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Parametrization of gas transfer velocities and sea-state-dependent wave breaking

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ABSTRACT

Both experimental estimates and different parametrizations of the transfer velocity of poorly soluble gases exhibit a very broad range of values at a given wind speed. Transfer velocities also appear to depend non-linearly on wind speed, and for high wind speeds this non-linearity is widely attributed to the influence of wave breaking. Both theoretical and experimental studies suggest that wave breaking, and associated whitecapping, is not simply dependent on wind speed but depends also on sea state. New parametrizations of gas transfer velocity based on an existing model of the dependence of transfer velocity on wind stress and whitecapping, supplemented by two sea-state-dependent parametrizations of whitecapping, are developed. These new models predict a diversity of transfer velocities at a given wind speed comparable to the diversity of existing parametrizations. Further, the results suggest that some of the existing parametrizations of transfer velocity reflect in part the wind fetch and sea state typical of the experiments used as a basis of the parametrization. It is suggested that transfer velocities may be estimated much more accurately through satellite retrieval of both wind speed and significant wave height than by wind speed alone.

1. Introduction

Air–sea fluxes of gases can be calculated via a Fickian flux equation.

$$\text{flux} = -K\Delta C \tag{1}$$

where K is the transfer velocity and ΔC is the effective concentration difference driving the net flux. K is the primary 'rate constant' and depends on turbulent and molecular transport near the surface of the ocean. In the case of poorly soluble gases it is molecular diffusion and turbulence in the upper millimetre of the ocean that is critical (Liss and Merlivat, 1986). This turbulence is usually driven by the wind and gas transfer velocities are usually parametrized in terms of wind speed (more specifically, the equivalent wind at 10 m elevation in conditions of neutral atmospheric stability). However, there is not a unique relationship between gas transfer and wind speed due to a number of effects including surfactant damping and the sea-state dependence of wave breaking. It is the purpose of this paper to consider the sea-state dependence of wave breaking and the influence that sea state thereby imposes on gas transfer velocities.

First, some existing parametrizations of transfer velocity are considered, noting particularly the diversity of predicted values at high wind speeds. The contribution of large-scale wave breaking to gas transfer is considered, and then the relationship of wave breaking and whitecapping to wind and sea state are discussed. An existing model that explicitly describes the contribution of whitecapping to gas transfer is combined with two parametrizations of whitecapping. This demonstrates the sensitivity of gas transfer velocities to sea state. The actual relevance of sea state to gas transfer velocities is discussed, and an outlook for future algorithms designed to estimate transfer velocity is proposed.

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2. Background and methods

2.1. Transfer velocity

There have been a large number of laboratory and field experiments to determine directly or indirectly the transfer velocity of gases and a similar number of attempts to place these measurements in a model framework. A multitude of experimental details may have affected each parametrization. Several existing parametrizations of gas transfer velocity in terms of the instantaneous wind speed are considered here, but each limited to a "standard gas", chosen to be a gas with a Schmidt number ($Sc = \nu_w/D$ where ν_w is the kinematic viscosity of water and D is molecular diffusivity) of 600. (This corresponds to CO_2 in fresh water of 20°C; a Schmidt number of 660, i.e. CO_2 in sea water at 20°C, has advantages, but would introduce some ambiguities in implementation.) The transfer velocities for this

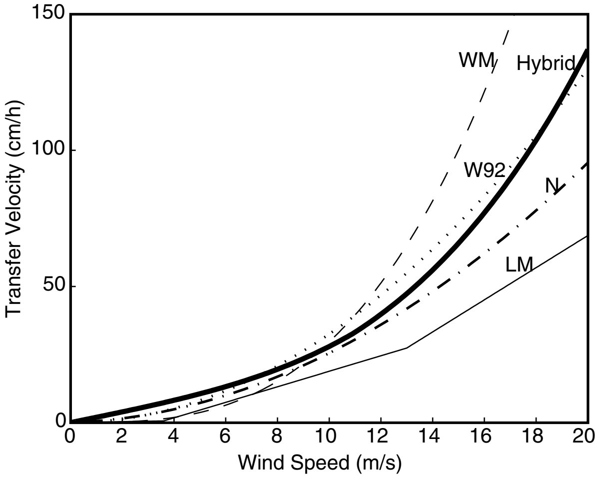

Fig 1. Model relationships of transfer velocity (Schmidt number = 600) to wind speed. Four standard parametrizations (referenced in the main text) are shown by four thin curves as labelled and a "hybrid model" by a thick black curve as defined by eqs (2) to(6).

