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Seasonal Cycles and their Spatial Variability [and Discussion]

M. J. Howarth, K. R. Dyer, I. R. Joint, D. J. Hydes, D. A. Purdie, H. Edmunds, J. E. Jones, R. K. Lowry, T. J. Moffat, A. J. Pomroy, R. Proctor and W. Van Leussen

Phil. Trans. R. Soc. Lond. A 1993 **343**, 383-403
doi: 10.1098/rsta.1993.0054

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Seasonal cycles and their spatial variability

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[Plates 1–4]

Seasonal variations dominate many processes in continental shelf seas. A comprehensive coherent inter-disciplinary data set for one seasonal cycle was obtained by repeating the same cruise track in the southern North Sea at monthly intervals from August 1988 to October 1989. Measurements were made throughout the water column in vertically homogeneous and summer stratified regions and near the major estuaries.

97% of the surface temperature's variance was in the seasonal cycle, driven by solar forcing; spatial variability was related to stratification and to contrasts between the waters off northeast England and the German Bight. The salinity seasonal cycle was small; spatial variability was governed by fresh water river inputs. Suspended sediment concentrations were largest near river mouths and coasts; material was transported eastward from East Anglia towards the German Bight in a distinct plume whose magnitude varied with seasonal wind patterns. There were large regional differences, with the greatest phytoplankton biomass and oxygen supersaturation developing in the Southern Bight and German Bight, those regions which experience extensive phytoplankton blooms in the spring. Annual primary productivity ranged from 79 gC m^{-2} a^{-1} for the English coastal region to 261 gC m^{-2} a^{-1} for the German Bight. Low oxygen concentrations were measured in late summer below the thermocline in regions on either side of the Dogger Bank. A budget of nutrient concentrations throughout the region suggests that nutrient supply to the phytoplankton in the winter is dominated by regeneration processes, rather than input from river run-off.

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Phil. Trans. R. Soc. Lond. A (1993) **343**, 383–403
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1. Introduction

The focus of the North Sea Project was the development of water quality models applicable to, for example, predicting the effect on algal blooms, on algal species composition and on dissolved oxygen levels of changes in the quantity of agrochemicals reaching the sea, or the long term effects of the disposal in the sea of contaminants such as trace metals and synthetic organics (Huthnance *et al.*, this Symposium). Although the foundations for such models are three-dimensional transport and mixing models, based on physics, water quality models also involve inter-related chemical, biological and sedimentary processes. Since testing model predictions against observations is an integral stage in model development, what data sets will furnish critical tests of the models? Apart from tides, most processes within continental shelf seas (for instance advection, mixing, temperature, salinity, turbidity, plankton growth) exhibit strong seasonal cycles, ultimately forced by the weather – sunshine, winds, rainfall – with the different processes peaking at different times of the year. Measurements of a particular seasonal cycle will, therefore, provide data for initializing and testing models, in terms both of the seasonal cycle and of deviations from it, and will also enable studies of the processes involved.

The North Sea is an excellent case study for continental shelf seas since conditions, particularly water depths and tidal current strengths, vary widely (§2). Although it is one of the best studied seas in the world, observations are patchy in space, particularly in the vertical, where they are concentrated at the sea surface, and in time, with data sets from different disciplines obtained at different times. Only for a few variables, notably temperature and salinity, are enough data available even for the determination of an average seasonal cycle. A coherent inter-disciplinary set of measurements of a seasonal cycle was obtained in the southern North Sea between August 1988 and October 1989 (§3). A subset of the measurements are presented here in §§5–11, with other measurements presented in four other papers in this volume. The departures from normal weather conditions experienced during the measurement period are outlined in §4.

2. Southern North Sea: a synopsis

The southern North Sea is semi-enclosed (figure 1) surrounded by industrialised countries through which several major rivers flow, the largest of which are the Rhine and the Elbe (table 1). There are two open sea boundaries; a narrow connection to the English Channel through the Dover Strait and a wide northern boundary. Whereas large areas of the sea are less than 40 m deep (the Southern and German Bights and the Dogger Bank) there are two deeper regions, to east and west of the Dogger Bank: in the latter depths exceed 90 m. There are extensive sandbanks off the Norfolk coast and in the Southern Bight. Tidal currents, which dominate the kinetic energy spectrum, vary widely; the mean spring amplitude exceeds 1.2 m s^{-1} in some places whereas it barely reaches 0.2 m s^{-1} in others (figure 2). The combination of tidal currents and water depths is such that heat input at the sea surface in summer is sometimes mixed throughout the water column, in the Southern Bight, for instance, whereas elsewhere it stratifies (figure 5). The Flamborough and Frisian fronts separate the two regions. Haline stratification has greater spatial and temporal variability than thermal stratification but is common in the German Bight

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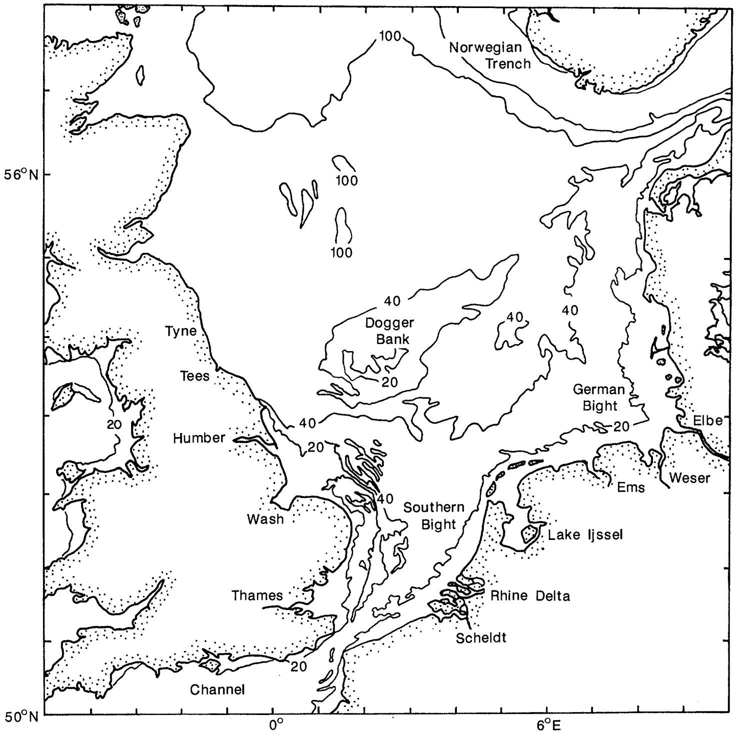

Figure 1. Map of North Sea and surrounding coasts, with the 20, 40 and 100 m isobaths.

Figure 2

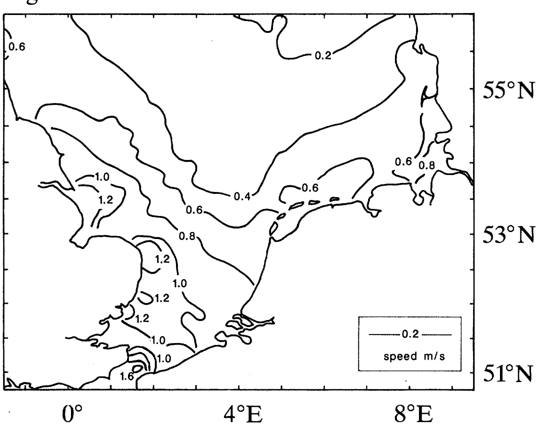

Figure 3

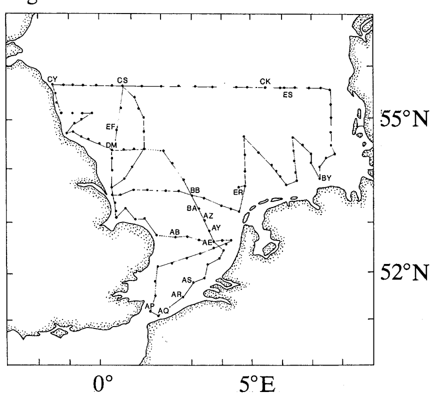

Figure 2. The maximum current for an average spring tide (M2+S2), predicted by a depth-averaged numerical model. (Courtesy of *Cont. Shelf Res.* **12**, 605 (1992)).

Figure 3. Ship track and CTD sites. Moorings were deployed at AB, AE, BB, CK, CS, DM; cores were obtained at AS, BB, CS, EF, ER, ES (ER and ES were not part of the CTD grid).

(figure 7*c*). Broadly, the average circulation resulting from the nonlinear tides, from mean wind and the sum of the storms and from the horizontal density distribution is anti-clockwise, with a northeastward flow through the Dover Strait. For reviews of the physical oceanography of the North Sea see Lee (1980), Eisma (1987) and Otto *et al.* (1990).

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Table. 1. *Average river discharges for August 1988 to October 1989*

river	discharge/($m^3\ s^{-1}$)	river	discharge/($m^3\ s^{-1}$)
Forth	108	Thames	40
Tyne	40	Rhine	1897
Tees	17	Weser	238
Humber	178	Ems	63
Wash	52	Elbe	521

Table 2. *Cruise details*

(The basic workload consisted of temperature; salinity; suspended sediments; chlorophyll (not cruises 66a, 72a); nutrients (not cruises 66a, 72a); dissolved oxygen (not cruises 28, 66a, 72a); air/sea fluxes; moorings.)

Challenger cruise no.	dates	number of CTD sites visited	extra work load
28	29/4–14/5/88	54+99	cores; trace metals
33	4/8–16/8	108	zooplankton; trace metals
35	3/9–15/9	103	zooplankton; cores
37	1/10–13/10	72	zooplankton; cores
39	1/11–13/11	106	zooplankton
41	1/12–13/12	65	zooplankton; cores
43	30/12–12/1/89	103	zooplankton; trace metals
45	28/1–10/2	98	zooplankton; trace gases; cores
47	27/2–12/3	120	zooplankton; trace gases
49	29/3–10/4	75	zooplankton; trace gases; cores
51	27/4–9/5	105	zooplankton; trace gases; trace metals
53	26/5–6/6	110	zooplankton; trace gases; cores
55	24/6–6/7	115	zooplankton; trace gases
57	24/7–6/8	99	zooplankton; trace gases; cores
59	23/8–3/9	108	trace gases; cores
61	21/9–3/10	114	trace gases; trace metals
66a	20/5–1/6/90	88	
72a	20/9–2/10	80	

3. Measurements

The aim was to obtain a coherent data set of physical, chemical, biological and sedimentary variables spanning at least a year in the southern North Sea. Coherency was assured by making the interdisciplinary measurements simultaneously, using the same ship and instrumentation throughout. Nine different experiments participated in the seasonal cycle study: dynamics, density, suspended sediment, biology, nutrients, trace metals (Burton *et al.*, this Symposium), air-sea fluxes (Chester *et al.*, this Symposium), benthic fluxes (Nedwell *et al.*, this Symposium) and biogenic trace gases (Liss *et al.*, this Symposium).

(*a*) *Plan*

A sampling strategy was established in which cruises lasting 12 days were repeated every 29 days (two spring/neap cycles) for the 15 month period August 1988 to October 1989 (table 2). The cruise duration was a compromise between the desire to cover a wide area and to minimize errors because coverage would not be synoptic.

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Processes with timescales less than one month (e.g. storms, plankton blooms, the onset of stratification, the autumnal overturn) were either covered by the 'process' studies or by time series measurements at six moorings. The instrumentation, procedures and strategy were tested on a shakedown cruise in May 1988. This cruise, combined with the 15 month cruise period and two further cruises in 1990, enabled the observation of the onset of stratification (May/June) and of the autumnal overturn (September/October) in three consecutive years (1988–1990).

