Role of Micro Bubbles in the Ocean

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Abstract

Invisible micro air-bubbles produced by breaking waves are not only responsible for the chain reaction that ultimately leads to the regulation of earth's climate, but also for the convective transport that provides essential life-giving oxygen and carbon dioxide to living things in the ocean and nourishing water to the continent.

Introduction

Production of air bubbles by breaking waves is of vital importance not only to the mechanics of sea-air interface, but also to the living organisms both under and above the sea. The rich concentration of oxygen and carbon dioxide in the water along the seashore is related to the ever-present breaking waves and their associated entertainment of gas bubbles. Therefore, the high concentration of living organisms along shorelines should be attributed to the primary factors of oxygen and carbon dioxide, rather than to the secondary factor of nutrients. In deep ocean, the diffusion of these life giving gases by turbulence of breaking waves is further enhanced by the presence of large internal waves (Kao and Pao 1979, Briscoe 1984) and currents, which can carry and diffuse the gas to a much greater horizontal distance and vertical depth. Living organisms both in the sea and on land are generally classified into two categories: the symbiotic kingdoms of animal and plant. The animal kingdom lives on hydrocarbon and oxygen from plants in order to maintain their primary (exothermal) living process. The plant kingdom lives, however, on carbon dioxide from animals, water and additional radiative energy from the sun to maintain their primary metabolic process. Thus, sufficient concentration of both oxygen and carbon dioxide are vital to the wellbeing of all living systems. On the other hand, the energy of high wind over the ocean is brought about by the buoyant effect of moisture derived primary from the evaporation of micro droplets, which in turn are produced by the popping of entrained micro-bubbles at the sea surface. Micro bubbles in turn are produced by the intense breaking waves under high sea-states (Ling 1988). Here, one notes that this is a major system of nature that regulates the earth's climate by transferring any excessive thermal energy from the upper ocean to outer space. The main objective of this paper is, therefore, to call on the attention of scientists concerning the role played by micro bubbles, which can no longer be neglected in any studies for both living and climatic systems.

Role of micro bubbles on climate

Because both micro air-bubbles and micro water-droplets at the sea-air interface are invisible to the naked eye, they were not taken into consideration for the mechanics of the sea-air interface. These are now measurable by instruments specially designed for such an application. The entraiment energy of air bubbles by breaking waves is responsible for the generation of very large-scale turbulence in the mixed layer of the ocean. Both the intensity and the scale of turbulence are such as to make the diffusivity of heat so high that the temperature gradient in the mixed layer is estimated to be 0.0001°C/m. This makes measurements of heat flux by temperature-gradient method a non-viable task. Likewise measurement made above the sea surface is also difficult, because under high sea-state, there is no clear sea-air interface. The humidity at the sea surface is largely saturated and filled with flying foam and droplets. Attempts to correlate heat and mass exchange by the bulk exchange coefficients of Newton have caused large under estimations of vertical fluxes for high sea-states. This has influenced Ling (1976 and 1993) to consider the simultaneous measurements for the profiles of micro droplets, humidity, temperature, and wind speed at the sea-air interface. The data is then used as ground truth for establishing a set of inter-coupled conservation equations for droplets, humidity, heat and momentum. The solutions from the analyses, covering a wide range of sea states, are applied to formulate the water-vapor flux as a function of reference wind speed and vapor pressures:

$$F_v = 6.54 \times 10^{-4}(e_{10s} - e_{10})u_{10}^2 + 5.58 \times 10^{-4}(e_{ws} - e_{10})u_{10}, \qquad (1)$$

where F_v is the net vertical water-vapor flux in g/m^{2}s, e vapor pressure in milli-bars, and u wind speed in m/s. Subscript 10 is value evaluated at 10m above sea level. Subscripts $10s$ and ws are saturated vapor pressure of water droplets at 10m and saturated-vapor pressure at the sea surface, respectively. The first right-hand term of Eq.1 represents the evaporative flux from flying micro droplets and the second term represents contribution near the sea surface. In contrast, the bulk-vapor flux equation, in common use, is expressed as:

$$F_v = C_v(e_{ws} - e_{10})u_{10}, \qquad (2)$$

where C_v is the coefficient for vapor flux. Under high sea-state, experimentally derived values for C_v varies by a factor of more than 10 times from their mean value. Thus, the confidence level that one might place on Eq.2 is almost nil. The size distribution of micro water-droplets that is responsible for most of the vapor flux is shown in Fig. 1. The ordinate in the figure F_{vd} is the vapor flux contributed by the d size band of droplets evaluated at two mean wave height $\bar{z} = 2$, F_v the net vertical vapor-flux, and Δd the droplet size band. The abscissa indicates the droplet size d in μm. For the case of deep sea fog after storm, the band of droplets that contributed to the vapor flux is very

