the contribution of sulphur dioxide emissions from ships to coastal deposition and air quality in the channel and southern north sea area

Prepared for the CONCAWE Air Quality Management Group, based on work carried out by the Special Task Force (AQ/STF-40):

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ABSTRACT

The purpose of this report is to present a detailed analysis of the impact of sulphur emissions from ships within the heavily trafficked southern North Sea and Channel as a contribution to the debate on the need to limit the sulphur content of bunker fuels.

The fuel consumed by all shipping in the study area was estimated at 4 Mt/year. This compares to a bunker production in Europe of some 25 Mt/year.

The study clearly identifies in-port emissions as a significant source of ship emissions in the study area with ships in port contributing some 26% of the total emissions from ships. As a consequence, the data presented show that in the major ports of Rotterdam, Europoort, Antwerp and Le Havre, ships make a significant contribution to atmospheric concentrations of sulphur dioxide. In addition, they contribute significantly to overall deposition. Throughout the study area, the contribution of ships operating outside territorial waters was less than 5% of total deposition.

In areas where ship emissions contribute most significantly to overall deposition and air quality, the study indicates that emission reduction measures in just four of the major ports (of the 80 ports in the study area) would offer a greater benefit to the environment than the control of all at-sea ship emissions within the study area. Furthermore, the cost of achieving a unit reduction in deposition in such areas through in-port control is some 10-20% of the cost for control of ships operating outside the 12 mile territorial limit.

KEYWORDS

Ships, ports, emissions, sulphur dioxide, modelling, deposition, air quality

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SUMMARY

Over the past several years, the International Maritime Organization has been developing an Air Pollution Annex to the UN Convention on Maritime Pollution (MARPOL 73/78). Among other pollutants to air, this annex will address sulphur dioxide emissions. At the beginning of this process the focus was on stringent "global" reductions of SO_2 emissions from ships. Recent developments have refocussed on the "special areas" concept. With this approach, any required reductions in emissions would be confined to ships sailing within designated areas where their emissions contribute significantly to an identified environmental problem. The purpose of this study is to provide data to assist in the process of designating such special areas.

The study assesses the impact of SO_2 emissions from ships in the Channel and southern North Sea on both air quality and deposition. The study area is bounded in the north by a line from Great Yarmouth to Den Helder and to the south by a line from Portland Bill to Cap de la Hague. This area, of some 70 000 square kilometres, represents one of the most heavily trafficked shipping areas in the world, with more than 290 000 ship movements in excess of 250 gross registered tonnes and some 270 000 port visits each year. It also includes a number of very large ports such as Rotterdam and Antwerp. The results of this study are documented in detail in the emissions inventory report "Quantifying Marine Sulphur Emissions in the Southern North Sea and English Channel" and the deposition/air quality modelling report "The Contribution of Sulphur Dioxide emissions from Ships to Coastal Acidification". These reports are available from CONCAWE. This report serves to summarize the main findings of these studies.

The study clearly identifies in-port emissions as a significant source of ship emissions in the study area, with ships in port contributing some 26% of the total emissions from ships. These emissions are from essentially static sources located near to land. As a consequence, the data presented show that in the major ports of Rotterdam, Europoort, Antwerp and Le Havre, they contribute to high atmospheric concentrations of sulphur dioxide. In addition, they also contribute significantly to overall deposition.

Comparison of ship deposition with EMEP total deposition indicates that in only nine out of the 315 land grid squares in the study area (less than 3%) does the contribution of ship emissions exceed 10% of the total. In the four land grid squares with the highest percent contribution from ships, the dominant source was in-port emissions. In the two grid squares with the highest deposition from ships, emissions from the ports of Rotterdam, Europoort and Antwerp alone were found to contribute more to these two squares than all the at-sea movements in the study area.

Given their proximity to land, a higher proportion of in-port emissions deposit on land than emissions from ships at-sea. Therefore, assuming that the costs of reducing sulphur emissions per unit of fuel consumed are constant, it is more cost effective to reduce in-port than at-sea emissions to achieve a given reduction in deposition to land. Based on the study data, CONCAWE estimates that for the four grid squares with the highest percent contribution from ships, the relative cost of in-port control is some 10-20% of that for control of ships outside territorial waters (12 mile limit) and some 15-50% of that for control within territorial waters.

In the remaining five grid squares where the contribution of ships to total deposition exceeds 10%, the contribution of ships within territorial waters is

the most significant source of the ship contribution to overall sulphur deposition on land. For these grid squares, the relative cost of control for ship emissions within territorial waters was found to be some 30% of that for ships outside these waters.

