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DISPERSION OF DISSOLVED MATTER IN THE NORTH SEA

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Abstract

A good understanding of the main physical processes responsible for the dispersion of dissolved matter in the North Sea has been obtained from the combination of measurements (currents, and distributions of natural and artificial tracers) and mathematical modelling.
The mathematical models are a great help in the understanding of the results of the measurements, while the field data provide the necessary parameter values for the mathematical models. Variation of parameter values in the models gives insight in the relative importance of the various mechanisms and in the requirements for data and accuracy when the models are to be used for prediction purposes.
The parameters needed for proper modelling of dispersion can be derived from measurements and simulation on relatively small scales, say up to 40 kilometers, due to the possibility of modelling water movements on larger scales in a deterministic way. The necessary smaller scale information includes the mixing rates and the velocity structure in the vertical. The latter can in principle be derived from a deterministic three-dimensional flow model or even some kind of "2½-D" flow model.
The influence of vertical velocity structures, as induced by friction, wind and Coriolis forces, can be investigated separately by using various analytical approximations of vertical velocity structures, without deriving these directly from 2½- or 3-D flow models. This has been done by using particle simulation techniques. The examples to be shown demonstrate the relative importance of the 3-D effects up to horizontal scales of several kilometers.
From the rather large number of tracer experiments in the North Sea , a fair estimate of the spectral distribution of the energy of the horizontal water movements can be made, when taking into account the part that is taken in the total dispersion process by the effects in the vertical.

Résumé

Une bonne compréhension des principaux processus physiques responsables pour la dispersion des matières dissoutes dans la Mer du Nord a été obtenue par la combinaison des résultats des mesures (courants et répartitions de traceurs naturels et artificiels) et de la modélisation mathématique.
Les modèles mathématiques contribuent à la compréhension des résultats des mesures, tandis que les données du champ fournissent les valeurs paramétriques nécessaires pour les modèles. La variation des valeurs paramétriques dans les modèles donne une notion de l'importance relative des différents

mécanismes ainsi que des exigences auxquelles doivent répondre les données de même que leur exactitude lorsque les modèles doivent être utilisés pour des prévisions.

Les paramètres qui sont nécessaires pour une bonne modélisation de dispersion peuvent être dérivés des mesures à des échelles relativement petites, disons jusqu'à 40 km environ, grâce à la possibilité de modéliser les mouvements d'eau aux échelles plus grandes de façon déterministe. L'information nécessaire sur les échelles plus petites comprend également le taux de mélange et la structure des vitesses dans la verticale. Celle-ci peut être obtenue en principe d'un modèle courantologique tridimensionnel ou même d'une sorte de modèle courantologique "2½ D".

L'influence des structures verticales de vitesse, due à la friction, au vent et aux forces Coriolis, peut être étudiée séparément à l'aide de différentes approximations analytiques, sans nécessité de déterminer ces structures directement au moyen de modèles courantologiques 2½- ou 3D. Ceci a été fait par l'application de techniques de simulation de particules. Les exemples qui seront présentés montrent l'importance relative des effets 3D jusqu'aux échelles horizontales de plusieurs kilomètres.

A l'aide d'un nombre suffisant d'épreuves au moyen de traceurs dans la Mer du Nord, une estimation acceptable peut être faite de la répartition spectrale de l'énergie des mouvements d'eau horizontaux, à condition que la partie des effets dans la verticale soit prise en compte dans le processus total de dispersion.

1. Experimental data

In the years 1962 to 1982 a rather great number of dye experiments in the North Sea was performed by researchers from the Netherlands (Westhoff et al., 1971; Suijlen et al., 1980, 1982, 1988; Van Dam et al., 1963, 1966, 1968, 1970, 1982[a,b]) and from other countries (Barrett et al., 1969; Joseph et al., 1964; Talbot and Talbot, 1974; Weidemann, 1973).
For technical and economical reasons, the range of length scales covered by these experiments is limited. Sometimes (Weidemann, 1973; Suijlen et al.) length scales of a few tens of kilometers were reached ; in most cases the maximum scale was not more than one to a few kilometers. Usually, extensive measurements were only made in the upper layers (5 m or less below the surface) and information on vertical spread was derived mainly from the mass of detected dye.
Similar experiments in other parts of the world added to the knowledge and understanding of dispersion in (relatively shallow) tidal waters (Carter and Okubo, 1965; Fukuda et al., 1962; Ito et al., 1966; Kullenberg, 1974; Okubo, 1962, 1968, 1971; Ozmidov, 1965).
Additional information can be obtained from measured distributions of natural tracers like salt (or river water), temperature and turbidity. As a rule, these distributions give no direct information about the relatively small scales covered by the dye experiments. The sources of these natural substances mostly have a continuous character so that they can only by means of mathematical models be interpreted in terms of the usual dispersion parameters (an exception is the turbidity patch measured and analyzed by Joseph and Sendner (1958)).
The dye experiments in most instances use instantaneous sources and can therefore be interpreted more directly in terms of dispersion parameters like diffusion velocities and dispersion coefficients. At the same time they can easier be analyzed in terms of physical mechanisms such as eddies, horizontal current shear, vertical exchange and vertical shear. In some cases (Van Dam, 1965; Van Dam and Davids, 1966; Westhoff et al., 1971) a continuous release dye experiment was performed in order to check predictions by models based upon parameters derived from instantaneous releases or for the purpose of studying the mixing on very small scales, less than water depth (Suijlen et al., 1982, 1988).

2. Models and mechanisms

Analytical formulae for concentration distributions (from instantaneous point sources) as functions of time, usually based upon theoretical considerations (Joseph and Sendner, 1958; Okubo and Pritchard, 1960; Ozmidov, 1968; Pasmanter, 1980; Schönfeld, 1962; Talbot and Sendner, 1973) have been compared with measurements (Joseph et al, 1958, 1964; Nihoul, 1975; Ozmidov, 1968; Schönfeld, 1962; Talbot, 1974; Talbot and Sendner, 1973; Van Dam and Sydow, 1970; Weidemann (ed.), 1973) and applied in superposition models. The latter to obtain concentration fields for the case of continuous sources (e.g. waste release), usually in two dimensions only (Brooks, 1960; Carter, 1975; Okubo and Karweit, 1969; Shönfeld, 1964; Van Dam et al.,1966, 1975, 1976).
Besides, mainly in later years, it has been tried to model the dispersion in more detail. Much attention was given to shear dispersion, i.e. current shear combined with diffusion in transverse direction, both in horizontal and vertical planes (Carter and Okubo, 1965; Nihoul, 1975; Okubo, 1966, 1967,

1968[b]; Van Dam, 1987[a,b], 1988).
This approach could profit by earlier work on dispersion in pipes (Taylor, 1953, 1954) and its application to rivers and channels (Fischer et al., 1979, and references therein). It was realized (e.g Nihoul, 1975) that at sea, horizontal dispersion due to vertical shear and vertical exchange is not only an important mechanism but usually is the dominating agent of dilution of an instantaneous point release during a considerable period after injection. Kalkwijk (1985) has pointed out that in practice this stage is mostly preceded by a phase of much slower patch growth, namely during the time needed for spreading in the vertical after injection: most tracers and pollutants are brought in at a specific level such as at the water surface or near the bottom. Kalkwijk's analytical model is two-dimensional (2DH) so that it can only account for the effects of the initial vertical mixing phase by applying a time shift, leading to a qualitative approximation. In a threedimensional approach a quantitative and more detailed simulation becomes possible; this can be done numerically and can conveniently be realized by applying discrete particles (section 5).

The second important mechanism for horizontal spread of matter, is the differential transport by the velocities of an inhomogeneous horizontal velocity field, especially enhanced by the presence of vorticity at various length scales. After some time, better: from a certain length scale, this mechanism dominates the first one, the effect of vertical current shear.
It may be useful to point out that if we look at the process from the view-point of size or concentration as function of time, a patch, at the moment the horizontal eddies become the dominating spreading agent, has become much larger than it would be at the same point of time if the vertical shear effect were small or absent. This "lead" is conserved for quite some time after the shear mechanism itself has become of minor importance.

