 | 4·10‡ | — | — |
| 10 | Strait | 28–31 | 13·20–16·05 | 30 | Cu Sc 6/8–7/8 | 4–5 | 4·15 | 4·10‡ | — | — |
| 11 | Bay | 32–38 | 11·30–16·21 | 30 | Cu Sc Ac 4/8–7/8 | | 4·0‡ | 2·64† | 1·5‡ | — |
| 12 | Bay | 39–45 | 11·06–15·50 | 30 | Cu Cb Sc 4/8–7/8 | | 4·0‡ | 3·95† | 1·95† | — |
| 13 | Bay | 46–55 | 12·15–15·52 | 10 | Cu Sc 1/8–3/8 | | 5·81† | 3·95† | 1·95† | — |
| 14 | Bay | 56–60 | 10·56–14·36 | 30 | Ac As 8/8 | | 4·15 | — | — | — |
| 15 | Strait | 61–66 | 11·37–15·39 | 30 | Cu Cb Sc 4/8–7/8 | 4 | 4·15 | — | — | — |
| 17 | Bay | 67–75 | 11·41–15·12 | 10 | Ci 7/8 | | 4·15 | — | — | — |
| 18 | Strait | 76–81 | 12·05–15·39 | 10 or 30 | Cu 1/8 | 5 | 4·19 | 2·78† | — | — |
| 20 | Bay | 82–89 | 11·27–16·16 | 30 | Cb As 8/8 | | 4·19 | 3·68† | — | — |
| 21 | Bay | 90 | 13·20–13·50 | 30 | Cu Sc 6/8 | | 5·85† | 3·68† | — | — |
| 22 | Bay | 91–100 | 10·30–16·05 | 30 | Cu 1/8–4/8 | | 5·85† | 4·23 | 3·68† | — |
| 23 | Bay | 101–104 | 12·56–14·27 | 30 | Cu 1/8, Ac 1/8 | | 5·85† | 4·23 | 3·68† | — |
| 24 | Strait | 105–112 | 10·48–15·47 | 30 | Cu Sc 1/8–2/8 | 8 | 5·85† | 4·23 | 3·68† | — |
| 26 | Strait | 113–116 | 08·04–10·51 | 30 | Cu Cb 5/8–7/8 | 8 | 5·85† | 4·23 | — | — |

* This anemometer was rigged forward of the anemometer mast by 4·2 m in runs 5–7, by 2·7 m in runs 8–10, and by 1·5 m in runs 11–13.

† Rigged 2·7 m forward of anemometer mast using boom of $1\frac{1}{2}$ in. pipe.

‡ On these occasions the arms on the anemometer mast were extended in length from the original 0·6 m to 1·5 m and the longer arms were used for the anemometer at heights between 4·15 and 4·23 m on all occasions after October 13.

