Tellus (1991), *43B*, 224–235

Sinks and sources of CO_2 in coastal seas: the North Sea

By S. KEMPE and K. PEGLER, *SCOPE/UNEP International Carbon Unit, Institute of Biogeochemistry and Marine Chemistry, University of Hamburg, Bundesstr. 55, 2000 Hamburg 13, Germany*

(Manuscript received 17 October 1989; in final form 7 December 1990)

ABSTRACT

Alkalinity, $\sum CO_2$ and pH were measured and the respective PCO_2 was calculated for over 1000 water samples from the North Sea. Distribution of these parameters in the surface waters in May–June, 1986, shows that three principle water masses exist in the North Sea: North Atlantic water, Skagerrak water and German Bight water. The carbonate parameters of the German Bight water are indicative of an intense plankton bloom which reduced the PCO_2 to values as low as 88 ppmv. Assuming an average thickness of the stagnant boundary layer of 40 μm, the CO_2 flux entering the areas with a PCO_2 below that of ambient air (346 ppmv in 1986) amounted to 3.1×10^9 moles CO_2 d^{-1}. However, at the same time, areas with a PCO_2 up to 518 ppmv and therefore higher than the atmospheric PCO_2 co-existed in the central North Sea and near the British coast. These areas formed a source for CO_2 to the atmosphere in the size of 1.1×10^9 moles CO_2 d^{-1}. Taken together, the North Sea had an area-averaged PCO_2 of 323 ppmv and formed a net sink for CO_2 in the range of 2.0×10^9 moles d^{-1} or 7.5×10^4 moles km^{-2} d^{-1} or 24×10^3 t C d^{-1} in summer 1986. It is estimated that a total of 4.3×10^6 t C enters the North Sea in the warm season. This size is comparable to the additional CO_2 uptake by phytoplankton induced by the anthropogenic input of nutrients which amounts to $5–6 \times 10^6$ t C a^{-1}.

1. Introduction

The rapid anthropogenic release of CO_2 from fossil fuel and from biosphere destruction has upset the natural carbon cycle (e.g., Degens et al., 1984). Roughly half of the surplus CO_2 stays in the atmosphere, while half enters the ocean because of the chemical buffer capacity of the aqueous carbonate system. Additionally, phytoplankton might sequester CO_2 in coastal seas because of ongoing eutrophication. It is estimated that phosphorus and nitrogen inputs to coastal seas have increased by a factor of ten since 1850 (Walsh et al., 1985). One of the most polluted coastal seas is the North Sea (Kempe et al., 1988). It is situated between 51°N and 61°N and 4°W and 9°E and covers an area (A) of 525,000 km^2. It receives an excess of nutrients from British and Central European rivers (Kempe et al., 1989, 1990). The annual load of phosphorus and nitrogen to the North Sea is estimated to be 120×10^3 t and 970×10^3 t, respectively (ICES, 1978). The elemental ratio of C:N:P of phytoplankton (Redfield ratio, 105:15:1; Broecker and Peng, 1982) suggests an additional sequestering of carbon of roughly $5–6 \times 10^6$ t C annually.

However, several questions remain unclear in this approach. First, it is not certain that this carbon is derived from the atmosphere, it may be derived from the high carbonate alkalinity of rivers entering the North Sea. Second, phosphorus may be buried bound to inorganic compounds and nitrate might be denitrified, thus diminishing the nutrients available for plankton blooms. Third, much of the organic matter produced is respired again leading to interannually increasing nutrient concentrations and an increase in the annual amplitude of plankton blooms, but not necessarily to a net subtraction of organic matter with settling sediments. These increases are in fact observed in the long-term record of nutrient concentrations and primary productivity at Helgoland (Radach and Berg, 1986).

Permanent deposition of additionally fixed

carbon is also hampered by the shallow depth of the North Sea (average 80 m; Anon. 1980). Much of its southern reaches are even less than 40 m deep. Storms can thus resuspend fine-grained sediments. In fact, permanent deposition of fine sediments is, except for a few isolated small areas, possible only in the Skagerrak and in the Norwegian Trough where water depths exceed 100 m (Salge and Wong, 1988).

In order to gain more insight into the question of CO_2 fixation in eutrophied coastal seas we attempt in this study to calculate the CO_2 exchange between the North Sea surface and the atmosphere.

2. Material and methods

For this purpose we investigated the carbonate system in the North Sea 1985 and 1986 on four cruises during the project "Biogeochemistry and Distribution of Suspended Matter in the North Sea and Implications to Fisheries Biology" funded by the German Minister for Research and Technology (BMFT). At 205 stations a total of 1000 water samples were taken and their pH values, alkalinities and total inorganic carbon concentrations ($\sum CO_2$) measured (Pegler, 1989). Salinity, temperature, oxygen, chlorophyll, POC, and nutrient concentrations were simultaneously measured by other colleagues. The most extensive data set was obtained during the R/V Planet and R/V Gauss cruises 2 May–13 June 1986, which were organized by the BMFT project "Circulation and Pollutant Transfer in the North Sea." Results from that cruise allow one to draw maps of the summer conditions of the total North Sea surface with regard to the parameters of the carbonate system.

Alkalinity and $\sum CO_2$ were determined with a high precision, computerized, automatic Gran titration using similar equipment and software as described by Bradshaw et al. (1981). Titration was done at 25°C with 20 or 25 mm^3 increments of 0.2 eq dm^{-3} HCl + 0.45 eq dm^{-3} NaCl as a titer. The closed cell had a volume of 137.75 ± 0.1 cm^3 which gives a precision of ± 2 μeq kg^{-1} at average alkalinities of 2.3 meq kg^{-1}. Further details of the method are given in Pegler and Kempe (1988). The pH was measured immediately after recovery of the sample with a WTW-pH91 meter and an INGOLD combination electrode PT-408 standardized against

pH = 7.385 at 25°C/INGOLD 9806,

pH = 9.180 at 25°C/INGOLD 9807

(DIN 19266 and NBS).

