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GAS EXCHANGE, TIDAL DISPERSION AND BIOGENIC VOLATILES IN THE SOUTHERN NORTH SEA

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CONTENTS

CRUISE OBJECTIVES:

1) To measure the rate of gas transfer across the sea surface as a function of wind and sea conditions by the release of volatile tracers into the water column.

2) To investigate rates of dispersion and advection due to tidal and residual currents by means of the same tracer release.

3) To investigate the biological sources of oxygen, methane, dimethyl sulphide and a suite of halocarbons in the coherent body of water marked by the tracers, with a view to obtaining budgets of these gases.

INTRODUCTION

Challenger cruise 48 of the NERC North Sea programme was a process study involving release of the deliberate tracers sulphur hexafluoride (SF_6) and helium-3, in order to measure air-sea gas exchange rates and simultaneously determine rates of tidal shear diffusion in the energetic environment of the Southern North Sea. At the same time dissolved gases having biological sources and sinks were measured both in areal surveys and while on station over 24- hour intervals, in order to develop an accurate picture of their rates of production and consumption. Combining these activities with the tracer release and budgeting provided a unique opportunity to make these measurements against a well-defined reference. (As our experiments have shown, even the drifting buoys used in the North Sea project, which have very low windage, do not move entirely with the water column however well they are drogued.) This was the first time that such a tracer release experiment had been carried out at sea.

The chosen cruise area was in the Dutch sector of the southern North Sea and was selected because of its shallow, uniform bathymetry and likely lack of a significant vertical physical structure in the water column. These considerations are extremely important to the success of the gas exchange experiments: the results are most easily interpreted when the water column is shallow and vertical mixing is complete. Therefore the cruise began with a brief areal survey designed to define the overall hydrographic and biological structure of the region. At CTD stations along the survey track, measurements of dissolved gases and nutrients were made in addition to the usual suite of North Sea parameters. Samples were also collected from the overside pump while the vessel was steaming in order to provide intermediate data between the CTD casts. We had hoped that the survey would reveal significant biological productivity so that the remaining cruise objectives could be accommodated. However, the survey results showed that the general level of biological activity was surprisingly low. The highest productivity occured adjacent to the Dutch coast, but this was unsuitable from the point of view of the tracer release because of the possibility of the tracers being advected onshore. Consequently, we were forced to uncouple the major cruise objectives. The selected tracer release site was centered on 52°30.0N, 3°30.0E (Fig. 1), and was acceptable from all points of view with the exception of biological productivity. We therefore decided to carry out separate biological surveys in the productive coastal regions in between the main tracer surveys.

Following this survey, we performed an exercise to examine the accuracy of the live navigation systems: a Dahn buoy and drouged Argos buoy were deployed, the ship steamed away from them, navigated a circular course and returned. In this way the relative error in the live navigation display relative to the actual buoy positions could be determined. About half way through this exercise the main radar system failed and we had to return to Gt. Yarmouth for 24 hours for repairs before continuing with the planned cruise timetable.

Repairs to the radar system took the better part of 24 hours. When we were able to leave, we proceeded to the study site and made contact with the MAFF vesses R/V Corystes, which was due to release the tracers. The tracer release exercise went according to plan, with the Challenger remaining upwind of the Corystes during release to minimise contamination and releasing argos buoys at intervals to aid in keeping track of the tagged water. At the end of the tracer release personnel were transferred from the Corystes to Challenger and the Corystes departed for home.

Over the remainder of the cruise, we alternated surveys of the tracer patch, including CTD stations to determine helium concentrtations, with biological work either in the form of forays in towards the coast to sample for methane and halocarbons, or time series of CTDs to study productivity by oxygen evolution. Three tracer surveys were completed, two coastal surveys and one series of CTDs for productivity measurements. About 12 hours was lost to a severe storm which stopped all work on 24 March. Overall, the tracer gas exchange work came out well, though we completed one fewer surveys than we had hoped to do, those we did complete gave good data. The methane analyses were also of great interest, showing very high concentrations associated with the Rhine outflow. The productivity work was less exciting, mostly because of the unexpectedly low biological activity in the area.

DESCRIPTION OF SUB-PROJECTS.