TABLE 5

WIND AND TEMPERATURE OBSERVATIONS AND COMPUTED RESISTANCE COEFFICIENTS*

| Run No. | Wind Direction (deg. T.B.) | Fetch (naut. mile) | Wave Height (ft) | $T_a - T_s$ (°F) | $\Delta\theta$ (°F) | $u(13)$ (cm/sec) | $u(6\cdot4)$ (cm/sec) | $u(a)$ (cm/sec) | $u(b)$ (cm/sec) | $u(c)$ (cm/sec) | $u(d)$ (cm/sec) | $\Delta u$ (cm/sec) | $Ri(13:4)$ $\times 10^3$ | $u(10)$ (m/sec) | $c_{10}$ $\times 10^4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 005 | 22(1) | — | 3·3 | (0·5) | 609 | 547 | 506 | 455 | | | 90 | (100) | 5·9 | 14 |
| 2 | 005 | 22(1) | 1·5 | 4·2 | (0·6) | 770 | 691 | 629 | 569 | | | 117 | (75) | 7·4 | 17 |
| 3 | 355 | 20(1) | 1·5 | 4·6 | (0·6) | 784 | 641 | 628 | 561 | | | 128 | (60) | 7·5 | 22 |
| 4 | 340 | 20(1) | 1·5 | 4·1 | (0·6) | 770 | 672 | 604 | 547 | | | 136 | (55) | 7·4 | 26 |
| 5 | 345 | 12 | 2 | 2·9 | — | 527 | 439 | 376 | 382 | | | 123 | — | 5·0 | — |
| 6 | 345/360 | 12 | 2 | 3·4 | — | 576 | 488 | 420 | 425 | | | 128 | — | 5·5 | — |
| 7 | 355 | 13 | 2·5 | 4·0 | (0·6) | 644 | 564 | 498 | 499 | | | 123 | (67) | 6·1 | 30 |
| 8 | 350 | 14 | 2·5 | 4·7 | 0·82† | 834 | 731 | 655 | 650 | | | 145 | 53 | 8·0 | 26 |
| 9 | 350 | 11 | 2·5 | 4·6 | 1·16† | 830 | 726 | 647 | 641 | | | 149 | 71 | 7·9 | 25 |
| 10 | 350 | 11 | 2·5 | 4·5 | 1·73† | 904 | 792 | 706 | 705 | | | 166 | 86 | 8·6 | 24 |
| 11 | 000 | 14 | 4 | 3·8 | 1·07† | 899 | 812 | 742 | 712 | | | 133 | 81 | 8·7 | 16 |
| 12 | 350 | 14 | 3–4 | 4·0 | 0·99† | 966 | 856 | 771 | 748 | | | 163 | 51 | 9·3 | 25 |
| 13 | 000 | 13 | 3 | 4·8 | 0·77† | 950 | 855 | 777 | 752 | | | 146 | 49 | 9·2 | 20 |
| 14 | 220 | Large | 1 | —0·15 | —0·10† | 524 | 498 | 470 | 456 | | | 47 | 0 | 5·1 | 10 |
| 15 | 220 | ,, | 1 | +0·1 | 0·05† | 384 | 377 | 347 | 344 | 340 | | 30 | 0 | 3·8 | 7 |
| 16 | 220 | ,, | 1·5 | 0·0 | —0·02† | 553 | 530 | 504 | 491 | 486 | | 42 | 0 | 5·4 | 7 |
| 17*a* | 220 | ,, | 1·5 | —0·6 | —0·12† | 700 | 671 | 626 | 615 | 607 | | 56 | —70 | 6·9 | 20 |
| 17*b* | 220 | ,, | 2 | —0·6 | —0·17† | 668 | 640 | 598 | 586 | 579 | | 52 | —110 | 6·6 | 22 |
| 18*a* | 210 | ,, | 2 | —0·6 | —0·10† | 753 | 731 | 664 | 672 | 655 | | 59 | —50 | 7·4 | 17 |
| 18*b* | 210 | ,, | 2 | —0·6 | —0·07† | 731 | 711 | 647 | 646 | 637 | | 59 | —40 | 7·2 | 15 |
| 18*c* | 210 | ,, | 2 | —0·6 | —0·12† | 720 | 694 | 630 | 627 | — | | 67 | —40 | 7·1 | 23 |
| 19 | 200 | 10(3) | 1·5 | —2·2 | (—0·25) | 655 | 631 | 610 | 583 | 562 | 570 | 47 | (—200) | 6·5 | 23 |
| 20 | 200 | 9(1½) | 1·5 | —2·5 | (—0·25) | 656 | 628 | 608 | 578 | 560 | 570 | 51 | (—170) | 6·5 | 26 |
| 21 | 200 | 10(2½) | 1·5 | —2·3 | —0·31 | 694 | 661 | 638 | 611 | 584 | 590 | 57 | —160 | 6·8 | 29 |
| 22 | 200 | 10(2½) | 1·5 | —2·4 | (—0·25) | 619 | 600 | — | 552 | 531 | 542 | 41 | (—250) | 6·1 | 21 |
| 23 | 200 | 8(1) | 1·5 | —1·9 | (—0·25) | 647 | 620 | 596 | 569 | 546 | 552 | 51 | (—160) | 6·4 | 28 |

