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IMO /FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP JOINT GROUP OF EXPERTS ON THE SCIENTIFIC ASPECTS OF MARINE POLLUTION - GESAMP -

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AN OCEANOGRAPHIC MODEL FOR THE DISPERSION OF WASTES DISPOSED OF IN THE DEEP SEA

INTERNATIONAL ATOMIC ENERGY AGENCY

Report and Studies No. 19

IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts
on the Scientific Aspects of Marine Pollution (GESAMP)

AN OCEANOGRAPHIC MODEL FOR THE DISPERSION OF WASTES DISPOSED OF IN THE DEEP SEA

International Atomic Energy Agency
Vienna, 1983

NOTES

1. GESAMP is an advisory body consisting of specialized experts nominated by the Sponsoring Agencies (IMO, FAO, UNESCO, WMO, WHO, IAEA, UN, UNEP). Its principal task is to provide scientific advice on marine pollution problems to the Sponsoring Agencies and to the Intergovernmental Oceanographic Commission (IOC).

2. This report is available in English from any of the Sponsoring Agencies.

3. The report contains views expressed by members of GESAMP who act in their individual capacities; their views may not necessarily correspond with those of the Sponsoring Agencies.

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Definition of Marine Pollution by GESAMP

"POLLUTION MEANS THE INTRODUCTION BY MAN, DIRECTLY OR INDIRECTLY, OF SUBSTANCES OR ENERGY INTO THE MARINE ENVIRONMENT (INCLUDING ESTUARIES) RESULTING IN SUCH DELETERIOUS EFFECTS AS HARM TO LIVING RESOURCES, HAZARDS TO HUMAN HEALTH, HINDRANCE TO MARINE ACTIVITIES INCLUDING FISHING, IMPAIRMENT OF QUALITY FOR USE OF SEA WATER AND REDUCTION OF AMENITIES."

* * *

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An oceanographic model for the dispersion of wastes disposed of in the deep sea (19).

PREFACE

Limited quantities of potentially harmful substances have been and are being released into the marine environment, usually under the control of national or international regulatory bodies. In assessing the amount of a substance that can be released, consideration is usually taken of the "capacity" of the environment to receive the substance. The capacity itself is determined by considering the fate of the substance in the environment and the possibility that human populations or the marine ecosystem (or parts thereof) might receive amounts or concentrations of the substance at levels detrimental to their health. Such an approach to environmental protection is discussed in the GESAMP Report on The Review of the Health of the Oceans.

The deep-sea dumping of packaged radioactive wastes has been carried out within the limitation set by the London Dumping Convention, making use of recommendations provided by expert panels of the International Atomic Energy Agency (IAEA) concerning unacceptable dumping limits. It has become clear however that, although these dumping limits can be set so as to protect human populations or the environment, estimates of the transport of radionuclides from a dump site to man's food chain by oceanic processes are difficult to make, especially with the accuracy needed to compare land and sea disposal options. With this in mind and recognizing that the IAEA's recommendations to the London Dumping Convention would have to be reassessed in the early 1980's, the IAEA asked the eleventh session of GESAMP in February 1980 to establish a working group to provide advice on the most suitable oceanographic modelling techniques to be applied to the deep-sea dumping of both radioactive and non-radioactive substances.

Recognizing the opportunity to make a substantial scientific contribution to important marine environmental problems, GESAMP agreed to establish the Working Group on an "Oceanographic Model for the Dispersion of Wastes Disposed of in the Deep Sea" with the following terms of reference:

(i) to review the present knowledge of pathways by which substances might be transferred from a deep ocean dumping area to man;

(ii) where possible, to recommend methods for calculating the concentration of substances, arising from containers deposited on the deep ocean floor, in the water column throughout an ocean basin; and

(iii) to assess the reliability of the calculated concentrations and, where possible, to recommend ways and means by which these might be improved.