A) GAS EXCHANGE AND TIDAL DISPERSION BY TRACER RELEASE

Introduction:

In order to calculate the rate at which a gas such as methane (CH_4) or dimethyl sulphide exchanges across the air-sea interface, values for an appropriate transfer velocity, k, are required. Experiments in wind tunnels have clearly established a strong dependence of k on the prevailing conditions of wind speed and sea state. Unfortunately however, the wind tunnel results are substantially modified by the geometry of the particular tunnel used, and it has so far proved impossible to adequately simulate the full range of expected sea conditions, even in the largest such facilities. A technique for measuring k directly at sea, by budgeting the natural background of radon in the surface mixed layer, has been used for many years but the results are subject to large errors which principally arise from uncertainties in the sources and sinks of radon. A serious consequence of this is that the data have to be integrated over several months in order to be meaningful.

On this cruise the gas exchange measurements involved the simultaneous release of the two gaseous tracers sulphur hexafluoride (SF_6) and helium-3 into the water column and subsequent monitoring of the decline of their concentrations with time as they escaped to the atmosphere. Both gases make excellent passive tracers: they are inert, non-toxic and non-radiogenic, and can be measured at extreme dilution in seawater. An additional advantage for gas exchange work is that the large difference in their molecular weights gives rise to a large difference in their evasion rates. Wind tunnel data show that irrespective of changes in the absolute transfer velocities of the two tracers due to variations in wind speed and sea state, the ratio of their transfer velocities remains approximately constant. Therefore, the measured decline in the concentrations of the two tracers with time can be used to evaluate their transfer velocities. The measurements are much more well constrained than is the radon deficit technique, and can provide accurate measurements over quite short timescales, typically 12-48 hours. The method works best in a shallow, well-mixed water column, hence the choice of the SE. North sea as the study site. An additional method of determining the gas exchange rate involves "budgeting" one of the tracers in order to monitor its total mass in the water and its rate of change with time. The approach is impractical for helium-3 because it cannot be analysed on board ship, but it is possible for SF_6 with a purpose built apparatus which determines SF_6 concentrations in real time from an over-the-side pump. Budgeting the tracer involved repeated surveying of the tracer patch in a grid like pattern with continuous automatic sampling of the surface water for SF_6 by means of this apparatus.

A different type of information can also be recovered from these surveys: tracer releases have in the past been used to document water advection and dispersion due to tidal and wind forcing. Normally a fluorescent substance such as rhodamine is used for this purpose. However, a very large release of rhodamine would be required in order to follow its dispersion over periods in excess of a week. In contrast, the SF_6 tracer release facilitates a relatively long-term study of tidal dispersion processes.

Tracer deployment

In order to avoid the gross contamination problems which can arise from the use of high concentration tracer sources on board a survey ship (i.e. *Challenger*), a second vessel, RV *Corystes*, was borrowed from MAFF to be used for the tracer preparation and release. Because both tracers are only sparingly soluble (and also because helium-3 is very expensive), they were first concentrated in a known volume of seawater (~ 1000 l) in an enclosed steel tank on board *Corystes*, en route to the chosen release site. The tracers were dissolved into the water by continuously bubbling them around in a nearly closed circuit: in the case of SF_6, which is relatively inexpensive, a continuous bleed of SF_6 through the circuit was introduced in order to strip out the atmospheric gases initially present in the water. In the case of helium-3, which was added after the SF_6, the circuit was kept rigorously closed.
At the release site the tracers were deployed over a six hour period from H.W. to L.W. slacks. *Corystes* maintained a fixed position while *Challenger* remained ~200 m uptide. On board *Corystes* the tank contents were displaced by more seawater pumped from the ships non-toxic supply with the tank hose outlet held 10 m below the sea surface. The release rate was adjusted by a stopcock and was increased steadily throughout the release period in order to compensate for the steady fall in tracer concentrations inside the tank. This release procedure ensured that the tracers were not exposed to the atmosphere prior to release, which would have resulted in contamination and a non-constant initial ratio of helium-3 to SF_6.

Tracer measurement

At 5 times subsequent to the tracer release, CTD/multisampler casts were made to determine helium-3/SF_6 ratios. Generally, 4-5 samples for SF_6 and 1 for helium-3 were collected at each of 3 depths (2m, 10m and 25m). The SF_6 samples were analysed within a few hours of collection. Helium-3 samples were stored for subsequent analysis after the cruise. Gas transfer velocites determined with this method (and converted to those for carbon dioxide) are shown in Fig. 2 where they are compared with estimates derived using other methods. Briefly, our results have important implications for rates of CO_2 absorption by the oceans, implying a net uptake rate which is substantially lower than that required to balance the global carbon budget. A more detailed interprepation of these results awaits additional estimates from a later cruise.

