The importance of model plane location and movement in dense discharge assessment

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Abstract

As dense plumes in the sea tend to form relatively thin layers at the seabed, flexible model vertical structure is needed to provide optimal resolution of plumes without requiring excessive computational resources. An Automatic Mesh Redistribution (AMR) method, based on a generalisation of the traditional sigma mesh, is presented, and demonstrated in application to the simulation of dense plume dispersion in the sea. The results of preliminary simulations for schematic and more realistic test cases are encouraging.

It is demonstrated that the AMR method can adapt to relatively thin dense plumes, without the iterative refinement of plane locations that would be required to achieve similar results with some form of sigma mesh. The main details of plumes simulated with the AMR method are shown to be very similar to those obtained with a traditional sigma mesh after such a refinement process.

The preliminary results presented here are to be investigated further, and will form the basis of an enhanced set of test cases. To date, only the clustering of model planes around steep vertical gradients in the concentration of a single tracer has been considered. However, the technique can be extended to multiple tracers, velocity shear, and/or other physical or derived quantities.

Comprehensive data sets defining dense plume thicknesses in the field have not been available until relatively recently. It is planned to further test the AMR method in the light of a new data set in the near future.

Keywords
Dense discharge; numerical model; adaptive meshing; sigma mesh

Introduction

Releases of negatively-buoyant effluent to the sea are now relatively common, and include discharges from desalination plants, solution mining operations and LNG import facilities. The negative buoyancy of such dense discharges is associated with significantly depressed temperature and/or elevated salinity relative to the receiving water. The resulting plumes tend to sink to the seabed, and to flow down any seabed gradient, whilst also experiencing the dispersing effects of tidal and wind-driven currents.

Planners of developments that will involve dense discharges need some knowledge of how effluent will disperse in the sea, in order to comply with legislative requirements, optimise construction/operation, minimise environmental impact and reduce any recirculation from the plant outfall to the intake. Numerical models are key tools in the prediction of dense discharge behaviour and, for most proposed discharges, models are required to be three-dimensional (3D), in order to represent correctly the buoyancy-driven dispersion.

As dense plumes tend to form relatively thin layers at the seabed, flexible model vertical structure is needed to provide optimal resolution of plumes without requiring excessive computational resources. It has been demonstrated (Wood and Mead 2008) that the results of dense plume simulations can vary with plane separations near the seabed, so that some sensitivity testing of plane distributions is necessary to optimise model results. To date, this testing has typically been an iterative process, with the vertical positions of the model planes being specified manually as model input. Such methods are time consuming, and require significant expert judgement by the model user.

Recently, sophisticated plane location procedures, that avoid the need for the manual specification of model plane positions, have been tested by HR Wallingford. These procedures allow the plane locations to evolve in time and space, based on chosen physical variables, such as vertical density gradients. Testing of the procedures is ongoing at the time of writing, with encouraging preliminary results.

This paper presents the preliminary results of the testing outlined above, for dense plume applications. Traditional and new methods of model plane placement are presented and discussed briefly, and the results of schematic and real model applications are illustrated.

Methods of plane placement

The 3D model used by HR Wallingford to simulate dense plume dispersion is TELEMAC-3D, part of the open source TELEMAC system owned by EDF-LNHE. In order to compute a 3D density field, this model uses a number of model planes at different vertical locations between the water surface and bed. The density is calculated as a two-dimensional field on each plane, from which the density at every location in the water body can be deduced by interpolation.

