International Hydrographic Review, Monaco, LVII (1), January 1980.

NOTE ON THE USE OF FIELD DATA TO TEST AND VERIFY NORTH SEA MODELS

by A. M. DAVIES and N. S. HEAPS
Institute of Oceanographic Sciences, Bidston Observatory,
Birkenhead, England

ABSTRACT

The development of three hydrodynamic North Sea models is discussed in relation to field data taken during the JONSDAP '76 Oceanographic Exercise. Computed residual circulations are described with reference to observational results.

INTRODUCTION

The JONSDAP '76 Oceanographic Exercise took place in the North Sea during the Spring of 1976. Here we consider the physical measurements taken during the Exercise in relation to various hydrodynamic North Sea models. By testing and verifying the models against the observations we hope ultimately to set up a theoretical system to predict the motion of the North Sea under a range of conditions of tide, wind, atmospheric pressure and open-boundary forcing. The purpose is to study the observational data and the models together, as far as that can be done, in order to see if there is agreement or at least some measure of coherence between them. Out of this synthesis can come our most reliable and comprehensive knowledge of the sea's behaviour.

THE OBSERVATIONS

The deployment of current meter rigs and offshore tide gauges which made up JONSDAP '76 is shown in figure 1. These moored instruments

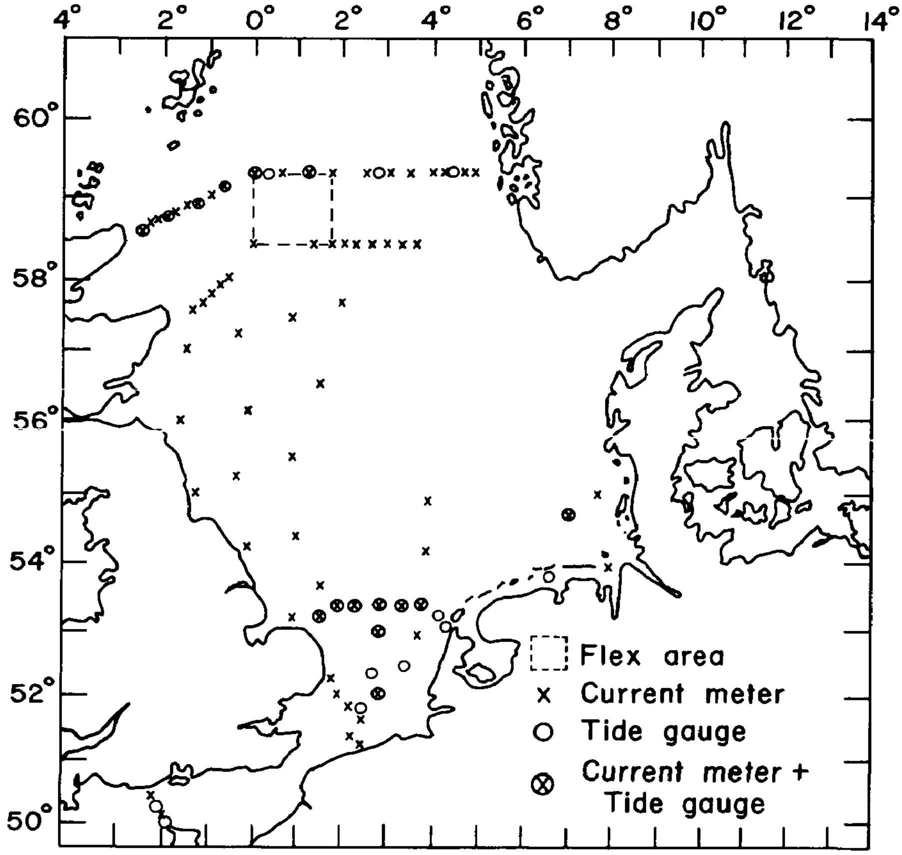

FIG. 1. — JONSDAP '76 "INOUT" moored network.

were designed to be in position for 40 days from 15 March 1976. A closer array of instruments was allocated to the FLEX area (figure 2) for the purposes of a joint physical, chemical and biological experiment from mid-March to mid-June 1976. A full account of the planning of the Exercise has already been given by RAMSTER (1977). From the outset a main objective was to take a widespread set of simultaneous current measurements in the northern North Sea in an attempt to obtain a better understanding of the residual circulation there (DOOLEY 1974). By way of precedent, an earlier oceanographic project, JONSDAP '73, had deployed a large array of current meters and tide gauges in the Southern Bight of the North Sea during September/October 1973. Initially it was proposed that the new observations should be taken exclusively in northern waters between Scotland and Norway in an area extending from about 57° to 61° N latitude. However, for practical reasons and to take in a greater range of international interests, it was decided to include measurements from the whole of the North Sea and part of the English Channel while still having an appropriate concentration of them in the northern region.

From this emerged the concept of a field deployment to fit a numerical model for tides, surges and residual currents in the whole of the North

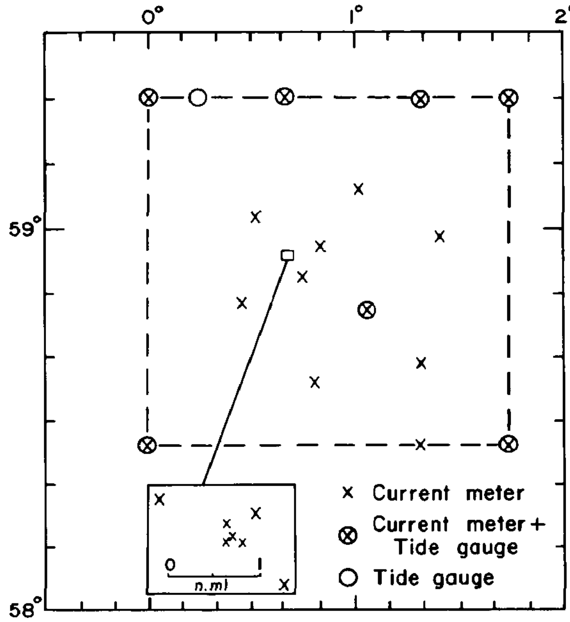

FIG. 2. — Moored JONSDAP '76 stations in the FLEX area.

