Studies of Turbulent Diffusion of Dye Patches in the Ocean[1]

TAKASHI ICHIYE

Oceanographic Institute, Florida State University, Tallahassee

Abstract. Experimental data on diffusion of dye patches in the sea obtained in near shore areas, including estuaries of the coast of the Gulf of Mexico are analyzed and compared with theories of turbulent diffusion. Change of radius of dye patches with time is explained from theories of G. I. Taylor and others. Detailed structure of diffusion pattern is discussed by use of the data obtained at a platform off Panama City, Florida. Particularly the speed of diffusion, vertical eddy accompanying the bottom layer of dye patches and strange pattern of edges of patches are discussed in relation to the environmental, hydrodynamical conditions such as vertical stability, mean velocity, and sea surface conditions.

Turbulence in the upper and lower layers of the ocean is important in understanding the mechanism of surface phenomena like slicks, streaks, foam lines, and ripple marks as well as such other phenomena as heat exchange between the atmosphere and the ocean, the flushing and disposal of polluted water, the mixing of different water masses, sedimentation and erosion of bottom substances, and propagation of sound in water. Turbulence seems to be a more complicated process in the ocean than in the atmospheric boundary layer, for in the ocean we have to consider interaction with atmospheric turbulence and wind waves, the effects of bottom and coasts, and the predominance of tidal currents. It is not surprising, therefore, that we lack adequate knowledge of turbulence in the ocean, although a theory of turbulence in general and of atmospheric turbulence in particular, based on a statistical concept of turbulence, has been developed during the past decade.

The study of turbulence is handicapped by the difficulty of measuring directly such elements as velocity correlations and spectra. Recent developments in electronics have started to fill the gaps in such measurements, as the result of efforts of several groups, including Russian oceanographers [*Kolesnikov,* 1959]; and some results of Canadian and British groups are presented in this symposium. Our group, from the A & M College of Texas, the U. S. Navy Mine Defense Laboratory, and Florida State University, plan experiments this fall with two platforms off Panama City on the northern Gulf coast of Florida.

Turbulent diffusion instead of turbulence itself, in the ocean, has been studied and frequently mentioned in oceanography in relation to distributions of various physical and chemical elements in the ocean and even to distributions of plankton. The statistical theory of turbulence, developed in other fields, was first applied to the data obtained by diffusion experiments in the ocean. Two kinds of experiments on diffusion can be explained by statistical theory. When we accept the terminology of *Batchelor and Townsend* [1956] we may use one-particle and two-particle analysis. *Richardson and Stommel* [1948] introduced the idea of neighbor diffusivity in their experiment on diffusion in the ocean. *Olson and Ichiye* [1959] and *Ichiye and Olson* [1960] developed the idea and provided confirmation that Richardson's 4/3 law for neighbor diffusivity is valid for a range of distance scale between 1 and 10^8 cm, on the basis of admittedly crude data of drift bottles, sheets of paper, etc.

The application of one-particle analysis to oceanic diffusion was also initiated by *Stommel* [1949]. His experiment with mimeograph sheets was later elaborated by *Bourret and Broida* [1960] in determining the diffusion coefficient from the change of mean distances of various floating materials with time. The float method,

[1] Based on a paper presented at the International Symposium on Fundamental Problems in Turbulence and Their Relation to Geophysics sponsored by the International Union of Geodesy and Geophysics and the International Union of Theoretical and Applied Mechanics, held September 4-9, 1961, in Marseilles, France.

Oceanographic Institute Contribution 180.

although simple in analyzing the results, may be inadequate in obtaining information on the detailed structure of eddies, owing to difficulties in tracking and also to the limited number of floats. In contrast, another method of one-particle analysis, the release of dye in water, is much simpler in practice and yet gives more detailed pictures of small-scale eddies in the ocean.

There are two methods of releasing dye in the water: instantaneously, and continuously from a source. The continuous method is usually unfavorable in practice, owing to the difficulty of pouring dyed water at a constant rate, particularly from a small skiff. The instantaneous method is generally feasible under any conditions. Figure 1 shows results of analysis of the data obtained by *Gunnerson* [1956] in Santa Monica Bay off California, in relation to the study of the disposal of polluted water in the bay. The bay and the sites of the experiments are shown in the left-hand side of the figure. Gunnerson released 1 pound of fluorescein and determined boundaries of the dye patches by visual observation. In the right-hand side of the figure the change of radius of the dye patches is plotted against time for two sets of experiments carried out in the bay. The radius of the patches is determined from an area of each patch, which is assumed to be circular. The radius thus determined indicates a general pattern of a gradual increase at the start and then a rather rapid decrease until the patch disappears. Such a pattern can be explained by Taylor's theory of random flight [*Taylor*, 1921; *Frenkiel*, 1953] under the assumptions that the visual boundary of patches corresponds to an isoline of some critical concentration and that the diffusion time is much smaller than the Lagrangian time scale. (*Monin* [1959] rejected the first assumption in his study of smoke patches in the atmosphere.) Theoretical curves obtained with such assumptions are drawn in full lines in Figure 1. The mean-square turbulent velocity is 0.6 and 0.7 cm/sec for experiments I and II, respectively. The dashed lines are theoretical curves computed under a different assumption, that the diffusion time scale is larger than the Lagrangian time scale. The chained lines are curves computed by a theory of *Joseph and Sendner* [1958], who derived a diffusion formula based on the idea of probable turbulent velocity and proved that it is valid for diffusion with a scale of 10 to 1500 km. Both these curves seem inadequate to explain the feature revealed by the data.

