The Effect of Inaccuracies in Weather-Ship Data on Bulk-Derived Estimates of Flux, Stability and Sea-Surface Roughness

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ABSTRACT

An analytical error analysis (or sensitivity study) is performed for the momentum, heat, and humidity flux estimates made from weather-ship observations by using the bulk flux method. Bulk-derived stability and roughness errors are also examined. The analysis is performed with two scenarios for the constituent wind speed, air temperature, water temperature, humidity, barometric pressure, and measurement altitude uncertainties. The error scenarios are constructed from published estimates and used to simulate the typical sensor inaccuracies and ship-induced distortions of meteorological measurements made from weather ships. Four bulk transfer coefficient schemes are tested. The combined influence of the sensor inaccuracies and ship-induced distortions is found to result in a typical uncertainty of about 30% for an average stress of 0.2 N m$^{-2}$, 50% for an average sensible heat flux of 0.25 W m$^{-2}$, 50% for an average latent heat flux of 0.40 W m$^{-2}$, 80% for an average Monin-Obukhov stability of $\pm 0.06$, 40% for an average roughness length of $3 \times 10^{-4}$ m, and 60% for an average roughness Reynolds number of 6. Because the analysis generally employed conservative estimates of the measurement uncertainties and left out other sources of error, it is argued that the results of the analysis represent a best case situation.

1. Introduction

The fluxes of momentum, heat, and moisture must be measured to properly characterize the interaction of the lower atmosphere and the ocean. These turbulent exchanges play a key role in the energy transport mechanism that influences the weather and the surface conditions of the sea. Because three-quarters of Earth’s surface is covered by oceans, a determination of these exchanges is essential to global and long-term weather and wave forecasting. Although the technology for sensing the marine atmosphere from satellites and aircraft has made great strides over the last decade, it is still not yet technically feasible to make direct flux measurements on the temporal (years) and spatial (thousands of square kilometers) scales necessary. There does exist, however, a large body (more than 31 million observations) of rudimentary surface measurements of wind speed, air and water temperature, humidity, barometric pressure, and sea state made from merchant, military, and weather ships which date as far back as 1860. This has lead to the widespread use of an indirect technique known as the bulk method to estimate the atmospheric fluxes by using the available ship observations, and to a number of subsequent studies which have sought to describe the climatology over various regions of the ocean. For example, the work of Bunker (1976) seeks to describe the North Atlantic; Goldenberg and O’Brien (1981) the tropical Pacific.

Roll (1965), Dobson (1981), and others have demonstrated that the quality of rudimentary marine meteorological measurements can vary substantially, depending on the type of instrumentation used and the influence of the ship. How significant are these sources of uncertainty and how do they typically influence the accuracy of estimated bulk-derived fluxes? How are the resulting determinations of stability and roughness affected? Does the influence of the errors depend on which of the several published bulk transfer coefficient schemes is used? How do the influences of the errors vary as a function of the bulk parameter magnitude? In an effort to determine the best case situation, we conducted an error analysis on a 1-year sample of the best quality rudimentary measurements available using published estimates of the sensor accuracies and ship-induced distortions.

2. The bulk-derived parameters

The bulk method estimates the turbulent exchanges of downward momentum flux or stress ($\tau$) in N m$^{-2}$, sensible heat flux ($H_S$) in W m$^{-2}$, and moisture or latent heat flux ($H_L$) in W m$^{-2}$ for the lower part of the marine atmosphere using the rudimentary shipboard observations by

$\tau \approx \rho C_D u_{10}^2$,

$H_S \approx -\rho C_{H} u_{10}(\theta_{10} - \theta_w)$,

$H_L \approx -\rho L_v C_{E} u_{10}(q_{10} - q_w)$,
where $C_D$, $C_H$ and $C_E$ are the bulk transfer coefficients of drag (momentum), sensible heat and humidity (evaporation or condensation); $u$ is the wind speed in m s$^{-1}$; $\theta$ is the potential temperature in °C; and $q$ is the specific humidity in kg kg$^{-1}$. By convention, a positive sign is used to indicate an upward flux and a negative sign a downward flux. The subscript 10 is used to denote a measurement made at an altitude of 10 m, and $W$ a measurement made at the surface of the water. In actual practice the lower temperature and humidity measurements are usually inferred from a water temperature measurement made just below the surface and the upper measurements are usually made at an altitude other than 10 m. When measurements are not made at the “standard” 10 m altitude, they are usually adjusted to correct for the altitude difference. At present, there is no universally accepted method for making this adjustment. Three different methods are shown in Dobson (1981), Blanc (1985) and in section 4.

The air temperature can be expressed in a variety of ways: in the usual manner ($T$); in terms of the virtual temperature ($T_v$) which takes into consideration the thermodynamic influence of humidity

$$T_v = \{(T + 273.16) \times [1 + (0.608 q)]\} - 273.16;$$

in terms of the potential temperature ($\theta$) which incorporates the decrease in barometric pressure with altitude expressed approximately by

$$\theta = T + \Gamma z,$$

where $\Gamma$ is the adiabatic lapse rate (0.0098°C m$^{-1}$) and $z$ is the altitude in m; and in terms of the virtual potential temperature ($\theta_v$) which combines both considerations

$$\theta_v = T_v + \Gamma z.$$

All four temperatures are in °C.

The density of moist air ($\rho$) in kg m$^{-3}$, the specific heat of moist air at constant pressure ($c_p$) in J/(kg K), and the latent heat of vaporization ($L_v$) in J kg$^{-1}$ are determined by

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

$$c_p = 1.004[1 + 0.9(\theta_{10})] \times 10^3,$$

$$L_v = 4.1868(597.31 - 0.56525T_{10}) \times 10^3,$$

where $P$ is the barometric pressure in Pa and the overbar is used to denote the average ambient value for the indicated parameter.

