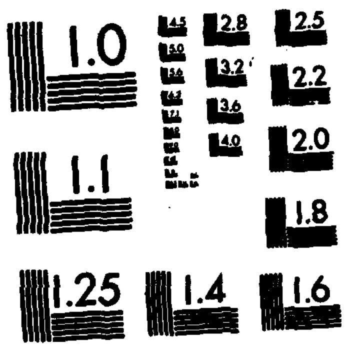
AD-A125 327 PROFILE-BULK METHOD FORMULAS FOR CALCULATING FLUX AND STABILITY IN THE MA..(U) NAVAL RESEARCH LAB WASHINGTON DC T V BLANC 30 DEC 82 NRL-8647 SBI-AD-E000 529 1/1

UNCLASSIFIED F/G 4/2 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ade000 529

(2)

NRL Report 8647

Profile-Bulk Method Formulas for Calculating Flux and Stability in the Marine Atmospheric Surface Layer and a Survey of Field Experiments

THEODORE V. BLANC

Atmospheric Physics Branch
Environmental Sciences Division

December 30, 1982

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Report 8647	2. GOVT ACCESSION NO. AD-A125 327	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PROFILE-BULK METHOD FORMULAS FOR CALCULATING FLUX AND STABILITY IN THE MARINE ATMOSPHERIC SURFACE LAYER AND A SURVEY OF FIELD EXPERIMENTS		5. TYPE OF REPORT & PERIOD COVERED Final report on one phase of a continuing NRL problem. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Theodore V. Blanc		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Code 4320 Washington, DC 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N; RR0330242; 43-1765-0-3
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research NRL Non-Special Focus Program Washington, DC 20375		12. REPORT DATE December 30, 1982 13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Marine micrometeorology
Air-sea interaction

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A comprehensive survey of profile flux experiments conducted in the marine atmospheric surface layer over the last 25 years is presented with an extensive bibliography and the formulas for computing fluxes and stability.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

PROFILE-BULK METHOD FORMULAS FOR CALCULATING FLUX AND STABILITY IN THE MARINE ATMOSPHERIC SURFACE LAYER AND A SURVEY OF FIELD EXPERIMENTS

Abstract

A comprehensive survey of profile flux experiments conducted in the marine atmospheric surface layer over the last 25 years is presented with an extensive bibliography and the formulas for computing fluxes and stability.

INTRODUCTION

A survey of marine profile flux experiments has not appeared in the literature since Roll (1965). An updated catalog has been prepared with an extensive bibliography of field experiments, methods, and instrumentation. The constituent equations used to compute the profile and bulk fluxes are distributed over a variety of sources, which contain different notations and approximations, and several have typographical errors. A complete and accurate set of formulas is presented for the first-time user.

SURVEY OF MARINE SURFACE LAYER PROFILE FLUX DATA

One of the earliest experiments to be found in the literature is that of Wüst (1920), which reported wind profile measurements taken from a ship in the Baltic Sea. Perhaps the earliest observations, as noted by Barenblatt et al. (1975), were those conducted by G. I. Taylor in 1913 using instruments sent aloft with a kite from the stern of a whaling ship under sail off the coast of Newfoundland. A list of marine surface layer profile measurements reported up to 1962 may be found in Tables X and XXIV of Roll (1965). A current survey of marine surface layer wind profile observations accompanied by temperature and/or humidity profile measurements is presented in Table 1.

As indicated in the table, there are two basic observational strategies for acquiring such profile data. The first is to employ a number of identical sensors permanently situated at various altitudes, which acquire data on a continuous basis. The second is to employ a single sensor, which is sequentially moved from one altitude to another, acquiring data while stationary at the desired altitude.

Our literature searches revealed the existence of only about 2,100 h of offshore ocean profile measurements in which all three of the primary fluxes had been measured; 85% of the data had been obtained in the equatorial region of the Atlantic Ocean. It was further determined that only 1% of that data base had been acquired under stable atmospheric conditions and that little data existed for wind speeds in excess of 12 m/s.

PROFILE FLUX AND STABILITY CALCULATIONS

Encompassed within the profile method are several semiempirically derived profile-flux relationships which have been summarized by Yaglom (1977). The two principal competing relationship schemes are those proposed by Dyer and Hicks (1970) and by Businger et al. (1971). Dyer (1974) has reviewed the differences the two schemes. Lo and McBean (1978) found that the two schemes could

Manuscript approved November 9, 1982.

Table 1 — Marine Surface Layer Wind Speed Profile Observations Accompanied by Temperature and/or Humidity Profile Measurements Reported Over the Last 25 Years

Source	Experiment (name or location)	Type and Number of Profile Measurement Levels			Altitude Cross-Section Above Mean Sea Level (m)	Observational Strategy (M=Multiple sensors fixed at measurement levels; S=Single sensor sequentially moved to measurement levels)	Environmental Regime	Measurement Platform	Averaging Period (min)	Amount of Data (hours)	Approximate Range of Wind Speeds at 10 m (m/s)
		Wind Speed	Temperature	Humidity							
Deacon et al. (1956)	Port Phillip Bay	6	2	—	1.5–13	M	Coastal & Inland Water	Ship	30	49	1–14
Takahashi (1958)	Kagoshima Bay	5	5	5	0.3–4	M&S	Inland Water	Boat & Offshore Pole	10	67	1–7
Fleagle et al. (1958)	East Sound	8	4	4	0.4-4	M&S	Inland Water	Raft	60	30	3–9
Bruce et al. (1961)	Lake Erie	6	6	—	0.6–13	S	Coastal	Ship	30	20	3–6
Deacon (1962)	Port Phillip Bay	3	2	—	3.0–13	M	Coastal & Inland Water	Ship	30	93(?)	4–15
Bogorodskiy (1964)	?	2	2	—	1.0–10	M	?	Boat	10	13	2–7
Hoeber (1969)	Equatorial Atlantic	4	4	4	1.6–9	M	Open Ocean	Buoy	10	288	4–10
Miyake et al. (1970a)	Spanish Banks	5	5	5	0.6–5	S	Coastal	Offshore Mast	45	6	4–9
Badgley et al. (1972)	Indian Ocean	6	6	6	1.6–8	S	Open Ocean & Coastal	Buoy	40	79	2–8
Garratt (1972)	Lough Neagh	5	5	5	1.0–16	M	Inland Water	Offshore Tower	10	<1	7
Paulson et al. (1972)	BOMEX[a]	4	4	4	2.0–11	S	Open Ocean	Stabilized Ship	48	113	2–8
Hsu (1973)	Fort Walton Beach	6	3	—	0.2–6	M	Beach	Onshore Towers	15	13	3–6
Donelan et al. (1974)	Lake Ontario	5	5	3&5	2.4–12	M&S	Open Lake	Offshore Tower	30[d]	132	1–17
Dunckel et al. (1974)	ATEX[b]	7	4	4	1.2–8	M	Open Ocean	Buoy	10	124	4–11
Hasse et al. (1975)	GATE[c]	9	5	5	0.5–8	M	Open Ocean	Buoy	10	6	2–7
Peterson (1975)	Risø	7	8	—	7.0–123	M	Beach & Inland Coastal	Onshore Tower	?	?	6–9
Hupfer et al. (1976)	Baltic Sea	5	5	—	1.5–7	S	Beach	Onshore Pole	30	4	~7
Krügermeyer (1976)	ATEX[b]	7	4	4	1.2–8	M	Open Ocean	Buoy	10	124	4–11
Vugts & Businger (1977)	Schiermonnikoog Island	5	5	—	0.5–13	M	Beach	Onshore Towers	60	45	4–8
Hasse et al. (1978b)	GATE[c]	7	5	5	1.1–8	M	Open Ocean	Buoy	10	1,419	1–12
Thomson (1979)	Risø	4–8	2–3	—	1.0–27	M	Beach & Inland Coastal	On- & Off-shore Towers	10	32	2–7
Blanc (1981)	San Nicolas Island	2	2	2	9.2–18	M	Coastal	Onshore Tower	30	136	2–17

[a]BOMEX — Barbados Oceanographic and Meteorological Experiment, 1969.
[b]ATEX — Atlantic Trade Wind Experiment, 1969.
[c]GATE — Global Atmospheric Research Program Atlantic Tropical Experiment, 1974.
[d]30-min running average updated ever 10 min.

yield differences as large at 40% in the estimated fluxes; they suggested that the discrepancies could be resolved by setting the von Kármán constant equal to 0.40, instead of the recommended 0.35, when using the Businger et al. scheme. This, in effect, renders the Businger et al. scheme equivalent to that of Dyer and Hicks. A justification for this approach was subsequently provided by Wieringa (1980). For additional information see Wyngaard et al. (1982), Wieringa (1982), and Gill (1982). An international turbulence measurement comparison conducted over land and reported by Francey and Garratt (1981) proposed a von Kármán constant of 0.38 (±0.04). An alternative analysis of the same comparison presented by Dyer and Bradley (1982) suggested a constant of 0.40. A rationale for the minimum height of the lowest measurement level and the separation between adjacent levels is presented in Blanc (1983a).

