

Uncertainties in wind speed dependent CO₂ transfer velocities due to airflow distortion at anemometer sites on ships

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Abstract. Data from platforms, research vessels and merchant ships are used to estimate ocean CO₂ uptake via parameterisations of the gas transfer velocity (k) and measurements of the difference between the partial pressures of CO₂ in the ocean ($p\text{CO}_2^{\text{sw}}$) and atmosphere ($p\text{CO}_2^{\text{atm}}$) and of wind speed. Gas transfer velocities estimated using wind speed dependent parameterisations may be in error due to air flow distortion by the ship's hull and superstructure introducing biases into the measured wind speed. The effect of airflow distortion on estimates of the transfer velocity was examined by modelling the airflow around the three-dimensional geometries of the research vessels *Hakuho Maru* and *Mirai*, using the Large Eddy Simulation code GERRIS. For airflows within $\pm 45^\circ$ of the bow the maximum bias was +16%. For wind speed of 10 m s^{-1} to 15 m s^{-1} , a +16% bias in wind speed would cause an overestimate in the calculated value of k of 30% to 50%, depending on which k parameterisation is used. This is due to the propagation of errors when using quadratic or cubic parameterisations. Recommendations for suitable anemometer locations on research vessels are given. The errors in transfer velocity may be much larger for typical merchant ships, as the anemometers are generally not as well-exposed as those on research vessels.

Flow distortion may also introduce biases in the wind speed dependent k parameterisations themselves, since these are obtained by relating measurements of the CO₂ flux to measurements of the wind speed and the CO₂ concentration difference. To investigate this, flow distortion effects

were estimated for three different platforms from which wind speed dependent parameterisations are published. The estimates ranged from –4% to +14% and showed that flow distortion may have a significant impact on wind speed dependent parameterisations. However, the wind biases are not large enough to explain the differences at high wind speeds in parameterisations which are based on eddy covariance and deliberate tracer methods.

1 Introduction

The gas transfer velocity k can be estimated from measurements of the air-sea CO₂ flux F and differences between the partial pressures of CO₂ in the ocean $p\text{CO}_2^{\text{sw}}$ and atmosphere $p\text{CO}_2^{\text{atm}}$ ($\Delta p\text{CO}_2$);

$$k = F / (p\text{CO}_2^{\text{sw}} - p\text{CO}_2^{\text{atm}}) \quad (1)$$

Previous studies have shown that k varies with wind speed but the relationship between k and wind speed differs from one study to another (Wanninkhof et al., 1985; Liss and Merlivat, 1986; Wanninkhof, 1992; Wanninkhof and McGillis, 1999; Nightingale et al., 2000; McGillis et al., 2001a, b; Jacobs et al., 2002; Wanninkhof et al., 2004; Ho et al., 2006; Weiss et al., 2007). The parameterisation of k is subject to numerous uncertainties caused by e.g. measurement errors, surfactants and sea-state. These wind speed dependent parameterisations of k are used to obtain the air-sea flux of CO₂ when measurements of the flux themselves are not available. For example, climatologies of wind speeds and $\Delta p\text{CO}_2$ are used to estimate the exchange of CO₂ over the



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global ocean. The delta $p\text{CO}_2$ climatologies are derived from in-situ measurements made from e.g. platforms, research ships and voluntary observing ships (VOS, e.g. Padin et al., 2007). A number of countries are involved in equipping ships with underway CO₂ systems, and given the lack of in-situ data it is hoped that these efforts will be continued, and expanded upon. A global map of all observation obtained between 1968 and 2008 is available from the Carbon Dioxide Information Analysis Center (CDIAC, 2010).

Estimates of the oceanic CO₂ uptake can differ by 30 to 50% when using different parameterisations of gas exchange as a function of wind speed assuming the same wind field (Wanninkhof et al., 2001; Takahashi et al., 2002). These differences are commonly attributed to physical causes such as the effects of surfactants or the sea-state. However, Asher (2009) recently showed that around half of the observed scatter in k -models, when utilizing the dual tracer method, may be due to measurement uncertainties of the gas concentration and the mixed-layer depth. The uncertainty in k parameterisation may also be method based. For example deliberate tracer experiment and eddy covariance measurement employed in parallel yielded differences in transfer velocity of a factor of 2.5 on average (Jacobs et al., 2002). Recently, Griessbaum and Schmidt (2009) introduced a tilt correction method for flow distortion effects on eddy covariance measurements in complex environments. The correction was applied to eddy covariance measurements from a land based massive radio tower and errors in CO₂ fluxes of up to 15% were determined. This was the same magnitude as the WPL correction for density fluctuations (Webb et al., 1980). The flow distortion effect on shipboard eddy covariance measurements due to the large body of the ship may be higher.

In addition to possible uncertainties in the parameterisations of k , mean wind speed measurements obtained from ships are subject to biases caused by airflow distortion over the platform: this varies with the relative wind direction (i.e. the angle of the ship to the wind direction).