The results of this study indicate that even in this highly trafficked area, apart from the four grid squares effected by high in-port emissions and five grid squares effected by ships operating within territorial waters, ships emissions are not a significant contribution to deposition. Throughout the study area, the contribution of ships operating outside territorial waters was less than 5% of total deposition.

In areas where ship emissions contribute most significantly to overall deposition and air quality, the study indicates that emission reduction measures in just four of the major ports (of the 80 ports in the study area) would offer a greater benefit to the environment than the control of all at-sea ship emissions within the study area. Furthermore, the cost of achieving a unit reduction in deposition in such areas through in-port control is some 10-20% of the cost for control of ships operating outside the 12 mile territorial limit.

1. INTRODUCTION

Over the past several years, the International Maritime Organization has been developing an Air Pollution Annex to the UN Convention on Maritime Pollution (MARPOL 73/78). Among other pollutants to air, this annex will address sulphur dioxide emissions. At the beginning of this process the focus was on stringent "global" reductions of SO_2 emissions from ships. Recent developments have refocussed on the "special areas" concept. (i) With this approach, reductions in emissions would be confined to ships sailing within designated areas where their emissions contribute significantly to an identified environmental problem (e.g., acid rain critical load exceedance or high levels of SO_2 concentrations at ground level). The purpose of this study is to provide data to assist in the process of designating such special areas.

CONCAWE's earlier study on "The European Environmental and Refining Implications of Reducing the Sulphur Content of Marine Bunker Fuels" [1] was largely based on the results of the regional modelling work carried out under the UN-ECE EMEP programme. Whilst this study served to demonstrate that global reductions in the sulphur content of bunker fuel oil are not justified, it also highlighted the need for further work on the local impact of ship emissions.

Given this background, CONCAWE commissioned a major study of the impact of SO_2 emissions from ships in the Channel and southern North Sea. This area of some 70 000 square kilometres represents one of the most heavily trafficked shipping areas in the world, with more than 290 000 ship movements in excess of 250 gross registered tonnes (GRT) and some 270 000 port visits each year. It includes a number of very large ports such as Rotterdam and Antwerp. The results of this study are documented in detail in the emissions inventory report "Quantifying Marine Sulphur Emissions in the Southern North Sea and English Channel" [2] and the deposition/air quality modelling report "The Contribution of Sulphur Dioxide emissions from Ships to Coastal Acidification". [3] These reports are available from CONCAWE. This report serves to summarize the main findings of the study.

Footnote: (i) A so-called "global sulphur cap" designed to avoid increases in current levels of sulphur emissions from ships is also being discussed.

2. SCOPE OF STUDY AND METHODOLOGY

This study is the most detailed analysis of its type. It is based on a very comprehensive inventory of ship emissions and on calculations of sulphur dispersion and deposition on a fine spatial scale.

The area considered is shown in **Figure 1**. It is bounded in the north by a line between Great Yarmouth and Den Helder, and in the south by a line from Portland Bill to Cap de la Hague.

The work was carried out in two distinct stages. Firstly a detailed emission inventory for the area was generated in which all emissions from ships were assigned to line or point sources. Secondly a source-receptor model was developed that estimated the air concentration and deposition of sulphur from the emission inventory.

The development of the emission inventory and of the source-receptor model are dealt with in detail in the subsequent two sections.