Repeated pH-measurements differed by ± 0.01 and drift between standardizations stayed below ± 0.02 pH. Thus total accuracy of pH determination was probably better than ± 0.03 pH.

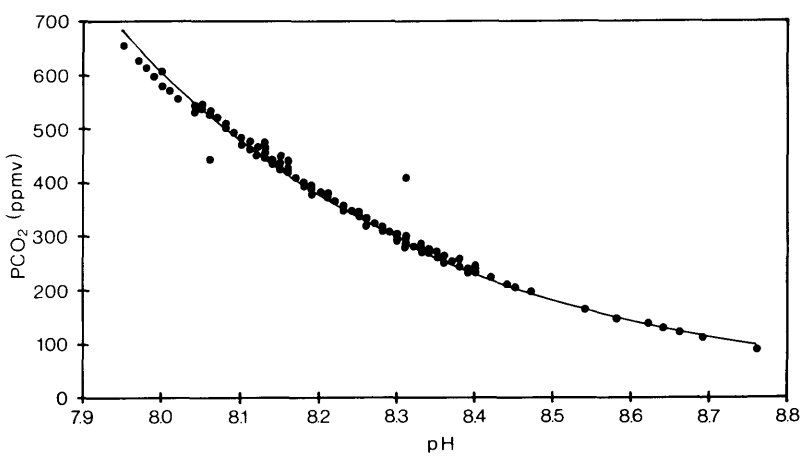

Fig. 1. Empirical transfer function $PCO_2 = 158.06 \times 10^9 \times e^{(-2.422 \times pH)}$ with a correlation coefficient $r = -0.97$ as derived from $N = 528$ water samples taken throughout the North Sea and from various depths in May–June 1986.

From the pH, salinity, temperature, and alkalinity data the PCO_2, the carbonate ion concentrations, and the calcite saturation index was calculated with the program WATMIX of Wigley and Plummer (1976). The program uses a full ionic model and is valid for all salinities. This approach was chosen because of the wide range in salinities, alkalinities and pH values encountered in the North Sea instead of the calculation of PCO_2 using the apparent carbonate system equilibrium constants for seawater (e.g., Broecker and Peng, 1982).

As is expected from carbonate thermodynamics, the results of this procedure show that the relation of pH to PCO_2 is exponential and highly significant ($\alpha < 0.1\,\%$). The relation is described by the equation (Fig. 1):

$$PCO_2 = 158.06 \times 10^9 \times e^{(-2.4220 \times pH)}.$$

This transfer function is based on 528 water samples taken in May and June 1986 from various depths in the North Sea and is valid between 700 and 100 ppmv PCO_2 and 7.95 and 8.75 pH and for a wide range of salinities, alkalinities, $\sum CO_2$, and temperatures. It allows to calculate PCO_2 reasonably accurately from simple pH measurements and makes thus fast surveys of PCO_2 in the North Sea feasible without complicated titration of alkalinity and $\sum CO_2$ and complex computations.

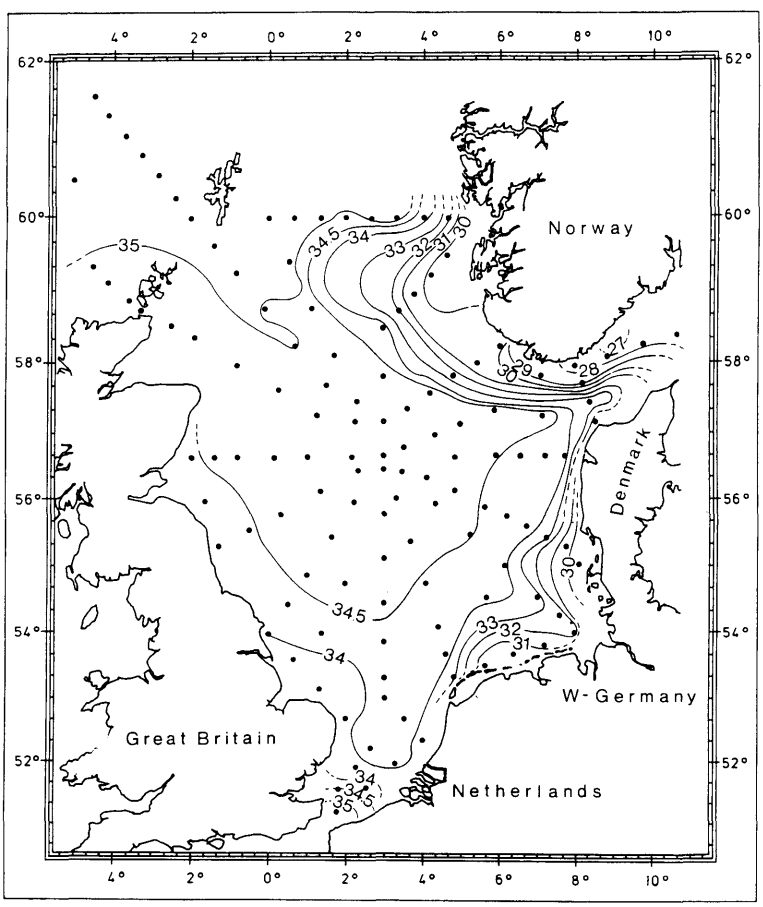

Fig. 2. Distribution of salinity (5 m depth) in the North Sea in May–June 1986.

3. Water masses of the North Sea

The distributions of the salinity, alkalinity and $\sum CO_2$ (Figs. 2–4) show that essentially three water masses exist in the North Sea.

(1) The North Atlantic water mass which enters the North Sea from the Northwest and through the English Channel and carries high salinity (>35 permil) and $\sum CO_2$ (>2.10 mmoles kg^{-1}) and an intermediate alkalinity (2.32–2.34 meq kg^{-1}).

