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Phil. Trans. R. Soc. Lond. A 1986 **319**, 177-187
doi: 10.1098/rsta.1986.0095

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Phil. Trans. R. Soc. Lond. A **319**, 177–187 (1986)
Printed in Great Britain

Dispersion in the ocean by physical, geochemical and biological processes

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The physical, geochemical and biological processes that lead to the dispersion of radionuclides throughout the marine environment and to interactions with man and his food chain are outlined. Although much remains to be understood about the details of these processes, certain limits may be put on radionuclide transport rates. Some of these limits are applicable to many situations, others are strongly dependent on the half-life, reactivity, etc., of the radionuclide or on the details of its source. Although physical and geochemical processes tend to dominate transfer mechanisms, the biological aspects of radionuclide transport attract much attention. It is shown that, even though our knowledge of deep-sea biology is far from perfect, certain quantifiable limits can also be put on these transport rates. An attempt is made to put these and other oceanic aspects of the deep-sea disposal of radionuclides into perspective.

INTRODUCTION

During the past few years, more and more effort has been directed towards the modelling of the transport of pollutants, particularly radionuclides, from deep-sea disposal sites. Although recently this has been supported by experimental studies, for the most part those involved in the analysis have had to rely on the generally available knowledge regarding physical, geochemical and biological processes in the deep sea. The application of the knowledge to the estimation of the hazard of a particular deep-sea disposal site must be done with considerable care.

One problem facing modellers is that most of our knowledge of oceanic processes is inferred from the distribution of properties that have surface sources. This is so for temperature, salinity, many chemical species, and most pollutants. One can note that even the present oceanic inventories of caesium-137 and plutonium-239 arise primarily from the surface input of the fallout from atmospheric nuclear explosions or from coastal discharges. The upper ocean is also more easily sampled than the deep ocean, and has been the subject of more detailed analyses and experimental investigations. Thus for oceanographers the development of reliable models for the transport of pollutants from the deep sea is a problem of significant scientific challenge. This challenge is now being met by many in the marine scientific community.

Most of the earlier work on modelling radionuclides from deep-sea disposal sites was done to estimate the hazard of the deep-sea dumping of low-level wastes under the auspices of the London Dumping Convention. Responsibility for the estimation of the general environmental risk has been given to the International Atomic Energy Agency, which in 1980 requested the IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) to provide advice on how to estimate the

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transfer of radionuclides from deep-sea disposal sites to man and his food chain. The report of GESAMP on this subject (GESAMP 1983) provided what could be considered as the first widely based scientific approach to the problem and its advice has been widely used in recent considerations of low-level dumping limits. Since much of this review paper is based on ideas given in the report, it is pertinent to consider first the general approach that was taken.

The principle that recurs most often in the GESAMP report is that, given our limited knowledge of the ocean, one must design oceanographic models carefully to meet the particular task at hand. No single model is likely to serve all tasks. The report stated that, if one uses models complicated enough to include the necessary basic processes but simple enough to be understood in principle and tested against known constraints, it is possible in most cases to put reliable limits on pollutant transfer rates. On the important question of assessing model accuracy, the report could do little more than recommend that the range of uncertainty be estimated from the results obtained when the input parameters are varied over their full range of possible values. Models should also be tested against their sensitivity to the inclusion of omitted processes and, of course, against available data sets.

The report provided estimates of transfer rates by various mechanisms that have been suggested by concerned parties. It also recommended that all identifiable potentially significant transfer mechanisms should be quantified to the accuracy possible, since only in this way may they be put into proper perspective. In any event, the report states that for all scenarios four processes should be evaluated for their importance. These are: physical advection and mixing; radioactive decay or chemical degradation; interactions of the contaminant with particular matter both in the water column and on the bottom; and mixing, diffusion or burial in the bottom sediments. All are discussed briefly below.

Physical transport mechanisms

Physical processes affecting transport rates from a deep-sea disposal range in space scales from those of salt-fingers (millimetres) to the large-scale oceanic circulation (tens of thousands of kilometres), and in characteristic time scales from seconds to thousands of years. Clearly, only a limited range can or need be considered in any particular problem. A cartoon representation of some of the processes and the regions of the ocean where they may be important is given in figure 1. This is based on a diagram presented by Robinson & Kupferman (eds) (1985), who provide a detailed analysis of many relevant physical processes.