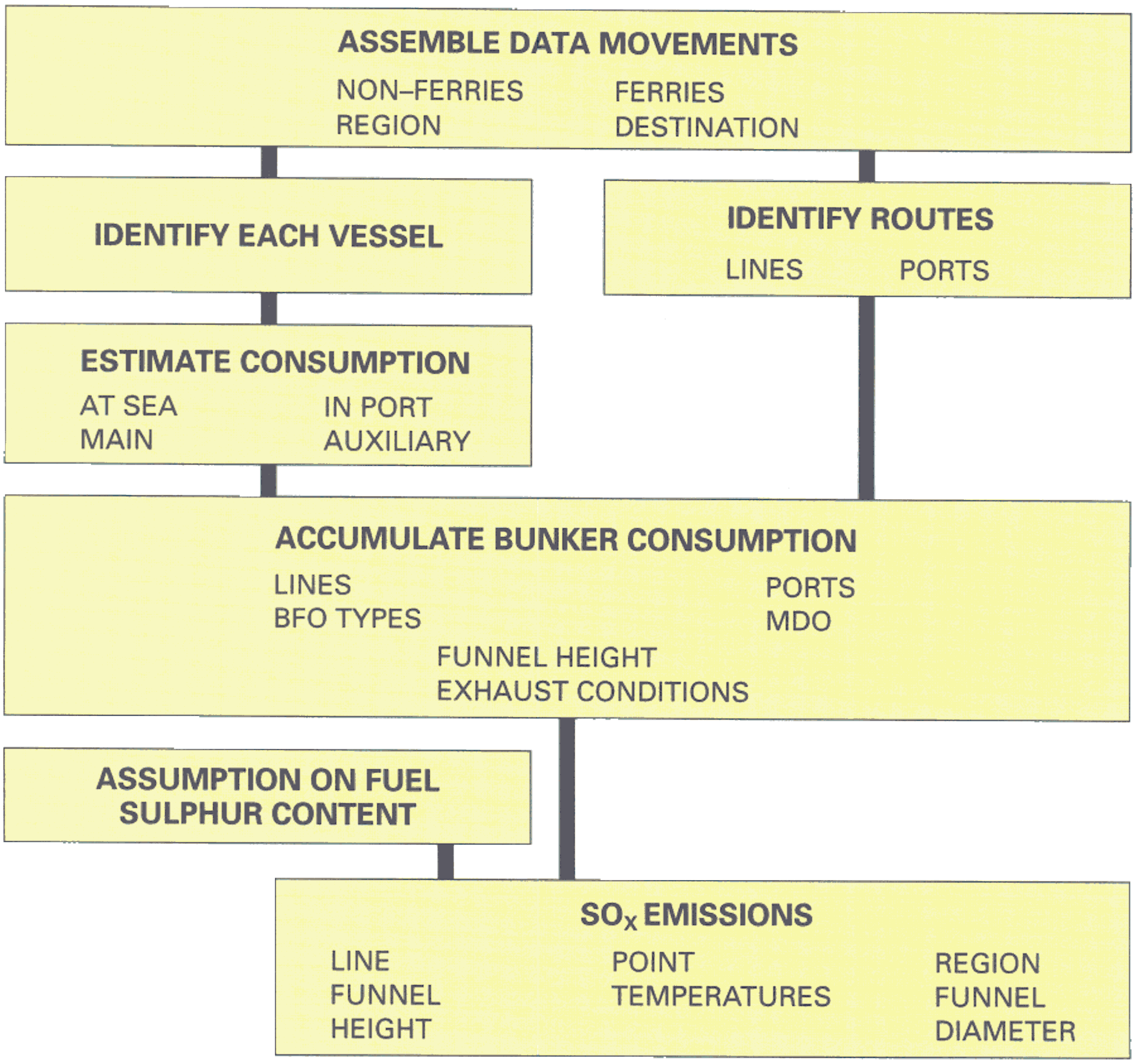
Figure 1: Map of study area

3. DEVELOPMENT OF SULPHUR EMISSION INVENTORY

The sulphur emission inventory was prepared by maritime consultant Robin Meech with assistance from a number of other experts. [2]

The overall approach is outlined in **Figure 2**. The main steps in the process are described below.

Figure 2: Approach to development of emissions inventory



3.1. TRAFFIC

Data obtained from Lloyds Register of Shipping and from ferry operators allowed each vessel known to have operated in the study area in 1992 to be identified. The traffic patterns and details of the fleet operating in the study area are tabulated below:

Traffic Patterns
1000s Movements

	Non Ferries	Ferries	Total
Within study area	58	85	143
Into the area	61	2	63
Out of the area	61	2	63
Through traffic	24	0	24
Total	204	89	293

Fleet Statistics

	Non Ferries	Ferries	Total
Movements (1000s)	204	89	293
Number of vessels	11400	80	11480
Average vessel GRT	9700	7800	9130
Average movements per vessel	18	1110	25

Note: Only 1.7% of the vessels had steam propulsion systems.

Unreported movements such as fishing vessels, pleasure craft and naval vessels were estimated to contribute an additional 3% to total movements and emissions in the area.

Putting these data into context, world fleet statistics of ships above 250 gross registered tonnes (GRT) show some 58 000 vessels with a total tonnage of 442 million GRT and an average tonnage of 7620 GRT.