standard gas predicted by some parametrizations (Liss and Merlivat (1986) (hereafter LM); Wanninkhof (1992) (W92); Wanninkhof and McGillis (1999) (WM); Nightingale et al. (2000) (N)) at a range of wind speeds is illustrated in Fig. 1. It may be noted that each of these four parametrizations predicts a very different transfer velocity, especially at high wind speeds where $K_{\mathrm{WM}} > K_{\mathrm{W92}} > K_{\mathrm{N}} > K_{\mathrm{LM}}$. Each of these parametrizations was developed from knowledge of (or accounting for) a different set of experimental results. Therefore, while the curves are not a substitute for the original experimental results they do to a large extent reflect different bodies of evidence.

Of the four models featured above, only LM quantify the role of wave breaking, but the authors of most models identify non-linearity in the relationship of transfer velocity to wind speed with the role of wave breaking. The mechanism by which wave breaking enhances gas transfer is uncertain; some investigators favour bubble-mediated transfer (e.g. Woolf, 1997) while others consider that the influence of turbulent plumes is more important (e.g. Monahan and Spillane, 1984; Asher et al., 2002). The strong non-linearity in gas transfer reported in many field and laboratory experiments cannot be explained by microscale breaking (Csanady, 1990) or a homogeneous increase in upper ocean turbulence associated with wave breaking (Kitaigorodskii, 1984) and requires either bubble-mediated transfer or high rates of transfer above the isolated turbulent plumes of large breaking waves (Woolf, 1995). It is at least reasonable to assume that a fraction of the transfer scales with the measured coverage of these plumes, e.g. the optically measured whitecap coverage.

Here, we adopt a single model (Woolf, 1997) that explicitly separates "breaking" and "non-breaking" contributions. In this model, the parametrization of the non-breaking contribution is based on theoretical considerations and observations in wind-wave tanks (Jähne et al., 1987):

$$K_0 = 1.57 \times 10^{-4} u^* (600/Sc)^{1/2}. \tag{2}$$

Here u^* is the friction velocity of the wind and the expression is supported by observations of gas transfer at a clean, rough surface (moderate or high winds). While this is nominally the "non-breaking" fraction, microscale breaking may be an underlying mechanism of this transfer and more generally expresses the direct (and linear) effect of wind shear on gas transfer. The simple relationship to friction velocity is likely to be confounded by the effects of surfactants at low wind speeds and possibly by saturation of microscale breaking at high wind speeds. Buoyancy effects are also ignored and, as described below, a simple relationship of wind stress to wind speed (ignoring sea state) is arbitrarily imposed. Nevertheless, this simple model serves as a useful test bed and we will not modify the "non-breaking" formulation in this study. Friction velocity is related to wind speed at a specified height by a drag coefficient:

$$\text{windstress} = \rho_a u^{*2} = \rho_a C_D U^2. \tag{3}$$

Here ρ_a is the density of air, C_D is the drag coefficient and U is wind speed. In the figures of this paper we use a simple expression for drag coefficient (sensitive to wind speed but not sea state) proposed by Large and Pond (1981) for neutral atmospheric stability. In the model it is assumed that the contribution of wave breaking to transfer velocity is proportional to fractional whitecap coverage, W. The coefficient was based on calculations of bubble-mediated transfer, and therefore depends on the solubility of the gas, but here we will use a single formula, appropriate for CO_2 at 20°C (Woolf, 1997):

$$K_b = 850W \tag{4}$$

(coefficient in cm h^{-1}). Further, it is assumed that the transfer velocity is a simple sum of the two contributions

$$K = K_0 + K_b. \tag{5}$$

The transfer velocity according to this simple "hybrid model" in its original form is included in Fig. 1. Below, we will consider revisions of this model arising from different parametrizations of whitecap coverage.

