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Suspended Particulate Matter in the North Sea: Field Observations and Model Simulations [and Discussion]

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Suspended particulate matter in the North Sea: field observations and model simulations

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[Plate 1]

A major part of land ocean interaction in the coastal zone consists of the transport of suspended particulate matter (SPM). Its mass balance is determined by the input from rivers, atmosphere and adjacent seas, by advective and diffusive fluxes, and by deposition and resuspension at the sea bottom.

For the North Sea, a three-dimensional lagrangian model has been developed which includes all these components. It is driven by the actual atmospheric forcing, the tides and the baroclinic currents.

Model results of SPM spreading and deposition for specific years are presented and compared with *in situ* observations and satellite images.

1. Introduction

The global change of our environment is a consequence of changing fluxes of momentum, energy and matter between land and ocean. An essential part of these exchange processes is formed by the transport of suspended particulate matter (SPM), especially on the continental shelf. Ultimately, the global cycling of carbon and nutrients as well as contaminants, i.e. the development of climate and marine ecosystems, is controlled by SPM fluxes.

Substances entering a shelf sea via rivers or atmosphere (from land) or by currents (from the deep ocean) may be dissolved or attached to SPM. The ratio of these two phases depends on the substance and also on the hydrographical environment. The present paper considers the carbon, nutrients, organic (e.g. PCB) and inorganic (e.g. lead) contaminants that are cycled in association with SPM. Dissolved and suspended substances, i.e. passive and active tracers, are transported significantly different. It is not possible to deduce the spreading of SPM simply from the motion of the carrying water. The SPM dynamics must be investigated separately.

Here SPM means the mass of fine solid material in the water with a grain diameter less than 20 μm and greater than 0.4 μm. SPM in the North Sea consists of microflocs of mineral particles and organic matter. In winter, the mass-proportion of organic matter (mainly detritus) in SPM is about 20% (Schröder 1988). According to Eisma & Kalf (1987*b*) in January 1980 about 85% of the mineral mass was smaller than 20 μm, peaking between 2 and 5 μm.

As usual in oceanography information on fluxes of SPM and its budget can be obtained from field measurements and model simulations. Due to the considerable logistical effort required only a few comprehensive data sets from ship cruises are available (see, for example, Eisma 1981; Eisma & Kalf 1987*a*, *b*). In recent times new data has been gained from satellite based remote sensing (see Doerffer *et al.* 1993);

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this information, however, is constrained to the very surface of the sea. In any case, as a consequence of the high stochastic variability of the North Sea, the available field data represents only the respective observation period. One final aim in SPM research is therefore the development of a verified three-dimensional transport model which interprets the existing data and allows for reliable scenario calculations.

2. Field observation of SPM

The most complete data sets on the regional distribution of SPM concentration and bottom sediments based on ship cruises are elaborated by Eisma & Kalf (1987*a*, *b*) and Eisma (1981). They have been used for the validation of the transport model described below. North Sea measurements are described in Howarth *et al.* (this symposium).

In the frame of the German ZISCH project (Zirkulation und Schadstoffumsatz in der Nordsee) quasi-synoptic recordings of SPM concentrations have been carried out on a star-shaped grid in summer 1986 and winter 1987 (Brockmann *et al.* 1993). These are compared in the following with remote sensing data and results from model simulations.

For the determination of water constituents, data of the Coastal Zone Color Scanner (CZCS, satellite NIMBUS 7) have been analysed. The relevant method, an inverse modelling procedure, has been recently developed by Fischer & Doerffer (1987) and Doerffer (1990).

Three different scenes from the ZISCH–STAR summer 1986 period have been selected: May 1, May 22 and June 16. For all the three images the concentration maps of phytoplankton chlorophyll, SPM, gelbstoff and aerosol path radiance have been derived. The SPM concentrations are shown in figure 1†, plate 1, together with the ZISCH–STAR data. The horizontal distribution shows similar general patterns in both data sets: there are large patches in the shallow southern North Sea with concentrations of more than 10 mg dm^{-3} and low concentrations (less than 1 mg dm^{-3}) in the deep northern part. Because of the high spatial resolution, the satellite images show many more details, particularly in the central part of the North Sea. Significant temporal changes can also be seen. The ship data, in contrast to this, represent a mixture of spatial interpolation and time averaging over six weeks.