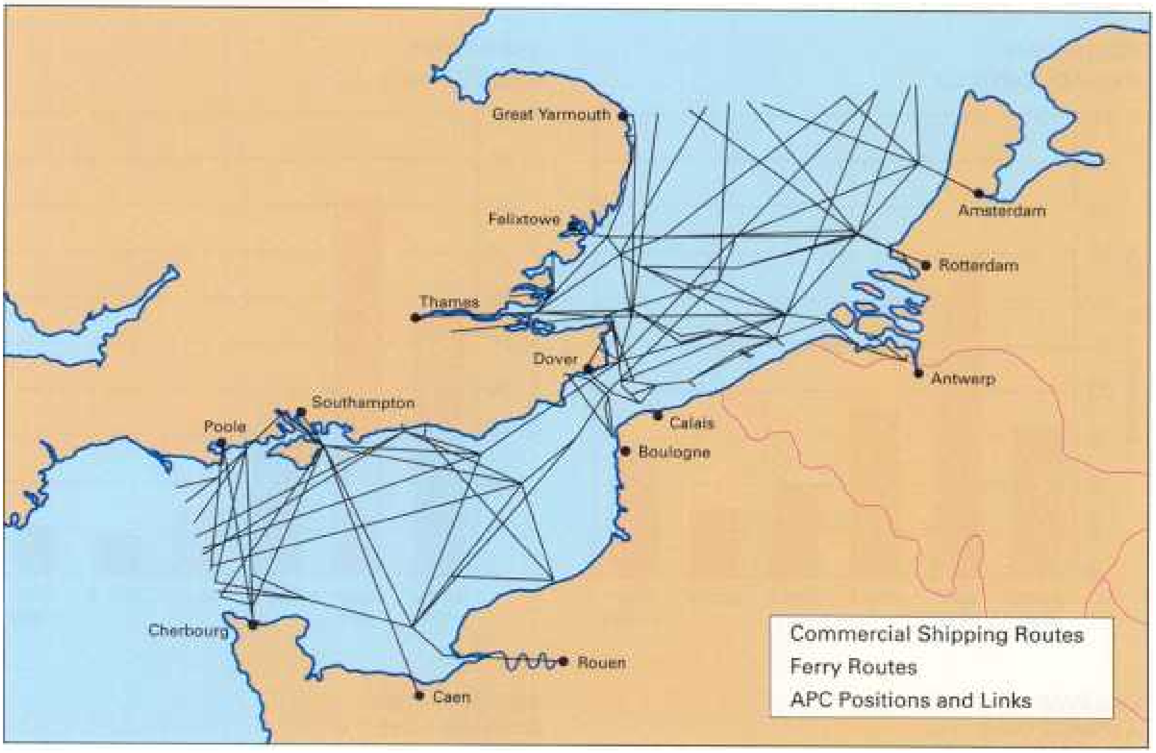
3.2. ROUTES

All shipping routes in the study area were defined as a series of 'links' which followed the actual traffic patterns. Emissions were assumed to be constant along the length of each link. Four types of link were identified, viz

- predominantly used by non-ferry traffic within study area
- used by through traffic
- predominantly used by ferries
- short connections within estuaries and port approaches.

A map of the commercial shipping and ferry routes are shown in **Figure 3**.

