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Study on the Influence of Waves on Coastal Diffusion Using Image Analysis

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Abstract. A series of novel image analysis techniques have been used to study surf-zone hydrodynamics taking advantage of recent advances in digital processing of images taken from video recordings of the sea surface near the coast. The use of image analysis allows the estimation of both spatial and temporal characteristics of wave fields, surface circulation and mixing in the surf zone. The dispersion of blobs of dye released at different distances from the coastline under very different sea conditions is used to measure surface eddy diffusivities. A preliminary set of field measurements were done in the Ebro Delta where the methodology was tested. Further experiments have been performed at Vilanova, Spain and Recife, Brazil.

There is an increase of diffusivity with wave height but only if the wave Reynolds number, Rw, is greater than 10^3. No such trend is observed for Rw greater than 10^6. The other important factors are wind speed and tidal and longshore currents.

Key words: wave flows, surf zone turbulence, dispersion.

1. Introduction

The effect of waves and wind activity on coastal diffusion is hard to quantify, because most of the times there is a combination of these effects together with mean currents that may occur due to tides or to wave radiation (longshore currents). We present the results of several field experiments that took place between 1993 and 1997 at coastal locations in Spain and Brazil.

The study of near-shore dispersion, with the added complexity of the interaction between wave fields, longshore currents, turbulence and beach morphology, needs detailed measurements of simple mixing events if we are ever to understand the complexity of coastal dynamics. In this paper we use image analysis in a similar way as in [1]. In the several experimental sets described here video recordings of the coastal area were used in combination with other measurements described below and in previous papers [2–5]. Spectral analysis on the images has also been used in order to estimate dominant wave periods as well as the dispersion relations of dominant instabilities. The measurements presented here consist on the diffusion coefficients measured by evaluating the spread of blobs of dye (milk) as well as by measuring the separation between different buoys released at the same time.

Horikawa et al. [6], Lippmann and Holman [7–9] and Sonu [10] have also used image analysis to describe the coastal zone using elevated points or balloons.

2. Description of the Experiments

The selection of different coastal areas measuring the relevant parameters and comparing the field data with numerical predictions or laboratory data allows us to use the flow visualization in accurate and efficient way. Video recording and digital processing to the study of coastal processes include several aspects such as horizontal velocity field from buoys, dye mixing, angle and period of incident waves, wave runup, surf zone width, sand bar morphology, shoreline response and several statistical parameters. Here we will concentrate on measurements of dispersion of dye tracers.

Experiments in three different sites will be presented, two campaigns were made in the Trabucador bar in the Ebro Delta in Spain, in December 1993 and November 1996. A series of measurements was also taken during 1994, 1995 and 1996 at St. Gervasi Beach in Vilanova i la Geltru, near Barcelona. Another site used, where tidal effects are important, is the city of Recife in Brazil, here measurements were taken at Olinda beach, Recife harbour and Suape. The bathymetry was measured in all cases before and after the measurements, these included simultaneous time series of waves, current velocities, wind speed and sediment concentrations from surf zones in case of breaking areas.

2.1. EBRO DELTA EXPERIMENTS

The first campaigns at the Trabucador beach site in May and December 1993 were used to validate the analysis. Results from three days with quite different sea conditions were compared and longshore current and dispersion measurements from the tracking of dye blobs were obtained. We also showed promising results from the intercomparison between on site measurements with a movable sledge measuring wave height and the video images carried out during December 1993. For more details, see [1, 4].

The main characteristics of the incident wave field were measured independently by means of an omnidirectional wave rider (DWR) placed just in front of the chosen Trabucador site, 1500 m offshore at 7 m water depth in the Ebro Delta experiments [2]. During the experiments video images were recorded in a S-VHS system. The camera was placed in a waterproof housing In the Ebro Delta experiments it was placed at 20 m above the sea surface by means of a crane, several fiducial points were marked with white flags both at the coastline and 60 m offshore.