3. Numerical modelling of SPM transport

The following investigations are based essentially on an SPM transport model developed by W. Puls in the frame of the ZISCH project (Puls & Sündermann 1990; Pohlmann & Puls 1993).

(*a*) *Model foundations*

The movement of SPM is simulated by a tracer method. 40000 to 60000 tracer particles represent the SPM in the North Sea. Each particle is loaded with a certain mass of suspended matter. New particles enter the model area from land (rivers, cliff erosion, dumping), from the atmosphere, from adjacent seas and by bottom erosion. Particles can lose their load partly or totally when deposition of SPM occurs. Finally,

† In figures 1 and 3 the white dots in (*d*) mark the observation sites.

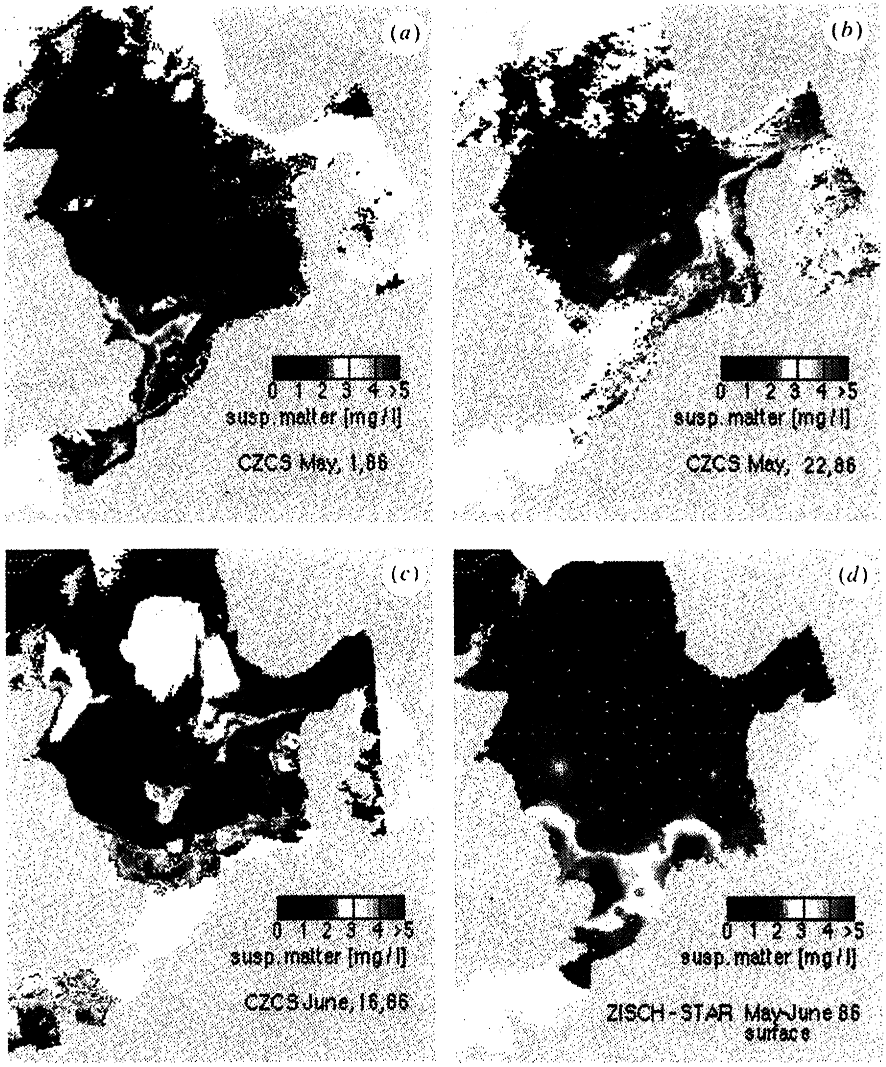

Figure 1. Suspended matter concentrations (mg l^{-1}) in the North Sea during the ZISCH-STAR period May / June 1986. Comparison of three CZCS images (*a*) 1 May, (*b*) 22 May, (*c*) 16 June with ship surface data (*d*).