The duration of each cruise and the use of one ship restricted coverage to the southern North Sea, which had the advantage that the study area was removed from shelf edge processes, from exchanges with the Atlantic, from the Baltic outflow, from the Norwegian Coastal Current and from the Norwegian Trench. Two main requirements determined the cruise track (figure 3); first, to sample longshore and offshore gradients near all the principal estuaries (Tyne, Tees, Humber, Wash, Thames, Rhine, Ems, Weser, Elbe) and, secondly, to sample well-mixed, summer stratified and frontal regions. Estuaries are sources of fresh water, and hence determine the coastal density field, and are also major sources of contaminants. Measurements were only made off their mouths, thus avoiding the region which often acts as a buffer and which is dominated by complex, small scale processes (some of which were investigated by a 'process' study). Stratification has a major impact on exchange rates, inhibiting vertical exchanges between the surface mixed layer and the near bed layer, affecting lateral exchanges across fronts and enhancing advection along fronts. Satisfying these two requirements required that the cruise track visited a wide variety of water depths and tidal current strengths (figures 1 and 2).

Four different types of measurement were made: continuous underway; CTD and water bottle profiles at 120 sites (CTD measurements were normally made to within 2 m of the sea bed, in rough weather this increased to *ca.* 5m); moorings were maintained at six sites; cores were obtained at a different six sites (figure 3).

(*b*) *Implementation*

RRS *Challenger*, which has a scientific complement of fourteen, was dedicated to the experiment. Since some of the activities were labour intensive, not all could be conducted on every cruise (table 2) but the different disciplinary groups working alongside each other fostered a community spirit. Neither equipment failure/loss nor bad weather caused serious problems so that over the 18 cruises (220 days of sea time) 82 % of possible CTD profiles were recorded, with, in general, the lower priority sites being missed most frequently. Six cruises were seriously affected by bad weather (total time lost 12 days); the ship's bow thruster needed repairing on cruise 57 and the gyro compasses failed on cruise 66a (time lost 5 days); the CTD was lost but recovered by divers on cruise 72a (time lost 1 day).

(*c*) *Data handling*

At the end of every cruise data were transferred on magnetic tape to the British Oceanographic Data Centre who managed all subsequent data handling (an innovation for them and the individual scientists (Lowry 1993). The data were in several forms: as well as the continuous underway and CTD data, there were water bottle, time series, primary production measurements, plankton species and benthic fluxes data. The majority of the data were on the computer tapes from the ship, but some required laboratory analysis. The data handling and management skills of the data centre were applied to working up the data, to providing access to the data and

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to publishing the data. Working up the data involved close interaction with the scientists for checking and calibration. Access was provided by creating an on-line relational data-base which could be accessed via the JANET Wide Area Network. The data from 38 cruises (including 3800 CTD profiles and 10000 water bottle samples (Blackley *et al.* 1991)) were included in the data-base. The data have been published in the form of a CD-ROM supported by display and retrieval software.

4. August 1988 to October 1989 in context

Was the weather during the cruise period typical? Since weather exhibits considerable small scale variability, both spatially and temporally, patterns are clearer in integrated variables such as river discharge and sea surface temperature. Compared with the average, rainfall was 25% less and coastal sea surface temperatures were 1 °C warmer during the cruise period.

(a) *Wind/storms*

Winds were difficult to set in context. Observations from Spurn Point suggested that it was less windy than normal, particularly from October to December 1988 and from May to September 1989. The stormiest months were December 1988 to February 1989.

(b) *Rainfall and river discharge*

Daily mean river discharges were obtained for the Forth, Tyne, Tees, Humber, Wash, Thames, Rhine, Ems, Weser and Elbe. The U.K. data have been adjusted for inputs below the gauging station to estimate total discharge and were compared with monthly mean flows from 1960 to 1989. Monthly averaged rainfalls were obtained from Seahouses, Bridlington, Cromer and Dover and compared with 1961–1990. The observational period was drier than usual, particularly from November 1988 to February 1989 and from May to October 1989, averaging 25% less overall. Discharges from the Forth were exceptional, exceeding the average by 13%. Principal component analysis of the daily discharges for 1988 and 1989 showed that 57% of the variance was in the first mode, describing uniform behaviour, and 30% of the variance was in the next two modes, which split the rivers into three groups: Forth to Tees, Humber to Thames and Rhine to Elbe.

(c) *Air and sea surface temperature*

Air temperatures obtained from Hull and coastal sea surface temperatures from around the U.K. tabulated in Jones & Jeffs (1991) showed that 1989 was about 1 °C warmer than average. Two stations in Jones & Jeffs (1991) had long records – for Longstones (1924–1989) 1988 was the warmest year and 1989 the second warmest and for Dover (1926–1989) 1989 was the second warmest year. January–March and May–September 1989 were all warmer than average (see also figure 6). The U.K. Meteorological Office's annual summary states 'for Central England 1989 was the warmest year since records began in 1659'.

5. Temperature

Principal component analysis of the surface (0–5 m) temperature showed that the first component contained 98% of the total variance, indicating that the behaviour at each CTD site was the same. The component was dominated by an annual cycle,

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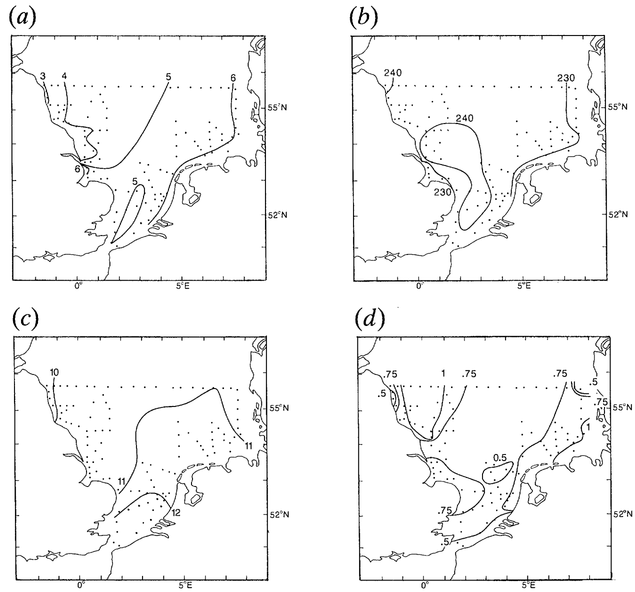

Figure 4. Sea surface temperature. (*a*) amplitude of annual cycle (°C); (*b*) phase of annual cycle (days); (*c*) mean (°C); (*d*) amplitude of semi-annual cycle (°C).

although a smaller semi-annual cycle was present. The spatial distribution of the annual cycle and of the mean (figure 4*a–c*), are similar to previous descriptions, allowing for the anomalous weather, and can mostly be explained by latitude and depth variations (Becker 1981; Bowers & Simpson 1990; Elliott & Clarke 1991). There is, however, a striking contrast between temperatures off the English and continental coasts – the temperature was an average 1.5 °C warmer and the annual cycle's amplitude was twice as large in the German Bight compared with water off England – perhaps caused by the average anti-clockwise circulation around the North Sea. Maximum temperatures in the annual cycle occurred mostly between 18 and 27 August (figure 4*b*). The semi-annual cycle's amplitude ranged from 0.4 to 1.4 °C, generally increasing towards the coast but also large offshore of the northeast English coast (figure 4*d*).

In continental shelf seas tidal mixing largely governs the development of thermal stratification, with summer stratification predicted by the parameter h/u^3 (h is the water depth and u the tidal current strength). South of 54° N (approximately) stratification is absent since depths are shallow and tidal currents strong, whereas to the north, both to the east and west of the Dogger Bank stratification was observed (figure 5). On the Dogger Bank, parts of which are shallower than 20 m, the water column did not stratify. Although the two stratified regions appear separate, they were connected further north, beyond the Dogger Bank. The thermocline depth west of the Dogger Bank was between 30 and 40 m, with the maximum surface to bottom temperature difference (about 8 °C) occurring in August. The water is deep (100 m in places) and the front between stratified and well-mixed water was manifest at the seabed. East of the Dogger Bank the presence of haline stratification in early summer encourages thermal stratification, when heat input is concentrated in the thin fresher surface layer. The spatial extent of thermal stratification was greatest in June and July when, at some sites, the surface to bottom temperature difference was

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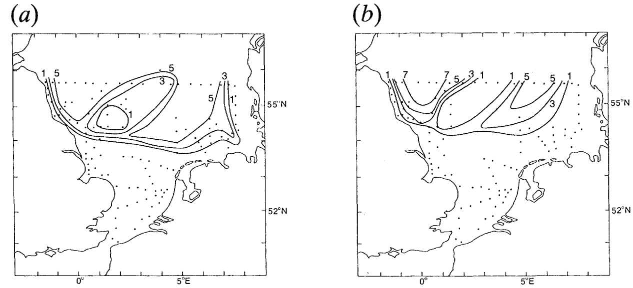

Figure 5. Surface to bottom temperature difference in °C. (*a*) 24 June to 6 July 1989; (*b*) 23 August to 3 September 1989.

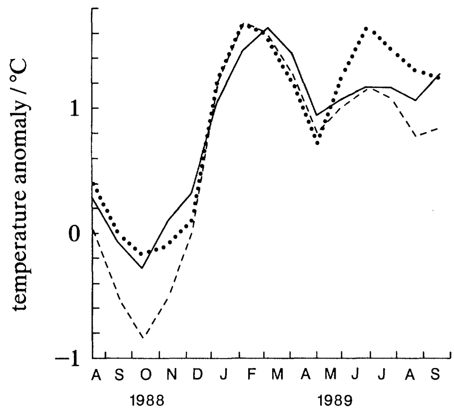

Figure 6. Temperature anomaly averaged over each cruise: surface relative to 1905–1954, solid line, relative to 1968–1985, dashes; and bottom relative to 1968–1985, dots.

also greatest (compare figure 5*a*, *b*). The thermocline depth was between 15 and 30 m. The two stratified regions were also connected to the south of the Dogger Bank by a narrow band about 30 km wide. The magnitude of the stratification here was greatest in June and July (cf. the eastern region), when the maximum surface to bottom temperature difference was 5 °C. In both 1988 and 1989 thermal stratification started towards the end of April. Stratification is destroyed in the autumn by cooling at the sea surface and by enhanced mixing during storms, breaking down in the shallower eastern region (maximum depth about 50 m) earlier than in the western. The maximum in the bottom temperature annual cycle, attained when stratification has completely broken down, occurred in the east at the beginning of October and in the west at the beginning of November.

The response of the southern North Sea to the warmer than average weather conditions (§4*c*) is shown in figure 6. Two climatological atlases of monthly temperatures and salinities in the North Sea have been published by ICES (1962) of surface values measured between 1905 and 1954 and by Damm (1989), which includes depth variations and refers to 1968 to 1985. The temperature anomalies with reference to 1905–1954 (surface) and to 1968–1985 (surface and bottom), show similar patterns; an average to cool autumn in 1988, a warm winter (the anomaly increased by over 1.8 °C in 4 months ending with temperatures 1.6 °C above average) and a warm summer in 1989 (temperatures over 1 °C above average). The same pattern is

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shown by the first component of a principal component analysis, containing 55% of the variance. Figure 6 also shows the semi-annual cycle detected in the observations (figure 4*d*) suggesting that this is not present every year, although it has been observed previously, for instance Dietrich (1953). A feature of the temperature anomaly was the relative warming of bottom water at the edges of the stratified regions, particularly in a narrow band along the English coast north of the Humber. The stratified area was, therefore, slightly reduced and the well-mixed region close to the English coast was marginally wider than usual (here the surface water was on average cooler than normal so that in the summer of 1989 the surface to bottom temperature difference was at times 5 °C less than usual).

