CHAPTER 143

Mixing processes in a shallow lagoon

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Introduction

Lagoons are enclosed water basins at the boundary between the land and the ocean; they usually have one or a number of streams entering around the perimeter and are open to the ocean at one or a number of entrances. Lagoons are shallow and the motion of water within them is governed by a delicate balance between tidal forces, wind stresses, bottom friction and density induced pressure forces. In general, ocean water enters a lagoon via deeper channels whereas the river inputs enter through alluvial fans. The freshwater, being lighter, overflows the lagoon waters whereas the entering ocean water, being heavier, underflows. This leads to a strong vertical stratification in the main channels and a general horizontal stratification in the shallows. Much work has been done on estimating the net horizontal mixing in large water bodies and, in general, it is assumed that the water column is fully turbulent and the horizontal scales of motion range from the size of the lagoon to millimetres and vertical scales from the depth to millimetres. Under such conditions it is assumed that there is a cascade of energy similar to normal turbulent shear flow (Tennekes and Lumley, 1972). For water bodies which have dimensions in the tens of kilometres, it is found both by fitting the results from numerical models (Di Silvio and Fiorillo, 1981) and from large scale field comparisons (Dronkers *et al.* 1981) that a horizontal diffusion coefficient of the order of 50 to 500 $m^2\ s^{-1}$ is applicable.

This logic, however, ignores two major recent findings. First, in shallow waters, Wolanski *et al.* (1984) have found that the bottom friction is usually sufficient to overcome the horizontal inertial forces so that the *effective* Reynolds number of the flow can be as low as 30 or 40. Numerous cases have now been documented where the wake behind islands, flows over undulating topography or past headlands. All appear to shed eddy structures which are reminiscent of slow viscous flow rather than of an inertial turbulent regime. Second, with recent remote sensing techniques and fast fine-scale sampling (Luketina and Imberger, 1987) it has been revealed that lagoons and coastal waters are partitioned by a complicated network of fronts. These fronts form a mosaic of lenticular structures which move under the influence of the tide, the wind field and baroclinic forces. The role of the fronts is to enhance mixing at small scales through shear flow dispersion, but they appear to inhibit the natural cascade of energy from the larger scales through the intermediate scales to the smaller scales of the horizontal eddy structures. Thus both bottom friction and the presence of fronts prevents an energy cascade and the development of a full turbulent velocity spectrum. It therefore remains to be explained why the net horizontal eddy diffusion coefficients in shallow lagoons are comparable to the open ocean values summarised by Okubo (1974).

Field Campaign

Two field campaigns (respectively commencing 11th June 1990 and 2nd March 1991) were carried out in the Lagoon of Venice, involving detailed fine-scale temperature and conductivity measurement surveys. The aim of these experiments was to assess the role and influence of the buoyancy introduced around the perimeter, by freshwater inputs, on the dispersion in the lagoonal waters. A portable fine-scale profiler was used both in a vertical profiling mode and in horizontal tow mode. The fine-scale profiler was equipped with SeaBird conductivity and temperature sensors and a Digiquarts pressure transducer (Fozdar *et al.* 1985). The resolution of these sensors was 10^{-4} Sm^{-1}, 10^{-3} °C, and 10^{-3} m respectively. In addition to these fine-scale measurements, in the winter experiment some temperature and conductivity microstructure was also gathered in order to estimate the turbulent kinetic energy dissipation (Imberger and Ivey, 1991). During both experiments velocity estimates were obtained using bucket drogues, drogued to different depths.

During the summer experiment, most of the data collection was in the area influenced by the Dese River (Figure 1). By comparison, the winter experiment concentrated on the Venice Lagoon as a whole in order to obtain a broader overview (Imberger, 1991).

The investigations showed the following major features:
(a) The tidal flow in the canal system is a mixture of barotropic and baroclinic flows; the degree of baroclinicity being dependent on the phase of the tide and on the salinity difference within the canals and was strongest in the areas which had direct freshwater input. However, the measurements show that sufficient salinity differences existed almost everywhere for baroclinicity to be important.
(b) The water masses on the shoals appeared to be formed in an orderly explicable way. As the water rose in the channels and reached a point where the water broached the shoals, the salinity of the inflowing water was completely determined by the surface salinity at the point of broachment in the tidal channel. A shoal may thus be envisaged as a region of land with a perimeter were water of increasing salinities is ejected on the rising tide. It appeared that these injections formed well-defined lenticular structures which were separated by stable fronts, leading to a patchwork of water masses over the shoal at high tide which retained their identity throughout the tidal cycle but which were moved by the tidal motion and the surface wind stresses. These lenticular structures, observed throughout the whole lagoon, originate from buoyant jets at the river mouths and move over the shoals and along the channels with little tendency to decay. The shallowness of the water of the shoals led to a pseudo potential flow.