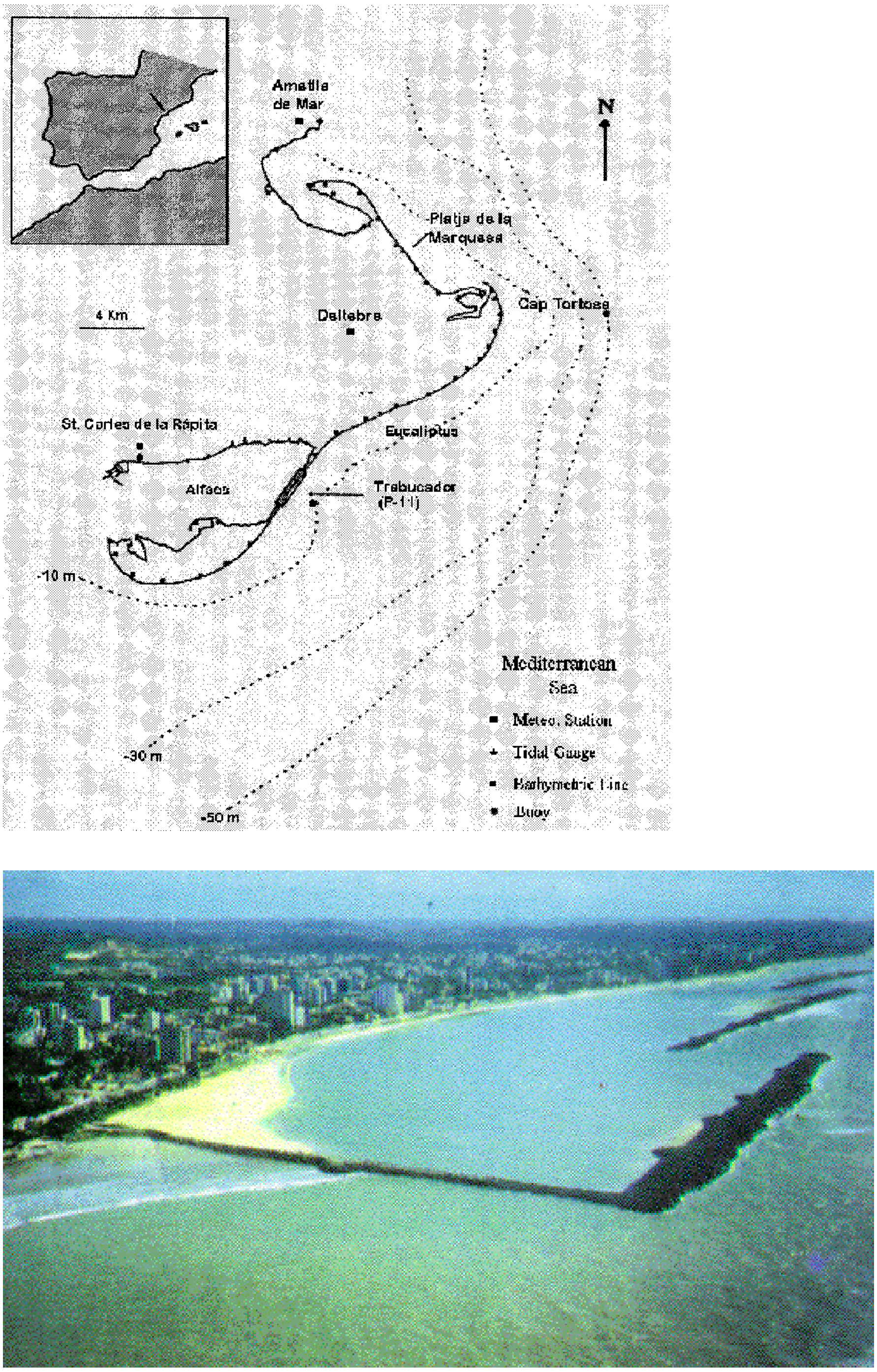

Figure 1. Areas of study. (a) Ebro Delta. (b) Recife.

Instrumental sledge with 6 electromagnetic sensors, 1 wave gauge, 3 optical back scatters, 1 compass and 1 optical prism

Figure 1. Continued. (c) and (d) Experimental configuration.

