A small non-research vessel as a platform for lake surface flux measurements

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Abstract:

To study the spatial variability of water surface fluxes, turbulence measurements on a moving platform are useful. However, such measurements have only been carried out with large research vessels over the ocean. We tested the feasibility of flux measurements with a small excursion ship over Lake Kasumigaura, the second largest lake in Japan. After the formal application of coordinate rotations to account for the ship's movements, we derived mean wind velocities as well as latent and sensible heat fluxes. They were compared with spatially interpolated wind velocities from meteorological stations and with fluxes estimated from the bulk method. Equally good agreements were found with those reported in previous studies over the ocean, indicating the feasibility of ship measurements in a lake. Possible error sources were identified for the improvement of the accuracy of flux estimation.

KEYWORDS lake; surface flux; eddy correlation method; ship measurements

INTRODUCTION

Lake surface fluxes play an important role in many aspects of lake ecosystems (e.g. Sugita *et al.*, 2020). As a result, attempts have been made to measure them in various parts of the world (e.g. Nordbo *et al.*, 2011; Wang *et al.*, 2014; Mammarella *et al.*, 2015; Zhao and Liu, 2018). However, except for a few studies, they are based on point measurements by essentially assuming that lake surface fluxes are spatially uniform. Recent studies (Sugita *et al.*, 2014; Sugita, 2019; Sugita *et al.*, 2020) based on fine energy balance maps demonstrated that this assumption is not entirely valid for the turbulent fluxes of latent heat flux (*LE*) and sensible heat flux (*H*) over Lake Kasumigaura, a shallow, 172-km² lake in Japan. Thus it is necessary to change our current practice of treating a lake as a one-dimensional entity.

In the above studies, however, there is still room for improvement in study methods. In particular, *LE* and *H* were estimated by the bulk method defined by equations (1)–(2),

$$LE = \rho L_e C_E \overline{U}(\overline{q_s} - \overline{q}) \quad (1)$$

$$H = \rho c_p C_H \overline{U}(\overline{t_s} - \overline{t}) \quad (2)$$

applied to each of 90×90 m pixels covering the entire lake's surface. C_E and C_H are the bulk transfer coefficients for water vapor and heat, respectively; U is the wind speed; t is the air temperature; t_s is the surface temperature; q is the specific humidity; q_s is the surface specific humidity; ρ is the density of air; L_e is the latent heat for vaporization; and c_p is the specific heat of air at constant pressure. Overbars denote time averages. Although the bulk method has been used for many years, there remains a weakness in the method, particularly in the values used for C_E and C_H (e.g. Wei *et al.*, 2016). Bulk coefficients are usually determined as a function of wind speeds. Such functions were obtained through regression against measurements that generally exhibit a considerable scatter. Atmospheric stability correction is necessary and applied in some cases, but the influence of waves are generally ignored. These factors all result in uncertainty in the fluxes. Thus a method to determine lake surface fluxes by direct measurements of *LE* and *H* are preferred over indirect approaches to better understand the nature of surface fluxes.

Currently, the eddy correlation method, (3)–(4) for *LE* and *H*

$$LE = \rho L_e \overline{w'q'} \quad (3)$$

$$H = \rho c_p \overline{w't'} \quad (4)$$

is virtually the only direct method that produces accurate turbulent heat fluxes with a fine time resolution of <1 hour, provided that careful attention is given to measurements and data processing (e.g. Foken, 2008). The prime denotes the departure from the time averages. This method is usually applied to the measurements on a fixed platform, but it has also been applied with measurements on a moving platform such as a research vessel (e.g. Mitsuta and Fujitani, 1974; Pedreros *et al.*, 2003; Brut *et al.*, 2005; Kondo and Tsukamoto, 2007) or an aircraft (e.g. Desjardins *et al.*, 1992; Samuelsson and Tjernström, 1999; Strunin and Hiyama, 2004; Dobosy *et al.*, 2017) particularly over the ocean. This is attractive as fluxes can be determined along the route within a relatively short period. However, in the case of ship measurements, application has been limited to large research vessels. To our knowledge, it has never been applied over a lake's surface and on a non-research vessel

such as a pleasure boat. Since the size of the majority of lakes is small (e.g. Downing *et al.*, 2006), it is often necessary to rely on small to medium-sized non-research vessels. However, the characteristics specific to such smaller vessels may cause unknown problems in the application of the eddy correlation approach. Also, there are environmental conditions specific to lakes, such as lower wave height and lack of swell (except for a few huge lakes).