At altitudes $z = 6$, 12, and 24 m, for example, 30-min-averaged measurements are made of the air temperature ($\overline{T}_n$) in °C, the dew-point temperature ($\overline{T}_{dn}$) in °C, and the wind speed ($\overline{u}_n$) in m/s. The 30-min-averaged barometric pressure ($\overline{P}$) in pascals is measured at the middle altitude and is used for all levels. For simplicity, the overbar notation used to indicate time-averaged measurements will be implied but not indicated. Thus, at $z = 24$ m (z_{24}): T_{24}, T_{d24}, u_{24}; at $z = 12$ m (z_{12}): T_{12}, T_{d12}, u_{12}, P, and at $z = 6$ m (z_6): T_6, T_{d6}, u_6. If the dew-point temperature is not measured at each altitude, then the wet-bulb temperature or relative humidity should be measured instead.

The saturated vapor pressure (e_{sn}) in pascals at each altitude (z_n) is calculated by

$$e_{sn}(P,T) = Pa_1^{b_3} \times 10^{a_2 b_4 + a_4 b_5 + a_5 b_6},$$

where

$$a_1 = \frac{373.16}{T_n + 273.16},$$

$$a_2 = a_1 - 1,$$

$$a_3 = 1 - \frac{1}{a_1},$$

$$a_4 = (10^{a_2 b_1}) - 1,$$

$$a_5 = (10^{a_3 b_2}) - 1,$$

the Goff-Gratch humidity formulation constants are

$$b_1 = -3.49149, \quad b_4 = -7.90298,$$

$$b_2 = 11.344, \quad b_5 = 8.1328 \times 10^{-3},$$

$$b_3 = 5.02808, \quad b_6 = -1.3816 \times 10^{-7};$$

and $n = 6$, 12, and 24.

The water vapor pressure (e_n) in pascals at each altitude (z_n) is calculated by

$$e_n(P, T_d) = Pa_1^{b_3} \times 10^{a_2 b_4 + a_4 b_5 + a_5 b_6},$$

where

$$a_1 = \frac{373.16}{T_{dn} + 273.16},$$

a_2 through a_5 are calculated in the same manner as above, and $n = 6$, 12, and 24. In the event that the wet-bulb temperature (T_{wbn}) in °C or the relative humidity (RH_n) in % is measured at each altitude instead of the dew-point temperature (T_{dn}), then the water vapor pressure can be calculated by

$$e_n(P,T,e_s,T_{wb}) = e_{sn} - 6.6 \times 10^{-4}[1 + (1.15 \times 10^{-3}\, T_{wbn})]P(T_n - T_{wbn})$$

or

$$e_n(e_s,\mathrm{RH}) = \frac{e_{sn}\,\mathrm{RH}_n}{100}.$$

The specific humidity (q_n) in kg/kg at each altitude (z_n) is calculated by

$$q_n(P,e) = \frac{0.622\, e_n}{P - (0.378\, e_n)}.$$

The absolute humidity or water-vapor density (ρ_{vn}) in kg/m^3 at each altitude (z_n) is calculated by

$$\rho_{vn}(T,e) = e_n\left[\frac{1}{R_v(T_n + 273.16)}\right],$$

where R_v is the water-vapor gas constant, 4.615×10^2 J/(kg K). The mixing ratio (r_n) in kg/kg at each altitude (z_n) is calculated by

$$r_n = \frac{0.622\, e_n}{P - e_n}.$$

The relative humidity (RH_n) in percent at each altitude (z_n) is calculated by

$$\mathrm{RH}_n(e,e_s) = \left(\frac{e_n}{e_{sn}}\right) \times 100.$$

In each case $n = 6$, 12, and 24.

The virtual temperature (T_{vn}) in °C at each altitude (z_n) is calculated by

$$T_{vn}(T,q) = \{(T_n + 273.16) \times [1 + (0.608 q_n)]\} - 273.16.$$

The potential temperature (θ_n) in °C at each altitude (z_n) is calculated by

$$\theta_n(T,z) = T_n + (0.0098 z_n).$$

The virtual potential temperature (θ_{vn}) in °C at each altitude (z_n) is calculated by

$$\theta_{vn}(T_v,z) = T_{vn} + (0.0098 z_n).$$

Again, $n = 6$, 12, and 24.

The geometric mean height (gmh) is the geometric middle altitude when vertical distance is represented on a log scale. Because the three measurement altitudes (z_6, z_{12}, z_{24}) were selected such that $(\ln z_{24} - \ln z_{12}) = (\ln z_{12} - \ln z_6)$, z_{12} is, also, the gmh:

$$\mathrm{gmh} = (z_6 z_{24})^{1/2} = z_{12}.$$

Since profiles tend to vary approximately logarithmically, the gmh of the profile measurement levels is the altitude for which the profile measurements are typically most valid.

The Richardson number stability (Ri_{gmh}), a dimensionless quantity, valid for the geometric mean height of the component measurement altitudes is calculated by

$$\mathrm{Ri_{gmh}} = \mathrm{Ri}_{12} = \frac{g\,\dfrac{\partial\theta_v}{\partial z}}{(T_{v12} + 273.16) \times \left[\dfrac{\partial u}{\partial z}\right]^2},$$

where

$$\frac{\partial\theta_v}{\partial z} \approx \frac{\theta_{v24} - \theta_{v6}}{\mathrm{gmh}\ \ln(z_{24}/z_6)},$$

$$\frac{\partial u}{\partial z} \approx \frac{u_{24} - u_6}{\mathrm{gmh}\ \ln(z_{24}/z_6)},$$

$$\mathrm{gmh} = z_{12},$$

and g is the acceleration constant due to gravity, 9.8 m/s^2. The approximations for the partial derivatives are accurate to about $\pm 3\%$.

If $\mathrm{Ri}_{12} < 0$, the atmosphere is unstable and the Monin-Obukhov stability (ζ_{12}) at $z = 12$ m (z_{12}) is calculated by

$$\zeta_{12}(-0.01 < \mathrm{Ri} < 0) \approx 1.3\ \mathrm{Ri}_{12},$$

$$\zeta_{12}(-1.5 \leqslant \mathrm{Ri} \leqslant -0.01) \approx -10^{c_1+c_2+c_3},$$

where

$$c_1 = 2.8443 \times 10^{-2},$$

$$c_2 = 0.96125[\log(-\mathrm{Ri}_{12})],$$

$$c_3 = 1.3655 \times 10^{-3}[\log(-\mathrm{Ri}_{12})]^2,$$

or

$$\zeta_{12}(-\infty < \mathrm{Ri} < -1.5) \approx 1.05\ \mathrm{Ri}_{12}.$$

The middle-range ζ_{12} approximation is a least-squares polynomial fit to the reverse solution of the Businger et al. (1971) equation for Ri ($\zeta < 0$). All three of the approximations are accurate to about $\pm 2\%$. The quantity ζ is of questionable validity for $\mathrm{Ri} < -2$.