Sea basin: with a northern open boundary running along the line from Wick in Scotland to position 59° 20′ N, 0° 0′ W and then along latitude 59° 20′ N to the Norwegian coast, and a southern open boundary crossing the English Channel along the meridian 2° W. Figure 1 shows a high density of tide gauges and current meter rigs along these lines, this arrangement being designed to provide detailed open-boundary conditions on sea-surface elevation and current for the model. The observations within the model area provide checks on model output: the verification procedure.

NORTH SEA MODEL

The model grid, with a resolution of 1/9° latitude by 1/6° longitude, is shown in figure 3. Computations are two-dimensional and solve the vertically-integrated equations of motion yielding elevations and depth-mean currents at the centre of the mesh elements. Nonlinear terms are included, and a quadratic law of bottom friction is assumed. Ignoring variations in water density, the influences of temperature and salinity stratification on the sea's motion are not resolved. The formulation is due to DAVIES (1976) who has computed the distribution of the principal M_2 tide, determining the sensitivity of the distribution to changes in the prescribed M_2 open-boundary data. This was done before the observations along the open boundaries became available, and at that time was used to assess the best positions for five or six offshore tide gauges along the northern boundary. With the tidal boundary data now available from the Exercise, the model is being used to re-determine the M_2 tides and tidal currents for comparison with those observed in the interior of the area. The higher tidal harmonics M_4 and M_6 are also being determined. In the near future it is hoped to use this model to derive co-tidal charts of the diurnal tides, in particular K_1 and O_1. In the longer term it should be possible to run the model with both M_2 and S_2 and examine the higher harmonics generated in the shallow areas through the interaction of these two tidal constituents.

The model has been used as a surge predictor for the North Sea area in association with another similar model of coarser mesh (say S_0) covering the entire continental shelf surrounding the British Isles (DAVIES and FLATHER 1977). Used in this mode, it forms one component of a proposed system of real-time surge prediction for the North Sea (HEAPS 1977). No significantly large surges occurred in the North Sea during JONSDAP '76 but the period was at times quite a disturbed one meteorologically, particularly in the north. A set of hourly meteorological data, forecast pressures and winds from the 10-level model of the atmosphere at the British Meteorological Office, was available up to 21 April 1976 to enable runs

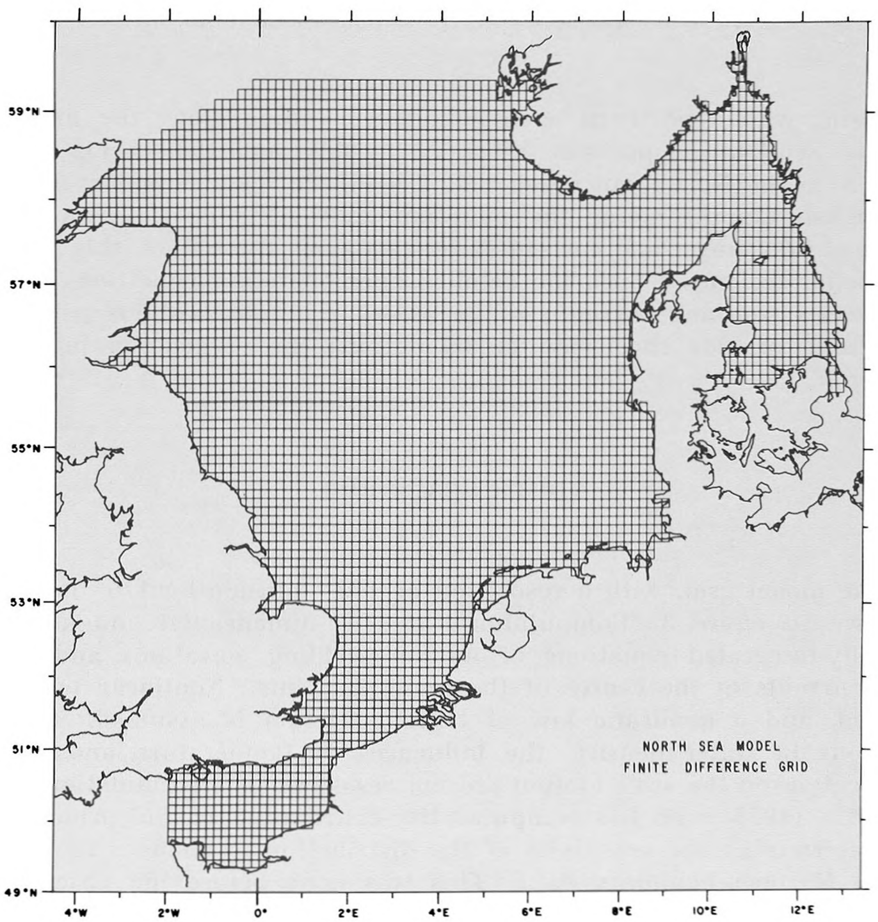

FIG. 3. — Two-dimensional North Sea model: finite difference grid.

with the model to be carried out to determine surge currents and elevations for comparison with the surge currents and elevations derived from the analysis of current meter and tide gauge observations. Here, the results from a tide run are subtracted from the results from a run of tide plus surge to yield the residuals. Without any analysis, it would be possible to compare the observed currents and sea level elevations with those currents and elevations coming from the model when subjected to an input consisting of the measured open-boundary elevations (or currents) and the estimated fields of wind stress and atmospheric pressure gradient over the sea surface. This model output could also be filtered to give, say, daily residuals for comparison with observed daily residuals. The JONSDAP observations were taken over approximately one month or more to enable satisfactory tidal analyses to be performed on both the surface elevation and the current data. Analysis determines the various tidal components in a record and thence the continuously changing surge residuals may be found.