Since 1960 the author has been making a series

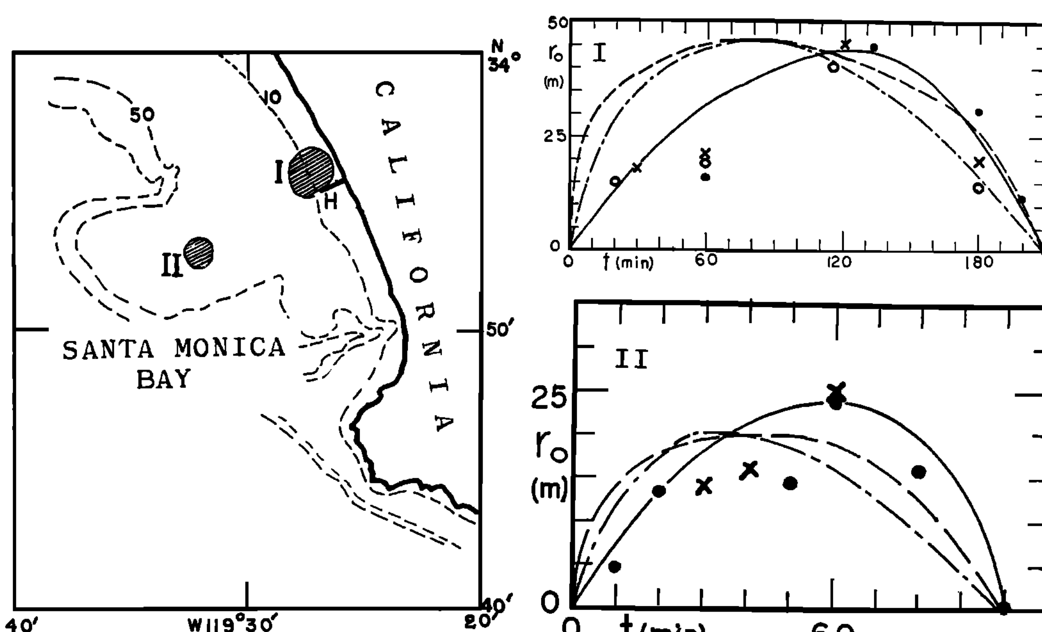

Fig. 1. Analysis of diffusion experiments in Santa Monica Bay, California.

of diffusion experiments using dye patches released from a small skiff in some bays on the northern Gulf coast of Florida, to study the structure of eddies less than 50 meters long and lasting less than 30 minutes. Since early in 1961 one of the Navy platforms 2 km off Panama City has been made available for these experiments. The procedure was to release 0.5 liter of dyed water (50 grams of fluorescein to 1 liter of sea water) by means of a bucket from a skiff or a paper box or a balloon from the platform. Usually the dye patch was photographed every 30 seconds. For size reference a stick of known length or a pair of floats having both vertical and horizontal scales attached was released at the same time as the dye. In some tests skin divers watched or took 16-mm underwater movies of side views of the patch to study its vertical diffusion.

Figure 2 shows for one series of experiments a change of pattern of a patch plotted every minute. Also are shown the wind data measured with a hand anemometer at 3-meter height, currents measured with an Ekman current meter, and a BT record. The contours of the patch indicate the concentration of dye judged from color films, which suggest that the concentration beyond the visible boundary is zero as *Monin* [1959] stated. This figure indicates that the patch was diffused more intensely along the direction of the wind and that, when the patch entered in the wake of the platform against the surface current, it was broken in several pieces

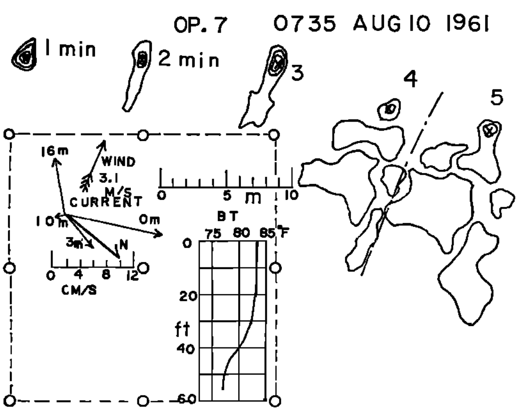

Fig. 2. An example of diffusion experiments at a platform of Panama City, Florida. Patterns of a patch are shown every minute relative to the platform, indicated by nine piles. Crosses show the position of the source of the dye.