Simulation of dense plumes at HR Wallingford has, to date, been undertaken mainly using the traditional sigma coordinate system available in TELEMAC-3D. This is similar to systems in use by others (see, for example, Bleninger 2006). In this coordinate system, each model plane is located at a fixed proportion of the water depth. The simplest form of this system involves planes being distributed evenly through the depth throughout the model domain (Figure 1a). In this case, vertical plane positions vary only from point to point as the depth of the seabed varies, and with time at individual points as the water depth fluctuates in tidal applications. This simple form is not often used by HR Wallingford in dense plume applications. Rather, it is standard practice to use a form of sigma coordinates that allows model planes to be mostly closer together near the seabed. This can involve planes being distributed unevenly through the water column, whilst still being at constant proportions of the water depth (Figure 1b and Bleninger 2006). Such an approach has been used with some success, but has the disadvantage that plane separations still vary with time- and space-varying water depths.
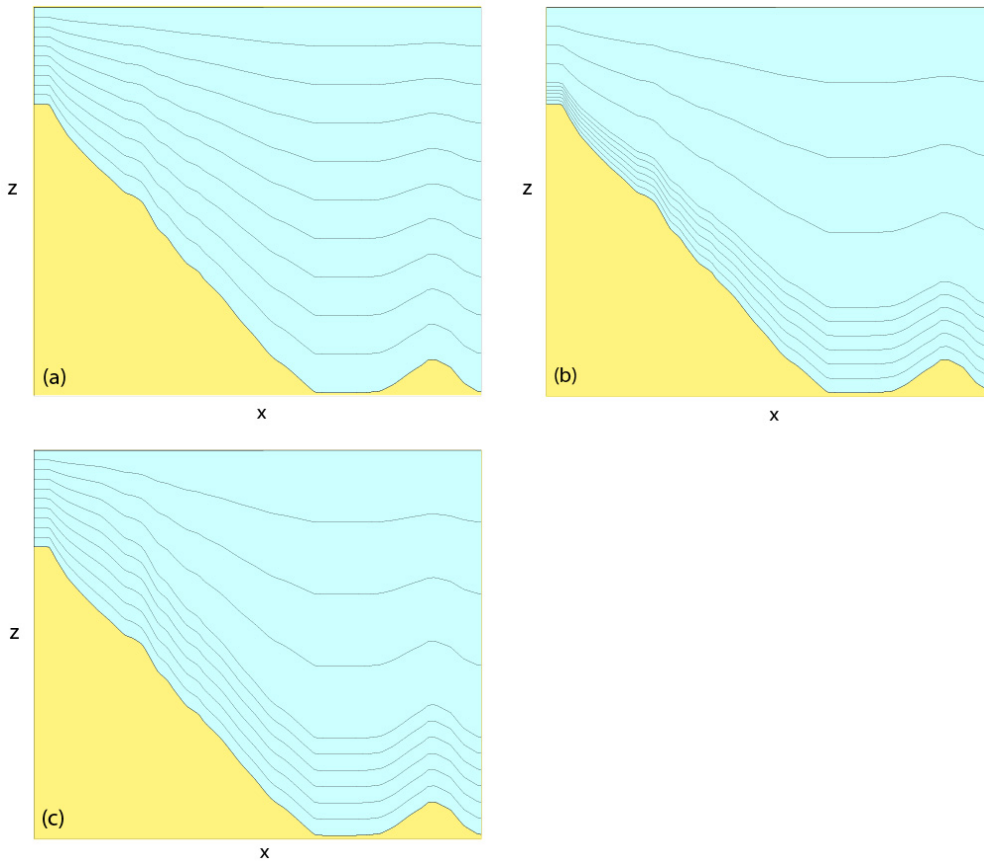
Figure 1: Traditional sigma mesh plane distributions: a) evenly distributed planes, b) unevenly distributed planes with near-bed resolution enhancement, and c) unevenly distributed planes with a reference plane. In (b), the planes are at fixed proportions of the water depth, whilst in (c) the near-bed planes are at fixed heights above the seabed.

An alternative approach, that goes some way in alleviating issues associated with varying plane separations, involves one of the model planes being fixed at a given elevation above the seabed (Figure 1c). The nodes above and below this plane are distributed between the intermediate plane and the surface and bed, following a traditional sigma mesh distribution in both cases. In tidal applications, this approach results in vertical plane positions varying with the tide above the reference plane, but remaining fixed below that plane.

Both of the uneven plane positioning methods described above require considerable judgement by the model user, and a degree of foresight as to likely plume locations and thicknesses. To automate the vertical positioning of model planes to some extent, an Automatic Mesh Redistribution (AMR) method has been implemented in TELEMAC-3D by HR Wallingford. This method dynamically calculates mesh placement, based on computed physical variables. For the preliminary tests discussed here, the clustering of model planes around steep vertical gradients in the concentration of a single tracer is considered. The extension of the technique to multiple tracers, velocity shear, and/or other physical quantities, is in progress.

