Displacement Measurement Errors from Moving Platforms

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(Manuscript received 3 September 2002, in final form 7 January 2003)

ABSTRACT

Errors in eddy correlation measurements from moving platforms (aircraft, ships, buoys, blimps, tethered balloons, and kites) include contamination of the measured fluctuations by superficial fluctuations associated with vertical movement of the platform in the presence of mean vertical gradients. Such errors occur even with perfect removal of the motion of the platform. These errors are investigated here from eddy correlation data collected from the LongEZ research aircraft and the air–sea interaction spar (ASIS) buoy during the Shoaling Waves Experiment (SHOWEX).

1. Introduction

Except for towers, eddy correlation measurements of turbulent fluxes are generally made from moving platforms such as aircraft, buoys, ships, and suspended platforms from tethered balloons, blimps, kites, and aircraft. Errors in the measured velocity fluctuations occur due to incomplete removal of the platform motion, normally recorded with accelerometers, gyroscopes and differential GPS (Lenschow 1986; Edson et al. 1998). Improvements in such systems are constantly reducing the errors associated with platform motion. Even with complete removal of platform motion, eddy correlation errors still occur due to the fact that the time series is not collected at a constant height above the mean surface and mean vertical gradients are normally not zero, particularly near the surface (Fig. 1). Examples of vertical displacement are shown for the aircraft and buoy in Fig. 2. As a result of the vertical platform displacements, superficial fluctuations may be generated by the variation of the height of the measurement platform due to the vertical mean gradients. These errors were briefly examined in Lenschow (1973) and Vickers and Mahrt (1997) but otherwise are generally not considered in the literature. This study examines such errors in more detail. The errors due to vertical platform displacement are just one of a number of instrumental and sampling errors contaminating eddy correlation measurements from fixed or moving platforms (Moore 1986; Mann and Lenschow 1994; Mahrt 1998 and Massman 2000).

2. The data

For aircraft data, the errors due to vertical platform displacement are most easily examined over water, where variations of surface elevation do not complicate the definition of height above ground. This study analyzes eddy correlation data collected from the LongEZ research aircraft over Atlantic coastal water off the Outer Banks near Duck, North Carolina, during the Shoaling Waves Experiment (SHOWEX) in March 1999 and November–December 1999 (Crescenti et al.

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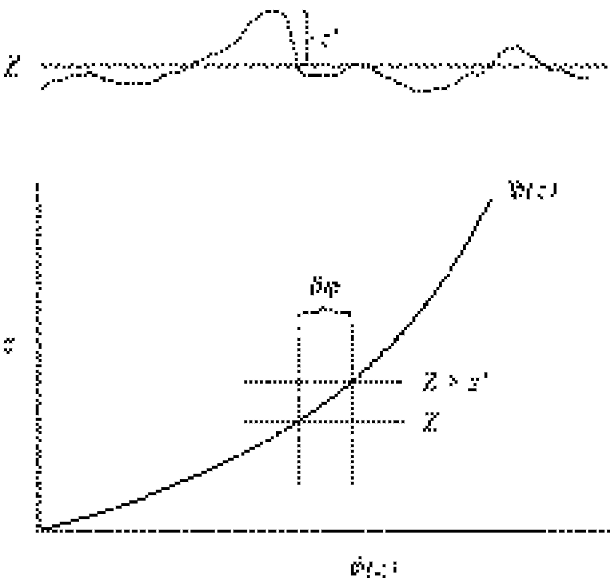

FIG. 1. Geometry of superficial fluctuations due to vertical platform displacement in the presence of mean vertical gradients. (top) Here z' and Z are defined for a hypothetical times series of platform height. (bottom) Artificial fluctuations generated by vertical platform displacement in the presence of mean vertical gradients.