Figure 3: Shipping routes



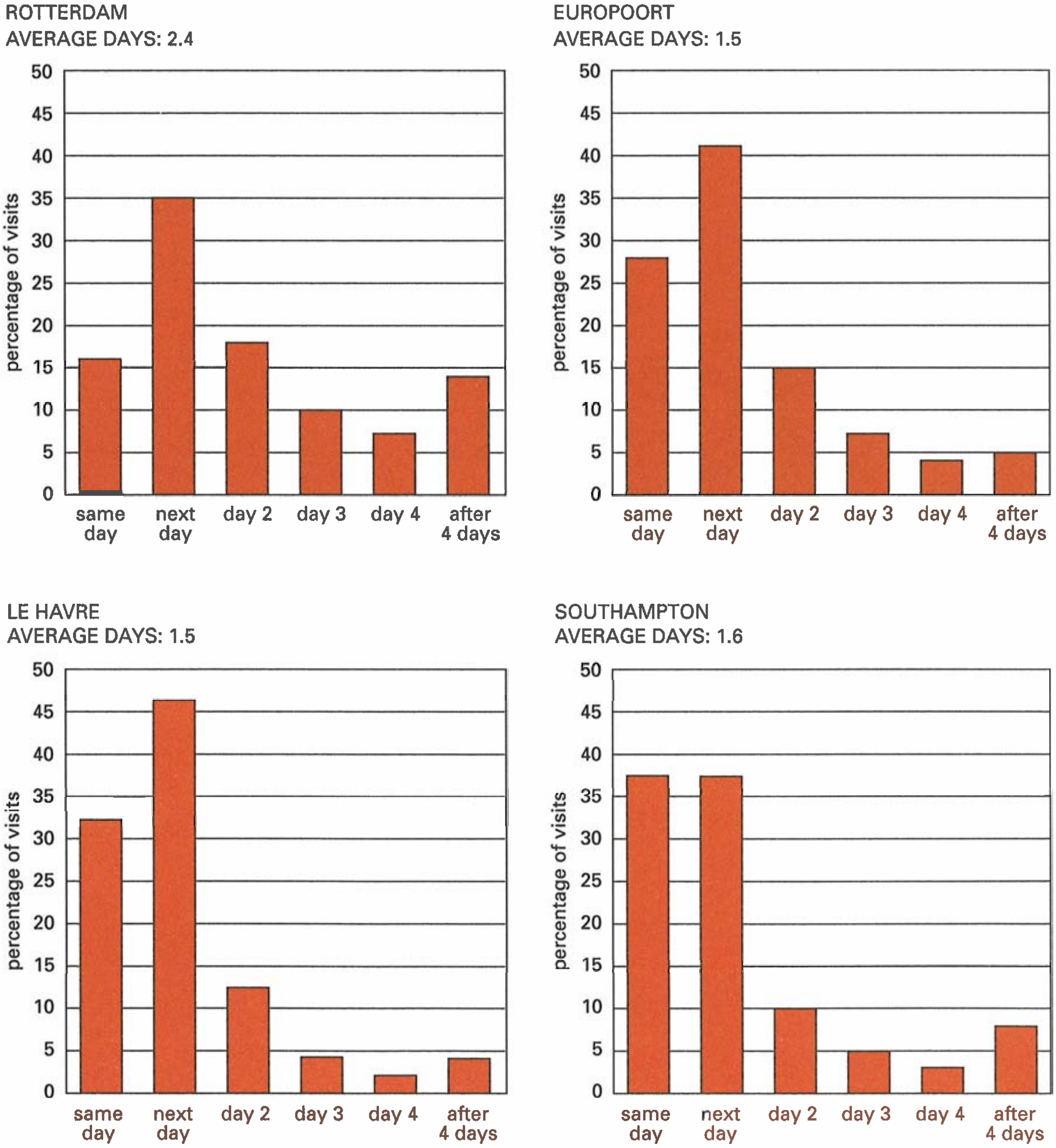
3.3. PORT VISITS

The time spent in port is a significant factor in the estimation of in-port emissions. For ferries actual times were reported by ferry operators; the average stay was 6.4 hours. This is very short compared with non-ferry type traffic where unloading/discharging times result in much longer turnaround times.

Time in port for other vessels was estimated individually from Lloyd's data. Typical data for four ports in the study area are shown in **Figure 4**.

These times compare with an average time at-sea in the study area of some 12 hours.

Figure 4: Typical time in port - excluding ferries



3.4. FUEL CONSUMPTION

For each vessel, the rates of consumption of fuel oil (BFO) and marine diesel oil (MDO) at sea were estimated taking into account sizes of main and auxiliary engines, ship type and age, average load factor and actual speed relative to service speed.

Similar estimates were made for in-port consumption taking into account manoeuvring time, average time in port and pumping operations where appropriate. It is important to note that there are large differences in in-port consumption between vessel types. For example, the unloading of oil tankers, gas tankers and other tankers requires about 40% of main engine-at-sea fuel consumption (in tons/day). This can rise to 70% for larger oil tankers and 100% for LNG tankers. While for other types of vessels, including ferries, consumption is 10% or less.

For ferries, detailed information was made available from operators which allowed for accurate estimates to be made of consumption.

Information on engine size and type, ship design and vessel size was used to estimate funnel heights and diameters and exhaust velocities and temperatures. These values were grouped in the emissions inventory into 5 funnel heights, 8 funnel diameters and 2 exhaust temperatures.

3.5. FUEL SULPHUR LEVELS

Data on the sulphur levels of MDO and the three grades of BFO supplied in the study area were obtained from Det Norske Veritas (DNV). These data are tabulated below. The averages values for each fuel type were used in this study.