The Monin-Obukhov length (L) in meters is then calculated by

$$L = \frac{z_{12}}{\zeta_{12}}.$$

Once L is calculated for one altitude, the Monin-Obukhov stability (ζ_n) for any altitude (z_n) can be computed by

$$\zeta_n(z) \equiv \frac{z_n}{L}.$$

When $\mathrm{Ri}_{12} < 0$, then $\zeta_{12} < 0$. Under near-neutral conditions ($\zeta_{12} \approx 0$) the various profiles exhibit a linear form when plotted on a semilogarthmic plot. Under non-neutral conditions the profiles need to be corrected for stability-dependent curvature (see Fig. 1) to properly compute the fluxes. The stability- and altitude-dependent profile corrections for potential temperature (ψ_θ), for specific humidity (ψ_q), and for wind speed (ψ_u) are calculated by

$$\psi_{\theta n}\ (\zeta < 0) = \psi_{qn}\ (\zeta < 0) = \ln\left[\frac{1 + y_n}{2}\right]$$

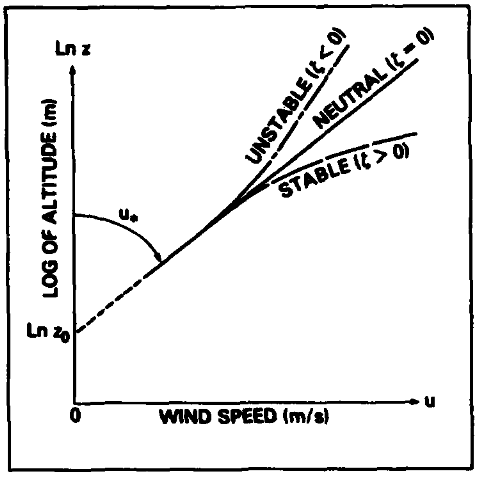


Fig. 1 — Typical stability-dependent curvatures in a semilogarithmic profile representation produced by non-neutral conditions. The scaling parameter, in this case the friction velocity (u_*), is a convenient shorthand for expressing the profile and is inversely proportional to the stability-corrected profile slope. The roughness length (z_0) is defined as the altitude at which the wind speed would be zero if the stability-corrected wind profile were projected downward.

and

$$\psi_{un}\ (\zeta < 0) = 2 \ln \left[\frac{1 + x_n}{2}\right] + \ln \left[\frac{1 + (x_n)^2}{2}\right] - [2 \arctan x_n] + \frac{\pi}{2},$$

where

$$x_n = (1 - 15\zeta_n)^{1/4},$$
$$y_n = (1 - 9\zeta_n)^{1/2},$$

arctan x_n is expressed in radians, and

$$n = 6,\ 12,\ \text{and}\ 24.$$

If $\mathrm{Ri}_{12} = 0$, the stability is said to be neutral, $\zeta_{12} = 0$, and

$$\psi_{\theta n}(\zeta = 0) = \psi_{qn}(\zeta = 0) = \psi_{un}(\zeta = 0) = 0.$$

If $\mathrm{Ri}_{12} > 0$, the atmosphere is stable and the Monin-Obukhov stability (ζ_{12}) at $z = 12$ m (z_{12}) is calculated by

$$\zeta_{12}(0.2 \geqslant \mathrm{Ri} \geqslant 0) = \frac{-d_2 - (d_2^2 - 4d_1d_3)^{1/2}}{2d_1},$$

where d_1 through d_3 are the components of a quadratic reverse solution of the Businger et al. (1971) equation for $\mathrm{Ri}(\zeta > 0)$, in which

$$d_1 = (22.09\,\mathrm{Ri}_{12}) - 4.7,$$
$$d_2 = (9.4\,\mathrm{Ri}_{12}) - 0.74,$$

and

$$d_3 = \mathrm{Ri}_{12}.$$

The quantity ζ is undefined for Ri > ~0.2. The Monin-Obukhov length (L) in meters is calculated, as before, by

$$L = \frac{z_{12}}{\zeta_{12}}.$$

Again, once L is calculated for one altitude, the Monin-Obukhov stability (ζ_n) for any altitude (z_n) can be computed by

$$\zeta_n(z) \equiv \frac{z_n}{L}.$$

When $\mathrm{Ri}_{12} > 0$, then $\zeta_{12} > 0$. The stability- and altitude-dependent profile correction for potential temperature (ψ_θ), for specific humidity (ψ_q), and for wind speed (ψ_u) are calculated by

$$\psi_{\theta n}(\zeta > 0) = \psi_{qn}(\zeta > 0) = \frac{-4.7\zeta_n}{0.74}$$

and

$$\psi_{un}(\zeta > 0) = -4.7\zeta_n,$$

where

$$n = 6,\ 12,\ \text{and}\ 24.$$

The mean stability-corrected slope of the potential temperature profile $\langle S_\theta \rangle$ is calculated by

$$\langle S_\theta \rangle = \frac{S_{\theta(6,12)} + S_{\theta(12,24)} + 2\,S_{\theta(6,24)}}{4},$$

where

$$S_{\theta(n,m)} = \frac{(\ln z_m - \psi_{\theta m}) - (\ln z_n - \psi_{\theta n})}{\theta_m - \theta_n}$$

and n,m = 6,12; 12,24; and 6,24. The mean stability-corrected slope of the specific-humidity profile $\langle S_q \rangle$ and the mean stability-corrected slope of the wind-speed profile $\langle S_u \rangle$ are calculated by inserting, respectively, q for all θ's and u for all θ's in the above two equations. The profile slopes are utilized here, instead of the more conventional profile gradients, to eliminate the confusion that exists in the literature between the contradictory Western and USSR definitions of gradient and lapse rate.

The scaling potential temperature (θ_*) in °C, the scaling specific humidity (q_*) in kg/kg, and scaling wind speed (u_*) in m/s (see Fig. 1) are calculated by

$$\theta_* = \frac{k}{0.74 \langle S_\theta \rangle},$$

$$q_* = \frac{k}{0.74 \langle S_q \rangle},$$

and

$$u_* = \frac{k}{\langle S_u \rangle},$$

where k is the von Kármán constant of 0.40. The scaling wind speed parameter (u_*) is more commonly called the friction velocity. The roughness length (z_0) in meters is computed from the wind-speed profile by

$$z_0 = e^{(\ln z_{12} - \psi_{u12}) - (k u_{12}/u_*)}.$$

The density of moist air (ρ) in kg/m^3 for all altitudes is computed by

$$\rho(P,T_v) = \frac{(3.4838 \times 10^{-3})P}{T_{v12} + 273.16}.$$

The specific heat of moist air at constant pressure (C_p) in J/(kg K) for all altitudes is computed by

$$C_p(q) \approx 1.004[1 + 0.9(q_{12})] \times 10^3.$$

The latent heat of water vaporization (L_v) in J/kg for all altitudes is computed by

$$L_v(T) \approx 4.1868(597.31 - 0.56525T_{12}) \times 10^3.$$

Employing a negative flux value to indicate a downward direction and a positive flux value to indicate an upward direction, the sensible heat flux (H_s) in W/m^2 is computed by

$$H_s = -\rho\, C_p \theta_* u_*.$$

The water-vapor flux (E) in kg/(s m^2) is computed by

$$E = -\rho\, q_* u_*.$$

Frequently the moisture flux is presented in terms of the latent heat flux (H_L) in W/m^2,

$$H_L = E\, L_v.$$

The momentum flux (M) in N/m^2 is computed by

$$M = -\rho u_*^2.$$

Frequently the mechanical flux is represented by the stress (τ) in N/m^2,

$$\tau \equiv -M.$$

BULK FLUX AND STABILITY CALCULATIONS

Encompassed within the bulk method are more than 20 different semiempirical bulk-flux relationship schemes. Partial summaries may be found in Pond et al. (1974), in Friehe and Schmitt (1976), and in Kondo (1977). The various types of proposed schemes run the complete gamut in terms of complexity and sophistication. For example, where Friehe and Schmitt use single statistical conglomerate coefficients, Krügermeyer (1976) employs stability-dependent coefficients, and Liu et al. (1979) utilize a computational iteration technique requiring five input parameters for twelve dependent variables in five equations which reduce to three simultaneous equations of three unknowns. At the present time there is no single universally accepted bulk-flux scheme. Depending upon which scheme is used, the same input data can yield estimated fluxes differing by as much as 100%.

Admittedly, because of the wide variety from which to choose, the selection of a bulk scheme to accompany the profile method is of necessity somewhat arbitrary. Here I employ the sensible heat flux and latent heat flux schemes proposed by Friehe and Schmitt (1976), as used in Friehe and Pazan (1978), and the momentum flux scheme proposed by Smith (1980a). I have selected these schemes because of their simplicity and statistically broad data bases. Other types and forms of profile-bulk combinations have been proposed by Okamoto et al. (1968), Fujita (1978), Itier (1980), and Wang (1981).