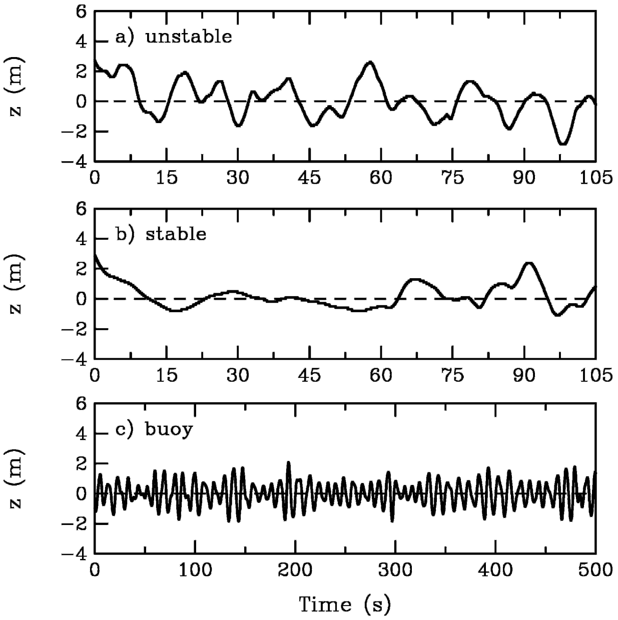

FIG. 2. Examples of vertical displacement of the LongEZ for (a) unstable conditions and (b) stable conditions, and (c) for the ASIS buoy for slightly stable conditions with 13 m s^{-1} mean wind and a large significant wave height of 4 m.

1999; French et al. 2000; Sun et al. 2001; Mahrt et al. 2001) using low-level aircraft data from 37 flights on 35 days at an average height of 15 m above the sea surface. The LongEZ is able to fly at this very low level for several hours at a time.

Fluxes are computed for 2-km segments of the aircraft legs using unweighted averaging. For a wind of 5 m s^{-1}, this volume of air would pass a stationary platform in about 7 min. Records with negative moisture flux, upward momentum flux (presumably driven by swell), and flight levels above 25 m are excluded since some of the calculations will employ surface layer similarity theory. Records are excluded where the absolute value of z/L exceeds 5 where fluxes may be strongly contaminated by flux sampling errors and where similarity theory is suspect. Here, L is the Obukhov length and z is the distance above the mean surface height. When computing bin-averaged values of ratios, such as the relative flux error (section 5), for different intervals of stability, z/L, the values of the numerator and denominator are averaged first and then the ratio is computed. This procedure avoids ratio averaging problems where a few very large values of the ratio, due to small denominators, can dominate the average of the ratio. For some calculations, the data will be divided into stable and unstable classes. Here we exclude near-neutral cases where the magnitude of z/L is less than 0.001.

The air–sea interaction spar (ASIS) buoy (Graber et al. 2000) is a partial surface follower, essentially following waves with periods longer than 8 s. This latter property allows measurements within several meters of the interface in most conditions. The data used here are from the "Romeo" buoy during SHOWEX in autumn 1999. Romeo is equipped with a three-axis Gill R2A sonic anemometer, located on top of a mast at roughly 6 m above mean sea level. The buoy is also equipped with a full motion package, allowing the measured wind velocities to be corrected for the motion of the platform. The instantaneous height of the anemometer above the surface is calculated from a capacitance wave staff positioned directly below the anemometer. For the calculations in this study, 30-min records were selected every 10 h to provide a more manageable dataset and to represent a cross section of conditions during the 38-day deployment: $1 < U < 15$ m s^{-1} and $-2 < z/L < 1$. The fluxes are computed with simple unweighted averaging (equal weighting of all points).

3. Platform displacement errors

Aircraft vertical displacement from a constant height above the surface is induced by turbulent updrafts and downdrafts and perhaps fluctuations of lift due to horizontal velocity fluctuations. Vertical displacement of buoys and ships is controlled by the surface wave field.

The artificial fluctuations due to the height variation of the observational platform for arbitrary variable ϕ (Fig. 1) can be estimated as

$$\delta\phi(z') = z'(t)\frac{\partial\overline{\phi}}{\partial z}, \tag{1}$$

where $\delta\phi(z')$ is the change of variable ϕ due to the vertical displacement of the platform from its mean elevation

$$z'(t) = z(t) - Z, \tag{2}$$

where Z is the time-averaged height of the platform and $z(t)$ is the instantaneous height of the platform. Then any variable measured from the platform can be expressed as

$$\phi(z', t) = \phi(Z, t) + z'(t)\frac{\partial\overline{\phi}}{\partial z}, \tag{3}$$

where $\phi(Z, t)$ is the desired instantaneous value measured at a fixed height. We will assume that the vertical mean gradient does not change significantly across the layer defined by $z'(t)$ and that the flow is stationary.