Problems in wind speed were discussed in various studies concerning transfer velocity experiments and application of the derived wind speed parameterisations. Discussed issues are wind speed distribution effects on CO₂ flux calculation (e.g. Wanninkhof, 1992), the standard correction of wind speed to 10 m measurement height asl (e.g. Nightingale et al., 2000; Ho et al., 2006), wind sector control to exclude heavily disturbed wind directions (e.g. Wanninkhof and McGillis, 1999; McGillis et al., 2001a; Jacobs et al., 2002; Weiss et al., 2007), and the correction of flow distortion by a simple numerical model of nearby instruments (e.g. Jacobs et al., 2002). Other studies do solely mention the effect of flow distortion (e.g. Ho et al., 2006) or refer to an earlier flow distortion intercomparison of a bulky and a non-bulky platform to estimate the flow distortion effect on flux measurements (Edson et al., 1998; McGillis et al., 2001a). Some studies also intercompare ship based mea-

surements – not corrected for flow distortion – with satellite based measurements to try to improve data quality (e.g. Wanninkhof, 2004; Ho et al., 2006). However, scatterometer products usually employ in-situ wind measurements from e.g. buoys as ground truth. It might be hoped that this would lead to scatterometer winds being unbiased but in practice there are also problems when winds from different remote-sensing platforms are compared to each other, with significant global mean biases (order 1 m s^{-1} , e.g. Schlax et al., 2001) observed and larger or smaller biases seen depending on time and location.

There are also issues with wind speed climatologies which may affect the calculation of the transfer velocity from published parameterisations. For example, an apparent increasing trend in global marine wind speeds obtained from Voluntary Observing Ships from the late 1950's to the late 1980's can be largely explained by differences in reporting methods (i.e. wind speeds measured using anemometers rather than using a visual observation of the sea state) and the increasing heights of anemometers above sea level due to increasing ship size (Cardone et al., 1990; Thomas et al., 2008). The spatiotemporal variability of marine wind speed also impacts the estimation of k and the global CO₂ exchange (Wanninkhof et al., 2002, 2004; Olsen et al., 2005). This paper focuses on the effects of flow distortion, both on the determination of k from direct flux measurements, and conversely on the estimation of the flux from published parameterisations of k .

Correcting for air flow distortion requires complex quantification of the mean wind speed biases with changes in the relative wind direction. This is obtained by modelling the airflow over three-dimensional ship models using computational fluid dynamics (CFD) (Yelland et al., 1998, 2002; Dupuis et al., 2003; Weill et al., 2003; Popinet et al., 2004; Moat et al., 2006a, b), see Moat et al. (2005) for an overview of CFD modelling of the airflow over ships.

Besides research vessels, several thousand voluntary observing ships (VOS) are used to obtain wind measurements, mostly with anemometers located above the bridge. It was found that for various types of merchant ships (e.g. tankers, bulk carriers and containers ships), characteristic dimensions (e.g. height of bridge top) scale linearly with the ship's length (Moat et al., 2005; Kent et al., 2007). Generic representations of different vessel types were created and the airflow was studied using CFD. Large biases in wind speed of 10% acceleration to decelerations of 100% are possible (Moat et al., 2006a).

While it is possible to generate generic representations of some merchant ship types, research vessels vary a great deal in shape and size and are difficult to model generically. This is especially true for the different superstructure shapes and the location of the anemometer relative to the superstructure (Yelland et al., 2002). The second challenge for parameterisations of wind speed biases is the effect of individual obstacles close to the anemometer location (e.g., mounting

support, device boxes, etc.). The airflow over each research vessel should be modelled individually to obtain the most accurate wind measurements.

If we are to achieve accurate wind speed measurements from ships, new ship designs must have minimum airflow distortion and CFD modelling should be an integral part of the ship design process, i.e. as in the RRS *James Cook* (Moat and Yelland, 2008).

This study presents the wind speed biases due to effects of air flow distortion around the two differently sized oceanographic research vessels *Hakuho Maru* and *Mirai* of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Section 3.1 describes and compares the biases in mean wind speed due to flow distortion at the foremast, funnel mast and bow boom anemometer locations. Section 3.2 describes the possible impact of flow distortion on previously published wind speed dependent parameterisations of k . Section 3.3 describes the error propagation when estimating k from published parameterisation using biased wind speed data.

2 Method

In this study, the open source Large Eddy Simulation (LES) (GNU General Public License, GPL) code GERRIS (Popinet, 2008) was used to simulate the mean air flow around the research vessels *Hakuho Maru* (HK) and *Mirai* (MR). The code solves the three-dimensional, time-dependent Euler equations for an incompressible and inviscid fluid of constant density. The adaptive mesh projection method is based on octree discretisation, and a multilevel Poisson solver is used to obtain the pressure. Complex solid boundaries are represented using a Cartesian cut-cell approach. The temporal discretisation was based on a classical fractional-step projection method (Chorin, 1968; Peyret and Taylor, 1983; Brown et al., 2001). In this study, the described numerical model does not include an explicit turbulence model for turbulence scales smaller than the mesh size. Several authors (Boris et al., 1992; Porter et al., 1994) showed that the numerical dissipation due to higher order errors associated with the discrete representation of the solution describe turbulent subgrid energy transfer as well, or sometimes even better, than more complex LES models. GERRIS is described in detail by Popinet (2003) and was validated by comparison of model results to in situ wind measurements around a research vessel (Popinet et al., 2004). The comparison of model results with experimental data showed very good agreement in mean flow, standard deviation and turbulent spectra, even in areas with strong turbulence.

Previous CFD modelling has shown that the wind speed error is much more sensitive to the relative wind direction than to the wind speed itself. The effect of wind speed on the wind speed error is negligible (Yelland et al., 2002; Dupuis et al., 2003; Popinet et al., 2004). Similar results were found

for CFD modelling of a land based meteorological tower at two different wind speeds (Perrin et al., 2007). Therefore, a constant uniform inflow velocity profile at the upstream inlet was specified for the simulation, as in (Dupuis et al., 2003) and (Popinet et al., 2004). A simple outflow condition was specified at the downstream outlet, and slip conditions were specified for all other surfaces.

