Horizontal Diffusion

Abstract. The neighbor diffusivity for pairs of diffused particles is determined from observations on drifts of various kinds of materials such as drift bottles in many parts of the ocean and a lake. Its values are expressed as the 4/3 power of separation of particles over a range from 10 to 10^8 cm.

A recent work by Joseph and Sendner on horizontal diffusion in the sea seems to give promise of an eventual resolution of the Fickian versus neighbor diffusivity problem (*1*). Among other things, it has caused us to reexamine our own work on the subject. The purpose of this note is essentially to extend the range in which the 4/3 power law appears to be valid.

It will suffice to consider only the one-dimensional aspect of diffusion. If $\nu(x)$ is the concentration of particles at x, there will be $\nu(x)dx$ particles between x *and* $x+dx$. By analogy to classical concentration, the neighbor concentration $q(l)$ is defined as the number $q(l)dl$ of pairs of particles whose separations are in the range l to $l+dl$. The Richardson diffusion equation

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial l}\left[F(l)\,\frac{\partial q}{\partial l}\right] \qquad (1)$$

is analogous to the classical Fickian equation since $F(l)$, the neighbor diffusivity, takes the place of the ordinary diffusivity K. Stommel postulated that the initial separation l_0 is large compared with $l_1 - l_0$, where l_1 is the separation after time T (*2*). With this restriction, he derived the relation

$$F\left[\frac{1}{2}\,\overline{(l_1 + l_0)}\right] = \frac{\overline{(l_1 - l_0)^2}}{2T} \qquad (2)$$

where the bars indicate averages. Stommel checked the validity of this equation by using pieces of parsnip with spacings of the order of 25 to 200 cm (Richardson and Stommel, *3*) and dye spots with spacings 1000 to 10,000 cm and sheets of mimeograph paper with spacings 40 to 1000 cm (Stommel, *2*). These data are shown by crosses in Fig. 1. Later, Olson (*4*) showed that his drift card data (*5*) and Platania's (*6*) drift bottle data also seemed to satisfy Eq. 2 in spite of the severe deviation from the conditions imposed in deriving the equation. This may be seen in Fig. 1 where Platania's data are represented by a square and Olson's data by triangles.

Ichiye treated drift bottle data from Japanese waters in a somewhat similar manner (*7*). Since he was interested at that time in verifying an approximation occurring in one of his derivations, the data were not plotted as they are in our Fig. 1. By plotting these data in this manner, however, we find (see circles) that they are in excellent agreement (*8*). The line shown in Fig. 1 was determined by least squares for the condition that the slope is 4/3. It represents the equation

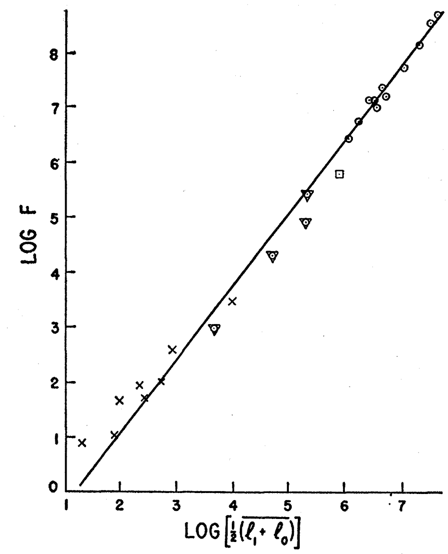

Fig. 1. Composite graph of data from Stommel (crosses), Olson (triangles), Platania (square), and Ichiye (circles). The line is a least-square fit of

$$\log F = \frac{4}{3}\log\left[\frac{1}{2}\,\overline{(l_1 + l_0)}\right] + a,$$

where a was determined to be -1.609.

$$F(l) = 0.0246\,l^{4/3} \qquad (3)$$

where $l = \frac{1}{2}(l_1 + l_0)$.