Models now exist that include most of the processes illustrated in figure 1, either explicitly or via an appropriate parametrization. Some are analytical in nature, others strictly numerical. In general, they are capable of representing the effects of the most important processes in a generic manner. As detailed representations of specific oceanic areas, however, they are usually not so effective, because of difficulties in accurately modelling the non-uniform distribution of the intensity of mixing processes and the large-scale very-low-frequency or steady flows, which are so important to the final distribution of a pollutant. The oceanic geostrophic eddies cause particular problems in this regard since they have length scales that are not resolved in most ocean models and cause significant non-uniform horizontal mixing. This aspect of ocean modelling has many of the same requirements for improvement as are necessary for satisfactory ocean climate predictions and the determination of such basic oceanographic quantities as the large-scale ocean heat and salt fluxes. These problems are attracting increasing interest in the oceanographic community and will no doubt see real advances in the coming few years.

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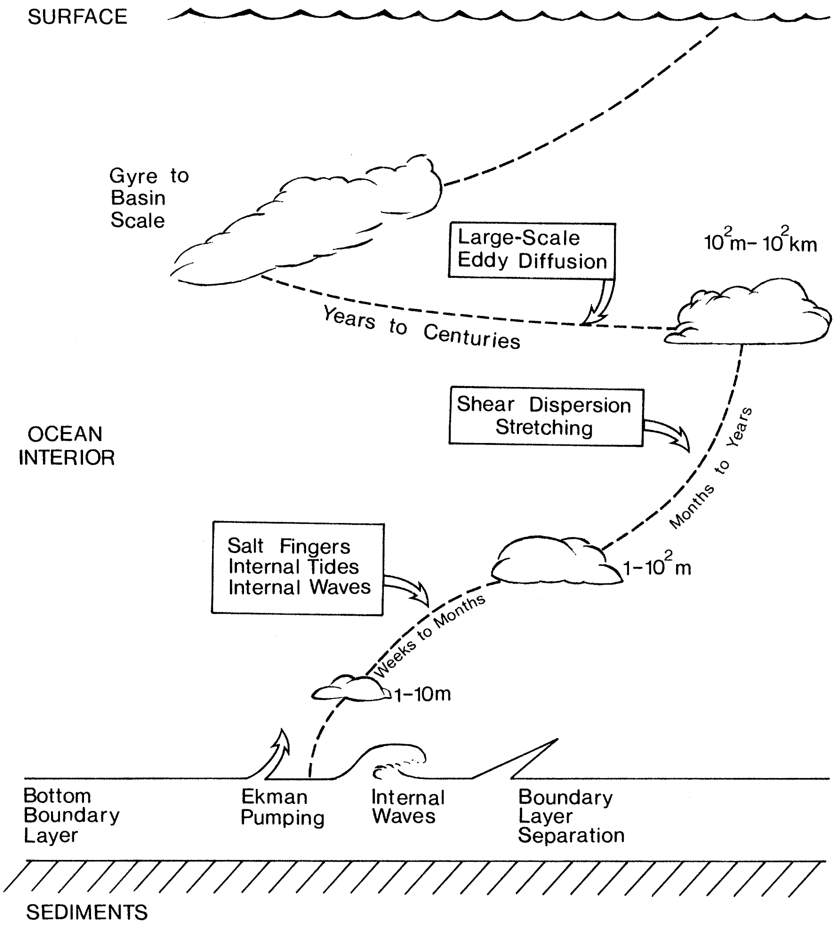

Figure 1. A cartoon illustrating the various processes leading to the dispersion of a substance from the deep-sea dump site.