An example of the large scale field experiment set up is described in Figure 1 for the last experiments performed in the Ebro Delta in November 1996. It consisted on video images from two positions, from the 20 m crane as well as images from a balloon placed zenithally over the study area. The movable sledge had 8 electromagnetic current meters, a wave gauge, an anemometer, and two optical sediment sensors. In most experiments the wave characteristics were measured *in situ* using

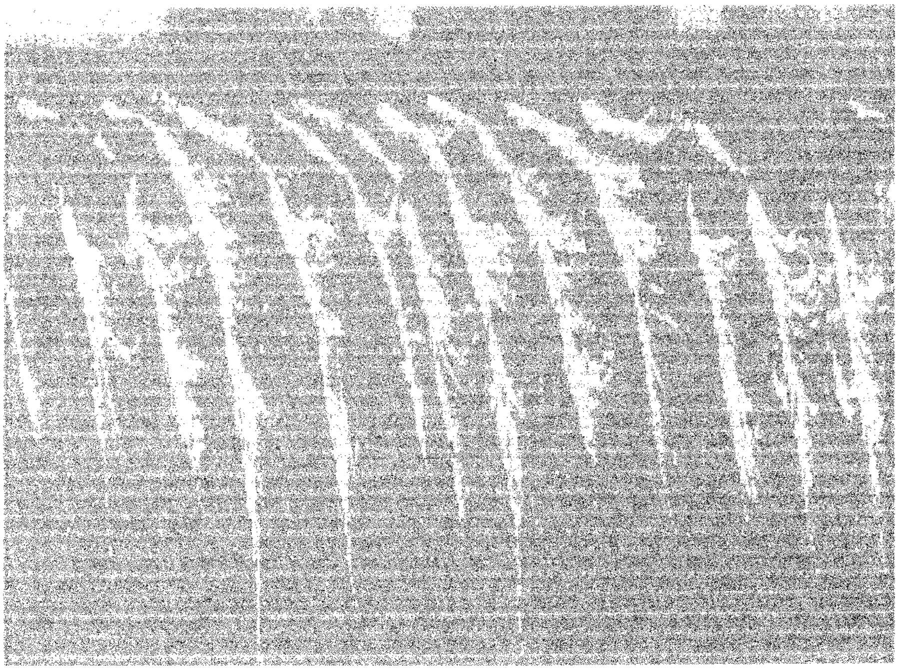

Figure 2a. Incoming waves, evolution in time of a video line perpendicular to the shore.

wave gauges as well as the video analysis. Several blobs of dye as well as sets of 20 buoys were released at different distances from the shore.

The site is a linear beach of more than 4 km and most of the times the dominant feature was the strong longshore current.

2.2. Vilanova experiments

This site is an enclosed beach between two large boulder wavebreakers separated 240 m. Only with strong waves a longshore circulation appears and then two or more cells produce recirculation between the wavebreakers. An elevated road at 10 m from sea level was used to film the dispersion of dye blobs or buoys. The absence of a strong longshore current allowed to concentrate on the effect of waves on horizontal dispersion.

2.3. Recife experiments

Some of the experiments reported here were performed at Olinda's enclosed beach not far from Recife, an artificial breaker lies parallel to the shore with offset openings between different sections of the beach (Figure 1c). For a more detailed description, see [11]. Another site used was the entrance to the Recife harbour.