For the data as a whole, the correlation coefficient $r = 0.993$. For Ichiye's data alone, $r = 0.992$. A least-squares fit for the data as a whole gives a slope of 1.29; for Ichiye's data, the slope is 1.37.

Figure 1 is remarkable in many respects. Included in it are observations on parsnips, dye spots, sheets of paper, drift cards, and drift bottles. The observations were made in the Atlantic and Pacific oceans, in the Mediterranean Sea, and in Lake Erie. Drift card and drift bottle data are notoriously inaccurate. Most of the points were obtained under conditions which nowhere met the requirements made by Stommel in his derivation of Eq. 2. Yet the correlation over a range from 10 to 10^8 cm is 0.993 (*9*).

F. C. W. Olson
U.S. Navy Mine Defense Laboratory, Panama City, Florida

Takashi Ichiye
Oceanographic Institute, Florida State University, Tallahassee

References and Notes

1. J. Joseph and H. Sendner, *Deut. hydrograph. Z.* **11**, 49 (1958).
2. H. Stommel, *J. Marine Research (Sears Foundation)* **8**, 199 (1949).
3. L. F. Richardson and H. Stommel. *J. Meteorol.* **5**, 238 (1948).
4. F. C. W. Olson, "An empirical expression for horizontal turbulence," *Florida State University Studies* **7**, 32 (1952).
5. ———, "The currents of western Lake Erie," dissertation, Ohio State Univ., (1950); *J. Marine Research (Sears Foundation)* **10**, 190 (1951).
6. G. Platania, "Experiments with drift bottles (second report)," *Rept. Danish Oceanog. Expeditions, 1908–1910, to the Mediterranean and Adjacent Seas* (1923), p. 3.
7. T. Ichiye, *Oceanog. Mag.* **3**, 83 (1951).
8. Actually l_1 was taken as the distance between recovery points of pairs of drift bottles thrown at the same station and l_0 was put to zero.
9. This report is contribution No. 119, Oceanographic Institute, Florida State University.

4 June 1959

Zinc-65 in Foods

Abstract. Small quantities of Zn^{65} have been found in a wide variety of foods obtained from the local markets serving Cincinnati, Ohio. The highest levels of radioactivity were observed in oysters harvested from Chesapeake Bay; however, none of the samples contained significant quantities of this radionuclide in terms of a potential radiological health hazard. In view of the widespread occurrence of Zn^{65} in foods, it has been postulated that this radionuclide has been dispersed by high-altitude fallout.

Recently Perkins and Nielsen (*1*) have reported the presence of Zn^{65} in produce from farms irrigated with water from the Columbia River and also in animals and people eating this farm produce. They state: ". . . Zn^{65} from nuclear tests has not been ob-

Table 1. Concentration of Zn^{65} in foods.

Sample	Date of sampling	Zn^{65} ($\mu\mu c$/kg)
Oysters (Chesapeake Bay)	Jan. 1959	178
Oysters (Chesapeake Bay)	Mar. 1958	124
Clams, hard-shelled (East Coast)	May 1958	40
Mixed Meats*	Sept. 1958	17
Mixed fresh leafy vegetables (washed)†	Aug. 1958	12
Mixed fresh root vegetables (washed)‡	Aug. 1958	10
Eggs	Aug. 1958	6
Mixed fresh legumes and corn (washed)§	Aug. 1958	4
Milk	Jan. 1959	4
Mixed fresh fruits (washed)‖	Aug. 1958	3

* Equal parts of chicken, lamb, beef, and pork; † equal parts of lettuce, cabbage, spinach, broccoli, celery, and cauliflower; ‡ equal parts of potatoes, sweet potatoes, carrots, beets, radishes, and turnips; § equal parts of shelled peas, string beans, shelled lima beans, and corn; ‖ equal parts of apples, grapes, grapefruit, oranges, peaches, plums, strawberries, and cantaloupe.