Three complete surveys of the tracer patch were completed, each lasting on the order of 24 hours. During these, surface water obtained using an overside pump was passed continuously through an automated purge and trap system attached to the gas chromatograph. Cryotrapped samples were analysed for SF_6 every 3 minutes. The results were relayed to the ships computer workstation and displayed in the plot room as a map of tracer concentrations which was then used as a guide to navigating the ship around the tracer patch. Due to the time delay in the pumping and purge and trap systems, concentrations were plotted about 7 minutes behind real time. In order to increase the spatial resolution of the surveys, the ship steamed at 7-8 Kts, somewhat below full speed. Fig. 3 shows some preliminary budgeting results from one one the surveys, derived from the "liveplot" tracks. These tracks differ substantially from the actual ship's tracks over the ground, being approximations to the ships movement through the water. The data are presently being analysed in much greater detail.

B) OXYGEN AIR-SEA EXCHANGE AND PRODUCTIVITY MEASUREMENTS

Study objectives

1) To estimate rates of dissolved O_2 evasion to the atmosphere in a well characterised, productive region of the North Sea.

2) To evaluate daily rates of primary production throughout the water column using both O_2 and ^{14}C techniques and to estimate the proportion of this production contributed by the picoplankton.

3) To determine biomass distributions and rates of bacterial production in the survey region.

4) To map the spatial distribution of dissolved O_2 in near-surface waters and to evaluate changes in dissolved O_2 concentrations with depth at selected sites.

Methods

On 2 occasions (19-20 and 25-26 March), oxygen evasion rates were determined by comparing in situ changes in dissolved O_2 at three depths, measured at bi-hourly intervals during the hours of darkness, with those in a laboratory control experiments. Subsamples for chlorophyll, particulate organic carbon (POC) and cell count measurements were also collected.

Three oxygen and ^{14}C incubations (on 16, 18 and 20 March) were carried out in order to determine potential rates of primary productivity: near-surface water samples were collected at dawn and incubated until dusk on deck at in situ temperature under 6 different screened light intensities. Picoplankton (< 3um) production was determined concurrently.

Bacterial production rates were determined at several stations using the ^{3}H-Thydimine technique. Samples were preserved for subsequent cell counts.

Spatial variations of dissolved O_2 in near-surface waters were evaluated using an Endeco pulsed O_2-electrode system. Further samples, collected from the ships non-toxic supply, were analysed for dissolved O_2 using Winkler titration, which facilitated regular calibration of the Endeco electrodes. Dissolved O_2 measurements made on bottle cast samples were also used to calibrate the electrode data.

Chlorophyll measurements were made at all stations and used to calibrate the underway fluorimeter. At selected sites, samples were collected and filtered for later POC analysis and phytoplankton enumeration.

Preliminary results

The results of the oxygen evasion rate experiments show that differences between in situ and in vivio oxygen consumption rates are small and therefore that rates of oxygen evasion are negligible. Surface waters were generally less than ~102 % O_2-saturated. In contrast, saturation levels at the peak of a phytoplankton bloom can be as high as 160 %.

Rates of photosynthesis determined from the incubation experiments were small and picoplankton production accounted for only a trivial proportion of the total.

An extensive catalogue of near surface dissolved oxygen concentrations was compiled. These data will compliment those from the monthly surveys and allow us to construct comparatively detailed maps showing temporal changes in dissolved O_2.

A total of 137 chlorophyll samples were collected. A further 76 were filtered for subsequent POC analysis, and 62 were stored for phytoplankton enumeration.

The unexpectedly low biological activity found during the cruise lead us to reduce the total number of experiments that we had originally planned to carry out. In addition, adverse weather conditions forced us to reduce the number of stations sampled.

Further interpretation of the results will be possible when corresponding data from the remaining cruises becomes available.

C) *METHANE*

Introduction and objectives

Methane (CH_4) is a biogenic gas frequently encountered in ocean surface waters at concentrations much higher than would be predicted from solubilty criteria alone. Although the existence of a significant shallow water CH_4 source is clearly demonstrated by this CH_4 "excess", it has previously proven difficult to clearly define either its nature or magnitude. The objective of the work carried out during this cruise was to determine rates of CH_4 production and supply using measurements of CH_4 concentrations in seawater and air, combined with accurate estimates of the major sinks for CH_4 (biological oxidation and air-sea exchange).

