PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The North Sea Project: An Overview and the Way Forward

J. H. Simpson

Phil. Trans. R. Soc. Lond. A 1993 **343**, 585-596
doi: 10.1098/rsta.1993.0068

The North Sea Project: an overview and the way forward

By J. H. Simpson

School of Ocean Sciences, University of Wales Bangor, Menai Bridge,
Gwynedd LL59 5EY, U.K.

[Plates 1 and 2]

> I am never content until I have constructed a (mechanical) model of the subject I am studying. If I succeed in making a model, I understand; otherwise I do not.
>
> Lord Kelvin

1. Introduction: achievement in relation to objectives

It will, I suspect, be some considerable time before we can see the impact of the North Sea Project in full perspective. It has brought radical changes, not only to our way of doing science, but also to the motivation and philosophy that underlies it. The stimulus for these changes has come, in part, from the recognition of the increasing environmental threat to the North Sea and the requirement for its proper future management. As the fearful imperatives of wartime give an impetus to science, so the looming environmental problems of our shelf seas have prompted more coherent action and given us a keener sense of purpose. There seems little doubt that we needed a spur of this kind and that we have benefitted from it, not least in the freer flow of resources which it has brought.

This urgent, practical concern about the future management of the North Sea was reflected in the ultimate goal of water quality models. It is also clearly apparent in the specific objectives which we set for the project (see the introductory paper) and, in attempting an appraisal of the study, we ought perhaps first to consider how well we did in relation to these objectives?

To a large extent I think we can claim to have achieved the targets we set. We do now have a working transport model which advects density and resolves motion down to a scale of a few kilometres and that is a big leap forward from where were at the start of the project. The Process Studies have advanced knowledge in their areas to varying degrees; all have made some significant progress and some of that has involved advances in previously intractable areas. Moreover, in the documenting of the seasonal cycle in a comprehensive way and making it readily available to all, we have a unique achievement which will lay the foundation for future studies and benefit our science for years to come. The goal of water quality models has not yet been attained, although we have moved a big step closer to it and models for some of the simpler, well-behaved constituents are now within our grasp.

So in relation to our declared objectives and the final goal, the project does seem to have made good progress. Science, however, has its own agenda and measures of progress, which are not always directly coupled to the solution of practical problems.

Phil. Trans. R. Soc. Lond. A (1993) **343**, 585–596
Printed in Great Britain

More important than testing by objectives we have to ask about how well the project has advanced our science and whether it has laid an improved foundation for future developments in the study of the shelf seas.

2. Scientific appraisal: innovative approaches

It has to be said that the project has not yielded any one great ‘discovery’, no new blinding flash of insight that changes our view of the way the whole system works. We have not destroyed the paradigm of tidal mixing or radically altered our view of the circulation or discovered ‘black smokers’ in the Norwegian trench. We would not have expected drama of that kind; almost by definition you cannot programme the exciting (and therefore probably unexpected) breakthrough.

But there have been many important new insights and specific achievements. This can be judged from the papers in this volume summarising progress in the individual areas. Taken together they represent an impressive list of achievements for a five year project, which I am sure would compare favourably with what we would have produced over the same five year period without the radical initiative of the North Sea Project. I shall resist the temptation to compile a superleague of highlight achievements. Such a procedure would be invidious and any current ranking is likely to be overturned by future developments.

What I think might be more valuable is to try and draw out some of the innovative new approaches which have emerged from this exercise and which will, I suspect, come to be seen as the most significant and lasting achievement of this Community Research Project.

(a) *Convergence of models and observations*

The first of these concerns the relation of theory, as represented in modelling, to observation. The requirement to develop and validate the transport model has brought about a new and much more vigorous interaction between those of us who go to sea and observe the ocean and those who model it. Indeed there has been a healthy blurring of the boundary between the two and, in some areas a convergent development of understanding. Let me illustrate this with an example:

The stratification-mixing paradigm described in the introduction represented much of our understanding of water column physics at the start of the project. It emphasized vertical exchange as the first-order process and neglected advection. Clearly the new generation of models needs to assimilate the basic physics involved here, but it must also take account of advection and diffusion in giving a more accurate and complete simulation of the seasonal cycle. A neat half-way step to achieving this synthesis was made by Elliott & Clarke (1991). They started by comparing the results of the one-dimensional vertical exchange model with observations and found they were in fair, but not precise, agreement for the temperature stratification and heat content (figure 1*a*, *b*). An inverse method was then used to answer the question of what mean flow field would best reconcile model results and observations?

The result for summer conditions (figure 2*a*) is a weak anti-clockwise circulation like that inferred from tracer distributions. In winter (figure 2*b*) it comes out to be slightly stronger but in the same sense. So, in addition to the first-order influence of vertical exchange, the inverse method here indicates that there is a weak, but significant, second-order influence of advection by the mean flow in the determination