(2) The Skagerrak water mass which is formed by the outflow of Baltic Sea water and which is characterized by low salinities (27–32 permil), low $\sum CO_2$ (2.05–1.90 mmoles kg^{-1}) and low alkalinities (2.32–2.12 meq kg^{-1}). And

(3) the German Bight water mass which is influenced by the fresh water input of Central European rivers. It has low salinities (34–30 permil), a low $\sum CO_2$ (2.05–1.90 mmoles kg^{-1}) and high alkalinities (>2.34 meq kg^{-1}).

The mixing of these three water masses is quite evident in the alkalinity-salinity scatter plot (Fig. 5, top). Two linear trends appear, one, with a negative slope, encompassing the data from the German Bight and one, with a positive slope, including the Skagerrak samples. Both regressions

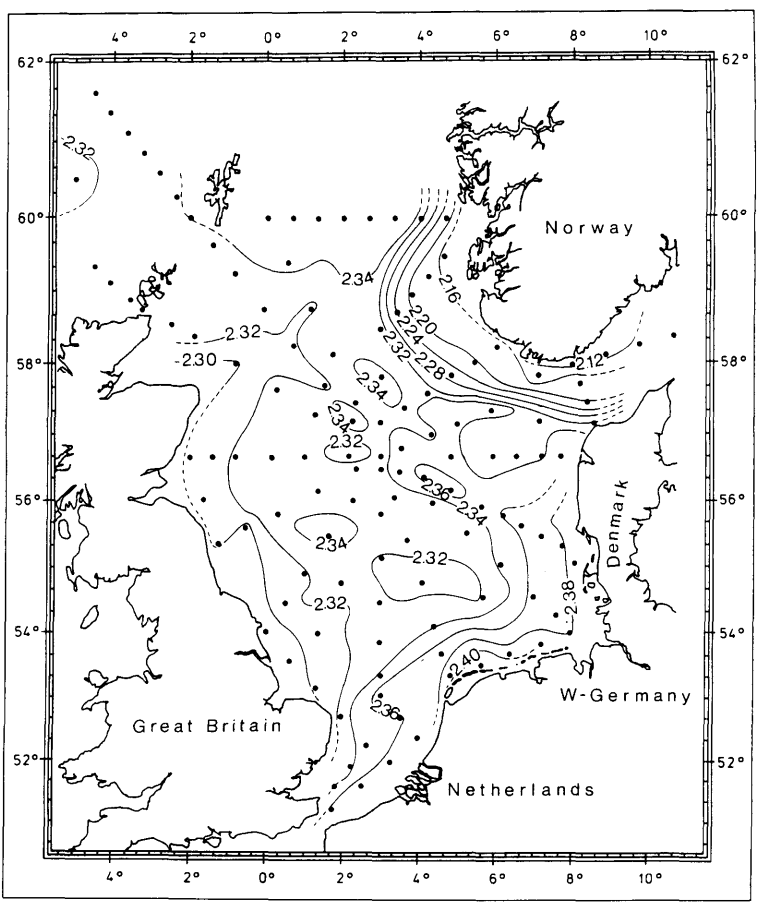

Fig. 3. Distribution of alkalinity (5 m depth) in the North Sea in May–June 1986.

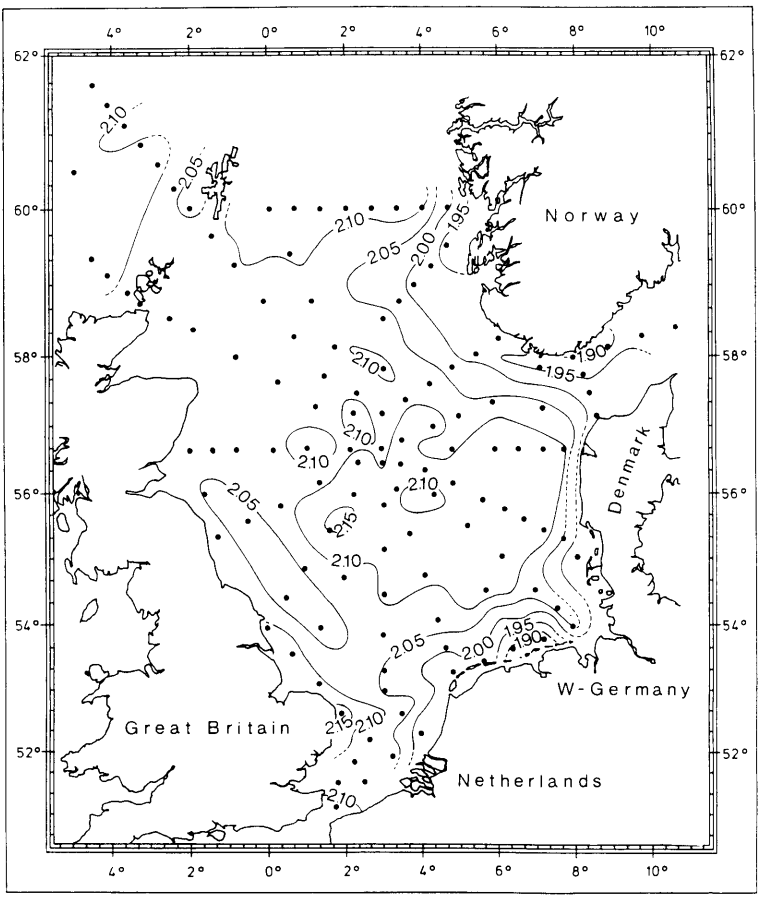

Fig. 4. Distribution of $\sum CO_2$ (5 m depth) in the North Sea in May–June 1986.

converge towards the North Atlantic water mass of S ca. 35 permil and Alk. ca. 2.35 meq kg^{-1}. The salinity-$\sum CO_2$ scatter plot (Fig. 5, bottom), however, does not show these two mixing lines and both the Skagerrak and the German Bight water masses appear to fall on the same mixing line.

