Oceanic whitecaps: Sea surface features detectable via satellite that are indicators of the magnitude of the air-sea gas transfer coefficient

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Stage A whitecaps (spilling wave crests) have a microwave emissivity of close to 1. Thus if even a small fraction of the sea surface is covered by these features there will be a detectable enhancement in the apparent microwave brightness temperature of that surface as determined by satellite-borne microwave radiometers. This increase in the apparent microwave brightness temperature can as a consequence be routinely used to estimate the fraction of the sea surface covered by stage A whitecaps. For all but the very lowest wind speeds it has been shown in a series of controlled experiments that the air-sea gas transfer coefficient for each of a wide range of gases, including carbon dioxide and oxygen, is directly proportional to the fraction of the sea surface covered by these stage A whitecaps.

1. Introduction

When wind waves break trapping air this air goes into the formation of great numbers of bubbles in a sub-surface bubble plume. The plume that forms just as a wave breaks is very rich in bubbles (the α-plume of Monahan and Lu 1990), and is "capped" at the sea surface by a bright stage A whitecap (see figure 1). Once the wave stops spilling, turbulent mixing, coupled with the loss of the larger bubbles as they rise to the surface and break, results in the evolution of the α-plume into a larger, less bubble rich, β-plume, which is topped at the sea surface by a decaying foam patch, or stage B whitecap, which is paler and less distinct than the original stage A whitecap.

It has long been known (see, e.g., Ross *et al* 1970; Nordberg *et al* 1971; Stogryn 1972; Webster *et al* 1976) that spilling wave crests (or stage A whitecaps, as defined in Monahan and Lu 1990) will markedly enhance the emissivity of the portion of the sea surface they cover, making that portion of the sea surface approximate a microwave black body with an emissivity of close to unity. This increase in sea surface emissivity that occurs when even only a very small portion of the sea surface within the "footprint" of a satellite-borne microwave radiometer is covered by stage A whitecaps causes an increase in the microwave brightness temperature as recorded by the radiometer. This enhancement in microwave brightness temperature has long been proposed as a means of remotely measuring surface wind speeds (see Gloersen and Barath 1977 as regards SMMR applications, and Schluessel and Luthardt 1991 as regards SSM/I applications). These applications follow from the monotonic dependence of whitecapping on wind speed (Monahan 1971; Monahan and O'Muircheartaigh 1980, 1986), or more precisely on the fact that wind speed can be expressed as a monotonic function of oceanic whitecap coverage (Monahan and O'Muircheartaigh 1981, 1998).

Ross and Cardone (1974) predicted the increase in microwave brightness temperature that would result from the presence of whitecaps, and Wang