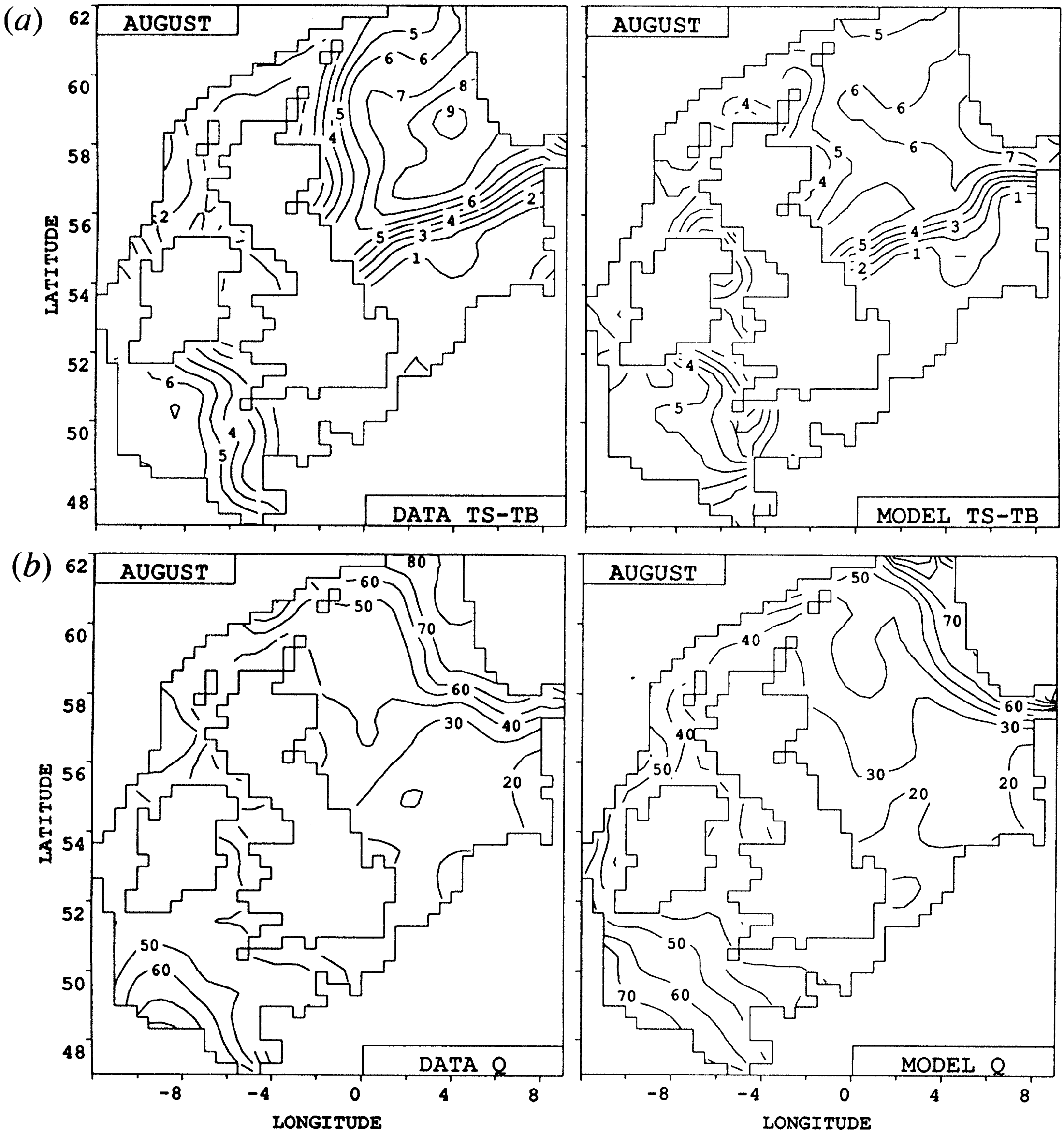

Figure 1. Comparison of observations from data bank with the results of a 1D vertical exchange model without horizontal advection: (*a*) Surface to bottom temperature differences (°C) in August. (*b*) Water column heat content (10^8 J m^{-2}) in August.

of the seasonal cycle of temperature structure. That is not to say that advection is generally of secondary importance; its influence on the distribution of a dissolved component depends on the disposition of sources and sinks and characteristic timescales of turnover in the water column. For many components with long timescales which do not enter or leave through the sea surface or seabed and have their primary sources and sinks at the lateral boundaries, advection may be the dominant control and vertical mixing is then relatively unimportant. (Prandle *et al*. this symposium).

Using the 3D density-advecting models developed during the project, we are now in a position to fully represent both vertical and horizontal transport and describe

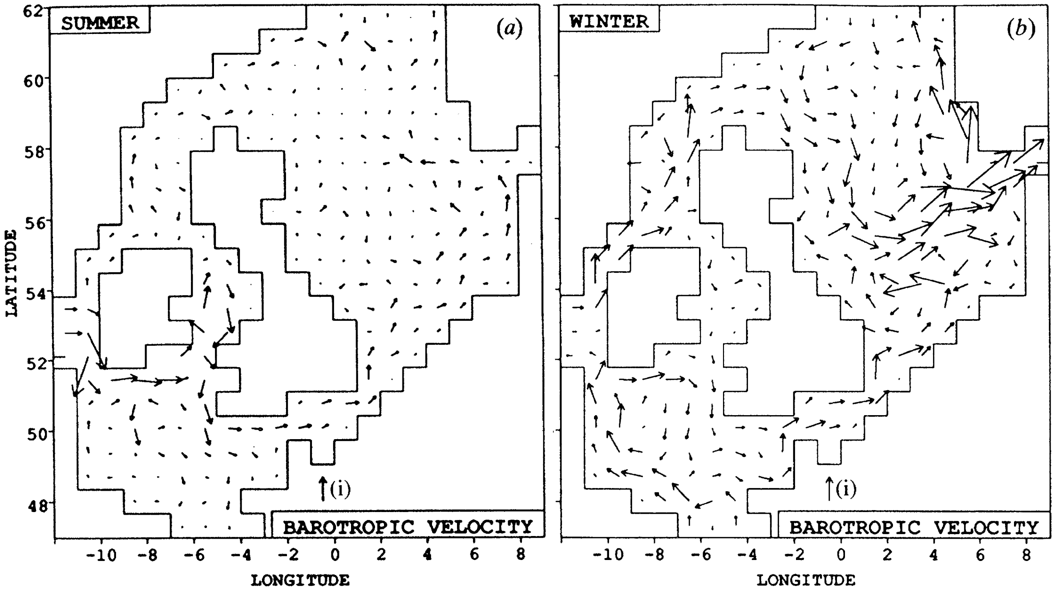

Figure 2. Inferred circulation from inverse calculation for (*a*) mean summer conditions; (*b*) mean winter conditions. (i) Arrow represents 0.5 m s^{-1}.

the evolution of stratification in detail (Huthnance *et al.*, this symposium). Full validation of the transport model will involve detailed examination of its ability to reproduce the seasonal cycle of stratification in comparison with the simpler models and inverse calculations which have so far guided our understanding.

With these new high-resolution models it should be possible to simulate the vertical structure on horizontal scales down to 1 km and, thus include all the subtlety of the internal dynamics of the front, which were clearly beyond the scope of the 1D models and inverse methods. In this way we can start to look at 'third-order' processes and use the models to help identify new features for observational study.

One such candidate feature has already been suggested by a model of the Flamborough Head front. The flow along the Yorkshire coast seems to be stabilized by the combined effects of topography and friction, but when the flow leaves the coast large meanders appear to develop. To test the notion that these large-scale features really exist will require a fast sampling survey with an undulating CTD but in the meantime we have some encouragement from satellite IR images which sometimes, though not always, show indications of frontal meandering near Flamborough Head with approximately the same scale (Hill *et al.*, this symposium).