Three-dimensional digital models of the research vessels (Fig. 1) were created from two-dimensional drawings using the commercially available CAD (computer aided design) package Rhinoceros (McNeel, 2006). Each model was scaled down by 3 times the ship length to fit in a standard Gerris domain. The whole simulation domain was built up using two layers of interconnected standard Gerris domains, each layer consisted of 12 domains (4 long, 3 wide). The overall size of the computational domain was 12 (length), 9 (width) and 6 (height) times the ship's length.

This corresponded to 1.2 km/0.9 km/0.6 km (HK) and 1.5 km/1.2 km/0.8 km (MR), respectively. The vessels were placed 8.25 ship lengths downstream of the inlet. The cell sizes varied throughout the domain. The mesh dynamically adapts to follow the evolving flow structure. It produced finer meshes in areas of high vorticity and coarser meshes at large distances from the ships, where the flow does not vary very much. The mesh size close to the ships also varied depending on the complexity of the geometry. The mesh sizes in the regions where the anemometers were located varied from 0.07 m to 1.2 m (HK) and 0.1 m to 1.5 m (MR). The digital models of the vessels were rotated in the simulation domain by increments of 15° from 0° to 345°. This produced individual results for 24 different relative wind directions. The wind speed bias of airflow at the top and side boundaries of the simulation domain was less than 1% of the inflow wind speed profile. This indicates that the blockage of the tunnel by the ship geometry was not significant. The number of grid points used to resolve the fully developed turbulence regime were about 220 000 (HK) and 490 000 (MR), respectively. The three-dimensional wind vectors (u : inflow, v : lateral, w : vertical) were recorded at a number of monitoring points which corresponded to the positions of the ship's anemometers and other potential anemometer locations.

The initial condition of the simulation was a potential flow solution. With time, a laminar regime developed upstream and a turbulent regime developed downstream of the vessel's digital geometries. Each simulation ran for 7 non-dimensional time steps $t^*=tU/L$, where t is the time, U is the inflow velocity and L is the domain length. A fully developed turbulence regime evolved at $t^*=3$. Hence, the time window $t^* \in [3, 7]$ was used later for the calculation of mean values of 3-D wind speed. Normalised wind speeds, i.e. distorted wind speed expressed as a fraction of the undisturbed speed, were obtained using the averaged time window. All simulations were run simultaneously using 48 processors (HK: 64 bit Opteron 246, 2GHz; MR: 64 bit Opteron 848 2.2 GHz) on Linux-clusters in three (HK) to five (MR) weeks.

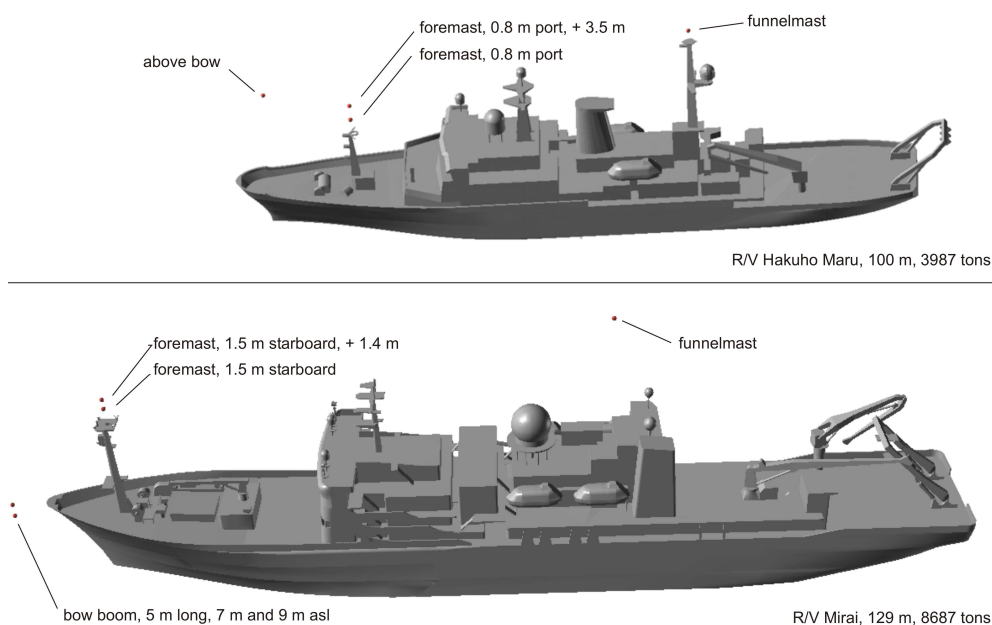


Fig. 1. Digital geometries of R/V Hakuho Maru [top] and R/V Mirai [bottom], spheres indicating various anemometer locations.

3 Results and discussion

3.1 Mean wind speed bias calculation using LES

The values of the mean normalised wind speed, u , were calculated for each relative wind direction at various anemometer locations. The results are displayed in Fig. 2 and Fig. 3. Both ships had anemometers located on a foremast in the bows of the ship, and on a funnel mast above the superstructure. These two locations are discussed in turn, with other possible locations discussed last.

