Anais X SBSR, Foz do Iguaçu, 21-26 abril 2001, INPE, p. 753-757, Sessão Especial - Workshops

Improved estimates of gas transfer using scatterometer

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1. Introduction

Current estimates of air-sea gas exchange vary by over a factor of two depending on the parameterization of the piston velocity from wind speed. Uncertainties in the parameterization occur because wind speed is not necessarily an accurate descriptor for the characteristics of the turbulent water boundary layer. Parameterizations derived from wind tank studies cannot account for all the processes occurring in the real ocean. Recent experimental tank and *in situ* results suggest that the dynamics of capillary waves are responsible for most gas transfer. In these tank experiments, gas transfer shows a higher correlation with the mean short wave slope than with wind speed. We want to calculate the gas exchange coefficient, E, from scatterometer measurements of surface roughness, which is related to the amplitude (or mean short wave slope) of gravity-capillary waves of approximately 4.5 to 6 cm. The exchange coefficient derived in this manner has higher spatial and temporal resolution than traditional estimates parameterized with wind-speed and over a similar altimeter-based approach. This increased resolution implies higher variability in E and likely more large values. From a global perspective the new parameterization of gas transfer will enable improved understanding of the magnitude and scales of variability in the uptake of fossil-fuel CO_2 by providing unprecedented coverage and resolution of E, a major source of uncertainty in the flux calculation.

2. Importance of air-sea gas transfer

In a scenario of continuing emissions of greenhouse gases, it is crucial to quantify the role of the ocean as sink or source in the global balance. The oceanic component of the global budget changes in space and time due to the varying concentrations in the atmospheric and oceanic pools and of the rate of exchange between the two. Here we address the crucial link of gas exchange between atmosphere and ocean. Current estimates of the air-sea gas exchange coefficient, E, vary by over a factor of two depending on the parameterization from wind speed. Uncertainties in the parameterization occur because wind speed is not necessarily an accurate descriptor for the state of the turbulent water boundary layer. Although the sign of the local CO_2 flux depends on the difference in partial pressure between ocean and atmosphere, the integrated flux estimate can change sign when using different parameterizations of E. We present here a new method to determine E which uses QuikScat measurements of sea surface roughness, and thus provides a more direct measure of air-sea exchange than a wind-based parameterization.

If we can constrain the value of the air-sea exchange coefficient and use scatterometer measurements to obtain its value, we will improve our understanding of the ocean's role in the uptake of fossil-fuel CO_2 as well as of the magnitude of the scales of variability. Existing estimates indicate that the variability in the air-sea exchange is of comparable order of magnitude as the mean (Lee *et al.*, 1998). It is thus of paramount importance that we parameterize E in a manner that maximizes the resolution of existing sampling systems.

3. A global approach to estimate E using surface roughness

One approach to better quantify the exchange coefficient is to characterize the energy contained in cm-scale capillary waves which are thought to be responsible for gas exchange (*e.g.*, Bock, 1999). Microwave scatterometer measurements of the ocean surface, such as those made by QuikScat, NSCAT, and ERS-1/2, provide the exciting possibility of directly quantifying the dynamics of gravity-capillary waves, as they make direct observations of ocean surface roughness at the most relevant scales for air-sea gas transfer. The scatterometer measures the radar cross-section or returned power from quasi-Bragg scattering associate with waves of 4.5–6 cm in length, known as gravity - capillary waves. Soon after the 4.5–6 cm waves appear on the ocean surface they generate parasitic capillary waves which are responsible for the bulk gas transfer as well as for the dissipation of the longer (gravity-capillary) waves. Since the time scale for this process is short (tens of seconds), the energy cascade from the 4.5–6 cm gravity-capillary waves to capillary waves is a very localized process. Consequently observational methods which minimize averaging are needed to characterize the sea surface, such as the snapshots provided by remote sensing.

A very similar approach is taken by Frew *et al.* (1999). They estimate the gas transfer velocity surface roughness due to small-scale waves from radar backscatter. The differential scattering of the Ku-band and the C-band pulses of the TOPEX/Poseidon altimeter allow small-scale waves to be distinguished from the mean square slope. By relying on a different sensor, our approach is complementary and maximizes available sampling resources.

