We thank the referees for their positive and thoughtful comments.

Our responses (italics) are inline with the referee comments below. A revised manuscript incorporating the described changes has been submitted.

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Reviewer 1.

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1. General Comments

The topic of this paper, correcting eddy covariance estimates of fluxes from spurious ship effects, is highly topical and necessary. Air-sea interaction requires far more study, and direct measurements (such as described) are essential to reduce the community dependence on derived fluxes.

I think the paper suffers from lack of rigour, edging towards the circular, although the detail of the analysis is very good. This may be my relative weakness in understanding of the topic, but I would then argue that if further clarity is needed for myself, then others may feel the same.

We appreciate the reviewer's honesty and hope that the revisions described below have improved the clarity of the paper.We do not believe the arguments presented to be in any way circular nor lacking in rigour.

The issue (I understand) is that an observed peak in the spectral signal of atmospheric turbulence may be spurious due to ship motion, rather than inherent in the flow (e.g. eddies in the air being due to air flowing over waves on the surface). Further, the observed signature is due to the motion of the instrument (bolted to the ship) rather than the moving ship generating additional variable diffluence.

The reviewer is correct in their summation of the problem in the first sentence of this paragraph. The second sentence however suggests the reviewer has misunderstood the problem – the issue is not one of the instrument moving relative to the ship (it is rigidly mounted), nor one of diffluence (divergence of nearby flow from the measured streamline), but of the measured streamline changing orientation over time in response to the changing orientation of the ship. Changes to the flow over the ship can include confluence (convergence of streamlines) as well as diffluence, though neither are necessarily present, and are certainly not necessary as causes of the distortion observed. We provide evidence suggesting that the source of the signature is time-varying flow distortion correlated with the changing ship orientation..

IF this is the overall theme of the argument (and I may be confused) then the argument may be assisted by some re-arrangement of the presentation, some editing, and attention to figures.

Some Instances

1.1 Figure 1. A schematic positioning and flow diffluence field would be most useful here, to introduce the concept (from front, side and above)The photo does not clearly indicate position of sonic back from the bow point.

A new version of Figure 1, incorporating a schematic, has been provided. The location of the sonic anemometer relative to the ship is also given in Appendix B. The problem addressed does not relate to diffluence per se, so illustrating this adds nothing useful to the discussion. Incorporating flow streamline information from the CFD modeling (described in the given reference Yelland et al., 2002) adds little. Note that the CFD model can only be run for a stationary ship, so does not allow the time-

varying flow distortion to be assessed. Figure 4 illustrates the time-varying changes in the streamline orientation (as illustrated by the measured tilt) with changing ship attitude.

1.2 Figure 2. Ogive does not offer much relevant information. Far ore useful would be equivalent spectra from the ship accelerometers.

The ogive is widely used within the turbulence community to assess the quality of turbulence measurements and provides essential information – demonstrating the impact of the distortion in the spectra on the final flux estimate. The ogive is particularly useful when assessing sample lengths for stationarity (see comment 2.1 below), since the ogive (being a cumulative representation) is smoother than the cospectrum.

The requested spectra of the ship's vertical velocity (derived from integration of the accelerometers in the motion pack collocated with the sonic anemometer) are already given in Figure 5.b. Figure 5.d gives cospectra of measured <u'w'> which is almost entirely dominated by the ship velocity since no motion corrections have been applied.

In order to present our results more clearly, addressing both this point, point 3.3 below and point 13 from Reviewer 2, we have removed panel 5d, and added a panel to Figure 2 showing the cospectra prior to applying motion correction (following Edson et al., 1998). This is a more appropriate point to demonstrate the large distortions present in 'raw' cospectra.

1.3 p 15549 line 18: "these frequencies are associated with platform motion...". This is the hypothesis? Then should not be stated.

This is not the hypothesis. The hypothesis is that "Signals in cospectra at scales associated with waves and platform motion (the "motion-scale") result from motion error (due to…) rather than being a turbulent signal induced by wind-wave interaction. We agree that this could be expressed more clearly and have rewritten the sentence for clarity.

1.4 p 15550, line 1 "Motion-scale signal can be removed..." (my italic) . Again, perhaps the issue is whether it is due to
motion and secondarily whether it should be removed.

We believe motion-scale signal is an appropriate term, as regardless of its source, the signal does occur at the frequency scale of wave-induced platform motion. Whether it should be removed is the subject of the paper. At this point in the paper we merely state that it can be removed in a straightforward manner: discussion of whether it should be removed comes later on.

1.5 p 15552: set of processes
Again, not my expertise, but I would think that a large ship such as JCR rock like a see-saw in moderate waves, with a near sationarity at the centre of buoyancy (where the gyro's used to be kept). How much difference is there between the observed change flow angle and the pitch of the ship? This information may be in Figure 4 but the presentation is unclear. Perhaps presenting the data as correlation with error of the variables against a single parameter (e.g. sensor height, z_platform), or amplitude and phase (again with error). These data would aid the unraveling of the question.

In terms of ship's pitch only, then the see saw analogy is reasonable, as demonstrated in the oscillation of the pitch variable in Figure 4. However, the flow angle depends not just on pitch, but both it and the vertical platform displacement (z) and secondarily on roll and yaw and motion in the *associated axes. Unraveling the exact way in which the different ship attitude/motions may impact air-flow at a given point on the platform is challenging, is likely platform dependent, and beyond the scope of this manuscript (which simply seeks to determine whether these motions lead to a measurement error) as we state later on page 15556, lines 7/8.*

We should also note that a fit to (correlation with) a single parameter (z platform, pitch, vertical velocity) does not provide a unique solution for the streamline angle – the same pitch or vertical displacement occurs for both positive and negative vertical velocity; the same vertical velocity occurs at both positive and negative displacements from the mean. Further, because acceleration/velocity/displacement are related via integration over time, and pitch similarly related through the rotation about the centre of mass; the choice of independent variables is – to some extent – somewhat arbitrary, as long as the pair chosen provide a unique description of the ship's position/motion over time. Our choice of vertical acceleration and velocity is made based on the best correlations observed, and is theoretically able to account for 'pumping' of the air over the deck (forced changes of local pressure) in a way that say vertical displacement and pitch could not. This point is noted in the text.

2. Specific Comments

2.1 p 15547 "Fluxes were calculated over 30 minute periods. " Was any study of varying the integration time to ensure stationarity attempted, especially under differing stability?

This is an important point for flux measurement, for which there is always a balance between capturing the full range of turbulent contribution, and minimizing the amount of data lost to non-stationarity, To ensure stationarity in our measurements, quality control criteria as described in the manuscript were applied (principally the ship maneuvering criteria, and procedures detailed by Foken and Wichura, 1996; Vickers and Mahrt, 1997 – as noted in the text) to remove non-stationary periods. The effectiveness of these criteria has been demonstrated in many previous studies, and was checked here through inspection of the low frequency limits of ogives, from which 30-minute periods were deemed a suitable flux length. With regards to stability, this paper is primarily concerned with moderate to high wind speeds (and the wave conditions that result from them). At winds above 6 m/s, all flux measurements were in unstable or near neutral conditions (here defined as $10/L < 0.2$), the norm for the open ocean. At wind below 6 m/s, less than 20% of the measurements were in stable conditions.

2.2 p 15548 "aligned with the mean stream line". Confirm that this sensible even for mean w rotation: for instance, if flow is diffluent (with a mean updraft) do the eddies also align instantly with the new wind vector?

Yes, this is sensible - this rotation into the mean streamline is standard practice in studies of air-sea turbulent exchange.

2.3 p 15548 Diffluence was estimated to increase wind flow altitude by "1.3 and 3.2 m". Comment on effect on stability (perhaps with ref to Froude number)

We cannot say anything about the effect of stability here – the lifting of the streamline over the ship is determined via a CFD modeling study for neutral stratification. See our response to point 2.1 above for general comments on stability. The primary impact of changes in stability would be to modify the vertical wind speed profile. Some tests have been conducted in the past for CFD modeled flow over commercial ships; even with an extreme change of profile from logarithmic to constant with altitude, the impact on flow distortion was small compared with the absolute distortion.

2.4 p 15549 Comment on justification for elimination of "outliers".

*Drag coefficients above 5*10-3 are, particularly for moderate to high wind speeds, well outside the accepted range of physically plausible values. For the data here, limiting the measurements to our acceptable range of relative wind directions, there were 38 measurements deemed outliers, of which just 6 were for wind speeds of 6 m/s and greater. A note on this has been added to the text.*

2.4 p 15550 Eq 2 "MSC" should be defined early on, e.g. prior to reference to Fig 2.

The motion-scale signal is first shown in Figure 2, and the description and correction of it both follow from this. To improve clarity, we have added a definition of MSC to the caption for Figure 2.

3. Technical Corrections

3.1 p15550 Eq 2 In general, should a wind velocity (m/s) be corrected with a mix of ship velocity (m/s : OK) and acceleration (not so good)? For example, dividing by w'_true gives alpha_2 dimensionless, but alpha_1 still has units.

*The velocity is <u>not</u> corrected by terms with other units. The coefficients are determined by regression, and thus alpha1 has units of s, and alpha2 is dimensionless. A more physical reasoning for these units is provided by the (equivalent) MSCf correction, where the coefficients are "*defined as the ratio of covariances of vertical wind and platform motion to variances of platform motion"*, ie. alpha1 = <w'accz'>/(std accz)^2 (units of s) and alpha2 = <w'velz'>/(std velz)^2 (dimensionless), thus the correction terms both have units of velocity.*

3.2 Figure 3. Offset each error bar group slightly in the horizontal so that over-plotting does not mask data.

We agree this figure could be clearer and have modified it accordingly.

3.3 Figure 5. Unclear why panel 4 has -ve flux. Clarify caption

The negative flux is only at the motion scale, and results from (uncorrected) platform motion. The y-axis labels on Figure 5c,d were erroneously shown as f.C, when they should have been –f.C. We have corrected the labels and altered the figure caption to clarify this (see also the response to point 13 from Reviewer 2 below). Note that the axis limits in figure 5 have be set close around the distortion in the spectra to allow the details to be seen clearly – they are greatly 'zoomed in' compared to those in figure 2. Please also see response to point 1.2.