In addition to those measurements made for the profile calculations, the bulk calculations require a water-temperature measurement (T_w) in °C, made at or just below the sea surface. The potential temperature (θ_{10}) in °C, the absolute humidity or water-vapor density (ρ_{v10}) in kg/m^3, and the wind speed (u_{10}) in m/s at the standard bulk measurement altitude of $z = 10$ m (z_{10}) can be computed from the profile measurements at $z = 6$ m (z_6) and $z = 12$ m (z_{12}) by

$$\theta_{10} \approx \theta_{12} - 0.263\,(\theta_{12} - \theta_6),$$

$$\rho_{v10} \approx \rho_{v12} - 0.263\,(\rho_{v12} - \rho_{v6}),$$

and

$$u_{10} \approx u_{12} - 0.263\,(u_{12} - u_6),$$

where

$$\frac{\ln z_{12} - \ln z_{10}}{\ln z_{12} - \ln z_6} = 0.263.$$

The mean vertical velocity (ω)-temperature (θ) covariance $<\omega'\theta'>$ in (m K)/s is computed by

$$<\omega'\theta'> \approx 0.002 + [C_H u_{10}(T_w - \theta_{10})],$$

where C_H is the bulk sensible heat transfer coefficient at the 10-m altitude, 0.92×10^{-3}.

The sensible heat flux (H_s) in W/m^2 is computed by

$$H_s = \rho C_p <\omega'\theta'>,$$

where the density of moist air (ρ), the specific heat of moist air at constant pressure (C_p), and the flux direction sign convention are the same as used in the profile calculations.

The water-vapor pressure near the water surface (e_w) in pascals is calculated by

$$e_w(P,T_d) = Pa_1^{b_3} \times 10^{a_2 b_4 + a_4 b_5 + a_5 b_6},$$

where

$$a_1 = \frac{373.16}{T_{dw} + 273.16},$$

the barometeric pressure (P) is in pascals, a_2 through a_5 and b_1 through b_6 are the same as for the profile calculations of vapor pressure, and the dew point near the water surface (T_{dw}) in °C is estimated by

$$T_{dw} \approx T_w,$$

assuming the relative humidity at or near the sea surface is 100%. The absolute humidity, or water-vapor density, at the sea surface (ρ_{vw}) in kg/m^3 is then calculated by

$$\rho_{vw}(T,e) = e_w \left[\frac{1}{R_v(T_w + 273.16)}\right],$$

where R_v is the water-vapor gas constant, 4.615×10^2 J/(kg K).

The mean vertical velocity (ω)-absolute humidity (ρ_v) covariance $<\omega'\rho_v'>$ in (m kg)/(s m^3) is calculated by

$$<\omega'\rho_v'> \approx C_E u_{10}(\rho_{vw} - \rho_{v10}),$$

where C_E is the bulk water-vapor transfer coefficient at the 10 m-altitude, 1.32×10^{-3}. The water-vapor flux (E) in kg/(s m^2) is computed by

$$E = <\omega'\rho_v'>.$$

As before, the latent heat flux (H_L) in W/m^2 is computed by

$$H_L = E\ L_v,$$

where L_v is the same latent heat of water vaporization employed in the profile calculations.

The momentum flux (M) in N/m^2 is computed by

$$M = -\rho C_D u_{10}^2,$$

where C_D is the bulk aerodynamic drag coefficient at the 10-m altitude,

$$C_D = (0.61 + 0.063 u_{10}) \times 10^{-3}.$$

As before, the stress (τ) in N/m^2 is computed by

$$\tau \equiv -M.$$

The scaling potential temperature (θ_*) in °C, the scaling specific humidity (q_*) in kg/kg, and the scaling wind speed or friction velocity (u_*) in m/s are calculated by

$$\theta_* = \frac{-H_s}{\rho u_* C_p},$$

$$q_* = \frac{-E}{\rho u_*},$$

and

$$u_* = \left(\frac{\tau}{\rho}\right)^{1/2}.$$

The Monin-Obukhov length (L) in meters is calculated by

$$L = \frac{-(\theta_{10} + 273.16) u_*^3}{gk <\omega'\theta'>},$$

where the acceleration due to gravity (g), 9.8 m/s^2, and the von Kármán constant (k), 0.40, are the same as used in the profile calculations.

The Monin-Obukhov stability (ζ_{12}) for the geometric mean height of the profile measurements at $z = 12$ m ($gmh = z_{12}$) is computed by

$$\zeta_{12}(z) = \frac{z_{12}}{L}.$$

If $\zeta_{12} < 0$, the unstable condition, the Richardson number stability (Ri_{12}) is computed by

$$\mathrm{Ri}_{12}(\zeta < 0) = 0.74\, \zeta_{12} \frac{(1 - 15\zeta_{12})^{1/2}}{(1 - 9\zeta_{12})^{1/2}}.$$

If $\zeta_{12} = 0$, the neutral condition, the Richardson number stability (Ri_{12}) is also zero.

If $\zeta_{12} > 0$, the stable condition, the Richardson number stability (Ri_{12}) is computed by

$$Ri_{12}(\zeta > 0) = \frac{(0.74 + 4.7\zeta_{12})\zeta_{12}}{(1 + 4.7\zeta_{12})^2}.$$

The roughness length (z_0) in meters is computed from ψ_{u12} (via ζ_{12}) and u_* in the same manner as for the profile method.

ACKNOWLEDGMENTS

The author is indebted to the Naval Research Laboratory, Library Reference Section, for their diligent effort in obtaining many of the more obscure articles which proved to be so helpful in preparing the bibliography. The author also wishes to thank the NATO Air-Sea Interaction Program for the 1980-81 Study Visit Grant which made possible the author's discussions with Drs. M. A. Donelan, L. M. Hasse and J. Wieringa. The San Nicolas Island experiments, which served as the impetus for this report, were funded by the Electro-Optics Meteorology Program of the United States Navy. Publication of the report was made possible by a basic research grant from the General Sciences and Technology Directorate of the Naval Research Laboratory.

BIBLIOGRAPHY

(Readers unable to obtain the more obscure manuscripts or the English translations of some of the references cited may contact the author to obtain copies.)

Andreas, E.L., 1981: "The Effects of Volume Averaging on Spectra Measured with a Lyman-Alpha Hygrometer," *J. Appl. Meteorol.*, **20**, 467-475.

Angell, J.K., and A.B. Bernstein, 1976: "Evidence for a Reduction in Wind Speed on the Upwind Side of a Tower," *J. Appl. Meteorol.*, **15**, 186-188.

Augstein, E., H. Hoeber, and L. Krügermeyer, 1974a: "Errors of Temperature, Humidity, and Wind Speed Measurements on Ships in Tropical Latitudes," *"Meteor" Forschungsergeb. (Berlin)*, Reihe B, No. 9, 1-10 (Naval Intelligence Support Center translation No. 6375, Washington, D.C.).

Augstein, E., H. Schmidt, and F. Ostapoff, 1974b: "The Vertical Structure of the Atmospheric Planetary Boundary Layer in Undisturbed Trade Winds over the Atlantic Ocean," *Boundary-Layer Meteorol.*, **6**, 129-149.

Augstein, E., and J. Wucknitz, 1969: "The Quality of Wind Speed Measurements on a Semistabilized Buoy," *"Meteor" Forschungsergeb. (Berlin)*, Reihe B, No. 3, 27-32.

Badgley, F.I., C.A. Paulson, and M. Miyake, 1972: *Profiles of Wind, Temperature, and Humidity over the Arabian Sea*, International Indian Ocean Expedition Meteorological Monograph No. 6, The University Press of Hawaii, Honolulu. [ISBN:0-8248-0101-6.]

Barenblatt, G.I., G.S. Golitsyn, A.M. Obukhov, and A.M. Yaglom, 1975: "G.I. Taylor (1886-1975)," *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.*, **11**, 687-688 (English translation).

Bill, R.G., Jr., A.F. Cook, L.H. Allen, Jr., and J.F. Bartholic, 1980: "Predicting Fluxes of Latent and Sensible Heat of Lakes From Surface Water Temperatures," *J. Geophys. Res.*, **85** (C1), 507-512.