2.2. *The energy balance of surface waves in deep water*

The growth and saturation of surface waves in deep water is generally described by the input of energy from the wind and a dissipation of wave energy primarily by wave breaking. (Non-linear interaction only redistributes energy, but wave propagation must also be considered in the local energy balance.) Thus, any formulation of wave breaking must be consistent with the observed development of wind waves in a steady wind. Wave height is generally a complicated function of the history of wind forcing both locally and far from the locality. Typically, seas will be larger following persistent high winds and where seas have sufficient sea room or "fetch" to build. The following formulae for significant wave height, H (in m), by Carter (1982), based on JONSWAP observations, encapsulate the tendency of wave heights to increase with wind speed (U, in m s^{-1}) and with fetch (X, in km) up to a fully developed wave height.

$$H = 0.0163X^{0.5}U \quad \text{at fetch } X\text{, developing waves} \tag{6}$$

$$H = 0.0246U^2 \quad \text{for fully developed waves.} \tag{7}$$

Note that at low wind speeds the fully developed state (eq. 7) is achieved within a fairly short fetch, but at higher wind speeds the wave height may be limited by fetch (eq. 6) in many circumstances. These equations apply to a pure wind sea and uniform winds; wave height may greatly exceed the fully developed height (eq. 7) in swell conditions where waves remain from earlier, and often distant, strong wind forcing.

In order for waves to grow, wind input must exceed dissipation, while the concept of a "fully developed sea" implies a balance between wind input and wave breaking at long fetches. The simplest models of energy input and dissipation assert a proportionality of both with the cube of wind speed (or friction velocity). This relationship is deducible by dimensional arguments and appears broadly correct, but observed wave growth requires either or both of the input or dissipation to be sea-state dependent. There are a number of models of deep-water wave breaking. Advanced operational wave models generally describe energy dissipation in terms of the wave spectrum (e.g. Wu, 1988). Two of the most established models are those of Hasselmann (1974) and Phillips (1985), which predict a linear and a cubic dependence on the spectral density of the waves, respectively. Measurements of ambient noise, which should be closely related to energy dissipation, appear to be reasonably consistent with either of these models (Felizardo and Melville, 1995). In practice, the two models predict fairly similar dissipation rates, proportional to the cube of friction velocity and increasing slightly with wave development (Zhao and Toba, 2001). The Hasselmann model is incorporated in most modern wave models (Wu, 1988). This could form the basis of a gas transfer model based on wave model output, but formulation in terms of wave spectra is inappropriate for widespread observational estimates of gas transfer due to the paucity of observed wave spectra. Instead, we consider below a simpler formulation requiring no spectral information.

The simplest non-spectral wave models mimic the observed growth and plateau of wave heights by simple formulations. The model of Donelan (1977) ignores dissipation entirely and instead supposes that wind input vanishes as the phase speed of the dominant waves approaches a multiple of the wind speed. If instead we impose an energy input to waves that is proportional to the cube of wind speed (irrespective of wave development) what expression for dissipation rate is appropriate in order to satisfy the saturation condition (eq. 7)? The simplest solution is a dissipation rate, E, related to the wind speed and wave height by:

$$E \propto UH. \tag{8}$$

The Hasselmann model, the Phillips model and eq. (8) all offer methods for estimating energy dissipation by wave breaking and subsequently gas transfer related to breaking waves. Establishing which if any model is satisfactory is more difficult. As mentioned above, measurement of ambient noise is a relatively direct approach to estimating energy dissipation. Felizardo and Melville (1995) have analysed the correlation of ambient noise to wind parameters, wave parameters and the energy dissipation predicted by the Hasselmann and the Phillips models. The correlation to total wave amplitude (including swell) was poor, but the results are too inconclusive to identify an ideal formulation. A more widespread methodology is to measure whitecap coverage by simple visual observation or analysis of photographs or video. In general, the fractional area of the sea surface whitened by surface foam or plumes of bubbles is of interest. Slightly different terminology is used by different investigators; some subdivide the whitened area into different classes, for example between active breaking (whitecap) or new foam patches and aged foam or elongated streaks (Ross and Cardone, 1974), or between active breaking (whitecap) and surfacing plumes (foam) (Bortkovskii and Novak, 1993). More commonly measurements are of "total whitecapping" by photographic or video means where the primary criterion is simply resolution of a sufficiently whitened area. If the threshold is high, the measured coverage corresponds closely to the area of active breaking ("*WA*"), while analysis with a lower threshold yields a coverage that is about a factor of 10 greater and includes the surfacing bubble plumes within seconds of each breaking wave ("*WB*" or "*W*") (Monahan and Woolf 1989; Monahan and Lu, 1990). Either measurement is likely to broadly reflect levels of energy dissipation, at least by breaking waves sufficiently large to produce a detectable whitecap (Hanson and Phillips, 1999). A simple proportionality between whitecap coverage and energy dissipation has been argued by many authors and is supported by the relationship between submerged air volume and energy dissipation found by Lamarre and Melville (1991). Whether the gas transfer associated with large breaking waves is primarily by turbulence or bubble-mediated exchange, it follows that the gas transfer should scale with whitecap coverage.