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Reviewer 2.

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Reviewers: Sebastian Landwehr and Brian Ward

General comments: This paper addresses the motion-correlated signal which has been observed in momentum flux spectra measured on ships, even after standard motion-correction procedures have been applied to the measured wind speeds. The authors present a dataset, where the motion-correlated signal is relatively large, and accounts on average for 20% – 30% of the measured momentum flux signal. The authors provide evidence that the peak in the motion-corrected momentum flux spec- trum is not caused by wind-wave interaction, but by recirculation of the air flow at the anemometer location which is caused by the push and pull of the bulky structures nearby. Further they present a simple and efficient way of removing the bias.

We do not agree with the authors suggestion that the overestimation of momentum flux measurements from ships that was reported by (*Edson et al*., 1998) and *Pedreros et al*. (2003) should be caused by the here addressed motion-correlated flow distortion. This is more likely due to the inaccurate mean wind vector tilt estimation. We see the here presented decorrelation method, however, as a practical approach to reduce bias in direct air-sea flux measurements. We recommend to publish this results with minor revisions.

We discuss the points here regarding the source of errors in previous publications in the specific comments below.

We also note that "recirculation" of the flow is only one of the ways in which flow distortion can be manifested and is not singled out or discussed in our manuscript. On page 15552, line 25 and page 15553 line 1 we briefly mention the possibility of vertical motion of the airflow caused by the vertical motion of the platform, but recirculation of the airflow is unlikely to play a role at all but the lowest wind speeds.

Specific comments:

We provide specific comments below, but there are also several comments embedded in the article file, which we also provide.

We have corresponded with the reviewers and confirmed that all comments are listed below, and that there is no additional article file.

1. (Title) This paper deals with ship motion-induced flow distortion effects in the momentum flux spectra, however, what is the motivation for “wave-induced” in the title?

The ship motion and resulting biases we are concerned with is ultimately induced by wave motion. We also want to highlight the fact that there are two possible causes for the motion scale signal and we are trying to determine which is the case here - a real wave-induced flux component or experimental error. Hence, we feel that this is an appropriate title.

2. (Page 15545, line 1): Add the following references: *O’Sullivan et al*. (2013) and *O’Sullivan et al*. (2015)

We thank the reviewers for highlighting these relevant references, they have been added as suggested.

3. (Page 15545, line 14-16): This is really not surprising considering the location of your mast shown in figure 1. It would appear that the flux instruments are several metres back from the bow. A considerable reduction in flow distortion could be achieved by placing the sensors as far forward as possible. Suggest you include a comment to this effect in the conclusions.

We would first note that the reviewers relate the comment cited to our installation, but it actually relates to the findings of Weill et al. (2003) and Brut et al. (2005) for the R V Thalassa. Nevertheless, we broadly agree with this comment and we have made some minor changes to the conclusions section to better clarify our position on flow distortion as the potential source of the observed bias. Locations of instrument installation are necessarily limited by the design of the ship; while moving the instruments up and forward would minimize flow distortion, it is not technically feasible since there is nothing to mount them on.

The ideal flux sensor location is a complicated issue, discussed fully in Yelland et al., 2002

(Y2002). The location of the mast on JCR is quite typical (see figs 16, 17 Y2002) and CFD modelling gave typical biases compared to other ships. However, the mast itself on JCR is quite a large, permanent structure whereas other ships often carry a temporary lattice mast. Similarly, the foremast platform on JCR carries quite a few small-scale objects which are not included in the CFD model geometry. These points are included towards the end of Section 2, and are included in the Discussion section (page 15551, lines 17-22).

4. On (Page 15545, lines 21–24): Both *Edson et al.* (1998) and *Pedreros et al.* (2003) show a complete removal of the motion-correlated peak in the momentum flux spectra. It appears therefore more likely to us, that the overestimation of the shipborne fluxes in (*Edson et al.*, 1998; *Pedreros et al.*, 2003) is due to the inaccurate tilt correction, as described in (*Landwehr et al.*, 2015). It is however possible that for the here presented measurements the "time-varying flow distortion" is of greater importance, due to the less favourable anemometer position, i.e., surrounded by bulky structures, while *Edson et al.* (1998) and *Pe- dreros et al.* (2003) mounted their instrumentation in more pristine locations on slim masts and close to the bow. We had originally applied a similar technique in (*Landwehr et al.*, 2015), but abandoned it for the final version, because one of the reviewers was not willing to discuss this. For this study the reduction in the momentum flux was ≈ 6%. (We did not publish this result in the final version)

We have added a comment to the third para of section 4 (discussion) mentioning the possible contribution of inaccurate tilt correction to the observed motion-scale signal. However, we don't fully agree with the reviewer's assessment of the results in Edson et al (1998) and Pedreros et al. (2003) – it is not possible from the information in those papers to unambiguously assign remaining bias in the flux to a particular source. Research vessels on dedicated flux experiments are often either on-station or steaming slowly. Edson et al., (1998) restricted their flux measurements to ship speed < 2 knots, i.e. errors due to inaccurate tilt correction would be very small. In addition Edson et al., (1998) only show a single, noisy cospectrum, presumably not their worst. Pedreros et al. (2003) QCd their measurements using a ratio of Urel / ship speed > 2 and wind direction bow-on. This does allow inclusion of high ship speeds when the wind speed is high, but much of their data was obtained in the vicinity of the ASIS buoy for their intercomparison. Also, at higher wind speeds ships tend to reduce speed or go hove-to, as shown in our figure A2. The cospectra shown by Pedreros has a log y-axis and broad frequency bins, but even so the measured spectrum is elevated in comparison to the ideal one for fz/U > 0.1, suggesting some uncorrected contamination. Finally, the FETCH experiment took place in the Gulf of Lion, in short fetches where sea state and ship motion would be low in the first place.

We don't claim that motion scale bias is the only issue, just a potentially significant one in some data sets.

5. (Page 15546, lines 8–10): The variation of the residual motion peaks in (*Miller et al.*, 2008) might have another cause: *Miller et al.* (2008) estimated the relative orientation of their anemometer and the inertial motion unit with the planar fit approach from (*Wilczak et al.*, 2001). Small errors in this tilt estimation can lead to a less efficient removal of the ship motion signal. Note that the magnitude of the tilt correction applied in (*Miller et al.*, 2008) was higher for the low level anemometers. We had observed this effect during the preparation of (*Landwehr et al.*, 2015) when we applied the tilt corrections to the wind vector prior to the motion-correction.

This is a good point and we have added a comment to this effect to the introduction. We have also noted that uncertainty in the alignment of sonic and motion unit (e.g. Brooks 2008) could also contribute.

6. (Page 15548, equation 1): Note that the identification of the natural coordinate system based on a single 30 minute averaging interval can be biased by possible offsets in the vertical wind speed measurement, as elaborated in (*Wilczak et al.*, 2001; *Landwehr et al.*, 2015) this can

lead to significant errors in the tilt estimation at low wind speeds.

We have added a comment to this effect to Appendix A, and have added the relevant reference Wilczak et al., 2001.

7. (Page 15550, equation 2): Did the coefficients α_1 and α_2 show any correlation with relative wind direction or the ship speed? If such a correlation exists it could be used as an argument for your hypothesis.

This is a reasonable suggestion. However, the coefficients are dependent on vertical ship motion, which will be correlated with ship speed, and also with relative wind direction (both ship operations, and platform motion are relative wind direction dependent). Hence use of the coefficient correlations to show the source of the signal is problematic. As we state in the manuscript, we do not attempt to provide a comprehensive correction, just an illustration of the problem, its potential size and likely cause.

8. (Page 15550, lines 14–18): The observation of *Edson et al*. (1998) and *Dupuis et al*. (2003) might be more related to the wind vector tilt-estimation, see comment to (Page 15545, lines 21–24).

See our response to comment 4.

9. (Page 15551, lines 9–11): The agreement with the COARE 3.5 parametrisation is no argument for the in-significance of the surface currents. Do you have mea- surements or estimations of the magnitude and direction of the surface currents?

Current measurements were not available for this experiment, though we anticipate that with the large, varied dataset we have compiled, most of the effect will average out. We have removed the suggestion that agreement with COARE 3.5 implies any effect is small.

10. (Page 15551, lines 12–14): You could mention (*Landwehr et al*., 2015) in this context.

We have added the reference to this section (see our response to point 4) as suggested.

11. (Page 15553, lines 19-21): Sharp thought!

12. (Page 15554, lines 23-26): This is a very strong argument.

13. (Page 15567, Figure 5): This is a nice illustration. You might zoom in further on the frequency range of interest. It might be worthwhile to increase the frequency resolution of the spectra, as it appears to be very close to the frequency shift that you want to show. I assume (c) and (d) show $f \cdot |C_{uw}|/u^2_*$?

We thank the reviewers for these good presentation suggestions. We have zoomed in further on the motion scale, and the frequency resolution has been increased. Note that this resolution change slightly alters some of the values given on page 15554, lines 12-19, but does not affect the conclusions drawn from them. We have also clarified the label on 5c and 5d and altered the figure caption to further clarify. Panel 5d has been removed and a similar panel added to Figure 2. More details on this change are provided in the response to Reviewer 1 point 1.2.

14. (Page 15568, Figure 6): Figure 6a shows that the average effect of the decor- relation is a reduction in CD, however in Fig. 6b it the effect is the increase the relative CD for abs(ship – relative wind direction) > 20° in comparison to the mea- surements where the wind was blowing bow on. What I want to say is: maybe the label in Fig. 6b should be “linear fit - CD”.

The label is correct – the fit in 6a is calculated from bow on measurements (-20 to +50 degrees) and *then the perturbation from that fit calculated as [100*(drag-fit)/fit] for drags at all wind directions.*

References

Dupuis, H., C. Guerin, D. Hauser, A. Weill, P. Nacass, W. M. Drennan, S. Cloché, and H. C. Graber (2003), Impact of flow distortion corrections on turbulent fluxes estimated by the inertial dissipation method during the fetch experiment on r/v l'atalante, *J. Geophys. Res.: Oceans*, *108*(C3), 8064, doi:10.1029/2001JC001075.