TABLE 5 (*Continued*)

| Run No. | Wind Direction (deg. T.B.) | Fetch (naut. mile) | Wave Height (ft) | $T_a—T_s$ (°F) | $\Delta\theta$ (°F) | $u(13)$ (cm/sec) | $u(6\cdot4)$ (cm/sec) | $u(a)$ (cm/sec) | $u(b)$ (cm/sec) | $u(c)$ (cm/sec) | $u(d)$ (cm/sec) | $\Delta u$ (cm/sec) | $Ri(13:4)$ $\times 10^3$ | $u(10)$ (m/sec) | $c_{10}$ $\times 10^4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 200 | 8(½) | 1·5 | —2·2 | —0·32 | 730 | 699 | 672 | 647 | 615 | 628 | 56 | —180 | 7·2 | 27 |
| 25 | 200 | 6(¼) | 1·5 | —3·0 | —0·37 | 699 | 666 | 646 | 614 | 586 | 590 | 57 | —200 | 6·9 | 31 |
| 26 | 200 | Large | 4 | —2·2 | (—0·24) | 656 | 613 | — | — | | | 79 | (—60) | 6·4 | — |
| 27 | 200 | ,, | 4 | —1·9 | (—0·24) | 702 | 656 | — | — | | | 85 | (—60) | 6·9 | — |
| 28 | 200 | ,, | — | —2·0 | (—0·23) | 656 | 611 | 574 | 570 | | | 85 | (—60) | 6·4 | — |
| 29*a* | 200 | ,, | — | —3·5 | (—0·25) | 680 | 648 | 609 | 608 | | | 68 | (—90) | 6·7 | — |
| 29*b* | 200 | ,, | 4 | —3·4 | (—0·25) | 694 | 652 | 609 | 607 | | | 84 | (—60) | 6·8 | — |
| 30 | 210 | ,, | — | —3·4 | (—0·25) | 751 | 712 | 665 | 665 | | | 83 | (—60) | 7·4 | — |
| 31 | 210 | ,, | — | —3·4 | (—0·25) | 766 | 717 | 668 | 669 | | | 96 | (—50) | 7·5 | — |
| 32 | 210/225 | 8(4½) | 1 | —4·8 | —0·10 | 499 | 480 | 453 | 460 | 438 | | 34 | —150 | 4·9 | 19 |
| 33 | 205/220 | 8(4½) | 1 | —4·8 | —0·16 | 465 | 451 | 422 | 431 | 412 | | 28 | —350 | 4·6 | 20 |
| 34 | 200/220 | 9(5) | 1 | —3·6 | —0·13 | 484 | 465 | 438 | 444 | 427 | | 34 | —190 | 4·8 | 22 |