2.3. *Parametrization of wave breaking and whitecap coverage*

The simplest empirical parametrizations of whitecap coverage and wave breaking are in terms of wind speed alone. For example, Monahan and O'Muircheartaigh (1980) propose the following relationship for whitecap coverage in terms of the 10 m elevation wind speed, U:

$$W = 3.84 \times 10^{-6}U^{3.41}. \tag{9}$$

Here and below, $W = WB$, the fractional coverage of mature whitecaps. This relationship was used for the original hybrid model of transfer velocity described above. However, a similar analysis of a different set of observations yields a different relationship (Zhao and Toba, 2001):

$$W = 2.98 \times 10^{-7} U^{4.04}. \tag{10}$$

Though "wind speed only" formulations are commonly used, it was realized during early research that a simple relationship to wind speed or friction velocity is not expected, and that there is a clear theoretical case to relate whitecapping to the wave field (Cardone, 1969; Ross and Cardone, 1974). Since then a number of studies, using data sets of varying size and quality, have sought to find a good parametrization of whitecap coverage (e.g. Ross and Cardone, 1974; Monahan and Monahan, 1986; Bortkovskii and Novak, 1993; Hanson and Phillips, 1999; Xu et al., 2000; Stramska and Petelski, 2003). Here we rely primarily on a study by Zhao and Toba (2001) who collected together very many data sets, including a variety of sea states and wind speeds up to and in excess of 20 m s^{-1}, and tested statistically a number of parametrizations. The trials included parametrizations in terms of wind speed or friction velocity alone and parameters that decreased with increased wave development. Two parameters, R_B and R_H, which increase with wave growth, performed much better than the other candidates. The use of R_B as a breaking wave parameter in a formula for gas transfer has been proposed by Zhao et al. (2003). Here, we single out the non-dimensional parameter, R_H:

$$W = 4.02 \times 10^{-7} R_H^{0.96} \tag{11}$$

$$R_H = u^* H / \nu_a. \tag{12}$$

In eq. (12), H is the significant wave height of the sea and ν_a is the kinematic viscosity of air; together with friction velocity they constitute a form of Reynolds number, R_H, for wind waves. These formulae introduce the sea state, in the form of significant wave height, as a major factor in determining the whitecap coverage, and imply that for a given wind speed, whitecap coverage is greater for a more developed sea. This tendency is implied by the results of the statistical analysis of many data sets by Zhao and Toba (2001) and is qualitatively supported by additional data sets (Monahan and Monahan, 1986; Stramska and Petelski, 2003).

For sea-state-dependent whitecap coverage, the whitecap coverage is not unique for a particular wind speed. Instead, we can combine eqs (6) and (7) with (11) and (12) to calculate a set of curves describing whitecap coverage at combinations of wind speed and fetch (Fig. 2); these are shown together with the two wind-speed-only relationships (eqs 9 and 10). Note that a very broad diversity of whitecap coverage at a given wind speed is predicted by the sea-state-dependent formula, especially at high wind speeds.