(*b*) *Interdisciplinary modelling*

Another important innovation in our approach to modelling has been the move towards interdisciplinary models starting from basic models of the physics. Most of us I think would share Lord Kelvin's desire to encapsulate our scientific ideas and intuitions in a testable model which both summarizes our current understanding and provides the basis for future learning. He was thinking about mechanical models but the argument is the same for our modern numerical versions.

The trouble was that, until recently, the technical problems of acquiring data in many marine disciplines seemed to consume all the available effort, the science remained descriptive and, in many instances, we did not get to the interesting business of process modelling. This difficulty was especially prevalent in the labour intensive analyses of chemistry and biology.

The impetus of the North Sea Project and the scale and efficiency of the data gathering and processing has helped to overcome the problem and establish a modelling approach in several key areas. A seemingly modest but crucial innovation has been the provision of the 'user-friendly' 2D model which has been developed at POL and made available to the community. This model and the accompanying support effort of workshops and tutorials did more than anything to de-mythologize modelling and expand the community involved in interdisciplinary modelling.

This 2D model has been applied, for example, to the phytoplankton production–nutrient supply problem in the Humber–Wash system by the introduction of modules to represent phytoplankton production and nutrient re-generation by Allen & Wood (unpublished). Conditions here are usually well mixed so the 2D approach is appropriate and the model yields a plausible first-order account of the nutrient distribution in this region where the strong estuary inputs are assimilated into the open sea environment.

This concept of a basic physics model with 'bolt in' modules for non-conservative processes in chemistry and biology has also pointed the way to a proper 'framework' approach to the larger 3D model which will be needed to facilitate the development of the water quality models (Huthnance *et al.*, this symposium).

Complementary to the 2D horizontal models, there has been considerable development of 1D vertical exchange models like that for phytoplankton growth which has been developed to explore the influence of physical controls on primary production. The results of these 1D models are encouraging and have already allowed an assessment of the extent of control by tidal stirring (Tett *et al.*, this symposium). It also seems that they can give good estimates of integrated production on a regional basis. The plankton biomass cycle is not yet predicted in detail, but the model does show the right kind of behaviour in that it predicts the sharp bloom peak which was missed by monthly sampling but resolved by the continuous fluorometer measurements of chlorophyll.

More important though, than the achievement of particular simulations, is the fact that the project has stimulated an effective attack on this problem and that we now have the modelling tools, the modelling strategy and the data base with which to pursue such questions. As in the case of the physical modelling, the project has helped to establish closer links and collaboration with European groups and the development of a common approach to bio-physical models was evident in the studied reported by Radach *et al.* (this symposium).

The other vital element is skilled and able people. Not the least important aspect of this growth of modelling has been the fact that the project has attracted into these areas a number of bright young researchers with mathematical and modelling skills and thus started the development of a new cohort of cross-disciplinary modellers. They will have a crucial role to play in future shelf studies in building the models which will be the true means of demonstrating and developing our understanding of processes.

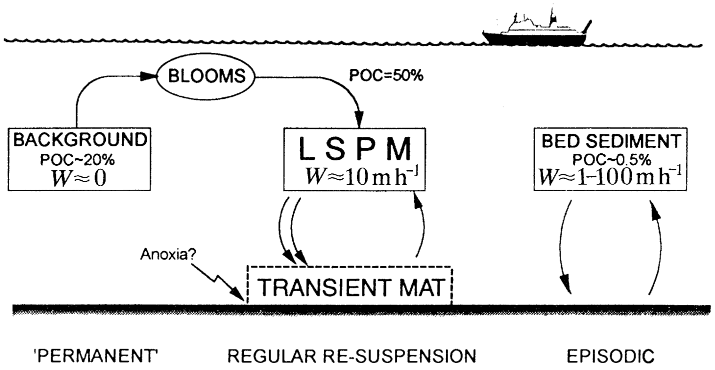

Figure 3. Components of the particulate matter suspended in the water column: POC, particulate organic carbon; W, settling velocity; LSPM, light suspended particulate matter.

(c) *Sediment re-suspension*

Another significant advance in cross-discipline modelling has been the success of a number of 'point models' using turbulent closure schemes to predict vertical exchange and, in particular, to model the results of the sediment re-suspension study. The extensive use of transmissometers to observe seston concentrations has revealed strong quarter and semi-diurnal tidal signals at the energetic southern site, with longer term variations associated with changes in stirring due to the springs-neaps cycle and windstress at the northern position. Both of these régimes can be understood to first order in terms of a model which allows for a combination of tidal advection and periodic re-suspension (Jago *et al.*, this symposium). At the start of the project, we had neither the models nor the recording transmissometers which have permitted the elucidation of these patterns of periodic behaviour.

It is in this area of resuspension that the project attempted its most speculative, interdisciplinary initiative and it seems that some interesting new perceptions of the fine sediment system are already apparent. The emerging hypothesis (figure 3) is that there are three forms of suspended particulate material with radically different behaviour: (i) a very fine background component which is settling so slowly that it is in very long-term suspension and is transported like a dissolved component, (ii) a light re-suspendable component (LSPM) which settles out twice each tidal cycle to form a transient mat on the seabed; this component is often characterised by high organic content from blooms which scavenge some of the finest mineral particles, (iii) the bed sediment proper which is disrupted and brought into suspension only during extreme combinations of waves and tidal currents.

Transmissometer measurements calibrated by gravimetric determinations of seston concentration also gave us valuable new spatial information so that we now have maps of the seasonal distributions which confirm inferences from the reflectance as seen by satellite scanners and will form the basis for testing 3D models like that described by Sündermann (this symposium).

(d) *Atmospheric inputs and nutrient budgets*

Another area where the Project opened up new territory was in the determination of atmospheric inputs and outputs. The year-round availability of the ship permitted, for the first time, a full range of measurements of atmospheric concentrations with giant sampling hoses deployed on *Challenger*'s foremast. The results were very

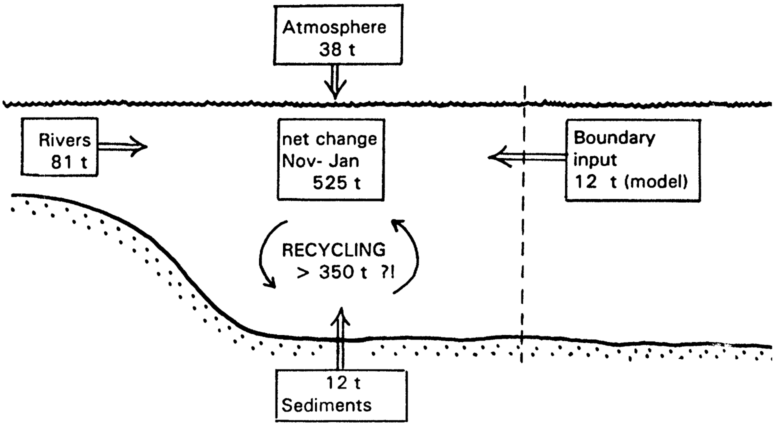

Figure 4. Nitrogen in nitrate budget for the southern North Sea over the period November 1988 to January 1989; t here means kilotonnes.

revealing, showing us, for example, that the atmospheric sources of trace metals compete with fluvial inputs and may even predominate as, for example, in the cases of nickel and lead (Chester *et al.*, this symposium).