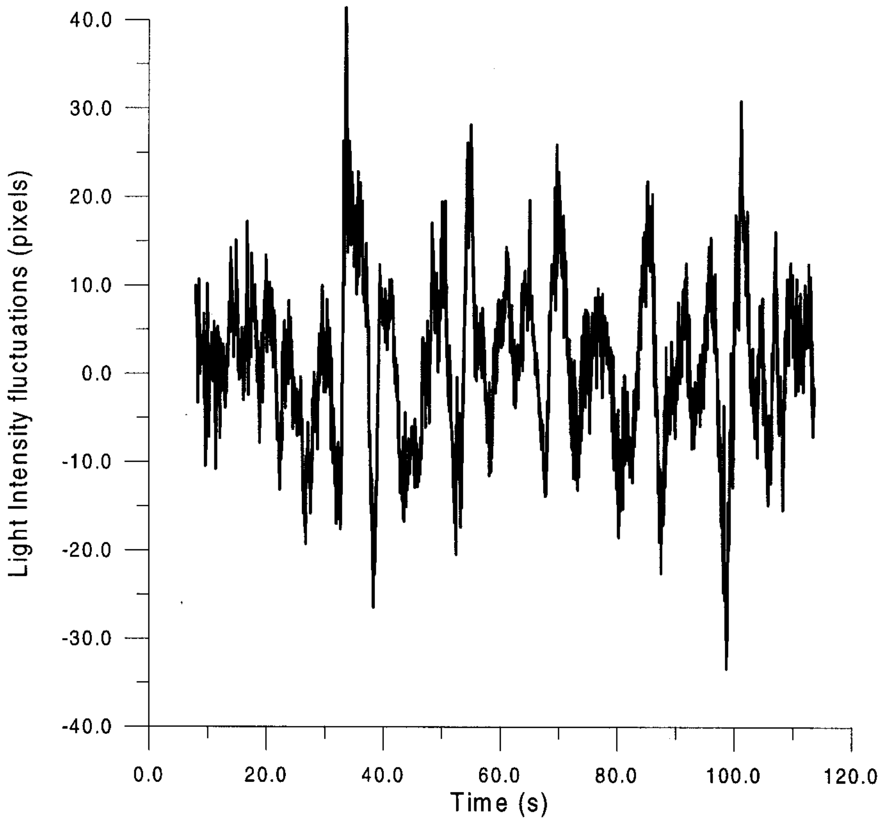

Figure 2b. Time evolution of the light intensity as waves break over a point.

The experiments were performed during 1996. In both locations the tidal currents played a significant role, the wind was also strong most of the times.

The tracers used to measure horizontal eddy diffusivities were selected after field intercomparisons of different types (fluoresceine, rhodamine, MnO_4K_2, SO_4Ca and milk). The best tracer depends on the ambient illumination, on the sun's position and on weather conditions because of the difference of contrast between dye and marine water, but milk and fluoresceine were the best ones because of their good contrast and persistence.

We obtained quantitative information from the video images using the DigImage video image analysis system, and an arithmetic frame grabbers (DT2861) on an IBM compatible computer, which allows a resolution of 512 by 512 pixels and 256 grey levels. Images can be digitally enhanced to stretch the contrast and filtered or enhanced to remove "noise" before analysis, The video may be controlled by the computer, allowing, remote control of the processing.

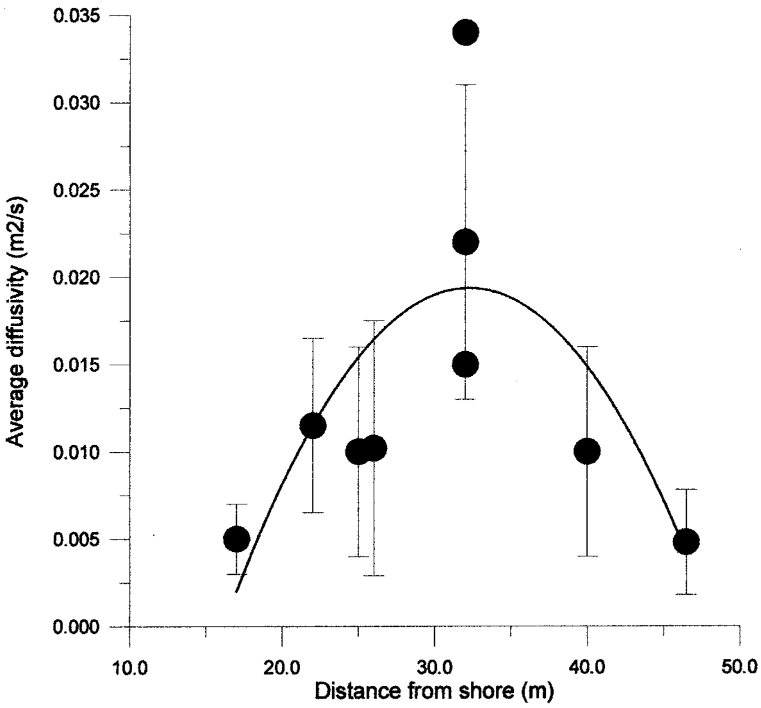

Figure 3. Cross-shore variation of dispersion coefficients.

3. Definition of Parameters and Results

The turbulent transport of a scalar (dye) in a turbulent field induced by waves or a combination of other causes such as current shear, bottom friction or wind may be considered in a first approximation as proportional to the scalar gradients

$$\overline{c'V'} = K \frac{\partial c}{\partial x} .$$

In order to estimate the effect of the waves on the turbulent eddy diffusivity, K, we use a Reynolds number of the flow induced by the wave as

$$\mathrm{Rw} = \frac{HV}{\nu} ;$$

where H is the wave height, ν is the kinematic viscosity of sea water and V is either the orbital velocity $V = H/T$, with T, the average period of the waves, or the wave phase speed $V = \lambda/T$, with λ the average wavelength.