Geochemical processes

Before discussing further the problems of modelling physical processes, let us consider the existing distributions of naturally occurring chemical species. For those that have residence times in the ocean longer than the time scale of large-scale mixing, physical processes alone would lead to uniform distributions. This is often far from true as can be seen from figure 2, which shows the vertical profile of three well known elements and compounds. One can see that copper, which is on average cycled many times in the ocean before deposition in the sediments, has a very non-uniform distribution with a maximum at or near the ocean floor. Nitrate and cadmium, on the other hand, have mid-depth maxima. The reason for these distributions is well known to be related to the adherence of these elements to the particles of organic and inorganic matter that continually sink from the upper ocean, especially under regions of high productivity. Some of these particles dissolve or are taken up by living organisms on the way down to the ocean floor and release the elements they carry, sometimes leading to maxima as seen for nitrate and cadmium. Others fall to the ocean floor, where some of the organic matter and most of the inorganic matter becomes part of the deep-sea sediments. Such particles contribute to the bottom maximum for copper. In all cases physical processes tend to smooth out the maxima and transport the substances both vertically and horizontally to regions of low concentration.

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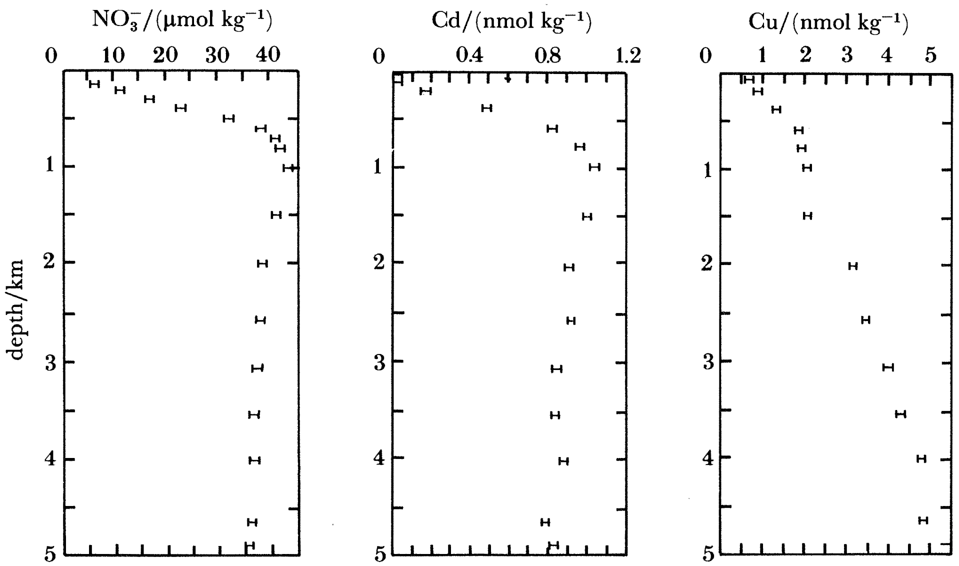

FIGURE 2. Vertical profiles of nitrate, cadmium and copper from station 17, H-77, in the eastern North Pacific. (From Bruland (1980).)

SIMPLE PHYSICAL–GEOCHEMICAL MODELS

To investigate the nature and significance of particle scavenging, the GESAMP report provided two simple models combining both physical and scavenging processes. Both have been used in the latest IAEA assessment of suitable low-level dumping limits and as comparisons or checks on other models assessing the hazard of both low-level and high-level deep-sea disposal. They have the advantage that they have limiting analytical solutions for useful parameter ranges.

Let us first examine a model suitable for investigating the effects of the removal of a contaminant from the water column at the bottom boundary by particulate interactions while the contaminant is being dispersed from a steady distributed source of a radionuclide (see figure 3). In the model, removal to the sediments is parametrized by assuming that the flux to the sediments may be written as a deposition velocity, V_d, times the water concentration, C. Such a representation can be used to describe processes such as pore water diffusion, bioturbation, and burial by accumulating sediments (GESAMP 1983), but is not appropriate for use in time-dependent problems, when a flux of the contaminant back from the sediment to the water may occur. The form of V_d depends on the particular boundary removal process being considered but is often dependent on K_D, the ratio of the concentration on sediments or particulate matter to the concentration in the waste phase. The removal of a substance from

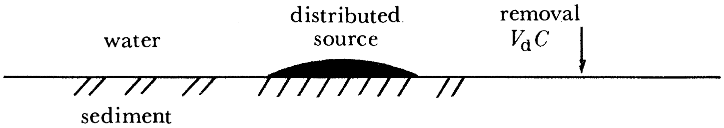

FIGURE 3. Schematic of a distributed source of a contaminant on the bottom sediments with removal from the water described by a deposition velocity.