The study also gave us improved estimates of the atmospheric source of nitrate which may amount to about 50% of river inputs. This and other nitrate fluxes estimated in the project allow the construction of a schematic mass balance for the southern North Sea (figure 4). The total change in the water column nitrate between November 88 and January 89 was determined as 525 kt of nitrogen by taking the difference between the monthly surveys. This figure may then be compared with the estimates of fluvial inputs and other sources which were measured in the project, namely: (i) the atmospheric flux which is about half of river input, (ii) boundary fluxes estimated from the 2D model and (iii) efflux from the sediments which was determined from 'bell jar' observations (Nedwell *et al.*, this symposium). It is clear that these inputs cannot account for the observed change in nitrogen content. Contrary to what was thought previously, the large additional contribution appears to have to come from regeneration in the water column and *not* in the seabed (Howarth *et al.*, this symposium). The obvious candidate host for the microbiological processes responsible for this rapid re-mineralization in the water column would be the organically rich LSPM identified in the re-suspension study.

By contrast the water column increase in silicate is largely accounted for by the observed efflux from the sediments, indicating that water column re-mineralization is much less important for this nutrient element.

(*e*) *Focus of resources*

In both the re-suspension and the nutrient flux studies, the focus of resources and effort has been crucial in helping us to evolve new insights into processes. The same benefit is evident in the concentration of technical resources in many aspects of the Project but is, perhaps, most notable in the frontal studies (Hill *et al.*, this symposium). Before the North Sea Project, the problems of measuring the rapidly moving and evolving 3D structure of the fronts with available techniques had proved largely intractable and progress had practically halted in the late 70s when drifter measurements and satellite pictures first made us recognize the complex nature of frontal flow.

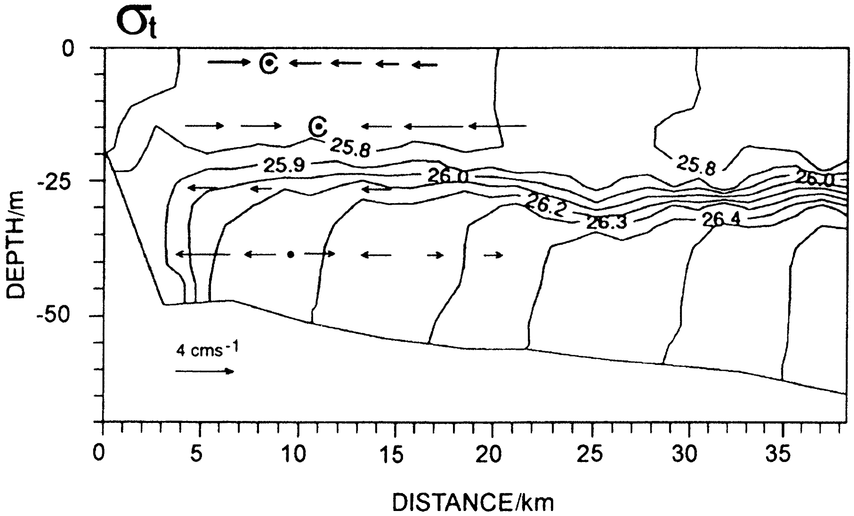

Figure 5. Residual circulation and density contours on a section normal to the Yorkshire coast. Near-surface velocities are based on OSCR HF radar measurements after the removal of tides and wind forced motions. Mean flow at other levels is based on analysis of repeated ADCP sections.

In the Project we were able to attack the problem afresh by marshalling a range of instrumentation, including three new techniques, HF radar, the ship-borne ADCP and ARGOS-DECCA buoys, along with conventional current meters to map currents in the frontal zone. These measurements revealed, for the first time, some of the detail of coherent circulations within the front, notably the along frontal jet and the cross-frontal circulation. The observed two-sided convergence of just a few cm $^{-1}$ (figure 5) is close to the noise level of both radar and acoustic systems but the consistency of independent measurements indicates that we are now able to detect these weak residual motions. The careful evaluation of these new techniques against each other and in comparison with parallel drifter and current meter measurements has helped to establish a sound basis for further combined studies of the complex flow in frontal zones.

(*f*) *The North Sea database*

Collaborative action and the focus of resources have also given us the BODC Database for the North Sea. All the primary data from the survey and process studies has been screened, edited and calibrated by BODC to make the largest, best calibrated and most coherent shelf sea data-set ever. Interlaced with the basic physical data are a full range of chemical, sediment and biological parameters including estimates of phytoplankton and zooplankton abundance and even, for example, the seasonal cycles of the biogenic trace gases (Liss *et al.*, this symposium).

I think we all recognize that the new BODC procedure has significantly raised standards in the collection and archiving of data and has set a pattern for all future operations. In addition, the Data Centre have made the rich set of data from the Project accessible to all through a variety of media, including the CD ROM. Such ready access is important if we are to make the most of the investment in a big project of this kind. There is always a danger that, in the rush to get on to the next project, we fail to fully utilize the treasures we already have and, in this context, it is pleasing to know that NERC is planning some additional special topic support to ensure that we have the marginal resource needed to continue studying the data base.