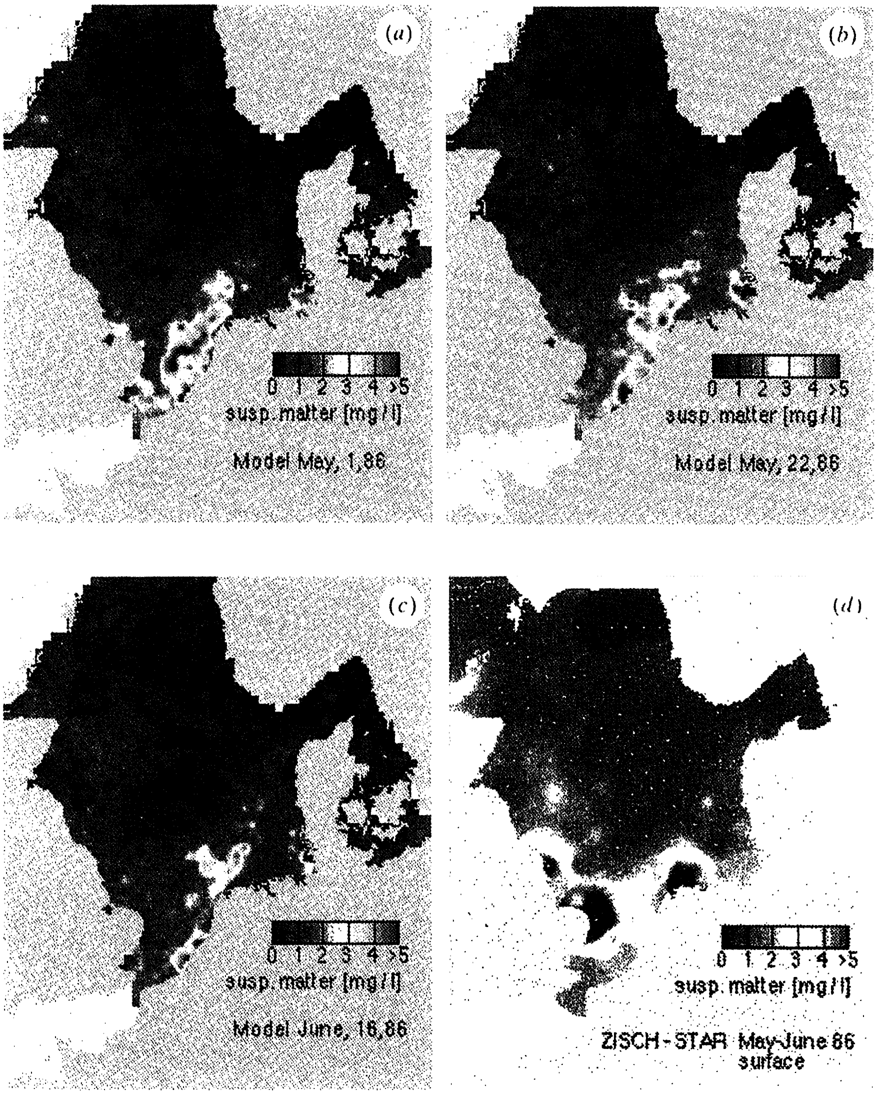

Figure 3. Suspended matter concentrations (mg l^{-1}) in the North Sea during the ZISCH-STAR period May / June 1986. Comparison of three calculated distributions (*a*) 1 May, (*b*) 22 May, (*c*) 16 June with ship surface data (*d*).

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particles can leave the North Sea by being transported over a seaward boundary. The time step for the transport computations is 40 min.

The SPM concentration in a grid box is simply determined by summing up the mass of all particles within the box and dividing by the box volume.

Within the model area, particles migrate through the three-dimensional grid by

(i) the 3D field of residual currents (wind- and density-driven) obtained from a previous run of the 'Hamburg' shelf model with horizontal resolution of 20 km and 12 vertical levels (Hainbucher *et al.* 1987);

(ii) the 3D currents of the M_2- and S_2-tide provided every 40 minutes from a previous run;

(iii) horizontal and vertical diffusion realized by a random walk of particles (Maier-Reimer & Sündermann 1982);

(iv) settling with velocities w_s depending on the specific SPM (*ca.* 0.1–30 m day^{-1}).