The difference between both ways of estimating the relevant velocity producing the stirring depends on $\tan\alpha = (2H/\lambda)$ which will vary if the waves are breaking or not. This will be also function of the depth, D and the criteria of the wave breaking index $\gamma = H/D = 0.78$ predicted by solitary wave theory [12].

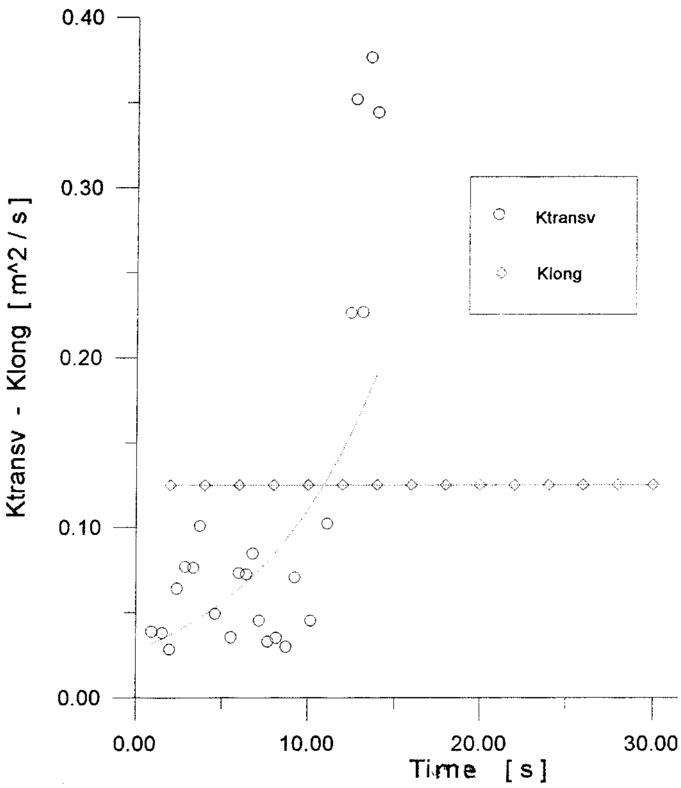

Figure 4. Evolution in time of the longitudinal and transversal turbulent eddy diffusivities.

For very shallow waters, the relevant wave phase speed may be approximated by $V = \sqrt{g(H + D)}$ and then Rw $\propto H^{3/2}$. for non-breaking waves of for the beginning of the surf zone Rw $\propto H^2$. In most cases we have used

$$Rw = \frac{2H^2}{\tan\ T} = \frac{\tan\ ^2}{2T} :$$

From the image analysis the wave period may be easily found as well as the wavelength. See Figure 2a for the evolution in time of a video image line and Figure 2b for the evolution of the light intensity at a point as the breaking waves pass by that point, from an FFT or simply from averaging the times between waves, the period may be found. The agreement with wave gauges placed close by is very good. What is noticeable is the variation in period with distance from the shore due to non-linear interactions between the waves. The evolution of wave frequencies with cross-shore distance was investigated using 100 s video intensity time series in order to resolve wave generated frequencies, the agreement with the DWR was also good, as shown in [1].

In the Ebro Delta experiments the longshore current measured at the region between the shore and the first bar where the dye blobs were released is typi-