Large Scale Flushing

In Figure 1 we show a typical set of salinity isohalines contoured over the whole Venice Lagoon. The data shown is depth averaged salinity and clearly shows that there was a major freshwater inflow into the Venice Lagoon in the northern and southern regions, but that the lagoon as a whole had a horizontal gradient of salinity from the perimeter to the three entrances. A bulk estimate of the horizontal diffusion coefficient may be obtained by equating the flushing time V_f/Q_f to an average horizontal mixing time L^2/ε_x where Q_f is the total freshwater input into the lagoon, V_f is the total volume of freshwater in the lagoon, L is a typical horizontal length scale of the lagoon and ε_x is an average horizontal diffusion coefficient. There are numerous other ways of estimating an average diffusion coefficient and we have calculated the estimate ε_x by a number of different techniques. Using the data collected in the campaign, the various methods gave a typical flushing time of approximately three tidal cycles and a horizontal diffusion coefficient ranging from 100 to 400 $m^2\ s^{-1}$. These values were compared against more detailed estimates obtained in two canals by fitting a horizontal advection diffusion model to the documented inter-tidal gradient of salinity. This techniques yielded estimates in the same range.

In summary, therefore, the fine-scale measurements in the Venice Lagoon yielded global dispersion coefficients averaged over many days (averaged over tidal and wind motions) of the same magnitude as found in open deep water.

Lenticular Structures

The mechanisms by which freshwater entered a particular shoal was investigated in considerable detail during the winter experiment. In Figure 2, we show a typical salinity plot at the commencement of the falling tide and it is clearly seen that the freshwater outflow produced a plume of fresher water extending a distance of 2 or 3 km from the mouth and being swept alongshore by the prevailing tidal current. A similar exercise was conducted in the central part of the lagoon (Figure 3) which shows that even in the middle of the lagoon, far removed from the direct influences of the fresh river inputs, lenticular structures with horizontal length scales of the order of 1 to 2 km could be clearly identified. As seen from Figure 3, the salinity differences associated with the lenticular structures, even in the central part of the lagoon, are comparable to those found at the perimeter near the entrance inflowing river plumes (Figure 2). Lastly a series of drogues released in this latter study area showed that even over a period of three to four hours, drogues placed in close proximity remained together. Thus, the horizontal dispersion was always minimal until some drogues pass from channel to shoal or viceversa. Only at this point did the drogues in the shoal lag behind those in the channel. The same is true for lenticular structures that are moved around the lagoon by the tidal motion and the wind induced stresses. These lenticular structures thus only mix across fronts and by vertical entrainment over channels. No evidence was found of large scale eddy type structures.

Conclusions

These and other findings lead to the conclusion that mixing in the lagoon operates at different scales:

(i) Large structures, with scales determined by the morphology and of under $10^4 - 10^3$ m are responsible for the global horizontal dispersion; they control the flushing of the lagoon as well as the distribution and the shape changes of the lenticular structures, but not the mixing.

(ii) Intermediate and small scale turbulence of the order of 10 metres and less control the mixing over the depth and the weak horizontal dispersion during the tidal cycle. This is responsible for the slow annthilation of the lenticular structures.

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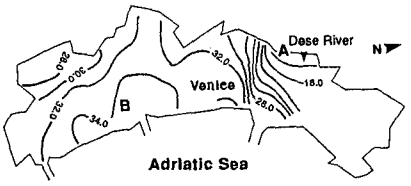

Fig 1. Averaged salinity in the Venice lagoon.

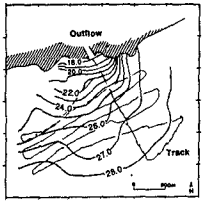

Fig 2. Plume of fresh water near the coast (joint A in Fig 1)

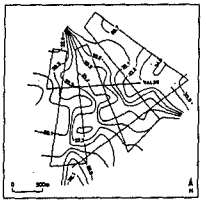

Fig 3. Lenticular structures in the middle of the lagoon (joint B in Fig 1)