A comparison of residual currents and elevations, derived on the one hand from the model and on the other hand from observation, needs some careful basic consideration. Thus there is a lack of reliable knowledge of mean sea level values, related to a common horizontal datum, over the model area. To make up this deficiency, local observationally-determined mean levels may be assumed to lie on the same horizontal surface. Then, however, with the model driven by observed open-boundary elevations, residual currents and elevations associated with gradients of mean surface level are ignored. For the JONSDAP period we neglect these long-term residuals in comparison with those of shorter term due to variations in wind stress and atmospheric pressure gradient over the sea surface. Residuals arising from density gradients in the sea are similarly neglected.

FURTHER DEVELOPMENTS

So far, our modelling for JONSDAP '76 has mainly employed a version of the two-dimensional model described above with its area extended northwards to the edge of the continental shelf (figure 4), and a three-dimensional model of the entire continental shelf of coarser mesh 1/3° latitude by 1/2° longitude (figure 5). The chief merit of both these models is that they have open boundaries fairly well remote from the primary area of measurement in the north of the North Sea, this area including the FLEX box. In the model computations, physically unrealistic currents are obtained near open boundaries due to conditions of prescribed elevation along them; it is therefore necessary to choose the boundaries at least three or four mesh lengths away from the region of the observations. Viewed in retrospect, therefore, for the purposes of model development it might have been worthwhile to have taken some tidal and current measurements along the northern shelf edge as part of the JONSDAP exercise. The use of a coarser mesh for three-dimensional studies was mainly dictated by the requirement to economise in the use of computer time. This emphasises the need for adequate computer funding for models when these are used in association with a large international project such as JONSDAP '76. By way of further illustration of this point, to make more refined three-dimensional computations for the motion within the FLEX box—to match the high density of observations there—would require a considerably greater computer budget than the one we presently have, albeit the work is important in an investigation of smaller scales of motion within the larger scales resolvable by the models described here.

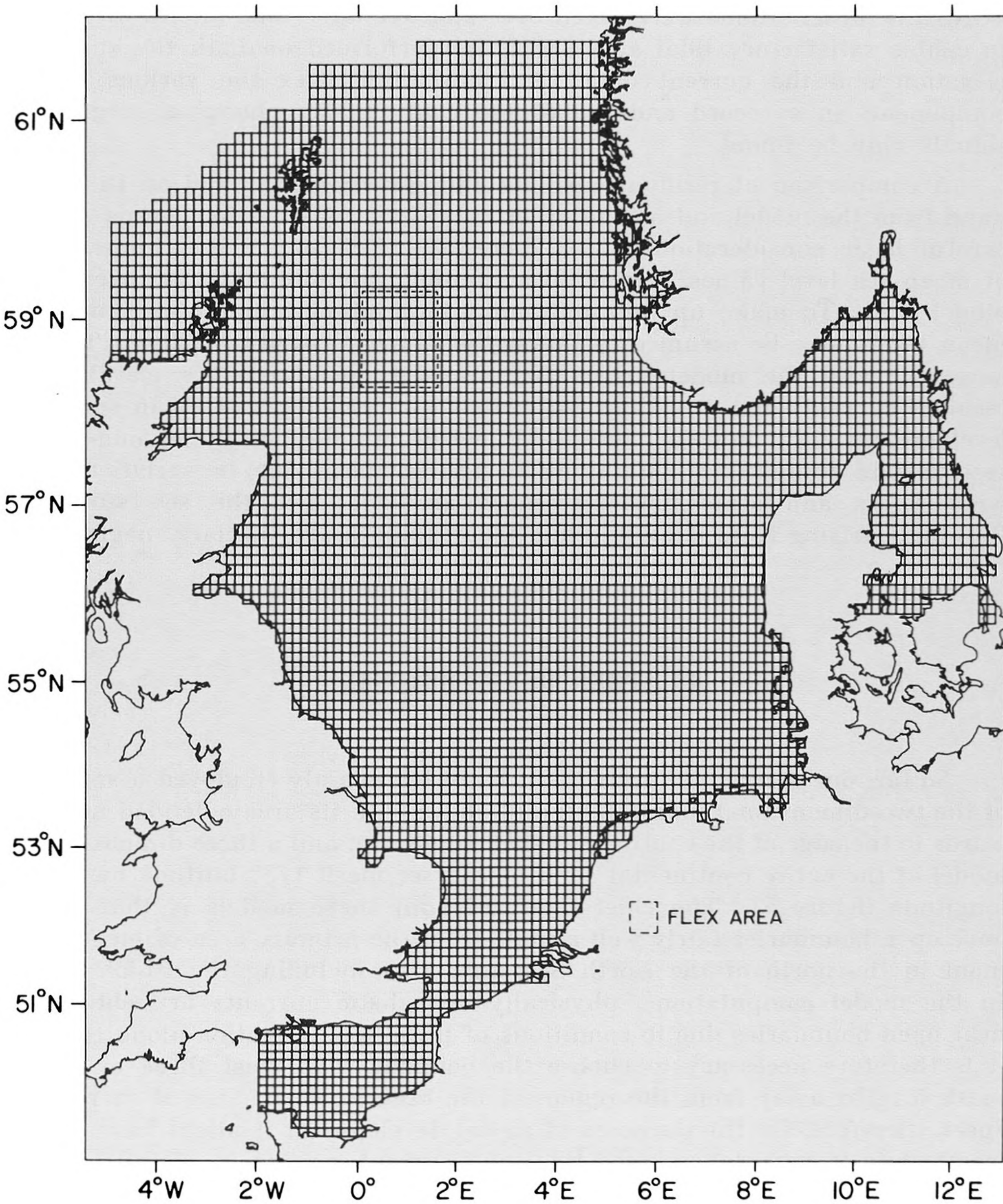

FIG. 4. — Enlarged two-dimensional North Sea model: finite difference grid.