3. Energy spectrum of horizontal movements

The dispersion at various length scales by the horizontal velocity field depends upon its spatial variability which can be characterized by a kinetic energy spectrum in terms of wave numbers. The degree of stationariness is not important as long as the field as a whole is not completely stationary (Van Dam, 1986[b], 1987, 1989). Therefore, from the viewpoint of dispersion, random eddies of a temporary nature are equivalent to more permanent ones related to topographic features. So both will contribute to spectra derived from dispersion measurements. In the scale region where (vertical) shear dispersion is dominant, derivation of the energy spectrum of the horizontal velocities from the dispersion of the dye patches is difficult. Approximations have to be based upon the short initial period before the dye has spread vertically and upon the behaviour at much larger times when the shear dispersion has become of minor influence. Unfortunately the latter is in practice restricted to a rather limited time range of roughly 50 to 500 hours after release, since dye experiments in the North Sea so far do not extend beyond times of 500 to 1000 hours and only very few of them really go that far. Nevertheless, a first estimate has been made (Van Dam, 1987[b]). In view of the uncertainties in the intermediate scale range of dominant (vertical) shear dispersion, there was no reason to use anything more complicated than the expression

$$E(k) = c_k \, k^{-m} \qquad (m^3 s^{-2}) \qquad (1)$$

(E(k)=kinetic energy density per unit mass and unit of k, k=wavenumber, c_k and m positive constants). In this one-dimensional form (no separate distribution of energy for various directions) simple forms like (1) do not account for anisotropic effects and therefore are not always adequate, e.g. near boundaries. This limitation may be admissible in our applications since from a certain scale on, velocity structures are given by flow models (next section) and for somewhat smaller scales anisotropic dispersion caused by vertical shear dominates other anisotropies.
If, in a numerical simulation, we combine dispersion corresponding with an (isotropic) energy spectrum of type (1) with explicit modelling of the processes in the vertical, a good fit with the data is obtained with m=1 and $c_k=2.87 \times 10^{-4}$ m^2s^{-2} (dimension of c_k depends upon m). The value of m is related to the slope of the C_{max} -curves such as given in figures 1 and 2 but slope and level of these curves are not sufficient for the determination of c_k. For determining the relation between dispersion rates and the absolute level of the kinetic energy spectra, the dispersion process was simulated numerically in an artificial eddy field of known spectral properties (Van Dam, 1987[b], 1989).

It might be possible to adjust the preliminary values of m and c_k if more experimental data were available. Some additional information may possibly be obtained from existing data, especially on vertical dispersion rates, but the problem is indeed that this kind of detail is often lacking in the experimental results from the past. The shape of the C_{max} curves (such as represented in figures 1 and 2) and the shape of dye patches (such as from aerial photographs (figure 3) or detailed fluorimetric surveys) both contain indirect information on the effects of vertical shear and exchange and it is tried to extract this by comparing measured shapes with those obtained by numerical simulation (examples of the latter in figures 2 and 4). This kind of analysis is still in progress.

4. The role of flow models

An extension of empirical dispersion data for the very large scales, beyond those reached in the dye experiments so far, seems desirable, but on the other hand, an important alternative exists. Just in the vicinity of the largest scales reached in the dye experiments, numerical North Sea flow models (with meshes of a few km) begin to reproduce the correct structure of the velocity field (which is not resolved at smaller scales). This happens, understandably, at scales quite a bit larger than the mesh width (figure 5) but fortunately just about where the tracer experiments end. In other words, up from scales of the concerned order of magnitude (patch diameters of some 20 km) the flow model can be used to provide the necessary velocity structures. This includes not only the spectral structure in a general and average sense (as represented by approximations like (1)) but also details like anisotropy, spatial variability, effects of wind (if incorporated in the flow model) and temporal variations of astronomical tides. This is one reason to use velocity fields from the flow models explicitly in numerical simulations of dispersion. Of course this explicit use is also useful at the smaller scales in order to obtain proper displacements of patches as a whole and proper superposition in the building up of plumes from continuous sour-

ces. The computed ("deterministic") flow fields are supplemented, in one way or another (section 5) to account for the structures at smaller length scales, not resolved in the flow model.
Till now, only 2DH flow models were applied in the research reported here. In order to include the vertical shear effects, the vertically averaged velocities have been decomposed in the vertical by means of analytical approximations such as "Van Veen verticals" (Van Veen 1936, 1939,) and directional variations as can be caused by Coriolis accelerations and by wind. The influence of the wind upon the vertical averages is supposed to be accounted for in the 2DH flow simulation. In figure 4 some results are visualized. Vertical exchange coefficients were so far taken independent of position in the water column.
The next step will be to utilize vertical velocity structures derived by so called 2½-D modelling (Van der Giessen and Jansen, 1988). Thereafter, 3D velocity fields from threedimensional flow models will be used. Especially in regions where density effects are important, this will almost be a nesessity for obtaining realistic simulations. For a picture of the hydrographic complexity of such regions be referred to papers C.M. 1989/C:14 and 15 of this meeting (Van der Giessen et al., 1989; Borst et al., 1989).

5. Particle techniques

The numerical simulations mentioned above and illustrated in some of the figures have become feasible by the use of discrete particle techniques (Maier-Reimer, 1973; Van Dam, 1982[c], 1985[a,b], 1987, 1988). These enable arbitrary spatial resolution and easy avoidance of numerical artifacts.
The best way to account for velocity variations at length scales not resolved by the flow models is to supplement the "deterministic" flow field with an additional, synthetic eddy field (Van Dam, 1980, 1982[c], 1987[b], 1989) covering the required range of length scales. The relatively great number of particles required when concentrations have to be calculated still makes this method in practice rather time consuming. Therefore, the technique of "scaled random walk" (Van Dam, 1982[c], 1985[a,b], 1986[a]), based upon an idea of Maier-Reimer (1973) is still in use. When applying this principle, the "scaling" of the random steps is levelled off near the length scale where the flow model begins to resolve the velocity structures. This corresponds with a cut-off of the spectrum of the supplementary eddies. In both cases, the cut-off is not made suddenly but gradually.
The scaled random walk technique is only to be used where it is necessary for economical reasons. One should always be aware of possible errors due to its shortcomings. The fundamental cause of these is the physically unrealistic assumption that individual particles "know" their age (as in the original concept of Maier-Reimer) or at least the average distances in the patch concerned. The distance criterion is better than the age criterion and expresses in fact the basic idea of M.-R. and avoids errors that would otherwise arise, e.g. when combining the (horizontal) random walk with a separate simulation of another effect such as dispersion by vertical shear, but other possible errors remain. These all vanish when applying the physically much sounder principle of placing the cause of the scale effects where it also is in nature: in the velocity field.
When scaled random walk is used in regions with varying depth, a depth gradient correction has to be applied (Van Dam 1985[a], 1988). Without such a correction, a 2DH random process sends just as many particles in the direc-

tion of upward slope as opposite so that after some time higher concentrations result at the shallower side. This effect usually plays no role in short time periods such as in most calamity applications. In figure 6 an example of a longer term computation (of a continuous release) is given, including the depth gradient correction. It is important in such a case to maintain the full time dependent deterministic flow field. The use of tidal averages may cause considerable deviations as indicated by results as those depicted in figure 7.

Figure 8 illustrates the more realistic aspect obtained with synthetic eddies as compared to the smooth distributions obtained with a (scaled) random walked technique. The qualitative agreement with observations such as by aerial photography is rather striking.