Deposition and erosion of SPM depend on the bed shear velocity v_* calculated from

(i) the current of the circulation model taking into account the bed roughness and the water viscosity,

(ii) sea and swell waves previously computed by a separate wave model.

The formulation of deposition and erosion is based on the combined action of currents and waves (Grant & Madsen 1979).

The bed is vertically divided into 43 computational layers and mud and non-mud sediments are distinguished.

Deposition happens by

(i) settling (if v_* is less than a critical velocity for deposition, which depends on w_s and the type of SPM (typical value: 0.01 m s^{-1}), and

(ii) filtration,

depending on SPM concentration near bottom and abundance of benthic organisms.

Deposition means incorporation of particles into the bottom, not only reaching the bottom by sinking.

Erosion takes place by

(i) bottom drag (if v_* is greater than a critical velocity for erosion, and it is different for a mud and non-mud bed (typical value: 0.03 m s^{-1}), and

(ii) trawling

this process is not yet realized in the model.

Finally, bioturbation of sediment by benthic organisms is included in the model.

The boundary conditions are given by the following net fluxes of SPM (million tons per year) (see Pohlmann & Puls 1993).

input		output	
Scotland/Shetland	12	Shetland/Norway	5
Channel	14		
Baltic	1		
rivers, cliffs	3		

Figure 2*b* shows the calculated bed shear velocity at the Forschungsplattform Nordsee, 30 km northwest of Helgoland for a one month period in November/December 1986. The combined action of tides and wind during four wind events exceeds a critical velocity for erosion of 0.028 m s^{-1}. In the upper panel the calculated SPM concentration is shown, compared with ZISCH measurements at the same time. Both are in fair agreement considering the coarse resolution of the computational grid.

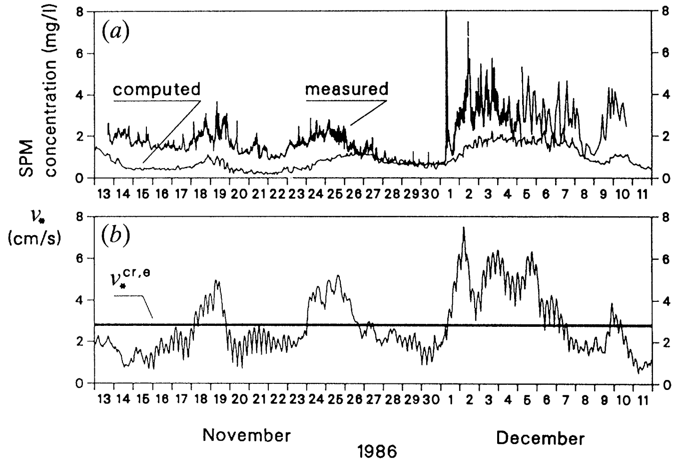

Figure 2. Three time series at the German Research platform (FPN), 30 km northwest of Helgoland, for the period 13 November 1986 to 11 December 1986. The total water depth is 28 m, sample depth 15 m. (*a*) Computed and measured SPM concentrations. (*b*) Computed bed shear velocity v_*, compared with a critical velocity for erosion $v_*^{cr,e}$.

(*b*) *Model verification*

The model has been extensively validated against available ship data (Puls & Sündermann 1990; Pohlmann & Puls 1993). Here a comparison is demonstrated with the ZISCH–STAR data of summer 1986 for coincident satellite images: May 1 and 22 and June 16 (see figure 3, plate 1).

Both, the satellite and the model data show SPM concentrations less than 1 mg dm^{-3} in the northern North Sea and more than 1 mg dm^{-3} in the southern part. For the model data this separation is quasi time-invariant. The separation line is between Humber and North Jutland. The most striking feature in the southern North Sea is the plume of high turbidity that extends north-eastward from East Anglia. This plume coincides approximately with the axis of minimal salinity (Lee 1980) indicating a high admixture of coastal water. Howarth *et al.* (this symposium) report an annual flux within this plume of 6.6 million tons of SPM eastward across the southern North Sea.

The mean concentration of all three simulated cases is about 0.8 mg dm^{-3} which is half the value of the ZISCH–STAR data and the CZCS image of May 22. Reasons for that are that the model does not include phytoplankton and that the resolution is too coarse to represent the coastal areas sufficiently.