3.1.1 Biases at the foremast anemometer sites

The anemometers on both vessels are located at the top of the foremast, close to the ship's centreline, HK 0.8 m to port, and MR 1.5 m to starboard. This results in an asymmetric bias caused by the different distances from anemometer locations to the ship's side. For instance, in case of MR, the biases during port-wind conditions are higher than those during starboard-side conditions, because the anemometer was located starboard of the ship's centreline. In addition, the pedestal at the foremast top, right below the anemometer location, creates additional flow distortion to the one caused by the vessels hull and superstructure. This local obstacle increased the bias in wind speed to the same extent as the vessel's hull.

For a wind sector quality criterion of $\pm 90^\circ$ of bow-on, the biases of the foremast anemometers are for -3.5% to 16% for HK and 2.7% to 16% for MR. In contrast, the biases are typically large and negative during aft-wind conditions (HK: -49% , MR: -13%). The standard deviation of the nor-

malised wind speeds derived from the time window of each relative wind direction simulation is displayed as error bar in Fig. 2 and Fig. 3. High standard deviations (up to $\pm 19\%$ for HK) are found if the superstructure is upstream of the anemometer location (i.e. the wind direction is within $\pm 45^\circ$ of the stern).

The variability of the biases with relative wind direction at the R/V *Hakuho Maru* foremast anemometer locations are higher compared to R/V *Mirai*. That can be mainly explained by the ratios of anemometer height AH and bridge top height BH to their distances to the bow (see Fig. 4). The ratio of BH to the distance of the bridge top from the bow BA+AB are for both vessels similar, 0.25 (MR) and 0.26 (HK). However, significant differences exist in the ratio of the height of the anemometer above deck AH to the distance of the anemometer from the bow BA, which is 1.6 (MR) and 0.64 (HK) respectively. A big difference was also observed in the ratio of the distance of the anemometer to the bridge AB and the anemometer to bow BA, of 3.8 (MR) and 1.8 (HK). The R/V *Mirai* has a slightly higher ratio of anemometer height AH to bridge top height BH (1.6) as compared to HK (1.4). The foremast on HK was closer to the bridge than to the bow, while the anemometer at the foremast top is only slightly higher than the bridge top. This indicates a larger and more variable wind speed bias for the foremast anemometer on the R/V *Hakuho Maru* in comparison to R/V *Mirai*.

The magnitude and the standard deviation of the bias would be reduced by mounting the anemometers at higher positions above the foremast platform. In order to show this effect, the ships anemometers were, in the simulation, lifted up by 3.5 m (HK) and 1.4 m (MR). In both cases the wind

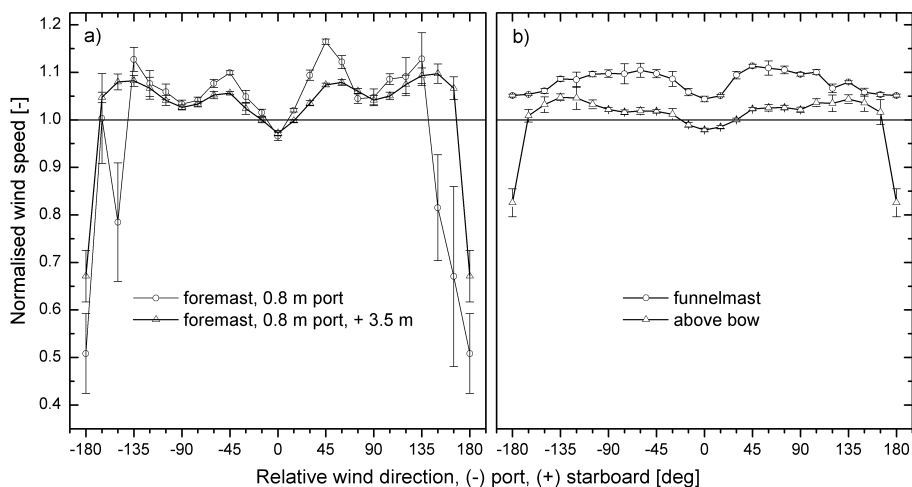


Fig. 2. R/V *Hakuho Maru*: normalised wind speed (as fraction of the undisturbed speed) against relative wind direction at various anemometer locations (see Fig. 1, top panel): [1] foremast (17 m a.s.l.), [2] foremast +3.5 m (20.5 m a.s.l.), [3] funnelmast (30.5 m a.s.l.), and [4] above bow (23 m a.s.l.). Error bars indicate standard deviation. A bow-on wind is represented by a relative wind direction of 0°.

