Wind and Wave Characteristics Observed During the LUMINY Gas Transfer Experiments

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Introduction

The parameterization of the greenhouse gas fluxes between the atmosphere and oceans as function of wind and sea state parameters remains a challenging problem, of key importance for climate modelling. It is well-known that exchange across the air-water interface of gases of poor solubility as carbon dioxide, methane, is governed by the mixing phenomena which affect the very upper water boundary layer in so far as this layer concentrates most of the resistance to transfer. However, these phenomena, dependent on various processes as momentum transfer from wind to waves and currents, turbulence generation in water, wave interaction with shear, wave breaking, thermal stratification or water surface contamination by surfactants, are complex and consequently, have been poorly described up to now. Therefore, most attempts to parameterize gas transfer have consisted essentially in measuring gas transfer rates over a large range of wind and wave conditions both in laboratory and field experiments and then, searching for empirical relations describing the gas flux evolution with wind speed (Liss et Merlivat, 1986; Wanninkhof, 1992). However, the available experimental data exhibit large discrepancies, in particular at high wind speeds, making these first attempts far from being completely satisfactory.

The experiments planned within the framework of the LUMINY project aimed at providing a better description of the dynamics of the air-water interface observed at high wind speeds when wave breaking is dominant, in order to identify more precisely the wind and wave parameters which control gas transfer in such conditions (for a more detailed presentation of the project, see De Leeuw et al (1998)). This paper is devoted to the observations performed during the gas transfer experiments in order to describe the "sea state" and the wind stress at the water surface. The approach adopted to characterize wave breaking is presented in detail and the first results obtained at high wind speeds are discussed briefly.

Experimental procedure

The experiments were carried out in the large wind-wave facility of IRPHE-Luminy Laboratory. This facility is composed of a water-recirculating tank 40 m long, 2.6 m wide and 1 m deep about at the test section, and an air-recirculating tunnel, 3.2 m wide and 1.5 m high (Fig.1). An axial fan and two water pumps allow to generate winds of speed varying between .5 and 14 m/s and water currents of velocity up to 12 cm/s. This facility is also equipped with a big submerged oscillating paddle controlled by an electrohydraulic system, and an absorbing

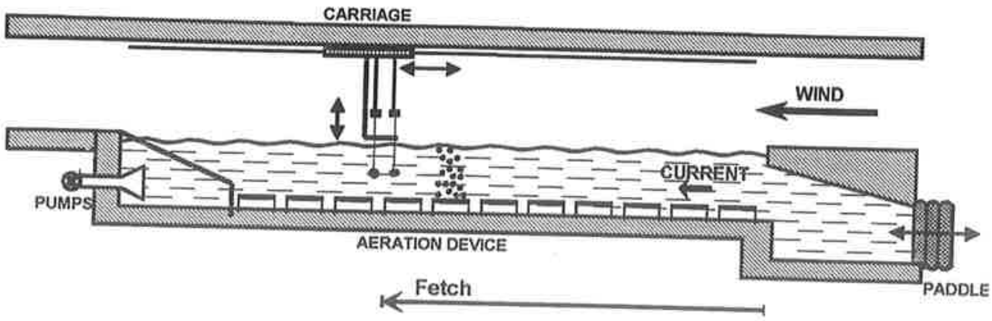

Fig. 1: Schematic view of the IRPHE-Luminy wind wave facility with the instrumentation set up for measuring wind and wave features along the tank.

beach. Thus, steady waves of frequency varying between 1 and 2.5 Hz can be generated as well as localized wave-focusing groups when applied slow variations of the monitoring frequency.

To describe the turbulent air flow properties throughout the surface boundary layer, measurements of the mean velocity U and the instantaneous velocities of the air flow in the longitudinal and vertical directions u(t) and w(t) were carried out at different levels above the water surface, using a Pitot tube and a hot X-wire probe set up on a vertical displacement. Measurements of wave heights were performed by two capacitance wave gauges separated by a distance of 5 cm and placed at the immediate vicinity of the wind probes. The probes were made of thin sensitive wires, .3 mm in diameter. The performance of this technique at high frequencies was high enough to allow derivation of the output signals by analog devices to get records of the time derivative of the wave heights.

To investigate the wind wave development with fetch and the coupled air boundary layer structure, the whole instrumentation was set up on a carriage moving along the tunnel between 14 m and 30 m fetches. In the wind and wave conditions selected for these experiments, this region corresponds with the water tank area where wave breaking of significant intensity first appears and develops.