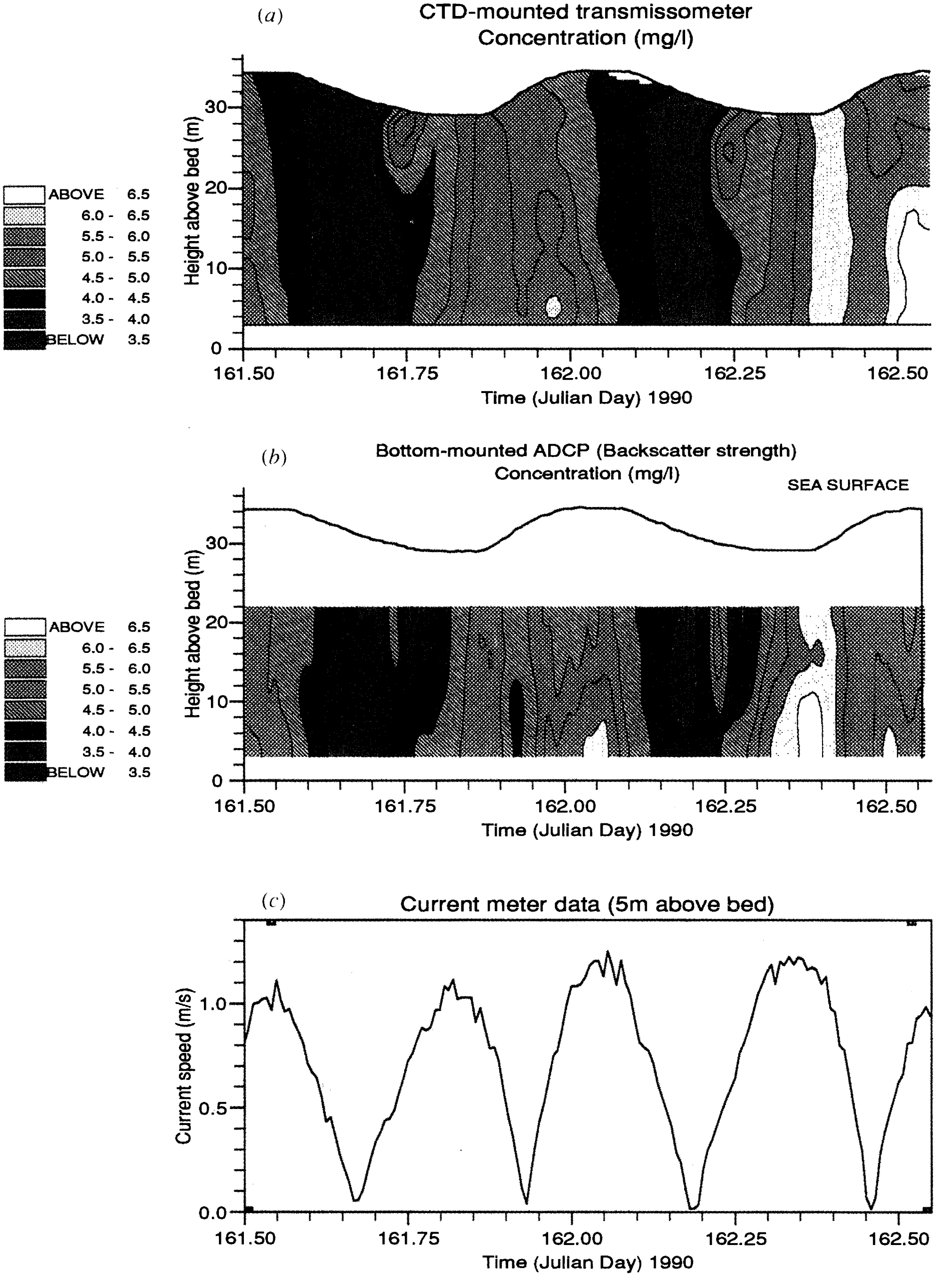

Figure 6. Comparison of annual-mean concentations in sub-regions 1, 2 and 3 (figure 3) obtained from: (i) model simulation, coloured columns, (ii) left arrow ► NSPS, (iii) right arrow ◄ 1987 Quality Status Report. Simulation used QSR data for river and atmospheric inputs, NSPS concentrations for boundary inflows.