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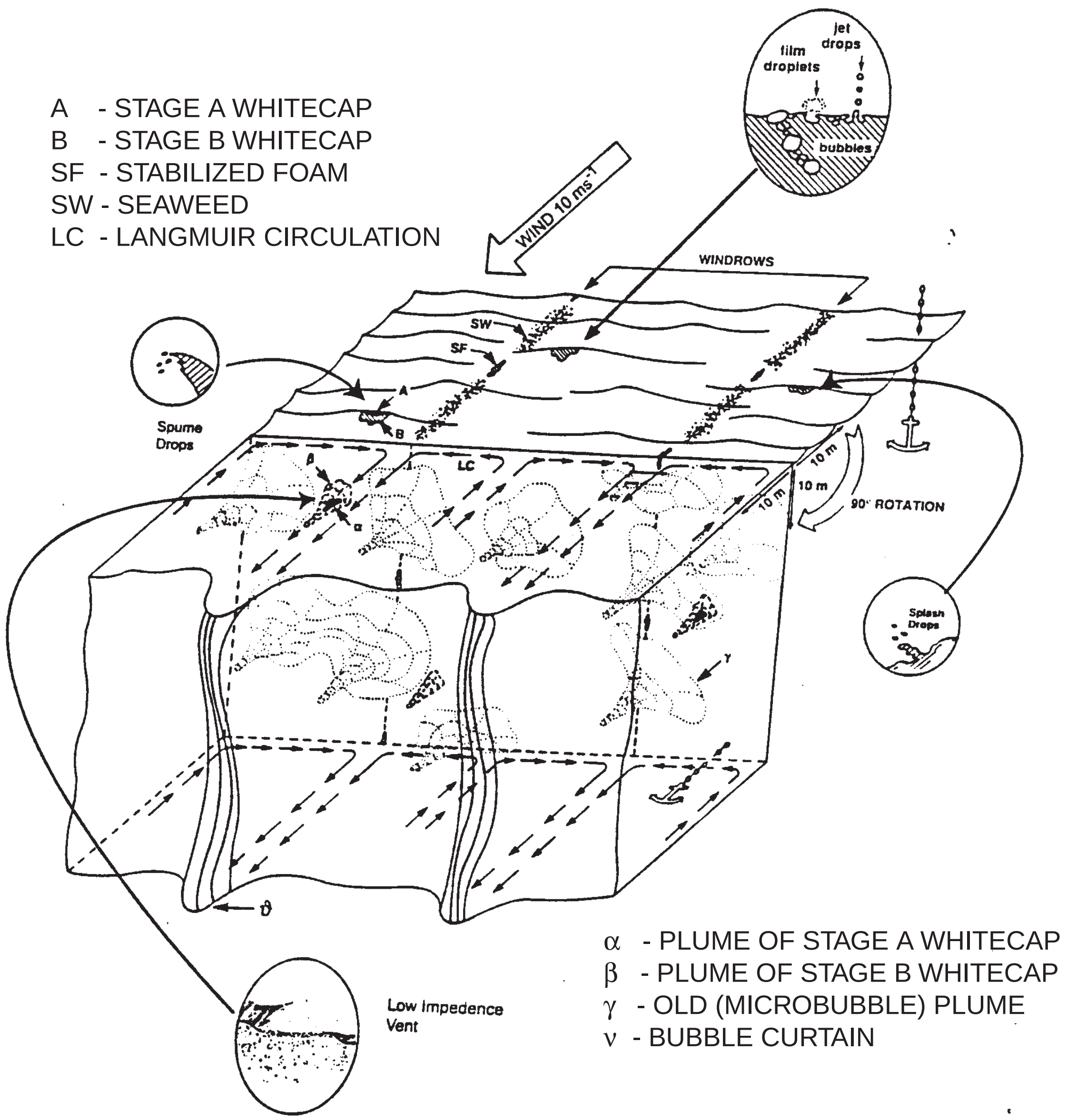

Figure 1. Diagram simultaneously depicting top and bottom view of a rectangular portion of sea surface when the winds are blowing (see arrow) 10 m/s. The top view **(A)** includes several stage A whitecaps whose collective presence can be detected via satellite-borne radiometers, as well as a variety of other features that can be detected optically. The bottom view **(B)** includes the various bubble plumes that hang beneath whitecaps in each stage of their decay. The top, magnified, insert shows how sea spray droplets are produced by the bursting of whitecap bubbles. The left and right inserts depict the mechanisms of direct drop production associated with breaking waves. The bottom insert shows schematically how a whitecap, and its associated bubble plume, serves as a low impedence vent facilitating the turbulent transport of gases to and from the immediate sea surface. Composite of elements adapted from figure 1 of Monahan and Lu (1990), figure 1 of Andreas *et al* (1995), and figure 1 of Monahan and Spillane (1984).

et al (1995) made detailed measurements in a large wave basin of the increases in brightness temperature associated with measured increases in stage A whitecap coverage.

It follows that the fraction of the sea surface covered by stage A whitecaps can be determined remotely from satellite radiometric measurements of the degree of enhancement in microwave brightness temperature of the ocean surface. If the fraction of the sea surface covered by stage A whitecaps can be determined by satellite remote sensing, then the magnitude of a range of sea surface exchange processes that are controlled by the extent of whitecap coverage can also be inferred from these same satellite measurements. In this paper the procedure whereby the magnitude of sea surface gas transfer coefficient can be determined from the degree of enhancement of the sea surface microwave brightness temperature will be discussed.