Results and discussion

The parameter to be known to characterize at best the dynamics of the near surface air and water flows, in particular turbulence in water, is the wind stress τ_0 at the water surface (or the air friction velocity u_* defined as $\tau_0 = \rho_a u_*^2$). To determine this quantity, the vertical turbulent momentum flux τ_z across the air surface boundary layer was first estimated from the X-wire probe signals, using an inertio-dissipative method (see Donelan et al, 1997), and its evolution with height and fetch was investigated. At first, for the whole set of experiments (wind alone, wind + paddle waves or wind + "bubbles"), τ_z was found remarkably constant throughout a near surface layer of well-defined depth increasing with fetch. In addition, as shown in Fig. 2, this quantity exhibits only very small variations with fetch, of order of a few per cent of its value, i.e. variations comparable with the measurement uncertainties. These results thus confirm that the air turbulent boundary layer developing over wind waves can be considered as a constant flux boundary layer and this, as soon as the wave field has reached a certain saturation in energy, i.e. at relatively short fetches (see hereafter). Consistently, only the average value of the air friction velocity was selected to describe the dynamical properties of the near surface flows for each experiment (see Table in De Leeuw et al., 1998).

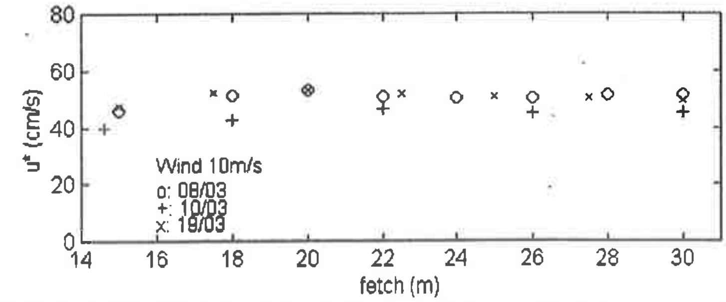

Fig. 2: Evolution with fetch of the air friction velocity u_* estimated at 10 cm height above the water surface by the inertio-dissipative method (here $u_*^2 = \tau_z/\rho_a$), for the three experiments made at 10 m/s wind speed.

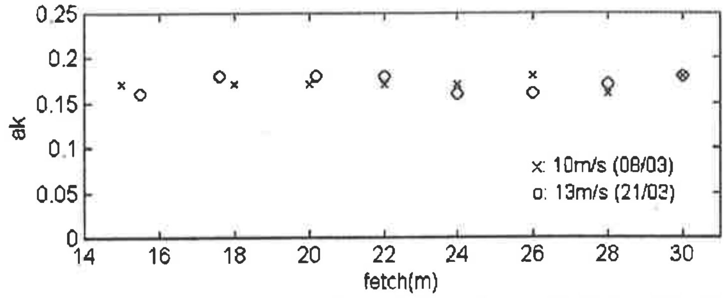

Fig. 3: Evolution with fetch of the mean wave steepness observed at 10 and 13 m/s wind speeds in the large IRPHE wind wave tank.

In order to describe the main features of the wave field developing in the tank during the gas transfer experiments, the signals from both wave probes were first analysed using classical techniques. The evolution with fetch of the RMS wave amplitude, the RMS wave steepness ak, the frequency n_0 and the wave speed c of the dominant waves were determined for each experiment. Fig. 3 illustrates one of the most striking features of the wind-amplified wave field observed at high wind speeds, which lies in the fact that the mean steepness of the dominant waves keeps a constant value with fetch even when the wave amplitude increases gradually with fetch. For pure wind waves, this value is quite small, of order of .17, and seems to be independent on wind speed. This saturation in energy is reached at relatively short fetches when the wind energy input to waves is balanced by wave dissipation due to breaking or microbreaking. The fact that this equilibrium is achieved at the same steepness for different wind conditions suggests that under both the action of wind and breaking, the wave field evolves with fetch in a self-similar manner.

The second stage of the analysis made on the wave field properties aimed at describing wave breaking. To that end, a geometrical criterion, as first proposed by Longuet-Higgins and Fox (1977) and later tested by Xu et al. (1986), has been chosen, looking the most appropriate to characterize breaking of wind-amplified waves, i.e. breaking resulting from a naturalwind-induced growth. This criterion was formulated for regular progressive Stokes waves. It lies in the fact such waves are no longer stable, and so breaks, when the wave slope at the crest exceeds 0.586.