The vertical gradients may be large near the surface, resulting in significant artificial fluctuations, even if the change of platform vertical position is small. Are such artificial fluctuations sufficiently correlated with vertical velocity fluctuations to significantly alter the computed flux? To investigate this issue, we expand the measured vertical flux as

$$\begin{aligned}\overline{w'(z, t)\phi'(z, t)} &= \overline{w'(Z, t)\phi'(Z, t)} + \overline{w'(Z, t)\delta\phi(z')} \\ &\quad + \overline{\delta w(z')\phi'(Z, t)} + \overline{\delta w(z')\delta\phi(z')},\end{aligned} \tag{4}$$

where the overbar is a simple unweighted average in order to satisfy Reynolds averaging. The first term on the right-hand side is the true vertical flux required for use in the basic conservation equation for $\overline{\phi}$. The remaining three terms on the right-hand side are error terms. The last two error terms on the right-hand side are related to heterogeneity of the mean flow through mass continuity in that artificial fluctuations of vertical velocity are proportional to $\partial\overline{w}/\partial\overline{z}$ [Eq. (1)]. These terms vanish for homogenous flow. Even if the platform was motionless with no vertical displacement, the estimate of the first term on the right-hand side of Eq. (4) from finite records contains a random flux error due to variability of the turbulence.

4. Vertical velocity correlation term

The second term on the right-hand side of Eq. (4) is due to the correlation between the vertical velocity fluctuations and the artificial fluctuations of ϕ. Estimating $\delta\phi(z')$ from Eq. (1), this term becomes

$$\overline{w'(Z, t)\delta\phi(z')} = \overline{w'(Z, t)z'(t)}\frac{\partial\overline{\phi}}{\partial z}. \tag{5}$$

To numerically estimate this error term, $w'(Z, t)$ is approximated by $w'(z', t)$. Below, $\phi'(Z, t)$ will be approximated by $\phi'(z', t)$. Such approximations correspond to only higher-order errors, which are small compared to $\overline{w'(Z, t)\delta\phi(z')}$, provided that z' is not too large.

The vertical gradient, $\partial\overline{\phi}/\partial z$, can be estimated in two ways. In the first approach, it is estimated by regressing $\phi'(z', t)$ on z. A potential difficulty of this "regression" approach is that the platform height might be correlated with the turbulence itself, in which case the estimated value of $\partial\overline{\phi}/\partial z$ is contaminated by turbulent fluctuations. For example, the aircraft is displaced by vertical velocity fluctuations while waves simultaneously displace the buoy and induce atmospheric velocity fluctuations.

In the second approach, the vertical gradient ($\partial\overline{\phi}/\partial z$) is estimated from similarity theory as

$$\frac{\partial\overline{\phi}}{\partial z} = \frac{\Phi_{\phi}(Z/L)\phi_*}{\kappa Z}, \tag{6}$$

where L is the Obukhov length, κ is the von Kármán constant, $\Phi_{\phi}(Z/L)$ is the specified stability function for variable ϕ, and

$$\phi_* \equiv -\frac{\overline{w'(Z, t)\phi'(Z, t)}}{u_*}, \tag{7}$$

where u_* is the true surface friction velocity. Substituting Eqs. (6)–(7) into Eq. (5), we obtain

$$\overline{w'(Z, t)\delta\phi(z')} = \overline{w'(Z, t)z'(t)}\frac{\Phi_{\phi}(Z/L)\overline{w'(Z, t)\phi'(Z, t)}}{\kappa z u_*}. \tag{8}$$

Dividing this relationship by the flux computed from a stationary platform, the relative error can be written as

$$\overline{w'(Z, t)z'(t)}\frac{\Phi_{\phi}(Z/L)}{\kappa z u_*}. \tag{9}$$

In the surface layer, Φ_{ϕ} for heat, moisture, and momentum decreases slowly with increasing instability and increases with stability. The principal uncertainty with this "similarity" estimate of the vertical gradient is errors in the similarity relationship with strong stability, advection, and nonstationarity and possible location of the platform within the wave boundary layer (roughness sublayer over land).