Sulphur Content of Bunker Fuel Oils - 1992 (Percent)

Viscosity cSt at 50°C at 100°C	15–100 5–15	100–250 15–30	250+ 30–35	Average all grades	Marine distillates
Fuel type	Low	Medium	High		
Amsterdam	2.50	3.01	3.20	3.10	1.44
Rotterdam	2.53	2.96	3.24	3.14	1.25
Antwerp	2.32	2.77	3.03	2.91	1.14
Flushing	2.16	2.84	3.01	2.80	0.80
Zeebrugge	2.58	2.79	3.10	2.93	1.29
Dunkirk	1.65	2.61	2.78	2.70	0.56
Le Havre	2.27	2.90	3.04	2.92	0.27
Rouen	2.57	3.24	3.39	3.09	0.26
Southampton	2.03	2.30	2.38	2.32	0.13
Thames Estuary	2.60	2.49	3.13	2.86	0.25
Average	2.41	2.89	3.16	3.04	1.18

3.6. MARINE FUEL CONSUMPTION AND SULPHUR EMISSIONS

Data on movements, fuel type, rate of fuel consumption and routes were then used to generate the inventory of sulphur emissions along some 280 individual routes (represented as line sources) and for 80 ports (represented as point sources). For the 11 largest ports in the study area, a more detailed approach was used to develop the emissions data and to identify the centre of activity in the ports.

The total amount of fuel consumed by ships (including in port consumption) in the study area was nearly 4 Mt/year. This compares with an overall total of some 25 Mt/year bunker fuel oil produced by European refineries. The breakdown into fuel type, vessel category and whether consumed at sea or in port is tabulated below. Consumption in port constituted 29% of the total.

Marine Fuel Consumption 1992 (kt/yr)

	Bunker Fuel Oil				Distillates
Viscosity	High	Medium	Low	Total	
<u>At-Sea</u>					
Non-Ferries	1397	172	84	1653	392
Ferries	17	454	128	599	87
Other	42	19	6	67	14
Sub Total	1456	645	218	2319	493
<u>In-Port</u>					
Non-Ferries	447	49	24	520	296
Ferries	1	135	68	204	44
Other	13	6	3	22	77
Sub Total	461	190	95	746	417
Total	1917	835	313	3065	910

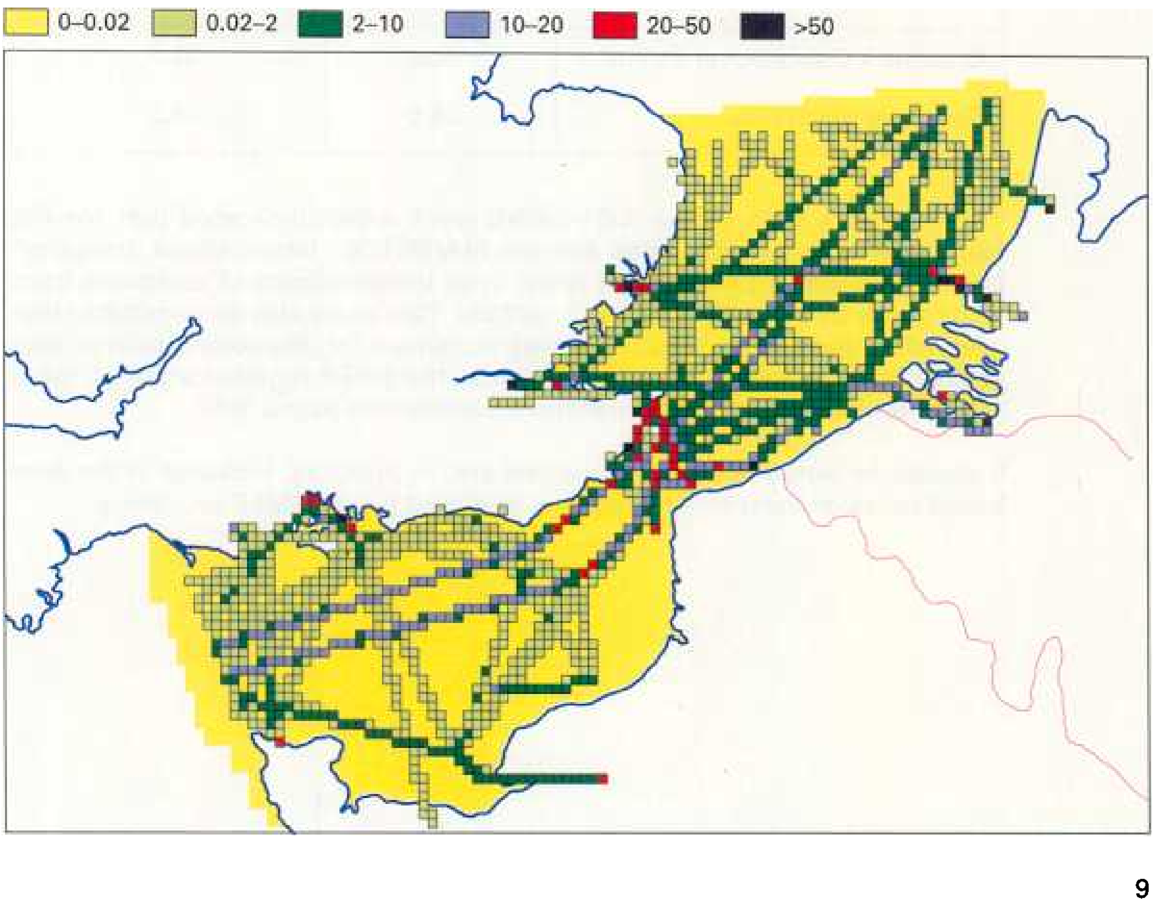
The corresponding sulphur emissions from ships in the study area were estimated to total some 100 kt/year, of which 26% ocurred in port. A detailed breakdown is given opposite.