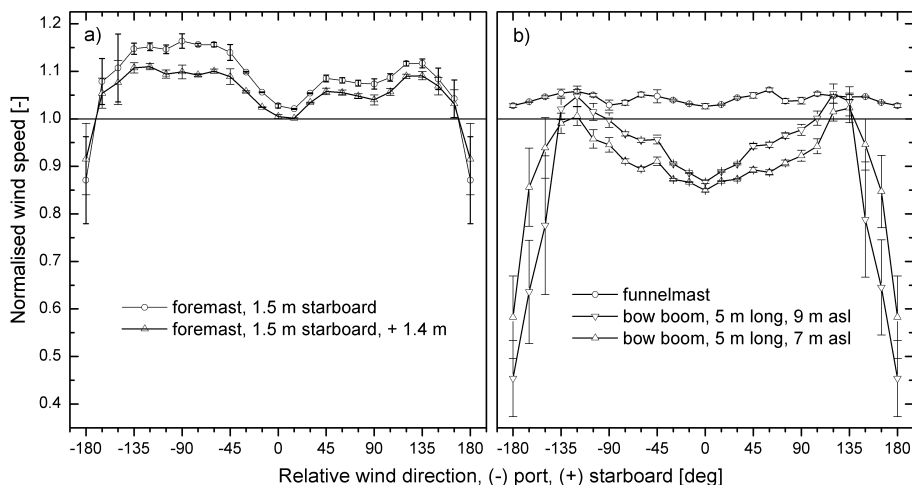


Fig. 3. R/V *Mirai*: normalised wind speed (as fraction of the undisturbed speed) against relative wind direction at various anemometer locations (see Fig. 1, bottom panel): [1] foremast (23.5 m a.s.l.), [2] foremast +1.4 m (24.9 m a.s.l.), [3], funnel-mast (35.6 m a.s.l.), [4] bow boom (7 m and 9 m a.s.l.). Error bars indicate standard deviation. A bow-on wind is represented by a relative wind direction of 0°.

speed bias, the standard deviation and its variability depending on the relative wind direction was reduced (see Fig. 2 and Fig. 3). The bias was reduced by a larger amount at relative wind directions with already pronounced biases, for instance during aft-wind conditions or at port wind conditions in case of MR. In comparison to MR, the steep increase in the wind speed bias for anemometers on the HK for on-bow flows ($\pm 45^\circ$ off the bow) was caused by the bridge being located closer to the foremast. Increasing the height of the HK foremast anemometer location by 3.5 m shows a less steep increase, since the anemometer is now higher relative to the bridge top.

3.1.2 Biases at the funnel mast anemometer sites

More symmetric and steady biases with lower standard deviations were found for anemometer locations on the funnel masts (see Fig. 1 for location and Fig. 2 and Fig. 3 for biases). At such elevations, the bias due to the asymmetrical ship's superstructure with respect to the relative wind direction was lower. The funnel mast anemometers on both ships do not suffer from shadowing of the superstructure during airflows over the aft deck. However, the maximum bias in mean wind speed for the R/V *Hakuho Maru* is still 10%, while the maximum bias at R/V *Mirai* is 5%. It should be noted that the funnel mast of R/V *Mirai* (a triangular lattice

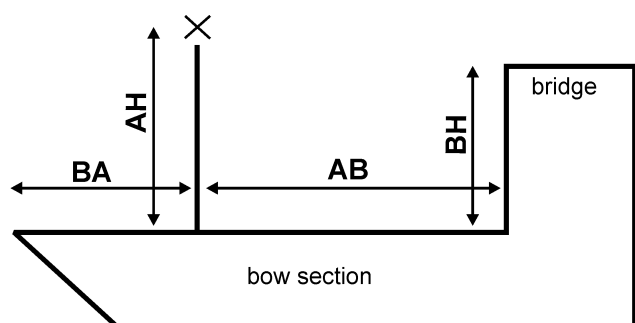


Fig. 4. Illustration is showing the distances of bow tip to anemometer location (BA), anemometer to bridge (AB), anemometer height above deck (AH) and bridge height above deck (BH). The cross above the foremast indicates the anemometer location.

tower, vertical pole diameter: 0.15 m, 0.4 m apart at the top) was not included in the model due to its geometric complexity. The anemometer was well-exposed and located 1.6 m above a small pedestal (0.6 m × 0.7 m), at the top of the mast. Perrin et al. (2007) found in a CFD-simulation study on a cylindrical meteorological mast, that an error of less than 1% is expected for an anemometer mounted at the wind ward side of the tower and five times the diameter (of the mast) above the mast. Therefore, the flow distortion effect of the lattice mast poles of the funnel mast is assumed to be negligible. The second expected flow distortion effect is caused by the small platform below the anemometer. The pedestal at the top of the foremast (MR) has a dimension of 3 m × 2.7 m, resulting in an acceleration of wind speed of up to 4%. Due to the much smaller platform below the funnel mast anemometer, the acceleration in wind speed is estimated at about 1%. Hence, the maximum wind speed bias at the funnel mast is about 6% (5% ship's body, 1% platform below anemometer), lower than that of R/V *Hakuho Maru* of up to 10%.

The funnel mast location on both ships seems to be the best location for mean wind measurements. However, this location may be inappropriate for measurements relying on undisturbed free stream turbulence, e.g. the eddy covariance method, as the airflow will be affected by the flow distortion generated by mechanical turbulence at the ships body.

3.1.3 Biases at alternative anemometer sites

In case of R/V *Hakuho Maru*, an anemometer location higher or closer to the bow would reduce the wind speed bias significantly. In following, we assume a hypothetical foremast location, 5 m from the bow (at ship's centreline), and the hypothetical foremast anemometer location 6 m higher (at 23 m a.s.l.) as at the current foremast anemometer. The bias obtained from this potential anemometer location above the bow (see Fig. 1, top panel) results in much lower biases and variability (see Fig. 2). The improved anemometer position is also reflected in the higher ratios of height of anemometer

AH to distance to bow BA (3.5), anemometer height AH to bridge height BH (2.2) and the ratio of bridge BA+AB and anemometer BA distance to the bow (6.2).