| 35 | 200/210 | 9(4½) | 1·25 | —3·2 | 0·10 | 538 | 515 | 484 | 488 | 468 | | 40 | —160 | 5·3 | 24 |
| 36 | 195/200 | 9(5) | 1·5 | —3·1 | —0·20 | 672 | 648 | 610 | 609 | 586 | | 49 | —140 | 6·6 | 21 |
| 37 | 195/205 | 8(4½) | 1·5 | —3·2 | —0·21 | 611 | 588 | 552 | 555 | 528 | | 44 | —180 | 6·0 | 23 |
| 38(*s*) | 195 | 8(4½) | 1·25 | —2·4 | —0·17 | 537 | 521 | 483 | 484 | 474 | | 36 | —220 | 5·3 | 21 |
| 39 | 200/220 | 11(4) | 2·5 | —4·4 | —0·18 | 868 | 835 | 788 | 786 | 752 | | 72 | —60 | 8·5 | 20 |
| 40 | 200/205 | 10(4) | 2·5 | —3·4 | —0·21 | 823 | 795 | 750 | 748 | 717 | | 65 | —85 | 8·1 | 21 |
| 41 | 200/210 | 10(3) | 2·5 | —3·4 | (—0·17) | 959 | 917 | 860 | 862 | 817 | | 87 | (—40) | 9·4 | 20 |
| 42 | 210 | 10(2½) | 2·5 | —2·2 | —0·16 | 1002 | 955 | 898 | 898 | 848 | | 95 | —30 | 9·8 | 18 |
| 43 | 205 | 9(2) | 2·5 | —3·3 | —0·18 | 968 | 923 | 866 | 866 | 826 | | 90 | —40 | 9·5 | 21 |
| 44 | 200 | 9(2½) | 2·5 | —3·0 | —0·25 | 1049 | 996 | 936 | 939 | 889 | | 99 | —45 | 10·3 | 23 |
| 45 | 210 | 9(2½) | 2·5–3·0 | —2·9 | —0·30 | 1112 | 1069 | 1007 | 1003 | 943 | | 100 | —50 | 10·9 | 23 |
| 46 | 270 | 12(3) | 1 | —1·5 | —0·01 | 345 | 337 | 331 | 319 | 290 | | — | — | 2·6 | — |
| 47 | 270 | 10(1¾) | 1 | —1·5 | —0·05 | 262 | 260 | 253 | 248 | 218 | | — | — | 4·0 | — |
| 48 | 250 | 6(1½) | 0·75 | —1·4 | —0·06 | 227 | 226 | 217 | 211 | 181 | | — | — | 2·3 | — |
| 49 | 260 | 6(½) | 0·5 | —1·7 | 0·37 | 98 | 93 | 84 | 86 | 39 | | — | — | 0·9 | — |