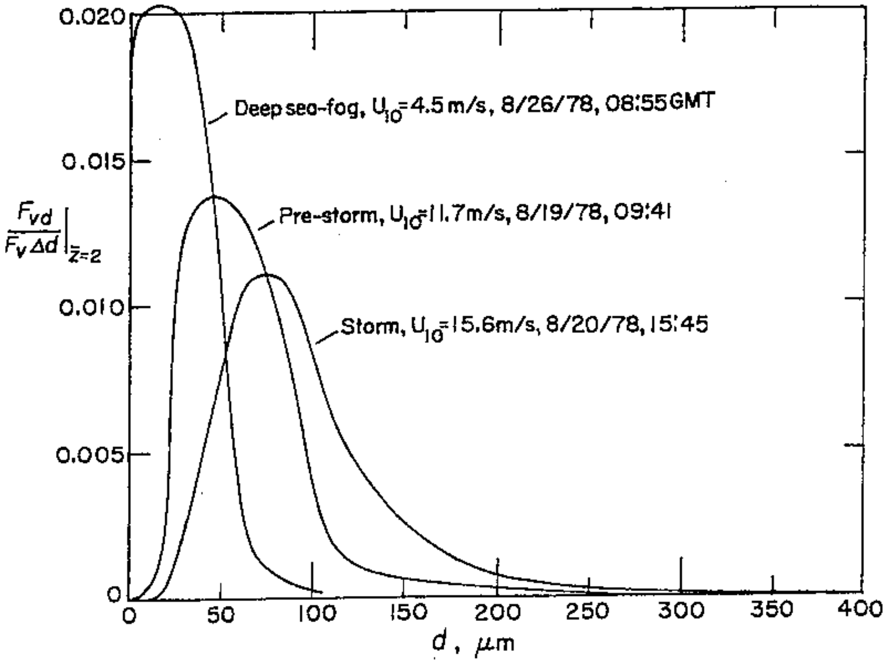

Fig. 1. Contribution to the vertical vapor-flux by different sizes of droplets under different sea-states.

narrow. While under high sea-states the band of contributing droplets is more expanded. Even under extreme sea states, one notes that droplets less than 200μm are responsible for most of the transport process. Contrary to general belief, large water droplets from sea sprays contribute to a relatively small percentage of the vapor flux, because large droplets fall back into the sea too quickly before they have a chance to evaporate within the high humidity zone near the sea surface. On the other hand, micro droplets having larger surface area to mass ratio can be convected by turbulence to a higher level of lower humidity and are completely evaporated.

It is interesting to find out what produces the micro droplets under high sea-states. Contrary to general belief, micro water-droplets are not produced by visible sea sprays and white caps. These generate mainly large water droplets. Invisible micro water-droplets are produced by invisible micro air-bubbles created through the action of intense wave breaking. Micro bubbles in the range of 200 - 400μm are the ones, according to measurements by Ling (1993), that generate most of the micro water-droplets. Micro bubbles have a large internal pressure due to surface tension and their small size. When these bubbles popped at the sea surface, the surface tension energy generates the few 200μm size jet-drops, which fly up from the water surface with a speed of few m/s. In addition, several hundred 40μm film-droplets puff into a miniature smoke-ring. These droplets are invisible to the unaided eyes. However, one can observe with the aid of a flashlight and magnifying glass similar droplets generated by popping of chilled soda water in a clear glass beaker. This makes the smoke ring produced by each popping bubble clearly visible. It is the evaporation of these invisible micro droplets that eventually absorbs approximately 80% of their latent heat from the sensible heat of the upper ocean and 20% from the sensible heat of the lower atmosphere (Ling 1993). The resultant moisture subsequently gathers from a continent-size area of the ocean and spirals into the eye of a storm. The massive concentration of buoyant energy of moisture is what develops into a large storm and hurricane winds, which in turn generates more breaking waves, bubbles, droplets and vapors – – a basic chain-reaction cycle of planetary scale (Ling 1999). The collected water vapor is then lifted directly into the upper atmosphere, where the immense latent heat of condensation released by the moisture is directly radiated out into the free space. Because, even though the upper atmosphere is at a low