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the water column may be similarly parametrized by representing the flux of the substance by particulate matter by V_{i} times the water concentration, where V_{i} is K_{D} times the flux of the particulate matter.

In this model, dispersion in the water is parametrized in the usual way through the use of horizontal and vertical eddy dispersion coefficients K_{h} and K_{v} respectively. Asymptotic forms of the solutions to this problem exist for large distances from the source that allow one to see in which parts of parameter space particulate interactions and radioactive decay limit the spread of the radionuclide. The results are indicated in figure 4 in terms of a dimensionless scavenging strength, $V_{\mathrm{d}} H/K_{\mathrm{v}}$, and a dimensionless rate of decay $(\lambda H^2/K_{\mathrm{v}})$, where H is the ocean depth and λ the radioactive decay constant. As is to be expected, short-lived or highly scavenged materials only have significant concentrations close to the source, whereas long-lived weakly scavenged materials can be found far afield either in the sediment or dispersed throughout the water column. The boundaries between the regions, while not in reality so clearly defined as indicated, may be explained in terms of the dominant transport and removal processes in each part of the non-dimensional space.

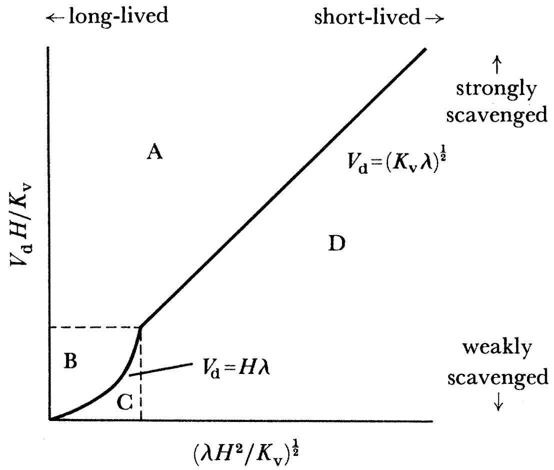

FIGURE 4. The boundaries between regions of different characteristic solutions of the diffusion-scavenging model. In regions A and D the contaminant is confined near the source by scavenging and decay respectively. In regions B and C the contaminant is widespread and is mostly in the sediments and the water column respectively.

In contrast to the three-dimensional diffusion model just described, one may consider an almost one-dimensional model similar to those in common use in marine geochemistry for some years. Such models allow more complete consideration of the vertical processes and, as discussed in the GESAMP report, may give reasonably accurate representations of the horizontally averaged distribution of both naturally occurring and anthropogenic substances because the strong horizontal mixing that occurs in the ocean tends to make their distributions more or less horizontally uniform. Correlations between regions of significant vertical velocity and the concentration of the substance being considered could, however, cause inaccuracies. Perhaps the simplest model of this type that can truly account for the overall oceanic cycling of a substance that has a reasonably long residence time is shown in figure 5. It differs from the usual one-dimensional geochemical models in that a region of polar sinking is explicitly included. This is necessary to include properly the downward flux in polar regions of long-lived

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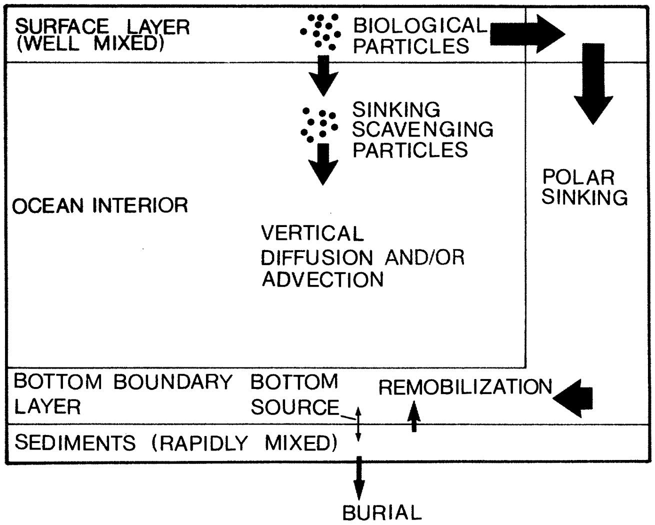