In the Luminy experiments, the instantaneous slope of the waves s(t) can be evaluated from the time derivative of the water surface heights η(t) using the relation:

$$s(t) = 1/c \, d\eta/dt$$

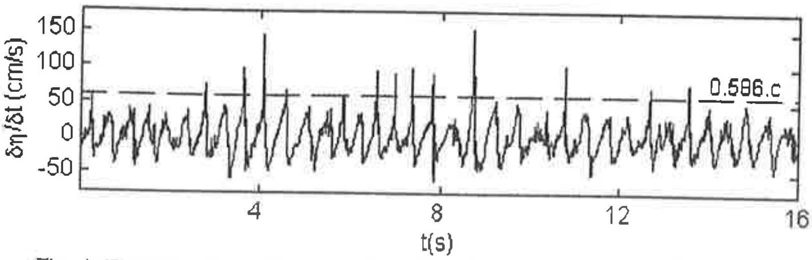

Fig. 4: Time sequence of the time derivative signal of the water surface heights measured by a capacitance wave gauge at 22 m fetch for 10 m/s wind speed.

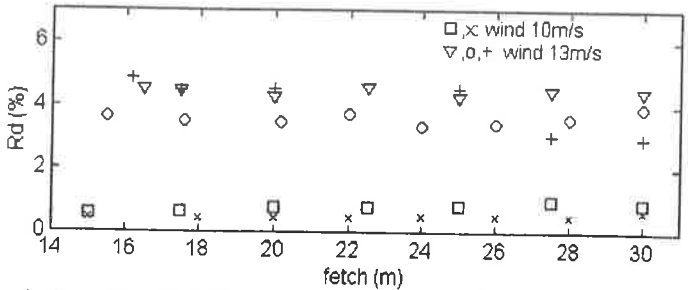

Fig. 5: Evolution with fetch of the breaking rate R_d observed for the different experiments made at 10 and 13 m/s wind speeds in the large IRPHE wind wave tank.

However, wave breaking was detected directly from the time derivative signals of the wave height when observed at any time between two successive zero down-crossings, values higher than 0.586c (Fig. 4).

Then, the features of the individual breaking waves as well as the breaking properties of the whole wave field could be described by the use of specific parameters, as for instance:

- the jump height J_h and the jump duration J_d, as first introduced by Longuet-Higgins and Smith (1983) to account for respectively the difference in water surface elevation and the duration between the times when the breaking wave slope rises above and falls down the critical value 0.586;
- the breaking rate R_d defined as the ratio between the sum of the breaking wave jump duration ΣJ_d and the total duration D of the time sequence.

Thus, at this stage of analysis, the breaking rate R_d was found as the most adequate parameter to characterize the wave breaking intensity during the gas transfer experiments. As an illustration, Fig. 5 displays the evolution with fetch of this quantity for 10 m/s and 13 m/s wind speeds. It can be seen that R_d remains nearly constant with fetch but strongly increases with wind speed. As previously for u_*, this evolution allows to describe the wave breaking conditions for each experiment only by the mean value of R_d.

At last, our investigation was devoted to the search for the relationship which may exist between the breaking rate and the wind friction velocity. The idea is to describe the wave breaking intensity by the smallest number of parameters not only relevant from a basic viewpoint but also easy to measure to be used for modelling of gas exchange coefficients at high wind speeds or heavy seas. On this hand, these experiments clearly show that the breaking rate and the air friction velocity evolve in a similar manner over the wide range of

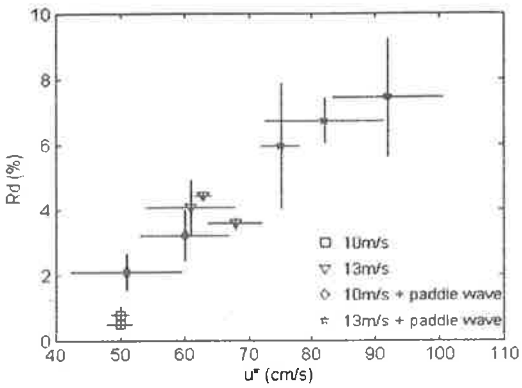

Fig. 6: Evolution with u_* of the breaking rate R_d observed for the different gas transfer experiments made at high wind speeds.

wind and wave conditions observed in the tank. Moreover, as seen in Fig. 6, the increase of R_d versus u_* exhibits a linear trend. This close relationship between such parameters observed at high wind speeds advocates that wave breaking is there directly controlled by wind forcing as well as when viewed from the opposite side, the sea surface roughness is entirely dependent on wave breaking, thus highlighting the strong couplings which must exist between wind and wave motions in such breaking conditions.

Acknowledgements
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