Operational use of particle simulation with scaled random walk is already being made in calamity models (Van Dam 1985[b], 1986[a]; Lefèvre and Van der Male, 1988; Delft Hydraulics Laboratory, 1989). Because of the relatively small scales of length and time involved, finite difference techniques are not feasible. In regions with rather uniform horizontal velocity fields, superposition of analytic functions (section 2) is an acceptable alternative as long as the vertical dimension is not explicitly modelled.
At present the analytical approximations of the 3D effects (section 3) are being incorporated in the above-mentioned North Sea calamity model (Delft Hydraulics Laboratory, 1989).

References

1. Barrett, M.J., D. Munro and A.R. Agg (1969), Radiotracer dispersion studies in the vicinity of a sea outfall. In: Proc. 4th Int. Conf. on Water Pollution, Pergamon Press, p. 863.

2. Borst, J.C., W.P.M. de Ruijter, A. van der Giessen and F.C. Groenendijk (1989), Response to varying wind and river discharge conditions of the vertical residual current structure in front of the Dutch coast. ICES, Hydrography Committee, paper C.M. 1989/C:15.

3. Brooks, N.H. (1960), Diffusion of sewage effluent in an ocean current. In: Proc. 1st Int. conf. Waste disposal in the Marine Environment, 1959, Pearson, E.A., ed., Pergamon Press, Elmsford, N.Y., p. 246.

4. Carter, H.H. (1975), Prediction of far-field exclusion areas and effects. In: Proc. Symp. Discharge of Sewage from Sea Outfalls, London, 1974, Pergamon Press, p. 363.

5. Carter, H.H. and A. Okubo (1965), A study of the physical process of movement and dispersion in the Cape Kennedy area. Final Rept. under U.S. AEC Contract AT (30-1)-2973. Ref. 65-2, Chesapeake Bay Intstitute, The Johns Hopkins Unversity, Baltimore.

6. Delft Hydraulics Laboratory (1989), Gebruikershandleiding MARS (Marine Spills). Rept. T470.

7. Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger and N.H. Brooks (1979), Mixing in Inland and Coastal Waters. Academic Press, N.Y.

8. Fukuda, M., Y.T. Tanigawa and Y. Kuniya (1962), Diffusion experiment off the coast of Tokai-mura. Activities in the Health Physics Division, No. 4, p.173.

9. Ito, N., M. Fukuda and Y.T. Tanigawa (1966), Small scale horizontal diffusion near the coast. Proc. Disposal of radioactive wastes into seas, oceans and surface waters. IAEA, Vienna.

10. Joseph, J., and H. Sendner (1958), Uber die horizontale Diffusion im Meere. Dtsch. Hydrogr. Z., 11,2:49.

11. Joseph, J., H. Sendner and H. Weidemann (1964), Untersuchungen über die horizontale Diffusion in der Nordsee. Dtsch. Hydrogr. Z., 17,2:57.

12. Kalkwijk, J.P.Th. (1985), Dispersion of matter at sea under homogeneous conditions. Dtsch. Hydrogr. Z., 38:245.

13. Kullenberg, G. (1974), Investigations on disperion in stratified vertical shear flow. In: Rapp. P.V. Réun. Cons. Int. Explor. Mer, 167:86.

14. Lefèvre, F.O.B., and C. van der Male (1988), Gebruikersdokumentatie programmapakket CALM t.b.v. deeltjesmodel CALM 14 (in Dutch). Rept. GWWS 88.407, Tidal Waters Division, Rijkswaterstaat, The Netherlands.

15. Maier-Reimer, E. (1973), Hydrodynamisch-numerische Untersuchungen zu horizontalen Ausbreitungs- und Transportvorgangen in der Nordsee, Dissertation, Mitt. Inst. für Meereskunde der Unversität Hamburg, XXI.

16. Nihoul, J.C.J. (1975), Passive dispersion models. In: Modelling of Marine Systems, Nihoul, J.C.J., ed., Elsevier, Amsterdam, chap. 3.

17. Okubo, A. (1962), Horizontal diffusion from a instantaneous point-source due to oceanic turbulence. Tech. Rept. 32, Ref. 62-22, Chesapeake Bay Institute, The Johns Hopkins University, Baltimore.

18. Okubo, A. (1966), A note on horizontal diffusion from an instantaneous source in a nonuniform flow. J. Oceanogr. Soc. Japan, 22:35.

19. Okubo, A. (1967), The effect of shear in an oscillatory current on horizontal diffusion from an instantaneous source. Int. J. Oceanol. Limnol., 1:194.

20. Okubo, A. (1968[a]), A new set of oceanic diffusion diagrams. Tech. Rept. 38, Ref. 68-6, Chesapeake Bay Institute, The Johns Hopkins Unversity, Baltimore.

21. Okubo, A. (1968[b]), Some remarks on the importance of the "shear effect" in horizontal diffusion. J. Oceanogr. Soc. Japan, 24:60.

22. Okubo, A. (1971), Oceanic diffusion diagrams. Deep Sea Res., 18:789.

23. Okubo, A., and J.J. Karweit (1969), Diffusion from a continuous source in a uniform shear flow. Limnol. Oceanogr., 14:514.

24. Okubo, A., and D.W. Pritchard (1960), unpublished note, see Pritchard, D.W., The application of existing oceanographic knowledge to the problem of radioactive waste disposal into the sea, in: Proc. Symp. Disposal of Radioactive Wastes, IAEA, Vienna, 1960, p. 229.

25. Ozmidov, R.V. (1965), Energy distribution between oceanic motions of different scales. Izv. Atm. Ocean. Phys. Ser., 1:439.

26. Ozmidov, R.V. (1968), Horizontal Turbulent Exchange in the Ocean. Publ. House "Science", Moscow.

27. Pasmanter, R.A. (1980), Diffusion in highly turbulent fluids. Phys. Lett. A75:366.

28. Schönfeld, J.C. (1962), Integral Diffusivity. J. Geophys. Res. 67:3187.

29. Schönfeld, J.C. (1964). Turbulente diffusie; lozing vanuit een bron in zee (in Dutch). Rept. MFA 6411, Phys. Div., Directie Waterhuishouding en Waterbeweging, Rijkswaterstaat (The Netherlands).

30. Suijlen, J.M. (1980), A dye experiment in the North Sea up to a very large scale. ICES, Hydrography Committee, paper C.M. 1980/C:29.

31. Suijlen, J.M. and L. Nienhuis (1982), Verslag van merkstofexperimenten gehouden in de periode maart-mei 1982 op ca. 60 km ten westen van Noordwijk i.h.k. van gecombineerde dispersieëxperimenten. Rijkswaterstaat, The Netherlands, Directie Waterhuishouding en Waterbeweging, Fysische Afdeling, report 05 82-FA (in Dutch).

32. Suijlen, J.M., J.S. Sydow, C. Heins and P.C. Beukenkamp (1988), Meting van turbulente diffusie in de Zuidelijke Noordzee met merkstof-experimenten in de jaren 1971, 1973, 1978 en 1979. Rijkswaterstaat, The Netherlands, Dienst Getijdewateren. Report in preparation.

33. Talbot, J.W. and G.H. Talbot (1974), Diffusion in shallow seas and in English coastal and estuarine waters. In: Rapp. P.V. Réun. Cons. Int. Explor. Mer, 167:93.

34. Talbot, J.W. an H. Sendner (1973), Consideration of the horizontal diffusion process during the experiment. In: The ICES Diffusion Experiment RHENO 1965 (H. Weidemann, editor). Rapp. P.V. Réun. Cons. Int. Explor. Mer, vol. 163.

35. Taylor, G.I. (1953), Dispersion of soluble matter in solvent flowing slowly through a tube. Proc. R. Soc. London Ser. A, 219:186.

36. Taylor, G.J. (1954), The dispersion of matter in turbulent flow through a pipe. Proc. R. Soc. London Ser. A, 223:446.