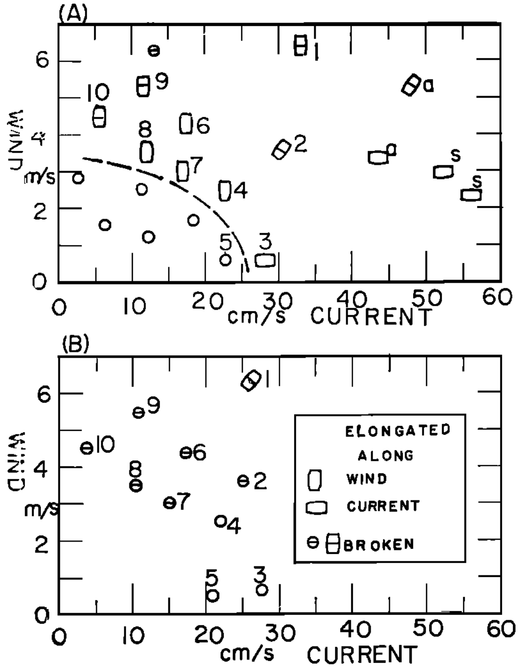

Fig. 3. Synoptic representation of patterns of dye patches. *A*. Free stream. *B*. In the wake of the platform. *a*, data at Alligator Bay; *s*, data at St. Andrew Bay.

and the pattern seemed to become more isotropic horizontally than outside the wake. Visual observation by a skin diver provided confirmation that the vertical diffusion at the time was limited to the upper 1 foot from the surface.

These two features, elongation and break-up of the patches, was frequently observed in the experiments. Figure 3 shows the occurrence of such features against the data of wind and surface current. All the points, except those marked *a* and *s*, are the data obtained at the platform. The velocity of the surface current was determined by the movement of the center of the dye patch, and wind speed was measured by a hand anemometer at 3-meter height as in Figure 2. The lower figure shows the results obtained in the wake of the platform, the number attached to each point identifying corresponding series of experiments made at the same time. The characteristic features indicated by the figures are: (1) Outside a wake a patch is elongated and/or broken into pieces for wind speeds greater than 3 m/s or surface currents faster than 10 cm/s. (2) When the wind is strong and the current weak, a dye patch is elongated in the direction of the wind, and vice versa. (3) In the wake a patch usually breaks up but shows more isotropicity in the horizontal direction.

Acknowledgment. This work was supported by ONR contract Nonr-988(06).

References

Batchelor, G. K., Small-scale variation of convected quantities like temperature in turbulent fluid, part 1, *J. Fluid Mech., 5,* 113–133, 1959.

Batchelor, G. K., and A. A. Townsend, Turbulent diffusion, in *Surveys in Fluid Mechanics,* Cambridge University Press, New York, pp. 352–399, 1956.

Bourret, R., and S. Broida, Turbulent diffusion in the sea, *Bull. Marine Sci. Gulf and Caribb., 10,* 354–368, 1960.

Frenkiel, F. K., Turbulent diffusion, *Advances in Appl. Mech., 3,* 61–107, Academic Press, New York, 1953.

Gunnerson, C. G., Progress report of 1955 and 1956 for oceanographic investigation of Santa Monica Bay (mimeographed), 1956.

Ichiye, T., and F. C. W. Olson, Ueber die 'neighbour Diffusivity' im Ozean, *Deut. Hydrograph. Z., 13,* 13–23, 1960.

Joseph, J., and H. Sendner, Ueber die horizontale Diffusion im Meere, *Deut. Hydrograph. Z., 11(z),* 49–77, 1958.

Kolesnikov, A. G., The vertical turbulent exchange under conditions of stable sea stratification, preprint, International Oceanographic Congress, 404, 1959.

Monin, A. S., Smoke propagation in the surface layer of the atmosphere, *Advances in Geophys.,* Academic Press, New York, *6,* 331–343, 1959.

Olson, F. C. W., and T. Ichiye, Horizontal diffusion, *Science, 130,* 1255, 1959.

Richardson, L. F., and H. Stommel, Notes on eddy diffusion in the sea, *J. Meteorol., 5,* 238, 1948.

Stommel, H., Horizontal diffusion due to oceanic turbulence, *J. Marine Research, 8,* 199–210, 1949.

Taylor, G. I., Diffusion by continuous movements, *Proc. London Math. Soc., 20,* 196, 1921.