The explanation of this difference between the mixing lines of alkalinity and $\sum CO_2$ is the eutrophication of the German Bight. Originally the rivers Rhine, Weser and Elbe discharged water high in alkalinity and high in $\sum CO_2$ (Kempe, 1982a, b). Because they have a very high PCO_2 (and a low pH) they do not have any appreciable carbonate ion content. Therefore alkalinity (in meq kg^{-1}) and $\sum CO_2$ (in mmoles kg^{-1}) must have the same numerical values (i.e., 2.6 according to the Y-axis intersect in the regression equation of Fig. 5, top). Since alkalinity is largely a conservative property, the $\sum CO_2$ must have been diminished by photosynthesis and by the production of organic carbon.

4. The CO_2 budget

This interpretation is substantiated by the distribution of the pH and the PCO_2 in North Sea surface waters (Figs. 6 and 7). The northern North Sea and the Skagerrak have pH values of between 8.2 and 8.4 corresponding to PCO_2 values of 300

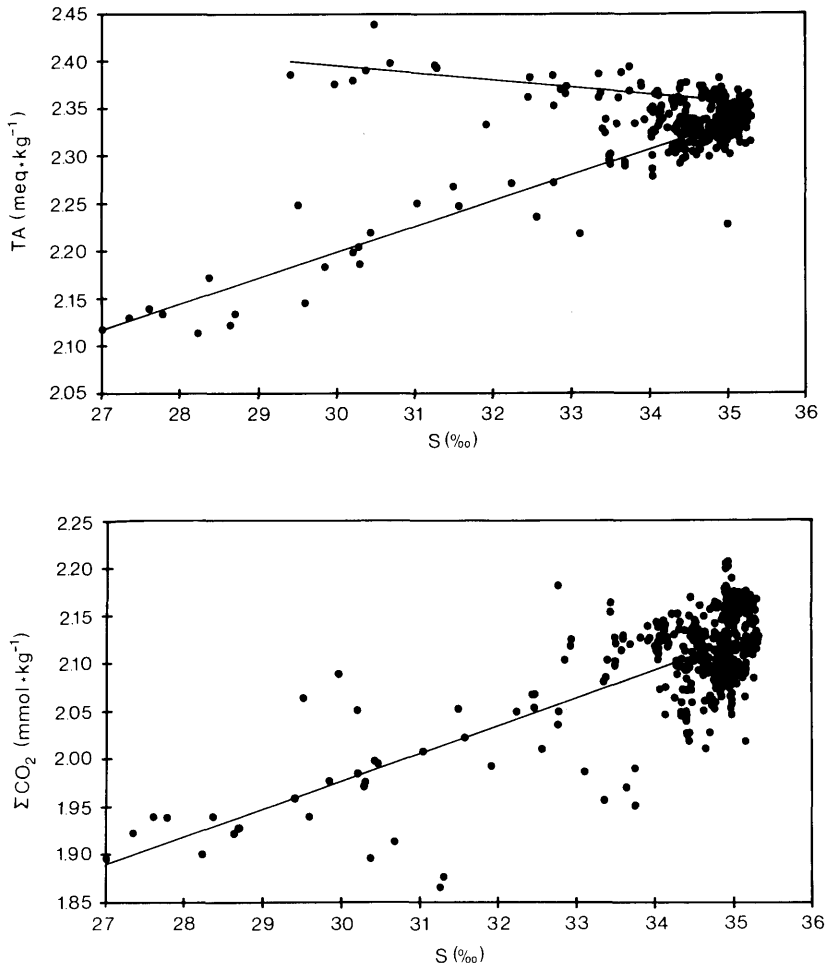

Fig. 5. Relation between salinity and alkalinity (top) and salinity and $\sum CO_2$ (bottom) for all North Sea samples of May–June 1986. The linear regressions are: $TA = -0.0074 \times S + 2.6150$ for $TA \geq 2.35$ ($r = -0.70$; $N = 119$), $TA = 0.0272 \times S + 1.3830$ for $TA < 2.35$ ($r = 0.91$; $N = 406$), and $\sum CO_2 = 0.0294 \times S + 1.0966$ ($r = 0.70$; $N = 525$).

to 400 ppmv, i.e., similar to atmospheric pressure (in 1986: 346 ppmv). The central North Sea and the British coast have low pH values corresponding to PCO_2 values of above 400 ppmv, indicative that the North Sea gives off CO_2 to the atmosphere. Values were as high as 518 ppmv near the Humber mouth, indicating that this part of the North Sea suffers from exceptionally high rates of respiration, possibly due to waste inputs. The German Bight, however, has very high pH values, up to 8.7, corresponding to very low PCO_2 values, indicative of CO_2 uptake from the atmosphere. One coastal station has a PCO_2 of < 100 ppmv. In this region an extremely active plankton bloom was encountered clearly seen in simultaneous high chlorophyll values. From Fig. 7, it is clear that during early summer the North Sea functions both as a sink and as a source for atmospheric CO_2.

If the North Sea were devoid of life, it should function in summer as a source for CO_2, simply because the solubility of CO_2 in warm water is less than in cold water. At winter temperatures of 3–7°C, 22.3 μmoles CO_2 kg^{-1} are needed to maintain a PCO_2 of 346 ppmv, while in summer at