The Monin-Obukhov stability ($z/L$) is a measure of the thermal-to-mechanical turbulent energy balance of the atmospheric surface layer defined in terms of the ratio of the altitude (in our case $z = 10$ m) to the characteristic turbulence scale length ($L$) such that

$$z/L = \frac{z g k \theta_*}{(\theta_{10} + 273.16)u_*^3},$$

where $g$ is the acceleration due to gravity (9.8 m s$^{-2}$), $k$ is the von Kármán constant (0.4), and the asterisk subscript is used to denote the gradient scaling parameter associated with the indicated quantity. By convention, a negative stability value denotes an unstable condition and a positive value denotes a stable condition. The gradient scaling parameters are determined by

$$u_* = (\tau/\rho)^{1/2},$$

$$\theta_* = \frac{-H_S}{\rho c_p u_*},$$

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

and

$$\theta_v* = (1 - 0.608q_10)\theta_* + [0.608(\theta_{10} + 273.16)]q_*.$$

They possess the same units as their namesake counterparts and are roughly proportional to the vertical gradient of the indicated quantity.

Under near-neutral stability conditions ($|z/L| < 0.02$), the wind gradient exhibits a linear form when plotted on a semilogarithmic graph in which altitude is represented on a vertical logarithmic scale. If the decrease in wind speed is projected downward in altitude to the virtual origin where the speed would be zero, this yields a characteristic surface roughness height known as the roughness length ($z_0$) in m. For nonneutral conditions, a stability correction ($\psi_u$) must be added to the roughness length equation so that

$$z_0 = e^{(lnz-x_0)2(\psi_u)}.$$

Another measure of the air–sea interface surface roughness of interest to meteorologists and oceanographers is the roughness Reynolds number ($R_r$) defined as

$$R_r = \frac{u_* z_0}{\nu},$$

where $\nu$ is the kinematic viscosity of the air in m$^2$ s$^{-1}$ determined by

$$\nu = \frac{(1.718 + 0.005T_{10}) \times 10^{-5}}{\rho}. $$

A more detailed description of the bulk-derived parameters, their derivation, and the stability correction ($\psi_u$) may be found in Blanc (1985).

3. Methodology

In general, a bulk-derived flux, stability, or roughness estimate ($F$) as described in Eqs. (1)–(6) is fundamentally a function of the wind speed ($u$), air temperature ($T$), water surface temperature ($T_w$), specific humidity ($q$), and to a lesser extent the barometric pressure ($P$) and the altitudes of the wind speed ($z_U$), air temperature ($z_T$), and humidity ($z_Q$) measurements. Thus,

$$F = f(u, T, T_w, q, P, z_U, z_T, z_Q).$$
From Fritschan and Gay (1979) it can be seen that the most probable error ($\delta F$) of the bulk-derived parameter ($F$) can be determined by combining the errors of the eight constituent measurements ($\delta u$, $\delta T$, $\delta T_w$, ..., $\delta z_q$) in terms of the root-mean-square (rms) such that

$$\delta F = \left[ \left( \frac{\delta u}{\partial u} \right)^2 + \left( \frac{\delta T}{\partial T} \right)^2 + \left( \frac{\delta T_w}{\partial T_w} \right)^2 \right]^{1/2} \left[ \left( \frac{\delta q}{\partial q} \right)^2 + \left( \frac{\delta F}{\partial T} \right)^2 + \left( \frac{\delta F}{\partial P} \right)^2 \right]^{1/2} \left[ \left( \frac{\delta z_u}{\partial z_u} \right)^2 + \left( \frac{\delta z_T}{\partial z_T} \right)^2 + \left( \frac{\delta z_q}{\partial z_q} \right)^2 \right]^{1/2}. \quad (7)$$

By an approach similar to the perturbation error analysis method used with profile measurements in Blanc (1983a), it can be seen that Eq. (7) can be solved for a computer by first calculating the bulk parameter ($F$) without considering any error

$$F = f_0(u, T, T_w, q, P, z_u, z_T, z_q),$$

and then recomputing the results using each of the eight constituent errors one at a time

$$F^+_u = f_0(u + \delta u, T, T_w, \ldots, z_q)$$
$$F^-_u = f_0(u - \delta u, T, T_w, \ldots, z_q)$$
$$F^+_T = f_0(u, T + \delta T, T_w, \ldots, z_q)$$
$$\vdots$$
$$F^+_Q = f_0(u, T, T_w, \ldots, z_Q - \delta z_Q)$$

until all 16 possible error-perturbed combinations of $F$ have been calculated. Because the bulk calculations involve differences (e.g., $\theta_{10} - \theta_{03}$) that can be of the same order of magnitude as the principle associated errors (i.e., $\delta T$ or $\delta T_w$), and because of the influence of a given error in computing the stability or roughness can be nonlinear (e.g., $|F^+_T - F| \neq |F^-_T - F|$), both the $F^+$ and $F^-$ errors need to be considered if the errors are random. However, because it is impossible for an actual measurement to be in error simultaneously in both directions, the two cases are averaged to determine the typical influence of the constituent error. The resulting differences in the computed value of $F$ due to each of the eight constituent errors ($\delta F_U$, $\delta F_T$, $\delta F_{T_w}$, ..., $\delta F_{ZQ}$) can then be calculated by

$$\delta F_U = \frac{|F^+_U - F| + |F^-_U - F|}{2}$$
$$\delta F_T = \frac{|F^+_T - F| + |F^-_T - F|}{2}$$
$$\delta F_{T_w} = \frac{|F^+_w - F| + |F^-_{T_w} - F|}{2}$$
$$\vdots$$
$$\delta F_{ZQ} = \frac{|F^+_Q - F| + |F^-_{ZQ} - F|}{2}.$$

In the event an error is not random but systematic, then only the appropriate $F^+$ or $F^-$ case need be considered. For example, if the solar heating influence of a ship's superstructure and deck only increases the air temperature measurement, then

$$\delta F_T = |F^+_T - F|$$

should be used.