ENLARGED NORTH SEA MODEL

Turning specifically to the North Sea model of figure 4 (model N_1, say), this was subjected to fields of mean wind stress (see figure 6) and atmospheric pressure gradient for the JONSDAP period 0000 hr 15 March to 0000 hr 15 April 1976. Simultaneously, M_2 tidal elevations along with residual elevations taken from a parallel run of the shelf model S_0 were introduced along the open boundaries. The motion determined by this tide plus surge computation was diminished by the motion for the M_2 tide alone, to yield the meteorologically-induced circulation shown in figure 7. It is interesting to compare this circulation with that suggested by the current-meter means of figure 8 (taken from a diagram of exercise means produced by Mr. J. W. Ramster of the Fisheries Laboratory, Lowestoft). The star against current vectors in this diagram indicates that the measurement had a Neumann factor (Ramster, Hughes and Furnes, 1978) of over 70 % and the length of the record exceeded 20 days. Thus, they are the measurements upon which the greatest reliability can be placed. There are some clear correspondences, both diagrams showing a strong south-easterly flow between the FLEX box and the Norwegian coast, a northerly flow

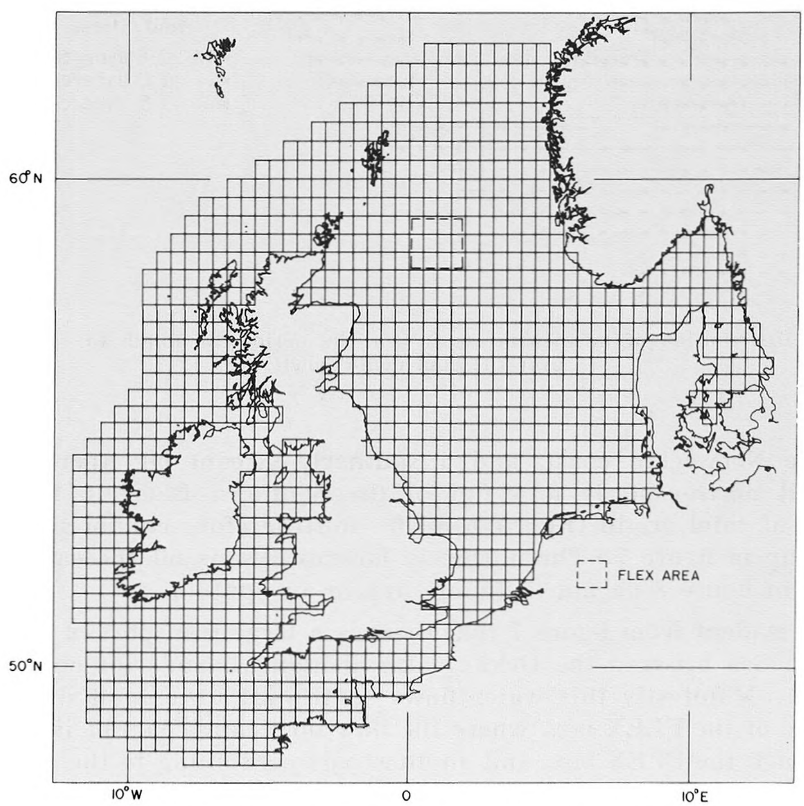

Fig. 5. — Three-dimensional shelf model: finite difference grid.

FIG. 6. — Distribution of mean-wind stress for the period 15 March to 15 April 1976 over the continental shelf.

along the Norwegian coast, and a southerly stream off Aberdeen. The significant north-easterly flow out of the Southern Bight in figure 8 is probably of tidal origin (FLATHER 1976) and therefore cannot be expected to show up in figure 7. The northerly flow directions off the east coast of England in figure 8 do not definitely appear in figure 7.

It is evident from figure 7 that there is a large transport of water into the North Sea between the Orkney and Shetland Islands (of order 0.35×10^6 m^3/s). Manifestly this water flows southward to a point due west of the centre of the FLEX box, where the flow bifurcates, part of it going due east through the FLEX box, and another part continuing to the south east. This south easterly flow turns eastward at a point about 100 km south of the FLEX box and subsequently joins a large south easterly flow of