6. Salinity

The salinity and temperature distributions contrast. Temperature is dominated by heat exchange at the sea surface and by the seasonal cycle, so that surface spatial gradients are weak. For salinity the main sources occur at the lateral boundaries (exchanges with the oceans and run-off down rivers) in addition to evaporation/precipitation at the surface. The consequence in the southern North Sea is a pronounced spatial variation (figure 7*a*) and a weak average seasonal cycle (figure 8). The saline sources result from exchanges with the English Channel (the saltiest water occurred between Great Yarmouth and the Netherlands where the maximum measured depth-averaged value was 35.36) and with the northern North Sea (depth-averaged values up to 35.09 were measured on the 55° 30′ N line). Fresh water sources were run-off from the continental (much the larger) and the British coasts (table 1). Figure 7*a* is similar to previously published pictures, for instance Schott (1966) and Lee (1980), although saltier close to the continental coast, and shows the importance of advection.

The lack of a clear seasonal cycle (figure 8*a*) contrasts with the situation in the English Channel and Southern Bight where there is a well defined cycle peaking in December, largely attributable to river discharges (Maddock & Pingree 1982). Prandle *et al.* (this symposium) show that the amplitude of the seasonal cycle is heavily damped for flushing times of the order of a year, appropriate to the southern North Sea. The amplitude of the annual cycle was largest (in the range 0.25–1 psu (figure 7*b*)) close to the coast but in general this represented less than 50% of the variance. Five regions were identified: four coastal, associated with rivers (Humber, Rhine, German Bight, Elbe), where the salinity cycle is related to river discharge and one offshore where it is related to the precipitation/evaporation cycle. The offshore region (figure 7*b* hatched) was interesting because although its amplitude was small, mainly in the range 0.1–0.15 psu, this represented 60–90% of the variance. The maximum occurred in the March and April, suggesting that precipitation minus evaporation was at a minimum in winter.

Salinity stratification occurs when mixing (generated by tides or storm waves) is not sufficiently vigorous to overturn the vertical density contrast. The potential for a density contrast is largest near estuaries, especially during winter and spring flood conditions, where, however, shallow water ensures that mixing is also large. The pattern of a haline stratification was, therefore, patchy in space and time and less coherent than that for thermal stratification. Maximum surface to bottom salinity differences up to 4 psu were measured. Along the continental coast there was a contrast between the limited stratification immediately resulting from the discharge from the

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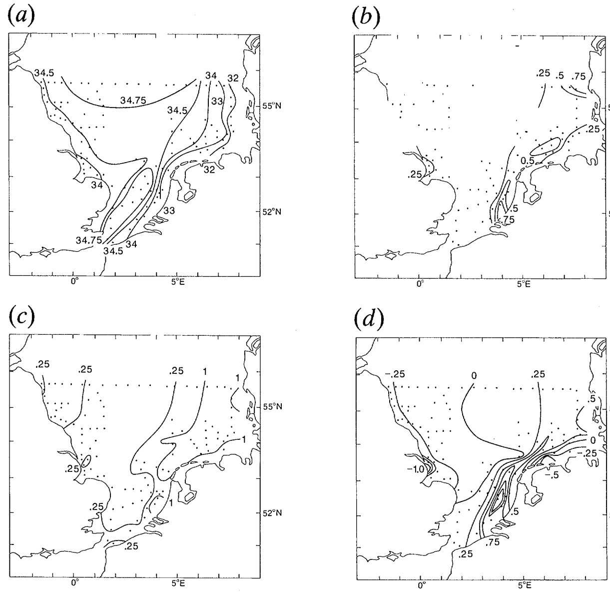

Figure 7. Depth-averaged salinity (*a*) Mean; (*b*) amplitude of annual cycle. The significance of the hatched region is described in the text. (*c*) Maximum surface to bottom salinity difference. (*d*) Mean bottom salinity anomaly.

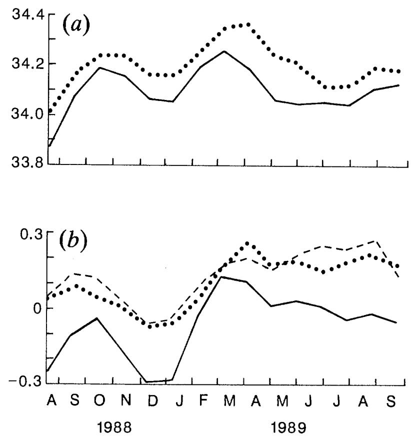

Figure 8. Average salinity cruise by cruise. (*a*) Observed surface (solid line) and bottom (dotted line); (*b*) Anomaly surface (relative to 1905–1954 solid line, relative to 1968–1985 dashed line) and bottom (relative to 1968–1985 dotted line).

Rhine and the more extensive stratification in the German Bight (figure 7*c*) presumably reflecting variations in tidal mixing (figure 2). Haline stratification was most widespread in spring (surface to bottom salinity differences were generally greatest in April–June) when river discharges were greatest and when thermal stratification was developing, leading to reduced mixing between the surface and bed layers. The depths of the thermocline and of the halocline were then generally about 10 m. The inter-relation between thermal and haline stratification can also be seen off the north English coast where there are no large sources of fresh water and yet surface to bottom salinity differences of up to 0.4 psu were measured in the summer.

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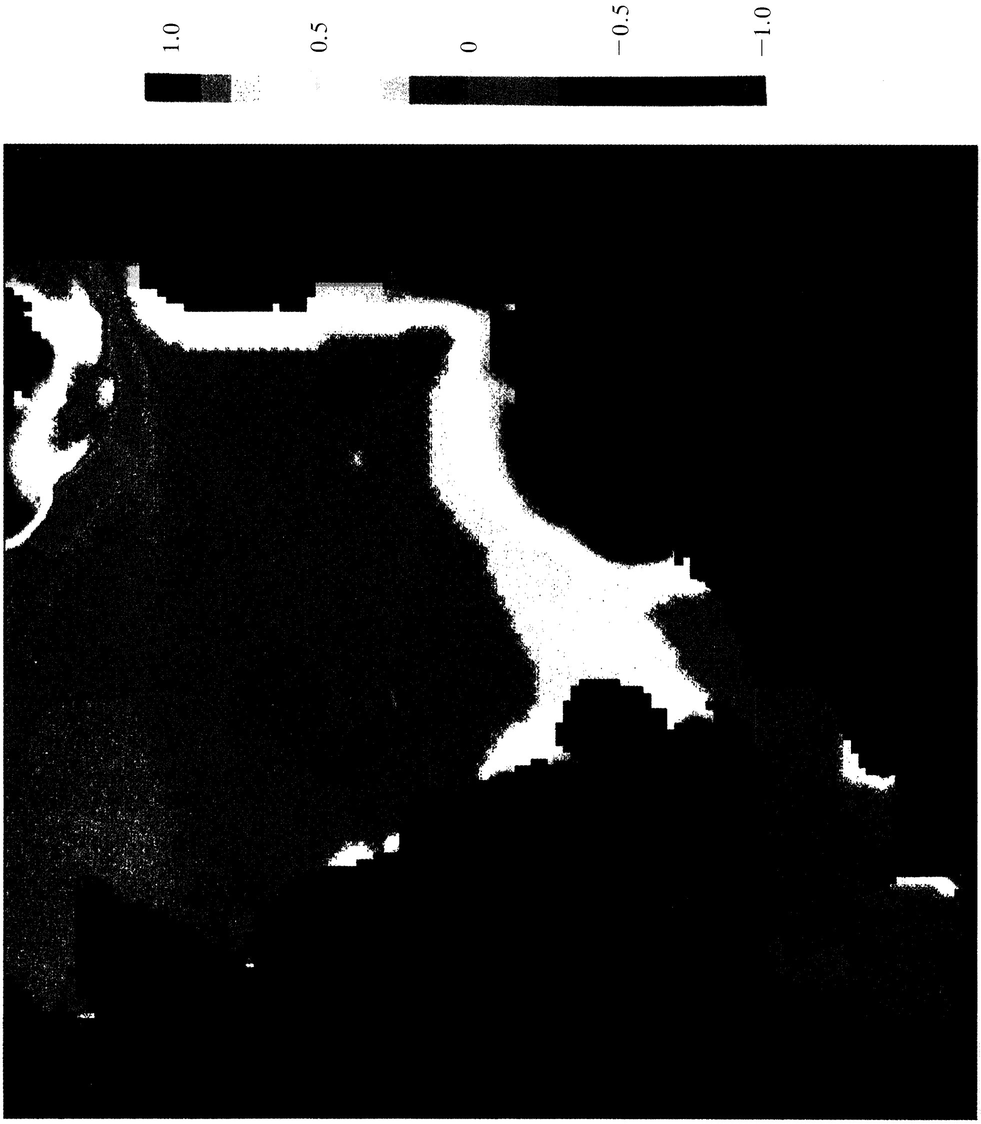

Figure 9. Model prediction of depth-averaged salinity anomaly, see text.

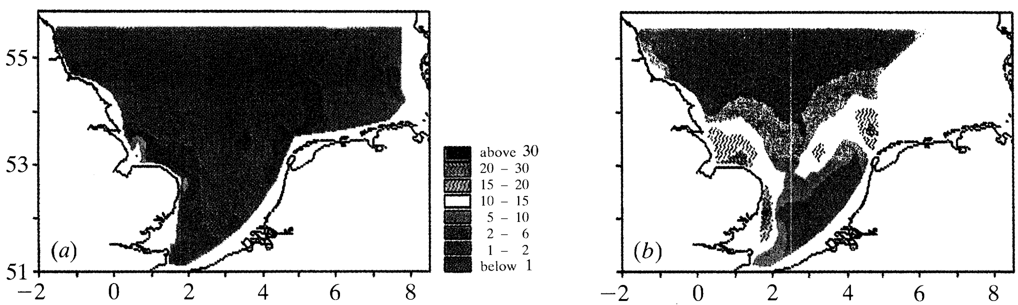

Figure 10. The distribution of total suspended matter (depth-averaged) (mg l^{-1}) for (*a*) Challenger 33, August 1988; (*b*) Challenger 41, December 1988.

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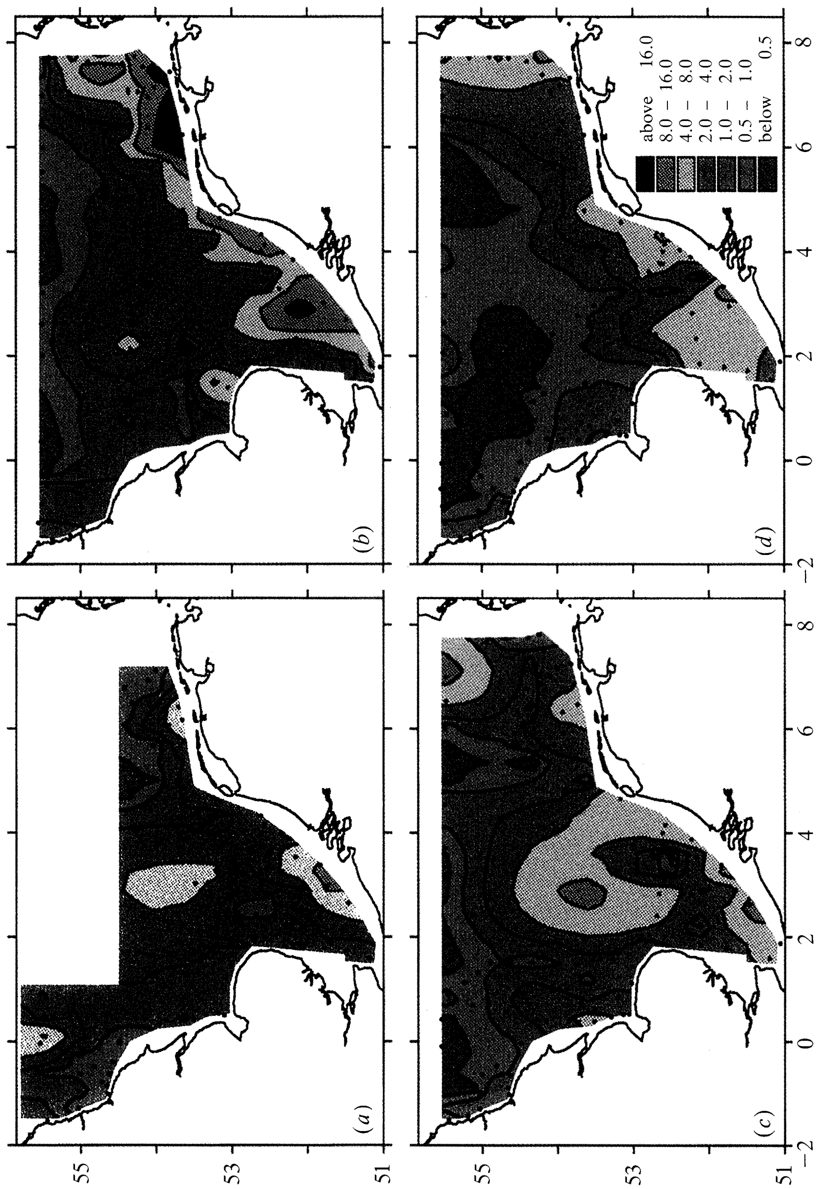

Figure 12. Surface chlorophyll (mg m^{-3}) concentration from March to July 1989; the stations used in generating this contour plot are shown as black dots. (*a*) 29 march to 10 April; (*b*) 27 April to 9 May; (*c*) 26 May to 6 June; (*d*) 24 June to 6 July.