FIGURE 5. Schematic of an ocean model with upwelling, diffusion, particle scavenging, removal to the sediments, and circulation driven by polar sinking.

substances that are not strongly scavenged. In the ocean interior the physical processes of vertical advection and diffusion are included. The model has a bottom sedimentary layer that can represent the usual processes that can remove a substance permanently or temporarily from the water column, including the burial by accumulating sediments that provides the ultimate oceanic sink for many stable elements. In the water column the model necessarily includes at least two types of particles to enable it to have widespread application for both natural and anthropogenic substances. Firstly, there are scavenging particles that can adsorb a substance from the water phase and release it in regions of low water concentration. Assuming that this can be represented as a first-order reversible process, it is natural to define rate constants k_1 and k_2 for adsorption and desorption respectively. Their ratio, properly normalized to take account of the fraction of the water column occupied by particles, is equal to the common parameter K_D defined previously. The second class of particles that must be included, which are referred to here as biological particles, are those that through biological activity near the surface incorporate a substance in organic matter. On sinking, these particles dissolve, often quickly enough to release the substance at mid-depths. This process leads to the mid-depth maxima of nitrate and cadmium shown in figure 2.

The details of this model's formulation and application may be found in the GESAMP report. It is shown that by using traditional values for oceanic diffusion, upwelling velocity, etc., and choosing the parameters describing the particle fluxes and decay times within experimentally verified limits, the model can describe the major features of the distribution of substances with such widely diverse half-lives, chemical reactivity and source location as thorium-230, radium-226, lead-210, manganese, copper, nickel and cadmium. As for the previous model, the resulting distribution is a strong function of both half-life and scavenging. This is illustrated by figure 6, which shows contours of equal concentration as a function of λ and K_D at various depths for a bottom source of unit strength (1 unit m^{-2} d^{-1}). Contour intervals are in units of m^{-3}. That short-lived and/or reactive (large K_D) elements from deep sources have low near-surface concentrations is evident from figure 6. Of some interest is the rapid decrease to

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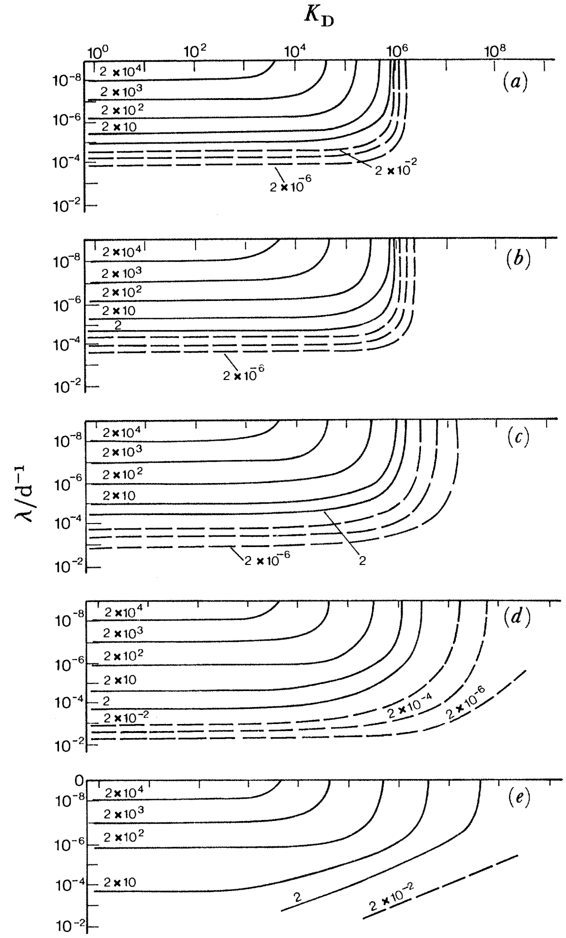

FIGURE 6. Results of the model illustrated in figure 5. Shown are contours of equal concentration at various depths as a function of λ and K_D: (*a*) surface; (*b*) 1800 m; (*c*) 3600 m; (*d*) 4500 m; (*e*) 5000 m (bottom).