Employing the same rms approach used in Eq. (7), we can then compute the most probable bulk flux, stability, or roughness error ($\delta F$) by

$$\delta F = (\delta F_U)^2 + (\delta F_T)^2 + (\delta F_{T_w})^2 + (\delta F_Q)^2 + (\delta F_P)^2 + (\delta F_{ZU})^2 + (\delta F_{ZT})^2 + (\delta F_{ZQ})^2)^{1/2}. \quad (8)$$

The most probable relative error in percent ($\xi F$) of the observed value for the bulk-derived parameter ($F$) is then

$$\xi F = \frac{\delta F}{|F|} \times 100. \quad (9)$$

4. The data base

Since we wished to determine the best case situation and because it is generally accepted that the best quality routine shipboard meteorological measurements are those made from weather ships, a 1-year sample of weather-ship data was used for our analysis. North Atlantic data were desirable because they would contain a diverse variety of stability and wind speed conditions. Located midway between Newfoundland and Ireland at 52°45'N and 35°30'W, data from Ocean Station C was typical of true open-ocean conditions. Subsequently, data from Station C was obtained from the National Weather Records Center for the year 1973, the last full year of the station's operation by the United States. An entire year's worth of data was acquired to ensure that the data base would contain a full spectrum of seasonal variations.

Collection of the data over the 1-year period required the use of 13 different ships of the general type shown in Fig. 1. The meteorological and oceanographic measurements were made once every 3 h over 18 consecutive measurement periods of approximately 20-days duration. The resulting data base (with some observations missing) consisted of 2745 sets of recorded measurements. Each measurement was averaged over a period of 2 min. The wind speed measurements ranged in altitude from 18 to 31 m above mean sea level and were made with electromechanical propellervane anemometer devices mounted on the upper portion of the forward-most mast (A in Fig. 1). The air temperature and humidity measurements ranged from 6 to 9 m in altitude and were made with hand-held sling psychrometers from the bridge or an upper deck (B in Fig. 1). The formulas necessary for calculating the specific and relative humidities from the wet- and dry-bulb temperatures are given in Blanc (1985). The water temperature was measured with bucket and
thermometer devices lowered from the aft main deck (C in Fig. 1). The barometric pressure measurements were made with mechanical aneroid-type barometers usually located inside the ship’s wheelhouse (D in Fig. 1). The wave height and wave period measurements were made visually by trained observers and will be used in our analysis for simulating the wave-induced distortions produced by the ship. The relevant ship and measurement altitude information is given in Table 1.

We adjusted the measurements to the "standard" altitude of 10 m by the simplest method possible. We assumed the wind speed, air temperature and humidity profiles varied linearly with the log of the altitude as if under neutral conditions. At the surface of the ocean we assumed the wind speed was equal to zero, the air temperature equal to the water, the relative humidity equal to 100%, and the effective roughness equal to 3 \times 10^{-4} m. The various bulk-derived flux, stability and roughness parameters were then calculated in the manner described in section 2.

The range and distribution of the resulting observations adjusted to the 10 m altitude are shown in Figs. 2–7. From Fig. 2 it can be roughly estimated that about 40% of the measurements were made under near neutral stability conditions \((u_{10} > 10 \text{ m s}^{-1})\); from Fig. 3 that about 30% were made under stable conditions \((T_W - T_{10} < -0.5^\circ \text{C})\); and from Fig. 4 that about 30% were made under conditions in which the humidity flux was in the downward direction \((q_W - q_{10} < 0)\). For the 1-year period the average wind speed at an altitude of 10 m was 9.37 m s\(^{-1}\), the average dry-bulb air temperature was 8.16\(^\circ\)C, the average water surface temperature was 8.72\(^\circ\)C, the average wet-bulb humidity temperature was 7.27\(^\circ\)C, the average specific humidity was 6.31 \times 10^{-3} \text{ kg kg}^{-1}, the average relative humidity was 94.4%, the average barometric pressure was \(1013 \times 10^2\) Pa, the average wave height was 2.23 m, and the average wave period was about 4.7 s.

5. The selected bulk transfer coefficient schemes

There exists more than 20 different published bulk transfer coefficient schemes. Blanc (1985) demonstrated that depending on which bulk scheme is selected, the same rudimentary shipboard measurements could yield substantial variations in the resulting estimated flux. Since there is no single universally accepted scheme, four were selected for our analysis.

Charnock (1955) using a dimensional argument suggested that over the ocean

\[
\frac{z_0}{u_{*}^2/g} = a,
\]

where \(a\) is a constant that now bears Charnock’s name. This empirical relationship implied that the surface roughness \((z_0)\) of the ocean should depend only on the scaling wind velocity \((u_*)\) since both \(g\) and \(a\) are constants. Equation (5) shows that, at a given altitude ranging from about 6 to 50 m and a given surface roughness, the scaling wind velocity (also called the friction velocity) should increase with increased wind speed. Equation (10) suggests that the surface roughness and the resulting bulk momentum transfer (drag) coefficient should increase as well. Similar arguments can
be made for the transfer coefficients of heat and moisture.