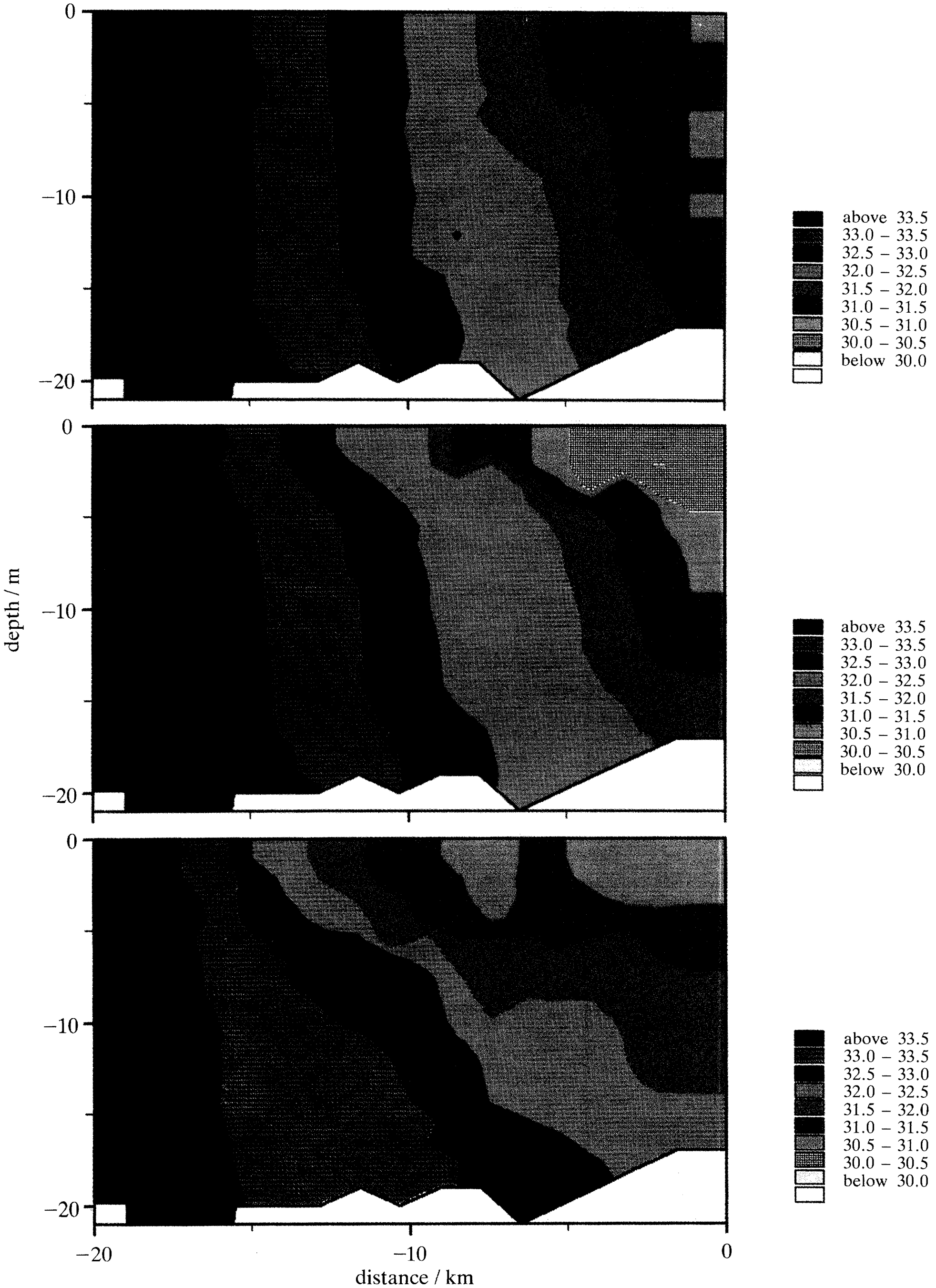

Figure 7. Cross-shore profiles of the salinity structure in the Rhine outflow ROFI showing the development of stratification following the decrease of wind mixing. Plots are based on profiles from a Searover undulating CTD with horizontal resolution of 500 m: (*a*) day 258, 2222–2311; (*b*) day 260, 2328–2359; (*c*) day 261, 0700–0802. The wind speed increased to more than 13 m s^{-1} soon after midday on day 259 and decreased rapidly to about 4 m s^{-1} on day 260.

3. Future developments?

The development of the transport model and its incorporation into water quality models will depend on future support from the U.K. and possibly the EC. The Department of the Environment has already taken on a commitment in this area and is helping to maintain the thrust towards Water Quality Models through support for the development of the transport model and modules for nutrients and trace metals.

The sort of thing that can be achieved already has been demonstrated by simulations of metal concentrations using the 2D model for the vertically mixed region of the Southern Bight (Prandle *et al.*, this symposium). The predicted distributions are already encouragingly close to reality suggesting that, for some of the components with straightforward chemistry, most of the relevant processes are included.

The extension of this sort of simulation to employ the 3D transport model is not difficult to see, though the practical implementation will require a lot of hard work and resources. By contrast, predicting the way forward in the more fundamental and innovative aspects of our science is more difficult although, even here, I suspect that we can see some of the new directions which are opening up.

In the testing of the new high resolution models, the closer interaction between the modellers and observationalists seems set to continue. In the physics, we have the prospect of being able to test the models at a different level by measuring the turbulence parameters. The turbulence closure schemes in the models are already calculating the parameters of the turbulence: the r.m.s. velocity and the energy dissipation and using the results to predict the vertical exchange coefficients. The question is whether they are getting it right? One way to check is to measure the vertical profile of these turbulence parameters using microstructure instruments like the FLY2 profiler which can measure the fine scale of velocity down to scales of 1 cm and hence estimate the dissipation (Dewey *et al.*, 1987). Together with estimates of the turbulent intensity from fast sampling current meters, these new measurements will give us a new, and, we might hope, enlightening check on how well the models represent the turbulence. In this regard the measurements of the variation of dissipation in the vicinity of the front on George's Bank (Loder *et al.*, this symposium) were of particular interest and would seem to confirm the viability of this way ahead.

New technology can also be expected to stimulate the interdisciplinary modelling. The development and deployment of recording fluorometers for the continuous measurement of pigments was a modest but important technical success of the project. It gave us, for the first time, the biological equivalent of the current meter: a robust instrument that could be left on moorings to give reliable time series data. We can look forward to other optical and chemical sensors for continuous observations.

Nutrient sensors, which are already being tested in long deployments, will be especially valuable in complementing the pigment measurements and ensuring that the modellers have data-sets for the main 'state variables' comparable with those already available for the physical system.

In some aspects the future is already here. The presentation by Prandle *et al.* (this symposium) described the measurements in the Dover Straits which started about half way through the period of the North Sea Project. These measurements broke new ground in terms of the long-term monitoring of the flow with OSCR, but just as significant in the long run may be the first measurement of the flux of particulates by acoustic doppler. The intensity of the back-scattered signal is a measure of the particle concentration in a particular size range as is evident from the comparison between seston determined by gravimetric calibration of the acoustic back-scatter and from parallel transmissometer measurements (figure 6*b*, *a*, plate 1). Combining the seston signal with the velocity (figure 6*c*), we should have a measure of the instantaneous flux over a large fraction of the water column depth, opening the way to good long-term estimates of shelf seston fluxes.

The measurement of fluxes will be one aspect of the continuing emphasis on seston. Another will be the study of the microbiological processes responsible for the substantial re-mineralization which apparently occurs in the water column.

The survey results highlighted the role of the Rhine outflow in maintaining a region of low salinity along the Dutch coast and around into the German Bight (see Howarth *et al.*, this symposium, figs 9 and 11). During the course of the project, we have come to recognize the distinct nature of such regions of freshwater influence (ROFIS) in two respects: firstly, the input of freshwater brings with it many of the contaminants and the nutrients which, thus, make their first and generally most severe impact in the ROFI; secondly, the freshwater also supplies buoyancy which modifies the physics by driving density currents which tend to stratify the system in competition with wind, wave and tidal stirring. The result is an environmental régime which is quite distinct from the seasonally stratified and permanently mixed areas which occupy the rest of the shelf.

In the absence of winds, the water column tends to switch between mixed conditions after spring tides and strong stratification all along the coast after neaps (Simpson *et al.* 1993). Recently we have observed more rapid switching between stratified and mixed states in response to changes in wind and wave stirring. Figure 7, plate 2, which is based on a survey with a Searover undulating CTD shows the development of stratification over a region extending about 15 km from the coast following the decrease of windstirring. The buoyant spreading here is analogous to that in the laboratory experiments of Linden & Simpson (1988) with the added complication of rotation which limits the horizontal movement to about one Rossby radius and thus constrains the intensity of the stratification after adjustment. Such stratification in shallow water is vulnerable to wind stirring and was observed to disappear in less than one day when the wind increased to 10 m s^{-1}.