Edson, J. B., A. A. Hinton, K. E. Prada, J. E. Hare, and C. W. Fairall (1998), Direct covariance flux estimates from mobile platforms at sea, *J. Atmos. Oceanic Technol.*, *15*, 547–562.

Landwehr, S., N. O'Sullivan, and B. Ward (2015), Direct flux measurements from mobile plat- forms at sea: Motion and air flow distortion corrections revisited, *J. Atmos. Oceanic Technol.*, doi:10.1175/JTECH-D-14-00137.1.

Miller, S., T. Hristov, J. Edson, and C. Friehe (2008), Platform motion effects on measurements of turbulence and air-sea exchange over the open ocean, *J. Atmos. Oceanic Technol.*, *25(9)*, 1683–1694.

O'Sullivan, N., S. Landwehr, and B. Ward (2013), Mapping flow distortion on oceanographic platforms using computational fluid dynamics, *Ocean Science*, *9*(5), 855–866, doi:10.5194/ os-9-855-2013.

O'Sullivan, N., S. Landwehr, and B. Ward (2015), Air-flow distortion and wave interactions: An experimental and numerical comparison, *Methods Oceanogr.*, *12*, 1–17, doi:10/5cw.

Pedreros, R., G. Dardier, H. Dupuis, H. C. Graber, W. M. Drennan, A. Weill, C. Guerin, and P. Nacass (2003), Momentum and heat fluxes via eddy correlation method on the r/v *L'Atalante* and an asis buoy, *J. Geophys. Res.*, *108*, 3339.

Wilczak, J., S. Oncley, and S. Stage (2001), Sonic anemometer tilt correction algorithms, *Boundary-Layer Meteorology*, *99*(1), 127–150, doi:10.1023/A:1018966204465.

Motion-correlated flow distortion and wave-induced biases in air-sea flux measurements from ships

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Abstract

Direct measurements of the turbulent air-sea fluxes of momentum, heat, moisture and gases are often made using sensors mounted on ships. Ship-based turbulent wind measurements are corrected for platform motion using well established techniques, but biases at scales associated with wave and platform motion are often still apparent in the flux measurements. It has been uncertain whether this signal is due to time-varying distortion of the air flow over the platform, or to wind-wave interactions impacting the turbulence. Methods for removing such motion-scale biases from scalar measurements have previously been published but their application to momentum flux measurements remains controversial. Here we show that the measured motion-scale bias has a dependence on the horizontal ship velocity, and that a correction for it reduces the dependence of the measured momentum flux on the orientation of the ship to the wind. We conclude that the bias is due to experimental error, and that time-varying motion-dependent flow distortion is the likely source.

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1. Introduction

Obtaining direct eddy covariance estimates of turbulent air-sea fluxes from ship-mounted sensors is extremely challenging. Measurements of the turbulent wind components must be corrected for the effects of platform motion and changing orientation (Edson et al., 1998; Schulze et al., 2005; Brooks, 2008; Miller et al., 2008). The ship also acts as an obstacle to the air flow forcing it to lift and change speed; this results in both the measured mean wind being biased (accelerated/decelerated) relative to the upstream flow and the effective measurement height being lower than the instrument height. This can significantly bias estimates of the 10 m neutral wind speed (U_{10n}) and the surface exchange coefficients (Yelland et al., 1998). Computational fluid dynamics (CFD) modelling studies of the flow distortion have been used to determine corrections for these mean flow distortion effects for a number of different research vessels (Yelland et al., 1998, 2002; Dupuis et al., 2003; Popinet et al., 2004; Moat et al., 2005; O'Sullivan et al., 2013, 2015) and also generic corrections for commercial vessels that report meteorological measurements (Moat et al., 2006a,b).

The modelled corrections show a strong dependence on the relative wind direction (Yelland et al., 2002; Dupuis et al., 2003) and a much weaker dependence on wind speed, but in general have been determined only for ships with zero pitch and roll angles. Weill et al. (2003) and Brut et al. (2005) reported on experiments with a 1/60 scale physical model of the *RV La Thalassa* to investigate the effect of pitch and roll angles on the mean flow distortion.

They found the tilt of the mean streamline to vary by more than 1° and the mean wind speed by up to 12% for pitch angles between ±10°; these effects were asymmetric about zero pitch. Roll angle had only a small impact on the measured wind speed, about 1% for roll of up to 10°, but this was examined for bow-on flows only and a larger impact might be expected for flows with a significant beam-on component. Comparison of in situ measurements from sonic anemometers, the physical model tests, and CFD modelling also revealed that the foremast itself, along with the instruments and electronics enclosures mounted on it, had a significant impact on flow distortion at the location of the sonic anemometer.

The studies of flow distortion cited above addressed only the mean flow for a fixed orientation of the ship with respect to the mean streamline; to the best of our knowledge no studies have investigated the effect of time-varying flow distortion as ship attitude changes. That the time-varying flow distortion has an impact can, however, be inferred from reported biases of ship-based eddy covariance measurements. Edson et al. (1998) compared eddy covariance estimates of the kinematic wind stress from two ships with those from a small catamaran and from the stable research platform FLIP. They found that the ship-based estimates were on average 15% higher than those from FLIP and the catamaran. They argued that the difference resulted from flow distortion over the ship rather than from inadequate motion correction because the catamaran experienced more severe platform motion. Pedreros et al. (2003) similarly found momentum flux estimates from a ship to be 18% higher than estimates from a nearby air-sea interaction spar buoy. Evidence of such biases, ascribed to flow distortion, led to the exclusion of ship-based direct flux measurements from the most recent update of the COARE bulk air-sea flux algorithm (v3.5; Edson et al., 2013).

Features in cospectra that manifest as significant deviations from the expected spectral form (e.g. Kaimal et al., 1972) at frequencies associated with waves and platform motion have been reported in observations of momentum fluxes measured from FLIP (Miller et al., 2008) and from fixed platforms (Deleonibus, 1971) and towers (Drennan et al., 1999). A decrease in the magnitude of the feature with height led Miller et al. (2008) to ascribe its source to interactions between the waves and atmospheric turbulence. The authors also note that the anemometers used were not co-mounted with inertial motion units and their tilt from horizontal was determined using the planar fit method; errors in the determined tilt or in estimation of anemometer and inertial motion unit alignment could also contribute to the observed features via incomplete correction for platform motion (Brooks, 2008; Landwehr et al., 2015). Edson et al. (2013) analysed wind profile measurements from three field campaigns and found little evidence of wave influence on winds at heights above 4 m in sea

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conditions with $c_p/U_{10n} < 2.5$, where c_p is the wave phase speed. In general, reported motion-scale signals in the turbulence have been observed in measurements made either at heights below 10 m (Deleonibus, 1971; Miller et al., 2008) or in conditions of fast, high swell where $c_p/U_{10n} \approx 2$ and $Hs_{swell} >> Hs_{wind}$, and Hs_{swell} and Hs_{wind} are the significant wave heights of the swell and wind-wave components of the wave field respectively (Drennan et al., 1999). Recent results from Large Eddy Simulations over moving wave fields also suggest that, in developing sea conditions waves are not expected to significantly influence turbulent winds at heights of more than about 10 m (Sullivan et al., 2014). In summary, the wave field is only expected to influence the turbulent winds near the surface or in conditions where swell dominates the wave field.

High frequency gas concentration measurements for studies of air-sea exchange have been shown to suffer significant motion-correlated biases resulting from the hydrostatic pressure change with vertical displacement (Miller et al., 2010), and potentially from mechanical sensitivities of the sensors themselves (McGillis et al., 2001; Yelland et al., 2009; Miller et al., 2010). These biases cause distortions of the cospectra between the vertical wind component and gas concentration (Edson et al., 2011) apparent in the cospectra at frequencies associated with the platform motion, and several recent studies have applied motion decorrelation algorithms to remove this signal (Miller et al., 2010; Edson et al., 2011; Blomquist et al., 2014).

Such an approach can also correct the apparent motion-scale bias in the momentum flux, but is controversial since, as discussed above, there are circumstances in which a real wave-correlated signal may be expected in the turbulence measurements. Here we present measurements which demonstrate a significant motion-scale feature in momentum flux measurements from a research ship. We show the impact of applying a simple regression procedure to remove the bias, and provide evidence that suggests the source of the bias is time-varying flow distortion correlated with ship motion and attitude.

2. Data

The measurements were made on the *RRS James Clark Ross* as part of the Waves, Aerosol and Gas Exchange Study (WAGES), a programme of near-continuous measurements using the autonomous AutoFlux system (Yelland et al., 2009). Turbulent wind components were measured by a Gill R3 sonic anemometer installed above the forward, starboard corner of the ship's foremast platform (Fig. 1). The measurement volume was approximately 16.5 m above sea level. Platform motion was measured with a Systron Donner MotionPak Mk II, mounted

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rigidly at the base of the anemometer and sampled synchronously with it. Wave field measurements were made using a WAVEX X-band radar installed above the bridge top. The WAVEX system obtains directional wave spectra and mean wave parameters every five minutes.

The fast-response instrumentation operated at 20 Hz, and flux estimates were calculated over 30-minute periods. The raw wind and motion measurements were first despiked and the wind components corrected for platform motion using the complementary filtering approach of Edson et al. (1998). The motion correction algorithm set out in Edson et al. (1998) and as usually applied corrects the measured horizontal winds for low frequency horizontal motions (ship's underway velocity) in the earth frame. This neglects the aliasing of the ship's horizontal speed into the vertical imposed by the non-horizontal mean streamline at the point of measurement due to flow distortion over the ship. The true vertical wind speed, w_{true} is determined from the measured, motion-corrected vertical wind, w_{rel}, and the horizontal true and relative winds (U_{true} and U_{rel}) as

$$w_{true} = w_{rel} - \left(\overline{w_{rel}} \times \left[1 - \overline{U_{true}} / \overline{U_{rel}}\right]\right) \tag{1}$$

where overbars indicate a time average (Tupman, 2013). The derivation of Eq. (1) and the impact of applying this correction are described in Appendix A. This correction addresses the same source of measurement error as that recently described by Landwehr et al. (2015) who address it by applying corrections for the ship's low-frequency horizontal velocity after rotating the ship-relative winds (corrected for high frequency motions) into the reference frame of the mean streamline for each flux averaging period.