Methods and results

Discrete CH_4 samples were collected at some 17 CTD stations and a series of underway measurements were made during three surveys along the Dutch coast. Preliminary data indicate that offshore CH_4 concentrations are in equilibrium with the atmosphere. In contrast, in coastal regions CH_4 levels were 2-20 times as great, with the highest values found in waters of intermediate to low salinity. It seems likely that rivers discharging into the North Sea along the Dutch coast are highly enriched in CH_4 and/or that coastal sediments constitute a significant local CH_4 source.

The rate of oxidation of CH_4 was investigated at 5 stations within the study region. The results of these experiments are presently being analysed.

D) DIMETHYL SULPHIDE and DMSP

Surface seawater samples were taken using both the CTD/rosette and the underway pump at intervals throughout the cruise. Dimethyl sulphide (DMS) was extracted and concentrated using a cryogenic purge and trap technique and analysed using a gas chromatograph with a flame photometric detector. Concentrations of dimethyl sulphoniopropionate (DMSP), the cellular precursor of DMS, were also measured. In addition, a further dozen halocarbon compounds were detected, including methyl iodide, bromoform, methylchloroform and tetrachloromethane. Samples for onshore chlorophyll analysis and phytoplankton identification and enumeration were also collected.

Because of a combination of bad weather and uncharacteristic analytical problems, fewer samples were collected than had originally been planned. In addition a greater that expected amount of time was spent on technical development of the halocarbon system. Lastly, most of the experiments originally planned for the cruise had to be abandoned because of the low productivity of the sampling area.

LOG OF MAJOR ACTIVITIES

12/03	1800	Departed from Gt. Yarmouth.
13/03	2141	Deployed Simrad pole and overside pump at 52°34.4N, 1°45.8E
14/03	0000	Arrived at edge of planned study region, 52°41.9N, 2°04.1E. Began large scale survey of area to determine water mass structure and overalll levels of productivity.
	0511	Deployed CTD at stn. 1585, 53°00.0N, 2°59.9E. Remained on station due to bad weather and effected essential repairs to the tracer measurement apparatus.
	0800	Bad weather abated and survey was recommenced.
	0830	Deployed continuous overside sampling pump at 53°02.9N, 2°56.3.
	1140	Suspect that overside pump lost or damaged. Hove to at 53°00.1N, 3°06.8E and hauled Simrad pole and pump onboard. Discovered that pump power connections had broken away. Continued along planned survey track and effected pump repairs.
	1309	Deployed CTD at stn. 1586, 52°54.7N, 3°23.0E, and then continued along survey track.
	1541	Deployed CTD at stn. 1587, 52°49.8N, 3°45.6E. Proceeded along survey track.
	1913	Deployed CTD at stn. 1588, 52°43.4N, 4°18.3E. Hove to on station for subsequent CTD drops.
	1940	Redeployed CTD at stn. 1588 in order to collect further water samples. Continued with survey. Weather conditions began to deteriorate.
15/03	0000	Proceeding at dead slow speed in large swell and 40kt winds.
	0200	Hove to and waited for weather to moderate.
	0745	Weather moderated. Resumed survey track toward stn. 1589.
	0848	Deployed CTD at stn. 1589, 52°32.5N, 3°24.0E. Proceeded along survey track.
	1148	Deployed CTD at stn. 1590, 52°37.9N, 3°00.2E.