The AMR method tested is based, to some extent, on the classical "variable diffusion" method (Winslow 1966), with some refinements (such at those proposed by Tang and Tang 2003). Similar approaches, that differ from the present approach in some details, have been applied by others (Hofmeister et al 2010) in parallel developments. The key feature of this type of method is the introduction of a coordinate transformation from a fixed computational domain into the physical domain. It can be shown that the transformation yielding an 'optimal' plane spacing can be described by the function $Z(\xi,x,y)$, where:

$$\frac{d}{dZ}\left(\omega\frac{d\xi}{dZ}\right) = 0 \qquad \text{for all x and y}$$

where ω is a monitor function that depends upon the local solution structure. This function may be chosen to suit the physical quantity of interest. For example, if one is most interested in resolving sharp gradients in tracer concentration, T, the monitor function could take the form:

$$\omega(z,T) = \sqrt{1 + a\left(\frac{dT}{dz}\right)^2}$$

where a is a constant, but may in general be a function of x and y. One could in principle consider different physical quantities, alone or in combination, or higher derivatives of the solution, by modification of this monitor function. The form of the monitor function above is constant if the tracer gradient is constant, meaning that planes will be evenly distributed in a region of constant tracer gradient. An important special case of this is that of zero tracer concentration. In this case, the solution of the diffusion equation is a linear function, so that we recover the sigma mesh of evenly distributed planes. However, in and around simulated plumes, planes will be more concentrated in regions of high tracer gradient.

In the implementation of the AMR method for TELEMAC-3D, the mesh diffusion equation is solved on each vertical line of nodes, fixing the top and bottom planes at the free surface and bed respectively.

In order to reduce mesh inconsistencies in regions of sharp horizontal tracer concentration gradients (which is rare in real applications, but important in some theoretical test cases), an additional horizontal smoothing is applied to the vertical structure over neighbouring vertical lines of nodes. Care is taken to maintain the locations of any local maxima or minima in the water column, in order to minimise numerical diffusion resulting from the mesh adjustment. No additional planes are introduced into the simulation using this AMR approach. Furthermore, the partially-Lagrangian implementation of TELEMAC-3D means that no explicit interpolation is necessary following the mesh adjustment.

Example applications

The AMR method of model plane positioning presented in the previous section is illustrated here for dense discharges with reference to two examples; a schematic test case and a real hypersaline brine discharge.

Schematic test case

The AMR method has been tested for a point-source dense discharge in a rectangular channel. The channel was 1 km long, 100 m wide and 10 m deep, with a flow rate adjusted to give typical depth-averaged ambient current speeds at the source of 1 m/s. For the source, a flow rate of 0.5 m^3/s was specified, with an excess salinity of 215 parts-per-thousand (ppt). The source was introduced at the bed. Results are presented in Figure 2 as vertical cross-sections of excess salinities parallel to the ambient flow direction after a steady-state had been attained (Figures 2a and 2b), and as horizontal excess salinity distributions at the seabed at the same time (Figures 2c and 2d). The vertical cross-sections include the plane vertical locations at the same time as the plume visualisations, and the vertical scale is exaggerated to facilitate results' interpretation. As well as the results for an 11-plane AMR mesh (Figures 2b and 2d), results are shown for a sigma mesh of 21 evenly distributed planes (Figures 2a and 2c), which corresponds to constant plane separations of 0.5 m.

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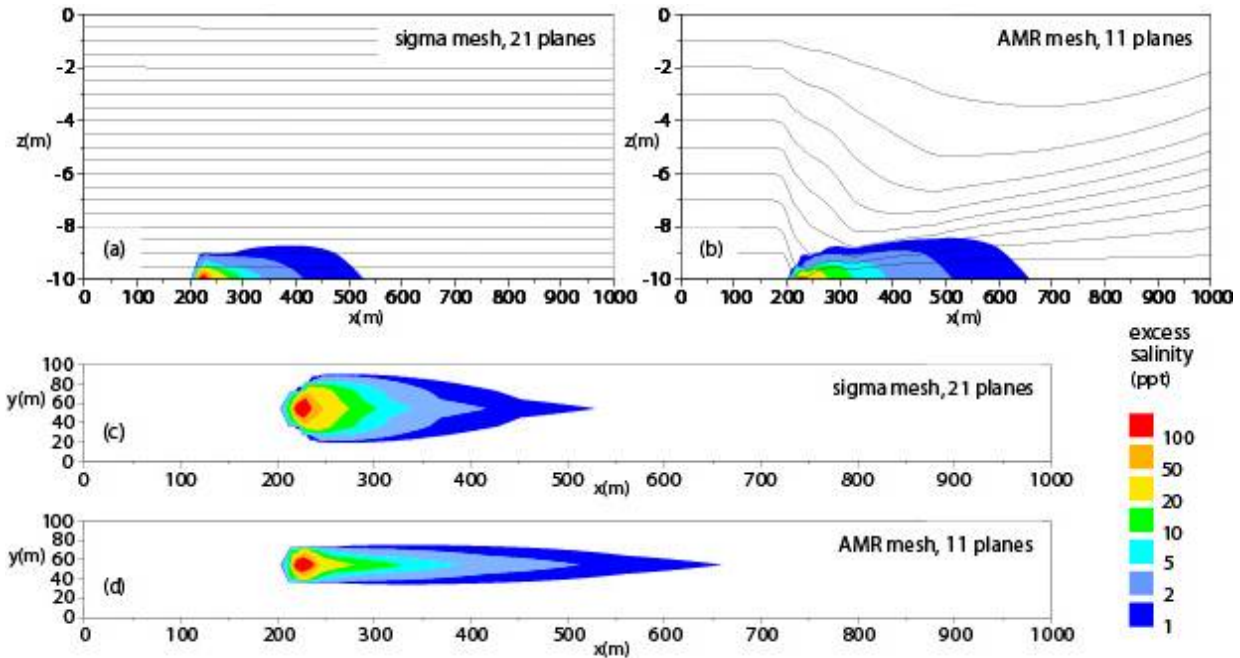*C. T. Mead, S. E. Bourban, C. J. Cawthorn and M. S. Turnbull*