be seen in the concentration near the surface as K_D is increased beyond 10^6. This arises, for the particular model parameters chosen, when K_D is large enough to make the downward flux of the substance by scavenging particles exactly balance the upward flux by upwelling. For larger values of K_D, scavenging effectively traps the element near the bottom with a vertical scale determined by the balance between the flux of the substance by sinking particles and upward diffusion. For lower values of K_D, scavenging particles are less effective and a variety of transport processes are important throughout the water column. It is interesting to note that the important element plutonium is usually given a K_D considerably less than 10^6 so that one would expect it to become widespread in the surface ocean even though its distribution throughout the ocean will be strongly influenced by particulate scavenging. The model was also used to investigate the degree to which a substance reaches chemical equilibrium between the falling particulate matter and the water column (GESAMP 1983). It was found that only for very reactive elements, which exhibit strong near-bottom concentration gradients, is there any substantial disequilibrium. However, even in this case it may be shown that the bottom water concentration, which controls the removal rate to the sediments, is almost the same as if equilibrium existed. Thus the common use of the equilibrium approximation in models for waste-disposal hazard assessments seems to be justified.

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BIOLOGICAL TRANSPORT PROCESSES

As has been pointed out above, biological processes are involved in the creation of organic particulate material in the near-surface ocean that can either incorporate a substance or be part of the scavenging mechanism. In either case they lead to the transport of the substance into the deep ocean as the particles sink. Similarly, living benthic organisms can cause relatively fast mixing of the substance into the surface sediments by bioturbation. The question that must be asked, however, is whether or not the direct transport of a substance by living organisms from the deep sea to man or his food chain can be important in comparison with the transport by physical or chemical processes, including the transport on falling particles (see Angel 1983). This has often been suggested to be the case and because living organisms can form a relatively direct route to man's food chain, it is important to consider their role carefully as a transport mechanism.

When considering deep-sea biological pathways it is useful to note that the accepted value for the living biomass per unit area of sea floor in the deep ocean is only about 0.3 g m^{-2}. Most of this exists close to the sea floor or in the sediments. Averaged over a narrow benthic boundary layer of 10 m, this gives a ratio (by mass) of biomass to water occupied of 3×10^{-8}. Thus if all this biomass were moving fish and they were to swim some reasonable distance on the average a hundred times faster than water moves in the boundary layer (for instance, 1 m s^{-1} or 80 km d^{-1} compared with 1 cm s^{-1}), the amount of a substance transported by the fish would be less than that by the water unless the concentration factor of the substance in the fish exceeded 3×10^5, a rather large value. It is worth noting that the ratio of 10^{-8} for living organisms to water obtained by concentrating the biomass in the bottom 10 m is about the same as for the ratio of sinking particulate matter to water. The particulate matter, however, exists throughout the water column and steadily transports adherent substances downward.

Can one conceive of mechanisms by which a substance could be transported to man by deep-sea living organisms? Several have been suggested but most, or all, seem difficult to justify as significant quantitatively. The most direct pathway is of course simply the consumption of deep-sea organisms. This possibility has been included in the IAEA's recent assessment of the hazards of deep-sea dumping even though no present exploitation of deep-ocean (below about 2000 m) fish stocks now takes place. For relatively short-lived nuclides, such as caesium-137, this would provide the critical pathway should a critical group of people eating deep-sea food actually exist. In this context, the GESAMP report provides estimates showing that the low deep-sea productivity means that the bottom area needed to produce enough fish to maintain a critical path to one individual is of order 10–100 km^2. Such an area is very much greater than that needed on the continental shelves or in the surface ocean to provide the necessary sustainable yield of fish. These regions will always supply most of man's supply of edible marine foodstuffs. Thus for long-lived non-reactive radionuclides, which will spread from a dump-site throughout the marine environment, the collective dose to man will surely come from near-surface direct or indirect pathways.