		Proceeded along survey track.
	1415	Deployed CTD at stn. 1591, 52°39.8N, 3°30.0E. Proceeded along survey track.
	1642	Deployed CTD at stn. 1592, 52°26.8N, 3°46.8E.
	1705	Redeployed CTD for further samples. Proceeded along survey track.
	1935	Deployed CTD at stn. 1593, 52°20.2N, 4°18.1E. Proceeded along survey track.
	2142	Deployed CTD at stn. 1594, 52°16.0N, 3°55.0E. Proceeded along survey track.
	2348	Deployed CTD at stn. 1595, 52°12.0N, 3°30.0E. Proceeded along survey track.
16/03	0214	Deployed CTD at stn. 1596, 52°07.0N, 3°00.0E. Proceeded along survey track.
	0715	Deployed CTD at stn. 1597, 52°34.0N, 3°40.0E. End of preliminary areal survey. Proceeded towards Argos and Dahn buoy deployment position.
	1055	Arrived at deployment position, 52°20.0N, 3°20.0E, and deployed Dahn buoy.
	1102	Deployed Argos buoy at 52°20.1N, 3°20.2E. Commenced "runs" at buoy positions in order to calibrate ships "live track" plotter.
	1327	Fault developed in main radar system.
	1500	Decided to terminate "live track" calibration, recover buoys and return to Gt. Yarmouth for repairs to radar.
	1741	Arrived at Argos deployment position and commenced search for Dahn buoy.
	1854	Abandoned search for Dahn buoy and made for Gt. Yarmouth.
17/03	1600	Departed from Yarmouth, bearing 270°.
	1620	Refitted Simrad pole and overside pump.
	1802	Altered course and made for last recorded Argos buoy position.
	2350	Began radio contact with R.V. *Corystes*.
18/03	0235	Recovered Argos buoy at 53°16.8N, 3°15.5E. Initiated further search for Dahn buoy.

	0325	Abandoned search for Dahn buoy and proceeded towards planned rendezvous with *Corystes*.
	0400	Arrived at rendevouz point, 52°,20.6N, 3°22.7E. Laid off from *Corystes* to await start of tracer deployment.
	0503	Deployed CTD, stn. 1598, 52°22.0N, 3°22.7E.
	0914	Argos buoy (1) deployed, 53°20.0N, 3°20.1E, to mark beginning of tracer deployment exercise.
	1038	Argos buoy (2) deployed, 53°20.1N, 3°20.2E.
	1301	Argos buoy (3) deployed, 53°19.6N, 3°19.1E.
	1428	Argos buoy (4) deployed, 53°19.6N, 3°19.7E. End of tracer deployment exercise.
	1455	Completed transfer of personnel (A. Watson, M. Liddicoat) from *Corystes* and D. Purdie to *Corystes*. Hove to for formulation of sampling strategy.
	1700	Commenced search for Argos buoy (4) in order to locate tracer patch.
	1840	At 52°19.5N, 3°19.7E : located Argos buoy (4) from satellite fix on a bearing of 310°.
	2028	Deployed CTD, stn. 1599, 52°18.5, 3°18.8E.
19/03	0600	Made visual contact with buoy (4).
	0700	Set course to cross tracer patch and then hove to.
	1047	Dahn buoy encountered and recovered at 52°18.0N, 3°20.9E.
	1300	At 52°15.2N, 3°24.9E : Start of first tracer survey.
	1345	At 52°18.0N, 3°21.0E : Hove to in order to effect repairs following failure of tracer survey equipment.
	1830	At 52°19.0N, 3°18.9E : restarted tracer survey.
	2000	Deployed CTD 1600, 52°23.0N, 3°26.2E.
	2213	Deployed CTD 1601, 52°21.6N, 3°25.0E.
20/03	0034	Deployed CTD 1602, 52°22.8N, 3°25.8E. Continued survey run.
	0212	Deployed CTD 1603, 52°25.2N, 3°27.5E. Continued survey run.

	0409	Deployed CTD 1604, 52^{o}27.1N, 3^{o}28.3E. Continued survey run.
	0600	Stopped at 52^{o}29.4N, 3^{o}26.2E for 30 min in order to make further repairs to tracer analytical rig. Continued survey.
	2200	Located centre of tracer patch. Hove to at 52^{o}22.0N, 3^{o}26.2E in order to deploy CTD 1605. Set course for coastal survey starting co-ordinates
	2343	Commenced coastal survey for CH_4 and halocarbons.
21/03	0510	Deployed CTD 1606, 52^{o}16.4, 4^{o}14.6 Continued with coastal survey.
	1100	End of coastal survey at 52^{o}21.5N, 3^{o}44.0E. Set course for tracer patch using last recorded Argos fixes.
	1800	Began second tracer survey at 52^{o}22.5N, 3^{o}25.8E.
22/03	0220	Visual contact with buoy (4) made at 52^{o}27.7N, 3^{o}34.0E.
	1038	End of second tracer survey at 53^{o}26.2N, 3^{o}30.6E. Hove to to collect samples from overside pump. Set course for start of second coastal survey.
	1115	Start of second coastal survey for CH_4 and halocarbons at 52^{o}25.9N, 3^{o}30.5E.
23/03	1422	Recovered Argos buoy which had drifted far ahead of the tracer patch at 52^{o}30.0N, 3^{o}44.1E.
	1526	Recovered a second Argos buoy at 52^{o}33.8N, 3^{o}48.81E.
	1800	Located and hove to near to buoy (1) at 52^{o}31.3N, 3^{o}41.8E, to effect scientific repairs.
	2219	Resumed survey, weather conditions began to rapidly deteriorate.
24/03	0410	Weather conditions became to severe to continue course : wind speeds in the range 30-50 kts were recorded. Hove to at 52^{o}33.8N, 3^{o}49.5E, until conditions improve.
	1455	Weather conditions substantially improved. Commenced search for tracer patch by setting course for buoy satellite fixes.
	1518	Crossed tracer patch at 52^{o}27.5N, 3^{o}34.3E. Hove to to collect samples and then continued search for buoys.