While anemometers are commonly mounted on masts, occasionally temporary booms are employed in front of the bow for profile measurements. The wind speed biases for boom anemometer locations, on a 5 m long boom at 7 m and 9 m above sea level were obtained (see Fig. 1, bottom panel). While the anemometer locations on the foremasts are mostly showing wind speed acceleration during on-bow wind directions (± 90 degrees, and more), the wind speed at the boom locations are decelerated by up to 14%. This result is similar to the CFD simulation determined bias of 13% deceleration (Yelland et al., 2002) at a boom setting at R/V *Polarstern* (vessel length: 110 m, bow height: 9.4 m above sea level (a.s.l.), boom length: 11 m, anemometer: 8 m a.s.l.), which has similar dimensions to R/V *Mirai* (vessel length: 129 m, bow height: 9 m a.s.l., boom length: 5 m). The boom anemometer locations exhibit the highest flow distortion impact when compared to the well exposed anemometers at the foremast or the funnel masts.

3.2 Possible biases in published wind speed dependent parameterisations

The bias in wind speed due to flow distortion impacts the calculation of k from direct measurements of the CO₂ flux, since the transfer velocity is strongly related to the mean horizontal wind speed. Some of the previously published parameterisation are given in Table 1 and shown in Fig. 5 (Liss and Merlivat, 1986; Nightingale et al., 2000; McGillis et al., 2001b; Weiss et al., 2007).

In the smooth surface regime at low wind speeds up to $\sim 5 \text{ m s}^{-1}$, the formulations show a similar behaviour (Fig. 5). The difference between the relationships gets larger with increasing wind speeds and result in high difference in k at wind speeds $> 10 \text{ m s}^{-1}$ in the breaking wave (bubble) regime. It should be noted that there are very few measurements of the CO₂ flux at high wind speeds and that many k parameterisations are extrapolated from the lower wind speed data. The extrapolated portions are indicated by the dotted lines in Fig. 5.

To demonstrate the maximum potential wind speed bias effect at high wind speeds, the formulations in Table 1 were compared against the formulation of LM86. For wind speeds over 8 m s^{-1} this formulation was based on the adaption of wind-wave tank experiments (Broecker et al., 1978; Broecker and Siems, 1984). For the sake of argument we assume here that the wind speeds used in the formulation of LM86 were completely unaffected by flow distortion, and then estimate the wind speed bias required to bring the other formulations into agreement with LM86. To obtain agreement wind speeds of 15 m s^{-1} , biases of about -17% for N00, -36% for MG01 and -55% for W07 are required to make all the curves overlie. To the other extreme, assuming

Table 1. Selected gas transfer velocity formulations. W07 is the Weiss et al. (2007), MG01 McGillis et al. (2001b), N00 the Nightingale et al. (2000) and LM86 the Liss and Merlivat (1986) model. The best guess wind speed bias of each platform is estimated based on the platform type, compared to already modeled platforms, and individual applied wind speed quality control, i.e. wind direction limitation. Note that the Schmidt numbers used in these studies varies between 600 and 660.

| Equation | Source | Best guess wind speed bias range | Anemometer site | Method | Measured field wind speed range |
|---|--------|----------------------------------|---|--|---------------------------------|
| $k_{660}=3.3+0.026\cdot U^3$ | MG01 | −4%* to 14% | R/V <i>Ronald H. Brown</i> , scaffold above bow, 17.9 m a.s.l., ±90° off bow | Eddy covariance | < 16 m s ^{−1} |
| $k_{660}=0.46\cdot U+0.365\cdot U^2$ | W07 | −2% to 4% | Arkona moored floating platform, 3 m boom to west, 7 m a.s.l., ex- cluded wind direction: 40°–110°, | Eddy covariance | < 18 m s ^{−1} |
| $k_{600}=0.1\cdot U+0.23\cdot U^2$ | N00 | 0% to 3% | Offshore platform Meet- posts Noordwijk (MPN). Anemometer above plat- form | Dual deliberate tracer experiment | < 15 m s ^{−1} |
| $k_{600}=0.17\cdot U$, $U\leq 3.6\text{ m s}^{-1}$ $k_{600}=2.85\cdot U-9.65$, $3.6<U\leq 13\text{ m s}^{-1}$ $k_{600}=5.9\cdot U-49.3$, $U>13\text{ m s}^{-1}$ | LM86 | n/a | lake-buoy, 1 m a.s.l., and wind-wave tank | $U\leq 8\text{ m s}^{-1}$: Deliberate tracer gas exchange ex- periment $U>8\text{ m s}^{-1}$: extrapolated, adapted after wind-wave tank experiments | < 8 m s ^{−1} |

* The deceleration of 4% is modelled for bow flow of 0° (Yelland et al., 2002).

that MG01 had no flow distortion effects, the other formulations would have been overestimating the measured wind speeds by 1% for W07, 23% for N00 and 37% for LM86, when collapsing to the MG01 curve. The large hypothetical biases required to bring all the relationships into agreement are possible for cases of severe flow distortion (e.g. winds from astern), but are unrealistically high for the wind data set which were quality controlled, i.e. limited to more reasonable wind directions such as ±90° of bow-on.

To obtain more realistic estimates of the possible biases in the k formulations, we estimated a mean wind speed bias for each platform used in the previous studies (Table 1). If no CFD studies were made for a particular platform or wind direction, then a best guess error in mean wind speed is determined by comparing the platform to previous flow distortion studies of similar platforms. In this evaluation the anemometer position relative to the platform, the relative wind direction with respect to the applied wind quality control, i.e. wind direction, and the shape and dimension of the platforms were considered. The best guess errors given here are the expected lowest and highest possible wind speed biases over a range of relative wind directions used in the formulations.