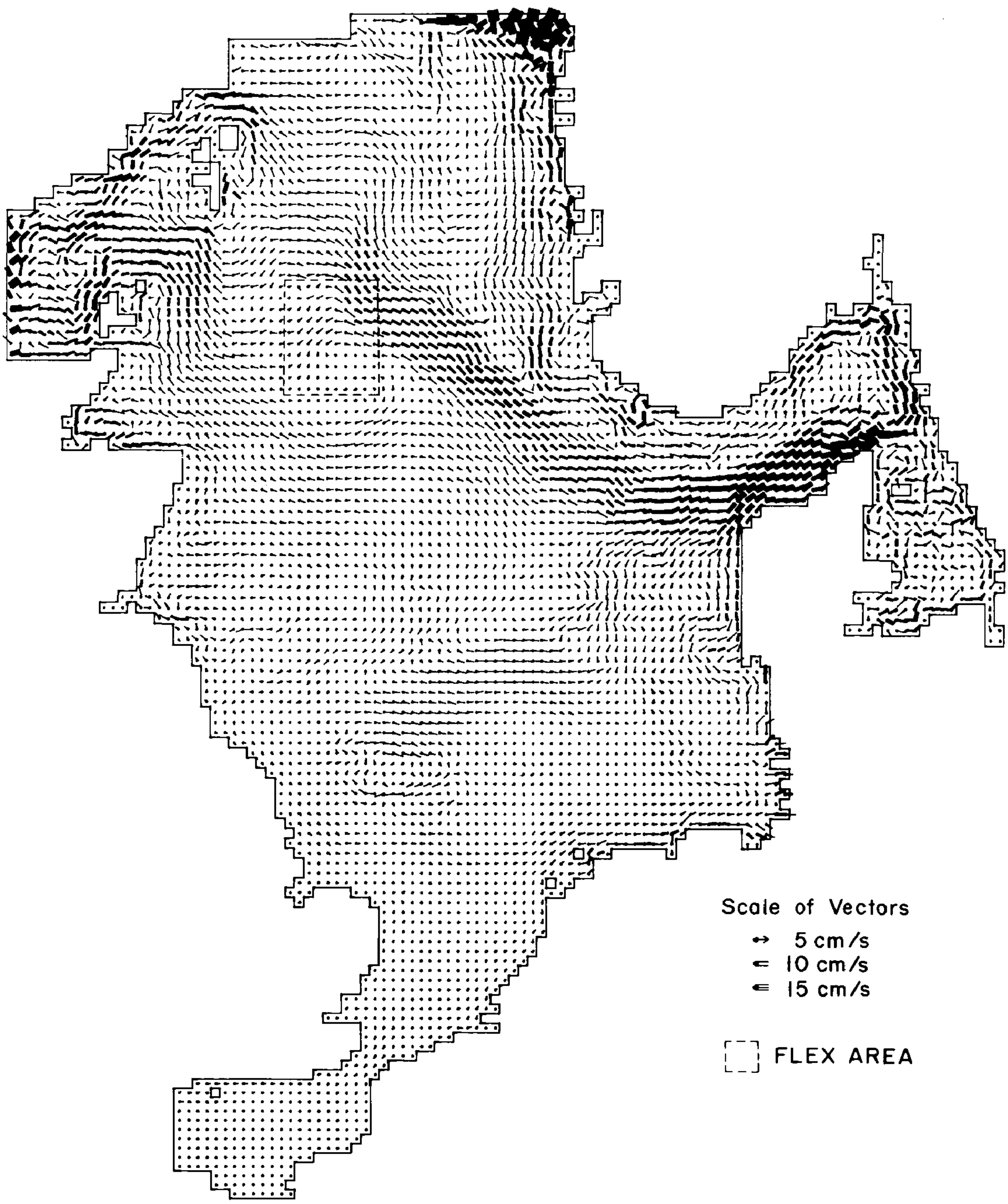

FIG. 7. — Meteorologically-induced depth-averaged currents, means for the period 15 March to 15 April 1976, computed with the enlarged two-dimensional North Sea model.

water coming from the area to the north of the FLEX box. This south easterly transport continues into the Skagerrak along the north coast of Denmark, producing currents in excess of 20 cm/s in this region. At the eastern end of the Skagerrak a counter-clockwise gyre is evident and a westward flow out of the Skagerrak along the Norwegian coast can be seen. The northerly transport of water along the Norwegian coast at latitude 59° 20′ N computed with the model was the order of 1.03×10^6 m^3/s which agrees well with observations taken during the period (FURNES and SAELEN 1977).

The flow in the northern part of the North Sea agrees well with that postulated by DOOLEY (1974, see in particular his figure 10). The south-easterly flow into the North Sea between the Orkneys and Shetlands, subsequently flowing eastward off the Scottish coast in the region to the east of Aberdeen, and the southward flow to the west of the Norwegian Trench, along with the northward flow within the Trench, agree well with the current pattern postulated by DOOLEY.

The circulation in the Skagerrak and Kattegat is particularly interesting. Results from the ICES Skagerrak Expedition have been presented by SVANSSON (1968) and TOMCZAK (1968) and their results have been plotted by LEE (1970, figure 5). The circulation pattern in the Skagerrak shown in figure 7 is very similar to that given by LEE, except that the currents to the north of Denmark computed for the period mid-March to mid-April 1976 were about 5 to 10 cm/sec higher than those observed during the ICES Skagerrak Expedition. Also during the ICES Expedition the flow along the Norwegian coast was much stronger than the flow into the Skagerrak along the Danish coast. Clearly there was a different distribution of current magnitudes to those computed here. The period during the ICES Skagerrak Expedition during which the strongest currents occurred corresponded to north-easterly winds of force 5 on the Beaufort scale: much higher winds than the average wind field used here (of order force 3) and from a different direction. Also, in the numerical model, the boundary at the southern end of the Kattegat is closed and consequently flow of water into or out of the Baltic is not possible. This means that in the steady state the flow into the Skagerrak must balance the flow out of the Skagerrak. Since the water is deep along the Norwegian coast, a small depth mean current there can transport an amount of water equivalent to that transported by a much higher current along the north Danish coast.

This difference in wind field, together with the closed boundary at the southern end of the Kattegat partly explains the large difference in current magnitude computed with the model and observed during the Skagerrak Expedition. The closed boundary at the southern end of the Kattegat is probably not physically realistic during periods in which the wind-induced currents are high. However, the complex circulation pattern in this area computed with the model is very similar to that given by LEE, and the complexity of the circulation is presumably largely determined by the bottom topography.

Figure 7 shows that the horizontal variability of the flow in the region of the FLEX box is considerable. The mean wind stress over the FLEX box is quite uniform, and hence the variability of current in