Given the uncertainty of flux measurements over a lake's surface on a small non-research vessel, it is necessary, first, to investigate the feasibility of flux measurements; i.e., whether they are worth considering at all. Once they are proved feasible, it is further necessary to identify the issues that need to be resolved to improve the accuracy of flux measurements. To deal with the second point, we will examine known causes of errors on ship measurements such as errors involved in coordinate rotation and removal of ship's motion from the raw measurements (e.g. Fujitani, 1985), flow distortion due to the ship's superstructure (e.g. Pedreros *et al.*, 2003), and the impact of superficial fluctuation measurements due to the ship's vertical motion (e.g. Mahrt *et al.*, 2005) to explore any similarity or dissimilarity between the large ship measurements over the oceans and small ship measurements over a lake. These investigations should help establish measurement technology applicable to lake surfaces. The purpose of the study should therefore be considered exploratory.

METHODS

Study area

Flux measurements were made over Lake Nishiura (also known as Lake Kasumigaura; Figure 1). The average depth of the lake is 4 m. A maximum depth of approximately 7 m occurs at the center of the lake.

Ship measurements and correction for the moving platform

A small excursion ship, the *White Iris* (a catamaran with 15 m long, 5.5 m width, 5.5 m height, and a gross tonnage of 19; see Lacusmarina (2008) for the ship plan and Ibaraki-Prefectural Tourism & Local Products Association (2020) for the ship's outer view), was the platform used for our measurements over four days in 2018. The ship has two decks with the bridge on the upper deck, which is covered by a sheet for shading that extends from the bridge top toward the stern end of the ship. The ship was operated on one to three routes on selected days for sightseeing purposes (Figure 1).

From the available measurements (Wang, 2020), we selected those on seven tracks based on weather conditions and data quality. Each track covers a distance of 20–30 km, but only the data taken along the quasi-straight portions of the track were used for further analysis. The selected tracks can be classified into three broad categories of (i) straight track, (ii) quasi-straight track with a gentle curvature, and (iii) a track that consists of two straight line portions that produce a quasi-straight angle. Also, we selected those tracks with a constant cruising speed of approximately 9.2 m/s because the time average differs from the ensemble average for the eddy correlation application on a moving platform unless the speed of the platform is a constant (Crawford *et al.*, 1993). The data on the selected straight tracks were divided into 15-min segments with some overlap. The measurements along these segments (Run 1-1 through Run 7-1; see Table SI) were subjected to the following analysis.

Continuous measurements were made using three types of instruments (turbulence, meteorology, and ship motion) installed on a mast on the upper deck (Table SII).

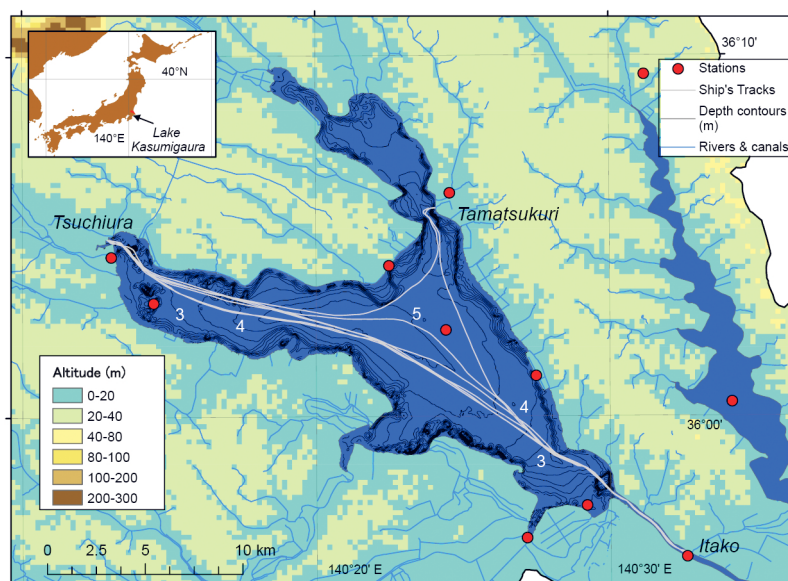The raw wind velocities $\mathbf{V_0}(u_0, v_0, w_0)$ measured by a