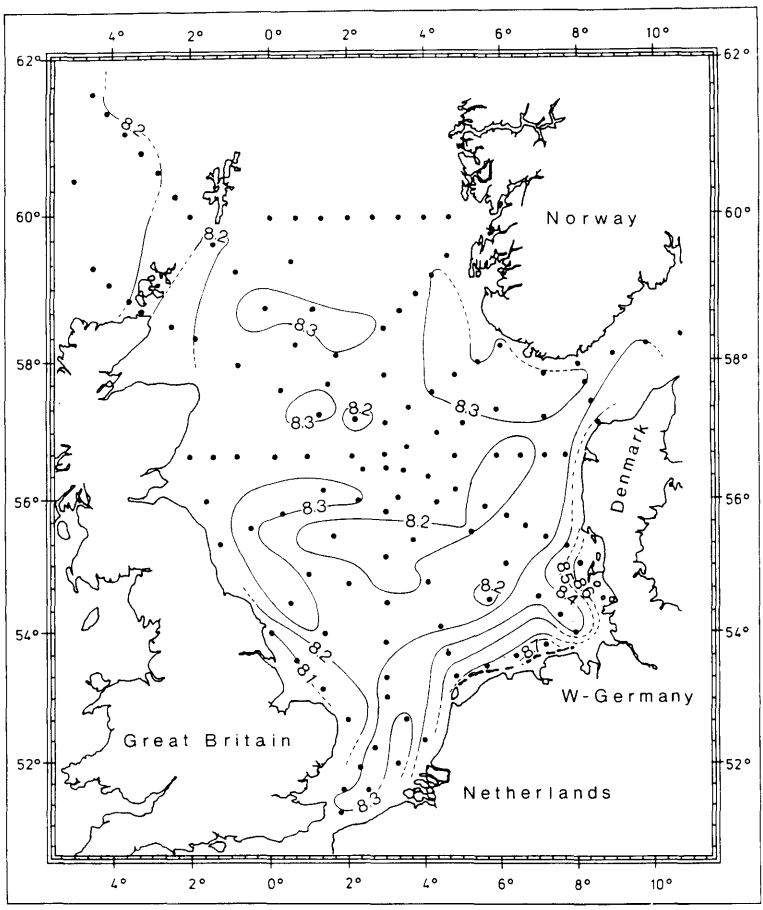

Fig. 6. Distribution of pH (5 m depth) in the North Sea in May–June 1986.

temperatures of 13–17°C, 16.2 μmoles CO_2 kg^{-1} maintain the same PCO_2. Compared to the annual average temperature of 10°C (corresponding to 19.0 μmoles CO_2 kg^{-1}) this would call for a daily flux of 4.5×10^9 moles CO_2 or 54×10^3 t C d^{-1} into the water in winter and out of the water in summer.

However, large parts of the North Sea act as a CO_2 sink also in summer. In order to estimate the total summer CO_2 flux the PCO_2 surface measurements were transferred to an area correct map (Fig. 7). Next, the areas between the isolines were integrated. Results are given in the bar-graph of Fig. 8, top, for 10 PCO_2 classes between 50 and 550 ppmv. The area weighted average PCO_2 of the North Sea derived from these values is 323 ppmv, i.e., the North Sea acts in fact as a net CO_2 sink during summer.

Finally, the mass flux (FCO_2) across the air sea interface was calculated using the equation (e.g., Broecker and Peng, 1982):

$$FCO_2 = D \times ([CO_2]_{air} - [CO_2]_{water}) \times z^{-1}$$

where D is the diffusion coefficient (1.32×10^{-5} $cm^2\,s^{-1}$ or 1.14×10^{-4} $m^2\,d^{-1}$ at the average temperature of 8.6°C during May–June 1986), $[CO_2]_{air}$ is the CO_2 concentration at 346 ppmv (i.e., 19.9 mmoles m^{-3}), $[CO_2]_{water}$ is the CO_2 concentration in the respective class and z is the thickness of the boundary layer (in μm). If we assume an average thickness of $z = 40$ μm

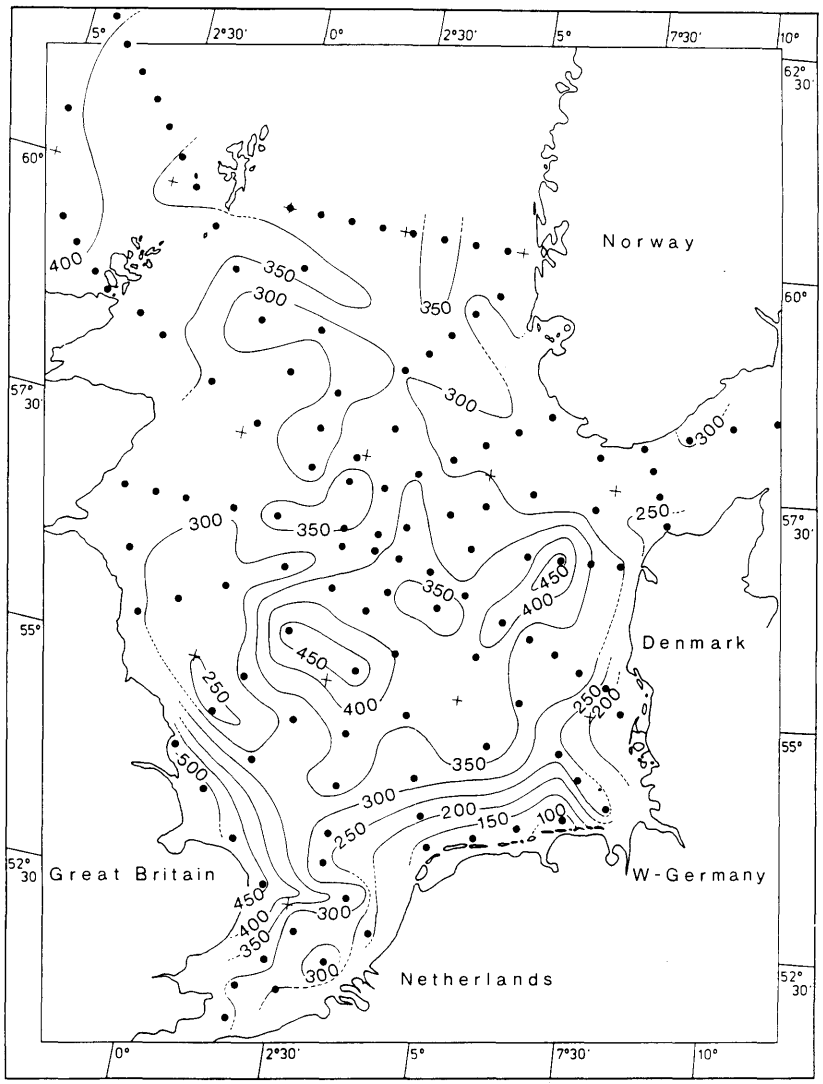

Fig. 7. Distribution of calculated PCO_2 (5 m depth) in the North Sea in May–June 1986 and locations of stations.