After motion correction, each 30-minute record is rotated into a reference frame aligned with the mean streamline, wind components were linearly detrended, and eddy covariance momentum fluxes calculated. CFD modelling of the air flow over the James Clark Ross was initially undertaken by Yelland et al. (2002), but only for flow on to the bow; we have extended the CFD study for a much wider range of relative wind directions and the results were used to determine direction-dependent corrections to the mean (30-minute averaged) relative wind speed and measurement height. The new CFD study is documented in Moat and Yelland (2015) and the primary results reproduced here in Appendix B. The modelled wind speed bias at the sensor location varied between -0.9% and 8.4% for wind directions between 20° to port of the bow and 120° to starboard, and the height by which the flow was raised varied between 1.3 m and 3.2 m. Wind directions beyond 20° to port of the bow were affected by small-scale obstructions on the foremast platform that are not included in the CFD model; these wind directions are thus excluded from the following analysis. After applying the corrections, the measured winds were corrected to 10 m height and neutral stability using the Businger-Dyer relationships (Businger, 1988) and the 10 m neutral drag coefficient, CD_{10n}, was calculated from U_{10n} and the momentum flux estimates.

The measurements used here were obtained between 09 January and 16 August, 2013 in locations throughout the North and South Atlantic, the Southern Ocean and the Arctic Ocean, at latitudes ranging from 62°S to 75°N. After excluding measurement periods when the ship was within sea ice, there were 2920 individual flux estimates available for analysis. Flux estimates were then rejected from the analysis where there was excessive ship manoeuvring, where flux quality control criteria were failed (Foken and Wichura, 1996; Vickers and Mahrt, 1997), and when the air temperature was less than 2°C when ice build up may affect the sensors. Of the remaining 1054 flux estimates, 80 were removed as outliers ($CD_{10n} > 5\times10^{-3}$). Unless otherwise indicated, mean relative wind direction limits of 20° to port, and 50° to starboard of the bow were applied, a condition met by 499 flux estimates. Of the removed outliers, 38 lay within acceptable relative wind direction limits; of these, 6 were at winds speeds of 6 m.s^{-1} or greater.

3. Removal of the ship motion-scale signal

Momentum flux cospectra and ogives for U_{10n} between 10 and 14 m s^{-1}, normalised (by f/u_*^2 and $1/u_*^2$ respectively, where f is frequency and u_* is the friction velocity) and averaged, are shown in Fig. 2. The cospectra and ogives differ from the typical forms obtained from experiments over land (e.g. Kaimal et al., 1972) at frequencies between approximately 0.06 and 0.25 Hz (0.09 and 0.37 in the non-dimensionalised frequency shown in Fig. 2), where a significant anomalous signal is present. These are frequencies associated with surface waves and with the platform motion that results, hence we term the cospectral signal at these frequencies the motion-scale signal.

At wind speeds above 7 m s^{-1}, the CD_{10n} measurements are biased high compared with previous results (Fig. 3). The bias relative to the eddy covariance parameterisation of Smith (1980) increases with wind speed from approximately 20% at 8 m s^{-1} to 60% at 20 m s^{-1}. Note that the Smith (1980) parameterisation was derived from eddy covariance measurements made from a slim floating tower moored so as to minimise platform motion

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and inducing minimal flow distortion. The bias is smaller when compared to the COARE 3.0 (Fairall et al., 2003) or COARE 3.5 (Edson et al., 2013) bulk algorithms.

The motion-scale signal can be removed from the vertical wind component, and a corrected vertical wind, w_{MSC}, obtained via a simple regression method:

$$w'_{MSC} = w'_{true} - \alpha_1 acc'_z - \alpha_2 vel'_z \qquad (2)$$

where acc_z and vel_z are the platform's vertical acceleration and velocity, measured at the base of the sonic anemometer, and primes denote fluctuations determined from Reynolds decomposition. The coefficients α_1 and α_2 are determined here by regression for each 30-minute flux measurement period. This algorithm, which we term the motion-scale correction (MSC), is based on the regression corrections of Yelland et al., (2009) and Miller et al., (2010). It is also similar to the motion decorrelation algorithm given in a spectral formulation by Edson et al. (2011), originally utilised to remove motion biases from CO_2 flux cospectra, and here termed the MSC_f. The MSC_f algorithm coefficients are defined as the ratio of covariances of vertical wind and platform motion to variances of platform motion. The MSC and MSC_f methods give almost identical results (Fig. 2).

Applying the MSC algorithm removes the motion-scale signal (Fig. 2) and results in a 20% to 30% decrease in CD_{10n} for wind speeds above 7 m s^{-1} and absolute values similar to those of COARE 3.0 or 3.5 (Fig. 3). The signal removed is similar in size and of the same sign as the biases in ship-based momentum flux measurements reported by Edson et al. (1998) and Dupuis et al. (2003).

Applying the MSC to the along-wind component as well as the vertical component makes an insignificant (<<1%) additional difference to the measured flux (shown as MSC_{uv} in Figs. 2 and 3). Interpolating the measured cospectra across the motion-scale frequencies gives similar results to the MSC algorithm under most conditions (shown as "interpolated" in Figs. 2 and 3: Prytherch, 2011; Tupman, 2013). However, interpolation requires selection of appropriate frequencies to interpolate between, in this case 0.04 and 0.4 Hz (0.06 and 0.59 in the non-dimensionalised frequency shown in Fig. 2), and is not dependent on a physical variable related to the presumed source of the error (platform motion-dependent flow distortion). For these reasons, correction using the MSC algorithm is preferable.

4. Discussion

Following application of the MSC the cospectral shape matches the Kaimal form expected. This suggests that the motion-scale bias is being effectively removed.

The MSC also results in drag coefficients that lie within the range of previous parameterisations. At the highest wind speeds (over 15 m s^{-1}) the parameterisations begin to diverge significantly and the WAGES CD_{10n} are larger than those given by Smith (1980) and lie between those of COARE 3.0 and 3.5. It should be noted that COARE 3.0 and 3.5 are both defined using wind speeds in the frame of reference of the surface currents (see Appendix in Edson et al., 2013), rather than in the earth frame of reference as used by Smith (1980). Surface current measurements were not available for the WAGES data. For surface currents aligned with the prevailing wind direction, adopting a surface current frame of reference would lead to a small apparent increase in the drag coefficients presented here.

While several previous studies have ascribed a high bias in drag coefficient estimates from ships to flow distortion (Edson et al. 1998, 2013; Pedreros et al. 2003), they have not examined the effect in detail. Inaccurate tilt estimation, a related source of error, may also contribute to this bias, particularly at low wind speeds (Landwehr et al., 2015). Few other studies have discussed such biases at all, and it seems likely that the severity of any motion-correlated bias is highly dependent on individual platforms and instrument installations in the same manner as the mean flow distortion. The bias is potentially worse here than in many other studies; the sonic anemometer is mounted lower on the foremast than would be ideal because the long-term measurement programme made it necessary to be able to service the instruments easily and without access to a crane. There are also a greater number of small-scale obstructions such as searchlights near to the measurement point than would be the case on lattice style masts often deployed on dedicated flux measurement campaigns. Because the measurements are continuous and autonomous, a large fraction of our data is also obtained with the ship underway. In contrast, dedicated eddy covariance studies of air-sea exchange would usually focus almost exclusively on measurements made on station when ship motion is substantially less than when underway. Finally it is possible that such biases are present in some fraction of the measurements of many studies, but are excluded from final analysis by quality control procedures without a close examination of the bias being made. Many studies with modest data volumes have quality controlled the individual flux estimates via a visual inspection of the ogive curves, rejecting those that do not closely match the expected form (e.g. Fairall et al. 1997; Norris et al. 2012).

As discussed in Sect. 1 above, there is evidence from previous studies that the influence of the wave field on the turbulent winds should be small at heights above some

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limit which is assumed to be related to the wave properties: values between 4 and 10 m have been cited (Miller et al. 2008, Sullivan et al. 2014). The Sullivan et al. (2014) results correspond to a height of order 1.5 times the significant wave height. Real wave effects are thus expected to be negligible for typical measurement heights of ship-based sensors (15-20 m) under most conditions. Below we provide more direct evidence that the wave-scale signal seen in the WAGES data is due, in large part at least, to the effects of flow distortion over a moving platform.

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4.1 Motion dependence of the streamline

The angle to the horizontal of the airflow measured at the sonic anemometer site was found to be dependent on the vertical motion of the ship (Fig. 4). Perturbations in the tilt of the streamline are approximately in phase with acc_z, out of phase with the vertical displacement and pitch, and lead vel_z by about 90°. There are multiple processes that may affect the streamline orientation as the ship moves over the waves:

- Vertical displacement of the ship changes the vertical extent of the obstacle that the ship presents to the flow and the relative height of the measurement volume with respect to that of the bow above the water line.
- The ship's pitch similarly changes both the effective size of the obstacle presented to the flow and the relative location of the sonic anemometer within the distorted flow above the bow.
- Vertical motion of the ship will force the overlying air to move.

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In the example here for 15 m s^{-1}, bow-on winds, the airflow tilt varies by about ± 3° around a mean of approximately 10°. The various parameters shown in Fig. 4a are all inter-dependent, but streamline tilt showed slightly more consistent trends with the velocity and acceleration parameters than with displacement or pitch suggesting that "pumping" of the air above the moving deck may be the dominant effect.

4.2 Characteristic frequencies of spectral features

For a platform moving through a wave field aligned with the direction of travel, it would be expected that the frequency of ship motion forced by the waves would differ from that for a ship on station with no mean horizontal velocity. The change could be of either sign depending on the ratio of wavelength to the length of the ship, with an increase in frequency for wavelengths much longer than the ship. The measured frequency of atmospheric turbulent structures would also be shifted to higher frequencies relative to those measured when on station. The nature of the frequency shift should differ for turbulent air motions, which advect with the wind and have a ship-relative velocity equal to the sum of wind and ship speeds, and wave-correlated features in the turbulence field which are phase-locked to the surface waves (Sullivan et al. 2000; 2008; 2014), and will have a ship-relative velocity of the sum of wave-phase and ship speeds. A signal due to real wind-wave interaction should thus appear at a different frequency to that from a ship motion-induced measurement bias.