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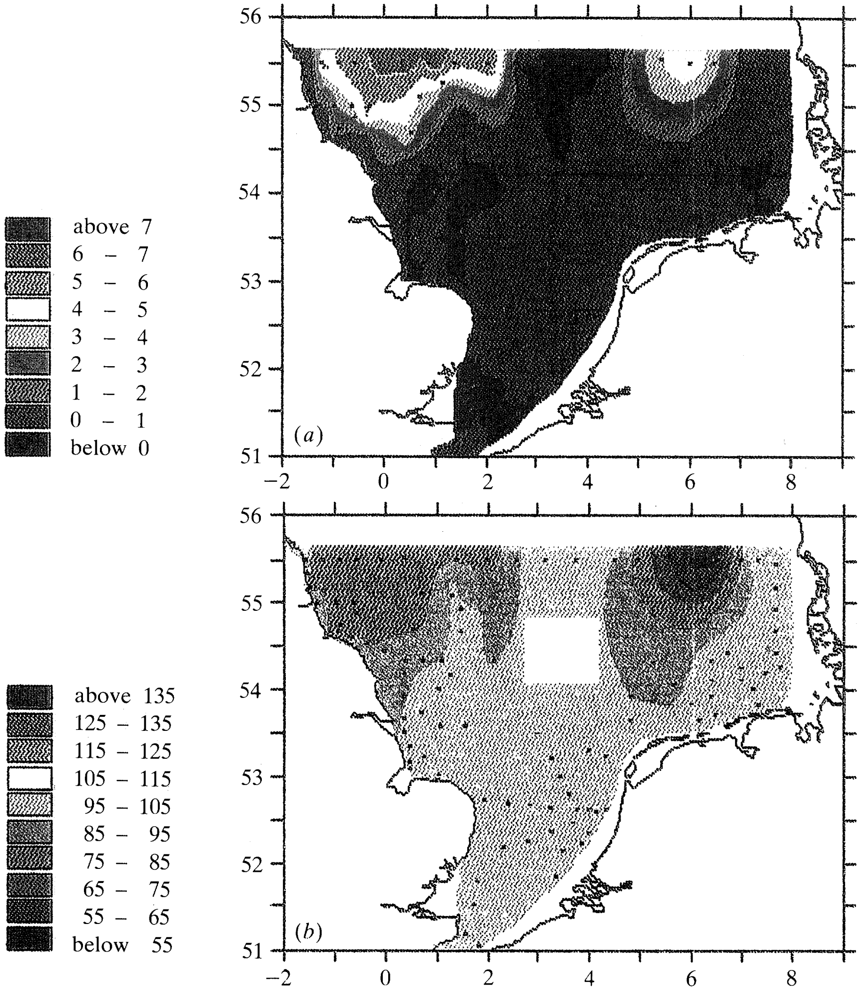

Figure 14. Contour charts of (*a*) the surface to bottom difference in water temperature (°C) in late September, showing the high degree of thermal stratification in the north of the region; (*b*) dissolved oxygen % saturation in the bottom 5m, showing regions of hypoxia where the water column is well stratified.

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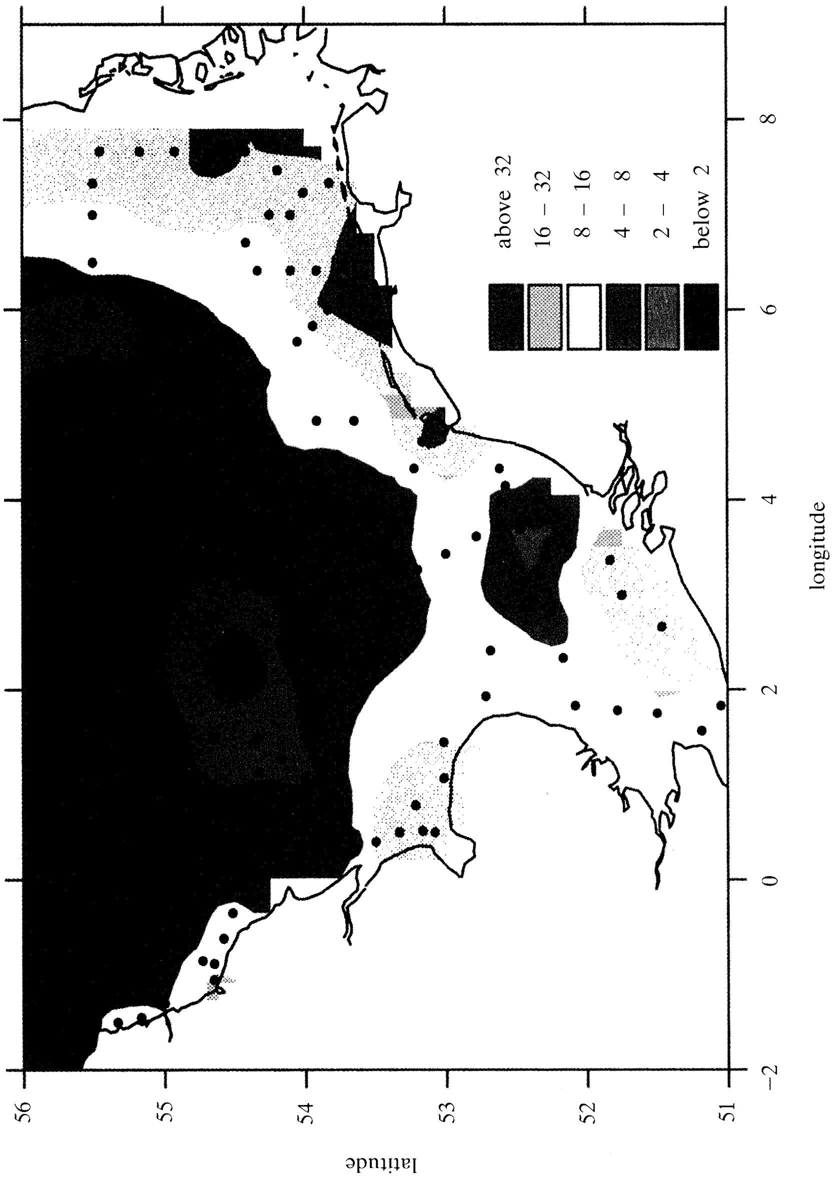

Figure 18. Distribution of dissolved nitrate-N (μM) compiled from measurements made during cruise Challenger 43 in the North Sea in January 1989.

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A salinity model of the North Sea was developed based on an 8 km grid depth-averaged advection/dispersion model. It was driven by tides, monthly mean winds (contributing to advection), river discharges (including a Baltic outflow) and by evaporation/precipitation. The latter was the most difficult to estimate and was found to have a significant impact away from the coast. The model reproduced the mean salinity field well, although predicting too high salinity close to the coast. This was insensitive to river discharge. The model was then run with observed winds, river discharges and reduced precipitation (in accordance with shore based observation (§4) and the difference calculated (figure 9, plate 1)). As expected there was an increase in salinity of at least 1 psu near all the major estuaries in response to the reduced fresh water input. The observed anomaly for bottom salinities, based on 1968–1985 averages, is shown in figure 7*d*. The first component of a principal component analysis showed a similar picture and contained 70% of the variance. Model and observations are in good agreement along the majority of the continental coasts, with observed differences up to 1.4 psu, and in the centre (little change) but are in conflict along the German and English coasts, where the observed anomaly, particularly off the Humber, up to 1 psu fresher, is hard to understand. The observed anomaly could be in error because of difficulties in determining the mean close to the coast through lack of observations, interpolation/extrapolation, significant gradients over the averaging area but the error is unlikely to be systematic. More likely, in view of its importance to the salinity distribution, is that the circulation has changed either in intensity or spatially. The time variation of the salinity anomaly (figure 8*b*) was very similar to the time variation of the observed salinity (figure 8*a*) emphasizing that there was no coherent seasonal salinity signal.

7. Suspended sediment and organic matter distributions

(*a*) *Measurement methods*

Vertical profiles were recorded with a 25 cm path length Sea-Tech transmissometer mounted on the CTD. During the cruises, calibration was carried out to correct for change in the light source intensity, and zero offsets were measured. The data were calibrated for suspended sediment distribution against filtered water samples obtained at the surface, mid-depth and bottom; the organic content was determined by weight loss on ignition.

(*b*) *Horizontal distributions*

The distributions are discussed in detail by Dyer & Moffat (1992). Generally the highest concentrations occurred in the western coastal waters of the Southern Bight and periodically off the European coastline and in the German Bight. However, the spatial coverage of the latter two areas was limited, restricting the results to lower concentrations than those determined by Eisma & Kalf (1979) and Visser *et al.* (1991). The lowest concentrations (less than 2 mg dm^{-3}) occurred particularly in the northern and central southern parts of the area. Consequently there was a gradient of total suspended matter (TSM) away from the coasts.

There were, therefore, three regions: (i) a region of high TSM off the East Anglia and Lincolnshire coasts; (ii) a region of low TSM north of about 54° N; and (iii) the water of the European coast and German Bight.

The region of high turbidity off the East Anglian and Lincolnshire coasts was present on all cruises. It is associated with sources of suspended sediment resulting

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from river discharge and coast erosion, and possibly also from sea bed erosion. During August 1988 (figure 10, plate 1†) TSM concentrations were in excess of 15 mg dm^{-3}, in the area of the Wash, at a time when concentrations were generally below 2 mg dm^{-3}. During autumn and winter, TSM concentrations increased to greater than 20 mg dm^{-3}, the highest concentrations being in the Humber–Wash area, and off Suffolk and Essex. At the same time a plume developed extending east-northeast from the East Anglian coast. It attained maximum prominence between November 1988 and January 1989, with values of 10 mg dm^{-3} from the Southern Bight towards the German Bight. This high turbidity zone remained well developed until the late spring, after which concentrations diminished to summer levels comparable with 1988. During the late summer and early autumn of 1989 the intensification of the plume recommenced. The turbid plume has been previously observed by Joseph (1957), Lee & Folkard (1969), McCave (1972) and Eisma (1987). The highest turbidity zone was generally of low organic content.

The region of relatively high turbidity was flanked to north and sometimes to the east by water of relatively low turbidity with TSM concentrations of 1–2 mg dm^{-3}, sustained by the inflow of low turbidity waters from the North Atlantic. During August and September 1988 this region extended from north to south through the Southern Bight. During late autumn and winter, as the plume developed, an area of isolated low turbidity occurred in the centre of the Southern Bight. In late spring 1989 the two low concentration zones became reconnected. The boundary between the northern low turbidity region and the plume coincided with that of the thermal front observed on satellite imagery and predicted by mathematical models. However, the plume is present in winter, whereas stratification occurs in summer. The organic content in the northern low turbidity water was high, averaging over 70% during spring and summer, but falling to less than 50% during the winter. Nevertheless, the absolute organic weights were comparatively low because the TSM concentrations were less than about 2 mg dm^{-3}.