(Broecker and Peng, 1982), then the area averaged PCO_2 of 323 ppmv ($=18.6$ mmoles CO_2 m^{-3}) yields a net flux of

$$FCO_2 = 1.14 \times 10^{-4} \times (19.9 - 18.6) \times 10^{-3} \times (40 \times 10^{-6})^{-1}$$
$$= 3.705 \times 10^{-3} \text{ moles m}^{-2} \text{ d}^{-1}$$
$$= 44 \text{ mg C m}^{-2} \text{ d}^{-1}.$$

If one repeats this calculation for the ten PCO_2 classes and their areas separately (Table 1 and bar-graph Fig. 8, bottom) the net uptake of the North Sea becomes 2×10^9 moles CO_2 or 24×10^3 t C daily. This flux figure is valid for $z = 40$ μm. During storms, z becomes smaller, at $z = 30$ μm the flux would increase roughly by 25% (Table 1). The inaccuracy in estimating z is the largest inaccuracy in assessing CO_2 fluxes across the air-sea interface.

Table 1. *Daily area-weighted CO_2 fluxes (FCO_2) for 10 PCO_2 classes between 50 and 550 ppmv (column 1) between atmosphere and the surface layer of the North Sea in May/June 1986*

PCO_2 Classes [ppmv]	Area (A) [km^{-2}]	$FCO_2A^{-1} \times 10^{-4}$ for $z = 30\ \mu m$ [moles $km^{-2}\ d^{-1}$]	$FCO_2A^{-1} \times 10^{-4}$ for $z = 40\ \mu m$ [moles $km^{-2}\ d^{-1}$]	$FCO_2 \times 10^{-6}$ for $z = 40\ \mu m$ [moles $A^{-1}\ d^{-1}$]
50–100	932	+5.928	+4.446	+41.4
100–150	5,852	+4.826	+3.620	+211.8
150–200	16,931	+3.724	+2.793	+472.9
200–250	22,691	+2.660	+1.995	+452.7
250–300	103,867	+1.558	+1.169	+1,214.2
300–350	218,113	+0.456	+0.342	+745.9
$\sum < 350$	368,386	-	-	+3,138.9
350–400	115,008	−0.646	−0.485	−557.8
400–450	20,704	−1.710	−1.283	−265.6
450–500	9,162	−2.850	−2.138	−195.9
500–550	4,212	−3.914	−2.936	−123.7
$\sum > 350$	149,086	-	-	−1,142.0
$\sum$ total	517,364	-	-	+1,996.9

CO_2 fluxes (moles $km^{-2}\ d^{-1}$) are calculated for boundary layer thicknesses of $z = 30\ \mu m$ and $z = 40\ \mu m$ (column 3 and 4). For $z = 40\ \mu m$ total fluxes for areas (A; column 2) are given (column 5). Positive values indicate sinks of atmospheric CO_2 and negative values sources for atmospheric CO_2.

All other inaccuracies like measurements errors, inaccuracies in chemical constants and contouring errors are small compared to the difficulties in establishing z. The calculated fluxes are therefore rough estimates only. The fluxes calculated are representative of an area of 517,000 km^2 since the Wadden Sea areas were excluded from the calculation (total North Sea area is 525,000 km^2). Since the data span a time period of one and a half month in May and June one can, as a first approximation, assume that the daily flux is representative of the conditions of the warm season. The total net uptake becomes then 4.3×10^6 t C within half a year (Fig. 9). This figure compares favourably well with the organic carbon production calculated from the nutrient input which was $5–6 \times 10^6$ t C a^{-1}.

This flux is still small when compared with the total primary productivity in the North Sea (Fig. 9). According to Aletsee and Rick (1988) the gross primary productivity reaches 170×10^6 t C in summer. 20×10^6 t C are consumed for autorespiration resulting in a net primary productivity of 150×10^6 t C. The total $\sum CO_2$ in the euphotic zone of the North Sea (assumed to have a depth of 20 m) is estimated to 270×10^6 t C which implies that the average carbon atom has only a residence time of 1.6 years in the inorganic pool. It also implies that the NPP is quickly recycled by heterotrophic respiration because otherwise the $\sum CO_2$ concentration would decrease to less than 50% its average value during plankton blooms. This, however, is not the case as can be seen from Figs. 4 and 5. The total phytoplankton mass in the North Sea is estimated to 1.4×10^6 t C (Aletsee and Rick, 1988) which suggests a turnover of its carbon every 1.3 days.

An extremely fast recycling of organic carbon is also indicated by the size of the vertical carbon flux leaving the euphotic zone. This flux was measured by two sediment traps, one moored in the Norwegian Trough, one moored in the Skagerrak