The first scheme we selected is that suggested by Kondo (1975). It is based on roughness Reynolds number observations combined with a theory of the heat and mass transfer above a rough solid surface. The roughness Reynolds number [Eq. (6)] is a function of the same principal variables ($u_10$ and $z_0$) as Charnock’s relationship [Eq. (10)]. The scheme assumes that the rates of heat and humidity transfer are controlled by purely molecular properties of the fluid and that the mechanical transfer of momentum is governed by skin friction and form drag. Skin friction is analogous to the momentum transfer over a flat plane; form drag is the result of pressure forces acting against the rough air-sea interface. Using data from his own experiments and a variety of other sources, Kondo’s scheme is designed for wind speeds ranging from 0.3 to 50 m s$^{-1}$. The scheme accounts for the influence of stability by

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{Coast Guard weather ship} & \textbf{Number of observations periods on station} & \textbf{Amount of time during the year for which observations were made*} & \textbf{Wind speed, $u_10$ (m/s)} & \textbf{Air temperature, $z_0$ (m)} & \textbf{Measurements altitudes** (m)} & \textbf{Ship dimensions (m)} & \textbf{Estimated wind speed measurement altitude to ship structure height ratio, $z_0/S_1$} \\
\hline
\textit{Ingham} & 2 & 5.9 & 29.9 & 6.4 & 15 & 13 & 94 & 2.0 \\
\textit{Gallatin} & 1 & 6.6 & 30.5 & 8.2 & 16 & 13 & 107 & 1.9 \\
\textit{Spencer} & 2 & 10.7 & 26.8 & 6.4 & 15 & 13 & 94 & 1.8 \\
\textit{Hamilton} & 2 & 12.9 & 30.2 & 8.5 & 16 & 13 & 107 & 1.9 \\
\textit{Taney} & 1 & 6.0 & 27.1 & 7.3 & 15 & 13 & 94 & 1.8 \\
\textit{Chase} & 1 & 6.6 & 24.7 & 8.5 & 16 & 13 & 107 & 1.5 \\
\textit{Duane} & 2 & 10.7 & 21.3 & 5.8 & 15 & 13 & 94 & 1.4 \\
\textit{Munro} & 1 & 6.3 & 23.2 & 7.6 & 16 & 13 & 107 & 1.5 \\
\textit{Morgenthau} & 2 & 10.1 & 28.3 & 8.2 & 16 & 13 & 107 & 1.8 \\
\textit{Ponichartain} & 1 & 5.5 & 24.4 & 8.8 & 13 & 13 & 77 & 1.9 \\
\textit{Cambell} & 1 & 7.1 & 24.1 & 6.4 & 15 & 13 & 94 & 1.6 \\
\textit{Dallas} & 1 & 4.7 & 26.2$^\S$ & 7.4$^\S$ & 16 & 13 & 107 & 1.6 \\
\hline
\end{tabular}
\end{table}

Notes:
* Observations were not available 0.9% of the time during 1973.
** Source: U.S. Department of Commerce, Weather Bureau Form WB A-1, WB 500-10, or WBAN-10D; Weather Observation Station Description and Instrumentation.
$^d$ Approximate maximum height of the ship’s superstructure above water (excluding masts) estimated from photographs.
$^1$ Source: Polmar (1981).
$^\S$ Not to be confused with a ship of the same name scheduled to be commissioned in 1984.
§ The indicated values were computed from the average of the other 12 ships and used in our analysis because the information was unavailable at the time. A reviewer has subsequently noted that Seguin et al. (1977) has indicated the altitudes as 23.8 m and 12.5 m.
incorporating a parameterization based on a water-air temperature difference ranging from $0^\circ$ to $\pm 20^\circ$C in which the transfer coefficients decrease with increasing stability.

The second scheme is that proposed by Liu et al. (1979). It suggests transfer coefficients based on the results of a model that considers the interfacial sublayers on both sides of the air-sea interface and the molecular constraints on transport. Their model assumes that the wind flow goes from smooth to rough and the momentum transfer increases with increased wind speed. After the wind speed exceeds a certain value, the heat and moisture coefficients decrease slightly. The Liu et al. scheme is designed for wind speeds from 1 to 18 m s$^{-1}$ and water-air temperature difference ranging from $0^\circ$ to $\pm 4^\circ$C. As in Kondo’s scheme, the coefficients decrease with increasing stability. The schemes require the use of a computer iteration program to solve three simultaneous equations. A listing of the computer program is presented in Liu and Blanc (1984).

The third scheme is that presented by Masagutov (1981). He uses a determination of the roughness Reynolds number to express the surface roughness and solves a series of five transcendental equations by successive computer approximation. The results of the analysis for the three transfer coefficients were presented as two nomograms, shown here in Figs. 8 and 9, for wind speeds ranging from about 2 to 21 m s$^{-1}$ and water-air temperature differences of $0^\circ$ to $\pm 4^\circ$C. Masagutov assumed that the heat and moisture coefficients were the same and, like the two previous schemes, found all three coefficients to decrease with increasing stability. The coefficient scheme is also presented in a tabular form in Blanc (1985).

The fourth scheme is that published by Large and Pond (1981, 1982). Their drag and heat transfer coefficients are based on measurements taken at wind speeds ranging between 4 and 25 m s$^{-1}$; their moisture transfer coefficient at wind speeds between 4 and 14 m s$^{-1}$.
If the observed wind speed or temperature difference in our data set exceeded the range for which any of the bulk schemes were intended, the coefficients were computed by projecting the coefficient relationships in a linear fashion. More information about these and other coefficient schemes may be found in Blanc (1985).

