A 5-Year Scientific Research Programme for Managing Coastal Seas

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The management of coastal seas requires scientific knowledge to: (i) link inputs to resulting concentrations, (ii) distinguish between natural variability and man's impact, and (iii) predict long term trends. This knowledge incorporates: (i) movement and dispersion of both water and sediments, (ii) partitioning of contaminants between dissolved and particulate phases, (iii) successive exchange processes between river/estuary/coastal zone/sea/ocean and between sea/sea-bed and sea/atmosphere.

The UK is presently mid-way into a 5-year, £15M oceanographic research programme in the North Sea involving the development of numerical models, systematic observations and fundamental research to fill gaps in basic knowledge. The programme will proceed through three stages, simulating physical, biological, chemical and sedimentological parameters: (i) over the well-defined annual seasonal cycle, (ii) over inter-annual variations, (iii) for long term trends.

Long-term data sets are vital for such programmes, systematic marine monitoring programmes must be initiated, involving combinations of remote sensing, sea-truth moorings and coastal stations.

This programme will be extended to consider the contribution to and effect from global pollution, specifically possible greenhouse effects such as rise in mean sea level and meteorological changes. The widespread impact of such phenomena emphasises the necessity for international co-operation in all aspects of these studies.

1. INTRODUCTION

The North Sea is an important resource shared by many nations, hence the balance between exploitation and conservation of the natural environment is vital. Effective management requires an improved scientific understanding of the sea, expressed in computer-based models able to differentiate (and predict) the impact of man's activities from natural variability.

Hydrodynamic models are required as the basis for transporting and mixing contaminants both horizontally and vertically. Since the dynamic processes involved occur over time scales of seconds (turbulent motions), to hours (tidal oscillations), to months (seasonal variations) with corresponding space scales from millimetres to thousands of kilometres, a range of models is required. For non-conservative substances, sources, sinks and exchange rates must be determined including complex interactions between dissolved and particulate phases and between chemical and biological parameters.

To develop these models, observational data are required for initialisation, external forcing and validation. While tidal motions are physically the most energetic, many parameters exhibit a large consistent seasonal cycle (e.g. heating, light, waves, river flows, stratification, nutrients, oxygen, plankton etc.). Hence, as an interim step towards long term prediction, an observational programme was designed to define this seasonal variability. To allow for inter-annual variability of the seasonal cycles, measurements extended over 15 months.

Even with one ship dedicated exclusively for this purpose for 15 months, only a limited region of the North Sea could be monitored. Figure 1 shows the ship's track followed routinely for the first 12 days of each month. For the rest of each month, the ship was used for more localised experiments, each contributing to the determination of the complex exchange rates referred to.

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2. AN OBSERVATIONAL PROGRAMME TO DETERMINE THE ANNUAL CYCLE OF THE NORTH SEA

From August 1988 to October 1989, the research vessel RRS Challenger completed a comprehensive survey of the seasonal cycle of the North Sea. This 15 month long database provides the most detailed set of observations ever undertaken of any shallow sea, and these will provide the basis for developing water quality models.

While sailing the same 1800 Nmile track each month, sea water pumped into the ship's laboratory was analysed continuously using accurate automatic sensors. Stopping at hourly intervals enabled instruments to be lowered to the bed providing sampling in three dimensions. Permanently moored instruments provided data of high temporal resolution at 6 selected sites.

Temperature and salinity (and hence density) were recorded by (i) continuous surface measurements underway, (ii) CTD profiles at 120 sites and (iii) thermistor chains at four sites of maintained moorings (A,B,C,D).

Currents were recorded at six maintained sites with sea bed acoustic doppler current profilers (ADCP) while the ship-borne ADCP recorded currents continuously.

Suspended sediment distributions were recorded by continuous transmissometer measurements underway and at CTD stations, calibrated by water bottle sample filtrations.

Benthic processes were investigated with cores taken on eight surveys at six regular sites of varied character, three being in the area of summer stratification. Oxygen uptake and sulphate reduction rates were measured (to investigate aerobic and anaerobic microbial activity); also fluxes and profiles of nutrients, and sedimentary characteristics: organic matter, water content, particle size and temperature. The oxygen content in the overlying water was also measured.

Nutrient distributions (nitrate, nitrite, silicate, phosphate and ammonia) were analysed from samples at three depths at all CTD stations. These observations compare in number with the total from the previous 20 years.

Oxygen distributions were recorded underway and at **CTD** stations.

Chlorophyll distributions were recorded by continuous fluorometer measurements underway and at CTD stations, calibrated by water samples.

Primary productivity was estimated on each cruise, the uptake of ^{14}C being measured in an on-deck incubator, simulating irradiance at six depths. In-situ measurements of primary productivity on two process cruises will be used to verify the measurements made with the on-deck incubator.