In addition to the empirical formula, eq. (11), it is interesting to consider a more theoretical approach, while paying attention to the observations. The similarity of eqs (11) and (12) to eq. (8) may be noticed, and suggests that a formulation based on eq. (8) is reasonable. In order to reach a dimensionless expression relevant to turbulence in the near-surface ocean we propose:

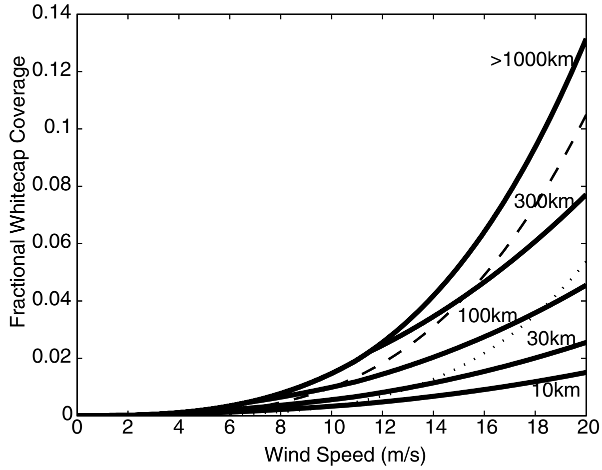

Fig 2. Model relationships of whitecap coverage to wind speed. The standard parametrization of Monahan and O'Muircheartaigh (1980) descried by eq. (9) is shown by a thin dashed curve, the wind-speed-only parametrization of Zhao and Toba (2001) described by eq. (10) is shown by a thin dotted curve and a sea-state-dependent parametrization by a family of thick full curves. Members of this family are plotted for a few fetches as labelled (in km).

$$W \sim R_{Hw} \tag{13}$$

where

$$R_{Hw} = u^* H / \nu_w. \tag{14}$$

Note that we chose the kinematic viscosity in water rather than air; as discussed by Zhao and Toba (2001); this appears to be more appropriate for characterizing the turbulence in the upper ocean. It is also more consistent with the observed sensitivity of wave breaking to temperature (Wu, 1988; Bortkovskii and Novak, 1993), which would be very weak if related only to the viscosity of air. This is sufficiently similar to the empirical result for whitecap coverage (eq. 11) to underpin that result, but also suggests a subtly different parametrization. These two parametrizations are applied to transfer velocity in the next section.

3. Results

The empirical sea-state parametrization (eq. 11) for whitecap coverage can be substituted into the hybrid model (eqs 2–5) with wave height calculated for various representative fetches (eqs 6 and 7). This new version of the hybrid model is displayed together with the four standard wind-speed-only parametrizations (Fig. 3a).

A slightly different version of the hybrid model is constructed using the theoretical sea-state parametrization of whitecap

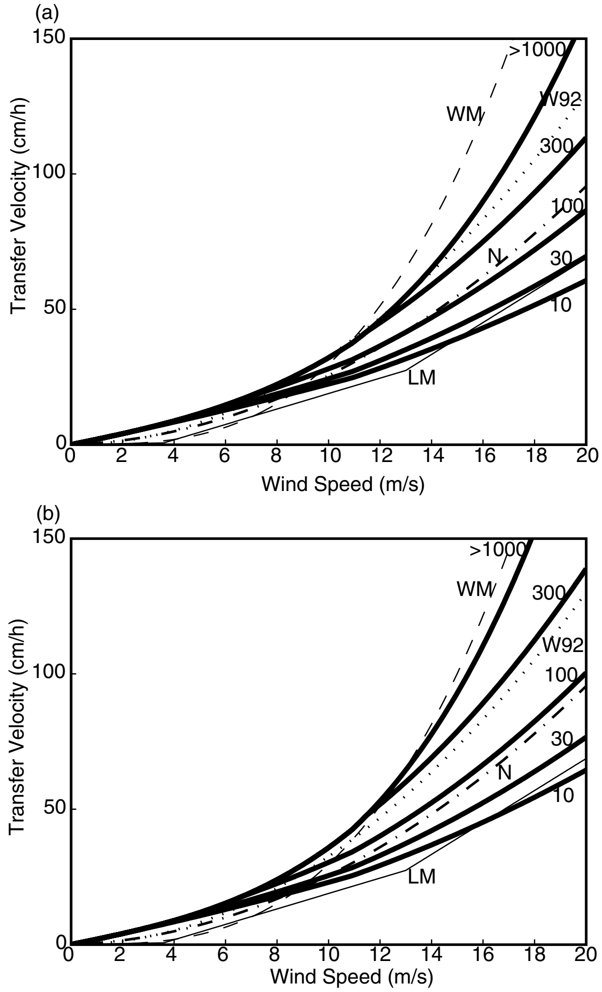

Fig 3. Model relationships of transfer velocity (Schmidt number = 600) to wind speed. Four standard parametrizations (referenced in the main text) are shown as in Fig. 1 together with two sea-state-dependent versions of the hybrid model: (a) based on eqs (4), (5) and (11) and (b) based on eq. (15). For each sea-state-dependent model, the predicted transfer velocity is shown by a family of thick full curves (calculated for the labelled fetch, in km).