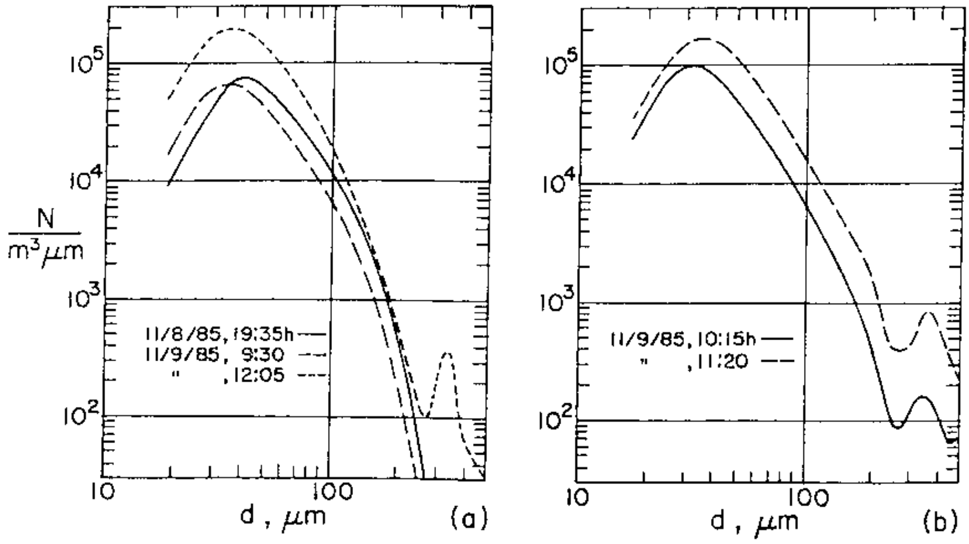

Fig. 2. a) Micro-bubble spectra at the 6m depth. b) At the 3m depth.

temperature of approximately 200°K, the free space is at the absolute 0°K. Further more, before the water vapor is condensed into cloud droplets, the latent heat of condensation has already radiated away. The immense quantity of micro water-droplets in the cloud is transported over land to provide the nourishing rainwater and latent heat of cooling for the continent. This planetary scale of heat and mass transport cycle is so dominant that it is beyond modification by any capping effect of the atmosphere. After all, it ought to be the ocean that regulates the climate, because its heat capacity is many orders greater than that of the atmosphere. One has to marvel that the seemingly insignificant micro air-bubbles can in fact trigger a chain reaction of planetary scale – – more than sufficient for regulating the climate of earth.

An example of micro-bubble spectra taken during the height of a storm in the North Sea is shown in Fig. 2. The sequence of data represent the increase in bubble population under a developing storm with wind speed rising steadily from 13m/s to 22m/s. Note the overall increase of bubble concentration with time. Micro bubbles of less than 50μm are shown to have the maximum number concentration. This is due in part to steady biological origin from zoo- and phyto-plankton, and in part from past breaking-wave sources (Ling and Pao 1988). These micro bubbles were noted to have a long life-span, with a typical time-constant of one-day time; and are responsible for the oxygenation and carbonization of the ocean. Also there is a distinctive second peaking of spectra at the 250 - 400μm band of bubbles. These are important bubbles produced by breaking waves. Figure 3 shows the local time and spatial variability of micro bubble-size concentration corresponding to the spatially averaged bubble-spectra shown in Fig. 2b. One notes the patchy concentration of large micro bubbles in patch size of 20m and 130m apart in spacing – – the basic spatial-distribution of breaking waves. These great patchy plumes of rising entrained micro bubbles are what contribute to the large-scale turbulence in the mixed layer of the ocean. The consequence of such intense eddy-diffusivity is the reason why there is a near zero temperature-gradient in the mixed layer – – the very cause for the general misconception that there is no large heat and mass transfer from the ocean under high sea states. More over, micro bubbles in the size range of 250 - 400μm are found to be the main contributor to the source of micro droplets in the atmosphere during high sea-state (Ling 1993). During the passage of a typical storm, the micro bubbles and its associated micro droplets can transfer into the upper atmosphere a 2.5cm layer of water and its equivalent latent heat of vapor from an

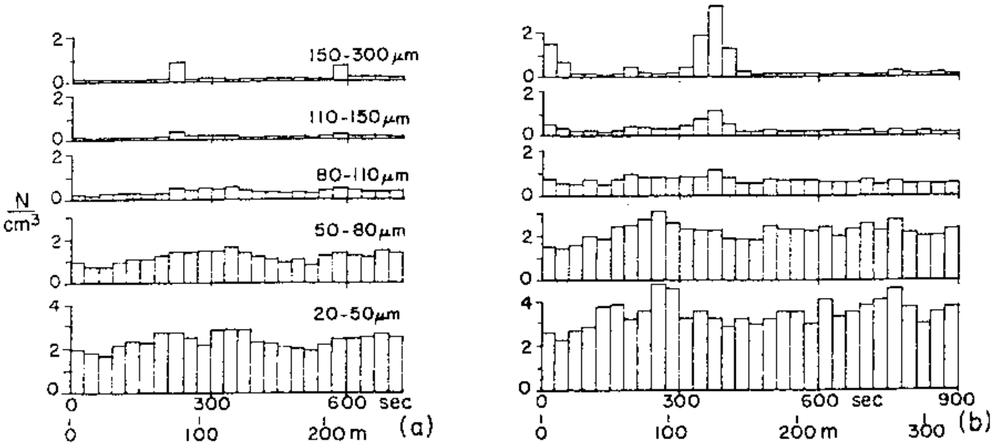

Fig. 3. Local time and spatial variability of micro-bubbles corresponding to bubble spectra showed in Fig. 2b.