37. Van Dam, G.C. (1963), Voorlopige resultaten van eerste metingen en berekeningen aangaande diffusieve verspreiding in de Noordzee op korte afstanden tot de Hollandse Kust. Rijkwaterstaat (The Netherlands), Directie Waterhuishouding en Waterbeweging, Fysische Afdeling, rept. FA-1963-1. Also in: Comm. Afvalwatervraagstuk zuidelijk deel Randstad Holland, Eerste Rapport (1965) (in Dutch).

38. Van Dam, G.C. (1965), Horizontal diffusion in the North Sea near the Netherlands coast in connection with waste disposal. Proc. XIth IAHR Congress, Leningrad, vol V:129.

39. Van Dam, G.C. (1968), Dispersie van opgeloste en zwevende stoffen, in zee gebracht ter hoogte van Wijk aan Zee op 3 km uit de kust. Rijkswaterstaat (The Netherlands), Directie Waterhuishouding en Waterbeweging, Mathematisch-Fysische Afdeling, rept. MFA 6812.

40. Van Dam, G.C. (1975), The Hague Outfall. In:Proc. Symp. Discharge from Sea Outfalls, London (1974). Pergamon Press, 1975, p. 393.

41. Van Dam, G.C. (1976), A two-dimensional water quality model based upon the superposition principle. In: Proc. Symp. Systems and models in air and water pollution, London, 1976. The Chameleon Press Ltd, London.

42. Van Dam, G.C. (1980), Scale dependent disperision of distinct particles in an artificial eddy field. Rept no. 07 80-FA, Physics Division, Rijkswaterstaat, The Netherlands.

43. Van Dam, G.C. (1982[a]), Analytical descriptions of instantaneous point source release in two dimensions. Section IV of Chapter 2 in: Pollutant Transfer and Transport in the Sea (G. Kullenberg, editor) vol. I. CRC Press, Inc., Boca Raton, Florida.

44. Van Dam, G.C. (1982[b]), Superposition and continuous sources. Section VI of Chapter 2 in: Pollutant Transfer and Transport in the Sea (G. Kullenberg, editor) vol. I. CRC Press, Inc., Boca Raton, Florida.

45. Van Dam, G.C. (1982[c]), Distinct particle simulations. Section VIII of Chapter 2 in: Pollutant Transfer and Transport in the Sea (G. Kullenberg, editor) vol. I. CRC Press, Inc., Boca Raton, Florida.

46. Van Dam, G.C. (1985[a]), Particle models (in Dutch). Rept. no. FA 8507, Physics Division, Rijkswaterstaat, The Netherlands.

47. Van Dam, G.C. (1985[b]), A particle model applied to the Western Scheldt. Liverpool Conference on Mixing and Disperion in Estuaries, 1985. Phys. Div. note 85-FA-226.

48. Van Dam, G.C. (1985[c]), Contribution to Delft Hydraulics report to the government. Classified.

49. Van Dam, G.C. (1986[a]), Particle modelling of 2 DH transport phenomena in the Western Scheldt Estuary. (Abstracts I.1.2.) Int. Symp. on Physical Processes in Estuaries, The Netherlands.

50. Van Dam, G.C. (1986[b]), Eddy simulation of 2-D horizontal dispersion. Neth. J. Sea Res. Publ. Series, 13:64.

51. Van Dam, G.C. (1986[c]), Residual currents and transport in two-dimensional model computations. J. Sea Res. Publ. Series, 13,:66.

52. Van Dam, G.C. (1987[a]), Dispersion of released matter in tidal waters (in Dutch). Rept. no. GWAO-87.015, Tidal Waters Division, Rijkswaterstaat, The Netherlands.

53. Van Dam, G.C. (1987[b]), Eddy simulation of dispersion. Rept. no. GWAO-87.022, Tidal Waters Division, Rijkswaterstaat, The Netherlands.

54. Van Dam, G.C. (1989), Numerical simulation of dispersion by eddy velocity fields in two dimensions. Submitted for publication.

55. Van Dam, G.C., and J.A.G. Davids (1966), Radioactive wase disposal and investigations on turbulent diffusion in the Netherlands coastal areas. In: Proc. Symp. Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters, IAEA, Vienna.

56. Van Dam, G.C., and A. Hendriks (1987), Numerical simulation of longitudinal dispersion in a well-mixed tidal river by means of a simple two-dimensional model (in Dutch). Rept. no. GWAO-87.014, Tidal Waters Division, Rijkswaterstaat, The Netherlands.

57. Van Dam, G.C. (1988), The mathematical modelling of transport phenomena in the North Sea in relation to experiments. Rept. no. GWAO-88.043, Tidal Waters Division, Rijkswaterstaat, the Netherlands.

58. Van Dam, G.C., and J.S. Sydow (1970), A diffusion experiment near the Dutch coast 10 km off Ter Heijde (in Dutch). Rept. no. MFA 7003, Math. and Phys. Div., Rijkswaterstaat, The Netherlands.

59. Van der Giessen, A., and R.R. Jansen (1988), Het 2½D-model. Een nieuwe methode ter bepaling van de verticale stromingsstructuur in de Nederlandse kustzône, Rijkswaterstaat (The Netherlands), Dienst Getijdewateren, rept. GWAO-88.013.

60. Van der Giessen, A., W.P.M. de Ruijter, J.C. Borst and H. Verbeek (1989), On the 3-D density distribution in The Netherlands coastal zone. ICES, Hydrography Committee, paper C.M. 1989/C:14.

61. Van Veen, J. (1936), Onderzoekingen in de Hoofden in verband met de gesteldheid der Nederlandse kust. Alg. Landsdrukkerij, Den Haag, Neth. (in Dutch).

62. Van Veen, J. (1939), Water movements in the Straits of Dover. J. Cons. int. Explor. Mer, 13:7.

63. Westhoff, J.W., J.A.G. Davids and G.C. van Dam (1971), Dispersion experiments with continuous injection off Petten at 3.5 km from the shore. I. Experiments (in Dutch). Rept. no. MFA 7101, Math. and Phys. Div., Rijkswaterstaat, The Netherlands.

64. Weidemann, H. (editor) (1973), The ICES Diffusion Experiment RHENO 1965, Rapp. P.V. Réun. Cons. Int. Explor. Mer, vol. 163.