The IAEA, as lead agency, has provided administrative and technical support for the work of the group, which has also received support from IMO, UNESCO, and UNEP. The Working Group met first in December, 1980 under the chairmanship of Dr. G.T. Needler and subsequently four more times before presenting its report to the thirteenth session of GESAMP in March, 1983.

CONTENTS

EXECUTIVE SUMMARY

The Terms of Reference given in the Preface were interpreted as specifying the following four objectives for the work:

(1) Review the present knowledge of oceanic processes that may transfer substances from a deep-sea dump site back to man or his food chain;
(2) Review methods and models presently available for estimating or calculating concentration distributions of contaminants arising from releases from deep-sea dump sites, if possible to make further developments or suggestions for developments, and give recommendations as to the presently most appropriate models;
(3) Assess the reliability of the concentration distributions obtained using these models;
(4) Recommend areas for further improvements and identify research needs.

The basic philosophy of the work, described in Section 2, has been that the level of sophistication introduced in the models should match what is actually known about processes occurring in nature, and to include in models only those processes, or a representation of the processes, that are essential. The attempt was made towards achieving a good correspondence between the recommendations on models and the review of present knowledge of oceanic processes. This approach often leads to the identification of a least complex model that is adequate for the purpose. In cases when relatively simple models indicate potentially hazardous situations or are found to be inadequate for the assessment of the hazard, more elaborate models may be needed to obtain more detailed or accurate results or to test the validity of approximations made. An iterative process is envisaged in which the conclusions of a hazard assessment programme will be analyzed and lead to the refinement of models now available by identifying critical processes and by including more accuracy or resolution. There will certainly be the need for further direct observations of the oceans to obtain information on oceanic processes or to enable appropriate validation of revised models.

The purpose of the models in the present context is to provide information which can be used in decisions on control measures for the protection of man and the environment from undesirable hazards due to contaminant releases. The primary aim is the protection of man, and a principal concern is that of average exposures over several decades. Thus, it is the average concentrations over such time periods for the whole ocean, not only short term maximum concentrations in small regions, that are of interest. In some circumstances however, extreme transfer events may also lead to a potentially significant hazard. If such events have low probability of occurrence, they may be both difficult to model and to put in proper perspective.

Models must often be chosen to provide answers to particular questions arising from the release of a contaminant. Such models may be unsuitable for answering other questions or dealing with other release scenarios. Thus, there is a need for both the potential impacts of releases and the nature of the release itself to be well defined.

The present knowledge of deep ocean processes controlling dispersion is meagre. Observations are often sparse in space and time, and of varying accuracy or resolution. In particular it is difficult, and in many cases impossible, to relate direct observations of small-scale processes to external, or large-scale, average variables. This implies that the parametrization of sub-grid scale processes in a model must usually be tested and related to observations on a case-by-case basis. This may severely limit the reliability and generality of the predictions from models requiring such parametrizations. The model outputs must therefore always be regarded as giving a range of possibilities. One useful method for checking the parametrization of dispersion models can be to apply them to naturally-occurring substances in the ocean (i.e. to use geochemical analogues).

It has been found useful to separate the concentration distribution into a near-field zone in the vicinity of the source (sometimes with a sub-region referred to as the extreme near-field), and a far-field zone. These regions usually exhibit different approaches to the average concentration field and fluctuations about that average and thus may require different models. The nature of these regions may be illustrated by the analogy of a smoke-filled room given in Section 2.

The principal results of the work are now described according to the identified objectives 1. to 3.

1. Oceanic Processes

These are discussed in most detail in Section 3.

1.1 Physical processes

Except in a few areas of deep-water formation or in transient patches of the scale of a few metres the ocean is stably stratified. Thus, the large-scale circulation has a strong tendency to follow isopycnal surfaces and transport across these surfaces is suppressed relative to exchange along them. The annual formation of deep and bottom water at high latitudes requires an upward return flow from the interior of the ocean. The spatial distribution of this return flow is not well known. The ocean circulation is also forced by the surface winds, which strongly influence most of the large-scale ocean current fields. Much of what is known about the large-scale processes comes from the study of properties such as heat and salt that have surface sources and sinks and rarely provide much information about deep ocean processes important for the transport of contaminants from deep-sea dump sites.