Figure 1. A map of Lake Kasumigaura. The ship routes, lake bathymetry, and the location of meteorological stations are indicated. Wanigawa meteorological station not shown on the map also provided data in our study (see Sugita *et al.*, 2020 for the exact location). The depth contour interval is 0.5 m

sonic anemometer-thermometer were corrected to derive the true wind velocities $\mathbf{V}(u, v, w)$ by following the method of Takahashi *et al.* (2005) given by

$$\mathbf{V} = \mathbf{T}\mathbf{V}_0 + \mathbf{V}_A \tag{5}$$

in which $\mathbf{T}$ is the coordinate transformation matrix for a rotation from the ship frame to the reference frame (Text S1, Fujitani, 1985; Anctil *et al.*, 1994; Goldstein *et al.*, 2002) with the pitch, the roll, and the yaw angles produced by an inertial measurement system (INS). $\mathbf{V}_A(u_a, v_a, w_a)$ is the translation velocity vector of the anemometer. The equation (5) is valid for measurements in which the position of the anemometer coincides with that of the INS. Otherwise, an additional term to account for the rotation of the anemometer around the INS becomes necessary (Fujitani, 1985; Pedreros *et al.*, 2003).

The derived wind speeds were further rotated to produce $\mathbf{V}_c(u_c, v_c, w_c)$ to force $\overline{v_c} = \overline{w_c} = 0$ where the overbar denotes time-averaging. Additionally, we derived $\overline{u_s}$ and $\overline{v_s}$ by horizontally rotating $\mathbf{V}_c$ with x-axis in the direction of the ship heading and y-axis perpendicular to it in the port direction over each of the 15-minute segments. Note that we did not apply the angle of attack correction (e.g. Nakai and Shimoyama, 2012) as a preliminary analysis indicated that 99.9% of the angle of attack values during the measurements were within ±20°, the manufacturer's stated operating range. This was likely because measurements were made under relatively calm conditions (see the significant wave height in table SI) over the catamaran.

Surface fluxes

Lake surface fluxes were estimated by applying the eddy correlation method given by equations (3)–(4) with w' replaced by w_c'. Also, reference surface fluxes were estimated by the bulk method (1)–(2). In the following, those fluxes from the eddy correlation method will be denoted by LE_e and H_e, and those from the bulk method by LE_b and H_b, respectively. For the application of equations (1)–(2), the C_E and C_H values under neutral conditions were first estimated by an empirical function of the neutral wind speed $\overline{U}$ at 10 m (Wei *et al.*, 2016) and then corrected for atmospheric stability by an iteration (Sugita *et al.*, 2020). The neutral $\overline{U}$ values at 10 m were determined from $\overline{u_c}$ by applying the wind profile equation (e.g. Brutsaert, 1982). The specific humidity of the lake water surface q_s was determined from surface skin temperature t_s. In equations (1)–(4), time averaging was performed over 15 minutes.

Spatial interpolation of wind velocity measurements at meteorological stations

To compare the ship-based measurements of horizontal wind velocities $\overline{u_s}$ and $\overline{v_s}$ with independent values, wind speed data measured at 12 stations in and around Lake Kasumigaura (Figure 1) were spatially interpolated to produce the corresponding values of $\overline{u_{s,i}}$ and $\overline{v_{s,i}}$. First, the height conversion of wind speed data at each station to the ship's anemometer level of 7.5 m was carried out using a neutral wind profile equation with an estimated surface roughness value at each station. Then the wind speed and wind direction were converted into wind velocity components. They were interpolated in time to estimate those at the central time of each run of our ship measurements.