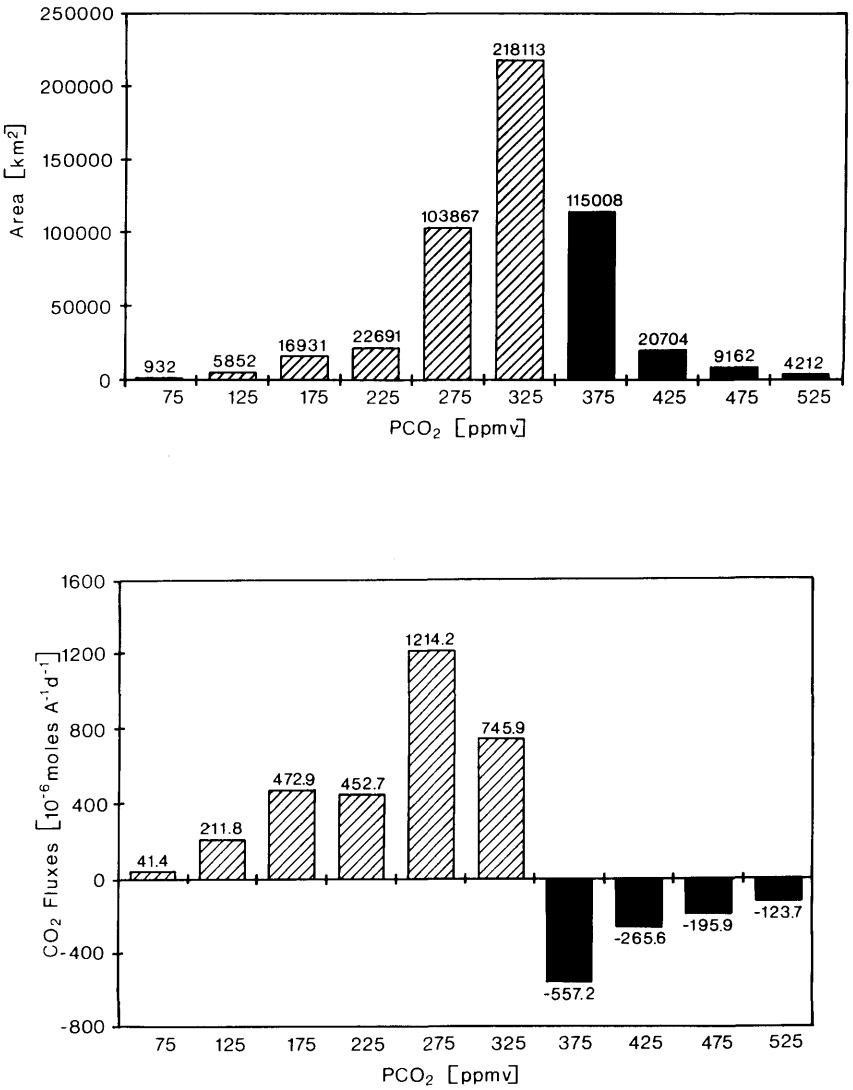

Fig. 8. Sizes of North Sea surface areas ($A = 517{,}000$ km^2) in various PCO_2 classes (top) and resulting daily net CO_2 fluxes (bottom). The North Sea gains 3.139×10^9 moles CO_2 A^{-1} d^{-1} from the atmosphere and loses 1.142×10^9 moles CO_2 A^{-1} d^{-1} to the atmosphere. The net CO_2 flux amounts to 1.997×10^9 moles A^{-1} d^{-1}.

(Kempe and Jennerjahn, 1988). Their average summer C_{org} fluxes amounted to 8.7 and 27 mg C m^{-2} d^{-1}, respectively, while their $CaCO_3$–C_{inorg} flux amounted to 2.4 and 8.0 mg C m^{-2} d^{-1}. Taking averages from these figures and assuming that this flux is representative for all of the North Sea, a total vertical carbon flux of 1.5×10^6 t C_{org} per half year and 0.3×10^6 t C_{inorg} per half year is indicated. This figure is small compared to the NPP, indicating that only 1% of the organic carbon produced in the North Sea has a chance to reach the sediment.

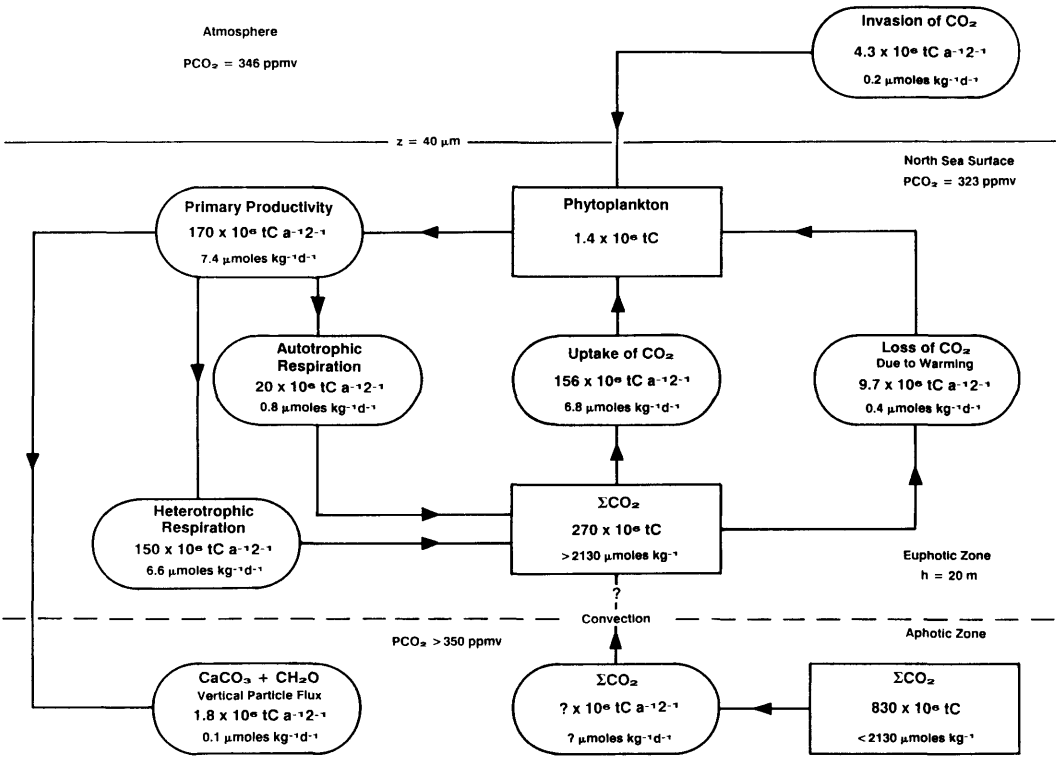

Fig. 9. Pools and fluxes of CO_2 in the North Sea according to various sources. For further explanations see text.