The meso-scale processes and fluctuations, of the order of several tens to hundreds of kilometres in space and weeks to several months in time, are dominated by eddies, rings and lenses. Their properties have been most closely documented for the upper 1-2 km of the ocean but they are known to occur at great depths. These stir the ocean. Due to this stirring the concentration field of a contaminant released from a point source will be streaky. Significant streakiness has been estimated to persist for times of the order of one year and within a few hundred kilometres of the source. However, new meso-scale features are still being found, for example, isolated lenses of water have been detected thousands of kilometres from their source.

Small-scale processes, of the order of metres and less, are mainly of interest in relation to their influence on transport across isopycnal surfaces. Effects of such processes are evident in high-resolution vertical profiles of oceanic properties.

Bottom boundary layers, due to the friction of the flow of water against the bottom, range in thickness from metres over the abyssal plains to several tens of metres over high kinetic energy zones along the continental rise and slope. Properties in these layers tend to be vertically homogeneous. The effects of meso-scale fluctuations on the structure of the boundary layer, and the dynamics and efficiency of mixing within them, are not yet well understood. The boundary layer is often rich in suspended particles. Interior nephel layers can be formed through detachment of the boundary layer from the bottom. The current and density field in the boundary layer near the dump site will influence the near-field concentration distribution but not the time-averaged far-field distribution.

1.2. Geochemical processes

Due to biochemical and geochemical interactions, reactive substances are cycled between suspended particulate material and the water phase. The particulates primarily carry such substances towards the ocean depths and the deep-sea sediments, where various transformations can occur. The water phase concentration field may be very different from that which would be present if only physical processes were present. The removal by particulates of substances from the dissolved phase is called scavenging and is discussed in detail. It may be parametrized in terms of residence time, deposition velocity and kinetics of uptake and release. The latter two formulations are used in the models discussed later for both bottom boundary and interior scavenging. It is concluded that although much remains to be learned about the process of scavenging, its inclusion in some form in models for waste disposal is required for reactive contaminants. It is also necessary if models are to be tested using the observed distributions of many natural analogues.

1.3. Biological processes

Mass transport of contaminants by living organisms in the interior of the ocean does not generally appear to be significant relative to other transport mechanisms because of the small amount of biomass in organisms relative to their surroundings. However, in the surficial sediments, bioturbation is a very significant transfer mechanism which must be appropriately included in formulations of boundary conditions. Likewise when contaminants are incorporated into biological material in the surface layer production zone, the subsequent downward transport through sinking particulate material is significant.

The transfer of contaminants in food chains must be estimated to assess the hazard to man and the environment. The minimum region required to supply food to sustain a yield of one demersal fish per day has been estimated to be of the order of hundreds of square kilometres of the deep ocean floor. For a sustainable fishery the area would be very much larger. This implies that the detailed concentration distribution in the vicinity of the dumpsite is unimportant for such a fisheries pathway since the fish required to sustain it must feed over a larger area. It is furthermore unrealistic to imagine eating fish that have fed only on prey which in turn have fed only in a region of peak concentrations. Biological considerations can thus determine the area over which average concentrations of a contaminant are required.

2. Model Considerations

2.1. Existing and potential models

Many different models of the ocean exist. No single model is appropriate for simulating all processes and as there is no single model appropriate for all purposes, a family of models will generally be required. A model of water movement by physical processes must be the framework on which effects of geochemical processes, such as scavenging, and of biological processes are superimposed. A series of models of near-field and far-field concentration distributions are discussed in Section 4 in increasing order of complexity. Some new models were developed and are described in the Appendices.