(*c*) *Model scenarios*

It is the advantage of a numerical model that it can be used after verification for multiple scenario simulations, such as sensitivity and parameter studies or prognostic runs. This has been done for many applications, e.g. the seasonal behaviour of SPM transport or the tracing of SPM from a particular source through the North Sea.

Figure 4 shows as an example the calculated deposition patterns of SPM originating from the erosion of cliffs and the input of rivers along the English coast. The material mainly accumulates in the central southern North Sea and in the Norwegian Trench. The calculated sedimentation rate of about 0.5 cm a^{-1} in the Oyster ground area agrees with observations of Nedwell *et al.* (this symposium).

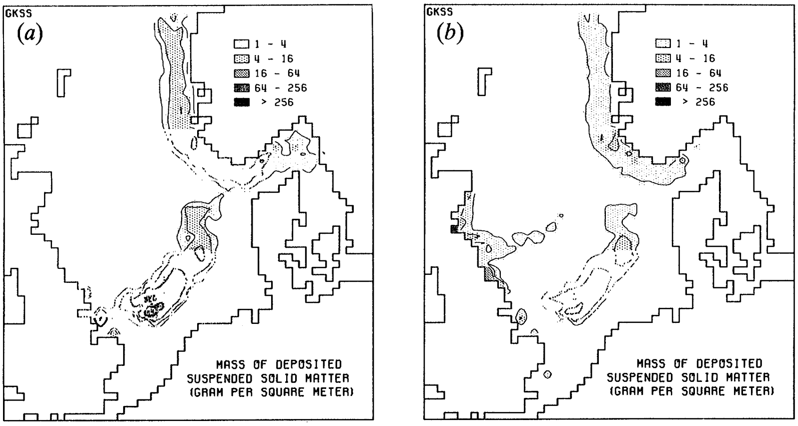

Figure 4. Distribution of mass of deposited SPM in the North Sea, calculated for July 31, 1979. (*a*) Sources English cliffs. (*b*) Sources English rivers.

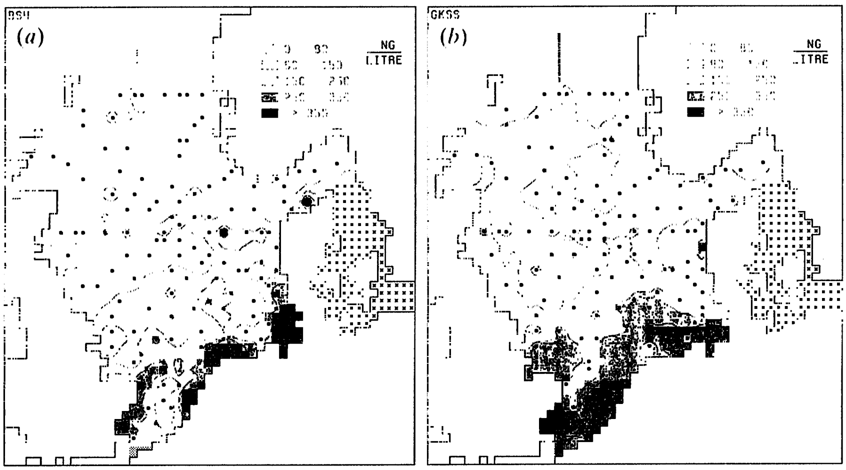

Figure 5. Distribution of total lead concentration in the North Sea during the ZISCH–STAR period January/February/March 1987. (*a*) Measured at 10 m depth. (*b*) Calculated for layer 0–20 m. The dots mark the observation sites.

Similar computations have been carried out for other sources including the Atlantic Ocean. They have in common that most of the SPM is finally deposited in the Norwegian Trench. The maximum sedimentation rate calculated by the model is 0.64 cm a^{-1} in the Skagerrak, which is in good agreement with measurements. (Eisma 1981).

On the basis of these investigations a model has recently been developed simulating the transport of lead in the North Sea (Sündermann & Puls 1990; Puls *et al.* 1993). This is especially relevant because lead is highly particle-reactive and is expected to be transported largely via mobile sediment. Figure 5 shows the calculated lead concentration in the North Sea in winter 1987 compared with the ZISCH–STAR data. As expected the most affected area is the southern North Sea. The agreement between both results is surprisingly good.