So instead of a regular seasonable cycle we have a system which is switching between stratification and mixing on timescales from one day to a fortnight or more. The implications for primary production and re-suspension are to be further explored in a MAST project which is being undertaken in collaboration with our Dutch, German and Belgian colleagues. The project will soon be extended to other ROFI regions in the Mediterranean. In this sense the outgrowth of the North Sea Project is acquiring a fully European flavour.

The export potential of the study does not end in Europe. Much of what we have learned about the North Sea is of course directly applicable to other tidally energetic shelf sea regions. The Yellow Sea, for example, is about the same area as the North Sea and has a comparable tidal régime with dissipation again of about 50 GW. It too is surrounded by a burgeoning industrial society, and as the North Sea has the Rhine, the Yellow Sea has the Changjiang, with a freshwater discharge 15 times greater, which must induce an extensive ROFI domain.

In addition to its relevance to practical problems, testing our models in this and other shelf seas with different characteristics is one of the most convincing methods of demonstrating that they are based on sound understanding. It is also, of course, the best way to refining our understanding and building a better model, as I am sure Lord Kelvin would have wanted us to go on doing.

4. The final balance sheet

In drawing up a final assessment of the project, we should, of course recognize that not all aspects have been positive and there are some real debit items that have to be faced:

Because you cannot plan a project on the basis of an undiscovered paradigm, you have inevitably to work within the existing framework of ideas and that rules out any wildcard ideas. At the same time, because of resource limitations, we were forced to accept arbitrary geographical constraints to the project; in order to cover the whole North Sea we would have needed three vessels like *Challenger* with matching manpower and resources. A fully international project would have helped to get around this problem of resource constraints and many of us would have liked to have worked on a European basis, but negotiating the oceanographic equivalent of the Maastricht treaty seemed a daunting and long-winded prospect which would have unduly delayed the project.

Perhaps the most worrying concern is that such a big project sweeps up too big a share of resources to the detriment of scientific creativity which depends ultimately on individual innovative contributions which may find no part in the big scheme. It seems to me that this is a real danger to which there is no general answer. We must, therefore, weigh each new proposal for a community project on its merits and not see the success of one project as a blanket justification for all future proposals.

Against these limitations must be set the considerable achievement of the project and a number of clear advantages that have accrued from organising ourselves in the North Sea Community Research Project. In this particular project, the focus of resources was well justified enabling many innovations which would not otherwise have been possible. Far from constraining us, in many areas it has created new opportunities and allowed us to complete the baseline task of documenting the seasonal cycle. With hindsight, the North Sea posed a set of problems tailor-made for the Community approach; the wonder is that we did not adopt a collaborative approach earlier.

Through presenting our science in a form that made its strategic relevance clear, the project has been successful to a degree in bringing extra resources into the study of shelf seas though not, perhaps, as much as we were hoping it would. There is no doubt, however, that the project has provided a major stimulus to many specific aspects of our science and, most importantly, to the modelling. It has made it more powerful and effective, more relevant and a great deal more interdisciplinary.

But in the long term, perhaps the most important benefit of the NSP is the way that it has integrated the community, eroding the barriers that used to separate us and putting a new vigour into our approach. The experience of the NSP has given us confidence in our ability to act together in collaborative projects and has brought about an irreversible change in giving our science a more cohesive and holistic approach. I sense that we as a community, are now much better placed to contribute to shelf sea science, not just around the North Sea, but worldwide.

The author is grateful to many colleagues within the project for helpful discussions during the preparation of this overview. Particular thanks are due to Alejandro Souza for the recent results shown in figure 7.

References

Dewey, R. K., *et al.* 1987 A microstructure instrument for profiling oceanic turbulence in coastal bottom boundary layers. *J. atmos. oceanic Technol.* **4**, 288–297.

Elliott, A. J. & Clarke, T. 1991 Seasonal stratification in the northwest European shelf seas. *Continental Shelf Res.* **11**, 467–492.

Linden, P. F. & Simpson, J. E. 1988 Modulated mixing and frontogenesis in shallow seas and estuaries. *Continental Shelf Res.* **8**, 1107–1127.

Simpson, J. H., *et al.* 1993 Periodic stratification in the Rhine ROFI in the North Sea. *Oceanologica Acta* **16**, 23–32.

Colour plates printed by George Over Ltd, London and Rugby.