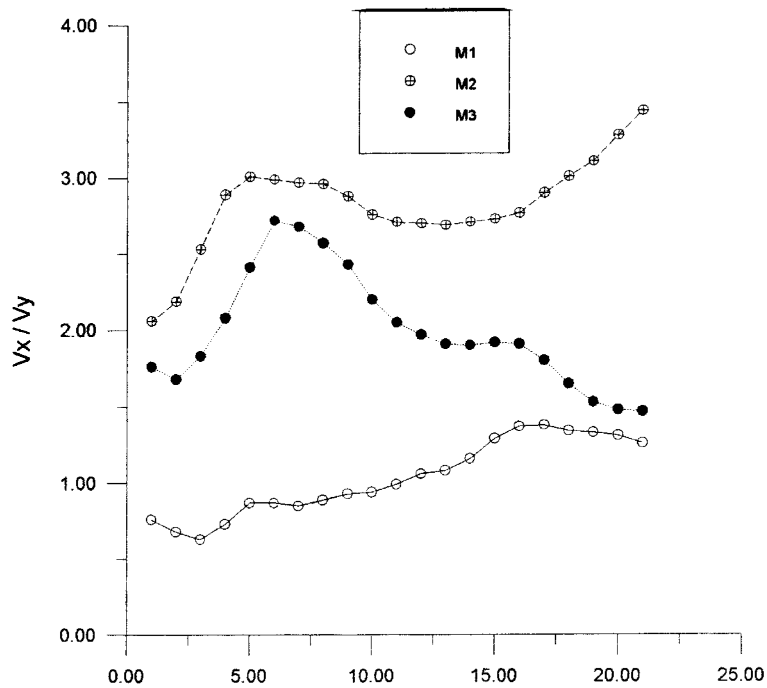

Figure 5. Evolution of the anisotropy (V_x/V_y) in time.

cally of 0.5 ms^{-1}, which agrees with the predicted maximum longshore currents, near the swell zone [2]. The detailed longshore velocity distribution needs further comparison with field data. In the 1996 campaign, series of simultaneous blobs were released at different cross-shore locations and further work will include comparisons between these measurements and the 1993 results. The profile in eddy diffusivity as a function of distance from the shore may be seen in Figure 3, there is a parabolic shape consistent with work by Thornton [12] and Sasaki et al. [13] but the formulations used in numerical models are larger than the measured values due to the inclusion of the effect of lateral shear stresses.

For this series of experiments, where 6 litres of milk with fluoresceine were released at different positions the wave and wind conditions were similar with breaking waves of $H \approx 0.5$ m. The range of transversal dispersion coefficients K_t perpendicular to the shoreline varied between 0.005 and 0.035 m^2/s, These values are slightly larger than in the case of the Vilanova experiments in a confined beach with no longshore current, there the range was 0.001 to 0.025 m^2/s. Other measurements from Horikawa et al. [6] have a similar distribution but much larger, 0.4 to 1.3 m^2/s. The reason for the larger values is the effect of the blob size, L, on dispersion as Richardsons law predicts using dimensional analysis