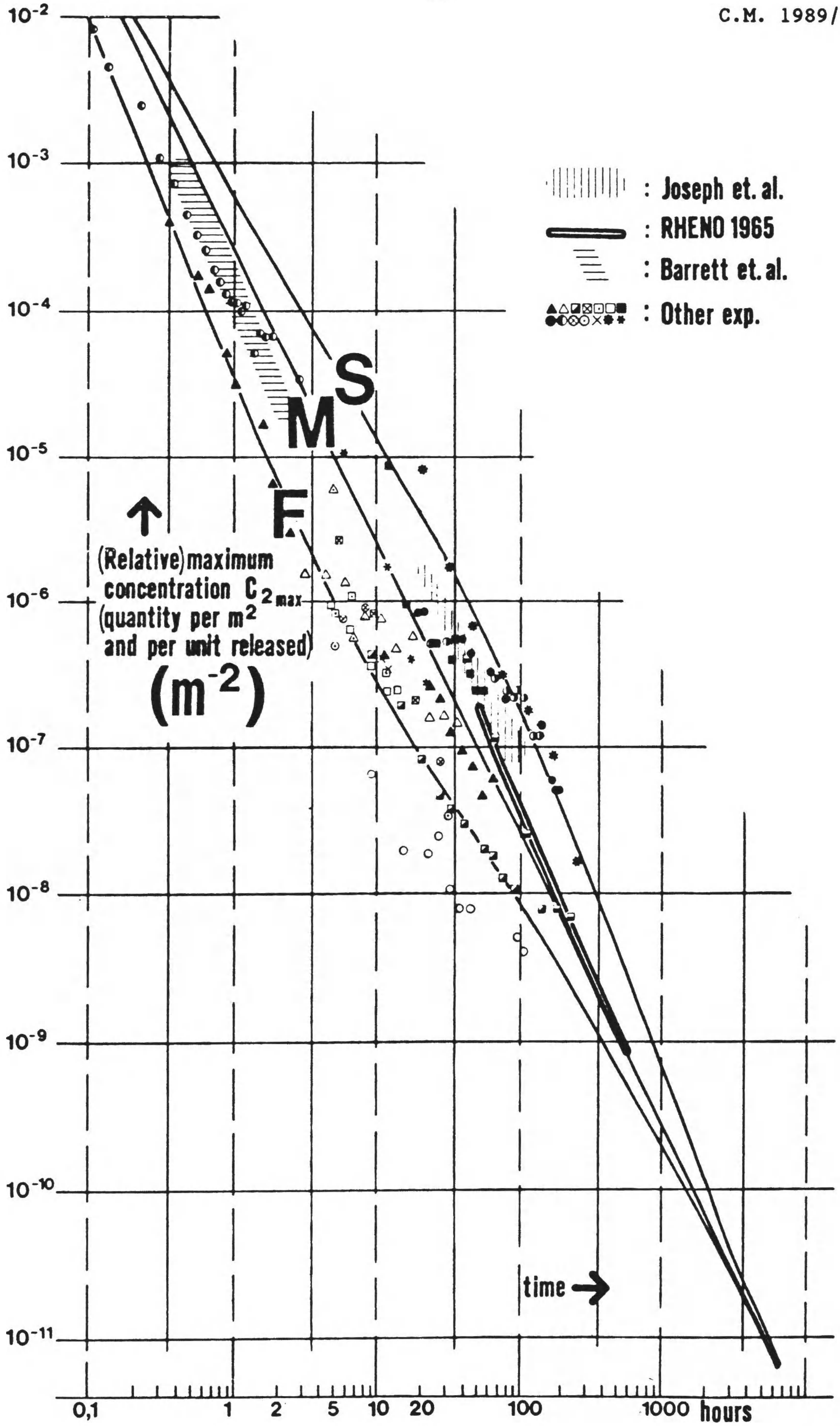


Figure 1. Maximum concentration data (2D) from instantaneous point source tracer-experiments in the North Sea. After van Dam (1982[a]). In the present context, the (rather arbitrary) global curves F,M and S have no significance.

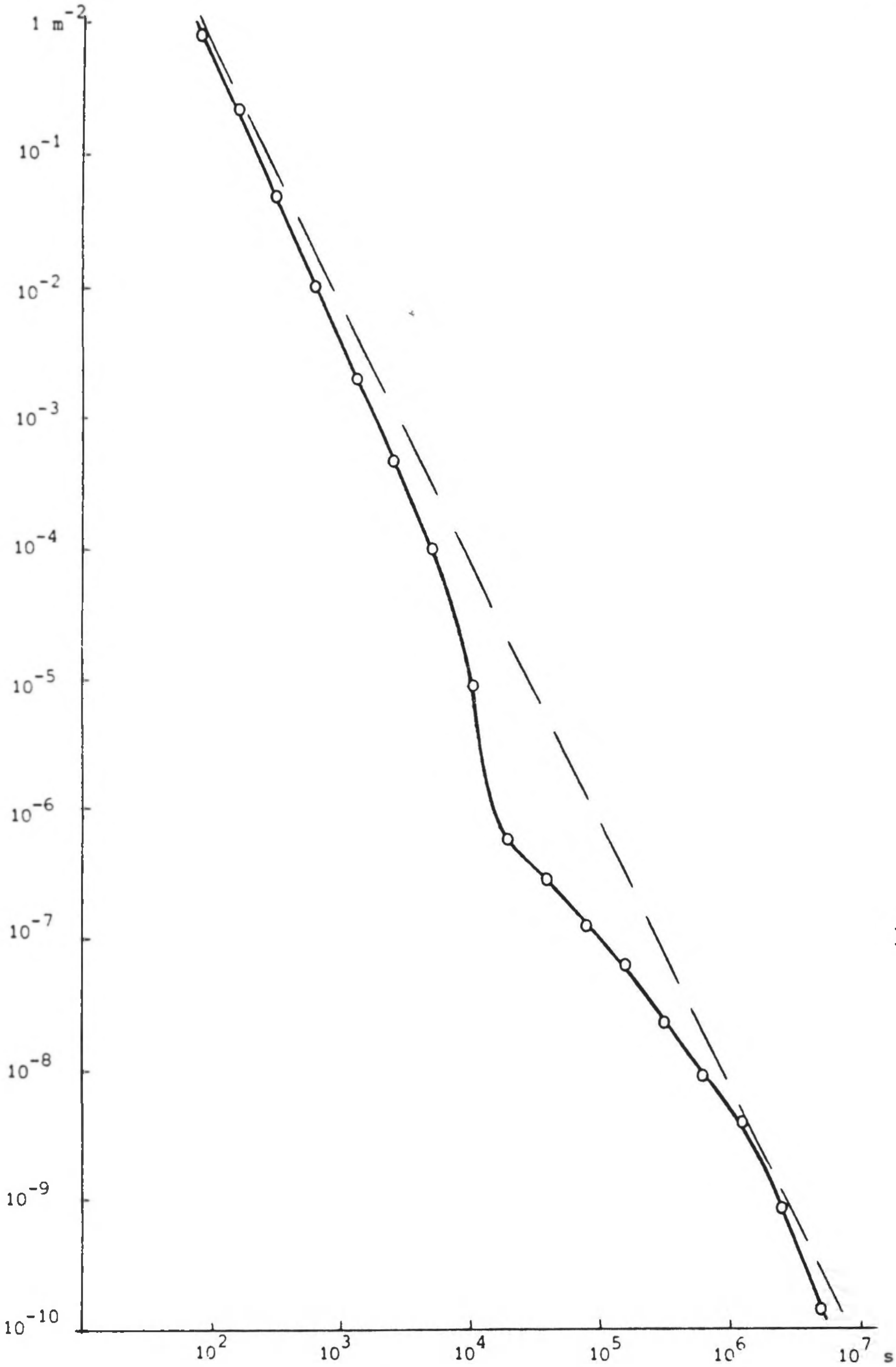


Figure 2.

Maximum concentration (2D) from 3D numerical simulation of an instantaneous point source of one unit near the surface (solid line).

The simulation employs a periodic tidal velocity field computed by a 2DH flow model for the southern North Sea (WAQUA-model "ZUNO-WAQ") supplemented by modelled (vertical) shear dispersion and a horizontal random process corresponding to $E(k) = 2.87 \times 10^{-4} k^{-1}$ $m^3 s^{-2}$, cut off (gradually) round a length scale of 20000 m(=global patch diameter 2L).

Vertical mixing time 10 hours. No distortion of vertical velocity distribution by wind.
Release some 50 km off the Netherlands'coast.
Dashed line represents the case of (spatial variations of) horizontal velocities with $E(k) = 2.87 \times 10^{-4} k^{-1}$ $m^3 s^{-1}$ in absence of other effects: $C_{max} \sim t^{-2}$.