Figure 5 shows a comparison of the power spectral density of platform vertical velocity (S_{velz}, Fig. 5b) and frequency weighted cospectral densities for the streamwise momentum flux (normalised by u_*) both for periods during which the ship was on station (V_{ship} < 1 m s^{-1}, where V_{ship} is the speed of the ship) and when underway (V_{ship} > 5 m s^{-1}). The cospectra are shown both before (Fig. 5d) and after (Fig. 5c) applying the standard motion correction to the measured turbulent velocity components, but without applying the MSC correction. Also shown are the spectral densities of the surface wave field (Fig. 5a). The wave radar provides wave spectra in the earth frame, corrected for ship speed; in order to compare these directly with the measured turbulence and ship-motion spectra when underway we need to transform them into a reference frame moving with the ship. This is achieved by plotting against a modified frequency, $f_{\mathrm{m}} = f_0(c_{\mathrm{p}} + V_{\mathrm{ship}})/c_{\mathrm{p}}$, where f_{m} is the frequency that would be measured in the ship reference frame and f_0 is the true frequency in the earth frame. The periods chosen all have bow-on winds, wind speeds of between 10 and 12 m s^{-1} and similar sea states: the (true) mean peaks of the mean WAVEX-derived non-directional wave spectra (S_{zwave}) are 0.120 and 0.110 Hz, and mean significant wave heights are 4.73 m and 3.51 m for the stationary and underway periods respectively.

For the on station measurements, the peak in the momentum flux cospectra (no MSC, Fig. 5c) is at 0.113 Hz, which matches that of the peak in ship vertical velocity (Fig. 5b) and is at slightly lower frequency than the peak in the ship-frame surface wave spectra (0.120 Hz, Fig. 5a). For the underway cases the peak in the ship-frame wave spectra is shifted to higher frequency (0.163 Hz) compared to the true spectra. The peak in the ship motion spectrum (0.148 Hz) is again lower than that of the wave spectrum and by a larger margin than for the on station case. The peak in the momentum flux cospectrum at 0.153 Hz is much closer to that of the ship motion than that of the wave spectrum.

The correspondence of the peak in momentum flux cospectra with that of the ship

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motion rather than that of the wave field suggest that the residual signal after motion correction is an artefact of motion-correlated flow distortion rather than a result of a real wave-correlated signal in the turbulence.

4.3 Directional dependence of drag coefficient bias

Mean flow distortion is strongly dependent on relative wind direction (Yelland et al., 1998), even for a motionless ship with zero pitch and roll angles. The dependence of the calculated drag coefficients on relative wind direction before and after applying the MSC algorithm is shown in Fig. 6. First, a linear fit was made between the drag coefficient and wind speed data obtained for wind directions between -20 and +50 degrees of the bow. Then the drag coefficient anomalies (individual minus fit) were calculated and averaged into 10° relative wind direction bins, and the results were plotted against relative wind direction. It can be seen that prior to applying the MSC algorithm the drag coefficient anomalies have a significant dependence on relative wind direction, and that application of the algorithm significantly reduces this dependence. For completeness the results are also shown without first applying the direction-dependent CFD-derived correction to the mean, 30-minute averaged, wind speed; this also reduces the dependence of the drag coefficient on relative wind direction.

Application of the MSC and the mean CFD correction does not completely remove all dependence of the drag coefficient on relative wind direction. This suggests that one or both corrections may need refinement. In the case of the MSC algorithm, the effect of the roll of the ship is likely to become significant when the wind direction is beam-on rather than bow-on. In the case of the CFD correction to the mean wind speed, the model of the ship geometry may have to be refined to take into account local flow distortion caused by small objects mounted on the foremast, close to the anemometer. These are areas for future investigation.

5. Conclusions

Methods for removal of motion-correlated signals from fast-response gas measurements made onboard moving platforms have become more commonly applied in recent years; however, these techniques remain controversial when applied to fast-response winds for the purpose of momentum flux calculation. The results here demonstrate these methods and their impact on ship-based momentum flux measurements where a significant motion-correlated bias is present in the motion-corrected cospectra. The motion-correlated signals are shown to be dependent on platform velocity relative to the wave field. In addition, the dependence of the flux on wind direction relative to the ship is reduced after applying the correction methods. These results suggest that the motion-correlated signal is due to the effects of time-varying flow distortion. Further investigation is required to resolve the details of the physical processes involved.

The recent revision of the COARE bulk flux algorithm (COARE 3.5, Edson et al. 2013) is determined only from data from platforms other than ships (buoys, towers, FLIP). These data all require motion correction, and Bigorre et al. (2013) report biases of a few percent in mean wind speed due to flow distortion around one of the buoys used to collect data at high wind speed, but these platforms generally do not suffer such significant flow distortion problems as ships.

For many applications ship-based measurements are the only option; for example, direct eddy covariance measurements of gas transfer require instrumentation that can only realistically be operated on a ship. A means of effectively dealing with biases induced by flow distortion around a moving platform is thus essential. The methods demonstrated above provide a successful correction; after its application the shape of the cospectra matches the Kaimal form expected and our drag coefficient results lie within the range of recent leading parameterisations.

Appendix A. Underway vertical wind speed

The motion correction algorithm of Edson et al. (1998) calculates a total platform velocity in the earth frame as the sum of highpass filtered wave-induced motions, obtained from the integration of accelerometers, and lowpass filtered velocities (the platform's underway motion). The latter are applied only in the horizontal since the mean vertical velocity is zero by definition. The corrected winds in the earth frame are obtained as the vector sum of measured and platform velocities. This neglects the impact of flow distortion on the measured winds (Fig. A1). At the point of measurement on the foremast of a ship, the mean flow is forced to lift resulting in a streamline tilted upwards from the horizontal. The measured along-streamline wind depends upon ship velocity as well as earth-relative wind. Since the streamline is tilted, a fraction of the ship velocity affects the measured vertical as well as the horizontal winds in the earth frame and must be corrected.

When conditions are stationary (an implicit assumption for direct flux measurement) the measured, motion-corrected vertical wind, w_{rel}, can be corrected for the horizontal platform mean velocity to obtain the true vertical wind speed w_{true}. The ratio of the mean true to mean relative vertical winds is equal to the ratio of the mean true to mean relative horizontal winds, i.e.

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$$\frac{\overline{U_{true}}}{\overline{U_{rel}}} = \frac{\overline{w_{true}}}{\overline{w_{rel}}} \qquad \text{(A1)}$$

(Fig. A1). Then, as

$$w_{true} = w_{rel} - \left(\overline{w_{rel}} - \overline{w_{true}}\right) \qquad \text{(A2)}$$

w_{true} can be determined via Eq. (1)

$$w_{true} = w_{rel} - \left(\overline{w_{rel}} \times \left[1 - \overline{U_{true}} / \overline{U_{rel}}\right]\right).$$

Note that this affects the mean vertical wind only, not the high frequency perturbations; however failure to account for the impact of flow distortion on the vertical wind measurements would result in the streamline orientation being incorrectly calculated, and both u' and w' values being biased after rotation into the streamline-oriented reference frame in which the fluxes are calculated. We also note that at low wind speeds (~< 5 m s^{-1}), the determination of the reference frame for a particular measurement interval may be biased by offsets in the vertical wind speed, leading to errors in the tilt calculation (Wilczak et al., 2001; Landwehr et al., 2015).

The effectiveness of this correction is demonstrated through comparison of drag coefficients from periods when the ship was stationary (V_{ship} < 1 m s^{-1}) and underway (V_{ship} > 5 m s^{-1}). Prior to correction, measurements from the underway ship are biased high relative to the stationary measurements (Fig. A2). Following correction, the stationary and underway measurements are in very good agreement for all but the very lowest wind speeds. Furthermore, for stationary periods (where the effect is small), the corrected and uncorrected results are also in good agreement.

Appendix B. CFD corrections for flow distortion

The relative wind direction dependent CFD corrections for the mean flow distortion over the ship are given in Table B1. These are strictly valid only for the location of our sonic anemometer (1.24 m to starboard, 16.5 m above the waterline, and 5.0 m aft of the bow), but should be broadly representative for nearby locations, and indicative of the directionally dependent flow distortion that might be expected on any similar installation on other ships.

Acknowledgements

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References

Bigorre, S. P., Weller, R. A., Edson, J. B. and Ware, J. D.: A Surface Mooring for Air–Sea Interaction Research in the Gulf Stream. Part II: Analysis of the Observations and Their Accuracies. J. Atmos. Oceanic Technol., 30, 450–469. doi: http://dx.doi.org/10.1175/JTECH-D-12-00078.1. 2013

Blomquist, B. W., Huebert, B. J., Fairall, C. W., Bariteau, L., Edson, J. B., Hare, J. E., and McGillis, W. R.: Advances in air-sea CO_2 flux measurement by eddy correlation, Bound.-Lay. Meteorol. 1-32, doi:10.1007/s10546-014-9926-2, 2014.

Brooks, I. M.: Spatially Distributed Measurements of Platform Motion for the Correction of Ship-Based Turbulent Fluxes. J. Atmos. Ocean. Tech., 25, 2007-2017, doi:10.1175/2008JTECHA1086.1, 2008.

Brut, A., Butet, A., Durand, P., Caniaux, G., and Planton, S.: Air–sea exchanges in the equatorial area from the EQUALANT99 dataset: Bulk parameterizations of turbulent fluxes corrected for airflow distortion, Q. J. Roy. Meteor. Soc., 131, 2497-2538, doi:10.1256/qj.03.185, 2005.

Businger, J. A.: A note on the Businger–Dyer profiles. Bound.-Lay. Meteorol., 42, 145–151, doi:10.1007/978-94-009-2935-7_11, 1988.

Deleonibus, P.: Momentum flux and wave spectra observations from an ocean tower. J. Geophys. Res., 76, 6506-6527, doi:10.1029/JC076i027p06506, 1971.

Drennan, W., Kahma, K., and Donelan, M.: On momentum flux and velocity spectra over waves. Bound.-Lay. Meteorol., 92, 489-515, doi:10.1023/A:1002054820455, 1999.