5. Displacement flux errors for the aircraft

The displacement flux error depends on record length, method of estimation of the vertical gradient, and atmospheric stability. The estimate of the vertical gradient $\partial\overline{\phi}/\partial z$ based on regressing $\phi'(z', t)$ on z for the LongEZ data produces larger vertical gradients than the similarity prediction of the vertical gradient and therefore larger estimates of the displacement error. We will focus on estimates based on similarity theory because the error estimates are less variable. Furthermore, it is not possible to isolate the influence of correlation between turbulence quantities and z' that would contaminate the estimation of the vertical gradient based on the regression method.

a. Random and systematic contributions

The dependence of the displacement error on the record length is partly due to the fact that a substantial fraction of the displacement flux error is random. We can theoretically express the displacement error for a particular record as

$$\mathrm{DE} = \mathrm{SE} + \mathrm{RE}, \tag{10}$$

where SE is the systematic part of the displacement error and RE is the random part of the displacement flux error. The total displacement error approaches the systematic error as the sample size becomes large, assuming that the sample is homogeneous. This random error is different from the random flux error associated with the estimate of the desired flux for a level platform [first term on the right-hand side of Eq. (4)]. The latter is due to the random distribution of transporting eddies and is always present. We refer to this random error simply as the "random flux error," as opposed to the random part of the displacement error. It is traditionally estimated for homogeneous records as the standard deviation of the flux, σ_F, divided by the square root of the number of subrecords, N:

$$\mathrm{RFE} = \frac{\sigma_F}{\sqrt{N}}. \tag{11}$$

For the aircraft, the subrecord width is 200 m, which omits some of the flux for unstable conditions. The intention here is to capture enough subrecords to estimate the standard deviation of the flux. For the present analysis of aircraft data, we evaluate the error term from 2-km records (section 2), which is smaller than the usual aircraft record length of 10 km or longer. The random flux error and the random part of the flux displacement error both decrease with increasing record length, as is verified below. In this sense, the following analysis for 2-km records provides an upper bound for the two random errors.

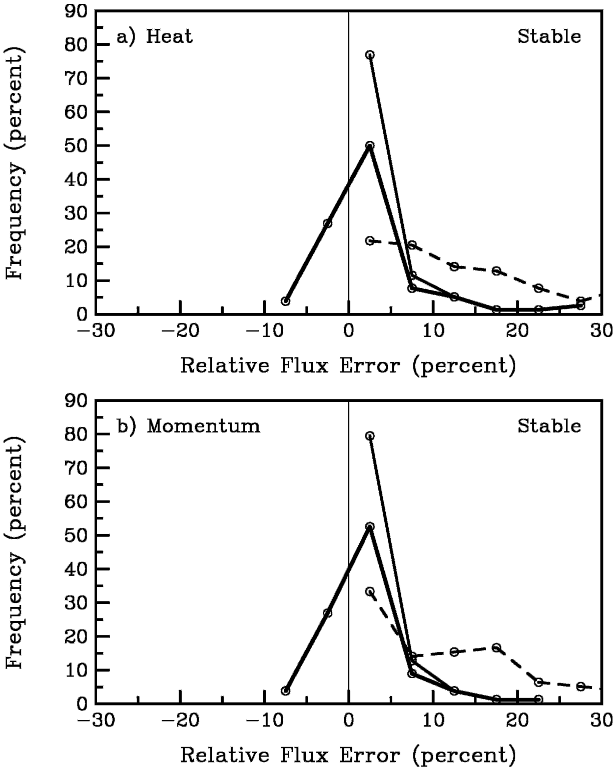

FIG. 3. The frequency distribution of the relative displacement error (thick solid line), the absolute value of the relative displacement error (thin solid line), and the random flux error estimated from Eq. (11) (dashed line) for the LongEZ aircraft data for stable conditions for (a) heat fluxes and (b) momentum fluxes.

b. Observed distribution

We now examine the behavior of the displacement error normalized by the flux for a stationary platform, as estimated from Eq. (9). The frequency distribution of this relative displacement error does indeed suggest that the random part of the displacement error is substantially larger than the systematic error (Fig. 3). The frequency peak of the relative flux displacement error for both heat and momentum fluxes appears to be positive for stable conditions, with a value of a few percent, within the uncertainty of the relatively crude resolution of the frequency distribution. The positive values of the relative displacement error correspond to artificial augmentation of the computed flux. Since the expected mean of the random part of the displacement error is zero, this suggests that the relative systematic error is positive, with a magnitude of a few percent for stable conditions. Based on the frequency distribution, the relative systematic error for unstable conditions also