coverage (eq. 13) together with a "convenient" coefficient, thus:

$$K = K_0 + 2 \times 10^{-5} R_{\mathrm{Hw}}. \quad (15)$$

The coefficient is consistent with observations of whitecap coverage and eq. (4), but has no firm basis. This model is also displayed with the standard parametrizations (Fig. 3b). Note that both sea-state-dependent models exhibit considerable sensitivity to fetch at high wind speeds, and that the slightly greater sensitivity of the second (compare eqs 13 and 11) has a substantial impact on the diversity of values at high wind speeds.

4. Discussion

This paper limits its scope to a consideration in the broadest terms of the influence of sea-state-dependent wave breaking on gas transfer velocities and therefore the treatment of the existing literature is also limited. It is certain that numerous other factors affect estimated transfer velocities (and the value of wind speed paired with each transfer velocity) in various studies, and thence the diversity in parametrizations. Nevertheless, this study demonstrates that variation in sea state, particularly as it affects whitecapping, is likely to be a major factor. The new sea-state-dependent parametrizations span much of the diversity of existing data and parametrizations. There appears to be a general correspondence between the particular experiments largely informing each parametrization and the resulting magnitude of whitecap coverage predicted by the sea-state-dependent formulae. Thus, the high-wind behaviour of LM is informed primarily by laboratory experiments (low fetch and low whitecap coverage), N is informed by a number of experiments but the few data for high winds were taken in coastal waters, while WM is informed primarily by Gas Ex-98—an experiment in the open North Atlantic (McGillis et al., 2001). The results of that study show that gas transfer velocities increase rapidly with wind speed, at least up to wind speeds of 15 m s^{-1}, an increase that is difficult to explain without a mechanism related to large breaking waves. Measurements in high winds on shelf seas (Watson et al., 1991; Nightingale et al., 2000) also show evidence of greatly enhanced transfer velocity in high winds, but not to the same degree as reported by McGillis et al. (2001) for the open ocean. Enhancements in transfer at high wind stress in laboratory experiments are generally more modest and in at least one important study (Ocampo-Torres and Donelan, 1994) there is no evidence of an acceleration in gas transfer at very high winds. W92 is less strongly associated with particular experiments, but the quadratic form mimics a number of observations and the global average exchange coefficient is consistent with isotopic estimates (Wanninkhof, 1992). Not all studies fit neatly into this pattern, but it does appear that far more studies can be reconciled on the premise that breaking waves are a major mechanism of transfer and wave breaking increases with fetch, as proposed here and by Zhao et al. (2003). Here, we will briefly discuss the available evidence.

It is generally difficult to interpret laboratory experiments. In some cases, wave breaking is likely to be enhanced by the shallow water depth, while in others cases friction velocity was estimated using an uncertain drag coefficient. In any case, while we can draw some insight from laboratory experiments, there is little to be gained from developing an empirical parametrization of gas transfer suitable for a wind tunnel. For some field sites, the "deep water" equations described here may be inappropriate if the site is shallow or interaction with currents is strong. For example, sea conditions at the research platform Meetpost Noordwijk near the Dutch coast appear to be influenced by water depth and currents (Kraan et al., 1996; Graham et al., 2004). Other experiments did not sample the high wind speeds that are necessary to test the models described here. We will briefly consider the most suitable experiments.

The deliberate tracer experiments in the southern North Sea summarized by Nightingale et al. (2000), the recent deliberate tracer experiment in the Southern Ocean reported by Wanninkhof et al. and the carbon dioxide measurements in the North Atlantic reported by McGillis et al. (2001) are among the most useful. In the first case, wave height information is available within the original paper and confirms (by applying eqs 6 and 7) that at the seven highest wind speeds reported (see Table 1 of Nightingale et al., 2000) the sea state was far from fully developed; for these seven cases the implied fetch was 180 km or less. Thus, while it is unlikely that much of the "scatter" of these seven results can be explained, the support of these results for relatively moderate transfer velocities in high winds (as in N) can be attributed to the sea state. In the case of the open ocean experiments, we have extracted daily wave-height estimates for the locality from a wave climatology (Caires and Sterl, 2005). These confirm that the highest winds in both experiments were accompanied by wave heights indicative of a fully developed sea. The results from the North Atlantic supported WM, while the recent Southern Ocean results are compatible with both W92 and WM. These observations again broadly support our interpretation.