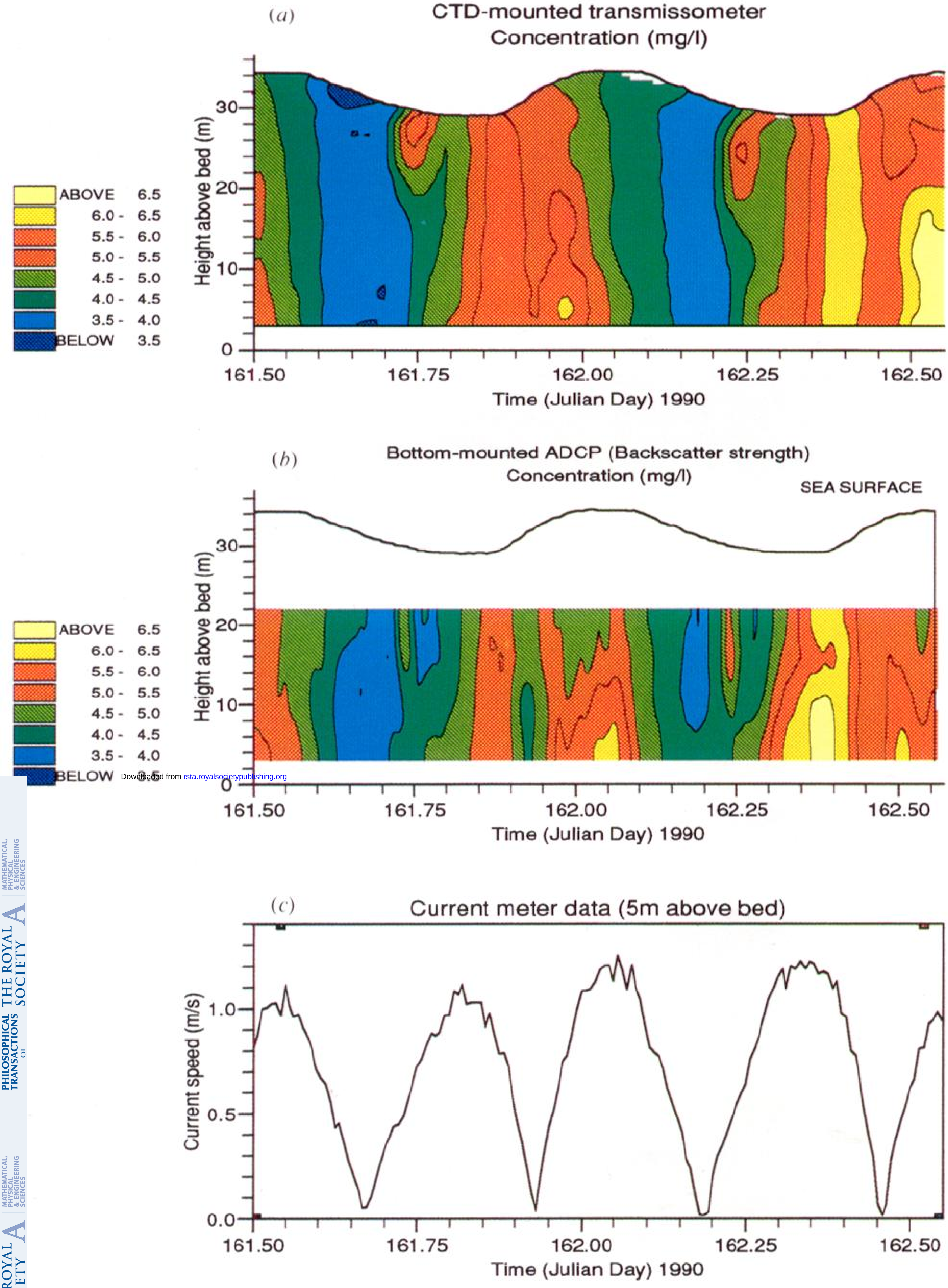

Figure 6. Comparison of annual-mean concentations in sub-regions 1, 2 and 3 (figure 3) obtained from: (i) model simulation, coloured columns, (ii) left arrow ▶ NSPS, (iii) right arrow ◀ 1987 Quality Status Report. Simulation used QSR data for river and atmospheric inputs, NSPS concentrations for boundary inflows.

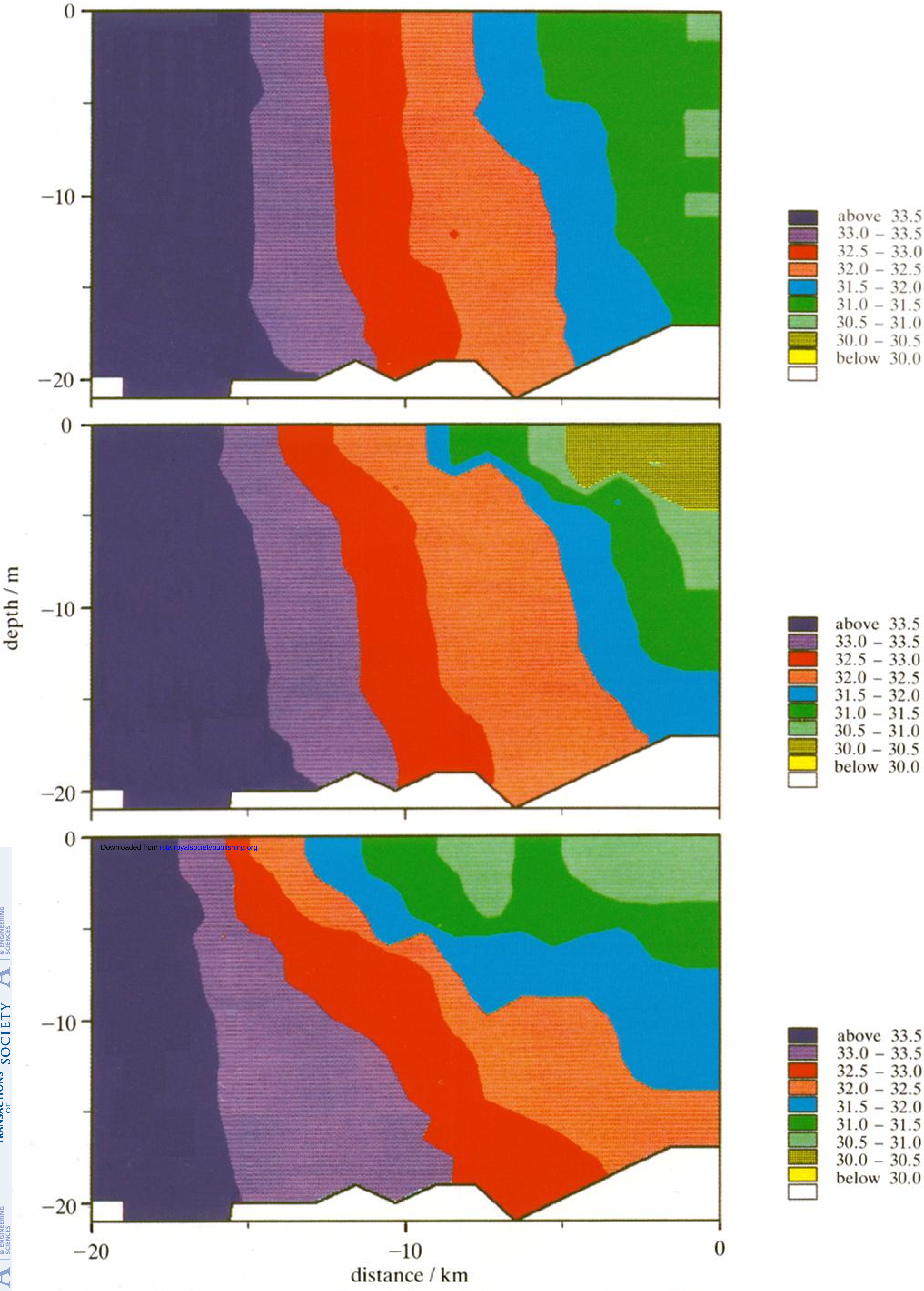

Figure 7. Cross-shore profiles of the salinity structure in the Rhine outflow ROFI showing the development of stratification following the decrease of wind mixing. Plots are based on profiles from a Searover undulating CTD with horizontal resolution of 500 m: (*a*) day 258, 2222–2311; (*b*) day 260, 2328–2359; (*c*) day 261, 0700–0802. The wind speed increased to more than 13 m s^{-1} soon after midday on day 259 and decreased rapidly to about 4 m s^{-1} on day 260.