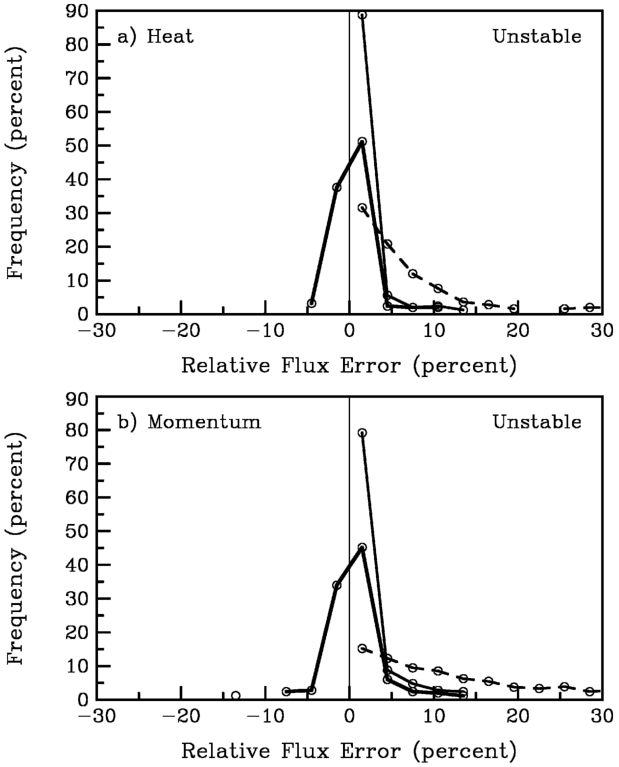

FIG. 4. The frequency distribution of the relative displacement error (thick solid line), the absolute value of the relative displacement error (thin solid line), and the random flux error estimated from Eq. (11) (dashed line) for the LongEZ aircraft data for unstable conditions for (a) heat fluxes and (b) momentum fluxes.

appears to be positive but cannot be safely distinguished from zero (Fig. 4).

As a quantitative estimate of the displacement error we average the relative displacement error (retaining the sign) for all of the 2-km segments (approximately 560 km of total data) within a stability class. The averaged value of the relative displacement error for stable conditions is +4% for heat and +2% for momentum. The corresponding values are only +0.5% for unstable conditions for both heat and momentum fluxes. For unstable conditions, the relative errors are much smaller, partly due to larger absolute values of the fluxes and partly because the vertical gradients at the aircraft level are generally smaller in the unstable case (thinner surface layer).

As the record length increases from 2 to 20 km, the random part of the displacement error is expected to decrease by a factor of $1/\sqrt{10}$. For 20-km records (not shown), the magnitude of the relative displacement error is substantially smaller than that for 2 km and rarely exceeds 5%. The relative flux displacement error increases with increasing stability, although the scatter is too large to confidently formulate such a dependence. The relative errors are generally largest for very stable conditions, where the flux magnitudes are small.

c. Origin of displacement error

The positive average values of the relative displacement error for stable stratification result from a negative correlation between the atmospheric vertical velocity and the aircraft displacement. The covariance is also generally negative for unstable conditions where the averaged relative displacement error is very small. Theoretically, one might postulate that the covariance should be near zero because the aircraft displacement, z', would reach its maximum positive value as the updraft switches to downdraft motion, and vice versa. Indeed, the actual correlations between the vertical velocity and the displacement for individual records average only about −0.03, but the correlation is negative for most of the records. The correlation is very small but systematic. The negative correlation suggests an overall lag in the aircraft response to updrafts and downdrafts, which might be influenced by the skewness of the vertical velocity fluctuations, pilot response characteristics, and aircraft aerodynamics. We conclude that the flux displacement error for short aircraft records is strongly influenced by the random part of the displacement error but is smaller than the usual random flux error and therefore of limited significance. For longer records, the systematic part of the displacement error is dominant but is only a few percent of the total flux, depending on stability and the transported quantity.

d. Random flux error

The random flux error is by definition positive but can be compared to the frequency distribution of the absolute value of the displacement error (Figs. 3 and 4, thin solid lines). As an example, the probability of significant relative displacement error greater than 10% is much less than that for the random flux error. The averaged random flux error is about 3 times greater than the absolute value of the displacement error for both heat and momentum fluxes for stable conditions and is an order of magnitude greater than the absolute value of the displacement error for unstable conditions. For individual 2-km records, the random flux error is greater than the total displacement error for 90% of the records for both heat and momentum for the stable case, while the random flux error is greater than the total displacement error for all of the records for the unstable case.