Figure 2: Excess salinities simulated for a schematic test case: vertical sections for a) a sigma mesh, and b) an AMR mesh; and quasi-horizontal sections at the seabed for c) the sigma mesh, and d) the AMR mesh.

The behaviour of the AMR mesh is evident in Figure 2b. Downstream of the source, all of the planes have been drawn below their default (evenly distributed) positions. The plane separations are smallest near the source itself. This is as expected, as the source is inevitably the location of the strongest salinity gradients. In the immediate vicinity of the source, the plane adaption has allowed a much thinner plume, with higher maximum salinities, to develop with the AMR mesh than was possible with this particular sigma mesh. It would be possible to achieve a similarly thin plume by enhancement of the traditional sigma mesh, but only through iterative adjustment of the plane locations. In all salinity contour bands shown, except the two highest, the plume extends further downstream of the source with the AMR mesh than with the sigma mesh, and this is believed to be due to the reduced upward spread of the plume in the immediate vicinity of the source with the sigma mesh.

Figures 2c and 2d demonstrate that the plume is significantly narrower perpendicular to its long axis for the AMR mesh than for the sigma mesh. Analysis not reproduced here has indicated that this is due to the increased blocking of the ambient flow by the thicker plume simulated on the traditional sigma mesh.

The preliminary results presented here will form the basis of an enhanced set of schematic test cases in due course, and some aspects of the results mentioned above will be investigated in more detail. At the present time, the comments in this section serve to demonstrate that the AMR method can adapt to relatively thin dense plumes, without the effort that would be required to achieve similar results with some form of sigma mesh. AMR meshes also have advantages over traditional sigma meshes, in that plane separations can vary as required by evolving solutions, rather than as necessitated by changing water depths.

Industrial brine discharge

The AMR method has also been tested for a less schematic application than that described in the previous section; a hypersaline discharge at an open coastal site (Wood and Mead 2008). The discharge was some

500 m off a relatively straight coastline, into coastal waters with tidally reversing currents and gradually sloping bathymetry. Tidal currents varied between less than 1 cm/s at slack water and up to around 0.4 m/s at peak current speeds. A source of dense effluent was introduced near the seabed, where the average water depth in the vicinity of the discharge was about 9 m. The excess salinity of the discharge was about 150 ppt, and the discharge flow rate was around 0.1 m^3/s. This concentration is typical of those associated with salt cavern leaching, with a density at the upper end of the normal range.