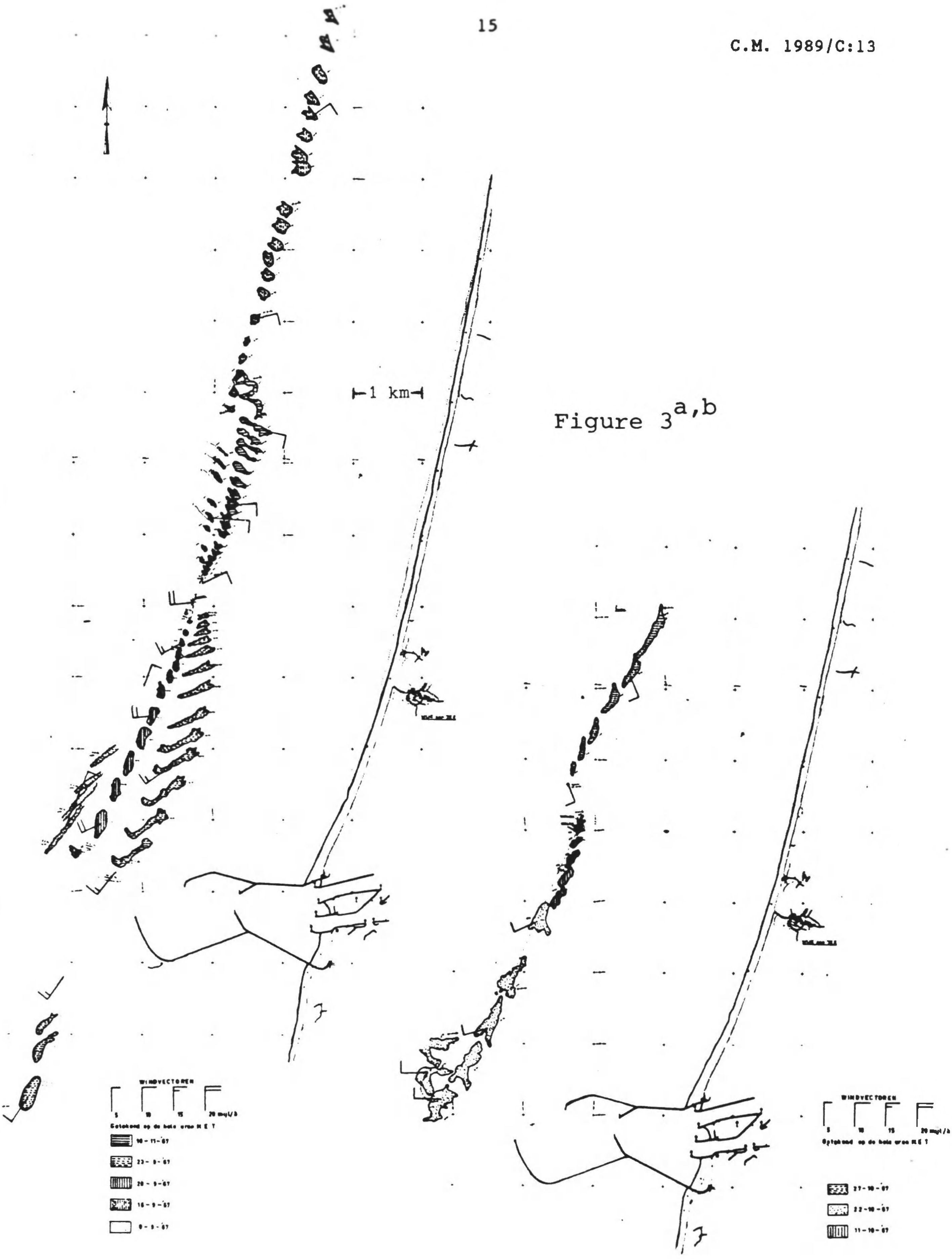


Figure 3. Patch contours from aerial photographs of instantaneous point source dye-experiments in front of the Dutch coast. After van Dam (1968).

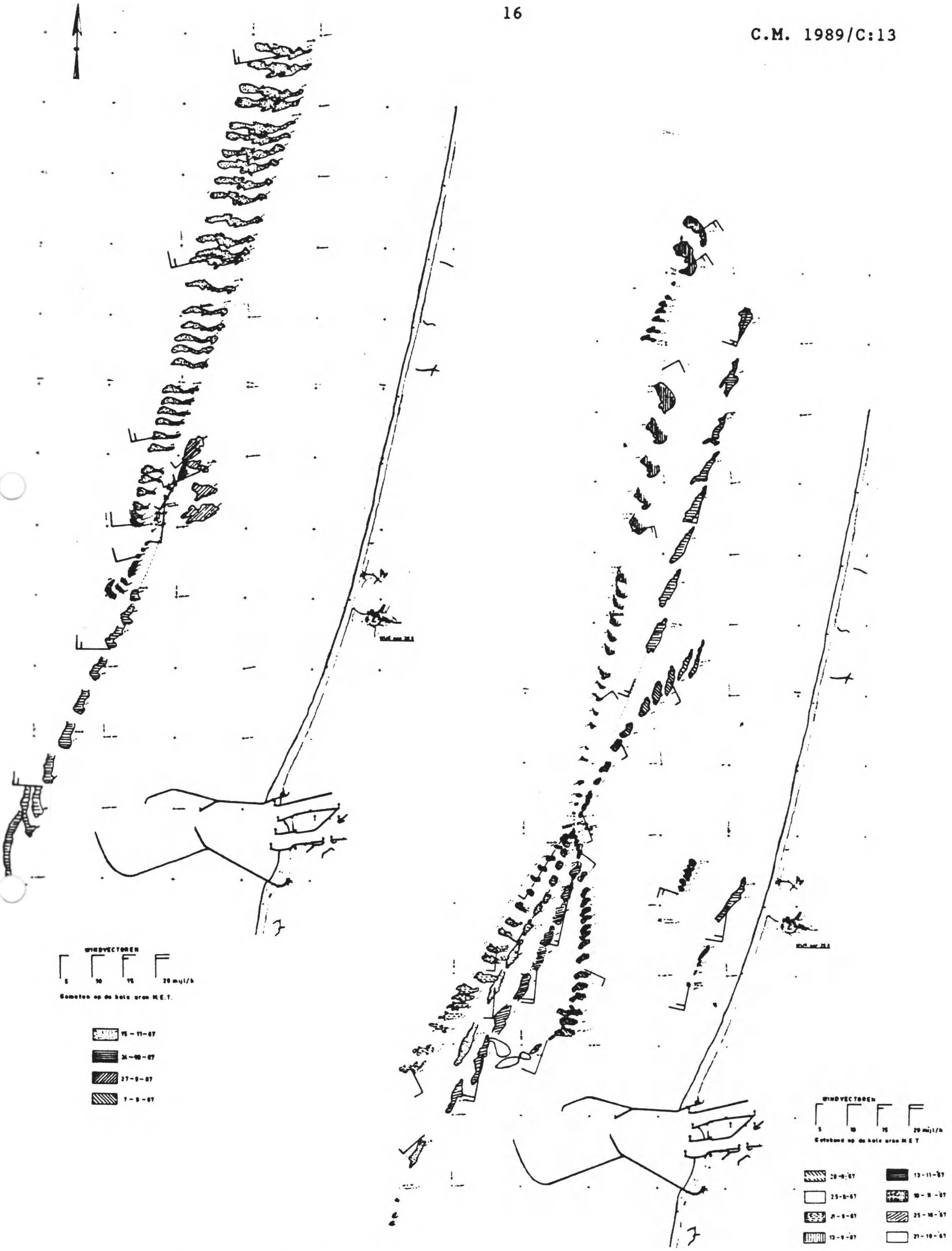

WINDVECTOREN
5
10
15
20 mijl/h
Gemeten op de hele uren M.E.T.
15-11-67
27-9-67
7-9-67
WINDVECTOREN
5
10
15
20 mijl/h