6. Buoy displacement flux errors

For ships and buoys, the height of the platform, $z(t)$, may also correlate with $w'(z, t)$ since eddies in the wave boundary layer exhibit phase relationships with the surface waves (e.g., Hare et al. 1997). Eddy correlation measurements are best taken above the wave boundary layer, in the surface layer, where the Monin–Obukhov similarity theory potentially applies, and such platform-induced errors should be smaller since the vertical displacement of the buoy and the atmospheric vertical velocity should become less correlated.

For a given value of the Obukhov length, the vertical gradients should be larger for the buoy since the buoy measurement level is closer to the surface (6 m compared to about 15 m for the aircraft). However, the relative displacement flux errors are not generally larger for the buoy, partly because both the atmospheric vertical velocities at the buoy observational level and the platform displacements are both generally smaller for the buoy compared to those for the aircraft.

The details of the above results are influenced by the definition of the zero reference height for the buoy. The platform height is separately computed with respect to the distance of the instrument from the mean water height and with respect to the distance from the instantaneous wave field. The latter is affected mainly by short waves since the buoy rides the long waves; that is, z becomes defined as the height above the long waves (swell). The influence of buoy tilt on the distance between the sensor height and wave surface is small. The eddies in the surface layer integrate out the influence of the shorter waves (by definition of the surface layer) so that the correlation between the turbulent vertical fluctuations and the short waves should be zero. The displacement flux errors for heat are approximately the same in both coordinate systems, but the momentum displacement error averages an order of magnitude smaller using the instantaneous height. In the following, we employ height above mean sea level because it is a little easier to interpret, does not depend on the wave riding ability of the buoy, and serves as a maximum error estimate.

The correlation between the buoy displacement height and $w'(z', t)$ is larger than that for the aircraft but still averages only -0.15. This correlation may be due to the atmospheric streamlines following the long waves. This possibility corresponds to location of the buoy anemometer within the wave boundary layer for the long waves. The displacement flux errors for the buoy depend on wave height through the influence on z' and depend on atmospheric stability through the influence on the vertical gradients. The data were partitioned into intervals of small and large significant wave height (rms of wave height greater than or less than 1.5 m) and further subdivided into stable and unstable classes. Sufficient data were available only for the unstable class. The relative errors for the momentum flux (Fig. 5) are shifted toward larger values for the class of large significant wave height. The random part of the error, as indicated by the spread, is less than that for the aircraft (Figs. 3 and4) because the buoy records are relatively longer (section 2). The relative displacement error for the heat flux does not show the same sensitivity to the wave height as that for momentum (Fig. 5), perhaps because scalar fields do not directly respond to pressure fluctuations. The pressure fluctuations are expected to be larger with large waves. Even for large waves, the relative displacement errors for both fluxes are relatively unimportant. The displacement error artificially increases the heat flux and decreases the momentum flux and, therefore, artificially increases $-z/L$.

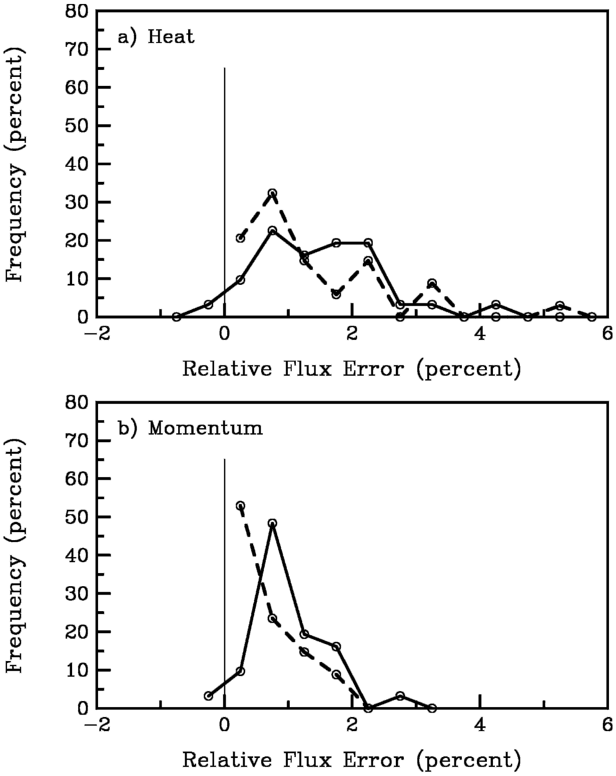

FIG. 5. The frequency distribution for the relative displacement flux error for the ASIS buoy for unstable conditions for (a) heat and (b) momentum, where the solid line represents the class of large significant wave height and the dashed line represents the class of small significant wave height.