Marine Sulphur Emissions 1992 (kt/yr)

	Bunker Fuel Oil				Distillates
Viscosity	High	Medium	Low	Total	
<u>At-Sea</u>					
Non-Ferries	44.5	5.0	2.0	51.5	4.6
Ferries	0.5	13.1	3.1	16.7	1.0
Other	1.4	0.5	0.1	2.0	0.2
Sub Total	46.4	18.6	5.2	70.2	5.8
<u>In-Port</u>					
Non-Ferries	14.2	1.4	0.6	16.2	3.5
Ferries	0.1	3.9	1.6	5.6	0.5
Other	0.3	0.2	0.1	0.6	0.9
Sub Total	14.6	5.5	2.3	22.4	4.9
Total	61.0	24.1	7.5	92.6	10.7

The ports of Amsterdam, Rotterdam, Europoort, The Hook, Antwerp and Le Havre (6 of the 80 ports in the study area) account for 50% of total in-port emissions. This reflects both the size and high proportion of tanker traffic (high in-port consumptions) in these ports. The detailed sulphur emission inventory mapped onto individual shipping lanes and ports in the study area is shown below.

Figure 5: Emissions (t(SO_x)/km^2/year) mapped onto shipping lanes and ports



This clearly shows the high rates of emission along the busiest shipping lanes and in the major ports. This data, in computer code form, was used in the dispersion and deposition model described in **Section 4.**

3.7. COMPARISON WITH EMEP EMISSION DATA

One of the concerns that has been expressed in the discussions within IMO has been the reliability of the ship emission inventory used by the EMEP in their regional modelling work.[4] The ship emissions data used by EMEP is derived from work by MARINTEK.[5] This was developed using data on international trade and therefore did not include the contribution from ferries or national shipping. Given the fact that all categories of shipping were accounted for in the CONCAWE study, the ship emission data in this study have been compared to those developed by MARINTEK as a check on the robustness of the data used by EMEP.

Using data from the MARINTEK study, a "MARINTEK" ship emissions inventory was developed for the three zones in the study area; the Channel, the Calais/Dover Straits and Southern North Sea. The MARINTEK data were found to be in close agreement with the more detailed inventory developed for this study for the Channel and Calais/Dover Straits. However, for the Southern North Sea area, the figures indicate that Marintek underestimates the emissions by about 50%. For the total study area the MARINTEK inventory appears to underestimate emissions by some 25%

A comparison table for annual sulphur emissions in kt is given below:

	MARINTEK	CONCAWE (At-Sea)
Channel + Calais/Dover Straits	36.5	38.7
Southern North Sea	24.5	37.3

This is in-line with earlier CONCAWE work which indicated that for the Norwegian Sea and the Baltic Sea the MARINTEK "International Shipping" inventory (used by EMEP) could result in an underestimate of emissions from ships at-sea by some 30-50%. (ref.1, p27/28) This study also demonstrated that even when such an underestimate was accounted for, the contribution of ship emissions to overall sulphur deposition at the EMEP regional scale of 150 x 150 km remained low (with a maximum contribution below 10%)

It should be noted that port emissions are, in principle, included in the land based emission inventory reported to, and used by, the EMEP modellers.