TABLE 5 (*Continued*)

| Run No. | Wind Direction (deg. T.B.) | Fetch (naut. mile) | Wave Height (ft) | $T_a$—$T_s$ (°F) | $\Delta\theta$ (°F) | $u(13)$ (cm/sec) | $u(6\cdot4)$ (cm/sec) | $u(a)$ (cm/sec) | $u(b)$ (cm/sec) | $u(c)$ (cm/sec) | $u(d)$ (cm/sec) | $\Delta u$ (cm/sec) | $Ri(13:4)$ $\times 10^3$ | $u(10)$ (m/sec) | $c_{10}$ $\times 10^4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 51 | 025/030 | 20 | 0·5 | —2·1 | —0·02 | 354 | 355 | 344 | 334 | 310 | | — | — | 3·5 | — |
| 52 | 040 | 19 | 0·5 | —2·3 | 0·10 | 316 | 319 | 308 | 298 | 275 | | — | — | 3·2 | — |
| 53 | 035 | 18 | 0·5 | —1·6 | 0·03 | 337 | 335 | 330 | 319 | 296 | | — | — | 3·4 | — |
| 54 | 035 | 18 | 0·75 | —1·8 | 0·03 | 402 | 397 | 388 | 376 | 354 | | — | — | 4·0 | — |
| 55 | 035 | 18 | 0·75 | —1·8 | 0·01 | 392 | 386 | 374 | 362 | 350 | | — | — | 3·9 | — |
| 56 | 000 | 27 | 4 | 1·6 | 0·45 | 934 | 855 | 807 | | | | 131 | 15 | 9·0 | 21 |
| 57 | 000 | 26 | 5 | 2·5 | 0·18 | 1178 | 1100 | 1037 | | | | 142 | 15 | 11·5 | 16 |
| 58 | 000 | 24 | 5 | 3·5 | 0·61 | 1271 | 1182 | 1117 | | | | 156 | 42 | 12·4 | 14 |
| 59 | 000 | 24 | 6 | 4·2 | 0·40 | 1412 | 1300 | 1230 | | | | 187 | 19 | 13·7 | 18 |
| 60 | 000 | 24 | 5 | — | 0·07 | 1055 | 962 | 908 | | | | 152 | 37 | 10·2 | 19 |
| 61 | 270 | 14 | 5–6 | 2·0 | —0·04 | 1388 | 1259 | 1180 | | | | 215 | (4) | 13·4 | 28 |
| 62 | 290 | 13 | 4–6 | 1·9 | (0·10) | 1208 | 1099 | 1038 | | | | 178 | (5) | 11·7 | 26 |
| 63 | 270 | 10 | 6 | 1·0 | 0·05 | 1335 | 1230 | 1156 | | | | 180 | 2 | 13·0 | 22 |
| 64 | 260 | 12 | 5 | 1·6 | —0·19 | 1160 | 1075 | 1015 | | | | 147 | (8) | 11·3 | 18 |
| 65 | 295 | 11 | 5 | 2·5 | —0·10 | 1133 | 1039 | 983 | | | | 156 | (14) | 11·0 | 21 |
| 66 | 290 | 8 | 3 | 3·7 | (0·30) | 1095 | 999 | 938 | | | | 160 | (20) | 10·6 | 22 |
| 67 | 000 | 20(1) | 2 | 6·5 | (0·85) | 1131 | 1001 | 936 | — | | | 204 | (34) | 10·8 | 31 |
| 68 | 000 | 20(½) | 1·5–2 | 6·5 | 0·85 | 1109 | 1004 | 949 | — | | | 168 | 51 | 10·7 | 20 |
| 69 | 000 | 20(1½) | 2 | 7·7 | 1·02 | 1073 | 961 | 900 | — | | | 179 | 54 | 10·3 | 24 |
| 70 | 000 | 20(1½) | 2 | 7·5 | 1·00 | 989 | 882 | 827 | — | | | 169 | 59 | 9·5 | 24 |
| 71 | 000 | 20(1) | 2 | 7·0 | 0·99 | 912 | 805 | 752 | — | | | 167 | 60 | 8·7 | 28 |
| 72 | 000 | 20(1) | 2 | 7·6 | 1·07 | 908 | 803 | 744 | — | | | 168 | 64 | 8·7 | 28 |
| 73 | 000 | 19(½) | 2 | 8·5 | 1·17 | 1281 | — | 1069 | — | | | 217 | 42 | 12·3 | 26 |
| 74 | 010 | 20(1½) | 2 | 8·2 | 1·22 | 1091 | — | 899 | — | | | 197 | 53 | 10·4 | 28 |
| 75 | 005 | 20(1) | 2 | 9·0 | 1·33 | 1235 | — | — | — | | | — | — | 11·8 | — |
| 76 | 230 | Large | 5 | —1·2 | — | 318 | 310 | 295 | — | | | — | — | 3·2 | — |
| 77 | 230 | ,, | 5 | —0·7 | —0·20 | 265 | 253 | 241 | — | | | — | — | 2·6 | — |