7. Heterogeneity terms

The third term on the right-hand side of Eq. (4) can be expressed as

$$\frac{\partial \overline{w}}{\partial z}\,\overline{z'(t)\phi'(Z, t)}, \tag{12}$$

where we have estimated $\delta w(z')$ from Eq. (1) in terms of the mean vertical gradient and platform displacement z'. For some applications, the horizontal divergence of the wind field might be more easily estimated than the vertical divergence of the vertical velocity. Using incompressible mass continuity, Eq. (12) becomes

$$-\frac{\partial \overline{u}}{\partial x}\overline{z'(t)\phi'(Z,t)}. \tag{13}$$

Here, x is assumed to be the primary direction of horizontal divergence $\partial\overline{v}/\partial y \approx 0$.

As an example, consider the case where the platform is a light aircraft and ϕ is the horizontal wind component for offshore accelerating flow, corresponding to horizontal divergence. With a head wind (tail wind), horizontal wind gusts increase (decrease) the lift and z', in which case the correlation is positive (negative) and the flux correction term for momentum is negative (positive). That is, the computed downward momentum flux is artificially enhanced with a headwind and reduced with a tailwind. This term was evaluated from flights perpendicular to the coast by estimating the horizontal gradient of the wind in terms of linear regression over 2-km segments. The term was small for both heat and momentum, generally less than 2% of the total flux. This term could be potentially important near surface discontinuities, such as flow immediately downstream from the coastline or over heterogeneous land surfaces. However, the flux calculation based on aircraft measurements becomes ambiguous over strong surface heterogeneity in that horizontal variations of the mean flow contaminate the computed turbulent fluctuations. This heterogeneity term could also be large with transient disturbances, but significant influences are probably limited to fronts and convective cloud systems. We conclude that this term is small for the heterogeneity encountered in SHOWEX.

Applying Eq. (1) to the fourth term on the right-hand side of Eq. (4), we obtain the scaling estimate

$$\overline{\delta w(z')\delta\phi(z')} = \frac{\partial \overline{w}}{\partial z}\frac{\partial \overline{\phi}}{\partial z}\overline{z'^2}. \tag{14}$$

Again, using incompressible mass continuity,

$$\overline{\delta w(z')\delta\phi(z')} = -\frac{\partial \overline{u}}{\partial x}\frac{\partial \overline{\phi}}{\partial z}\overline{z'^2}. \tag{15}$$

This term can be of either sign, depending on whether the flow is accelerating or decelerating. This term is also found to be quite small.

8. Error in mean values

An error in the mean profiles due to platform displacements occurs when the mean gradients are not constant with height. The mean flow measured on a moving platform can be expressed as

$$\overline{\phi(Z+z',t)} = \int_0^\infty \overline{\phi}(Z+z')f(Z+z')d(Z+z'), \tag{16}$$

where Z is again the averaged height of the platform, z' is the deviation of the platform height from Z, and $f(Z+z')$ is the frequency distribution of the height of the platform. Even if $f(Z+z')$ is a symmetric function of z', the time-average value of $\overline{\phi(Z+z',t)}$ will normally differ from the average at a fixed height, Z, because the time-averaged value of $\overline{\phi}$ is usually a nonlinear function of height. Since the mean shear decreases with height, the mean wind speed on a moving platform will be underestimated. That is, negative $z'(t)$ induces larger artificial fluctuations than positive $z'(t)$. The net effect of this error causes underestimation of the mean wind speed, which in turn causes overestimation of the drag coefficient and roughness length.