Finally, they were spatially interpolated to produce wind velocity maps at a 90-m spatial resolution. The details of this procedure are explained in Sugita (2019) and Sugita *et al.* (2020). The mean values of $\overline{u_{s,i}}$ and $\overline{v_{s,i}}$ along the segment were finally determined and used for comparison. A cross-validation test (e.g. Webster and Oliver, 2007) indicated that the root mean square error of the interpolated wind velocities was 1.5 m/s.

RESULTS AND DISCUSSION

Mean wind velocities

The values of $\overline{u_s}$ and $\overline{v_s}$ are compared in Figures 2 and 3 with $\overline{u_{s,i}}$ and $\overline{v_{s,i}}$. Data points were classified by the angle γ between the direction of the ship's heading and that of the horizontal wind vector. The angle is measured from the ship heading with a positive value in the clockwise direction, and a negative value in the anticlockwise direction.

Generally, good agreements were found with the coefficient of determination $R^2 = 0.993$ (for $\overline{u_s}$) and $R^2 = 0.930$ (for $\overline{v_s}$). However, the RMS difference (RMSd) was as large as 1.4 m/s for both components. Thus RMSd for the mean wind speed is on the order of 2 m/s. These relatively large RMSd values are not necessarily the result of a general scatter of points. Rather outlier points contributed to the large RMSd. They are the points with $-180° \leq \gamma < -135°$ and $135° \leq \gamma < 180°$ in the case of $\overline{u_s}$ and the points with $-45° \leq \gamma < -135°$ in the case of $\overline{v_s}$. They are respectively the case of bow-on flow and port-on flow, and they appear to be the condition where errors tend to be larger (see below, the *flow distortion errors* section). Also, the probable
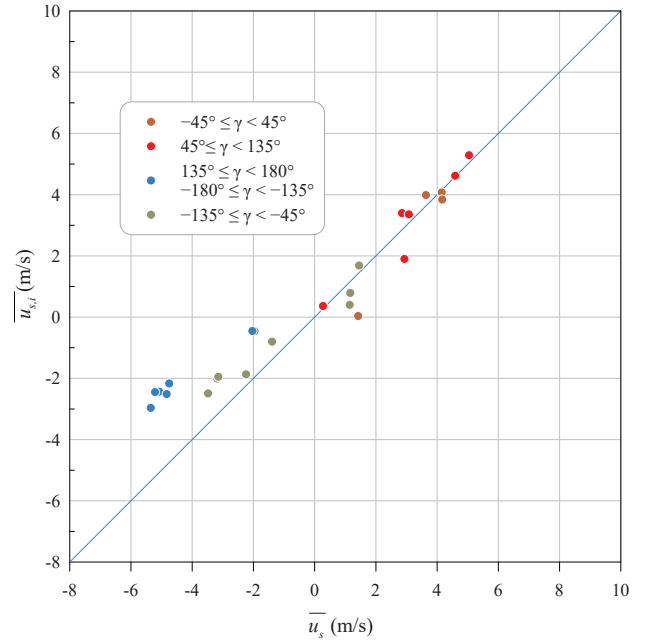

Figure 2. A comparison of wind velocity $\overline{u_s}$ in the direction of the ship's heading determined from ship-based measurements and those $\overline{u_{s,i}}$ determined by the spatial interpolation of meteorological stations' measurements. Locations of the meteorological stations are shown in Figure 1
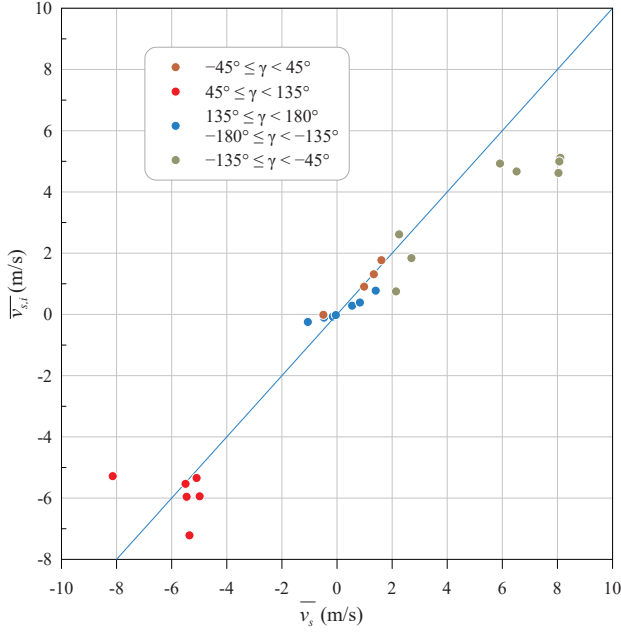
Figure 3. Same as Figure 2 but for $\overline{v_s}$ in the port direction perpendicular to $\overline{u_s}$. Data points are classified by the angle γ between the ship's heading and the direction of wind speed $\overline{U}$