area of ocean covering the size of a continent. In the case of a hurricane, the transfer of heat and mass from the ocean could be an order larger.

Method of measurement for micro bubbles

The technique for the measurement of micro bubbles in the size range of 10 to 400μm is shown in Fig. 4. Basically we detected the intensity of the forward 125° ray of specularly reflected-light from the bubble's surface to indicate its size. Bubbles are differentiated from the much weaker scattered light of a non-bubble emitting at the same specific angle. By using two photomultiplier tubes set at a known distance apart both the individual bubble size and its moving speed across the sensing volume can be calibrated and measured to indicate the bubble size-concentration. More detail concerning the detector can be found in Ling and Pao (1988).

Conclusion

This paper demonstrates the important part played by micro bubbles on the regulation of climate, and on the maintenance of the wellbeing of living systems – – a missing factor that can no longer be ignored.

References

Briscoe M.G., (1984) Tides, solitons and nutrients, *Nature* Vol. 312 1, p. 15.

Kao, T.W. and Pao, H.P., (1979) Wake collapse in the thermocline and internal solitary waves, *J. of Fluid Mech.*, Vol. 97, p. 115-127.

Ling, S.C., (1999) Cooling of sea-air interface along a storm track, *The Wind-Driven Air-Sea Interface*, Ed. M.L. Banner, ADFA Document Prod. Ctr., Canberra, Australia.

Ling, S.C., (1993) Effect of breaking waves on the transport of heat and vapor fluxes from the ocean, *J. of Physical Oceanography*, Vol. 23, p2360-2372.

Ling, S.C. and Pao, H.P., (1988) Study of micro-bubbles in the North Sea, *Sea Surface Sound*, Ed. Kerman, Kluwer Academic Pub., p. 197-210.

Ling, S.C. and Kao, T.W., (1976) Parameterization of moisture and heat transfer process over ocean under white cap sea-states, J *of Physical Oceanography*, Vol. 6, No. 3, p. 306-315.

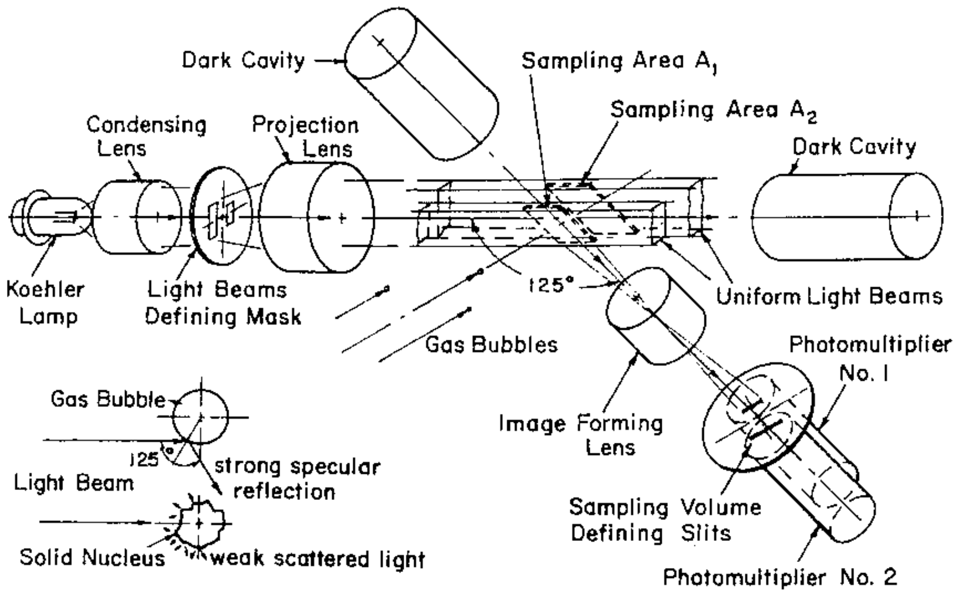

Fig. 4. Detection of micro-bubbles by the darkfield specular-reflection technique.