Only in case of the R/V *Ronald H. Brown*, used for the MG01 study, was the wind bias of 4% deceleration for bow-on flow (0°) determined by numerical flow distortion modelling (Yelland et al., 2002). The MG01 parameterisation was created using only flows within ±90° of the bow (McGillis et al., 2001b). The wind speed bias for research ships typically have a minimum for bow-on flows and increase for flows within ±90° of the bow (Fig. 2 and Fig. 3). The upper limit of 14% acceleration for the R/V *Roland H. Brown* for 90° flows was estimated by using the flow distortion modelled R/V *L'Atalante* (Dupuis et al., 2003), which has a similar anemometer location, bow section and ship length. The Arkona offshore platform used for the W07 study, a moored floating platform, is similar in shape to the foremast top (pedestal) of R/V *Mirai*. The wind sector was limited to 110° to 40°, excluding the wind directions with high flow distortion effects. The wind speed bias at the anemometer location on the Arkona platform was estimated by a similar modelled anemometer location in front of the pedestal mast of the R/V *Mirai*. The flow simulation was modelled with and without the pedestal, which resulted for on-bow flow in a difference of ~4% wind speed error. A

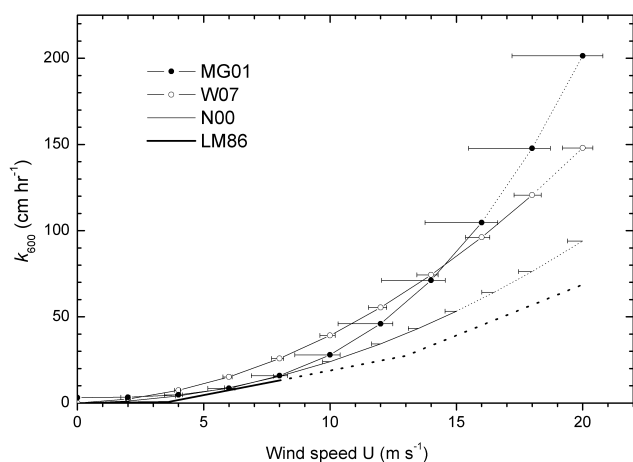


Fig. 5. Various transfer velocities (k) from selected gas transfer velocity formulations (see Table 1). Curves with circles indicate data from eddy covariance measurements; curves without circles show deliberate trace gas data. The error bars represent the change in wind speed based on best guess wind biases as given in Table 1. The solid lines indicate the range of wind speed measurements during the experiments, and the dotted lines indicate the extrapolated portions of the k -parameterisations. Note that the covariance relationships given in Table 1 have been modified here to allow for the difference in Schmidt number (resulting in a reduction in k of about 5%).

deceleration of wind speed of less than 2% for relative wind directions between 0° through 40° and 140° through 180° was estimated. The Meetposts Noordwijk (MPN) offshore platform is a bluff body that consists of two layers of containers, including a helicopter pad. The MPN anemometer was well-exposed and mounted on a slim mast, which was located 6 m in front of the platform and 10 m higher than the helideck (Starke, 2004). Due to the non-central location of the anemometer mast, the wind speed bias is sensitive to the relative wind direction. The best guess conservative wind speed bias was estimated to be $\sim 0\%$ to $+3\%$, using Moat et al. (2006b).

The assumed errors in wind speed due to flow distortion are displayed in Fig. 5. At high wind speeds, the parameterisations based on the eddy covariance approach (MG01 and W07) are in closer agreement when the possible biases are taken into account, but both are still significantly different from the deliberate trace gas based results of N00 and LM86. However, the possible measurement errors in gas concentrations and mixed-layer depth for the tracer gas experiments have not been taken into account (Asher, 2009). These additional errors could reduce the differences significantly.

In summary, the magnitude of any likely flow distortion induced wind speed bias is not high enough to entirely explain the differences between parameterisations at high wind speeds. Other factors play important roles, for example flux or $p\text{CO}_2$ measurement errors, the presence of surfactants on the ocean surface, or the sea-state.

An additional effect of flow distortion, which is not in the scope of this study, is the flow distortion induced uncertainties in eddy covariance based CO₂ flux measurements. EC-measurements from a land based tower showed errors due to flow distortion of 15% (Griessbaum and Schmidt, 2009), similar in size to the WPL-correction for density fluctuations (Webb et al., 1980).

3.3 Uncertainty when calculating k using wind speed dependent parameterisations

Published parameterisations of k , such as those discussed above, are used to obtain estimates of the CO₂ flux from wind speed and delta $p\text{CO}_2$ data obtained from a range of platforms (e.g. VOS, research vessels, offshore platforms, buoys, etc.) which themselves have very individual flow distortion patterns.

Research vessels typically have anemometers located in well-exposed locations above the ship's forecastle. The lowest biases in wind speed measurement on research vessels are generally found for on-bow flows, as shown in this and other studies. Nevertheless, in a comparison of the bow-on (0°) flows at anemometer locations above the bows of over 14 research vessels (ship lengths: 54 m to 129 m), the bias in wind speed ranged from -6% to 2.7% (Yelland et al., 2002; Dupuis et al., 2003; Popinet et al., 2004). These wind speed biases would result in biases a factor of 2 or 3 greater in the estimated transfer velocity k when employing quadratic or cubic k parameterisations respectively. For example, the maximum absolute bias for the on-bow research vessel comparison of 6% yields potential biases in k of 12% for quadratic and 18% for cubic relationships.