The brief discussion above has demonstrated that the few reports of relatively high transfer velocities do coincide with a mature sea, while those reporting more moderate transfer velocities are associated with only partly developed seas. This suggests that a sea-state-dependent parametrization of transfer velocity is appropriate, but confirmation will require both a more thorough analysis of existing key experiments and more field data on transfer velocities in a range of wind and sea conditions.

Parametrization of whitecap coverage remains difficult. Here, we have adopted formulae that are supported by a theoretical argument and by data sets collected by Zhao and Toba (2001). However, even within this collection there is one small set of data (Xu et al., 2000) that supports an opposing theoretical argument and parametrization. Each non-dimensional parameter used here implies a temperature dependence, but this dependence has not been proven. Many published data sets were not included in the study of Zhao and Toba (2001). More data, including whitecap and ambient noise measurements, are required to resolve parametrization issues.

The relationship of transfer velocities to whitecap coverage is also highly uncertain. Woolf (1997) has described a relationship between whitecap coverage and gas transfer based on calculations of bubble-mediated transfer (eq. 4). However, substantial uncertainty remains in the magnitude of bubble-mediated transfer and other mechanisms. The dependence of transfer on water temperature and upon the molecular properties of the gas also requires further work. The transfer related to "shear", eq. (2), also requires much attention but is outside the scope of this paper, as is the relationship of surface drag to wind and sea state. It should be noted that the formula used to relate drag coefficient to wind and sea state has a significant effect on the curves appearing in the figures of this paper, but the general thrust of this paper is robust to assumptions about drag coefficient since the sensitivity of whitecapping to sea state (according to eqs 8 or12) is stronger than the effect of sea state on drag coefficients.

The parametrizations presented above are prototypes of a new approach to mapping global transfer velocities. We have chosen to adopt a particular parametrization that includes wind speed and significant wave height, since satellite-borne radar altimeters can retrieve both of these. It should also be possible to implement parametrizations requiring wave period (Zhao et al., 2003; Gommenginger et al., 2003). Passive microwave radiometry might be used to retrieve whitecap coverage more directly (Monahan, 2002). Another approach would be to apply the dissipation terms in operational wave models to the calculation of transfer velocities. These approaches may prove to have significant advantages over those based solely on wind speed or radar backscatter cross-sections.

The prototype parametrization of gas transfer described in this paper requires both refinement and validation before it is applied. Two critical refinements are (1) defining dependence on water temperature and salinity, gas diffusivity and solubility, and (2) defining carefully the interrelationships of wind speed, wind stress and sea state. The first of these is fairly straightforward for K_0, assuming a simple relationship to Schmidt number, but for K_b is more difficult due to the complexities of bubble-mediated transfer. With regards to the second, the effect of sea state on drag coefficients has been ignored in this paper but should be included in later models. The behaviour of drag coefficients and of whitecapping at very high wind speeds also requires further attention, though we note that the data analysed by Zhao and Toba (2001) included wind speeds in excess of 20 m s^{-1}. Future "validation" exercises can include testing the relationship of whitecap coverage or wave energy dissipation to wind and sea state, but ideally should also include gas transfer velocity data and ancillary measurements of adequate quality to directly test proposed parametrizations of gas transfer velocity. Particular attention needs to be paid to the presence of swell; as currently written eqs (12) and (14) include the contribution of swell to significant wave height, but it is arguable that swell should be excluded.

5. Conclusions

Sea-state-dependent wave breaking is likely to be a major cause of the diversity of gas transfer velocities at a given wind speed, particularly at high wind speeds.

Future attempts to parametrize gas transfer velocities (experimental and theoretical) should address wind-wave development.

Retrievals of transfer velocity from satellites based on both wind speed (radar backscatter cross-section) and significant wave height may be more accurate than those based on radar backscatter cross-section alone.

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