The high turbidity region in the continental coastal waters and in the German Bight contained high concentrations of suspended matter during the winter, similar to the East Anglian region. Localized areas of intensification (concentrations in excess of 10 mg dm^{-3}) occurred in the German Bight in November 1988 and January and February 1989. There was a widespread increase in TSM concentrations during April and May 1989, coinciding with the spring phytoplankton bloom.

Concentrations of TSM tended to be marginally higher at the bottom than at the surface, most noticeably during the winter months of 1988/89, during April–May, and June–July 1989. An exception to this was the region of relatively higher concentrations in the surface waters near the Dogger Bank during March 1989.

(c) *Interannual variation*

The three spring TSM distributions in 1988–1990 showed similar patterns with high concentrations along the English coast, especially in the Humber–Wash area. In the Humber plume surface concentrations were higher than at the bed. High concentrations were also associated with the Rhine and the Ems discharges. The three autumn distributions also showed comparable patterns. Again, the Humber plume had higher surface than near bottom concentrations.

† The range 2–6 in this figure should read 2–5.

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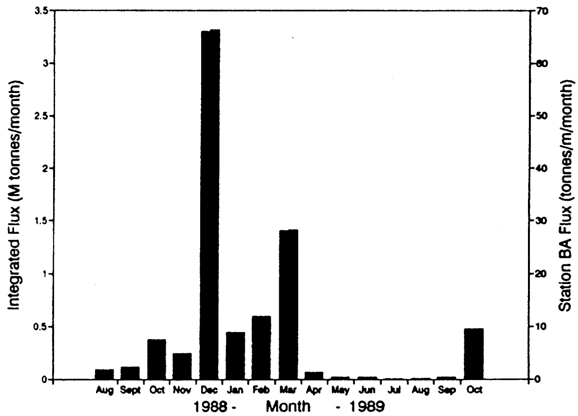

Figure 11. Integrated total suspended matter fluxes in the plume from East Anglia.

(*d*) *Suspended sediment fluxes*

Several stations were sited within the plume and AY, AZ, BA, BB lay on a cross section normal to its axis. At these stations the depth-mean residual velocities calculated from the POL storm surge model averaged over the period of each cruise were multiplied by the depth-mean TSM concentrations to obtain fluxes. To calculate the total flux within the plume, the fluxes were integrated across the plume, assuming that the plume could be represented by a normal distribution of width 80 km. The maximum flux, 3.3×10^6 tonnes month^{-1}, occurred in December 1988, with a further peak, 1.4×10^6 tonnes month^{-1}, in March 1989 (figure 11). The integrated flux for a year was 6.6 million tonnes, of which 71% occurred in two months when the winds were particularly strong from the southwest. Assuming an average organic content of 25% gives a flux of 4 million tonnes of inorganic material per year. Thus the plume provides a very significant transport path for sediment from the English coast towards the German Bight. The implications of this transport on the sediment budget of the coastal zone of eastern England are discussed by Dyer & Moffat (1993).

8. Seasonal changes in chlorophyll distribution

Chlorophyll fluorescence was measured on the CTD and continuously from surface water. Water bottle samples were routinely taken from three depths, filtered through glass fibre filters and frozen for chlorophyll analysis.

In August 1988, chlorophyll concentrations were less than 2 mg m^{-3} over most of the southern North Sea. In early September, the region of low (less than 1 mg m^{-3}) chlorophyll water extended through most of the western part of the region, with significantly higher concentrations (greater than 4 mg m^{-3}) in the German Bight and in Dutch coastal waters. Between December and February large areas of the region had concentrations less than 0.5 mg m^{-3} with concentrations greater than 2 mg m^{-3} at only a few isolated stations.

By the end of March 1989, the biomass of phytoplankton had significantly increased, with some chlorophyll concentrations exceeding 8 mg m^{-3} (figure 12, plate 2). By the end of April, very high phytoplankton biomass was found in the coastal waters of Belgium, the Netherlands and into the German Bight; concentrations were

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greater than 8 mg m^{-3} over most of the eastern North Sea, with 56 mg m^{-3} measured at one station. The very high chlorophyll concentrations were associated with extensive blooms of *Phaeocystis pouchetii*, sampled on two survey and one 'process' cruises, between the end of March and middle of May. By the end of May, the extremely high chlorophyll concentrations had declined, although the biomass remained high along the European coast. In late June and early July, chlorophyll concentrations were low over most of the central region and values of less than 0.5 mg m^{-3} were present in the stratified waters north of the Flamborough front; high values were again found in the mixed waters of the southern North Sea and in the German Bight. The last three cruises showed a return to the conditions which were found in August 1988 with high phytoplankton biomass in the German Bight in early August which decreased during August and September; the reproducibility in the seasonality suggests that the period sampled was typical.

9. Dissolved oxygen

Dissolved oxygen was monitored semi-continuously on all cruises except one (February 1989) using two pulsed dissolved oxygen sensors, located in a flow-through cell supplied with surface sea water. The electrodes were calibrated before most cruises and checked at least three time each day by analysing surface water samples for dissolved oxygen using the Winkler method (Purdie *et al.* 1993). Depth profiles of dissolved oxygen were obtained from a CTD mounted oxygen electrode, calibrated from surface oxygen data and from a limited number of oxygen bottle samples.

From late November to mid March, the whole area showed an oxygen saturation of 100% (i.e. ± 5%) indicating low biological activity throughout the water column, as would be expected from the low chlorophyll concentrations (figure 12, plate 2). In late March, the dissolved oxygen saturation increased in surface waters in the Southern Bight, to a maximum of 155% (figure 13), associated with higher rates of phytoplankton production. Oxygen data in late April confirmed that the algal bloom had developed in the coastal and offshore waters of the German Bight and off the Danish coast with some increased productivity also occurring in the Humber and northeast coast. By late May, oxygen saturation in surface waters had decreased along the European coasts but supersaturated waters occurred offshore in the middle of the Southern Bight and in the Humber plume. In late June, oxygen saturation had decreased to near equilibrium levels again, with limited regions of oversaturated water occurring only near to the coast in the Southern Bight. During early August, chlorophyll concentrations were again high (up to 16 mg m^{-3}) in the German Bight and oxygen oversaturated up to 125% was observed. These blooms persisted in coastal regions of the German Bight through early October.

Vertical profiles of oxygen concentration revealed the development of extensive regions of hypoxic waters below the seasonal thermocline in the offshore German Bight both in late summer 1988 and 1989. Reduced oxygen levels also formed below the thermocline to the west of the Dogger Bank across to the northeast English coast (figure 14, plate 3). The minimum oxygen level measured was 45%, in late September, in the waters above the sediment in the northeast of the region. This level of hypoxia may have caused some stress to the animals living in and on the bottom sediments in the region. Other measurements across the 55° 30′ N transect in September 1989 revealed low oxygen waters below the thermocline in both basins on either side of the Dogger Bank; undersaturated waters reached the surface along the

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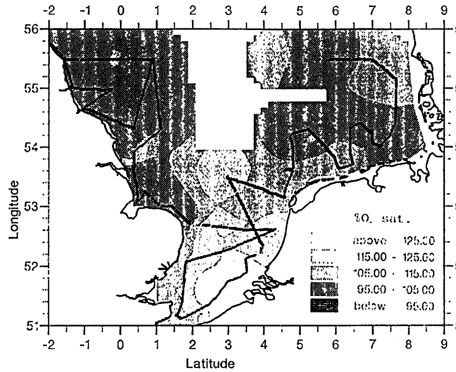

Figure 13. Dissolved oxygen concentrations measured in late March and early April in the surface waters of the southern North Sea. The cruise track is shown.

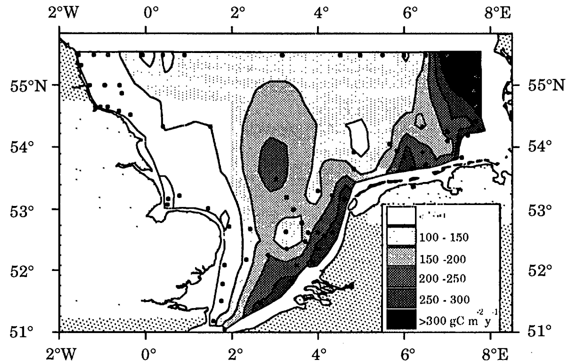

Figure 15. Annual primary productivity (gC m^{-2} a^{-1}) of the southern North Sea. The estimates obtained on each cruise were summed to give an annual estimate for each station and the data were contoured using UNIRAS software. If any station was not visited on a cruise, linear interpolation was used to estimate the value of one missing data point; if data were missing from two consecutive cruises, that station was not used in this analysis; the stations used in generating this contour plot are shown (●).

northeast coast during this month. Interestingly, hypoxia only occurred in the deep waters of the well stratified region and not in the well mixed regions of the highest phytoplankton biomass, where organic matter concentrations might be high.

10. Phytoplankton production

Primary production was measured on one station each day on each cruise using a simplified, on-deck incubation procedure (Joint & Pomroy 1992). Figure 15 shows a contour plot of the estimated annual phytoplankton productivity of the southern North Sea. The Southern and German Bights were significantly more productive than the central region. These are the regions where blooms of *Phaeocystis pouchetti* occur frequently in late spring (Bätje & Michaelis 1986; Lancelot & Mathot 1987). In contrast, the lowest rates of primary productivity and phytoplankton biomass were found in the English coastal region.

Monthly productivity (figure 16) has been estimated for regions based on the ICES flushing-time boxes (ICES 1983) and the data highlight large differences between the areas. The values of production are 79 gC m^{-2} a^{-1} for box 3″ (English coastal); 199 gC m^{-2} a^{-1} for box 4 (Southern Bight); 261 gC m^{-2} a^{-1} for box 5 (German

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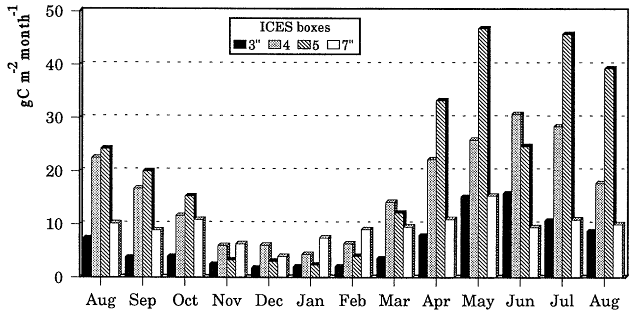

Figure 16. Estimates of primary production for each of the ICES flushing-time boxes in the southern North Sea; ICES box 3″ is the English coastal region, box 4 is the area including the Southern Bight, box 5 is the German Bight and box 7″ is the central area, including the Dogger Bank.

Bight); 119 gC m^{-2} a^{-1} for box 7″ (central area, including the Dogger Bank). The central region has high rates of winter photosynthesis which are half the summer values. The English coastal region has similar productivity to the central region in the spring, but significantly lower rates in the autumn and winter. The high productivity of the Southern and German Bights was due not only to the *Phaeocystis* blooms in the spring, when this one species can comprise up to 96% of the total phytoplankton biomass (Zevenboom *et al.* 1991) but also to high phytoplankton activity throughout the summer. The eastern North Sea was more than twice as productive as the centre but the English coastal region was significantly less so. Because of the comprehensive temporal and spatial nature of the North Sea surveys, these data represent the best estimate to date of the phytoplankton biomass and primary productivity of the North Sea.