The inadequacy of the wind speed to parameterize the rate of gas transfer across the water surface becomes clear when considering the partition of the transfer of momentum from wind to the surface waves. Kitaigorodski (1970), in a summary of research on momentum transfer from wind to waves, concludes that 80% of wind momentum is linked to capillary waves and the rest to longer waves. Theoretical calculations (Miles, 1962) suggest that normal stresses (indirectly related to the wind) are more important than tangential stresses in energy transfer from wind to waves. This is also reflected in more recent calculations of Fedorov and Melville (1998) and tank observations of Peirson and Banner (2000). These findings, in addition to the complicated underlying nonlinear dynamics between long and short capillary waves, indicate that wind speed is not the best indicator of the gas transfer across the air-ocean interface. An additional disadvantage of wind-based parameterizations is the spatial smoothing inherent in wind processing of scatterometer backscatter observations (see below).

Ideally a direct measurement of the actual energetics of the boundary layer within the top 10μm is desired. Lacking that, we propose to use surface roughness as an indicator of energetics to obtain gas exchange rates. The bulk of air-sea gas transfer is associated with the presence of capillary waves (Jahne and Haussbecker, 1998; Bock, 1999). By accounting directly for the spatial distribution and amplitude of gravity-capillary waves, we can provide an improved determination of gas transfer rates.

4. New estimates of gas transfer from the gravity-capillary wave spectrum

This approach is based on the backscatter cross section per unit area, σ_0. An quick look at the image of σ_0 overlaid with wind speed using reveals that the wind vectors are less variable due to median filtering.

We assume that the ocean surface consists of long gravity waves which carry short capillary waves. Since the two surfaces are statistically independent in most cases, the scattering cross section of the composite rough surface may be approximated by calculating the well known Bragg scattering (Valenzuela, 1978; Phillips, 1988) from each wind vector cell with:

$$\sigma_0 = 4\pi k^4 cos^4\theta F_1(\theta)\Psi(2ksin\theta, 0) \tag{1}$$

where: θ is angle of incidence, $k(k_x, k_y)$ is radar wavenumber for QuikScat corresponding to 4.5 cm wavelength, $F_1(\theta)$ depends on the polarization of the transmitted and received signal, and $\Psi(k_x, k_y)$ is the two dimensional surface wave spectrum such that:

$$(\bar{\xi})^2 = \int \Psi(k)dk \tag{2}$$

where $(\bar{\xi})^2$ is the mean square surface displacement. We will use for example the spectrum of the equilibrium range of limiting gravity-capillary waves (Phillips, 1988) for the capillary wave spectrum $\Psi(k)$

$$\Psi(k) = \alpha cos\phi^{1/2} k^{-7/2}. \tag{3}$$

where α is a constant, ϕ is the angle between wavenumber k and the wind. This results, for a given long wave slope and direction of propagation, in backscatter cross section per unit area:

$$\sigma_0(\theta, \phi) = 2^{-3/2} \pi \alpha cos\phi^{1/2} (ksin\theta)^{1/2} cos(\theta)^4 F_1(\theta). \tag{4}$$

The true σ_{obs} observed by QuikScat is a weighted sum over all possible slopes θ which gives:

$$\sigma_{obsv}(\phi) = \int \beta(\theta) \sigma_0(\theta, \phi) d\theta. \tag{5}$$

Here $\beta(\theta)$, the probability distribution of long wave slopes θ, depends on wind speed and direction, as given in Liu *et al.* (1995).

The observed radar return from the ocean, σ_0, also has observed dependence on azimuth wind/antenna angle. This dependence is well known; it is the basis for the vector wind direction estimate. This dependence, modeled here as $cos\phi^{1/2}$, will be removed in an integrated fashion from the spectral estimates, as we know the derived angle between antenna and wind for each cell. The resulting function will no longer be azimuth wind/antenna dependent. The value of this integrand is the input for the gas transfer estimates. The only external geometrical parameter at this stage is the angle of incidence θ which again is known for each cell and hence will be accounted for.

For each QuikScat cell (25km x 25km) we will calculate the spectral constant α and then use Equation(2) to estimate the mean square surface displacement for the waves of 4.5 to 6 cm wavelength. This parameterized displacement gives us the mean capillary wave slope as Mss (for waves of $k > 0.5cm^{-1}$):

$$Mss = (\int_{1/2cm^{-1}}^{\infty} k\Psi(k)dk)^{1/2} \tag{6}$$

Capillary waves of wavelengths smaller than 2 cm are primarily responsible for the bulk of gas transfer occurring across the interface. To calculate the gas transfer rates we will use results of Bock (1999), with measurements of *in situ* gas transport for a wide range of short wave slopes.

5. Conclusions

There is a great need for rapid global estimates of the CO_2 gas fluxes. This information is critical implications ranging from basic science to industrial applications. Current observations, most frequently in situ observations, however precise do not allow for a global coverage. Satellite, microwave observations are the only hope of achieving the stated goal.

3. References

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