One biological mechanism of potential importance, examined by the GESAMP group, is the transport of a substance to the sea surface as the result of the release of buoyant eggs from the bottom. Such a situation is schematically illustrated in figure 7. The basic premise is that fish from a large area could arrive at a dump site, coincident with their spawning area, release their eggs, which then equilibrate with the local concentration of released radionuclides, and

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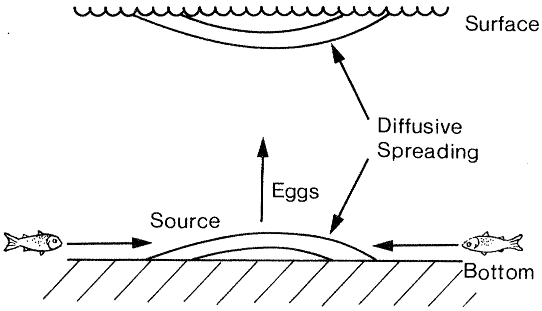

Figure 7. Schematic of a possible transfer of a substance from a dump site by buoyant eggs: a double 'hot spot'.

the eggs, on rising to the surface, could result in a surface concentration of a given strength. The GESAMP report refers to this as a double hot-spot (top and bottom). From estimates of deep-sea productivity it is not difficult to put an upper limit on this process. The results are hardly surprising. Even for substances that do not decay, the transport averaged over a basin is negligible compared with that from physical processes and is even negligible averaged over the dump-site area unless the concentration factor of the eggs is of order 10^4–10^5. It is obvious, however, that for short-lived radionuclides the surface concentration from this rapid (of time-scale equal to that for the eggs to rise to the sea surface) transfer mechanism would be greater than that by the physical processes that transport a substance slowly allowing radioactive decay to be effective.

The important question to ask of such a mechanism is, however, not whether in some limited circumstances it might be dominant but rather if in more general terms it is important. For the buoyant eggs, for example, it is difficult to contemplate a pathway to a critical group that would be significant considering the dispersion in the upper ocean. More important, however, is the consideration that pathways involving the deep-sea fish themselves are likely to be more significant even though, as mentioned earlier, they also are likely to be relatively insignificant in absolute terms (at least regarding the collective dose).

The arguments put forward above should not in any way be taken to indicate that in the future some sort of biological pathway may not be found to be critical. The point to be taken is that, in general, quantitative estimates can be made of the importance of such pathways and such estimates should be made for all rational possibilities.

Recent work

This short review of the oceanographic aspects of the deep-sea disposal of radionuclides would be seriously remiss if mention were not made of the considerable effort recently being applied to this problem by scientists from a number of countries around the world. Some has been done in direct support of the hazard assessment of the low-level dump site in the Northeast Atlantic. In this regard models have been developed (see NEA 1985) that are similar in nature to those devised by using inverse techniques (Wunsch 1978) but are actually more closely constrained by the qualitative views of oceanographers working in the area. This may often be the most appropriate approach for the hazard assessment of a particular area, since many inferences

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about the circulation in an area, which are difficult to incorporate in a strictly quantitative way, may be drawn from a wide variety of data sources.

Large-scale general circulation models (GCMS) have been applied to both the high-level and low-level disposal problems in a number of countries. A comparison of these models (Robinson & Marietta (eds) 1985) has revealed resolvable differences of general oceanographic significance. Simple box models, including biological and geochemical processes, are being developed and tested (Robinson & Marietta (eds) 1985) much in the spirit of the recommendations of the GESAMP report. This twofold approach with the use of both simple models and their full oceanic counterparts (the GCMS) in a coherent programme holds much promise.

Equally important in the long term is the investigation of the processes that are not well understood so that their importance may be assessed and/or their effects may be properly parametrized in models of hazard assessment. One can note the work on benthic fronts (Thorpe 1983) and on the interaction of geostrophic eddies with the bottom boundary layer (Richards 1984), a mechanism of importance regarding the entrainment of a substance from the boundary layers into the ocean interior. The question of advection and dispersion near a dump site has been addressed by Saunders (1983), and more recently estimates of deep-ocean diffusion rates in the deep ocean basin have been based on the budget of the heat from the geothermal bottom source (Saunders & Richards 1985). Measurements of geochemical and biological properties and mechanisms in the deep ocean of direct relevance to deep-sea dumping have been made by various investigators (see, for example, CRESP (1986) and Dickson *et al.* 1985).

Although much remains to be done, the progress made in addressing the oceanic aspects of the deep-sea disposal of radionuclides is encouraging. When compared with that of just a few years ago both the quality and the quantity of the work being carried out is impressive. Much is starting to appear in the open literature. In the future both directly applied oceanographic research and that of a general nature will improve the situation and allow increased accuracy in hazard assessments. Even now, however, few transfer processes exist that it is not possible to quantify with some degree of confidence.

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