Figure 3c,d

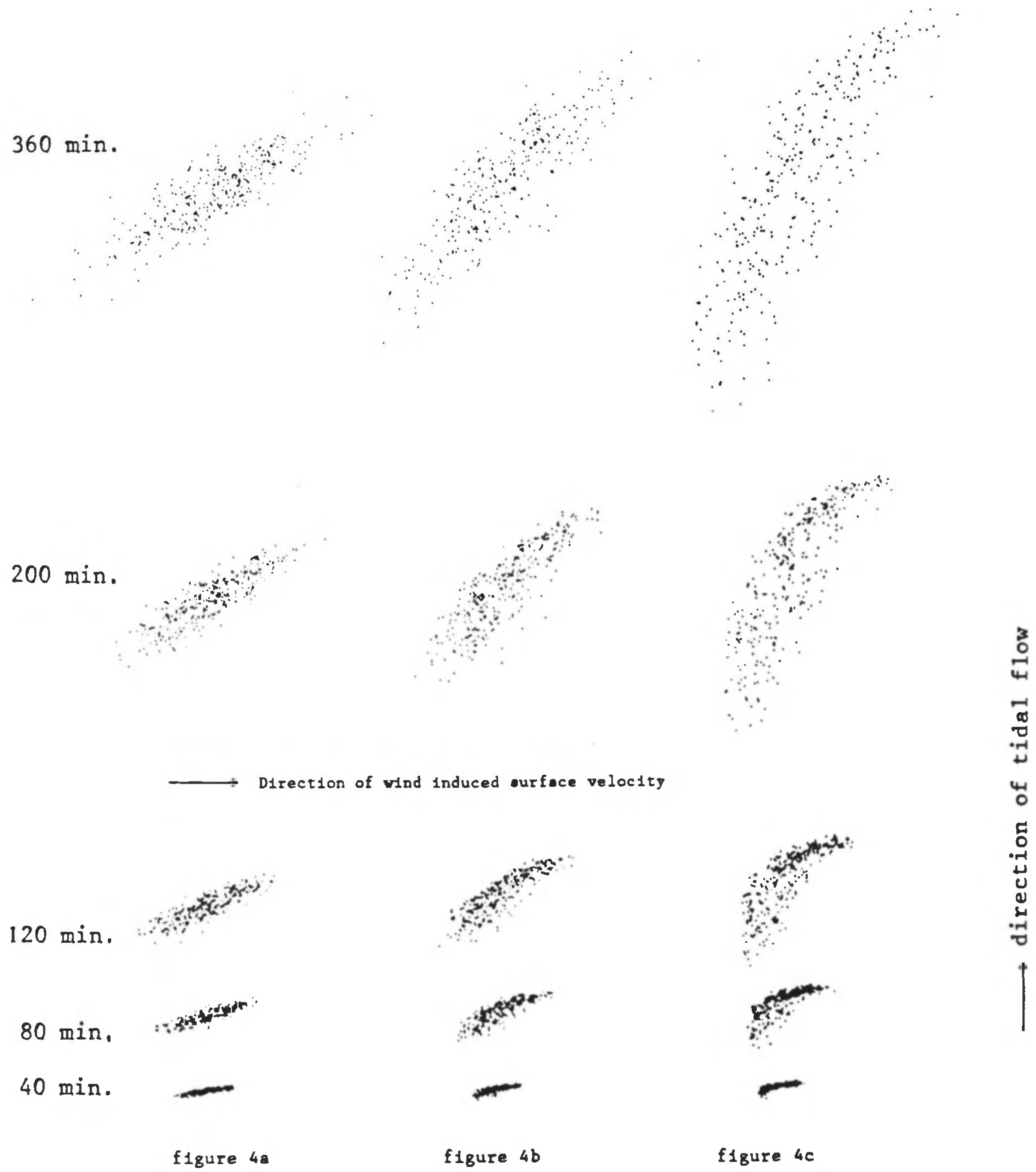


Figure 4. Patch shapes from 3D simulations.

Vertical mixing time
a. 1 hour
b. 2 hours
c. 4 hours

(arbitrary total water depth)

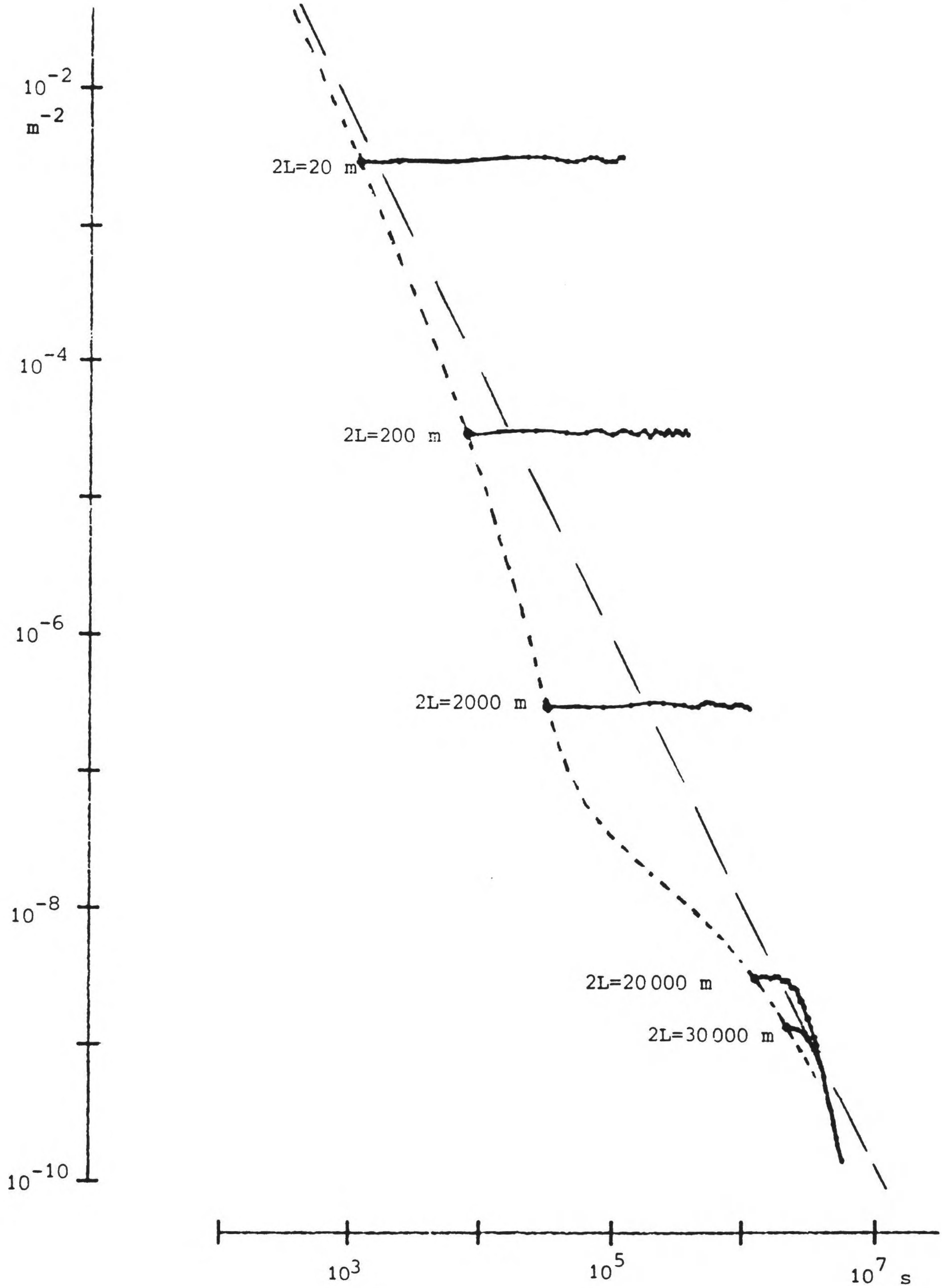
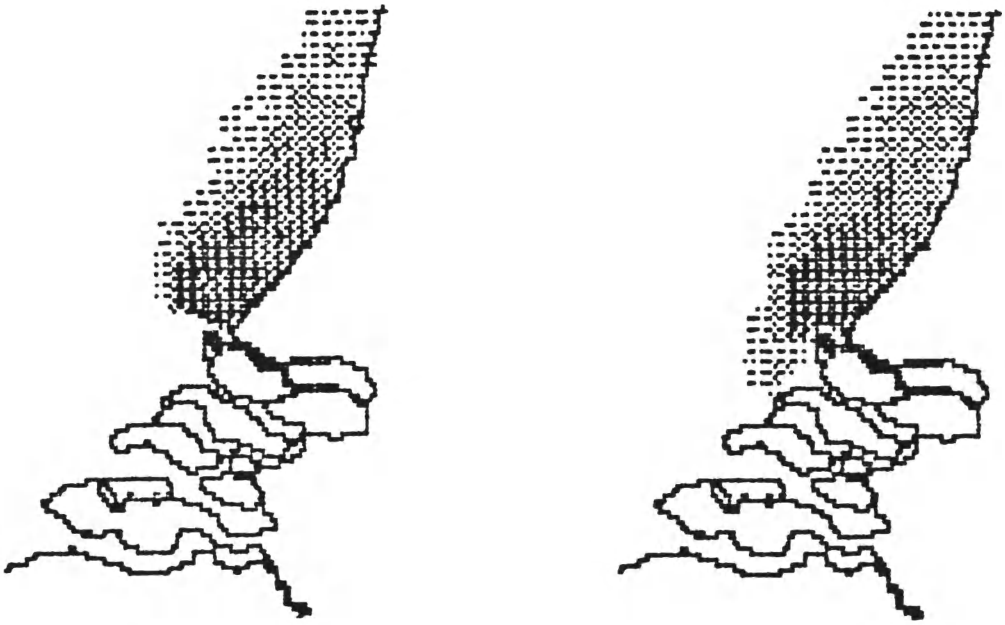