11. Nutrient distributions and budget

Nitrogen, phosphorus and silicon were measured onboard ship in their dissolved forms as ammonia, nitrate, nitrite, phosphate and silicate in subsamples taken from all water bottle samples, using continuous flow colorimetric methods (Hydes 1984). The nutrient data were interpolated onto a 12 km square grid to calculate tonnages present in solution. The budgets were drawn up for an area of the southern North Sea constrained by the positions of the sampling positions. The area of the North Sea interpolated in our model was 12.8% smaller than the total area of the sea between 51° and 56° N, and 5.0% smaller in terms of volume.

The growth of 3.3 kg of plankton typically requires 95 g phosphate, 832 g nitrate, 1.6 kg water, 4.6 kg carbon dioxide and 310 kJ of light; for some groups, e.g. diatoms, silicon is also required. Phytoplankton growth is limited when any one of these elements or light is in short supply. At the temperature latitude of the North Sea, the amount of light energy available in late autumn and winter limits plankton growth. The North Sea Project provided sufficient data to quantify the fluxes of nutrients, plus plankton and oxygen changes involved in this cycle. Distribution varies according to nutrient concentration, river run-off and with changes in circulation of the sea with the prevailing weather; subsequent *in situ* biological and benthic processes and exchange with the atmosphere and Atlantic Ocean determine the observed concentrations (Postma 1978; Brockman *et al.* 1988; Gerlach 1988), with highest concentrations occurring in winter, when phytoplankton production is

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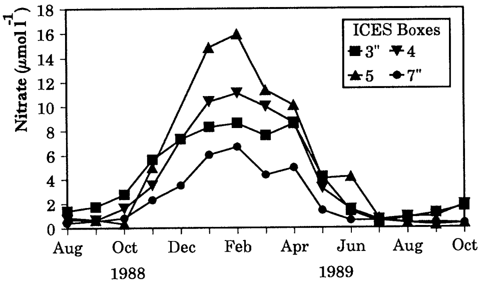

Figure 17. Calculations of the mean concentrations of dissolved nitrate present in each of the ICES boxes during the period of the North Sea Survey.

Table 3. *Comparison of nutrient input tonnages from different sources to the southern North Sea between November and January*

	nitrate/tonnes N	change N (%)	silicon/tonnes
total tonnage in January	959658	—	989979
change November to January	525672	—	241457
river input	81680	15.5	—[d]
atmospheric input[a]	38000	—	—[e]
cross boundary[b]	11500	2.2	—[d]
cross boundary[c]	245000	—	—
sediment exchange	10541	2.0	272978

[a] Atmospheric input taken as one sixth the annual input estimated for the North Sea Project area (Rendell *et al.* 1993).
[b] Calculations based on POL model.
[c] Estimates in Nelisson & Stefels (1988) based on ICES (1983).
[d] Silicon values are assumed to be proportional to nitrate.
[e] Atmospheric inputs of silicon are negligible.

at a minimum and lowest in the summer following the spring maximum in productivity. These features are clearly seen in the data; figure 17 shows the mean nitrate concentration estimated for each of the ICES boxes throughout the survey period.

The January nitrate distribution, when phytoplankton uptake is at a minimum, is shown in figure 18, plate 4. The change in total nutrient concentration between November and January has been used to estimate the relative contributions of regeneration and allochthonous inputs to the winter nutrient maxima (table 3). The estimates of river inputs are based on average flow and concentration data. Sediment and atmospheric inputs are estimated from data collected during the North Sea Project. The relative size of the sedimentary fluxes of nitrate and silicate is consistent with observations of the change in relative concentrations in waters isolated below the seasonal thermocline. Two estimates of nutrient input by the flow of water through the Dover Strait and across the northern boundary of the survey area at 56° N are given. The larger one is the estimate given by Nelissen & Stefels (1988) which simply multiplies the winter concentration of nutrients by the estimated water flux across these boundaries (ICES 1983). This is probably an overestimate as it assumes winter maximum concentrations of nitrate are present in the Channel year round and does not take account of export in the Jutland current. The smaller estimate is based on calculations of water movement during the survey period using the POL storm surge model.

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For silicon, regeneration from the sediment can explain the increase in concentrations between November and January. However, for nitrate, even when the larger estimate of cross boundary input is taken, there is still considerable shortfall. A simple calculation suggests that the missing nitrate may be supplied from the nitrogen stored in organic detritus suspended in the water column. A change in nitrate load of 5×10^5 tonnes in solution is equivalent to 2.8×10^6 tonnes of particulate carbon in suspension (assuming a Redfield ratio applied to the particulate material composition). This in turn is equivalent to 0.3 mg C dm^{-3}, a figure which is consistent with the observed changes between November and January in concentrations of chlorophyll and particulate carbon in suspended sediment filtered from the water. This suggests that the bulk of the change in dissolved nitrate between November and January is supplied by regeneration from organic material. Therefore, it appears that the total winter loading of nutrients in the southern North Sea is dominated by regeneration rather than the supply of 'new' nutrients from the rivers, atmosphere or ocean. This implies that productivity of the North Sea may be primarily influenced by the flushing characteristics, which retains nutrients within the region, rather than by supply from the rivers, as had been previously postulated.

12. Conclusions

(*a*) A comprehensive coherent inter-disciplinary data set of measurements throughout the water column was obtained in the southern North Sea from August 1988 to October 1989. The data set will provide a critical test for transport and water quality models.

(*b*) The observational period was warmer (*ca.* 1 °C), had less rain (by 25%) and less windy than normal.

(*c*) The temperature signal was dominated by the seasonal cycle: 95% of the surface temperature's variances was in a 12 month cycle and 2% in a 6 month cycle. The presence of thermal stratification was influenced by haline stratification, as well as by tidal and wind mixing.

(*d*) Spatial variations dominated the salinity distribution: the seasonal cycle was small. The effect of reduced rainfall was apparent in saltier water along the continental coast, but not along the English coast.

(*e*) Distributions of suspended sediment showed highest concentrations in a coastal zone related to river discharge and wave action. During windy periods a plume developed from East Anglia to the German Bight in which in excess of 6 million tonnes per year of suspended particulate matter was transported.

(*f*) Chlorophyll distribution charts have demonstrated large differences in phytoplankton abundance, with significantly higher chlorophyll concentrations occurring in the eastern North Sea; this is the region where blooms of *Phaeocystis* occur in the spring.

(*g*) In late summer, there are areas of low oxygen concentration in the near bottom waters on either side of the Dogger Bank; these are largely a consequence of the hydrodynamics; there was no evidence of oxygen depletion in those regions where phytoplankton blooms are a problem.

(*h*) The project resulted in the most comprehensive estimate to date of phytoplankton production in the southern North Sea. The annual productivity in the Southern Bight and German Bight is 200–260 g C m^{-2} a^{-1}, 3–4 times that in the western region, off the UK coast.

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(*i*) Nutrient budgets suggest that nutrient supply in the region in winter is dominated by regeneration, rather than as a result of agrochemical inputs from rivers.

The work would not have been possible without the enthusiastic participation of many staff at the Dunstaffnage Marine Laboratory, Institute of Oceanographic Sciences Deacon Laboratory, Plymouth Marine Laboratory, University of Plymouth, Proudman Oceanographic Laboratory, Southampton University, University College North Wales, University of East Anglia, of the scientific staff at the Research Vessel Services and of the officers and crew of RRS *Challenger*. The work was funded by NERC, by NERC Special Topic Grants and by contracts from MAFF and DOE.

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Discussion

W. van Leussen (*Tidal Water Division, The Netherlands*). (*a*) The fine-grained sediment fluxes were calculated from a multiplication of measured suspended sediment concentrations and residual currents from numerical models. However, fine-grained sediment transport under tidal action, especially in shallow (coastal) waters, is principally a step-wise process with cycles of sedimentation and resuspension. What is the effect of not including the step-wise transport on the accuracy of your flux predictions?

(*b*) You showed large fine sediment fluxes from the East Coast of U.K. to the German Bight. Do these fluxes reach the German Bight? Remote sensing observations give the impression that these fluxes often result in deposition in the frontal area in the central North Sea, leading to biologically rich areas with a relatively high percentage of fine sediment in the bottom (e.g. Frisian Front area). Also; please indicate the relative importance of these fluxes with respect to the fine sediment fluxes to the German Bight, which are flowing in the relatively narrow zone along the Dutch coast.

K. R. Dyer. (*a*) The concept is that there is a continuous sequence of movement from west to east across the North Sea which occurs on an intermittent basis depending on wind strength and direction. The fine grained sediment fluxes were

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calculated for a cross section of the plume and are, in effect, the transport during one step of the process. The period of measurement was less windy than normal so that the fluxes are likely to be an under-estimate.

(*b*) Deposition of the fine material does seem to occur north of the Dutch and German coasts, in the German Bight and in the Norwegian Trough. This has been documented in several publications by Eisma and co-workers. Since our measurements were not close to the Dutch coast direct comparison of the fluxes is not possible. However, deposition in the Waddensee is of the order of 2 million tonnes per year, which must be largely derived from the coastal source.

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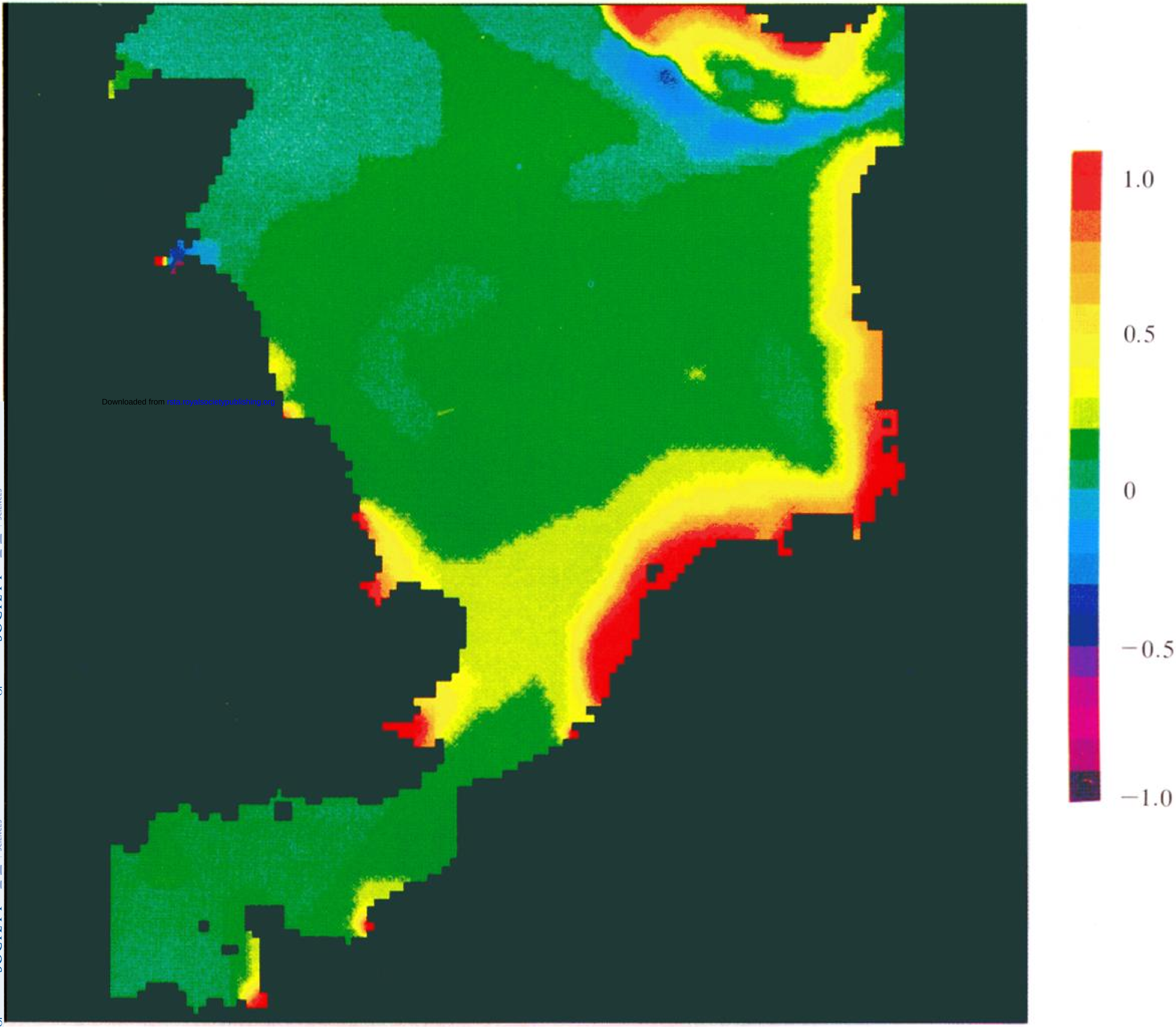

Figure 9. Model prediction of depth-averaged salinity anomaly, see text.