	1651	Recovered Argos buoy (1) at 52°35.7N, 3°48.8E
	1730	Recovered Argos buoy (4) at 52°35.6N, 3°51.5E. Resumed search for tracer patch.
	2017	Hove to at 52°34.1N, 3°40.9E due to inclement weather.
	2100	Resumed course.
	2140	Located centre of tracer patch at 52°30.9N, 3°39.8E.
	2222	Hove to for discrete tracer sampling from overside pump at 52°29.9N, 3°35.4E. Continued survey
25/03	0800	Hove to for repairs to tracer survey equipment at 52°30.7N, 3°42.4E and then continued survey.
	1930	Deployed CTD, stn. 1607, at 52°34.6N, 4°18.6E.
	2202	Deployed CTD, stn. 1608, at 52°33.7N, 4°19.6E.
26/03	0002	Deployed CTD, stn. 1609, at 52°30.9N, 4°17.6E.
	0201	Deployed CTD, stn. 1610, at 52°30.0N, 4°16.7E.
	0400	Deployed CTD, stn. 1611, at 52°29.8N, 4°14.6E.
	0602	Deployed CTD, stn. 1612, at 52°33.6N, 4°19.1E. End of third tracer survey. Science completed.
	0703	Last remaining Argos buoy recovered at 52°35.0N, 4°19.4E. Set course for return to Gt. Yarmouth.

SUMMARY OF CTD STATIONS SAMPLED

The following variables derived from the CTD package were recorded at all stations: temperature, salinity, fluorescence, transmissivity, oxygen electrode, upwelling irradiance, downwelling irradiance.
At all stations, water samples were taken at 2, 10, and 25 m.
Where samples were collected for CH_4, these are denoted by 'M'.

DATE	TIME	LAT(N)	LONG (E)	STN NO.	
14/03	0511	53°00.0	2°59.9	1585	M
	1305	52°54.9	3°23.6	1586	M
	1530	52°50.0	3°46.0	1587	M
	1932	52°43.8	4°19.0	1588	M
15/03	0840	52°32.4	3°24.0	1589	M
	1145	52°38.0	3°00.3	1590	M
	1410	52°39.8	3°30.0	1591	M
	1636	52°27.1	3°46.9	1592	M
	1930	52°20.1	4°18.1	1593	M
	2140	52°16.0	3°55.0	1594	M
	2341	52°12.0	3°30.2	1595	M
16/03	0210	52°07.0	2°59.9	1596	M
	0711	52°33.9	3°39.9	1597	M
18/03	0450	52°20.3	3°22.5	1598	M
	2030	52°18.2	3°18.9	1599	M
19/03	2000	52°22.9	3°26.2	1600	M
	2213	52°21.7	3°25.0	1601	
20/03	0034	52°22.8	3°25.8	1602	
	0212	52°25.1	3°27.5	1603	
	0409	52°27.0	3°28.3	1604	
	2200	52°21.8	3°26.2	1605	
21/03	0500	52°16.2	4°14.4	1606	
25/03	1942	52°34.7	4°19.7	1607	M
	2158	52°33.8	4°19.6	1608	
26/03	0000	52°31.0	4°17.6	1609	
	0200	52°30.0	4°16.2	1610	
	0400	52°29.8	4°14.6	1611	
	0602	52°33.6	4°19.1	1612	

ACKNOWLEDGEMENT

The science party would like to record their appreciative thanks to the officers and crew of *Challenger* for helping to make this a successful cruise.