6. Determination of the typical situation

Using the methodology and data base previously described and the scenarios for the sensor accuracies and the ship-induced distortions which are presented in the next two sections, it is possible to calculate the uncertainty of the resulting bulk-derived flux, stability, or roughness determination for a given bulk transfer coefficient scheme. A previous flux error analysis, Blanc (1983a), demonstrated that the uncertainties generally varied as a function of the flux or stability magnitude. Subsequently, the values of opposite sign were combined and the results analyzed in terms of the parameter's magnitude. An example of the results for sensible heat flux using the sensor accuracy scenario (Section 7) with the Large and Pond (1981, 1982) scheme is presented in Fig. 10 as a function of the flux magnitude. The scatter in the error results presented in the figure exists because a given calculated flux magnitude can be obtained from a variety of rudimentary input measurement combinations and, hence, result in differing values for the total error. If we assume that the selected 1-year data base is reasonably representative of the diversity of combinations possible, a fitted curve can then be used to portray the typical or average situation. Details of the curve-fitting procedure are given in Blanc (1985). Thus, from Fig. 10 it can be seen that for a sensible heat flux magnitude of 20 W m\(^{-2}\), the typical uncertainty when using the Large and Pond bulk scheme introduced by the inaccuracy of the sensors is about 40\%, or 8 W m\(^{-2}\). The same procedure was repeated for all six bulk-derived parameters by using the four selected bulk schemes and the two error scenarios.
7. The typical influence of sensor inaccuracies

A search of the literature of the last two decades indicated that there is a consensus as to the approximate accuracy of meteorological instruments used on weather ships and at other weather installations. For example, Bindon (1965) concluded that the best overall humidity accuracy that could be expected from a wet- and dry-bulb device properly shielded from solar radiation was about 2%. Saunders (1967) found that the typical bucket method temperature error was on the order of 0.3°C and under extreme conditions could be as large as 1°C. The work of Hinzpeter (1967) and Simpson and Paulson (1980) suggested that routine water surface measurements were accurate to about 0.5°C. For our error analysis of the instrumentation influence, we constructed a sensor accuracy scenario based principally on the instrument accuracy values published by the British Meteorological Office. The scenario values along with their published sources are presented in Table 2.

The humidity accuracy for a sling psychrometer is given in the table (as is customary) in terms of the accuracy of the wet- and dry-bulb thermometers. The true measurement accuracy of the wet- and dry-bulb technique itself is probably worse than that implied here. At the average wet- and dry-bulb temperatures for the year, the wet- and dry-bulb errors (δTwb and δT) indicated in Table 2 are equivalent to a specific humidity error (δq) of approximately 0.18 × 10⁻³ kg kg⁻¹ or a relative humidity error of about 2.6%. The formulas necessary for calculating the specific humidity from the wet- and dry-bulb temperatures are presented in Appendix C of Blanc (1985).

The altitudes for the various sensors are typically measured only when the sensors were initially installed or an on-deck measurement location chosen. We estimated the variation in the ship's mean vertical displacement in the water due to varying amounts of fuel and cargo to be 0.5 m.

The results of the analysis based on the Table 2 scenario are presented in Figs. 11–16 as a function of the parameter magnitude for the six bulk-derived flux, stability, and roughness parameters. The results do not include the distortions produced by the ship, which are covered in the next section. The average bulk parameter magnitudes for the 1-year period are indicated by a solid triangle in the figures. As anticipated in section 3, our analysis determined the influence of the barometric pressure measurement error and the sensor altitude errors to be relatively small; the combined influence was found to be typically less than 1% for the six bulk-derived parameters.

8. The typical influence of ship-induced distortions

Augstein et al. (1974), in a comparison of data taken simultaneously from the deck of a ship and from a buoy, concluded that the ship's hull and superstructure induced sizable distortions in the rudimentary measurements of wind speed, air temperature, and humidity. Hoeber (1977), in a specially designed experiment in which data were taken simultaneously from the deck and from a forward boom, found that rudimentary shipboard measurements including barometric pressure were very difficult; he estimated that the errors in some of the resulting bulk-derived fluxes could be as large as 100%.

Goers and Duchon (1980), with an arrangement similar to that of Hoeber, observed the air-temperature measurement to increase by more than 2°C due to the heating influence of the ship during the day. No temperature increase was observed during the night. Reed (1978) reported similar results. Shinners (1970) observed that because a ship absorbs solar radiation and contains a large internal heat source, it tends to significantly modify the ambient atmospheric and oceanic environments. He argued that a ship is engulfed in its own self-generated microenvironment.