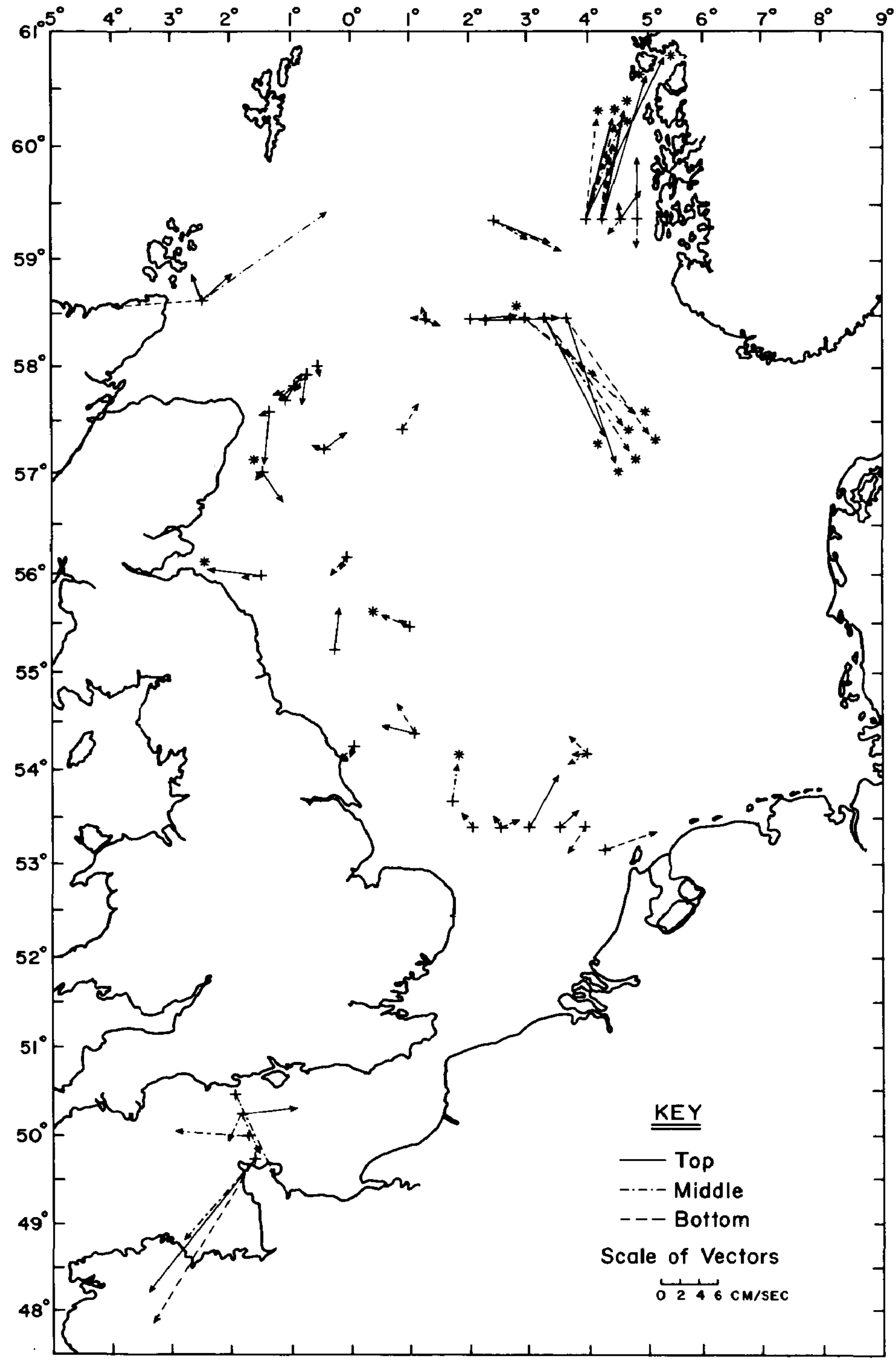

FIG. 8. — Mean currents derived from current meter measurements during March/April 1976 (the INOUT period).

this region must be due in part to local topographic effects, but in the main it is due to the horizontal spatial variability of the currents entering the FLEX area.

THREE-DIMENSIONAL SHELF MODEL

Considering next the three-dimensional shelf model of figure 5 (model S_1, say), this is of a design somewhat similar to an earlier Irish Sea model (HEAPS 1974). However, quadratic rather than linear bottom friction is postulated, and a method is employed involving the solution of the hydrodynamic equations by the Galerkin method with an expansion of the currents through the vertical water column in terms of simple cosine functions (DAVIES 1978). Along the open boundary with the Atlantic Ocean a radiation condition is employed to allow disturbances from the interior of the model to pass outwards. Boundary forcing is provided by M_2 tidal elevation, and a meteorologically-induced elevation is computed using the hydrostatic approximation. As for model N_1, this model was subjected to a time-averaged wind stress field and a time-averaged field of atmospheric pressure gradients corresponding to 15 March to 15 April 1976. Again, as before, the M_2 tidal motion was computed with the model and then this solution was subtracted from that computed with both tide and meteorological forces to yield the residual circulation.

The computed spatial distribution of meteorologically-induced surface current over the shelf is shown in figure 9, and comparing this with the computed distribution of bottom current in figure 10, a number of interesting points are evident. The major features of the depth mean flow in the North Sea for this period described previously (figure 7) are nearly identical to the depth mean currents (see figure 11) computed with the three-dimensional shelf model. This is encouraging since the three-dimensional shelf model does not contain the advective terms, which are present in the two-dimensional model, and has a coarser resolution. However, the variation in current magnitude between surface and bottom current is clearly evident (compare figures 9 and 10).

The horizontal variation of surface current in the region of the FLEX box to a first approximation is fairly uniform, reflecting the uniform wind stress fields, being essentially an eastward flow, at about 45° to the right of the wind field, as would be expected from Ekman theory. However, the bottom flow (figure 10) shows a large horizontal variation, being directed southward down the Scottish coast in the sea area to the east of Wick, then flowing eastward at the latitude of Aberdeen, and subsequently turning northward at a point about 100 km to the south of the FLEX box. The bottom flow through the FLEX box shows the current turning from a northward to an eastward flow, which then continues to the south east into the Skagerrak. This high horizontal spatial variation of bottom current in the northern North Sea is presumably due to the influence of bottom topography.