Bindon, H.H., 1965: "A Critical Review of Tables and Charts used in Psychrometry," *Humidity and Moisture, Measurement and Control in Science and Industry*, ed. by A. Wexler and R.E. Ruskin, Reinhold Publishing, New York, Vol. 1, pp. 3-15.

Blanc, T.V., 1981: "Report and Analysis of the May 1979 Marine Surface Layer Micrometeorological Experiment at San Nicolas Island, California," NRL Report 8363, Naval Research Laboratory, Washington, DC 20375, 149 pp. [NTIS:ADA110488.]

Blanc, T.V., 1982a: "Is the Bulk Aerodynamic Drag Coefficient Different Over Coastal Waters than Over the Open Ocean? Some Interesting Observations," *Preprints First International Conference on Meteorology and Air/Sea Interaction of the Coastal Zone*, May 1982, The Hague, Netherlands, American Meteorological Society, Boston, Mass., pp. 31-35.

Blanc, T.V., 1983a: "A Practical Approach to Flux Measurements of Long Duration in the Marine Atmospheric Surface Layer," submitted to *J. Appl. Meteorol.*

Blanc, T.V., 1983b: "Typical Influences of Mositure on Profile Measurements in the Marine Atmospheric Surface Layer," submitted to *Boundary-Layer Meteorol.*

Bogorodskiy, M.M., 1964: "Investigation of Tangential Friction, Vertical Turbulent Heat Exchange and Evaporation under Open Sea Conditions," *Okeanologiya*, **4**, 19-26 (in Russian).

Bogorodskiy, M.M., 1966: "A Comparison of Gradient Observations of Wind Velocity by Means of the Froude Spear-Buoy and a Shipboard Gradient Installation," *Oceanol. Acad. Sci. USSR*, **6**, 283-288 (English translation).

Bowen, A.J., and D. Lindley, 1977: "A Wind-Tunnel Investigation of the Wind Speed and Turbulence Characteristics Close to the Ground over Various Escarpment Shapes," *Boundary-Layer Meteorol.*, **12**, 259-271.

Bruce, J.P., D.V. Anderson, and G.K. Rodgers, 1961: "Temperature, Humidity and Wind Profiles over the Great Lakes," Great Lakes Research Division, Institute of Science and Technology, The University of Michigan, Publication No. 7, pp. 65-70.

Buck, A.L., 1976: "The Variable-Path Lyman-Alpha Hygrometer and its Operating Characteristics," *Bull. Am. Meteorol. Soc.*, **57**, 1113-1118.

Burt, W.V., 1979: "The Oceanography Program at the Royal Netherlands Meteorological Institute," *European Scientific Notes*, U.S. Office of Naval Research, London, **ESN 33-9**, 350-354.

Busch, N.E., and L. Kristensen, 1976: "Cup Anemometer Overspeeding," Risφ Report 339, Risφ National Laboratory, DK-4000, Roskilde, Denmark. [ISBN:87-550-0385-0.]

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

Byshev, V.I., and Yu. A. Ivanov, 1969: "The Time Spectra of Some Characteristics of the Atmosphere above the Ocean," *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.*, **5**, 8-13 (English translation).

Camp, D.W., and J.W. Kaufman, 1970: "Comparison of Tower Influence on Wind Velocity for NASA's 150-Meter Meteorological Tower and a Wind Tunnel Model of the Tower," *J. Geophys. Res.*, **75**, 1117-1121.

Campbell, G.S., B.D. Tanner, and E.C. Campbell, 1981: "A Portable Eddy Correlation System for Near-Surface Flux Measurements," *Bull. Am. Meteorol. Soc.*, **62**, 147 (Abstract only).

Campbell, G.S., and M.H. Unsworth, 1979: "An Inexpensive Sonic Anemometer for Eddy Correlation," *J. Appl. Meteorol.*, **18**, 1072-1077.

Champagne, F.H., C.A. Friehe, J.C. LaRue, and J.C. Wyngaard, 1977: "Flux Measurements, Flux Estimation Techniques, and Fine-Scale Turbulence Measurements in the Unstable Surface Layer Over Land," *J. Atmos. Sci.*, **34**, 515-530.

Ching, J.K.S., 1976: "Ship's Influence on Wind Measurements Determined from BOMEX Mast and Boom Data," *J. Appl. Meteorol.*, **15**, 102-106.

Chou, Min-Yui, 1966: "The Optimum Averaging Periods for Measurements of Meteorological Fields," *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.*, **2**, 291-295 (English translation).

Coantic, M., and C.A. Friehe, 1980: "Slow-Response Humidity Sensors," *Air-Sea Interaction Instruments and Methods*, ed. by F. Dobson, L. Hasse, and R. Davis, Plenum Press, New York, pp. 399-411.

Deacon, E.L., 1962: "Aerodynamic Roughness of the Sea," *J. Geophys. Res.*, **67**, 3167-3172.

Deacon, E.L., 1980: "Slow-Response Temperature Sensors," *Air-Sea Interaction Instruments and Methods*, ed. by F. Dobson, L. Hasse, and R. Davis, Plenum Press, New York, pp. 255-267.

Deacon, E.L., P.A. Sheppard, and E.K. Webb, 1956: "Wind Profiles over the Sea and the Drag at the Sea Surface," *Aust. J. Phys.*, **9**, 511-541.

Dobson, F., L. Hasse, and R. Davis, 1980: *Air-Sea Interaction Instruments and Methods*, Plenum Press, New York, pp. 1-10.

Donelan, M.A., 1982: "The Dependence of the Aerodynamic Drag Coefficient on Wave Parameters," *Preprints First International Conference on Meteorology and Air/Sea Interaction of the Coastal Zone*, May 1982, The Hague, Netherlands, American Meteorological Society, Boston, Mass., pp. 381-387.

Donelan, M.A., K.N. Birch, and D.C. Beesley, 1974: "Generalized Profiles of Wind Speed, Temperature, and Humidity," *Proceedings of the 17th Conference on Great Lakes Research*, International Association for Great Lakes Research, pp. 369-388.

Dunckel, M., L. Hasse, L. Krügermeyer, D. Schriever, and J. Wucknitz, 1974: "Turbulent Fluxes of Momentum, Heat and Water Vapor in the Atmospheric Surface Layer at Sea during ATEX," *Boundary-Layer Meteorol.*, **6**, 81-106.

Dyer, A.J., 1974: "A Review of Flux-Profile Relationships," *Boundary-Layer Meteorol.*, 7, 363-372.

Dyer, A.J., and E.F. Bradley, 1982: "An Alternative Analysis of Flux-Gradient Relationships at the 1976 ITCE," *Boundary-Layer Meteorol.*, **22**, 3-19.

Dyer, A.J., and J.R. Garratt, 1978: "The Variation of Eddy Fluxes with Height and Fetch in an Unstable Atmosphere," *J. Meteorol. Soc. Japan*, **56**, 19-24.

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

Dyer, A.J., and B.B. Hicks, 1972: "The Spatial Variability of Eddy Fluxes in the Constant Flux Layer," *Quart. J.R. Meteorol. Soc.*, **98**, 206-212.

Echols, W.T., 1970: "Modification in Surface Boundary Layer Wind Structure with Onshore Flow," Atmospheric Science Group, College of Engineering, The University of Texas, Austin, Report No. 23.

Echols, W.T., and N.K. Wagner, 1972: "Surface Roughness and Internal Boundary Layer Near a Coastline," *J. Appl. Meteorol.*, **11**, 658-662.

Elliott, W.P., 1958: "The Growth of the Atmospheric Internal Boundary Layer," *Trans. Am. Geophys. Union*, **39**, 1048-1054.

Fairall, C.W., K.L. Davidson, and G.E. Schacher, 1979: "Humidity Effects and Sea Salt Contamination of Atmospheric Temperature Sensors," *J. Appl. Meteorol.*, **18**, 1237-1239.

Fleagle, R.G., J.W. Deardorff, and F.I. Badgley, 1958: "Vertical Distribution of Wind Speed, Temperature and Humidity above a Water Surface," *J. Marine Res.*, **17**, 141-155.

Francey, R.J., and K. Sahashi, 1979: "Gill Propeller Anemometer Frequency Response over the Sea," *J. Appl. Meteorol.*, **18**, 1083-1086.