For the near-field, high spatial resolution is required, at least close to the source. This makes analytical models attractive although these are still hampered by the requirement of correct parametrization of small-scale processes. Point source models for a static, diffusive medium may adequately give order of magnitude estimates for the steady state concentration distribution close to the source. Such models can incorporate radioactive decay, a finite size source, and an absorbing boundary. Interior scavenging can also be taken into account. Simple plume solutions may be used to make allowance for flow and radioactive decay. Incorporation of all major processes simultaneously requires the construction of some sort of numerical model. Explicit simulation of turbulent dispersion introduces a major complication. This may, however, be desirable in order to validate advection/diffusion parametrization. For such purposes, eddy-resolving regional circulation models may be required, although these are probably best adopted to answer specific questions rather than for general use.

In the far-field the finiteness of the ocean is likely to be important, but the details of the near-field are not. The simplest model of a finite ocean is a well-mixed box, which assumes rapid flow and mixing processes and has no spatial resolution. One-dimensional (vertical) models have commonly been used to interpret geochemical tracer distributions, often with quite good overall results. They can however never adequately represent the near-field distribution or some aspects of important horizontally non-uniform processes such as downward vertical motion. Time-dependent results are also likely to be unreliable over some time scales. To overcome some of these problems a vertical scavenging model has been constructed that includes some realistic aspects of sedimentary interactions and the flow to and from the deep ocean.

A simultaneous representation of the effects of flow, mixing, decay, scavenging, and biological transport probably requires a numerical model in two or three dimensions. The spatial resolution may be as great as desired and there is no difficulty in similarly representing features of the ocean topography. Distinction should be made between numerical models in which the flow-field is specified, and those in which the flow-field is computed, sometimes as a function of time. The former type may be classified as dispersion, or diffusion/advection models, whereas the latter also are dynamical models. These are considerably more complex and costly than dispersion models with the same spatial resolution. Dispersion models can be formulated in an isopyncal coordinate system enabling better representation of processes across and along isopycnal surfaces.

Complex numerical models are required to obtain the fullest representation of the ocean and its dynamics. Such models have so far been used mainly for research into the dynamics of the ocean. Diagnostic calculations, that is those that infer the flow field from the observed density distribution, have in some cases yielded unrealistic features of the circulation, including vertical exchange processes. Prognostic calculations, including the calculation of the density field from given boundary conditions, may be preferable but also have known problems. Even more complex are the eddy-resolving models, which appear to be capable of showing the statistical effects of meso-scale eddies on tracer distributions.

Although complex high resolution models may be used for estimates of contaminant transfer, it is not clear that such models offer any advantage, since they contain uncertainties as great as in many simpler models and it is usually more difficult to interpret their results. The main role of these models may well be in relation to process studies.

2.2. Recommended models

The choice of an appropriate model for a particular contaminant will depend on its natural lifetime, its reactivity with various particulate matter, and on the purpose of the calculation. In considering simple models, various scales dependent on the properties of the ocean and the contaminant are identified. These scales indicate the size of the region over which some major transport mechanisms could be important. The following general conclusions resulted from initial estimates of the importance of various processes:

(1) Within the assumption of first-order scavenging, contaminants are likely to be well equilibrated between particulate and water phases in the ocean interior except near relative thin transition layers close to boundaries, sources, and sinks.

(2) For steady-state problems the effects of scavenging and/or mobilization at boundaries may usually be parametrized using deposition velocities. The importance of interior scavenging of the ocean water inventory may often also be adequately estimated by this method, but the details of the interior concentration field may not. The specification of the appropriate deposition velocity however demands careful attention to all the processes at work. This parametrization is usually inadequate for time-dependent problems, except in special cases.

(3) Within a radius of the order of 100 km around a source, the effects of advection on the concentration, averaged over times of about one year or more, are small and diffusive solutions are adequate for most purposes.

(4) In the deep ocean, the minimum area for spatial averaging required for models of transfer into food chains is of the order of 100 km^2, and the minimum period for time averaging is one year or more. Ensemble average concentrations (calculated using eddy diffusion coefficients, for example) are therefore adequate for most purposes.

(5) The concentration field in the extreme near field is only of relevance when considering effects on abyssal organisms.