Dupuis, H., Geurin, D., Hauser, D., Weill, A., Nacass, P., Drennan, W.M., Cloche, S. and Graber, H.C.: Impact of flow distortion corrections on turbulent fluxes estimated by the inertial dissipation method during the FETCH experiment on R/V L'Atalante, J. Geophys. Res., 108, 8064, doi:10.1029/2001JC001075, 2003.

Edson, J. B., Hinton, A. A., Prada, K. E., Hare, J. E., and Fairall, C. W.: Direct covariance flux estimates from mobile platforms at sea, J. Atmos. Ocean. Tech., 15, 547-562, doi:10.1175/1520-0426(1998)015<0547:DCFEFM>2.0.CO;2, 1998.

Edson, J. B., Fairall, C. W., Bariteau, L., Zappa, C. J., Cifuentes-Lorenzen, A., McGillis, W. R., Pezoa, S., Hare, J. E., and Helmig, D.: Direct covariance measurement of CO_2 gas transfer velocity during the 2008 Southern Ocean Gas Exchange Experiment: Wind speed dependency, J. Geophys. Res., 116, C00F10, doi:10.1029/2011JC007022, 2011.

Edson, J. B., Venkata Jampana, V., Weller, R. A., Bigorre, S. P., Plueddemann, A. J., Fairall, C. W., Miller, S. D., Mahrt, L., Vickers, D., and Hersbach, H.: On the exchange of momentum over the open ocean. J. Phys. Oceanogr., 43, 1589–1610, doi:10.1175/JPO-D-12-0173.1, 2013.

Fairall, C. W., White, A. B., Edson, J. B., and Hare, J. E.: Integrated shipboard measurements of the marine boundary layer, J. Atmos. Ocean. Tech., 14, 338–359, doi:10.1175/1520-0426(1997)014<0338:ISMOTM>2.0.CO;2, 1997.

Fairall, C. W., Bradley, E. F. , Hare, J. E. , Grachev, A. A., and Edson J. B.: Bulk parameterization of air□sea fluxes: Updates and verification for the COARE algorithm, J. Clim., 16, 571–591, doi:10.1175/1520- 0442, 2003

Foken, T., and Wichura, B.: Tools for quality assessment of surface-based flux measurements 1. Agr. Forest Meteorol., 78, 83-105, doi:10.1016/0168-1923(95)02248-1, 1996.

Kaimal, J. C., Izumi, Y. J., Wyngaard, C., and Cote, R.: Spectral characteristics of surface-layer turbulence, Q. J. Roy. Meteor. Soc., 98 (417), 563-589, doi:10.1002/qj.49709841707, 1972.

Landwehr, S., O'Sullivan, N., and Ward, B.: Direct Flux Measurements from Mobile Platforms at Sea: Motion and Air-Flow Distortion Corrections Revisited, J. Atmos. Ocean. Tech., (in press), doi:10.1175/JTECH-D-14-00137.1, 2015.

McGillis, W. R., Edson, J. B., Hare, J. E., and Fairall, C. W.: Direct covariance air-sea CO_2 fluxes. J. Geophys. Res.-Oceans, 106, 16729-16745, doi:10.1029/2000JC000506, 2001.

Miller, S. D., Hristov, T. S., Edson, J. B., and Friehe, C. A.: Platform motion effects on measurements of turbulence and air-sea exchange over the open ocean, J. Atmos. Ocean. Tech., 25, 1683-1694, doi:10.1175/2008JTECHO547.1, 2008.

Miller, S. D., Marandino, C., and Saltzman, E. S.: Ship-based measurement of air- sea CO_2 exchange by eddy covariance. J. Geophys. Res.-Atmos., 115, D02304, doi:10.1029/2009JD012193, 2010.

Moat, B. I., Yelland, M. J., Pascal, R. W., and Molland, A. F.: An overview of the airflow distortion at anemometer sites on ships, Int. J. Climatol., 25(7), 997-1006, doi:10.1002/joc.1177, 2005.

Moat, B. I., Yelland, M. J., Pascal, R. W., and Molland, A.F.: Quantifying the airflow distortion over merchant ships. Part I: validation of a CFD model, J. Atmos. Ocean. Tech., 23(3), 341-350, doi:10.1175/JTECH1858.1, 2006a.

Moat, B. I., Yelland, M. J., and Molland, A. F.: Quantifying the airflow distortion over merchant ships. Part II: application of the model results, J. Atmos. Ocean. Tech., 23(3), 351-360, doi:10.1175/JTECH1859.1, 2006b.

Moat, B. I. and Yelland, M. J.: Airflow distortion at instrument sites on the RRS James Clark Ross during the WAGES project. National Oceanography Centre, Southampton, U.K. Internal Document No. 12. Available from http://eprints.soton.ac.uk/373216/, 2015.

Norris, S. J., Brooks, I. M., Hill, M. K., Brooks, B. J., Smith, M. H., and Sproson, D. A. J.: Eddy Covariance Measurements of the Sea Spray Aerosol Flux over the Open Ocean. J. Geophys. Res., 117, D07210, 15pp, doi:10.1029/2011JD016549, 2012.

O'Sullivan, N., Landwehr, S., and Ward, B.: Mapping flow distortion on oceanographic platforms using computational fluid dynamics. Ocean Science, 9(5), 855–866, doi:10.5194/os-9-855-2013, 2013.

O'Sullivan, N., Landwehr, S., and Ward, B.: Air-flow distortion and wave interactions: An experimental and numerical comparison. Methods Oceanogr., 12, 1–17, doi:10.1016/j.mio.2015.03.001, 2015.

Pedreros, R., Dardier, G., Dupuis, H., Graber, H. C., Drennan, W. M., Weill, A., Geurin, C., and Nacass, P.: Momentum and heat fluxes via the eddy correlation method on the R/V L'Atalante and an ASIS buoy, J. Geophys. Res., 108, C11, doi:10.1029/2002JC001449, 2003.

Popinet, S., Smith, M., and Stevens, C.: Experimental and numerical study of turbulence characteristics of airflow around a research vessel, J. Atmos. Ocean. Tech., 21, 1575-1589, doi:10.1175/1520-0426(2004)021<1575:EANSOT>2.0.CO;2, 2004.

Prytherch, J.: Measurement and parameterisation of the air-sea CO_2 flux in high winds. PhD thesis, University of Southampton, 2011.

Schulze, E. W., Sanderson, B. G., and Bradley, E. F.: Motion correction for shipborne turbulence sensors. J. Atmos. Ocean. Tech., 22, 44-69, doi:10.1175/JTECH-1685.1, 2005.

Smith, S.: Wind stress and heat flux over the ocean in gale force winds. J. Phys. Oceanogr., 10, 709–726, doi:10.1175/1520-0485(1980)010<0709:WSAHFO>2.0.CO;2, 1980.

Sullivan, P. P., McWilliams, J. C., and Moeng, C.-H.: Simulation of turbulent flow over idealized water waves, J. Fluid. Mech., 404, 47-85, doi:10.1017/S0022112099006965, 2000.

Sullivan, P. P., Edson, J. B., Hristov, T., and McWilliams, J. C.: Large-eddy simulations and observations of atmospheric marine boundary layers above non-equilibrium surface waves, J. Atmos. Sci., 65, 1225-1245, doi:10.1175/2007JAS2427.1, 2008.

Sullivan, P. P., McWilliams, J. C., and Patton, E. G.: Large-Eddy Simulation of Marine Atmospheric Boundary Layers above a Spectrum of Moving Waves. J. Atmos. Sci., 71, 4001–4027. doi:10.1175/JAS-D-14-0095.1, 2014.

Tupman, D. J.: Air-sea flux measurements over the Southern Ocean. PhD thesis, University of Leeds, 2013.

Vickers, D., and Mahrt, L.: Quality control and flux sampling problems for tower and aircraft data. J. Atmos. Ocean. Tech., 14, 512-526, doi:10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2, 1997.

Weill, A., Eymard, L., Caniaux, G., Hauser, D., Planton, S., Dupuis, H., Brut, A., Guerin, C., Nacass, P., Butet, A., Cloché, S., Perderos, R., Durand, P., Bourras, D., Giordani, H., Lachaud, G., and Bouhours. G.: Toward a Better Determination of Turbulent Air–Sea Fluxes from Several Experiments, J. Climate, 16, 600-618, doi:10.1175/1520-0442(2003)016<0600:TABDOT>2.0.CO;2, 2003.

Wilczak, J., Oncley, S. and Stage, S.: Sonic anemometer tilt correction algorithms, Bound.-Lay. Meteorol., 99(1), 127–150, doi:10.1023/A:1018966204465, 2001.

Yelland, M. J., Moat, B. I., Taylor, P. K., Pascal, R.W., Hutchings, J. and Cornell, V. C.: Wind stress measurements from the open ocean corrected for airflow distortion by the ship, J. Atmos. Ocean. Tech., 28, 1511-1526, doi:10.1175/1520-0485(1998)028<1511:WSMFTO>2.0.CO;2, 1998.

Yelland, M. J., Moat, B. I., Pascal, R. W., and Berry, D. I.: CFD model estimates of the airflow distortion over research ships and the impact on momentum flux measurements, J. Atmos. Ocean. Tech., 19, 1477-1499, doi:10.1175/1520-0426(2002)019<1477:CMEOTA>2.0.CO;2, 2002.

Yelland, M., Pascal, R., Taylor, P. and Moat, B.: AutoFlux: an autonomous system for the direct measurement of the air-sea fluxes of CO_2, heat and momentum. J. Operation. Oceanogr., 15-23, doi:10.1080/1755876X.2009.11020105, 2009.

Relative wind direction (°)	wind speed bias at $z - \Delta z$ (%)	Δz (m)
-20	2.98	1.44
-10	0.41	1.35
0	-0.39	1.32
10	-0.86	1.41
20	0.7	1.54
30	2.92	1.76
50	5.11	2.27
70	4.86	2.73
90	8.35	2.96
110	6.97	3.15

Table B1. Variation of wind speed bias and vertical flow displacement with relative wind direction, determined at the location of the AutoFlux anemometer (height above sea level, z, 16.5 m). The wind speed bias and Δz are relative to a free stream location 2 seconds upstream of the anemometer site (after Yelland et al., 2002). A negative relative wind direction indicates a flow over the port side. Further details are given in Moat and Yelland (2015).