2. Whitecap coverage and the gas transfer coefficient

The suggestion that the air-sea gas transfer coefficient could, like the wind speed, be determined from the fractional whitecap coverage of the ocean surface was put forth by Monahan and Spillane (1984). Kerman (1984) likewise noted the potential role of breaking waves, and the resulting whitecaps and bubbles, in facilitating the air-sea transfer of various gases. Monahan and Spillane (1984) conceived of the whitecap and its associated bubble plume as serving as a "low impedence vent" that enhanced the air-sea exchange of gases such as carbon dioxide. Such a turbulent vent is depicted in the bottom insert in figure 1, and is in this figure identified (via an arrow) with a stage A whitecap and its associated α-bubble plume. Monahan and Torgersen (1990) proceeded to explicitly parameterize the air-sea gas transfer coefficient in terms of fractional stage A whitecap coverage, making use of the results obtained using a laboratory whitecap simulation tank. These models suggest that the gas transfer coefficient should vary in a linear fashion with stage A whitecap coverage. (The stage A whitecap, or more particularly its α-plume, because of its great buoyancy and many bubbles, is much more effective at stirring the ocean surface than is the β-plume, which is characterized by a much lower concentration of bubbles, and which thus lacks the buoyant potential energy of the new α-plume.) That this indeed was the case was demonstrated for a variety of gases (including oxygen, helium, and sulfur hexifluoride) in a further detailed series of whitecap simulation tank experiments (Asher *et al* 1992, 1995A).

3. Microwave brightness temperature and the gas transfer coefficient

That the microwave brightness temperature, as well as the air-sea gas transfer coefficients for some five gases, vary in a linear fashion with the fractional stage A whitecap coverage, and more particularly, that the air-sea gas transfer coefficients (specifically for helium and sulfur hexifluoride) vary in a linear manner with the microwave brightness temperature, was demonstrated in the large wave basin mentioned previously (Asher *et al* 1995B; Wang *et al* 1995). In these wave basin experiments the microwave brightness temperature was measured with a radiometer suspended over the center of the basin. The whitecap coverage was measured with video cameras, one mounted with the radiometer, and others mounted around the perimeter of the basin. The trace gases were first infused into the water in the basin, and then, as the "sea state" (whitecap coverage) in the basin was maintained at a fixed intensity using the wave generators with which the basin was equipped, the concentration in the water of these gases as they varied over time was measured. This experiment was repeated day after day, each day with a different "sea state" maintained in the basin.

4. Preliminary field confirmation

Given that the fraction of the sea surface covered at any instant by stage A whitecaps varies essentially as the cube of the wind speed (Monahan and Lu 1990; O'Muircheartaigh and Monahan 1992), and that at all but the lowest wind speeds, the air-sea gas transfer coefficent is projected in the "low impedence vent" model (Monahan and Spillane 1984) to vary linearly with the fraction of the sea surface covered by stage A whitecaps, it follows from this model that the air-sea gas transfer coefficient, at all but the lowest winds, should vary roughly as the cube of the wind speed. Just such a cubic dependence on wind speed has recently been reported for the air-sea gas transfer velocity of carbon dioxide by Wanninkhof and McGillis (1999). They arrived at this result from their analysis of the data collected during the Gas Ex-98 research cruise in the North Atlantic. Their expression for the air-sea transfer ("piston") velocity for carbon dioxide, as a function of 10-meter elevation wind speed, they plotted in figure 2 as curve WMcG99. Also in this figure is plotted (curve MS84) the early expression found in Monahan and Spillane (1984), and (curve MT90) the later relationship given in Monahan and Torgersen (1990). When the expression for the wind dependence of stage A whitecap coverage reported in Andreas and Monahan (2000), which was obtained from line A1 in figure 2 of Monahan (1989), is used in conjunction with the Monahan and Torgersen (1990) equation, curve MT90 + AM00 is obtained. This preferred relationship appears here as equation (1), where k_E, the gas transfer coefficient is expressed in centimeters per hour, and u, the 10 meter elevation wind speed, is given in meters per second (Monahan 2002).

$$k_E = 2.84 + 1.73 \times 10^{-2} u^{3.2}. \qquad (1)$$

The marked similarity of this curve, based explicitly on the "low impedence vent" formulation of Monahan and Spillane (1984), and the experimentally derived curve of Wanninkhof and McGillis is quite striking. The oft-cited curve (actually the sequence of line segments labeled LM86) of Liss and Merlivat(1986) is also presented