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4. Conclusions

Ultimately, the investigations aim at an adequate description of SPM dynamics, the interplay of atmospheric forcing, hydrographical field, and the spreading and deposition of matter by means of a three-dimensional prognostic model. This must be based on reliable sets of observed data; these are needed for the actual forcing at the boundaries, for continuous validation, for an appropriate formulation of processes. Field observations, however, from ships as well as the satellites, involve large logistical efforts and provide only very limited information in the space-time domain. Furthermore, only models have predictive capability which is generally required by the great challenges of modern marine research (e.g. global change).

The demonstrated good agreement and integration of ship measurements, remote sensing and model simulations is very promising. It could be achieved only by a very realistic and comprehensive modelling of the processes involved, with respect to both the analysis of satellite images and numerical simulations.

We learn from the model that the SPM dynamics of the North Sea is dominated by the input from the Atlantic Ocean, which leads to an annual net gain of 26 million tons. Compared with this, the terrestrial supply of four million tons per year by rivers, the atmosphere and dumping is relatively small. But the latter is heavily loaded with contaminants and therefore of essential importance for the marine ecosystem.

Because of topographic and hydrodynamic effects the terrestrial inputs (from single sources) are very differently distributed. From the English coast, SPM is transported to the southern central North Sea and finally to the Skagerrak. The Dutch–German inflows are moved northwards along the Danish coast. The bulk of the released SPM (together with the attached contaminants) is deposited in the Norwegian Trench. Its sediments (accretion rate about 10 cm per century) reflect the history of European industrialization (Puls & Sündermann 1990).

The models must be improved mainly in two directions. On one side, a finer space-time resolution should allow a better representation of important mesoscale regions (like the Wadden Sea). On the other side, further essential processes should be considered, such as flocculation, phytoplankton dynamics and bioturbation.

I am indebted to Roland Doerffer and Walter Puls from the GKSS Research Center Geesthacht for providing material and helpful comments. The research was supported by the German Ministry of Research and Technology (BMFT) in the frame of research projects ZISCH and PRISMA.

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Discussion

D. Prandle (*Proudman Oceanographic Laboratory*, *Birkenhead*, *U.K.*). How useful could chemical or radioactive analysis of shallow cores be in developing this model and could the model be used to indicate net-depositional areas where such cores could usefully be taken?

J. Sündermann. In principle, this analysis would provide an excellent possibility to verify the model. In the present case, the model is too coarse to resolve shallow cores. Besides the physico-chemical behaviour of the radio-tracers must be known (what parts are transported by water and by SPM).

R. Lankester (*North Sea Work Group*, *East Anglia*, *U.K.*). I was interested in your reference to trawling as a contributing factor to particulate suspension. There are other anthropogenic influences and I would draw your attention specifically to sea-bed sand and gravel extraction in the Thames and Humber Estuaries and the East Anglian coast of the U.K. Between 15 and 20 million tonnes of material on average is landed from these sources. However, to obtain these quantities of useable material, the figures should be multiplied by a factor of between 1.5 and 2.5 to derive the quantity of sea-bed sediments actually extracted. The rejected material is discarded over the side of the dredging vessel which is a major contribution to the volumes of suspended matter in the water column. The estimated quantities of rejected material would be approximately between 20 and 35 million tonnes consisting of various particle sizes.

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As the commercially valuable material is often beneath fine sediments this top layer, which is of no commercial use, must be removed first. In so doing it will also be contributing to the particulate matter transported eastwards across the North Sea.

I would suggest that this anthropogenic influence should be considered when assessing and calculating the quantities of particulate matter lost from the eastern coast of the U.K.

I. N. McCave (*University of Cambridge, U.K.*). The two principal regions of high concentration that were shown in figure 4*a* are not off source areas of cliffs. They are in fact off the Lincolnshire coast which is south of the main source of supply from Holderness and off the Suffolk coast which is south of the main source of supply from the Norfolk cliffs. I believe that the reason why these zones of high concentration exist is because there are inshore recirculations in these two areas which lead to the concentration of fine grained suspended sediment (Ramster, *ICES CM* **98**, 1965; Riley & Ramster *ICES CM* C: **15**, 1968; Robinson, *E. Midl. Geog.* **3**, 1964). Material is entrained from these regions of high concentration into the plumes which run across the Southern Bight, and they may therefore be regarded as virtual sources for the export of material across the North Sea.