Zooplankton samples were netted at about half the CTD stations by a scientist from NIOZ (Holland).

Biogenic gases - dimethyl sulphide, dimethyl-sulphoniopropionate (DMS, DMSP) and low molecular weight halocarbons - were analysed on the surveys from February to October 1989, from water samples at each CTD station.

Air-sea fluxes are being studied via trace organics and metals in aerosols and rain. 105 high volume filter samples have been collected for trace organic analyses (n-alkanes and PAHs) and likewise for trace metals.

Samples for **trace metal** analysis were taken on 4 survey cruises at over 100 stations and on some process cruises. On board, samples were pressure filtered and stored, either acidified to pH2 (for Cd, Co, Cu, Mn, Ni, Pb, Zn analyses) or frozen (for A1). Many samples provided suspended particulates for analysis.

3. MODELLING

Over the last 20 years, numerical models have been developed to simulate tidal motions in the North Sea and, to predict, on a routine basis, flood levels due to storm surges. These models were extended to simulate the long term transport of conservative substances. While the spread of ^{137}Cs discharged since 1963 from a nuclear re-processing plant was accurately reproduced, lack of observational data prevented further validation. Likewise, the development of sophisticated 3-dimensional models was severely handicapped by the lack of widespread synoptic observations on vertical profiles of current and density.

The data set described in section 2 provides the basic background field with which to set up and test numerical models incorporating transport, dispersion, sources and sinks, and interaction processes. These models must first reproduce the observed seasonal variation for specific parameters. Only then can we have the confidence to develop the models further, in particular to predict longer term changes.

A 'user friendly' depth-averaged model has simulated temperature and oxygen distributions with plans made for salinity, suspended sediments, metals, nutrients and phytoplankton in 1990. The model is also being used for detailed simulation of the Humber plume.

Meanwhile, significant advances have been made in modelling complex physics of dispersive elements - fronts and turbulence - and in preparing monthly climatology for temperature, salinity and circulation. High resolution modelling is also planned for turbulence over and around bed forms (especially sand banks) and in the presence of waves and currents. With access, provided by the Project, to the most advanced super-computers, development is moving (with international co-operation) towards a state-of-the-art 3-D, density-evolving circulation model that is being developed in partnership with overseas modellers.

Development of a model to simulate the annual cycle of phytoplankton involves simultaneous simulations of vertical and horizontal transport and mixing rates, suspended sediment concentrations, oxygen and nutrient concentrations.

4. SELECTED (PRELIMINARY) RESULTS

Solar Heating and Fronts. The wide scale synoptic observations of both the development (in spring) and breakdown (in autumn) of thermal stratification (or layering) has improved knowledge of heat fluxes in tidally stirred waters. The winter of 1988/89 was unusually mild, resulting in a sea temperature 2 degrees C higher than normal; the impact of this temperature anomaly on the chemistry and biology of the North Sea will provide some guide to the first effects of possible trends in global warming.

Fronts, or sharp vertical boundaries, occur between areas of deep stratified water and shallower vertically mixed water. Similar fronts form near coasts, separating lighter river water from heavier salt water.

These fronts can modify the spreading of contaminants, while the intense vertical mixing close to the fronts brings nutrients up into the surface layer providing (with light) the necessary conditions for plankton growth. Detailed observations of these fronts used:- satellites to determine their location; moored instruments to measure the rapid changes in currents, temperature and salinity; drifting buoys and dye injections to follow the dispersion of contaminants; and ship sampling (including a towed undulating vehicle 'sea-soar') to examine the effect on biological and chemical distributions.

A study of the dynamics of a near-coastal front used coastal-based radar. With a maximum range of about 30kms, this radar measures sea-surface currents averaged over each square kilometre - giving the equivalent of 100 moored current meters. These radar observations have shown: (i) the detailed dynamics of wind stirring - verifying, for the first time with such clarity, theoretical predictions made nearly 100 years ago, and (ii) the existence of persistent, strong (up to 20cm s^{-1}), surface currents. These persistent surface currents are almost impossible to measure by other techniques. They result from weak horizontal gradients in water density. Moreover, they are especially important in the movement of contaminants discharged in the coastal zone.

Nutrients and Algal Blooms

In 15 months as many observations of nutrients in the North Sea have been made as over the previous 20 years. Increased nutrient levels during the autumn and winter were mapped, and their consumption in primary production in the spring and summer was calculated. Patches of high nutrient levels in water of lowered salinity were traced to releases from the major rivers.

The winter nutrient distribution is dominated by river inputs. These follow the continental coast from Belgium to Denmark, not in a continuous stream as previously shown but in pulses. Water mass movements significantly affect nutrient distributions.