Francey, R.J., and J.R. Garratt, 1981: "Interpretation of Flux-Profile Observations at ITCE (1976)," *J. Appl. Meteorol.*, **20**, 603-618.

Freymuth, P., 1978: "A Bibliography of Thermal Anemometry," TSI Incorporated, St. Paul, Minnesota 55164.

Friehe, C.A., and C.H. Gibson, 1978: "Estimates of the Surface Fluxes Over the Ocean," *Turbulent Fluxes Through the Sea Surface, Wave Dynamics, and Prediction*," ed. by A. Favre and K. Hasselmann, Plenum Press, New York, pp. 67-79.

Friehe, C.A., C.H. Gibson, F.H. Champagne, and J.C. LaRue, 1975: "Turbulence Measurements in the Marine Boundary Layer," *Atmospheric Technology*, National Center for Atmospheric Research, Boulder, Colorado, No. 7, pp. 15-23.

Friehe, C.A., and S.E. Pazan, 1978: "Performance of an Air-Sea Interaction Buoy," *J. Appl. Meteorol.*, **17**, 1488-1497.

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

Fujita, T., 1978: "Determination of Turbulent Flux by the Bulk Method Using Measurements at Two Levels," *Papers in Meteorol. and Geophys. (Japan)*, **29**, 1-15.

Garratt, J.R., 1972: "Studies of Turbulence in the Surface Layer over Water (Lough Neagh). Part II. Production and Dissipation of Velocity and Temperature Fluctuations," *Quart. J. R. Meteorol. Soc.*, **98**, 642-657.

Gill, G.C., L.E. Olsson, J. Sela, and M. Suda, 1967: "Accuracy of Wind Measurements on Towers or Stacks," *Bull. Am. Meteorol. Soc.*, **48**, 665-674.

Gill, G.C., 1982: "Comments on 'A Reevaluation of the Kansas Mast Influence on Measurements of Stress and Cup Anemometer Overspeeding' by J. Wieringa," *J. Appl. Meteorol.*, **21**, 437-440.

Goerss, J.S., and C.E. Duchon, 1980: "Effect of Ship Heating on Dry-Bulb Temperature Measurements in GATE," *J. Phys. Oceanogr.*, **10**, 478-479.

Hasegawa, S., 1980: Private communication of November 1980 (Humidity Section, Thermal Processes Division, National Bureau of Standards, Gaithersburg, Maryland).

Hasse, L., M. Grünewald, and D.E. Hasselmann, 1978a: "Field Observations of Air Flow above the Waves," *Turbulent Fluxes Through the Sea Surface, Wave Dynamics, and Prediction*, ed. by A. Favre and K. Hasselmann, Plenum Press, New York, pp. 483-494.

Hasse, L., M. Grünewald, J. Wucknitz, M. Dunckel, and D. Schriever, 1978b: "Profile Derived Turbulent Fluxes in the Surface Layer under Disturbed and Undisturbed Conditions during GATE," "*Meteor*" *Forschungsergeb. (Berlin)*, Reihe B, No. 13, 24-40.

Hasse, L., J. Wucknitz, G. Kruspe, V.N. Ivanov, A.A. Shuskov, I.V. Nekrasov, J.A. Volkov, B.M. Koprov, L.G. Elagina, J. Müller-Glewe, and H. Hinzpeter, 1975: "Preliminary Report on Determination of Fluxes by Direct and Profile Method during Intercomparison IIa," Global Atmospheric Research Program, GATE Report No. 14, Vol. II, pp. 267-277.

Hay, D.R., 1980: "Fast-Response Humidity Sensors," *Air-Sea Interaction Instruments and Methods*, ed. by F. Dobson, L. Hasse, and R. Davis, Plenum Press, New York, pp. 413-432.

Hinzpeter, H., 1967: "The Diurnal Variation of the Water Surface Temperature in the Vicinity of the Equator," "*Meteor*" *Forschungsergeb. (Berlin)*, Reihe B, No. 1, 41-44 (Naval Intelligence Support Center translation No. 6376, Washington, D.C.).

Hoeber, H., 1969: "Wind, Temperature, and Humidity Profiles in the Atmospheric Surface Layer over the Equatorial Atlantic," "*Meteor*" *Forschungsergeb. (Berlin)*, Reihe B, No. 3, 1-25 (Naval Intelligence Support Center translation No. 6378, Washington, D.C.).

Hoeber, H., 1977: "Accuracy of Meteorological Observations on the Ocean," *Der Seewart (Hamburg)*, **38**, 204-213 (Naval Intelligence Support Center translation No. 6792, Washington, D.C.).

Hogben, N., and F.E. Lumb, 1967: *Ocean Wave Statistics*, Her Majesty's Stationary Office, London, England, p. 6.

Horst, T.W., 1973: "Corrections for Response Errors in a Three-Component Propeller Anemometer," *J. Appl. Meteorol.*, **12**, 716-725.

Hsu, S-A., 1973: "Dynamics of the Sea Breeze in the Atmospheric Boundary Layer: A Case Study of the Free Convection Regime," *Mon. Weather Rev.*, **101**, 187-194.

Hsu, S.-A., 1977: "Boundary-Layer Meteorological Research in the Coastal Zone," *Geoscience and Man*, **18**, 99-111.

Hupfer, P., T. Foken, and U. Bachstein, 1976: "Fine Structure of the Internal Boundary Layer in the Near-Shore Zone of the Sea," *Boundary-Layer Meteorol.*, **10**, 503-505.

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

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

Itier, B., 1980: "Une Méthode Simplifiée Pour La Mesure Du Flux De Chaleur Sensible," *J. Rech. Atmos.*, **14**, 17-34.

Ivanov, V.N., and A. Ye. Ordanovich, 1973: "Mesoscale Structure of the Atmospheric Boundary Layer and Its Interaction with Small-Scale Turbulence," *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.*, **9**, 387-393 (English translation).

Izumi, Y., and M.L. Barad, 1970: "Wind Speeds as Measured by Cup and Sonic Anemometers and Influenced by Tower Structure," *J. Appl. Meteorol.*, **9**, 851-856.

James, R.W., and P.T. Fox, 1972: "Comparative Sea-Surface Temperature Measurements," World Meteorological Organization Reports on Marine Science Affairs, No. 5, WMO-No. 336.

Kahma, K.K., and M. Leppäranta, 1981: "On Errors in Wind Speed Observations on R/V Aranda," *Geophysica*, (Helsinki, Finland), **17** (Nos. 1-2), 155-165.

Kaimal, J.C., 1969: Measurement of Momentum and Heat Flux Variations in the Surface Boundary Layer, *Radio Sci.*, Vol. 4, 1147-1153.

Kaimal, J.C., 1975: "Sensors and Techniques for Direct Measurement of Turbulent Fluxes and Profiles in the Atmospheric Surface Layer," *Atmospheric Technology*, National Center for Atmospheric Research, Boulder, Colorado, No. 7, pp. 7-14.

Kaimal, J.C., 1980: "Sonic Anemometers," *Air-Sea Interaction Instruments and Methods*, ed. by F. Dobson, L. Hasse, and R. Davis, Plenum Press, New York, pp. 81-96.

Kaimal, J.C., and J.A. Businger, 1963: "A Continuous-Wave Sonic Anemometer-Thermometer," *J. Appl. Meteorol.*, **2**, 156-164.

Kaimal, J.C., and D.A. Haugen, 1969: "Some Errors in the Measurement of Reynolds Stress," *J. Appl. Meteorol.*, **8**, 460-462.

Kaimal, J.C., and D.A. Haugen, 1971: "Comments on 'Minimizing the Levelling Error in Reynolds Stress Measurement by Filtering,'" *J. Appl. Meteorol.*, **10**, 337-339.

Kaimal, J.C., D.A. Haugen, and J.T. Newnan, 1966: "A Computer-Controlled Mobile Micrometeorological Observation System," *J. Appl. Meteorol.*, **5**, 411-420.

Katsaros, K., 1980: "Radiative Sensing of Sea Surface Temperature," *Air-Sea Interaction: Instruments and Methods*, ed. by F. Dobson, L. Hasse, and R. Davis, Plenum Press, New York, pp. 293-317.