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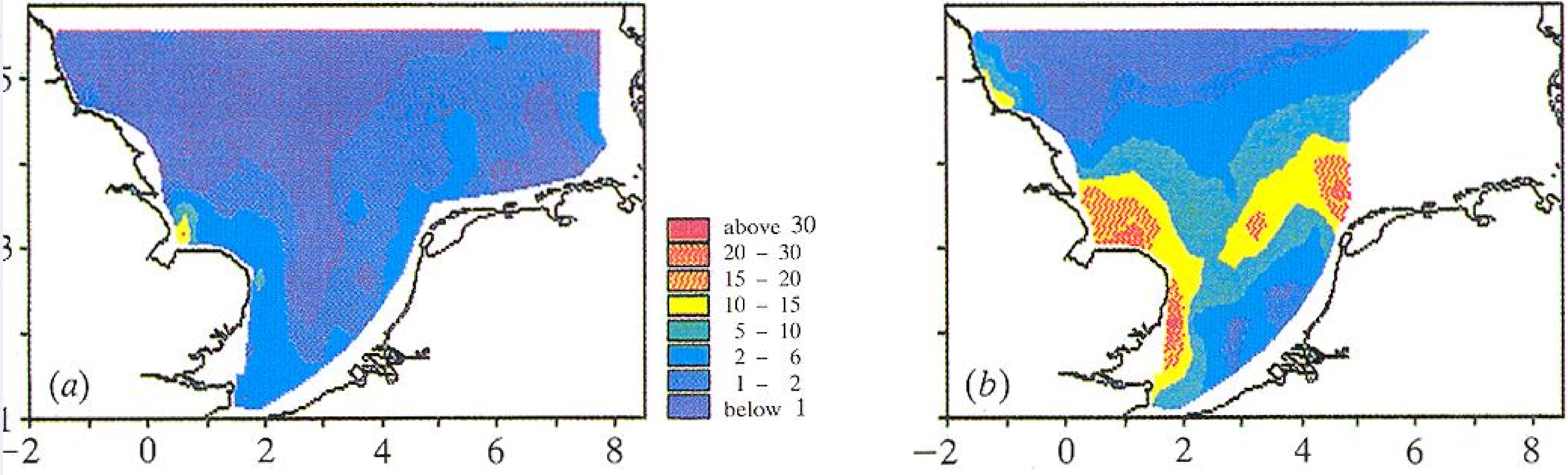

Figure 10. The distribution of total suspended matter (depth-averaged) (mg l^{-1}) for (*a*) Challenger 33, August 1988; (*b*) Challenger 41, December 1988.

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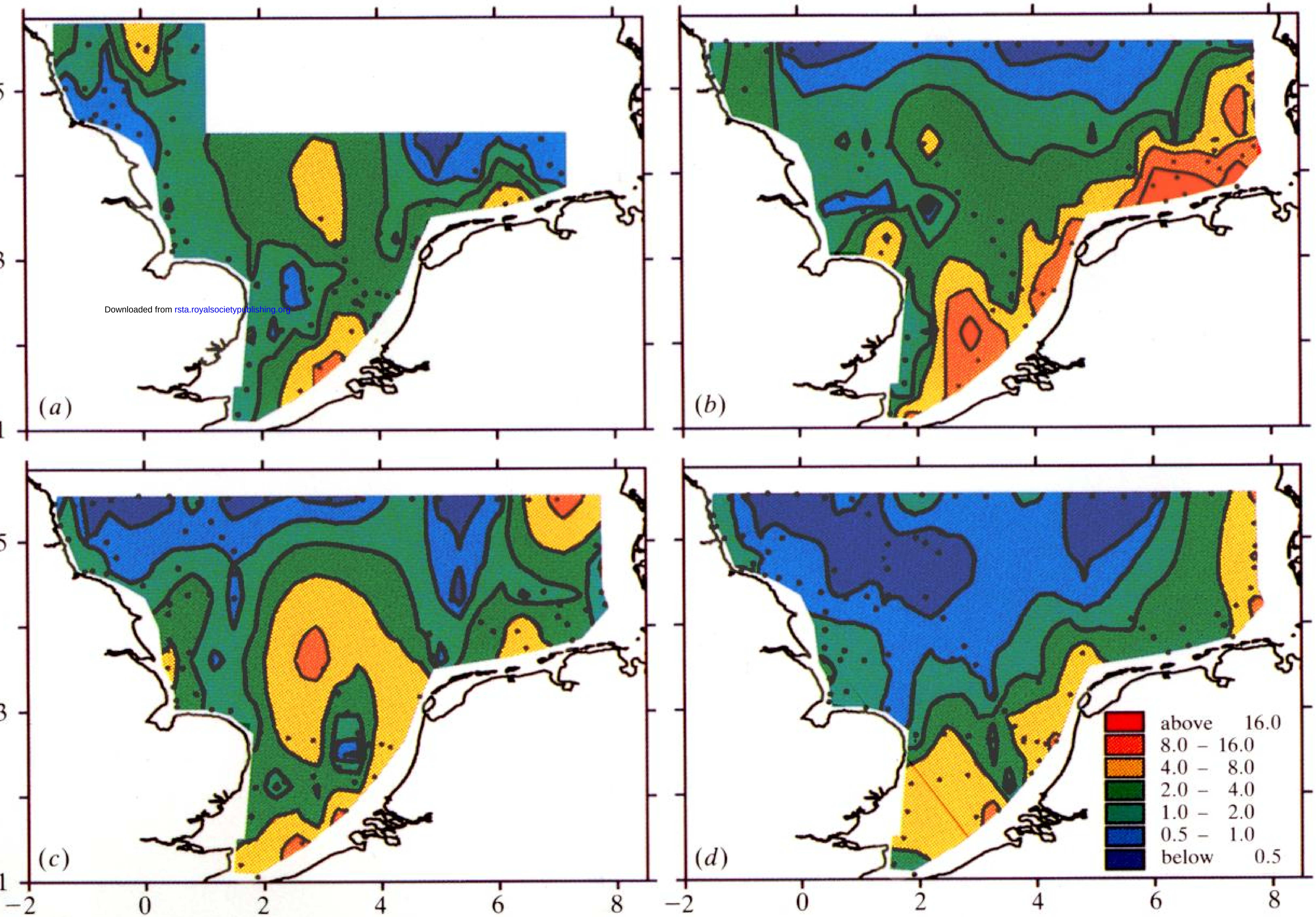

Figure 12. Surface chlorophyll (mg m^{-3}) concentration from March to July 1989; the stations used in generating this contour plot are shown as black dots. (*a*) 29 march to 10 April; (*b*) 27 April to 9 May; (*c*) 26 May to 6 June; (*d*) 24 June to 6 July.

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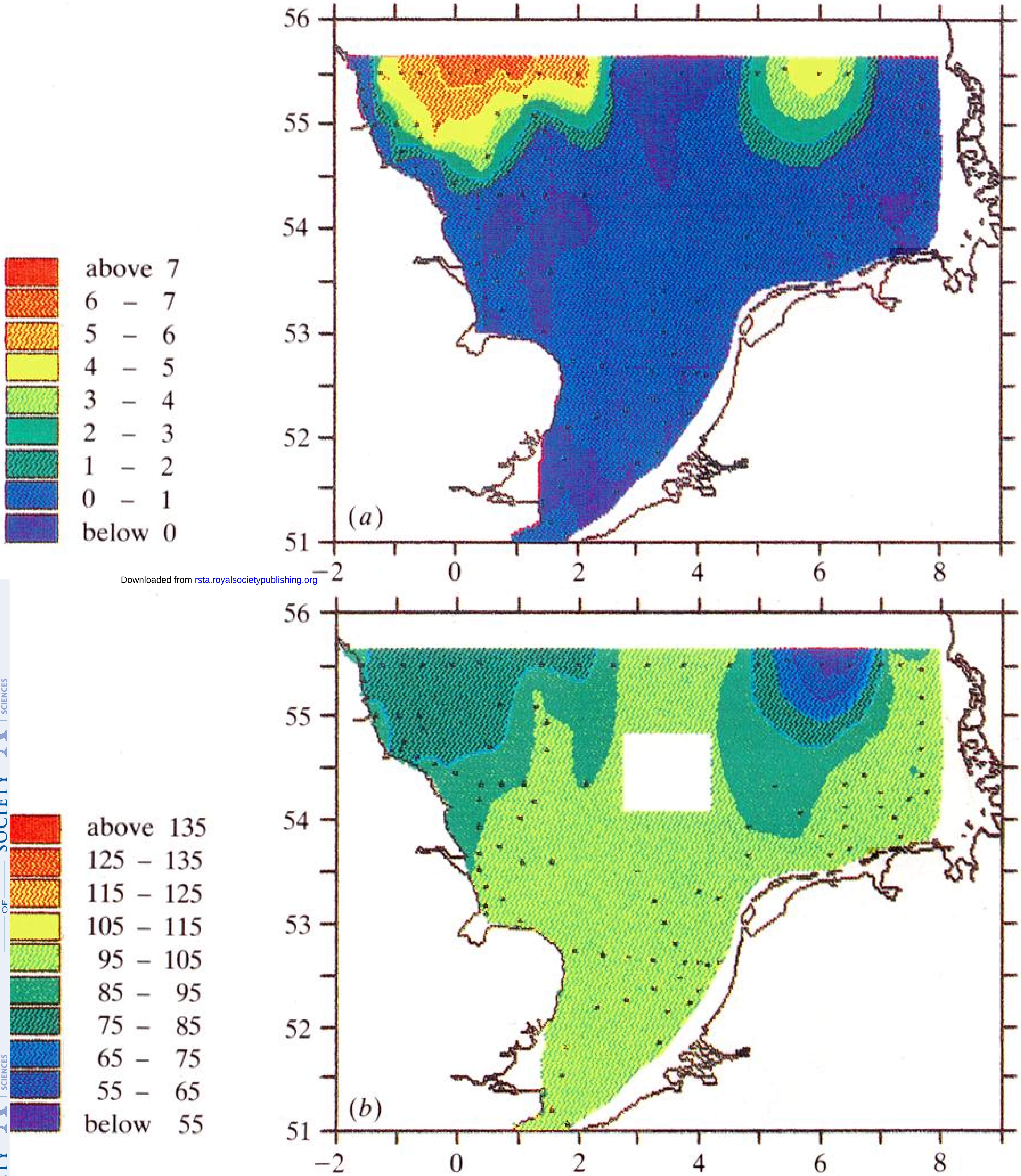

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Figure 14. Contour charts of (*a*) the surface to bottom difference in water temperature (°C) in late September, showing the high degree of thermal stratification in the north of the region; (*b*) dissolved oxygen % saturation in the bottom 5m, showing regions of hypoxia where the water column is well stratified.