Figure 4. A comparison between latent heat fluxes obtained by the bulk method LE_b and those by the eddy correlation method LE_e

error of the interpolated wind velocities ($\cong$1.5 m/s) should have contributed to the RMSd values. Thus, to minimize errors in the references and concentrate on the errors due to ship measurements, an experimental design that allows comparison of $\overline{u_s}$ and $\overline{v_s}$ with those measured on a fixed platform co-located near the ship is desirable.

We also classified the data points in terms of track shape. However, there is no clear difference in the agreements among the track shape. Thus, the requirement for a straight track appears not to be a highly rigid one in terms of accurate wind measurements.

Water surface fluxes

Figures 4 and 5 show the comparison between LE_b and LE_e, and H_b and H_e, respectively. A good correlation was obtained with $R^2 = 0.780$ for LE and 0.794 for H and RMSd = 49 W/m^2 for LE and =24 W/m^2 for H. The slope of a regression line through the origin was 1.1 for H and 1.2 for LE. Although these statistics are not necessarily satisfactory for certain purposes of estimating surface fluxes, they are similar to those reported in previous studies obtained on research vessels (e.g. Fujitani, 1981; Tsukamoto *et al.*, 1990, 1995; Takahashi *et al.*, 2005; Brut *et al.*, 2005). Therefore, it appears that flux measurements over a small non-research vessel are not particularly inferior. However, improvement of flux estimation accuracy is highly desirable to meet the requirements of various scientific needs. This can be done by minimizing errors and thus it is first necessary to identify error sources. Note also that a comparison was made with LE_b and LE_e in our study. However, the bulk method is not necessarily more accurate than the eddy correlation method. Therefore it is desirable in future experiments to obtain reference fluxes from the eddy corre-
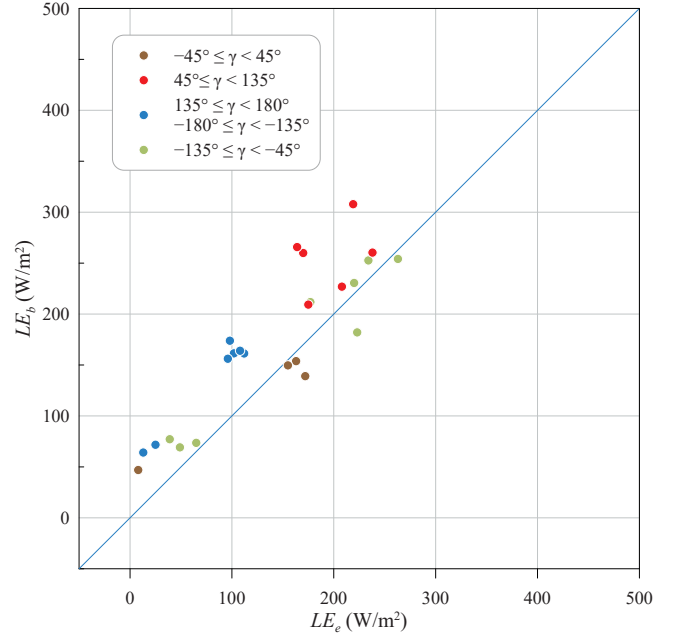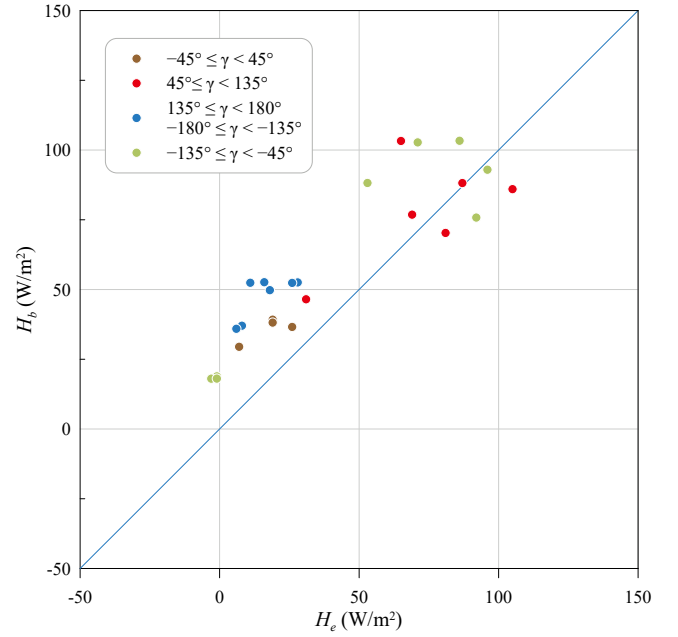