TABLE 5 (*Continued*)

| Run No. | Wind Direction (deg. T.B.) | Fetch (naut. mile) | Wave Height (ft) | $T_a - T_s$ (°F) | $\Delta\theta$ (°F) | $u(13)$ (cm/sec) | $u(6\cdot4)$ (cm/sec) | $u(a)$ (cm/sec) | $u(b)$ (cm/sec) | $u(c)$ (cm/sec) | $u(d)$ (cm/sec) | $\Delta u$ (cm/sec) | $Ri(13:4)$ $\times 10^3$ | $u(10)$ (m/sec) | $c_{10}$ $\times 10^4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 78 | 210/190 | Large | 5 | —1·0 | —0·08 | 341 | 348 | 334 | — | | | — | — | 3·5 | — |
| 79 | 190/020 | ,, | 4–6 | —1·0 | 0·07 | 638 | 613 | 582 | 534 | | | — | — | 6·3 | — |
| 80 | 190/220 | ,, | 4–6 | —0·6 | 0·06 | 545 | 533 | 510 | 461 | | | — | — | 5·4 | — |
| 81 | 215 | ,, | 4–6 | —0·5 | 0·06 | 332 | 332 | 319 | 284 | | | — | — | 4·5 | — |
| 82 | 350 | 24 | 3–4 | 4·6 | 0·77 | 827 | 758 | 711 | 694 | | | 121 | 89 | 8·0 | 15 |
| 83 | 340/010 | 22 | 3–4 | 3·8 | 0·69 | 757 | 673 | 636 | 614 | | | 131 | 68 | 7·2 | 24 |
| 84 | 350/300 | 21·5/ 12(4) | 3–4 | 3·5 | 0·65 | 1077 | 985 | 917 | 902 | | | 163 | 41 | 10·4 | 21 |
| 85 | 290 | 10(3½) | 3–4 | 0·2 | 0·04 | 1192 | 1138 | 1064 | 1052 | | | — | — | 11·7 | — |
| 86 | 310/330 | 9(3½) | 3–4 | —0·7 | —0·01 | 586 | 536 | 527 | 497 | | | 76 | —3 | 5·7 | 21 |
| 87 | 360/060 | 16 | 2 | —0·8 | 0·04 | 685 | 627 | 614 | 589 | | | 85 | 9 | 6·6 | 17 |
| 88 | 040/180 | 16/5 | 2 | 0·5 | 0·07 | 370 | 331 | 314 | 287 | | | 61 | 32 | 3·6 | 26 |
| 89 | — | — | — | — | (0·03) | 332 | 293 | 287 | 259 | | | 60 | (25) | 3·2 | 34 |
| 90 | 310 | 19 | 3 | 2·6 | 0·01 | 857 | 792 | 740 | 733 | | | 118 | 6 | 8·3 | 22 |
| 91 | 300 | 12(½) | 3–4 | —1·2 | (—0·18) | 967 | 921 | — | 882 | 870 | | 87 | (—40) | 9·5 | 20 |
| 92 | 300 | 12(½) | 3–4 | —0·6 | —0·14 | 1015 | 966 | — | 918 | 910 | | 96 | —26 | 10·0 | 14 |
| 93 | 300 | 12(5½) | 3–4 | —0·1 | —0·06 | 951 | 899 | 887 | 863 | 847 | | 94 | —11 | 9·3 | 13 |
| 94 | 300 | 12(4¾) | 3–4 | — | (0) | 794 | 744 | 740 | 718 | 707 | | 81 | (0) | 7·8 | 16 |
| 95 | 300 | 11(4) | 3–4 | 0·9 | 0·01 | 774 | 722 | 722 | 688 | 686 | | 85 | 12 | 7·6 | 13 |
| 96 | 300 | 11(5) | 3 | 1·3 | 0·02 | 692 | 644 | 642 | 615 | 614 | | 76 | 20 | 6·8 | 12 |
| 97 | 290/280 | 10(3) | 3 | 1·7 | 0·04 | 728 | 672 | 671 | 642 | 640 | | 86 | 39 | 7·1 | 13 |
| 98 | 270/290 | 11(1½) | 2 | 1·8 | 0·05 | 634 | 569 | 568 | 540 | 541 | | 96 | 42 | 6·1 | 21 |
| 99 | 280 | 11(2½) | 2 | — | 0·04 | 630 | 562 | 570 | 543 | 537 | | 91 | 40 | 6·1 | 19 |
| 100 | 280 | 10(1) | 2–1·5 | 2·4 | 0·03 | 594 | 524 | 524 | 491 | 493 | | 105 | 25 | 5·7 | 32 |
| 101 | 320 | 21(5) | 4 | 5·7 | — | 767 | 682 | 671 | 634 | — | | 139 | — | 7·3 | — |
| 102 | 320 | 21(5) | 4 | 4·2 | 1·13 | 671 | 580 | 570 | 540 | 526 | | 138 | 100 | 6·4 | 29 |
| 103 | 320/360 | 21 | 3 | 3·6 | 1·48 | 449 | 374 | 360 | 341 | 322 | | 119 | 175 | 4·2 | — |

TABLE 5 (*Continued*)