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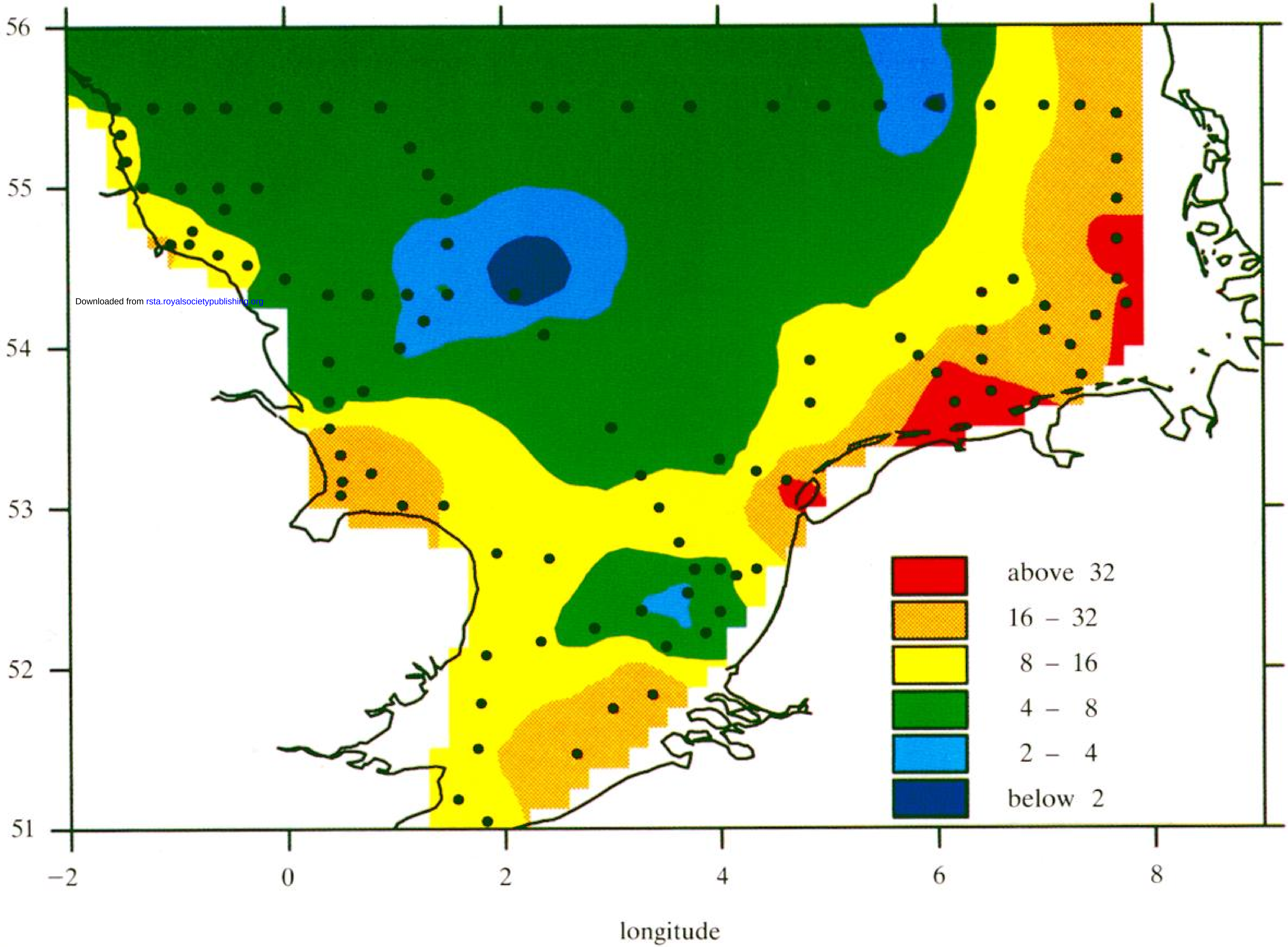

Figure 18. Distribution of dissolved nitrate-N (μM) compiled from measurements made during cruise Challenger 43 in the North Sea in January 1989.

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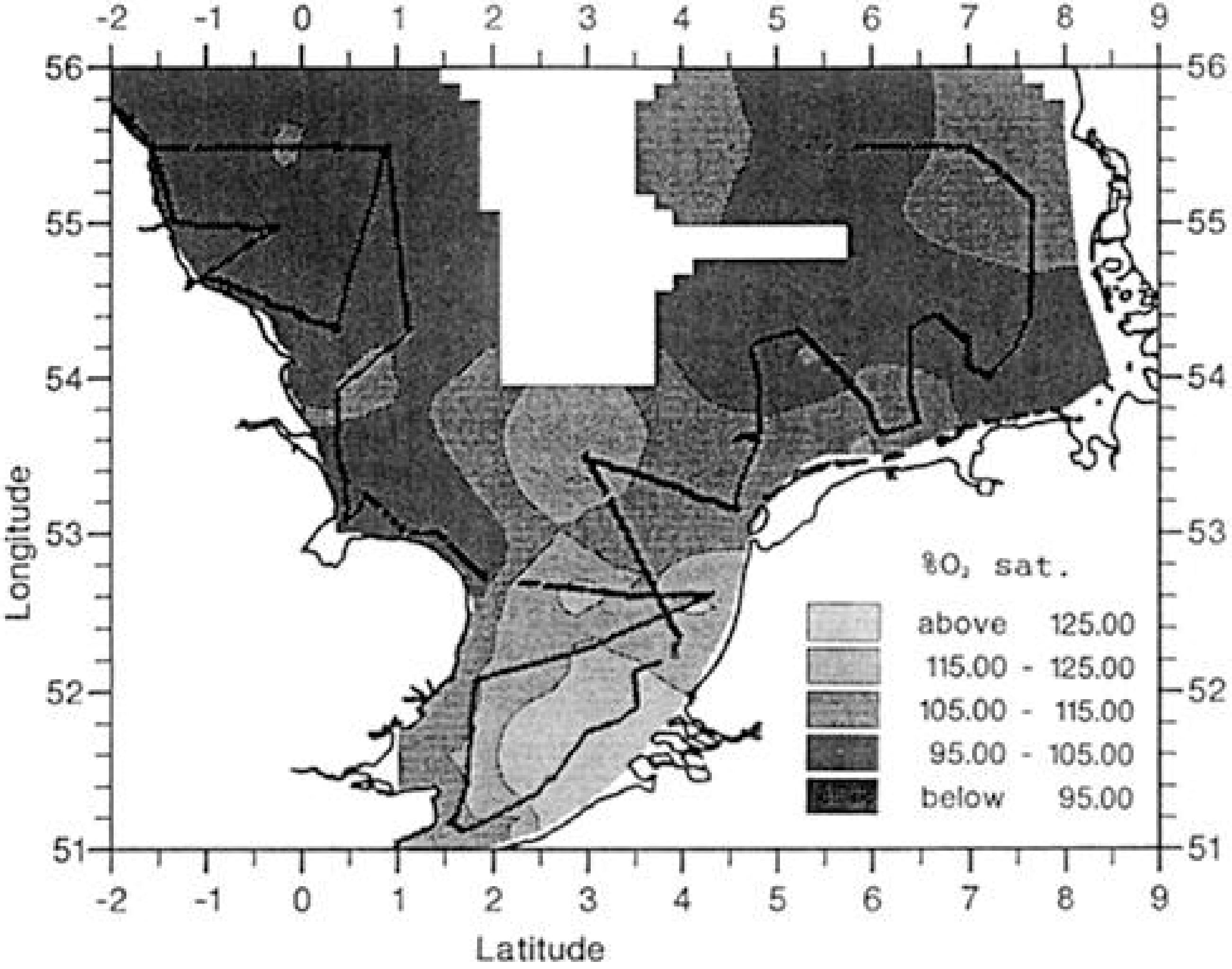

igure 13. Dissolved oxygen concentrations measured in late March and early April in the surface waters of the southern North Sea. The cruise track is shown.

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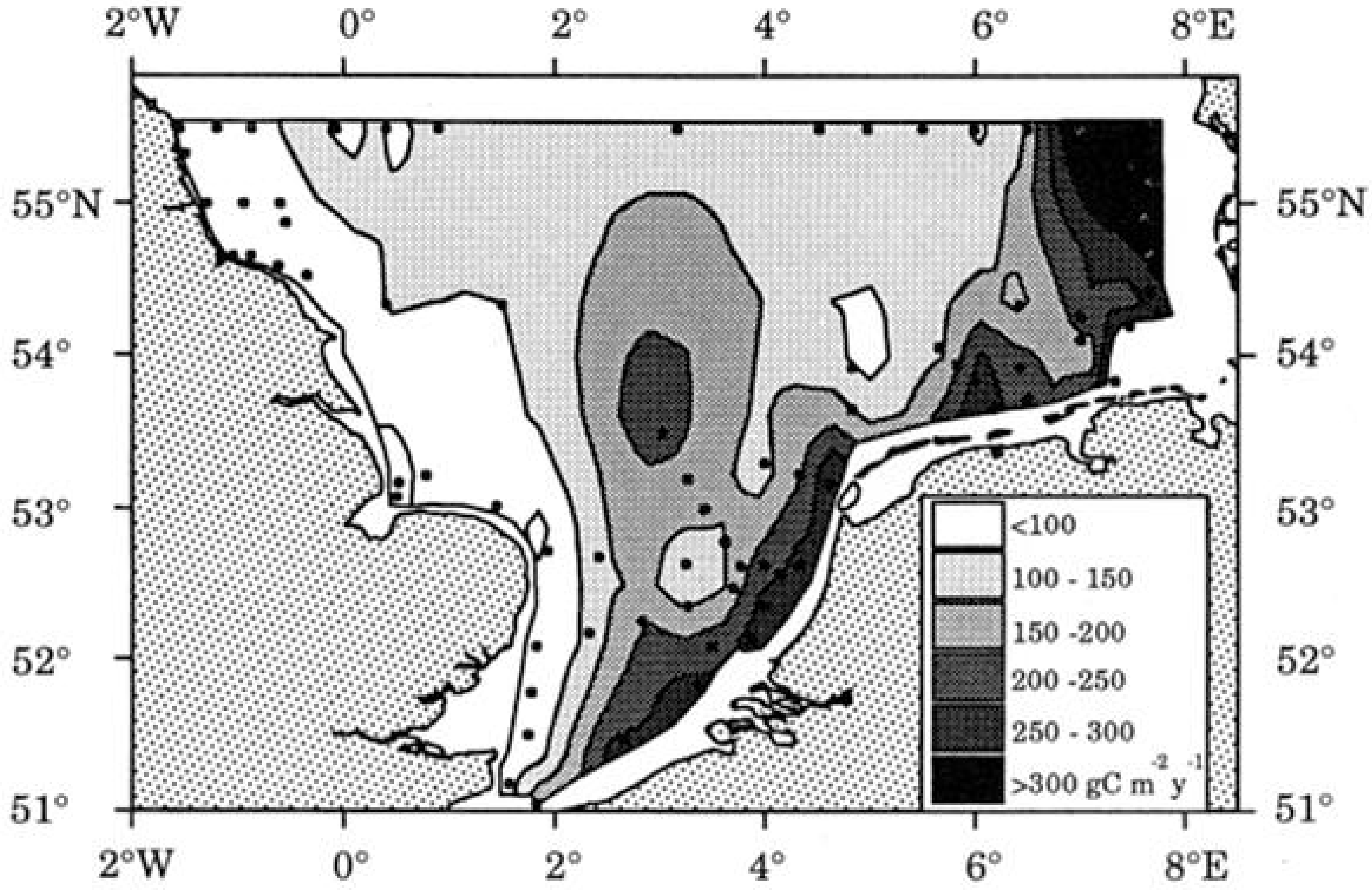

igure 15. Annual primary productivity (gC m^{-2} a^{-1}) of the southern North Sea. The estimates btained on each cruise were summed to give an annual estimate for each station and the data were ontoured using UNIRAS software. If any station was not visited on a cruise, linear interpolation 'as used to estimate the value of one missing data point; if data were missing from two consecutive ruises, that station was not used in this analysis; the stations used in generating this contour plot re shown (●).

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