6. Conclusions

In summer, the North Sea is a net sink for atmospheric CO_2. This is in spite of the seasonal warming, which tends to cause degassing. The cause of this reversal in trend is intensive photosynthesis. The question remains, if in winter respiration will cause the release of enough CO_2 to cause the North Sea to become a source of CO_2 in spite of seasonal cooling. Data by Weichart (1985) suggest that in fact CO_2 is degassed from the surface of the German Bight in winter. If this degassing is, however, large enough to make the entire North Sea a source for CO_2 and if this is more than the summer uptake, remains to be shown.

The magnitude of the summer sink of CO_2 in the North Sea, an estimated 4.3×10^{12} gC, is by no means trivial for the global carbon cycle. This is especially so because the North Sea represents only 1.9% of the 27.4×10^6 km^2 of continental self area of the world ocean, all of which is potentially vulnerable to anthropogenic eutrophication.

7. Acknowledgements

This work was funded as a part of the German Minister of Research and Technology project "Biogeochemistry and Distribution of Suspended Matter in the North Sea and Implications to Fisheries Biology" (project MFU 05438). We gratefully acknowledge the possibility to participate in the May–June 1986 Cruises organized by the project "Circulation and Pollutant Transfer in the North Sea" (MFU 0545).

REFERENCES

Aletsee, L. and Rick, H. 1988. Teilproject G5: Phytoplankton. In: *Zirkulation und Schadstoffumsatz in der Nordsee (ZISCH)*, Endbericht BMFT Projekt MFU 0545, 236–257. Selbstverl. Inst. für Meereskunde, Univ. Hamburg.

Anonymous. 1980. *Rat von Sachverständigen für Umweltfragen: Umweltpropbleme der Nordsee.* Sondergutachten. Stuttgart, Mainz, Verlag W. Kohlhammer GmbH, pp. 508.

Bradshaw, A. L., Brewer, P. G., Shafer, K. and Williams, R. T. 1981. Measurements of total carbon dioxide and alkalinity by potentiometric titration in the GEOSECS program. *Earth Planet. Sci. Lett. 55*, 99–115.

Broecker, W. C. and Peng, T.-H. 1982. *Tracers in the sea.* Palisades, New York, Columbia University, pp. 690.

Degens, E. T., Kempe, S. and Spitzy, A. 1984. Carbon dioxide: A biogeochemical portrait. In: *The handbook of environmental chemistry* (ed. O. Hutzinger) Vol. 1/C, Springer-Verlag, Heidelberg, 127–215.

ICES. 1978. *Input of pollutants to the Oslo condition area.* Coop. Res. Rep. 77.

Kempe, S. 1982a. Long-term records of CO_2 pressure fluctuations in fresh waters. Habilitationsschrift. *Mitt. Geol.-Paläont. Inst., Univ. Hamburg, SCOPE/UNEP Sonderbd. 52*, 91–332.

Kempe, S. 1982b. VALDIVIA cruise, October 1981: Carbonate equilibria in the estuaries of Elbe, Weser, Ems and in the Southern German Bight. *Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. 52*, 719–742.

Kempe, S., Liebezeit, G., Dethlefsen, V. and Harms, U. 1988. *Biogeochemistry and distribution of suspended matter in the North Sea and implications for fisheries biology.* Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP, Sonderbd. 65, pp. 547.

Kempe, S. and Jennerjahn, T. C. 1988. The vertical particle flux in the northern North Sea, its seasonality and composition. In: *Biogeochemistry and distribution of suspended matter in the North Sea and implications to fisheries biology* (eds. S. Kempe, G. Liebezeit, V. Dethlefsen and U. Harms) Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. 65, 229–267.

Kempe, S., Liebezeit, G. and Schröder, M. 1989. Inventory of phosphorus in the North Sea. In: *Phosphorus cycles in terrestrial and aquatic ecosystems, Regional Workshop 1: Europe* (ed. H. Thiessen) SCOPE Workshop, Proceedings, Saskatchewan Inst. of Pedology, University of Saskatchewan, Saskatoon, Canada, 319–339.

Kempe, S., Pettine, M. and Cauwet, G. 1990. Biogeochemistry of European rivers. In: *Biogeochemistry of major world rivers* (eds. E. T. Degens, S. Kempe and J. Richey), *SCOPE Report. 42.* J. Wiley, and Sons, Chichester, 172–213.

Pegler, K. 1989. Das Karbonatsystem der Nordsee - Verteilung von Alkalinität und Kohlendioxid in der Wassersäule. *Diplom Thesis, Univ. Hamburg*, pp. 287.

Pegler, K. and Kempe, S. 1988. The carbonate system of the North Sea: Determination of alkalinity and TCO_2 and calculation of PCO_2 and SI_{cal} (Spring 1986). In: *Biogeochemistry and distribution of suspended matter in the North Sea and implications to fisheries biology* (eds. S. Kempe, G. Liebezeit, V. Dethlefsen and U. Harms) Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. 65, 35–87.

Radach, G. and Berg, J. 1986. Trends in den Konzentrationen der Nährstoffe und des Phytoplanktons in der Helgoländer Bucht (Helgoland Reede Daten). *Ber. Biol. Anst. Helgoland 2*, pp. 63.

Salge, U. and Wong, H. K. 1988. The Skagerrak: a depoenvironment for recent sediments in the North Sea. In: *Biogeochemistry and distribution of suspended matter in the North Sea and implications to fisheries biology* (eds. S. Kempe, G. Liebezeit, V. Dethlefsen and U. Harms) Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderbd. 65, 367–380.

Walsh, J. J., Premuzic, E. T. and Gaffney, J. C. et al. 1985. Organic storage of CO_2 on the continental slope off the mid-Atlantic bight, the southeastern Bering Sea, and the Peru Coast. *Deep-Sea Res. 32(7)*, 853–883.

Weichart, G. 1985. High pH-values in the German Bight as an indication of intensive primary production. *Deut. hydr. Zeitschr. 38*, 94–117.

Wigley, T. M. L. and Plummer, L. N. 1976. Mixing of carbonate waters. *Geochim. Cosmochim. Acta 40*, 989–995.