| Run No. | Wind Direction (deg. T.B.) | Fetch (naut. mile) | Wave Height (ft) | $T_a$—$T_s$ (°F) | $\Delta\theta$ (°F) | $u(13)$ (cm/sec) | $u(6\cdot4)$ (cm/sec) | $u(a)$ (cm/sec) | $u(b)$ (cm/sec) | $u(c)$ (cm/sec) | $u(d)$ (cm/sec) | $\Delta u$ (cm/sec) | $Ri(13:4)$ $\times 10^3$ | $u(10)$ (m/sec) | $c_{10}$ $\times 10^4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 104 | 360 | 21 | 3 | 2·9 | 1·90 | 496 | 408 | 394 | 368 | 345 | | 139 | 165 | 4·6 | — |
| 105 | 260 | 24 | — | 3·9 | — | 930 | 855 | 832 | 795 | 803 | | 130 | (30) | 9·0 | 19 |
| 106 | 260 | 24 | 3–5 | 3·0 | 0·27 | 1251 | 1148 | 1115 | 1063 | 1073 | | 182 | 14 | 12·1 | 23 |
| 107 | 270 | 15 | 5 | 4·5 | 0·30 | 1201 | 1084 | 1055 | 997 | 1010 | | 178 | 16 | 11·6 | 24 |
| 108 | 270 | 14 | 4–5 | 4·8 | 0·32 | 1069 | 969 | 946 | 893 | 901 | | 171 | 18 | 10·3 | 28 |
| 109 | 270 | 12 | 5 | 5·6 | 0·47 | 927 | 826 | 817 | 771 | 774 | | 156 | 33 | 8·9 | 18 |
| 110 | 260 | 14 | 3–4 | 4·9 | 0·53 | 937 | 843 | 822 | 775 | 778 | | 159 | 35 | 9·0 | 17 |
| 111 | 260/250 | 13/15 | 3 | 4·3 | 0·54 | 877 | 789 | 770 | 724 | 729 | | 148 | 42 | 9·4 | 21 |
| 112 | 260 | 15 | 3–4 | 5·1 | 0·53 | 1200 | 1089 | 1064 | 1009 | 1009 | | 187 | 26 | 11·6 | 24 |
| 113 | 230/260 | Large/22 | 4 | —5·2 | —0·31 | 653 | 600 | 594 | 572 | | | 81 | —72 | 6·4 | — |
| 114 | 240/210 | 18/large | — | —4·9 | —0·20 | 713 | 670 | 667 | 639 | | | 72 | —59 | 7·0 | — |
| 115 | 210 | Large | — | —5·1 | —0·18 | 645 | 600 | 593 | 576 | | | 70 | —56 | 6·3 | — |
| 116 | 210 | Large | — | —3·7 | —0·20 | 515 | 479 | 472 | 460 | | | 57 | —95 | 5·0 | — |

* *Notes to Table* 5.—In the column headed " Fetch " two values are given in those cases where the first part of the fetch of the wind was over shallow water; the value in parentheses is the fetch over deep water.

Wave heights were estimated. They are more reliable for Port Phillip Bay than in Bass Strait, where the swell made estimation of wave height more difficult.

$T_a$—$T_s$ is the difference in temperature between air and sea and $\Delta\theta$ is the potential temperature difference between 4 m and 12·6 m except for those values marked with a dagger where the lower level is 3 m. Values of $\Delta\theta$ in parentheses were estimated from $T_a$—$T_s$ using the curve of Figure 10.

$u(a)$, $u(b)$, etc. signify the corrected wind speeds relative to the sea surface at the heights $a$, $b$, etc. given in Table 4.

$\Delta u$ is the difference in wind speed between 13 and 4 m as read from the smoothed wind profiles.

$Ri(13:4)$ is the layer Richardson number for the 4 to 13 m air layer calculated from the values of $\Delta\theta$ and $\Delta u$. Values in parentheses are based on estimated values of $\Delta\theta$.

$c_{10}$ is the drag coefficient, the reference height for wind speed being 10 m.

Values of the drag coefficient have not been calculated for either October 13 (run Nos. 46–55) or for October 18 (run Nos. 76–81) owing to the combination of marked instability and a variable light wind on the former occasion and the marked decrease of wind above 13 m shown by the balloon anemometer on the latter.

Drag coefficients are also not given for October 10 (run Nos. 26–31) or for October 26 (run Nos. 113–116) owing to rather heavy rolling in winds of less than 8 m/sec—a condition giving too great an error (see Section IV (*b*)) for trustworthy results.