$$K \propto \varepsilon^{2/3} L^{4/3}.$$

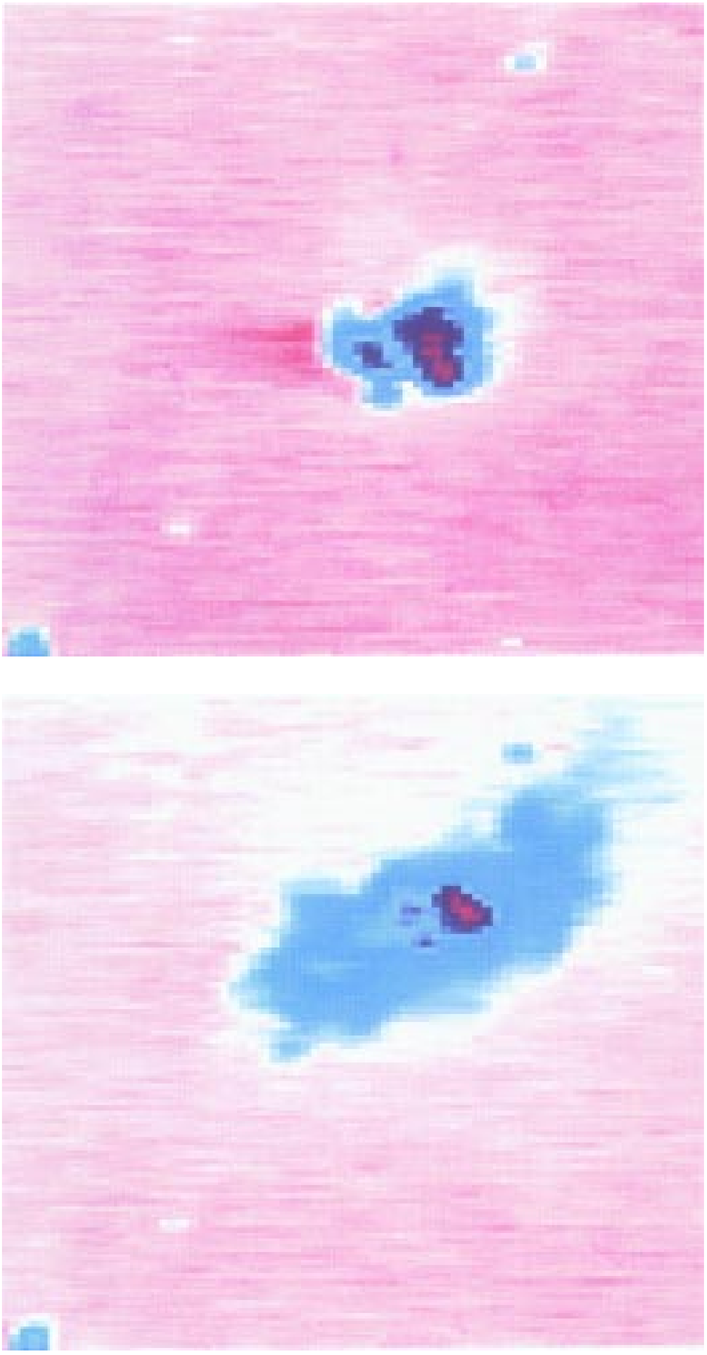

Figure 6. Shape of a blob of dye in the surf zone. (a) tD 10 s, (b) tD 100 s.

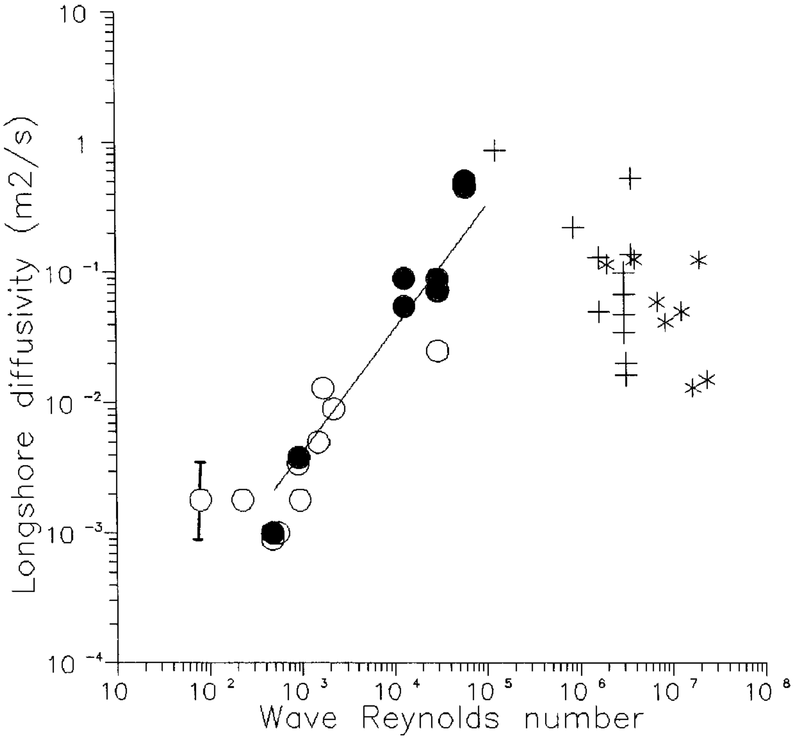

Figure 7. Variation of the longshore or longitudinal eddy diffusivity with wave Reynolds number. The symbols indicate different sets of experiments: Vilanova; Zeidler [14]; C Recife; Ebro Delta.

This scaling is not directly applicable to coastal diffusion, because the energy peaks in the energy spectrum due to wave breaking are too close and the inertial subrange is too small; nevertheless there is strong evidence of the increase of K with size L. Horikawa et al. [6] found

$$K \propto L^{1.15}:$$

We find different exponents for transverse and longitudinal coefficients, which also depend on the longshore current and on secondary instabilities, such as rip currents.

In the surf zone both the transversal, K_t, and longitudinal, K_l, turbulent eddy dispersion coefficients may vary more than a decade for the same wave conditions, depending on the breaking conditions, the distance from the shoreline and the longshore current.

As an example for dispersion under breaking waves (tests 8 and 9 from December 1993) the range of values for K_t was 0.035 m^2/s $< K_t < 0.376$ m^2/s with a strong variation in time, shown in Figure 4. On the other hand, the longitudinal dispersion coefficient $K_l = 0.124$ m^2/s hardly changed.