Figure 5. Same as Figure 4 but for sensible heat fluxes H

lation method based on measurements on a fixed platform near the ship just like the case for the wind velocity comparison.

In the eddy correlation method, the quality of turbulence data should influence the flux values. Thus, first, spectra and cospectra of the turbulence data of each run were created (Wang, 2020) and visually examined. It was found that they follow the well-known -5/3 power law for the inertial subrange (e.g. Kaimal and Finnigan, 1994) and no unusual

behavior was identified. Therefore it is safe to conclude that small ship-based measurements could produce reasonably good quality data for the eddy correlation method. Second, the points in Figures 4–5 were classified according to the test score of the steady-state test (e.g. Lee *et al.*, 2004), but there was no clear relation between the agreements and test scores. However, in recent studies (e.g. Finkelstein and Sims, 2001; Richardson *et al.*, 2006), methods to quantify the sampling errors have been proposed. It is desirable to apply such methods to the ship-based measurements to make more formal error assessments. This can be made using the side-by-side measurements mentioned above.

The angle γ appears to have played a role in the flux agreement. Those points for $-180° \leq \gamma < -135°$ and $135° \leq \gamma < 180°$ are consistently located toward the left of the 1:1 line both for *LE* and *H*. This is the bow-on flow condition, and the overestimation of $|\overline{u_s}|$ and $|\overline{v_s}|$ found above is a likely cause of larger LE_b and H_b. Points with $LE_b > LE_e$ are noticed for $45° \leq \gamma < 135°$. This is not the case for *H*. Therefore, this is not likely a flow-related issue.

Flow distortion errors due to ship's superstructure

As shown above, $|\overline{u_s}|$ and $|\overline{v_s}|$ values from the ship tend to be overestimated for certain wind directions. One likely source of error is the flow distortion due to the ship's hull and superstructure (e.g. Griessbaum *et al.*, 2010). For research vessels, this issue has been studied in detail. For non-research vessels, such information is generally not available. However, Moat *et al.* (2005; 2006) studied flow distortion over three generic types of vessels using a computational fluid dynamics (CFD) model. In their study, what was important was not the actual vessel size, but the ratios between various dimensions of the vessel. Therefore, application of their results to the *White Iris* could produce meaningful results even though the shape similarity with their generic vessels is not very strong.