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**Table 2. Weather ship sensor accuracy scenario.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter symbol</th>
<th>Sensor type</th>
<th>Sensor accuracy</th>
<th>Type of error:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>u</td>
<td>Electromechanical anemometer</td>
<td>δu = ±0.5 m s⁻¹</td>
<td>R (U.K. Meteorological Office 1980)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(u &lt; 20 m s⁻¹)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>δu = ±1.0 m s⁻¹ (u &gt; 20 m s⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>T</td>
<td>Sling psychrometer dry-bulb mercury thermometer</td>
<td>δT = ±0.3°C</td>
<td>R (U.K. Meteorological Office 1980)</td>
</tr>
<tr>
<td>Wet-bulb temperature</td>
<td>Twb</td>
<td>Sling psychrometer wet- and dry-bulb mercury thermometers</td>
<td>δTwb = ±0.3°C</td>
<td>R (U.K. Meteorological Office 1980)</td>
</tr>
<tr>
<td>(humidity)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea surface temperature</td>
<td>Tw</td>
<td>Bucket and thermometer</td>
<td>δTw = ±0.5°C</td>
<td>R (Roll 1965)</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>P</td>
<td>Aneroid barometer</td>
<td>δP = ±100 Pa</td>
<td>R (U.K. Meteorological Office 1980)</td>
</tr>
<tr>
<td>Altitude</td>
<td>Z_U, Z_T, Z_Q</td>
<td>—</td>
<td>δZ_U = δZ_T = δZ_Q = ±0.5 m</td>
<td>R (Comstock 1967)</td>
</tr>
</tbody>
</table>
Kahma and Leppäranta (1981) found that wind speed measurements made from ships could be in error by as much as 35%. Ching (1976), in a comparison of wind speed measurements made from a number of ships’ masts and forward-mounted booms, found that the magnitude of the observed error was a function of the wind’s relative angle of approach to the ship. The least amount of distortion occurred when the wind was aligned with the heading of the ship. Bogorodskiy (1966) found a poor agreement between shipboard wind profile measurements taken on the end of a forward-mounted 8-m boom and those taken from a buoy. Additional references and information on the distortions induced by various types of marine platforms may be found in Blanc (1983b).

Figure 17 shows the results of Kahma and Leppäranta (1981) depicting the typical acceleration of wind due to the presence of the ship’s superstructure when the wind direction and ship’s heading are aligned. From Table 1 it can be seen that the wind speed sensor altitude ($z_a$) to the ship’s superstructure height ($S_H$) ratio ranged from about 1.4 to 2.0 for the ships used at Ocean Station C. At these ratios the Kahma and Leppäranta findings would indicate that the wind speeds observed from the ship’s masts were accelerated by about 10 to 20% and, according to the Ching (1976) results, probably higher when the wind direction and ship’s heading were not aligned. For our analysis, we used the lower systematic error estimate of +10% and combined it with an estimate of the random error produced by the
Fig. 15. The typical (average) uncertainty in the bulk-derived roughness length \( z_0 \) due to sensor inaccuracies (Table 2) for four different transfer coefficient schemes displayed as a function of the roughness magnitude. The solid triangle denotes the average roughness magnitude observed at Ocean Station C in 1973.

Pitching and rolling motion of the ship. The scenario values along with their published sources for the ship-induced distortions are presented in Table 3. At an average wave height \( W_H \) of 2.23 m, the influence of the ship's wave-induced motion is estimated by the Table 3 formulation to result in an additional wind speed error of about \( \pm 6\% \). In terms of the section 3 methodology, \( \delta u = +16\% \) for \( u_U \) and \( \delta u = +4\% \) for \( \tilde{u}_U \). The average \( \delta u = +10\% \).

The Goerss and Duchon (1980) finding of a 2\(^\circ\)C increased air temperature due to the solar heating of the ship was based on measurements made during September in the tropical Atlantic under low to moderate wind speeds. We expect the solar heating influence to decrease with increased latitude, cloud cover, or wind speed. Hoeber (1977), from measurements made during April and May in the North Sea at a latitude 6\(^\circ\) farther north from the equator than Ocean Station C, found the dry-bulb air temperature measurement to be high by an average of about 0.5\(^\circ\)C due to the influence of the ship. We used this value, which was averaged over a variety of wind speed and cloud cover conditions, for our analysis and assumed that there was no error during the evening. To these values we added an additional estimated error of 0.2\(^\circ\)C to the wet-bulb temperature to account for the local increase in humidity produced by ship-generated sea spray. At the average wet- and dry-bulb temperature for the year, the systematic errors in both measurements (\( \delta T_{WB} \) and \( \delta T \)) are equivalent to a specific humidity error \( \delta q \) of approximately \( 0.08 \times 10^{-3} \) kg kg\(^{-1}\) or a relative humidity error of about 1.2% for both the day and night. Atmpt (1955) compared water temperature measurements made at various distances from a ship and found that those made close to the ship were high by about 0.3\(^\circ\)C.

To account for the ship-induced errors in the barometric pressure measurement produced by the wave-induced motion of the ship and the wind-induced pressure loading around the ship's superstructure, we estimated a random error which is a function of the wave height \( W_H \), the density of the air \( \rho \), and the wind speed \( \tilde{u} \). At the average wave height and wind speed for the year, the Table 3 formulation would estimate the error to be about 85 Pa. To account for the variation in the various sensor altitudes produced by the wave-induced motion of the ship, we estimated a random error based on the ratio of the ship's length \( (S_f) \) to the ocean wavelength \( W_L \). From Comstock (1967) it can be seen that

\[
W_L = \frac{g(W_P)^2}{2\pi},
\]