Comparing breaking and non-breaking waves, the breaking wave diffusivity values are often larger, the anisotropy defined as the ratio between longitudinal and

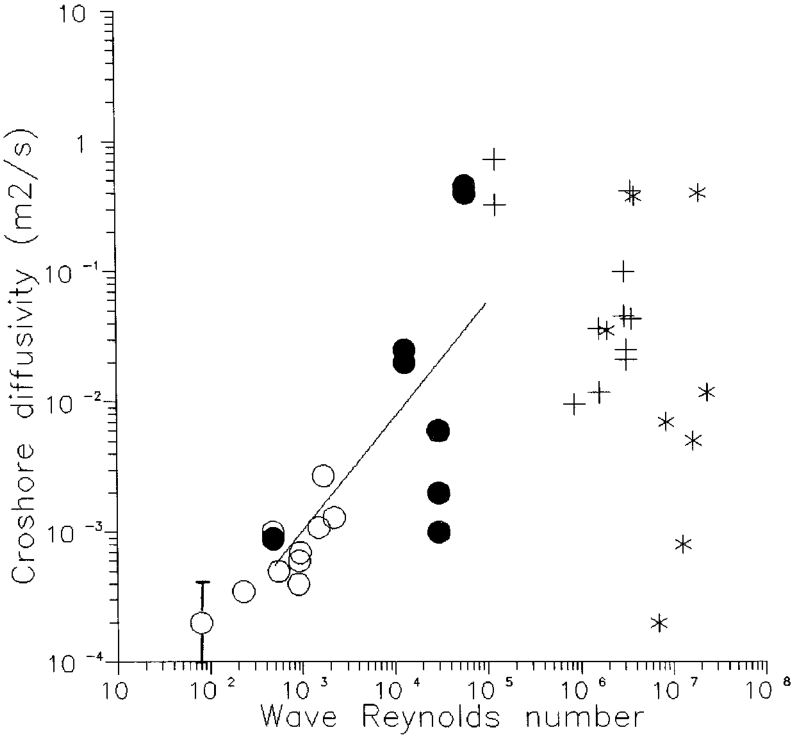

Figure 8. Variation of the cross-shore or transversal eddy diffusivity with wave Reynolds number, symbols are indicated in Figure 7.

transversal variances of the blob size $Vx=Vy$ is also larger for breaking waves. See Figure 5 for the evolution in time of the anisotropy for three experiments M1 in a non-breaking area and M2, M3 nearer the bar position in the surf zone.

The dye blobs often have elliptic shapes as shown in Figure 6, where a digitized blob for two different times is shown. In Figure 7 we show all measurements for the longshore component of the eddy diffusivity the closed circles show measurements without longshore currents at Vilanova and open circles were the experiments performed by Zeidler [14] for non-breaking waves, crosses indicate experiments performed at Recife and indicates the experiments performed in the Ebro Delta, both with breaking and non-breaking waves. The eddy diffusivity values are plotted against the wave Reynolds number Rw and it shows an increase of K_l between 10^3 and 10^6, for higher Rw other effects are more important, such as currents or wind. This is seen more clear in Figure 8, where the cross-shore diffusivity is plotted vs K_w The presence of currents and shear tends to elongate the blobs, this explains the low diffusivity values at R_w D 3 10^4 and at R_w D 10^7.

4. Conclusions

Measurements of dye dispersion at different distances from the shore (inside the surf zone) and in different sites have been used to obtain estimates for the variation of horizontal eddy diffusivity due to waves, longshore currents and other factors. Turbulence characteristics, such as the mean Lagrangian trajectories, mean and r.m.s. velocity integral lengthscales affect the shape and the anisotropy of the blobs, only the effect of waves has been presented here. For almost all cases the longshore diffusivities are larger than the cross-shore components, only in the cases where a rip current is present the opposite is true.

Video digitizing of field events seems a promising technique for extended quantitative measurements of sea surface behaviour including the effects of different coastal instabilities. The agreement between video spectra and DWR and wave gauges is good and allows us to describe in more detail the surf zone. The local characteristics may give differences of more than a decade.

The non-linear effect of the surf zone is apparent in enhanced images. There is a process of wave dislocations, between the surf and the swash zones that needs further study. This is also reflected in the changes in the dominant period of the waves as they approach the coastline, as measured with the image analysis. This produces a strong cross-shore variation of the eddy diffusivity values exhibiting a maximum between the first bar and the shore.

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