The complex process of generation and decay of algal blooms was studied using observations over large areas of oxygen levels, temperature, turbidity, light levels, nutrients and chlorophyll. Unique data were collected by moored fluorimeters able to sample the very rapid rates of change which occur during blooms.

In a *Phaeocystis* bloom off the Netherlands coast, production was exceptionally high (50mg m^{-3}), and marked decreases in nutrients were recorded.

Estuarine Plumes

Suspended solids, metals and nutrients in the Humber River plume generally show distributions closely related inversely with salinity, but dissolved mercury tended to increase with salinity, suggesting desorption from particulates moving seaward (similar behaviour was not evident off the Thames). Nutrients and metal concentrations in pore waters and sediments, their fluxes across the sediment/water interface, and redox conditions, all showed appreciable spatial variability, with some inter-correlations but only partly related to sediment type. Bioturbation influence appeared to be relatively small. Metal partition coefficients (K_d - particulate/dissolved) were determined at various locations using radio-tracer techniques.

Acidity & Air-Sea Gas Exchange

Dimethyl Sulphide (DMS) measurements showed a very pronounced seasonal pattern, with high values in the spring and summer, corresponding to times of maximum algal activity. In contrast, values are low in the autumn/winter, and it is clear that anthropogenic sulphur must dominate the acidity of rain over Europe during these times. However, in the spring/summer the biogenic source is potentially of greater significance. Maximum DMS values in the water occur in April/May. In order to convert measured DMS water concentrations into fluxes of sulphur to the atmosphere, it is necessary to use appropriate transfer velocities.

Air-sea gaseous exchange cruises took place in March and October 1989, using two purposefully added tracers, sulphur hexafluoride and helium-3. These provided the first ever field measurement of the air-sea gas exchange rate determined at a high wind speed (22m s^{-1}) confirming an earlier extrapolation from laboratory and lake studies. These results impinge on our understanding of the fate of man-made carbon dioxide, implying a significantly smaller ocean sink then hitherto assumed. Using the above information for both DMS concentrations and transfer velocities, the best estimates of the North Sea as a source of sulphur to air over Europe indicate that in the Spring/Summer, it is emitting at a rate which is equivalent to about 25% of the rate for man-made emissions from land-based sources. Thus, although anthropogenic sources are dominant, at these seasons the algae of the North Sea cannot be ignored.

Atmospheric Inputs

While the atmosphere is the major route by which most pollutants reach the open oceans, the situation in coastal areas like the North Sea with major rivers is less clear, but riverine, direct dumping, and atmospheric routes are all likely to be important.

Take the trace metal zinc (Zn) as an example. There is a clear decrease in Zn concentrations from south to north, as expected from the distribution of industrial sources. However, in order to estimate the amount deposited on the North Sea it is also necessary to examine the distribution of rainfall, since the scavenging of particles by rain is the primary deposition process. Rain measurements made at sea show that there is more precipitation in the north part of the region than in the south. This combined with the reverse trend of concentration leads to a rather even pattern of zinc deposition in the North Sea. The size of the atmospheric deposition (approximately 8,000 tonnes per year) is roughly equal to the amount of Zn coming down rivers.

5. CONCLUSIONS AND FUTURE PLANS

The Project has benefitted greatly from BODC (British Oceanographic Data Centre) expertise, in (i) defining formats for data coming off the ship and (ii) processing and calibrations immediately thereafter. A future data-handling strategy will follow this successful approach.

Much credit is also due to the NERC Research Vessel Services, to the ship RRS Challenger which incurred only 3 days downtime in 15 months, and to the technicians who prepared shipborne equipment (95% data return) and the moored instruments (over 80% data return).

The results for biogenic gas concentrations and air-sea exchange rates obtained from the North Sea have wider significance for acid rain and estimates of oceanic uptake of CO_2, respectively.

The importance of estuarine plumes and 'trapped' coastal waters has been demonstrated with high nutrient levels producing areas of peak primary production.

The development of a user-friendly transport model has been completed, and testing is underway of the seasonal cycles of temperature, salinity, suspended sediment, metals, oxygen, nutrients and phytoplankton.

The databases are close to completion for the testing of a suite of water quality models. The remaining 2 years of the Project should allow seasonal validation of these state-of-the-art models.

Several follow-up cruises are now scheduled. Surveys will be carried out in May and September 1990 (in each case the third year in succession) to record inter-annual variability as a subsequent test of the models' longer-term predictions. The Rhine plume will be surveyed in October, with emphasis on nearshore frontal dynamics, in collaboration with the Rijkswaterstaat, and the Humber plume will be studied in the spring and summer in anticipation of more biological activity than occurred during the winter process study and to initiate investigation of organic contaminants.