Results are presented in Figure 4 as vertical cross-sections of excess salinities approximately parallel and perpendicular to the main ambient flow direction, at a time of plume elongation parallel to the coast. The locations of the sections are shown in Figure 3. The cross-sections include the plane vertical locations at the same time as the plume visualisations, and the vertical scale is exaggerated to facilitate results' interpretation. As well as the results for an 11-plane AMR mesh (Figures 4b and 4d), results are shown for an 11-plane sigma mesh in which the planes are unevenly distributed to give enhanced resolution near the seabed (Figures 4a and 4c).
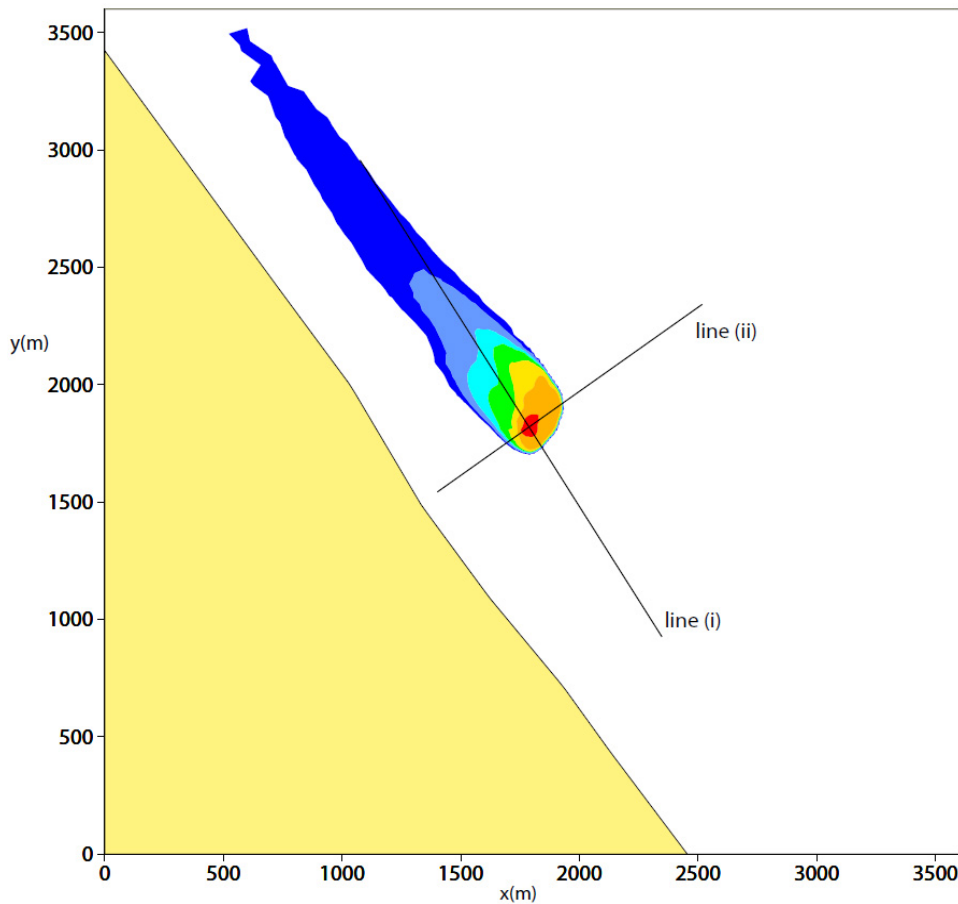

Figure 3: Locations of the vertical sections used in Figure 4 to illustrate the results of a simulation of the dispersion of industrial brine.