Khalsa, S.J.S., 1980: "Surface-Layer Intermittency Investigated with Conditional Sampling," *Boundary-Layer Meteorol.*, **19**, 135-153.

Kidwell, K.B., and W.R. Seguin, 1978: "Comparison of Mast and Boom Wind Speed and Direction Measurements on U.S. GATE B-Scale Ships," National Oceanic and Atmospheric Administration Technical Report EDS28, Washington, D.C.

Kitaigorodskii, S.A., 1973: *The Physics of Air-Sea Interaction*, Israel Program for Scientific Translations, Jerusalem (English translation).

Kondo, J., 1977: "Comparison of the Kondo's Bulk Transfer Coefficient with the Recently-Made Direct Observations of Fluxes on the Sea Surface," *J. Meteorol. Soc. Japan*, **55**, 319-323.

Kondo, J., G. Naito, and Y. Fujinawa, 1971: "Response of Cup Anemometer in Turbulence," *J. Meteorol. Soc. Japan*, **49**, 63-74.

Krügermeyer, L., 1976: "Vertical Transports of Momentum, Sensible and Latent Heat from Profiles at the Tropical Atlantic during ATEX," "*Meteor Forschungsergeb. (Berlin)*, Reihe B, No. 11, 51-77.

Krügermeyer, L., M. Grünewald, and M. Dunckel, 1978: "The Influence of Sea Waves on the Wind Profile," *Boundary-Layer Meteorol.*, **14**, 403-414.

Lang, A.R.G., and R. Leuning, 1981: "New Omnidirectional Anemometer with No Moving Parts," *Boundary-Layer Meteorol.*, **20**, 445-457.

Large, W.G., and S. Pond, 11981: "Open Ocean Momentum Flux Measurements in Moderate to Strong Winds," *J. Phys. Oceanogr.*, **11**, 324-336.

Larsen, S.E., F.W. Weller, and J.A. Businger, 1979: "A Phase-Locked Loop Continuous Wave Sonic Anemometer-Thermometer," *J. Appl. Meteorol.*, **18**, 562-568.

Larsen, S.E., J. Højstrup, and C.H. Gibson, 1980: "Fast-Response Temperature Sensors," *Air-Sea Interaction: Instruments and Methods*, ed. by F. Dobson, L. Hasse, and R. Davis, Plenum Press, New York, pp. 269-292.

LaRue, J.C., T. Deaton, and C.H. Gibson, 1975: Measurement of High-Frequency Turbulent Temperature," *Rev. Sci. Instrum.*, **46**, 757-764.

Liu, W.T., K.B. Katsaros, and J.A. Businger, 1979: "Bulk Parameterization of Air-Sea Exchanges of Heat and Water Vapor Including the Molecular Constraints at the Interface," *J. Atmos. Sci.*, **36**, 1722-1735.

Lo, A.K., and G.A. McBean, 1978: "On the Relative Errors in Methods of Flux Calculations," *J. Appl. Meteorol.*, **17**, 1704-1711.

Lockhart, T.J., 1975: "Variable Errors in Operational Data Networks," *Third Symposium on Meteorological Observations and Instrumentation*, Washington, D.C., American Meteorological Society, Boston, Mass., pp. 1-6.

Lockhart, T.J., 1979: "Representativeness of Wind Measurements in Coastal Transitional Flow," *Preprints, Second Conference on Coastal Meteorology*, Los Angeles, Calif., January 1980, American Meteorological Society, Boston, Mass., pp. 227-232.

McBean, G.A., 1972: "Instrument Requirements for Eddy Correlation Measurements," *J. Appl. Meteorol.*, **11**, 1078-1084.

McBean, G.A., editor, 1979: *The Planetary Boundary Layer*, World Meteorological Organization, Geneva, Switzerland, Technical Note 165, WMO No. 530 [ISBN: 92-63-10530-8].

McGavin, R.E., and M.J. Vetter, 1965: "Radio Refractometry and Its Potential for Humidity Studies," *Humidity and Moisture Measurement and Control in Science and Industry*, ed. by A. Wexler and E.J. Amdur, Reinhold Publishing, New York, Vol. 2, pp. 553-560.

McIntosh, D.H., and A.S. Thom, 1973: *Essentials of Meteorology*, Wykeham Publishers, London.

McKay, D.J., and J.D. McTaggart-Cowan, 1977: "An Intercomparison of Radiation Shields for Auto Stations," *World Meteorological Organization Technical Conference on Instrumentation and Methods of Observation* (Hamburg), WMO Report No. 480, pp. 208-213.

Mease, N., 1980: Private communication of November 1980 (Wind Tunnel Calibration Section, Fluid Engineering Division, National Bureau of Standards, Gaithersburg, Maryland).

Meshal, A.M., 1977: Comparison of Drag Coefficients Over Water Measured Directly and Determined by Wind Profile," *Atmosphere*, **15**, 166-177.

Meyer, S.L., 1975: *Data Analysis for Scientists and Engineers*, John Wiley and Sons, New York, p. 22.

Mitnik, L.M., 1979: "Possibilities for Remote Sensing of Temperature in a Thin Surface Layer in the Ocean," *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.*, **15**, 236-239 (English translation).

Mitsuta, Y., 1966: "Sonic Anemometer-Thermometer for General Use," *J. Meteorol. Soc. Japan*, **44**, 12-23.

Mitsuta, Y., and T. Fujitani, 1974: "Direct Measurements of Turbulent Fluxes on a Cruising Ship," *Boundary-Layer Meteorol.*, **6**, 203-217.

Miyake, M., M. Donelan, G. McBean, C. Paulson, F. Badgley, and E. Leavitt, 1970a: "Comparison of Turbulent Fluxes over Water Determined by Profile and Eddy Correlation Techniques," *Quart. J. R. Meteorol. Soc.*, **96**, 132-137.

Miyake, M., R.W. Stewart, and R.W. Burling, 1970b: "Spectra and Cospectra Turbulence over Water," *Quart. J. R. Meteorol. Soc.*, **96**, 138-143.

Moffat, R.J., 1962: "Gas Temperature Measurement," *Temperature, Its Measurement and Control in Science and Industry*, ed. by C.M. Herzfeld and A.I. Dahl, Reinhold Publishing, New York, Vol. 3, Part 2, pp. 553-571.

Mollo-Christensen, E., 1979: "Upwind Distortion Due to Probe Support in Boundary-Layer Observation," *J. Appl. Meteorol.*, **18**, 367-370.

Moses, H., and H.G. Daubek, 1961: "Errors in Wind Measurements Associated with Tower-Mounted Anemometers," *Bull. Am. Meteorol. Soc.*, **42**, 190-194.

Naito, G., 1978: "Direct Measurements of Momentum and Sensible Heat Fluxes at the Tower in the Open Sea," *J. Meteorol. Soc. Japan*, **56**, 25-34.

Nicholls, S., and C.J. Readings, 1979: "Aircraft Observations of the Structure of the Lower Boundary Layer over the Sea," *Quart. J. R. Meteorol. Soc.*, **105**, 785-802.

Ogawa, Y., and T. Ohara, 1982: "Observation of the Turbulent Structure in the Planetary Boundary Layer with Kytoon-Mounted Ultrasonic Anemometer System," *Boundary-Layer Meteorol.*, **22**, 123-131.

Okamoto, M., H. Uotsu, and T. Furukawa, 1968: "An Estimation of the Heat Flux and the Water Vapour Flux by the Bulk Aerodynamic Method," *Papers in Meteorol. and Geophys. (Japan)*, **19**, 231-241.

Pande, A., 1970: *Modern Hygrometry*, Somaiya, Bombay, India, pp. 19-31.

Panofsky, H.A., and A.A. Townsend, 1964: "Change of Terrain Roughness and the Wind Profile," *Quart. J. R. Meteorol. Soc.*, **90**, 147-155.

Paulson, C.A., E. Leavitt, and R.G. Fleagle, 1972: "Air-Sea Transfer of Momentum, Heat and Water Determined from Profile Measurements During BOMEX," *J. Phys. Oceanogr.*, **2**, 487-497.

Pedersen, K., and G. Bøyum, 1980: "Turbulent Flux of Heat and Water Vapor from the Ocean," *Tellus*, **32**, 320-325.

Peterson, E.W., 1969: "Modification of Mean Flow and Turbulent Energy by a Change in Surface Roughness under Conditions of Neutral Stability," *Quart. J. R. Meteorol. Soc.*, **95**, 561-575.