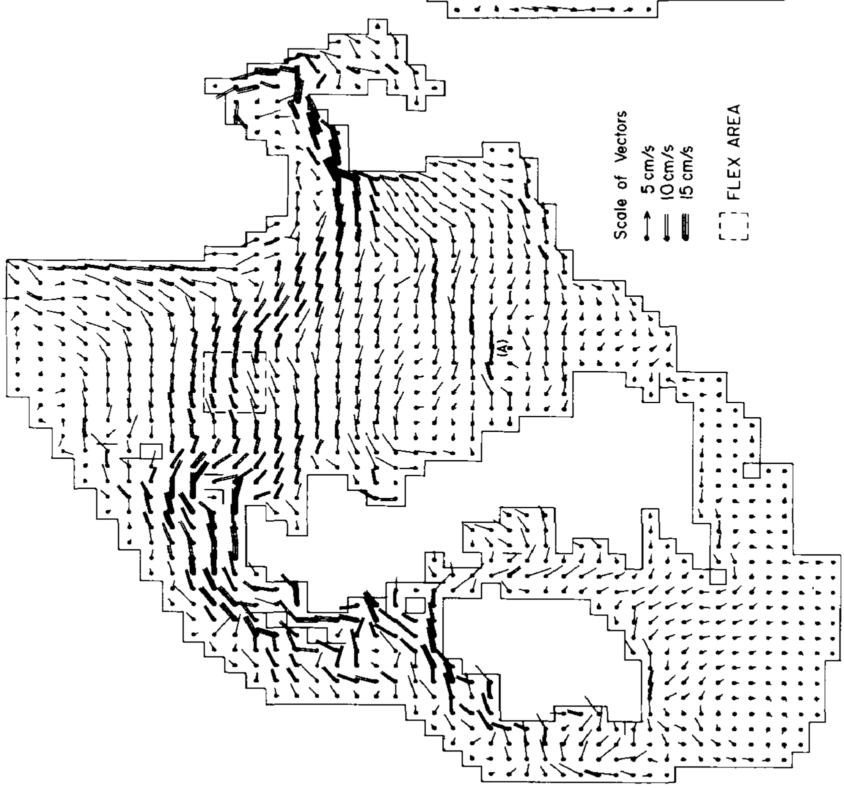

FIG. 9. — Meteorologically-induced surface currents, means for the period 15 March to 15 April 1976, computed with three-dimensional shelf model.

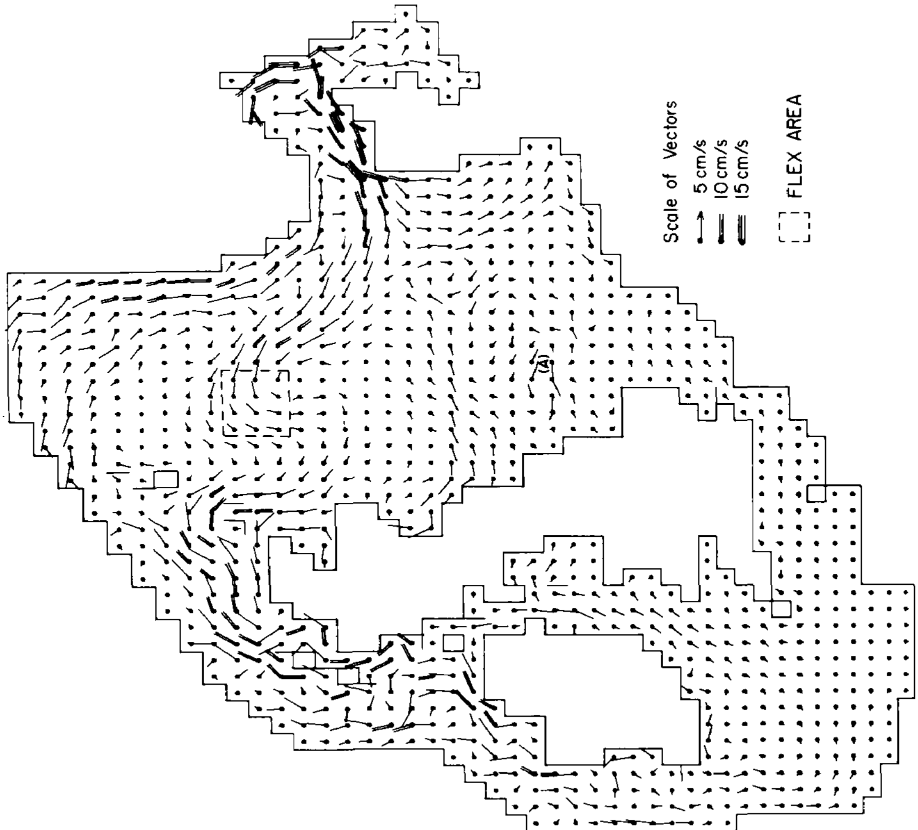

FIG. 10. — Meteorologically-induced bottom currents, means for the period 15 March to 15 April 1976, computed with three-dimensional shelf model.