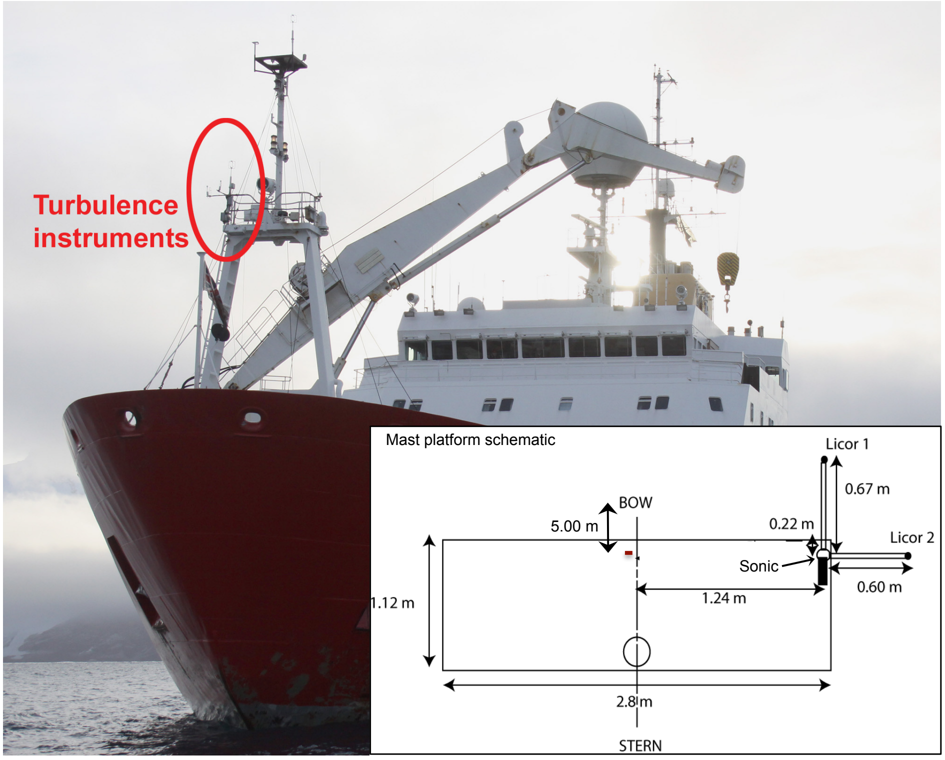

Figure 1. Locations of the flux instrumentation on the *RRS James Clark Ross*. The sonic anemometer is 2.0 m above the starboard forward corner of the platform. Note that the forecastle crane is generally stowed close to the deck while the ship is underway or on station.

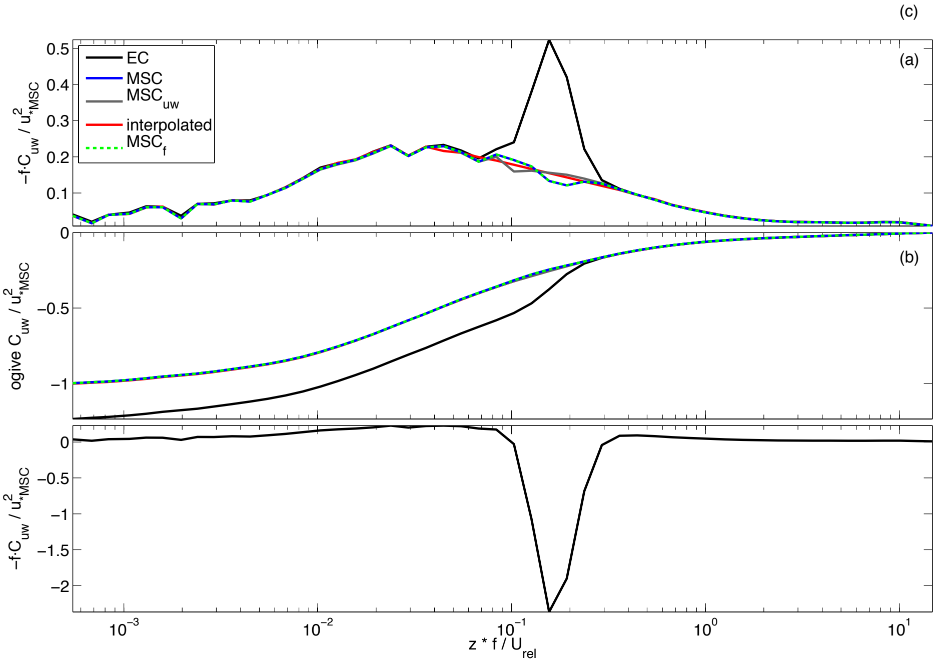

Figure 2. Frequency-weighted and normalised momentum flux cospectra (a) and normalised ogives (b), shown relative to frequency non-dimensionalised using measurement height *z* and mean relative wind speed U_{rel}. Also shown are frequency-weighted, inverted and normalised cospectra calculated prior to motion correcting the turbulent velocity components, which results in a large upwards flux signal at the motion scale (c). Results shown are an average of 131 30-minute duration measurements at mean wind speeds 10 m s^{-1} < U_{10n} < 14 m s^{-1}. EC indicates the cospectra after removing platform motion following Edson et al. (1998) and shows the residual signal at scales typical of the wave field. The interpolation across the wave scales has been applied between frequencies of 0.04 and 0.4 Hz. The motion-scale correction (MSC) can either be applied as per Eq. (2) (MSC), with Eq. (2) applied to both the along and vertical wind components (MSC_{uw}), or as described by Edson et al., (2011) (MSC_f). Normalisation of the five different sets of results is by u_* with MSC applied as per Eq. (2). Note that the MSC_f line overlies the MSC line at all frequencies, and the interpolated, MSC_{uw} and EC lines for frequencies away from the motion-scale.

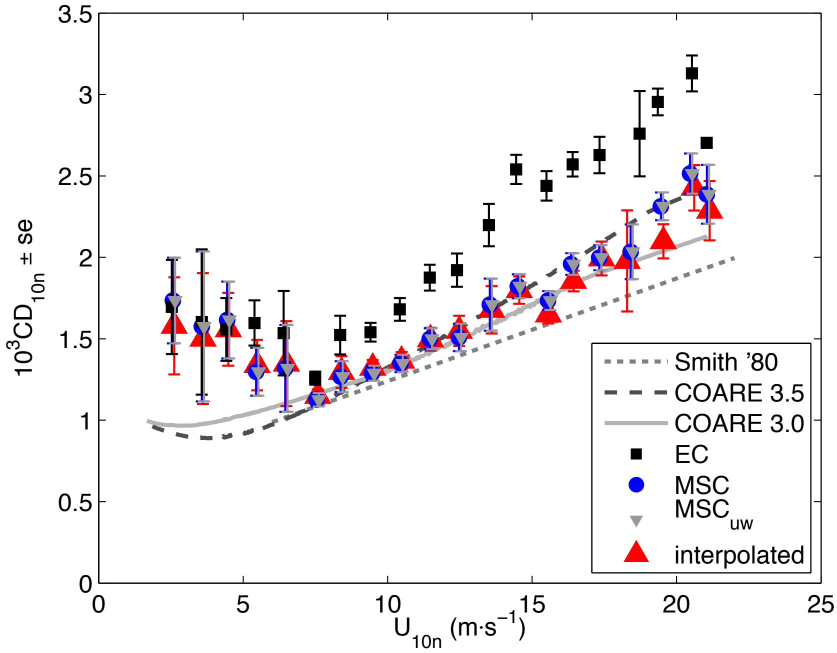

Figure 3. Drag coefficients bin-averaged by wind speed, relative to U_{10n} (n = 499). Measurements are shown either without correction for wave-scale bias (EC), or with correction applied to the vertical velocity only (MSC), both vertical and horizontal velocity components (MSC_{uw}), or via a simple interpolation across the wave-scale portion of the cospectra (interpolated). The bulk COARE 3.0 and 3.5 results are calculated without dependence on wave field or radiation.

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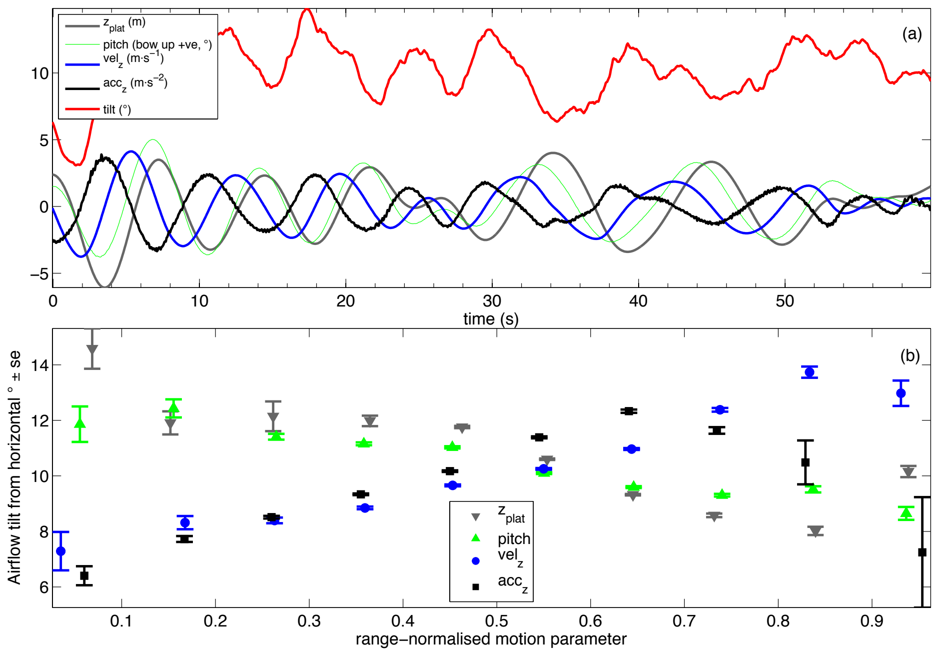

Figure 4. (a): Time series (60 s) of vertical platform displacement, velocity and acceleration, platform pitch, and tilt from horizontal of the streamwise airflow measured by the AutoFlux anemometer. The tilt has been smoothed with a 40-sample moving average. The measurements are sampled from a period (23 April 2013, 21:00-21:30 UTC) with near bow-on winds and mean U_{10n} of 15.2 m s^{-1}. (b): Variation of the tilt of streamwise airflow from horizontal, relative to the vertical platform displacement, velocity, acceleration and platform pitch each normalised by their measured range. Tilt averages were made over the 30-minute period that the measurements in (a) were sampled from.