Peterson, E.W., 1975: "The Risø Profiles: A Study of Wind and Temperature Data from the 123 m Tower at Risø, Denmark," *Quart. J. R. Meteorol. Soc.*, **101**, 107-117.

Pond, S., D.B. Fissel, and C.A. Paulson, 1974: "A Note on Bulk Aerodynamic Coefficients for Sensible Heat and Moisture Fluxes," *Boundary-Layer Meteorol.*, **6**, 333-339.

Pond, S., W.G. Large, M. Miyake, and R.W. Burling, 1979: "A Gill Twin Propeller-Vane Anemometer for Flux Measurements during Moderate and Strong Winds," *Boundary-Layer Meteorol.*, **16**, 351-364.

Pond, S., G.T. Phelps, J.E. Paquin, G. McBean, and R.W. Stewart, 1971: "Measurements of the Turbulent Fluxes of Momentum, Moisture and Sensible Heat over the Ocean," *J. Atmos. Sci.*, **28**, 901-917.

Raupach, M.R., 1978: "Infrared Fluctuation Hygrometry in the Atmospheric Surface Layer," *Quart. J. R. Meteorol. Soc.*, **104**, 309-322.

Raynor, G.S., S. Sethuraman, and R.M. Brown, 1979: "Formation and Characteristics of Coastal Internal Boundary Layers during Onshore Flows," *Boundary-Layer Meteorol.*, **16**, 487-514.

Redford, T.G., S.B. Verma, and N.J. Rosenberg, 1981: "Drag Anemometer Measurement of Turbulence over a Vegetated Surface," *J. Appl. Meteorol.*, **20**, 1222-1230.

Reed, R.K., 1978: "An Example of Shipboard Air Temperature Errors," *Mariners Weather Log*, **22**, 13-14.

Roll, H.U., 1965: *Physics of the Marine Atmosphere*, Academic Press, New York.

Saunders, P.M., 1967: "The Temperature at the Ocean-Air Interface," *J. Atmos. Sci.*, **24**, 269-273.

Schmitt, K.F., C.A. Friehe, and C.H. Gibson, 1978: "Humidity Sensitivity of Atmospheric Temperature Sensors by Salt Contamination," *J. Phys. Oceanogr.*, **8**, 151-161.

Schmitt, K.F., C.A. Friehe, and C.H. Gibson, 1979: "Structure of Marine Surface Layer Turbulence," *J. Atmos. Sci.*, **36**, 602-618.

Shaw, R.H., G. Kidd, and G.W. Thurtell, 1973: "A Miniature Three-Dimensional Anemometer for Use within and above Plant Canopies," *Boundary-Layer Meteorol.*, **3**, 359-380.

Sheppard, P.A., D.T. Tribble, and J.R. Garratt, 1972: "Studies of Turbulence in the Surface Layer over Water (Lough Neagh): Part 1. Instrumentation, Programme, Profiles," *Quart. J. R. Meteorol. Soc.*, **98**, 627-641.

Shir, C.C., 1972: "A Numerical Computation of Air Flow over a Sudden Change of Surface Roughness," *J. Atmos. Sci.*, **29**, 304-310.

Simpson, J.J., and C.A. Paulson, 1980: "Small-Scale Sea Surface Temperature Structure," *J. Phys. Oceanogr.*, **10**, 399-410.

Slob, W.H., 1978: "The Accuracy of Aspirated Thermometers," KNMI Scientific Report W.R. 78-1, Royal Netherlands Meteorological Institute, deBilt, Holland.

Smedman-Högström, A.-S., and U. Högström, 1973: "The Marsta Micrometeorological Field Project. Profile Measurement System and Some Preliminary Data," *Boundary-Layer Meteorol.*, **5**, 259-273.

Smith, S.D., 1980a: "Wind Stress and Heat Flux over the Ocean in Gale Force Winds," *J. Phys. Oceanogr.*, **10**, 709-726.

Smith, S.D., 1980b: "Evaluation of the Mark 8 Thrust Anemometer-Thermometer for Measurement of Boundary-Layer Turbulence," *Boundary-Layer Meteorol.*, **19**, 273-292.

Sutton, O.G., 1953: *Micrometeorology, a Study of Physical Processes in the Lowest Layers of the Earth's Atmosphere*, McGraw-Hill, New York.

Takahashi, T., 1958: "Micrometeorological Observations and Studies over the Sea," *Mem. Fac. Fish. Kagoshima Univ. (Japan)*, **6**, 1-46.

Tennekes, H., and J.C. Wyngaard, 1972: "The Intermittent Small-Scale Structure of Turbulence: Data-Processing Hazards," *J. Fluid Mech.*, **55**, 93-103.

Thomson, D.W., 1979: "Risø 78: Mean Profile and Turbulence Measurements at a Shoreline Escarpment," Risø Report R-410, Risø National Laboratory, DK-4000, Roskilde, Denmark. [ISBN:87-550-0633-7.]

Thornthwaite, C.W., W.J. Superior, and R.T. Field (1965): "Disturbance of Airflow around Argus Island Tower near Bermuda," *J. Geophys. Res.*, **70**, 6047-6052.

Vugts, H.F., 1980: "A Study of Terrain Inhomogeneity," *Bull. Am. Meteorol. Soc.*, **61**, 568-569.

Vugts, H.F., and J.A. Businger, 1977: "Air Modification Due to a Step Change in Surface Temperature," *Boundary-Layer Meteorol.*, **11**, 295-305.

Waletzko, J.A., 1975: "A New Ion Displacement System to Measure the Two Dimensional Wind Vector," TSI Incorporated, St. Paul, Minnesota 55164.

Wang, I.T., 1981: "The Determination of Surface-Layer Stability and Eddy Fluxes Using Wind Speed and Vertical Temperature Gradient Measurements," *J. Appl. Meteorol.*, **20**, 1241-1248.

Warner, J., 1971: "Observations of the Eddy Fluxes of Heat and Vapour over the Sea," *Quart. J. R. Meteorol. Soc.*, **97**, 540-547.

Warner, J., 1972: "The Structure and Intensity of Turbulence in the Air over the Sea," *Quart. J. R. Meteorol. Soc.*, **98**, 175-186.

Wieringa, J., 1980: "A Reevaluation of the Kansas Mast Influence on Measurements of Stress and Cup Anemometer Overspeeding," *Boundary-Layer Meteorol.*, **18**, 411-430.

Wieringa, J., 1982: "Reply to Comments on 'A Reevaluation of the Kansas Mast Influence on Measurements of Stress and Cup Anemometer Overspeeding,'" *Boundary-Layer Meteorol.*, **22**, 251-255.

Wood, D.H., 1978: "Calculation of the Neutral Wind Profile Following a Large Step Change in Surface Roughness," *Quart. J. R. Meteorol. Soc.*, **104**, 383-392.

Wucknitz, J., 1977: "Disturbance of Wind Profile Measurements by a Slim Mast," *Boundary-Layer Meteorol.*, **11**, 155-169.

Wucknitz, J., 1980: "Flow Distortion by Supporting Structures," *Air-Sea Interaction Instruments and Methods*, ed. by F. Dobson, L. Hasse, and R. Davis, Plenum Press, New York, pp. 605-626.

Wüst, G., 1920: "Die Verdunstung auf dem Meere," Veröffentl. Inst. Meereskunde Univ. Berlin, No. 6.

Wylie, D.P., and C.F. Ropelewski, 1980: "The GATE Boundary Layer Instrumentation System (BLIS)," *Bull. Am. Meteorol. Soc.*, **61**, 1002-1011.

Wyngaard, J.C., J.A. Businger, J.C. Kaimal, and S.E. Larsen, 1982: "Comments on 'A Reevaluation of the Kansas Mast Influence on Measurements of Stress and Cup Anemometer Overspeeding'," *Boundary-Layer Meteorol.*, **22**, 245-250.

Yaglom, A.M., 1974: "Data on Turbulence Characteristics in the Atmospheric Surface Layer," *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.*, **10**, 341-352 (English translation).

Yaglom, A.M., 1977: "Comments on Wind and Temperature Flux-Profile Relationships," *Boundary-Layer Meteorol.*, **11**, 89-102.