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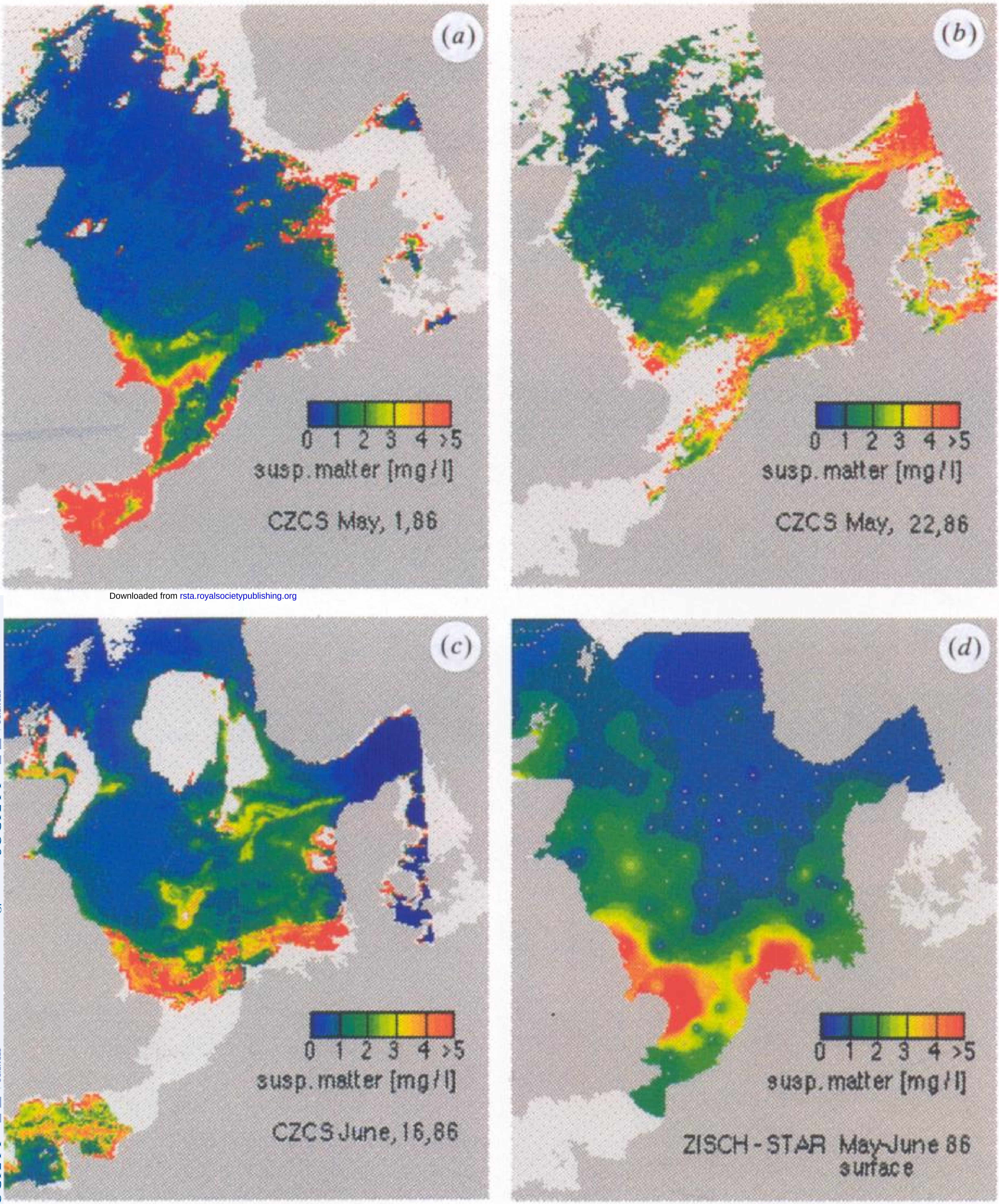