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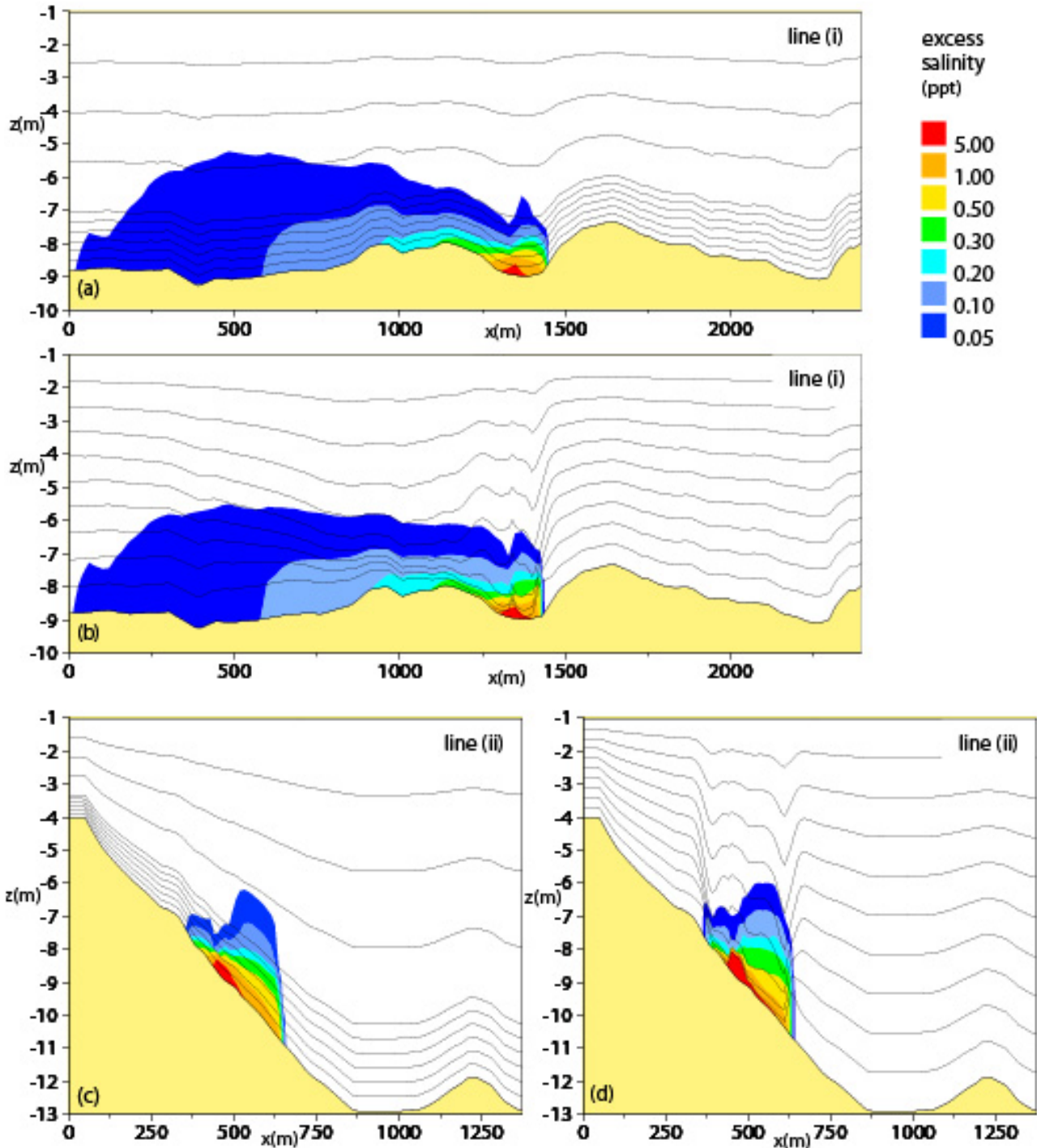*C. T. Mead, S. E. Bourban, C. J. Cawthorn and M. S. Turnbull*

Figure 4: Excess salinities simulated for an industrial brine discharge: line (i) for a) a sigma mesh, and b) an AMR mesh; and line (ii) for c) the sigma mesh, and d) the AMR mesh. The locations of lines (i) and (ii) are illustrated in Figure 3.

Whilst the plane separations of the sigma mesh were established in a sequence of model runs (Wood and Mead 2008), the AMR mesh is the result of a single model run with the same number of planes as the sigma mesh. Despite this, the salinity cross-sections for the two meshes are remarkably similar (Figure 4), confirming appropriate selection of the original sigma mesh, but also demonstrating the ease with which the

AMR technique has adapted to this application. The plane separations in the vicinity of the discharge point in the AMR simulation are similar to those of the original sigma specification. The exaggeration of the vertical scales in Figures 4b and 4d is emphasised, as it causes the slopes of the planes of the AMR mesh to appear steeper than is actually the case.

Conclusions

An AMR methodology has been established, and applied to the simulation of dense plume dispersion in the sea. The results of preliminary simulations for schematic and more realistic test cases are encouraging.

AMR meshes have advantages over traditional sigma meshes, in that plane separations can vary as required by evolving solutions, rather than as necessitated by changing water depths.

It has been demonstrated that the AMR method can adapt to relatively thin dense plumes, without the effort that would be required to achieve similar results with some form of sigma mesh. When applied to the simulation of a hypersaline plume from an industrial outfall, the main details of the plume were very similar to those obtained with a sigma mesh after a manually-guided process of refinement of the plane separations; demonstrating the power of the AMR technique.

The preliminary results presented here will form the basis of an enhanced set of test cases in the near future, and some aspects of the presented results will be investigated in more detail.

For the preliminary tests discussed here, the clustering of model planes around steep vertical gradients in the concentration of a single tracer is considered. The straightforward extension of the technique to multiple tracers, velocity shear, and/or other physical quantities, is in progress.

Comprehensive data sets defining dense plume thicknesses in the field have not been available until relatively recently. It is planned to further test the AMR method in the light of a new data set in the near future.

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