(6) Fluctuations from the mean are not likely to exceed the expected (average) concentration except in regions of high concentration gradient (for example, near the source).

(7) The characteristic time for the development of the expected concentration field near the source (say within 300 km radius) is of the order of a few years, and the concentration field is therefore in approximate steady state with the recent average release rate over such a time period.

(8) Within a reasonably general class of models, the laterally-averaged concentration field is given by the solution of a one-dimensional model (i.e. the ratio of contaminant inventory in the sediments to water inventory is no greater, or less, for dispersion in a three-dimensional ocean than is given by a one-dimensional model). Since the detailed lateral distribution does not affect the inventories, one-dimensional models have wider applicability than might have been expected.

(9) The detailed behaviour of the bottom boundary layer is unimportant except insofar as it affects average vertical transfer (i.e. K_V due to boundary mixing), or affects the concentration in the extreme near field.

(10) Transports by biological organisms, other than those associated with downward transport in biogenic particles and mixing of sediments, do not significantly affect the concentration field established by physical and geochemical processes.

Keeping all the above considerations in mind, the following models are recommended for use.

<u>Near-Field</u>

(a) Simple Finite Ocean Diffusive Model (Appendix IV)
(b) Modified for finite source size and scavenging. (Appendix VII).
(c) Plume solutions if the size of the near-field exceeds the scale K_H/U within which diffusion dominates.

<u>Far-Field</u>

(a) Well-mixed box (for contaminants with a long residence time).
(b) The one-dimensional scavenging models of Appendices VI and IX.
(c) The Simple 3-D Diffusion Model with Scavenging. (Appendix VII).
(d) A medium-resolution box model.
(e) Finite-difference models in 2- and 3-D.

For many applications the simpler models within each category will be sufficient. In others, a more elaborate model will be convenient to use for all contaminants of interest or as a test of the importance of extra features. The Working Group however identified four processes that should be examined in all cases with regard to their significance and included where appropriate. These are

(a) the movement and mixing of water within the ocean basin (although this takes place preferentially along isopycnal surfaces, the relatively <u>slow</u> vertical (or diapycnal) motions are of special importance);
(b) radioactive decay or chemical degradation of contaminants;

(c) the interaction of contaminants with particulate materials of various sorts, including biogenic particles, both within the water column and on the bottom; and

(d) mixing (e.g. bioturbation) and diffusion into (or out of) surficial sediments.

2.3. Reliability

Section 5 ends with a discussion on model sensitivity and reliability. Given the present state of our knowledge of the deep ocean, it is difficult to provide an accurate quantitative assessment of the reliability of the concentrations of contaminant calculated by a model.

This will depend on being able to identify all significant processes, having adequate knowledge of their nature, and being able to devise an adequate representation of their effect for use in the model being considered. Uncertainties in all these areas has led to the recommendation of the use of models using the simplest parametrizations that appear to describe adequately the known transport processes for a contaminant. It is thought that this will provide models that are generally valid, within their approximations, and that it is unlikely that the search for new important transfer mechanisms will result in any that will substantially change this situation. Care will always have to be taken however to investigate possibilities as they arise.

Given the above, some of the uncertainty in the results of most models may be investigated by examining the variability of the output of the model over the full range of variability of the input parameters, which may be quite large. This sensitivity of a model to its input parameters should always be presented as part of a model's output. It can provide valuable information about a model's performance, since:

(a) for those cases where a "best estimate" of the concentration field is needed, it indicates the range of possible uncertainty about this estimate;

(b) for those cases where the concentration field is needed for calculation of a critical path, it enables the determination of the maximum realistic concentration field within the model's assumptions and indicates its difference from the "best estimate"; and

(c) for all cases, it indicates the parameters to which the model's results are most sensitive. This can lead to an evaluation as to whether this is due to problems with the model's parametrization of known important processes or to lack of knowledge of these processes on which to quantify better their efforts.