where \( W_P \) is the wave period and \( g \) is the acceleration due to gravity (9.8 m s\(^{-2}\)). For an average wave period
### Table 3. Weather ship platform-induced distortion scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter symbol</th>
<th>Distortion description</th>
<th>Ship-induced distortion</th>
<th>Type of error</th>
<th>Source for ship distortion values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>$u$</td>
<td>Acceleration over ship’s superstructure ($\delta u_{\text{S}}$), Pitching and rolling influence of ship due to waves ($\delta u_{\text{W}}$).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta u = \delta u_{\text{S}} + \delta u_{\text{W}}$</td>
<td>$\delta u_{\text{S}} = +10%$</td>
<td>$R^b$</td>
<td>Kahma and Leppärinta (1981)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta u_{\text{W}} = \pm (0.25 \text{ m s}^{-2}) \times W_h$</td>
<td>$S^a$ and $R^b$</td>
<td>Roll (1965)</td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>$T$</td>
<td>Warming of air due to solar heating of ship’s superstructure and deck.</td>
<td>$\delta T = +0.5^\circ \text{C (Day)}$, $\delta T = 0^\circ \text{C (Night)}$</td>
<td>$S$</td>
<td>Hoeber (1977)</td>
</tr>
<tr>
<td>Wet-bulb temperature (humidity)</td>
<td>$T_{\text{WB}}$</td>
<td>Same as for air temperature plus increase in humidity due to ship-generated sea spray.</td>
<td>$\delta T_{\text{WB}} = +0.7^\circ \text{C (Day)}$, $\delta T_{\text{WB}} = +0.2^\circ \text{C (Night)}$</td>
<td>$S$</td>
<td>This author</td>
</tr>
<tr>
<td>Sea surface temperature</td>
<td>$T_w$</td>
<td>Thermal “pollution” due to the surrounding sea water being used to cool the ship’s engines.</td>
<td>$\delta T_w = +0.3^\circ \text{C}$</td>
<td>$S$</td>
<td>Ámot (1955)</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>$P$</td>
<td>Pitching and rolling influence of the ship due to waves ($\delta P_{\text{P}}$). Wind-induced pressure variations around ship’s superstructure ($\delta P_{\text{W}}$).</td>
<td>$\delta P = \pm [\delta P_{\text{P}}^2 + (\delta P_{\text{W}})^2]^{1/2}$</td>
<td>$R$</td>
<td>Roll (1965)</td>
</tr>
<tr>
<td>Altitude $z_U$, $z_T$, $z_Q$</td>
<td></td>
<td>Variation in altitude as observed from the ship due to waves.</td>
<td>$\delta z_U = \delta z_T = \delta z_Q = \pm \frac{W_h}{2} \left( \frac{W_i}{S_L} \right)$</td>
<td>$R$</td>
<td>U.K. Meteorological Office (1980)</td>
</tr>
</tbody>
</table>

Notes: $W_h$, wave height in m; $\rho$, air density (1.23 kg m$^{-3}$); $W_i$, ocean wave length in m; $S_L$, ship length (100 m); Day, Observations made at 07:00, 10:00, 13:00, and 16:00 LST. Local Standard Time (LST) = Greenwich Mean Time—2 h.

9. Conclusions and discussion

Our analysis shows that the general patterns and magnitudes of the typical influences due to sensor accuracy (Figs. 11–14) and ship-induced distortion (Figs. 18–21) on the bulk-derived determinations of flux and stability to be similar for the four selected bulk coefficient schemes. The exception to this rule was the Liu et al. (1979) coefficient scheme, which tended, on the average, to produce substantially larger uncertainties than the other schemes for large magnitude latent heat fluxes. Generally, the influence of the sensor and ship-induced errors on the bulk-derived determinations was largest at the smaller flux or stability magnitudes. The general patterns of the typical influences due to sensor accuracy (Figs. 15 and 16) and ship-induced distortion (Figs. 22 and 23) of roughness were found to be more different, varying substantially for the four selected bulk coefficient schemes. The influences of the sensor accuracy and ship-induced errors were found to vary in
excess of a factor of 10 and to be largest at either extreme of the roughness magnitude.

Our analysis confirms that the principal sources of uncertainty in the six bulk-derived parameters are due to the wind speed, air and water temperature, and humidity measurements. The influences of the barometric pressure measurement and altitude uncertainties combined are usually less than 1%.

A summary of the results based on a consensus of the four selected bulk coefficient schemes is presented in Table 4 for three general classes of bulk parameter magnitudes. The average bulk parameter magnitudes for the 1973 Ocean Station C data were approximately 0.2 N m\(^{-2}\) for stress, 25 W m\(^{-2}\) for sensible heat flux, 40 W m\(^{-2}\) for latent heat flux, 0.06 for the Monin-Obukhov stability, 3 \times 10^{-4} \text{ m} for roughness length, and 6 for the roughness Reynolds number. To determine the most probable joint influence of the sensor accuracy and ship-induced uncertainties, the error results were combined in an rms fashion as illustrated in Eq. (8). Based on a consensus of the four selected bulk coefficient schemes, it is estimated that the typical combined error at the average bulk parameter magnitudes is about 30% for stress, 50% for sensible heat flux, 50% for the latent heat flux, 80% for the Monin-Obukhov stability, 40% for roughness length, and 60% for the roughness Reynolds number.

Let us emphasize that the findings presented in this paper are typical insofar as they are based on average results from a representative data set. The data set used for this analysis contains only about 0.01% of all the rudimentary ship observations made worldwide for the
FIG. 22. The typical (average) uncertainty in the bulk-derived roughness length \( z_0 \) due to ship-induced distortions (Table 3) for four different transfer coefficient schemes displayed as a function of the roughness magnitude. The solid triangle denotes the average roughness magnitude observed at Ocean Station C in 1973.

FIG. 23. The typical (average) uncertainty in the bulk-derived roughness Reynolds number \( R_e \) due to ship-induced distortions (Table 3) for four different transfer coefficient schemes displayed as a function of the roughness magnitude. The solid triangle denotes the average roughness magnitude observed at Ocean Station C in 1973.