Figure 5. Behaviour of patches (2D max. concentrations) with initial values 20, 200, 2000 and 20000 m of "diameters" $2L = 2\sqrt{\sigma_x^2 + \sigma_y^2}$ (initially, variances $\sigma_x = \sigma_y$), with only deterministic velocities from "ZUNOWAQ" (mesh = 3200 m) taken into account.
For comparison, starting points (initial maximum 2D-concentration and time) have been drawn upon a realistic curve (like those in figs.1 and 2).



a   b

Figure 6. Results of simulation of a continuous release of two months, which means that concentrations are (periodically) stationary in the region shown.

a. Without simulation of 3D effect
b. With simulation 3D effect (vertical shear)

In both cases depth gradient correction included.

Total number of particles involved: about 11000 (each picture).
Shades represent vertically averaged concentration zones, not particles.
With a reasonable estimate of vertical mixing time and vertical velocity distribution, the 3D simulation reproduces reasonably an important part of the measured dispersion opposite to the direction of the (N.E. bound) net current. The effect of the variations of the latter in time is not included.

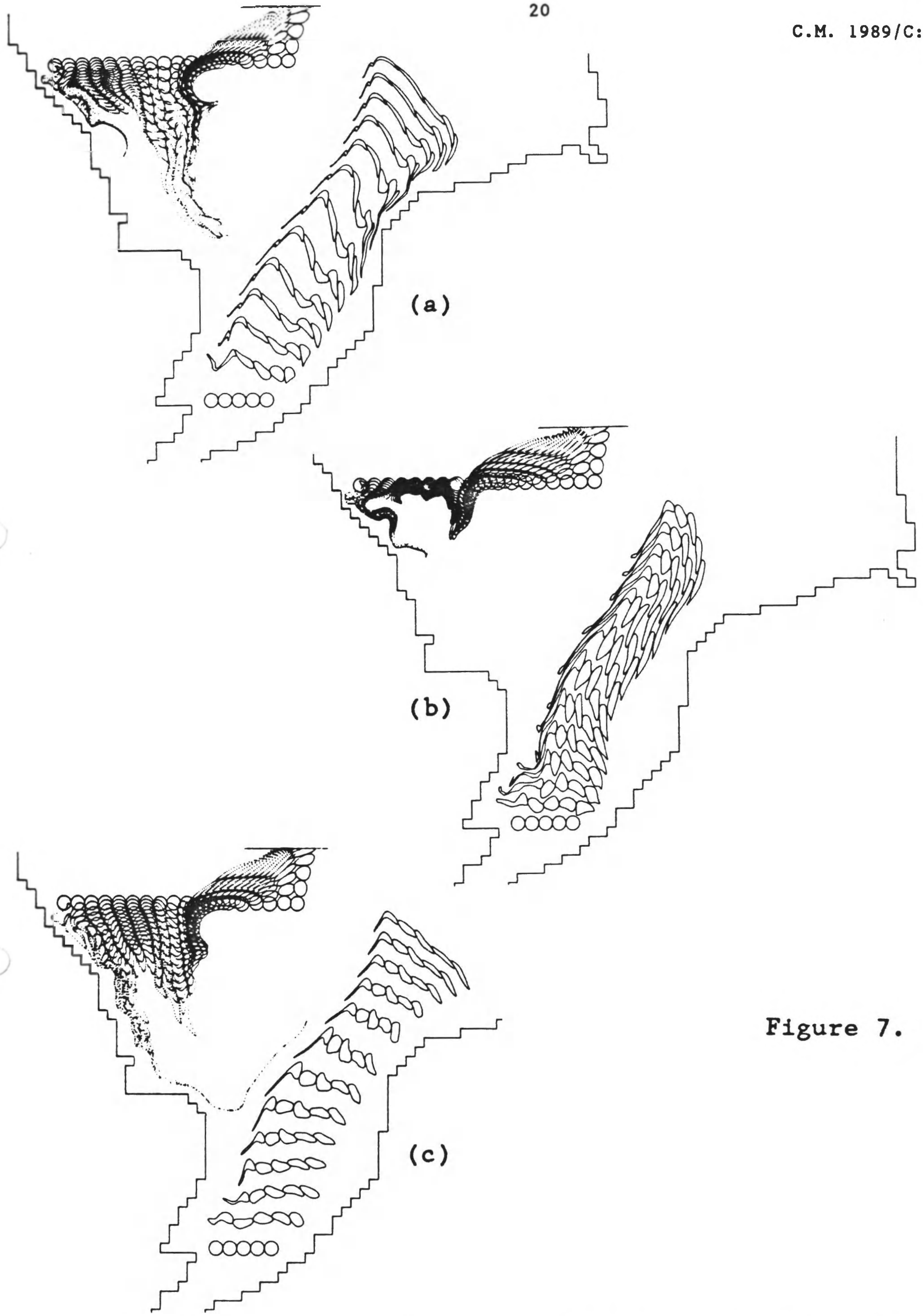


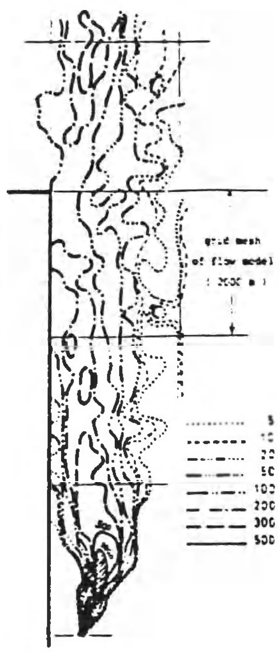
Figure 7.

Advection of circular contours by two types of tidal averages, (b) Eulerian residual current velocity and (c) Eulerian residual transport velocity as compared to the advection by the complete time dependent tidal velocity field (a) of a 10 km mesh flow model of the southern North Sea. Initial circles: 18 in NW region, 5 near the southern boundary. Output every 20 M2 periods. Totally 240 tidal periods. After Van Dam (1986[c]).

patches from instantaneous sources small compared with stage shown.

steady main flow (2D fashion of smoke plume)

tidal current



steady main flow in a lake (Van Dam 1985[c])

Figure 8. Visual aspect obtained with synthetic eddies is more realistic than the smooth shapes from (scaled) random walk techniques.