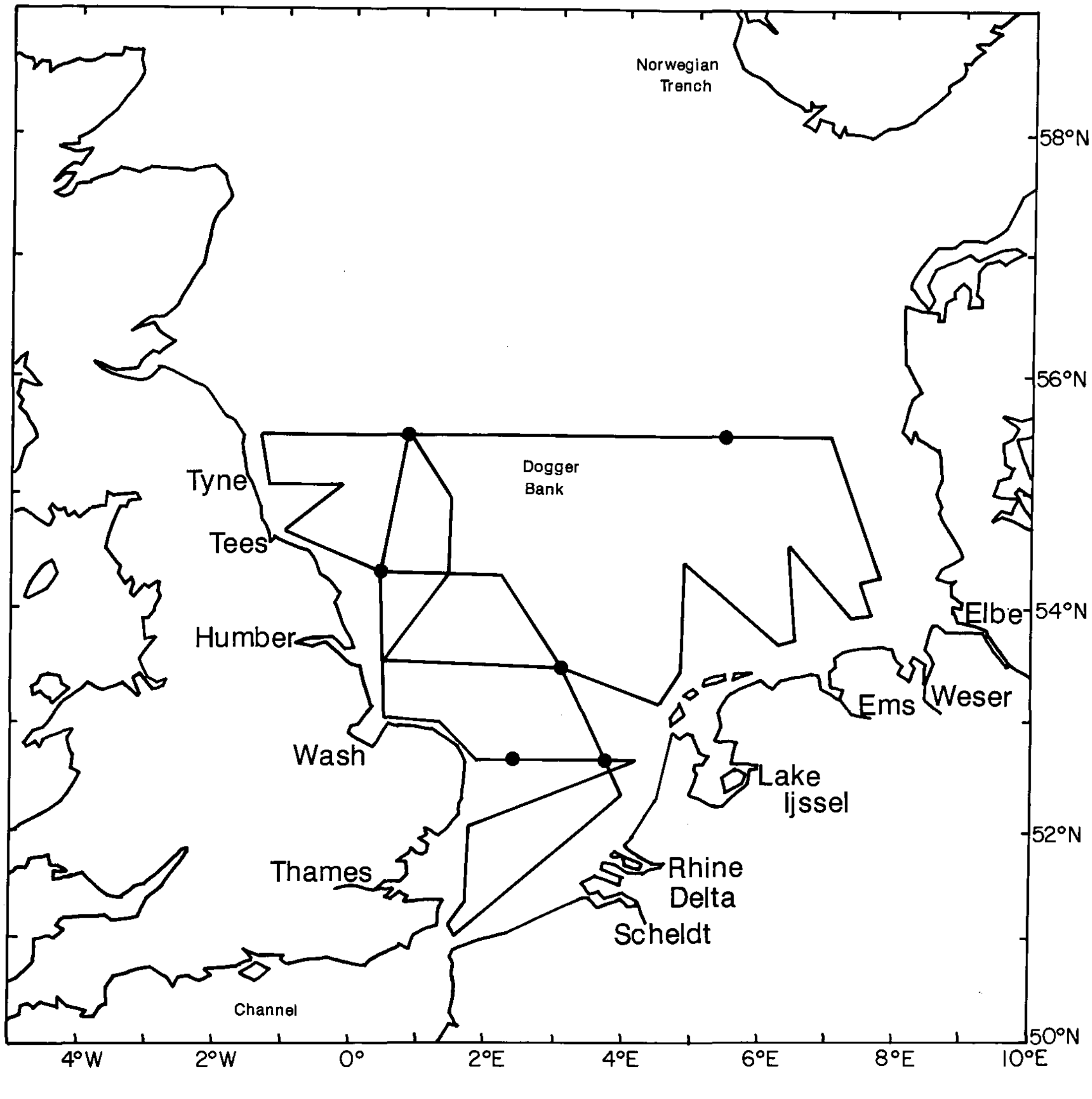
The Dover Straits are to be monitored with DoE support for a year, with a June cruise to better define spatial structures. This study will measure the amount of contaminants entering the North Sea via the Channel. The project will use high frequency radar and acoustic doppler current profilers which measure currents across the surface and at depths. There is also to be a cruise studying algal blooms and biogenic gases in relation to nutrient availability.

In the longer term, climate change will affect: sea level rise, patterns of storms, temperature, carbon dioxide and ultra violet light (UVB).

In the North Sea and its coastal margins, Britain's Natural Environment Research Council (NERC) is engaged in wide-ranging research into the physical and biological processes of the environment and the impact of both climate change and man on these. Its findings will help governments, industry and society, both in the UK and abroad make decisions towards sustainable development.

Acknowledgements

The North Sea Project has involved over 100 scientists from 15 institutions. The work described here provides only selective examples of the many detailed studies now proceeding. Further information can be obtained through the Proudman Oceanographic Laboratory.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Dogger Bank
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Weser
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Rhine Delta
Scheldt
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