The last 125 years. We therefore would anticipate the results to differ somewhat depending on the year or the location selected. For example, the occurrence of downward humidity fluxes, high average wind speeds, or stable atmospheric conditions would be much less likely over a tropical ocean. Further, as can be seen by the example given in Fig. 10, the results of any individual observation can vary substantially from the typical situation portrayed here for a given bulk scheme.

Our analysis does not include many other sources of error such as those involved in attempting to correct wind speed measurements made from a ship underway, not including the humidity buoyancy when computing.

TABLE 4. Summary of the results based on a consensus of the four selected bulk coefficients schemes for three general classes of bulk parameter magnitudes using the 1973 Ocean Station C weather ship data.

<table>
<thead>
<tr>
<th>Bulk parameter</th>
<th>Parameter symbol</th>
<th>General magnitude class</th>
<th>Magnitude value</th>
<th>Approximate typical uncertainty due to sensor inaccuracies using Table 2 scenario (%)</th>
<th>Approximate typical uncertainty due to ship-induced distortions using Table 3 scenario (%)</th>
<th>Most probable (rms) combination of typical uncertainties due to sensor inaccuracies and ship-induced distortions in percent of reading in parameter units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (N m(^{-2}))</td>
<td>( \tau )</td>
<td>small</td>
<td>0.05</td>
<td>20</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>average</td>
<td>0.20</td>
<td>10</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large</td>
<td>0.95</td>
<td>15</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>Sensible heat flux</td>
<td>( H_s )</td>
<td>small</td>
<td>10</td>
<td>85</td>
<td>60</td>
<td>104</td>
</tr>
<tr>
<td>(W m(^{-2}))</td>
<td></td>
<td>average</td>
<td>25</td>
<td>40</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large</td>
<td>140</td>
<td>15</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>Latent heat flux</td>
<td>( H_l )</td>
<td>small</td>
<td>20</td>
<td>50</td>
<td>50</td>
<td>71</td>
</tr>
<tr>
<td>(W m(^{-2}))</td>
<td></td>
<td>average</td>
<td>40</td>
<td>30</td>
<td>35</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large</td>
<td>280</td>
<td>20</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>Monin-Obukhov stability</td>
<td>( z/L )</td>
<td>small</td>
<td>0.01</td>
<td>180</td>
<td>150</td>
<td>234</td>
</tr>
<tr>
<td>at 10 m</td>
<td></td>
<td>average</td>
<td>0.06</td>
<td>60</td>
<td>55</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large</td>
<td>1.00</td>
<td>60</td>
<td>40</td>
<td>72</td>
</tr>
<tr>
<td>Roughness length (m)</td>
<td>( z_0 )</td>
<td>small</td>
<td>( 3 \times 10^{-5} )</td>
<td>25 to 120</td>
<td>15 to 55</td>
<td>81*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>average</td>
<td>( 3 \times 10^{-4} )</td>
<td>10 to 25</td>
<td>15 to 55</td>
<td>39*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large</td>
<td>( 3 \times 10^{-3} )</td>
<td>120 to 320</td>
<td>85 to 600</td>
<td>407*</td>
</tr>
<tr>
<td>Roughness Reynolds</td>
<td>( R_e )</td>
<td>small</td>
<td>0.2</td>
<td>65 to 130</td>
<td>45 to 110</td>
<td>125*</td>
</tr>
<tr>
<td>number</td>
<td></td>
<td>average</td>
<td>6</td>
<td>15 to 30</td>
<td>35 to 70</td>
<td>57*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large</td>
<td>80</td>
<td>20 to 70</td>
<td>60 to 80</td>
<td>83*</td>
</tr>
</tbody>
</table>

* Based on averages of the values given in columns 5 and 6.
the stability, the effects of using bucket or engine intake water temperatures rather than the skin temperature, or the use of wind speed measurements averaged for only 2 min. Blanc (1983c) found, for example, that if the humidity influence is not included in the stability correction the profile-derived fluxes can be in error by as much as 80%. Saunders (1967) has estimated that the difference between bucket and skin temperatures can be as large as 1°C. Most merchant and military ships use a water temperature measurement taken at the cooling intake to the engines. James and Fox (1972) found bucket and intake temperature measurements to disagree by as much as 3°C. Pierson (1983) argues that due to temporal atmospheric fluctuations, a shipboard wind speed measurement averaged for only 2 min. can be significantly in error, and recommends an averaging period in excess of 10 min. Lastly, our results are based on an analytical error analysis which assumes the bulk method to be absolutely accurate. This is almost certainly not the case. We have not considered those sources of uncertainty which are inherent in the method itself due to the simplicity of its underlying assumptions. For example, a comparison reported by Smith (1980) of bulk stress estimates and direct (eddy-correlation) stress measurements made simultaneously from the same specially designed buoy without the distortion produced by a ship disagreed by as much as 55%.

Our analysis demonstrates that sensor inaccuracies and the distortions produced by the observation platform can substantially influence even bulk estimates made from weather ships where good quality sensors are operated and maintained by specially trained personnel. Since the instrumentation and meteorological training of the personnel responsible for observations on other types of ships are most probably not of as high a caliber as on a weather ship and because we have generally used conservative estimates for the error scenarios, the results presented in this paper almost certainly represent a best case situation.

What then can be done in the future to correct or minimize these problems? It would make little sense to develop a more accurate seaworthy anemometer which is better than 5% when the very presence of the ship can produce a wind speed measurement error as large as 20%. One approach being investigated by the Naval Research Laboratory is to employ ship models in a special marine boundary-layer simulation wind tunnel. For a given mast location and type of ship, it is hoped that a correction algorithm can be developed which can be used to compute the true wind speed and direction as if the ship were not present.

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