FIGURE LEGENDS

1) The tracer release study area

2) Gas evasion rates determined during this cruise compared with rates determined by the radon deficit and carbon-14 budget techniques. The graph summarises all the values so far in the literature for gas exchange measurements at sea.

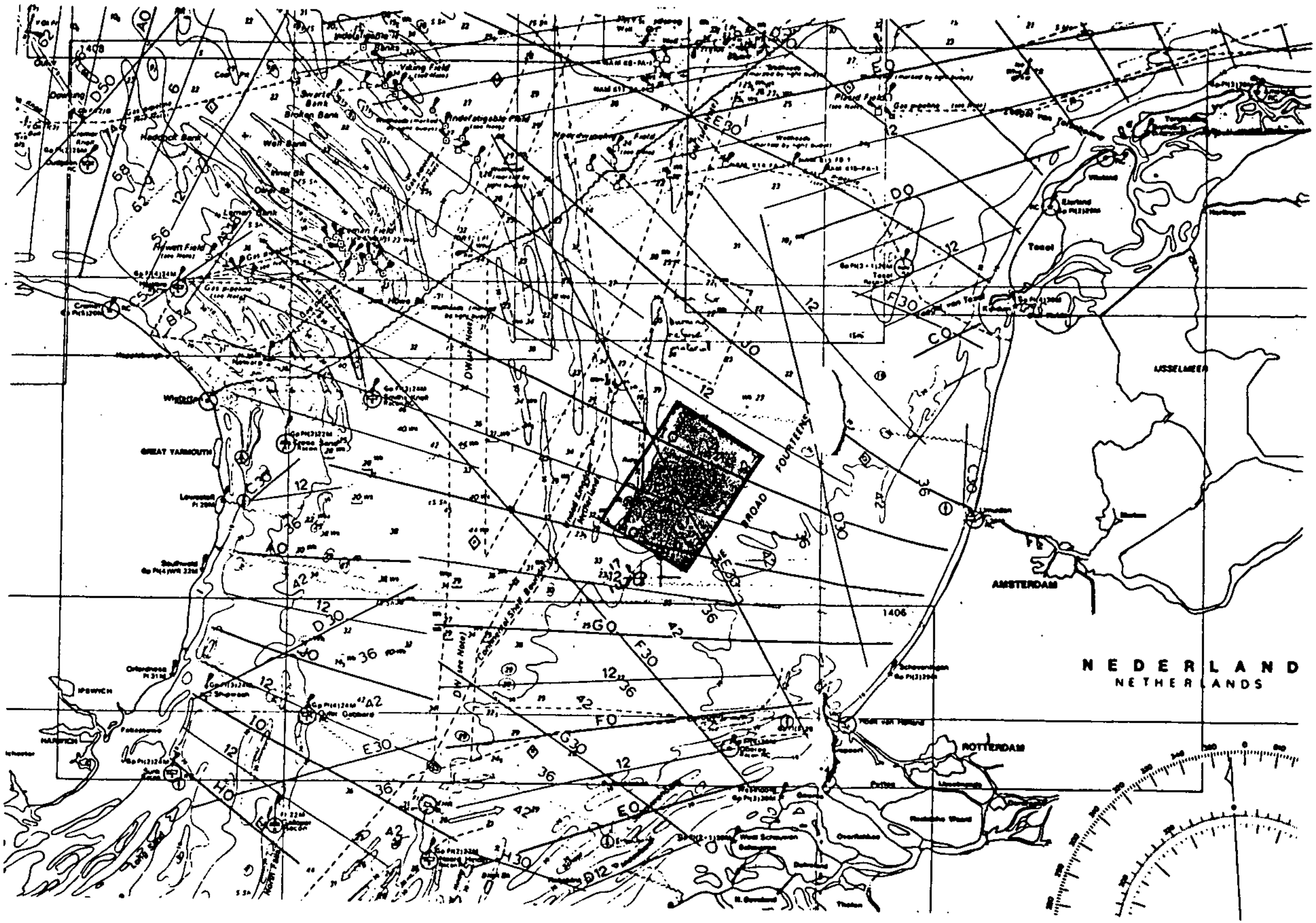

FIGURE 1. The study region, centered on 52° 30' N, 3°, 30' E.