For research cruise measurements, a commonly used approach to improve the wind speed data quality, without having access to CFD model results, is to limit the measurement to on-bow flow sectors, e.g. within $\pm 45^\circ$ or within $\pm 90^\circ$ of bow-on. This approach avoids the highest errors from aft wind directions, but reduces the data set available from a cruise. However, even limiting relative winds for flows within $\pm 45^\circ$ of the bow, the biases in the mean wind speeds at the standard ship anemometer locations of R/V *Hakuho Maru* and R/V *Mirai* are still up to 16%. Taking error propagation into account, the resulting biases for transfer velocities estimated from parameterisation will be a factor of 2 to 3 larger than the wind speed bias, for quadratic or cubical relationships. An overestimation of wind speed measurement of 16% results in an overestimation of the transfer velocity, especially at high wind speeds. Since the wind speed bias at other platform types can be also underestimated, the effect of over- and underestimation of 16% wind speed bias is discussed here. For wind speeds of 10 to 15 m s^{-1} , the cubic relationship of MG01 ($a+bU^3$) yields the highest k bias of about -38% to 52% . The quadratic relationships of N00 and W07 ($aU+bU^2$) overestimates the transfer velocities by

about -29% to 34%. Slightly lower mean biases of $\pm 28\%$ are found for the linear relationship of LM86 ($aU-b$).

It should be noted that much larger errors in k are possible when using wind speed data obtained from VOS since the wind speed biases can lie in the range of +10% to -100% (Moat et al., 2006a).

4 Summary and conclusion

Biases in wind speeds caused by flow distortion were obtained at various anemometer locations using a three-dimensional Large Eddy Simulation (LES) approach, implemented in the open source code GERRIS. Detailed geometries of the research vessels *Hakuho Maru* and *Mirai* were modelled in order to obtain the mean biases in wind speed at anemometer locations on the foremast, the funnel mast, a hypothetical foremast anemometer location close to the bow, and at a hypothetical boom in front of the bow. For each vessel, 24 relative wind directions (in 15° steps for 0° to 345°) were simulated.

Different flow distortion patterns were found between the well-exposed foremast anemometers located on the two ships. The highest errors and variability were observed at the foremast anemometer locations on the R/V *Hakuho Maru*. This was because the foremast anemometer location on this ship was relatively closer to the bridge than to the bow, and the anemometer was only slightly higher than the bridge top. The best foremast anemometer location was found on R/V *Mirai*, although, this measurement location has the disadvantage of the pedestal obstruction below the anemometer. However, even with the unfavourable effects of the pedestal, the bias in wind speed for bow-on flows compares with 2.7% favourably with other research vessels, see Yelland (2002), and off-bow winds biases of order 10% are commonly seen (e.g. Dupuis et al., 2003; Popinet et al., 2004).

The simulated boom anemometer locations in front of the bow indicate the largest wind speed errors. This is due to the short distance from the ship's body, even at upstream flow conditions.

In order to minimize flow distortion effects the anemometer location should be as high as possible above the ship, close to the bow-tip and far from the bridge. Nearby pedestals, common on mast tops for maintenance, should be small in size and the floor plate should not be solid, i.e. a metal grate is preferable to a solid plate. The wind sensor should be mounted as high above and preferably upwind of the pedestals (on ships the predominant relative wind direction is bow-on).

Anemometers located upstream of the ship's superstructure have the advantage that they are not contaminated by the mechanical turbulence produced by the ships superstructure (except for winds from astern). This is especially important for turbulence measurements, e.g. those required for the eddy covariance method of flux measurement. Measure-

ments made in front of the bow should be avoided, due to the high flow distortion effects.

It should be noted that uncorrected mean biases in wind speed, and any resulting bias in k , are unlikely to cancel between one study and another, even if the same platform and anemometer site is used. This is because the bias varies with wind speed and with relative wind direction: the distribution of both speed and direction would have to be the same in both experiments for the mean biases to cancel.

Estimated biases in wind speed may partially explain some of the uncertainties in published parameterisations of the transfer velocities. This study shows in accordance with the study of Asher (2009) concerning measurement errors of gas concentration and mixed-layer depth, that the uncertainties in k -models are significantly driven by measurement errors besides the forcing mechanisms as e.g. surfactants or sea state.

Employing published wind speed dependent k parameterisations and biased wind speed data results in biases in the calculated transfer velocity (and CO₂ fluxes) due to error propagation, especially at high wind speeds. Bow-on (± 45) wind data from research ship may be biased by up to about 16%, leading to possible biases in k of about 30 to 50% depending on which parameterisation is used. Since wind speed data obtained from individual VOS may have larger biases than data from research ships, the possible biases in calculated transfer velocity and fluxes may also be larger.

In order to compare ship-based wind speed parameterisations with satellite-based ones it is necessary to address the airflow distortion effect in the ship data as well as any bias in wind speed obtained from satellite-based measurements.

It is recommended that the air flow over research vessels is modelled for relative wind directions of at least $\pm 90^\circ$ of the bow, in order to obtain unbiased wind measurements. In order to reduce the uncertainty in the parameterisation and application of the wind speed dependent transfer velocity parameterisations of k , the wind speed bias must be removed.

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