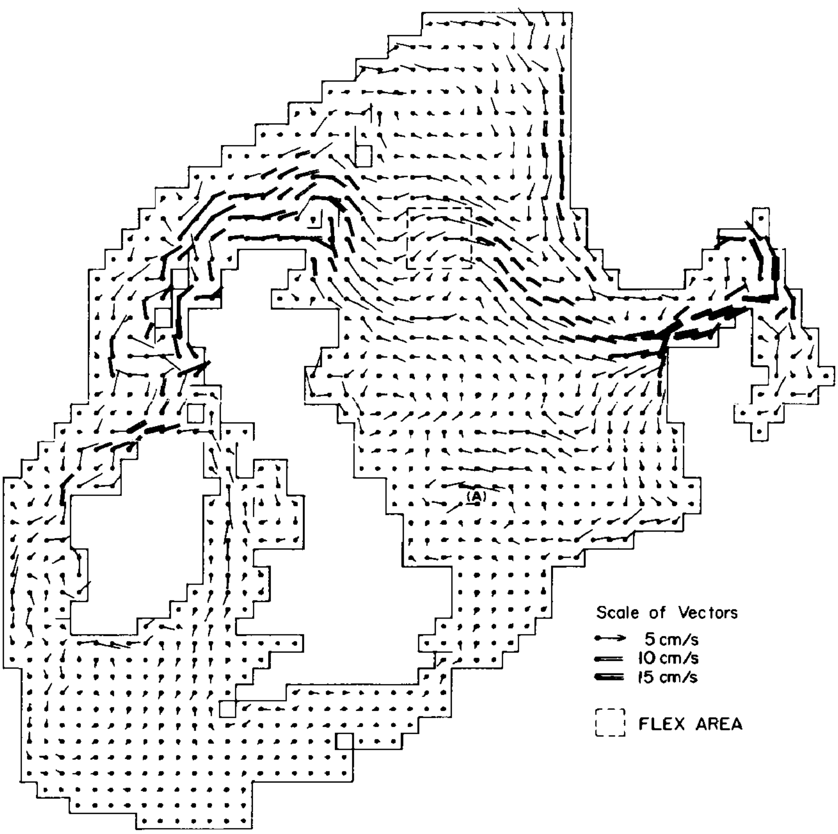

FIG. 11. — Meteorologically-induced depth-averaged currents, means for the period 15 March to 15 April 1976, computed with the three-dimensional shelf model.

Differences in direction between surface and bottom currents in the German Bight are also evident from figures 9 and 10. The surface current is mainly to the north east, moving water towards the coast, whereas the bottom current is to the north west, taking water away from the coast.

An interesting circulation pattern exists off the east coast of England in the region of the grid point marked (A) in figures 9 and 10. At grid point (A) the surface current is near zero, while the bottom current is the order of 3 or 4 cm/sec towards the coast. The surface currents in the area surrounding point (A) are predominantly off shore, whereas at point (A), and due west of it, the bottom current is towards the coast. This type of circulation has been observed a number of times by LEE and RAMSTER (1968). (See also HILL 1973.)

CONCLUDING REMARKS

This paper has presented a short account of some of the numerical modelling which has been carried out in association with the observations taken during the JONSDAP '76 Oceanographic Exercise. The field data set is not yet complete and there are more comparisons still to be made between observation and theory, particularly on the shorter time scales of hours and days. However, even at this stage, it is clear that the models are providing an important means of interpreting the measurements—including not only those taken during JONSDAP but also those taken in earlier expeditions. The design of oceanographic experiments in relation to theoretical modelling has received good impetus from the JONSDAP '76 experience.

ACKNOWLEDGEMENTS

The authors are indebted to Mr. J. W. Ramster for providing them with a diagram of exercise measurements from which figure 8 has been drawn. Also, they are grateful to Mr. R. A. Smith for preparing the diagram for publication.

The work described in this paper was funded by a Consortium consisting of the Natural Environment Research Council, the Ministry of Agriculture, Fisheries and Food, and the Departments of Energy and Industry.

REFERENCES

Davies, A.M. (1976) : A numerical model of the North Sea and its use in choosing locations for the deployment of offshore tide gauges in the JONSDAP '76 Oceanographic Experiment. *Dt. Hydrogr. Zeitschrift,* 29, pp. 11-24.

Davies, A.M. (1978) : Application of numerical models to the computation of the wind-induced circulation of the North Sea during JONSDAP '76. (In press : Meteor Forschungsergebnisse).

Davies, A.M. & Flather, R.A. (1977) : Computation of the storm surge of 1 to 6 April 1973 using numerical models of the North West European Continental Shelf and the North Sea. *Dt. Hydrogr. Zeitschrift,* 30, pp. 139-162.

Dooley, H.D. (1974) : Hypotheses concerning the circulation of the northern North Sea. *J. Cons. Int. Explor. Mer,* 36, pp. 54-61

Flather, R.A. (1976) : A tidal model of the North-West European Continental Shelf. *Mém. Soc. R. Sci. Liège,* sér. 6, 10, pp. 141-164.

Furnes, G.K. & Saelen, O.H. (1977) : Currents and hydrography in the Norwegian coastal current off Utsira during JONSDAP '76. *Report No. 2/77, University of Bergen.*

Heaps, N.S. (1974) : Development of a three-dimensional numerical model of the Irish Sea. *Rapp P.-v. Réun. Cons. Int. Explor. Mer,* 167, pp. 147-162.

Heaps, N.S. (1977) : Development of storm-surge models at Bidston. *Institute of Oceanographic Sciences,* Report No. 53, 30 pp. + figs.

HILL, H.W. (1973) : Currents and water masses, pages 17-43 in *North Sea Science*, ed. E.D. Goldberg, M.I.T. Press, Cambridge, Massachusetts 02142.

LEE, A.J. (1970) : The currents and water masses of the North Sea. *Oceanogr. Mar. Biol. Ann. Rev.*, 8, pp. 33-71.

LEE, A.J. & RAMSTER, J.W. (1968) : The hydrography of the North Sea. A review of our knowledge in relation to pollution problems. *Helgolander Wiss. Meeresunters*, 17, pp. 44-63.

RAMSTER, J.W. (1977) : Development of cooperative research in the North Sea. The origins, planning and philosophy of JONSDAP '76. *Marine Policy*, October 1977, pp. 318-325.

RAMSTER, J.W., HUGHES, D.G. & FURNES, G.K. (1978) : A 'steadiness' factor for estimating the variability of residual drift in current meter records. *Dt. Hydrogr. Z.*, 31, pp. 230-236.

SVANSSON, A. (1968) : The International Skagerrak Expedition 1966. Conditions in northern part of the Kattegat and along the Swedish coast of the Skagerrak. *Medd. f. Havsfiskelab., Lysekil* No. 56, 15 pp.

TOMCZAK, G. (1968) : Die Wassermassenverteilung und Strömungsverhältnisse am Westausgang des Skagerraks während der internationalen Skagerrak-Expedition im Sommer 1966. *Dt. Hydrogr. Zeitschrift*, 21, pp. 97-105.