Models should also always be evaluated in terms of the sensitivity of their results to the importance of neglected processes. In some cases it will be possible to do this on the basis of the results of simple models and it will not necessitate the detailed solution of a much more complex model. This approach has often been taken in this report in examining the significance of various processes.

Lastly, models should wherever possible be checked against existing data sets for the distribution of natural and/or anthropogenic substances. It must be remembered that although multi-parameter models may reproduce the distribution of substances, especially if the parameters have been adjusted for that purpose, they may nevertheless be unreliable for the prediction of the concentration field of a substance that is introduced or removed in some different manner. Thus, the choice of data sets for model "tuning" or verification must be done with considerable care.

3. Recommended Areas for Improvement

Improvement in the capability to predict concentrations of released contaminants seems to depend on obtaining further knowledge of critical processes and their parametrization along with the concurrent development of slightly more elaborate models designed to test the importance of various processes and assumptions. Recommendations in both these areas are made in Section 6.1 noting an importance of continental slope processes.

In particular, the research activities outlined below are identified:

(1) Geochemical Interactions in the Water Column. Studies needed include the interactions between contaminants and particle surfaces and the rates and reaction order of these interactions; the formation and decomposition rates of organic matter, the dissolution rate of tests and the rate of biological processing of particles and the formation of faecal pellets; and the geographical variations of the flux and composition of particulate matter.

(2) Vertical Mixing and the Thermohaline Circulation of the Oceans. Emphasis should be on the magnitude and spatial and temporal dependence of vertical (or diapycnal) exchange processes by both mixing and water movement. The specific requirements for contaminant transport in this regard are similar to those of climate research or programmes to determine the generation of the natural distribution of properties in the ocean.

(3) Horizontal Mixing and Advection. Emphasis should be given to the determination of the rates of exchange between ocean basins or regimes and the time-scale for horizontal mixing within them. Current oceanographic research using standard techniques is aimed at exactly these questions and needs to be maintained. Novel methods of attacking the problems should, of course, be sought and supported.

(4) Biogeochemical Processes in Sediments. Emphasis should be placed on the transformations that a contaminant associated with particles may be subject to in the surface sediments. Work is needed on the interaction between particles and contaminants in the sediment-pore water system; geographical variation of oxidation-reduction conditions within the depositional environment; the effect of the fauna on chemical transformations in the sediments, accumulation of contaminants in organisms; and the rate of particle mixing by the benthic fauna.

(5) Oceanic Distribution of Geochemical Tracers. In order to provide a test of a model's ability to represent geochemical interactions and physical mixing processes, work is needed to bring tracer data bases to a useful level for this purpose. Advantage should be taken of several ongoing oceanic tracer "experiments". Information on tracers with natural bottom

sources is particularly valuable since they perhaps more closely resemble the release of a contaminant from deep-sea waste disposal.

(6) Quantification of a variety of biological processes. The quantification of processes particularly those of large animals is needed. Knowledge of the extent of horizontal and vertical migrations of adult deep-sea demersal fish is of importance to assess the spatial scales of contaminant transfer into food chains. Information is also needed on the distribution of biomass and species assemblages, both in oceanic basins and slope regions, on the critical food web interactions among deep-sea organisms, on the amount of organic and inorganic material lost to burial and that available for biomass production, and on the response of deep-sea organisms to particular contaminants.

A number of useful models are identified, but others certainly exist. Since an important elaboration seems to be the introduction of vertical or horizontal variations to various basic models, the following should be considered:

(1) The construction of three-dimensional models with simple flow fields and particulate scavenging processes.

(2) The inclusion of vertical variation in various of the physical parameters in one-dimensional models such as those discussed in Appendices VIII and IX.

(3) The inclusion of a horizontal and vertical variation in the flow and scavenging regimes or time-dependence in the contaminant release in the hybrid model of Appendix IX.

(4) Using eddy-resolving or stochastic models to investigate the importance and nature of fluctuations about the average concentration field.

(5) More realistic oceanic plume models for the near field.