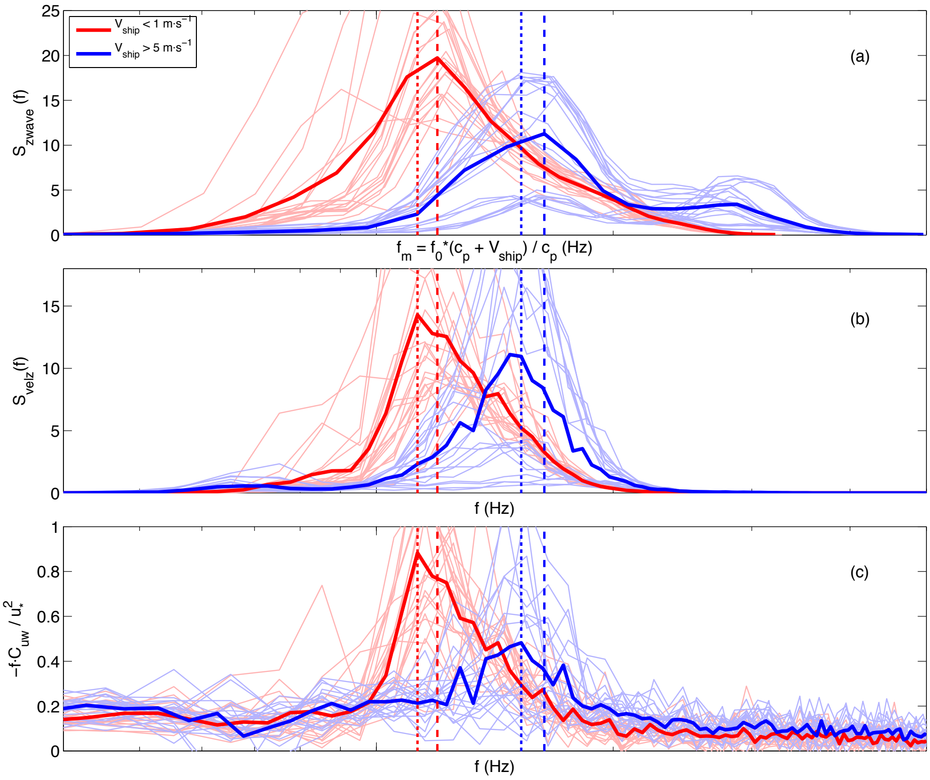

Figure 5. Comparison of averaged spectra. In all panels two sets of averaged data are compared, periods when the ship was stationary (V_{ship} < 1 m s^{-1}, 21 periods) and periods when the ship was steaming (V_{ship} > 5 m s^{-1}, 20 periods); the individual spectra are shown as pale lines for reference. For all measurements, U_{10n} was between 10 and 12 m s^{-1}. (a) Spectral density of non-directional wave heights from WAVEX with frequency shifted to the reference frame of the moving ship; (b) spectral density of platform vertical velocity as measured on the foremast; (c) frequency-weighted inverted cospectral density for the momentum flux (positive upwards) – turbulent velocity components are motion corrected, but the MSC correction is not applied. The dashed vertical lines indicate the peak frequency of the wave spectrum; dotted vertical lines indicate the peak frequency of the momentum flux cospectra in (c). Note that the axis limits are set very close to the scale of the ship motion to allow details to be seen clearly.

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Deleted: ; (d) frequency-weighted cospectral density for the momentum flux calculated prior to motion correcting the turbulent velocity components.

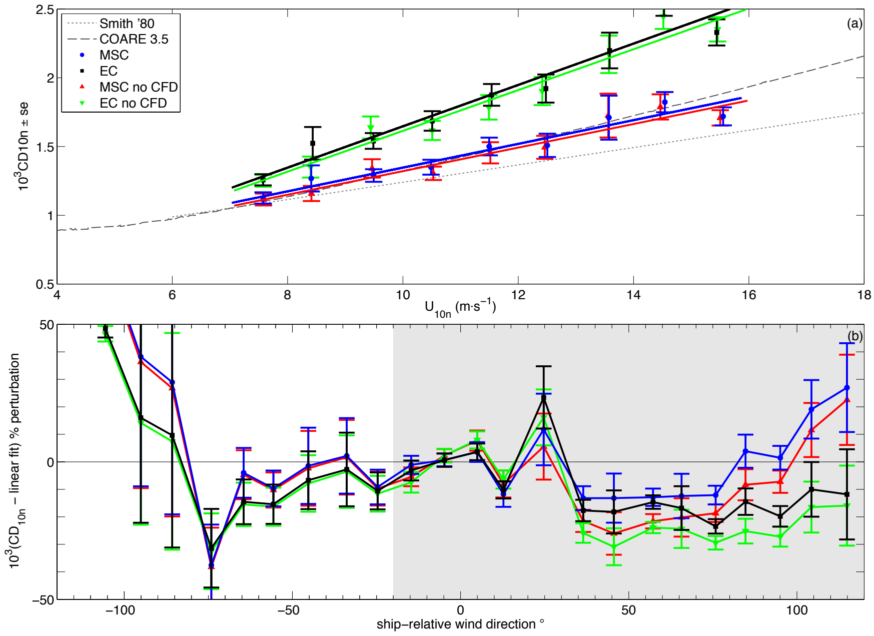

Figure 6. (a): Measurements either without correction for wave-scale bias (EC), or with correction applied to the vertical velocity only (MSC) for wind speeds 7 m s^{-1} < U_{10n} < 16 m s^{-1} (n = 335), and relative wind directions between -20° and +50° (where a wind on the bow is at 0°). Lines are linear fits to the measurements. (b): variation of the difference between measured drag coefficients and the linear fits against relative wind direction for the same wind speed criteria (n = 663). Both panels also show measurements (with and without MSC) which have not had CFD-derived corrections to mean wind speed and height applied. Note that CFD corrections were only applied for the shaded range.

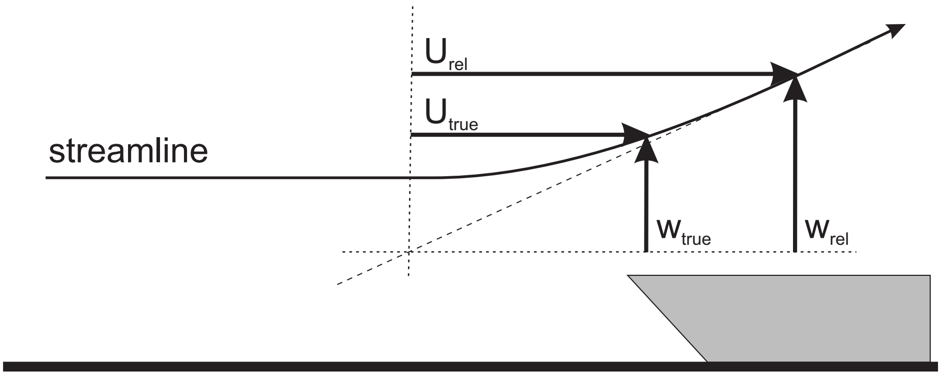

Figure A1. Schematic of the impact of ship horizontal velocity on non-horizontal airflow. The measured horizontal (U_{rel}) and vertical (w_{rel}) wind components must both be corrected for ship velocity to obtain the true wind components. Not correcting the measured vertical wind will result in an incorrect determination of the tilt angle of the flow from horizontal.

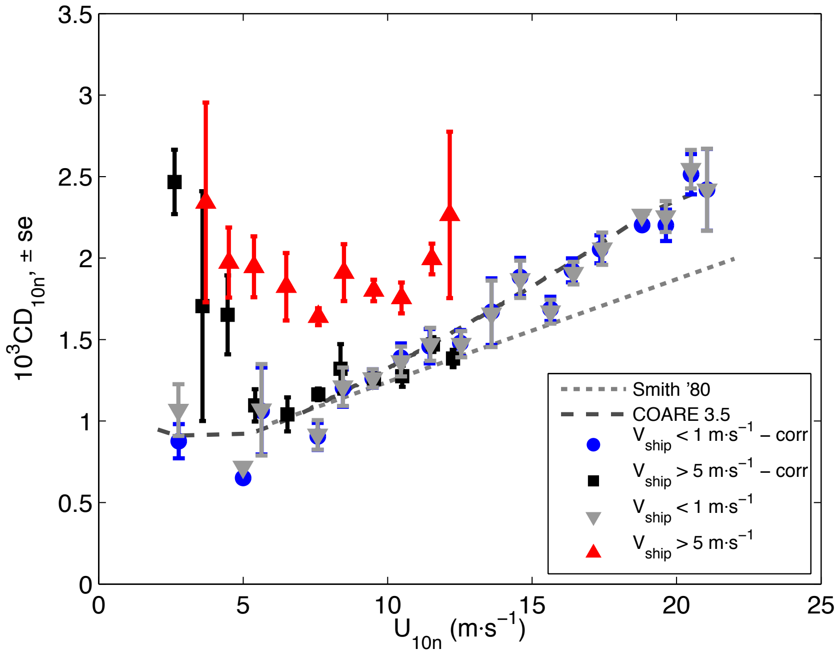

Figure A2. Wind speed-averaged drag coefficients, relative to U_{10n}. Two sets of measurements are compared: where the ship was deemed stationary ($V_{ship} < 1$ m s^{-1}, n = 233); and where the ship was underway ($V_{ship} > 5$ m s^{-1}, n = 182). The measurements are shown with ('corr') and without the vertical wind speed corrected as per Eq. (1).