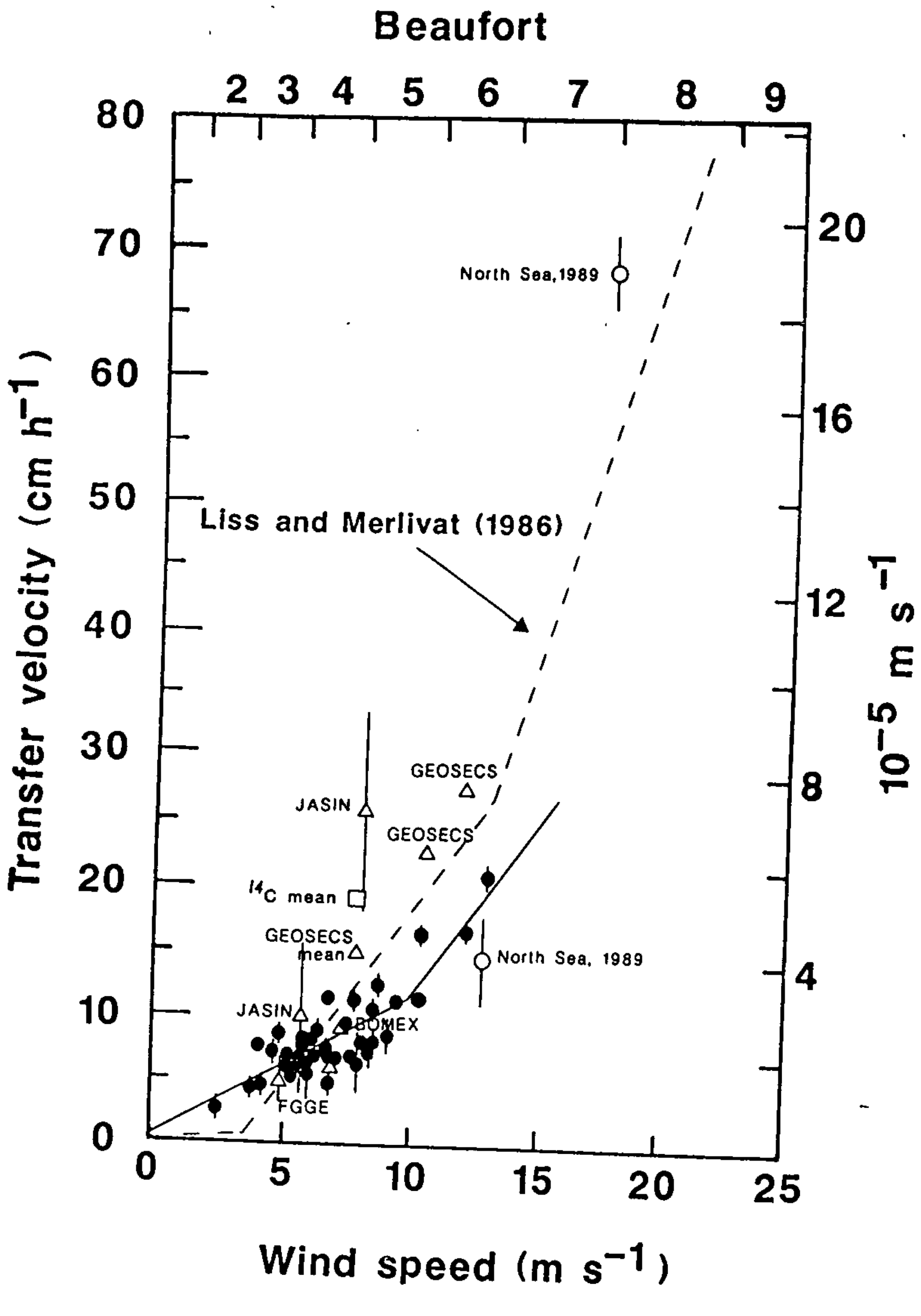

FIGURE 2. Gas transfer velocities as a function of windspeed and the corresponding Beaufort scale number: ○, our preliminary North Sea results determined by the ratio method; ●, recent lake results from our laboratory determined from SF_6 budgeting; △, ocean radon averages [24,25]; □ global ocean bomb-^{14}C mean [9]. The Liss and Merlivat curve [26] is an extrapolation of field and wind tunnel data based on model equations. All data refer to CO_2 at 20 ^oC with windspeeds normalised to a height of 10 m.