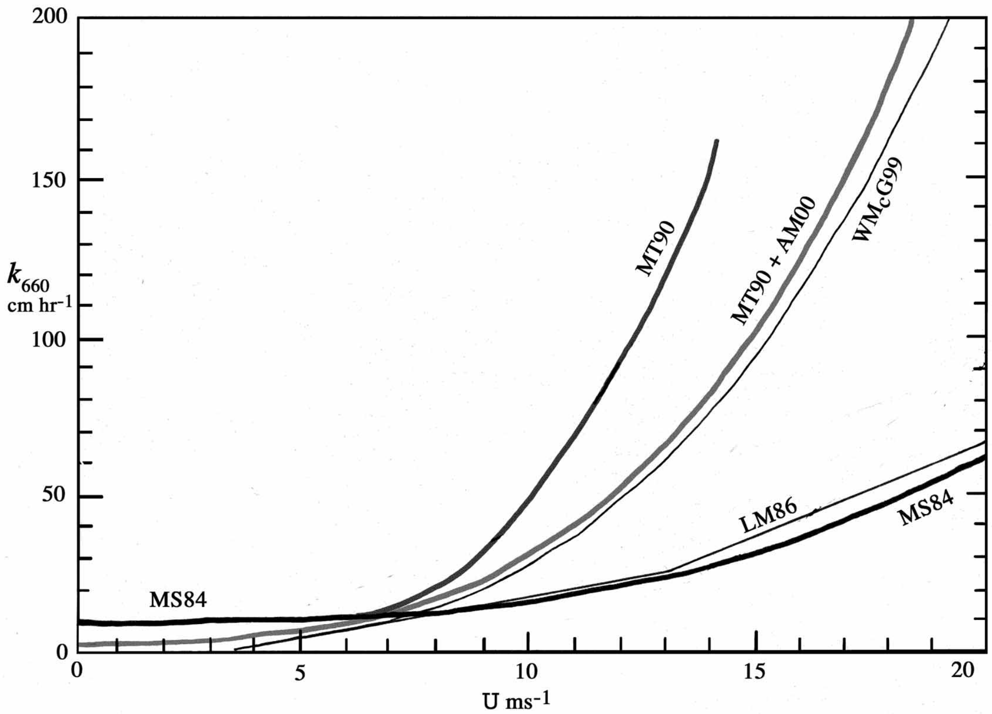

Figure 2. The gas transfer coefficient (or "piston velocity") versus 10m-elevation wind speed. Key: MT90, curve of Monahan and Torgersen (1990); MT90 + AM00, curve based on Monahan and Torgersen coefficients and Andreas and Monahan (2000) whitecap wind dependence; WMcG99, curve from Wanninkhop and McGillis (1999); LM86, wind dependence of gas transfer coefficient as given in Liss and Merlivat (1986); MS84, expression from Monahan and Spillane (1984).

for purposes of comparison on figure 2. A detailed, quantitative, comparison of several of the curves that appear in figure 2 is to be found in Monahan (2002).

5. Conclusions

Field evidence is now available to support the earlier findings, obtained from detailed whitecap simulation tank and wave basin experiments, that the air-sea gas transfer coefficient for gases such as carbon dioxide is, at all but the lowest wind speeds, simply proportional to the fraction of the sea surface covered by stage A whitecaps. The apparent microwave brightness temperature of the sea surface, a quantity readily determined from the data collected by satellite-borne microwave radiometers, has been shown to increase linearly with the increase in the fraction of the sea surface covered by spilling wave crests, i.e., stage A whitecaps. It is thus now time for our community to begin using satellite radiometer data to prepare daily, global, charts of the air-sea gas transfer coefficient. Such maps will be particularly beneficial in estimating the annual uptake of carbon dioxide by the world ocean.

The contribution of evaporating spray droplets, droplets produced by the bursting of whitecap bubbles, to the sea-to-air flux of heat and moisture may at high wind speeds be significant (Andreas *et al* 1995). The rate of production of these jet- and film-droplets (see insert at top of figure 1) has been described as being directly proportional to the fraction of the sea surface covered by whitecaps (Monahan, Spiel, and Davidson 1986), and thus can, like the gas transfer coefficient, be deduced from the apparent microwave brightness temperature of the sea surface as deduced from the output of satellite radiometers.

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