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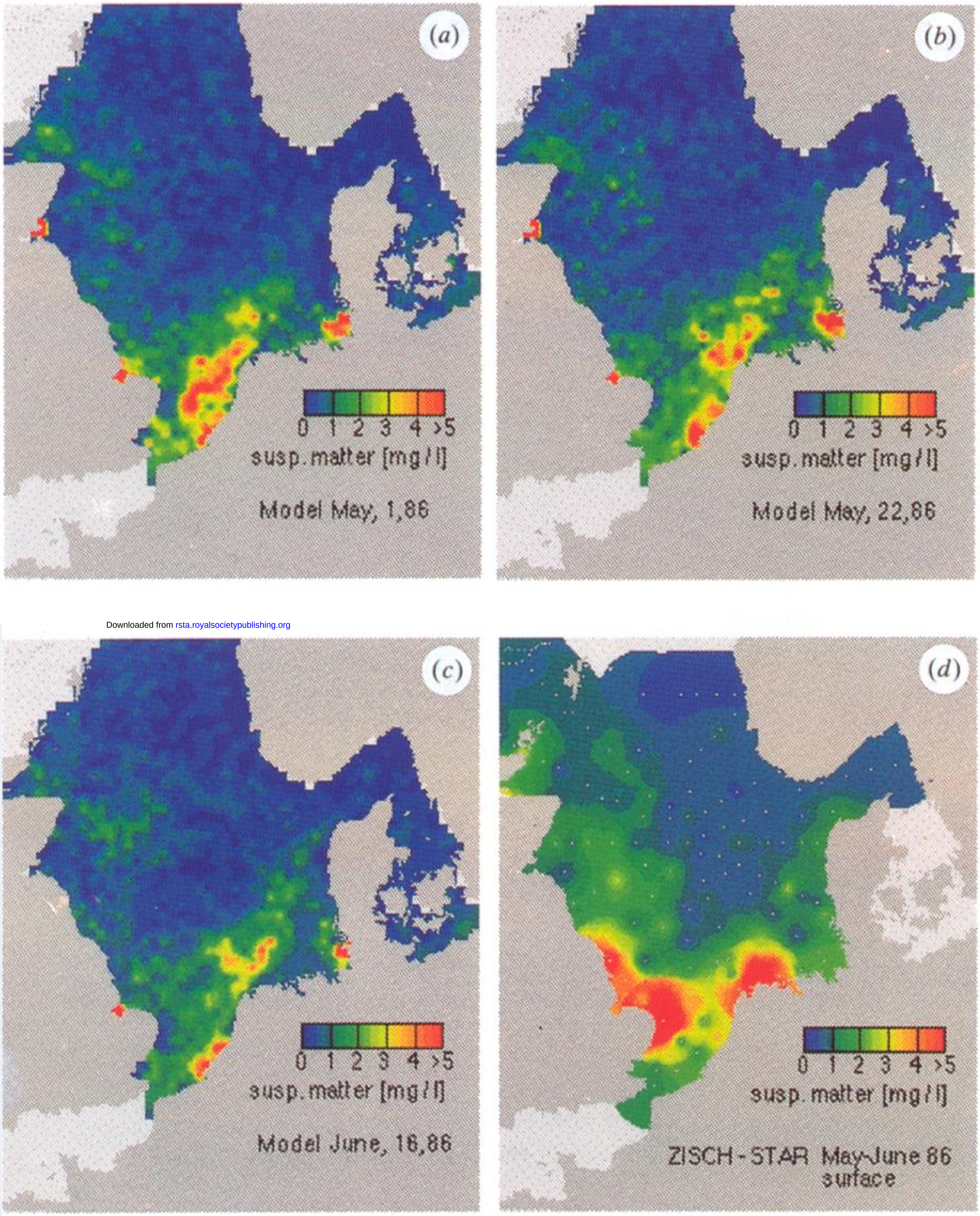

igure 3. Suspended matter concentrations (mg l^{-1}) in the North Sea during the ZISCH-STAR eriod May / June 1986. Comparison of three calculated distributions (*a*) 1 May, (*b*) 22 May, (*c*) 5 June with ship surface data (*d*).

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