An order-of-magnitude estimate of potential errors due to platform displacement can most easily be constructed for the case of neutral stability with a logarithmic wind profile:

$$\overline{u(z,t)} = \frac{u_*}{\kappa}\ln\frac{z}{z_o}, \tag{17}$$

where z retains traditional meaning and z_o is the aerodynamic roughness length, assumed to be small compared to the observational height. As the simplest possible estimate, assume the aircraft flies 50% of the time at level z_1 and 50% of the time at level z_2, so that the measured average wind speed for sufficiently long record length is

$$\overline{u(Z+z',t)} = \frac{u_*}{2\kappa}\left(\ln\frac{z_1}{z_o} + \ln\frac{z_2}{z_o}\right). \tag{18}$$

Noting that the true averaged wind speed for the average flight level can be expressed as

$$\overline{u(z,t)} = \frac{u_*}{\kappa}\ln\frac{(1/2)(z_1+z_2)}{z_o}, \tag{19}$$

the ratio of the measured wind speed to the true wind speed is

$$\frac{(1/2)(\ln z_1 + \ln z_2) - \ln z_o}{\ln(z_1+z_2) - \ln(2z_o)}. \tag{20}$$

Incrementally varying z_1 and z_2, corresponding to mean height variations between 4 and 20 m and height differences between 0 and 5 m, the relative platform error is found to be substantially less than 1%. This result was supported by numerically integrating Eq. (16) for the case of a Gaussian distribution of platform errors. Even for a mean observational height of 2 m and displacements of 1 m about the mean (corresponding to a 2-m wave height for waves greater than 8 s), the mean wind is underestimated by only 1%.

Defining the error in wind speed as

$$\epsilon \equiv \overline{u(Z + z', t)} - \overline{u(Z)}, \tag{21}$$

the drag coefficient estimated from a moving platform is

$$\frac{\overline{w'u'}}{\overline{u(Z,t)}^2 + 2\epsilon\overline{u(Z,t)} + \epsilon^2}. \tag{22}$$

Expanding the denominator in terms of a Taylor expansion, the percentage error in the drag coefficient due to errors in the mean wind is 2ϵ to lowest order. For example, a 1% underestimation of the mean wind leads to a 2% overestimation of the drag coefficient. We conclude that the effect of platform displacement on the mean wind and drag coefficient is not important. The percentage error for the mean shear will be substantially larger, particularly for larger values of z and smaller values of the difference between the observational levels used to estimate the shear.

9. Conclusions

We have studied the impact of errors due to vertical displacement of platforms resulting from contamination of the computed turbulent fluctuations by mean vertical gradients. Aircraft platform fluctuations for the present data lead to small overestimation of the heat and momentum fluxes for stable conditions and unimportant errors for unstable conditions. For typical record lengths, the magnitude of the displacement flux error is generally smaller than the usual random flux error, where the latter remains nonzero even for stationary platforms. Both random errors are reduced by increasing record length.

The displacement flux error can be theoretically partitioned into a random part (not to be confused with the usual random flux error) and a systematic part. The flux displacement error for short aircraft records is strongly influenced by the random part of the displacement flux error, which is smaller than the usual random flux error. For longer aircraft records, the random part of the displacement flux error decreases and the displacement flux error approaches the small systematic part of the error, typically a few percent of the total flux for stable conditions and less than 1% for unstable conditions. The systematic error tends to increase with stability. The general unimportance of the displacement error for the LongEZ is encouraging since this small aircraft is displaced more by atmospheric vertical velocity fluctuations compared to larger aircraft. Larger aircraft are unable to fly as close to the sea surface and are therefore less suitable for estimating surface fluxes in thin stable boundary layers over the sea. For flight levels closer to sea surface, the flux displacement error is expected to be larger because of larger vertical gradients. The present investigation considered only marine environments. Aircraft displacement errors may be greater over rougher land surfaces or more strongly heated surfaces, where aircraft displacements are larger. Unmanned aircraft may suffer larger platform displacement errors because of larger vertical displacements.

Compared to the aircraft, the buoy errors would be enhanced by stronger gradients at the lower observational levels of the buoy but are reduced by small magnitudes of the buoy displacement and the small vertical velocities close to the surface. The displacement flux error for the buoy becomes marginally significant only for large wave heights, in which case it averages a few percent.

Acknowledgments. The helpful comments of the reviewers are gratefully acknowledged. This material is based upon work supported by Grants N00014-97-1-0279 and N00014-01-1-0084 from the Office of Naval Research, Marine Meteorology, and Grant N00014-97-1-0348 from the Office of Naval Research, Coastal Dynamics.

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