For the *White Iris*, the ratio between *h* (water surface to the bridge top height) and *Z* (anemometer height above the bridge) is approximately 0.6. The ratio between the distance *X* from the upwind edge of the bridge top to the mast and *h* is 0.4 for port-on flow, 0 for starboard-on flow, 0.7 for bow-on flow, and 1.4 for stern-on flow. In the case of stern-on flow, we assumed the deck top extends toward the stern. Tables 1 and 2 of Moat *et al.* (2006) indicate the wind speed bias as a percentage of free-stream wind speed. It is +10% (actual error of 0.2–0.9 m/s) for the bow-on flow, +8% for port-on flow (0.1–0.7 m/s), and +4% (0.06–0.4 m/s) for starboard-on flow for the *Z/h* and *X/h* ratios of the *White Iris*. The larger positive biases for the bow-on and the port-on flow agree with our findings in Figures 2–3 for the case of $-45° \leq \gamma < -135°$ and for $-180° \leq \gamma < -135°$ and $135° \leq \gamma < 180°$. However, the magnitude of the estimated errors due to flow distortion is generally smaller than that of RMSd in Figures 2–3. This is likely because the error comes not only from the flow distortion but also from other sources (see below). It is also possible that the results for a generic vessel shape are not fully applicable to the case of *White Iris*. In particular, the short distance between the bow and the bridge might have affected the measurements. The ship hull at the bow causes the airflow to be deflected in the horizontal plane, and the area of this influ-

ence could have reached the turbulence sensors.

Although there is uncertainty in the exact error magnitude, an argument can be made to operate a small vessel under the beam-on flow condition that generally produces a shorter *X* in comparison to the bow-on or stern-on flow condition. Also, it is worth considering the use of a ship with a small hull height and small superstructure.

The flow distortion due to the ship's body could also influence the turbulence. However, not much is known on this because of the technical difficulty in the application of CFD models (e.g. Pedreros *et al.*, 2003). This is one of the areas where further studies are needed.

Errors due to the ship's motion

As explained above, ship motions need to be removed from the raw measurements of $\mathbf{V_0}$ by applying equation (5). Fujitani (1985) estimated the magnitude of the maximum error in this operation to be 6% of *u* and *v*, and 14% of *w*. Blomquist *et al.* (2010) determined the maximum estimation error to be 18% of the measured flux due to coordinate rotation and superficial fluctuation caused by the vertical motion of a ship (Mahrt *et al.*, 2005; Blomquist *et al.*, 2010; see below). This type of error could be lowered with the advent of more accurate INS.

When the ship moves up and down over the water surface, the instrument senses concentration and wind speeds fluctuation even if there was no actual fluctuation in the atmosphere. This is because a vertical gradient exists in the surface layer. Therefore the measured fluctuation under this condition is apparent and results in flux estimation error. This error should be larger when measurements are made near the surface where the gradient is larger. Mahrt *et al.* (2005) assessed this type of errors for concentrations for an aircraft measurement at height $z = 15$ m, and for the measurements on a buoy ($z = 6$ m) and concluded that the magnitude of this type of error is generally smaller than the usual random flux error for the aircraft measurement and it becomes significant for the buoy measurements only under large wave heights. Since wave heights in a lake are generally not very large (see also Table SI), this error might be insignificant. Also, the spectra and cospectra analysis mentioned above did not reveal any unusual peaks associated with the ship's vertical motion. This is another line of evidence showing a lack of influence due to the ship's vertical motion. Still, it is desirable to make measurements of height variation to verify the lack of displacement error under various conditions.

CONCLUDING REMARKS

To explore the feasibility of direct flux measurements over a lake using a small non-research vessel as a platform, exploratory flux measurements were carried out in Lake Kasumigaura. Fluxes were obtained by the eddy correlation method with similar accuracy as that reported in the past on research vessels over the ocean, indicating the feasibility of the method over lake surfaces. We identified possible error sources in the measurements which we found essentially the same as those reported from previous studies over the ocean. These error sources should be quantitatively investigated further in future experiments under various condi-

tions to find the optimum measurement strategy. Overall, we conclude that small ship measurements over a lake can probably be treated similarly to measurements on a large research vessel over the ocean.

ACKNOWLEDGMENTS

SUPPLEMENTS

Text S1. Coordinate transformation matrix **T** in equation (5)
Table SI. The general condition of measurements
Table SII. List of ship-based measurements

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