## Appendix II

### *Method of Evaluation of the Shearing Stress from the Non-neutral Wind Profiles using Rossby's Equation*

In applying Rossby's equation

$$\frac{u_*}{z\partial u/\partial z}=\frac{k}{(1+\sigma Ri(z))^{\frac{1}{4}}} \quad \ldots\ldots\ldots\ldots\ldots \quad (\mathbf{A1})$$

to the evaluation of $u_*$ from measurements of wind speed $u$ and potential temperature $\theta$ at two heights, $a$ and $b$, we proceed by using

$$\partial u/\partial z=cz^{-\beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (\mathbf{A2})$$

as a suitable interpolation formula between these levels. Rearranging equation (**A1**) and integrating with respect to height between levels $a$ and $b$ gives

$$\frac{k^2}{u_*^2}\int_a^b z^2\left(\frac{\partial u}{\partial z}\right)^4 \mathrm{d}z=\frac{\sigma g}{T}\int_a^b \frac{\partial \theta}{\partial z}\mathrm{d}z+\int_a^b \left(\frac{\partial u}{\partial z}\right)^2 \mathrm{d}z.$$

Using equation (**A2**) and the expression derived from it that

$$c=\frac{(1-\beta)(u_b-u_a)}{b^{1-\beta}-a^{1-\beta}}$$

gives

$$u_*^2=\frac{Fk^2(u_b-u_a)^2}{G+\sigma Ri(b:a)}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (\mathbf{A3})$$

where

$$F=\frac{(1-\beta)^4(p^{3-4\beta}-1)(p-1)}{(3-4\beta)(p^{1-\beta}-1)^4},$$

$$G=\frac{(1-\beta)^2(p^{1-2\beta}-1)(p-1)}{(1-2\beta)(p^{1-\beta}-1)^2},$$

$$p=b/a,$$

and $Ri(b:a)$ signifies the Richardson number for the layer $a$ to $b$ obtained by using $(u_b-u_a)/(b-a)$ for the wind velocity gradient and similarly for the potential temperature gradient. It now remains to be able to assign values to $\beta$. With very accurate wind measurements at a number of heights ranging from $a$ to $b$ it would be possible to evaluate $\beta$ from them but this is impossible in the present work so $\beta$ is calculated from equation (**A1**). To do this an assumption must now be made as to the form of the temperature profile and observation suggests

$$\partial\theta/\partial z=dz^{-\delta}$$

as a reasonable approximation. Using the fact that

$$\beta=-z\partial^2u/\partial z^2(\partial u/\partial z)^{-1}$$

and similarly for $\delta$, differentiation of equation (**A1**) with respect to $z$ readily gives

$$\beta=\frac{1+\sigma Ri(z)+\frac{1}{2}\delta\sigma Ri(z)}{1+2\sigma Ri(z)}. \quad \ldots\ldots\ldots\ldots\ldots \quad (\mathbf{A4})$$

Lacking information on $\delta$ we now have to make the further assumption of similarity of the profiles of $u$ and $\theta$ so that $\delta=\beta$, in which case

$$\beta=\frac{1+\sigma Ri(z)}{1+1\cdot5\sigma Ri(z)}. \qquad \text{(A5)}$$

The assumption of $\beta=\delta$ is unsatisfactory owing to the fact that there are differences in the transfer mechanisms for heat and momentum, but for the sea and over the range of stability here considered ($-0\cdot03<Ri<0\cdot10$) it is likely that the difference is not large and the nature of equation (**A4**) is such that small differences are not important. Taking, for example, the case of $\sigma=9$ and $Ri(z)=0\cdot11$ we see from equation (**A4**) that values of $\delta$ ranging from $0\cdot7$ to $0\cdot9$ only result in a range of $\beta$ from $0\cdot78$ to $0\cdot82$.

Values of $\beta$ calculated using equation (**A5**) with values of the layer Richardson number $Ri(b:a)$ are considered to be appropriate to the layer $a$ to $b$ for use in equation (**A3**) and in this way values of the proportionality constant between $u_*^2$ and $(u_b-u_a)^2$ as a function of $Ri(b:a)$ are derived. These are given in Table 2 of Section V of the present paper for the particular case of $a=4$ m and $b=13$ m.