4. THE OFFSHORE COASTAL AND PORT DISPERSION MODEL

Modelling of sulphur dispersion and deposition was carried out by the Imperial College Centre for Environmental Technology (ICCET). ICCET has been involved in running the UK ASSAM model to assess abatement strategies on behalf of the UK Department of the Environment for input to the development of the revised UN-ECE sulphur protocol.

The ICCET project for CONCAWE involved computer modelling of the dispersion and deposition of sulphur dioxide emitted from ships, allowing for the different characteristics of dispersion over sea and land surfaces. The Offshore Coastal and Port Dispersion Model (OCPD) developed by ICCET is a source-receptor model that estimates the air concentration and deposition of sulphur emitted by ships at-sea and in port.

4.1. OCPD MODEL DESCRIPTION

OCPD is a short range Gaussian plume diffusion model, whose rationale was based along the lines of the R-91 model [6] used to simulate atmospheric dispersion following an accidental nuclear release. OCPD assumed that the vertical dispersion of material is characterised by a Gaussian distribution, while the horizontal dispersion, for a continuous release, is uniform across a sector of fixed angle. In addition, the model assumed different dispersion characteristics as the plume moved over land and sea surfaces. Pollutant concentrations and depositions are calculated for each Pasquill stability category. The mixing layer depth, for receptors on land, varies according to the Pasquill stability class, but is fixed over the sea at a depth that is consistent with neutral meteorological conditions. The model contains several optional features which include plume rise, and an estimation of the contribution of sulphur deposition from ships sailing within a country's territorial waters.

4.2. MODEL RESOLUTION

UK land areas were modelled on a 20x20 km gridscale and Continental land areas on 25x25 km gridscale. This provides significantly more detailed data than available from the 150x150 km gridscale of EMEP. The major ports were modelled on a 1x1 km gridscale to enable a more detailed assessment of the contribution of ships in port to overall air quality.

4.3. DEPOSITION

The OCPD model differentiates between the characteristics of sulphur dioxide and sulphate. Sulphur dioxide is slowly oxidized to sulphate at the rate of 1% per hour which unlike SO_2 is subject to significant dry deposition. The model used source depletion techniques to simulate dry deposition processes.

The model assumes that the amount of scavenging of sulphur dioxide and sulphate by wet deposition is dependent on the annual average rainfall at the receptor, which is a function of the receptor position and altitude, thus allowing for any orographic enhancement. In addition the model assumes that wet deposition is dependent on the transitions between wet and dry periods and these in turn are related to wind direction. Under normal running conditions the dry deposition and washout coefficients used by OCPD for sulphur dioxide and sulphate are similar to those used by the EMEP model.

4.4. PLUME RISE

Hot gases released into the atmosphere will exhibit significant thermal buoyancy. Obviously deposition at the ground is a function of release height and consequently very different results are obtained when comparing the deposition fields of thermally buoyant and ambient plumes. This is particularly true close to the release point. Studies undertaken for this work showed that the exhaust gas temperature for ships varied from between 280 and 370°C, whilst the average exhaust gas velocity was around 30 m/s. The OCPD model incorporated a plume rise module.

Since the results with the plume rise option on are more likely to reflect the effective release heights these data have generally been used in this summary report.

4.5. METEOROLOGICAL DATA

Meteorological conditions within the region of interest were interpolated from Pasquill stability frequency analysis data supplied by the UK Meteorological Office. These data were averaged over a 10 year period and contained wind speeds, wind directions and Pasquill stability classes measured at 4 meteorological stations lying within the region of interest.

4.6. DISPERSION AND DEPOSITION ESTIMATES

Using the emission inventory described above the OCPD model was used to generate maps of air concentrations of sulphur dioxide and of sulphur deposition. These figures are based only on emissions from within the study area and do not include the transport of emissions into the area from ships operating outside the study area. However, these emissions are only likely to influence the grid squares on the eastern boundary of the study area (given the prevailing wind direction). The modelling results are analysed in detail in **Section 5.**

5. ASSESSMENT OF RESULTS FROM THE OCPD MODEL - 20x20 AND 25x25 KM GRID SQUARES

5.1. AIR QUALITY

Figure 6: Contribution to Annual Mean SO_2 Concentrations ($\mu g/m^3$)

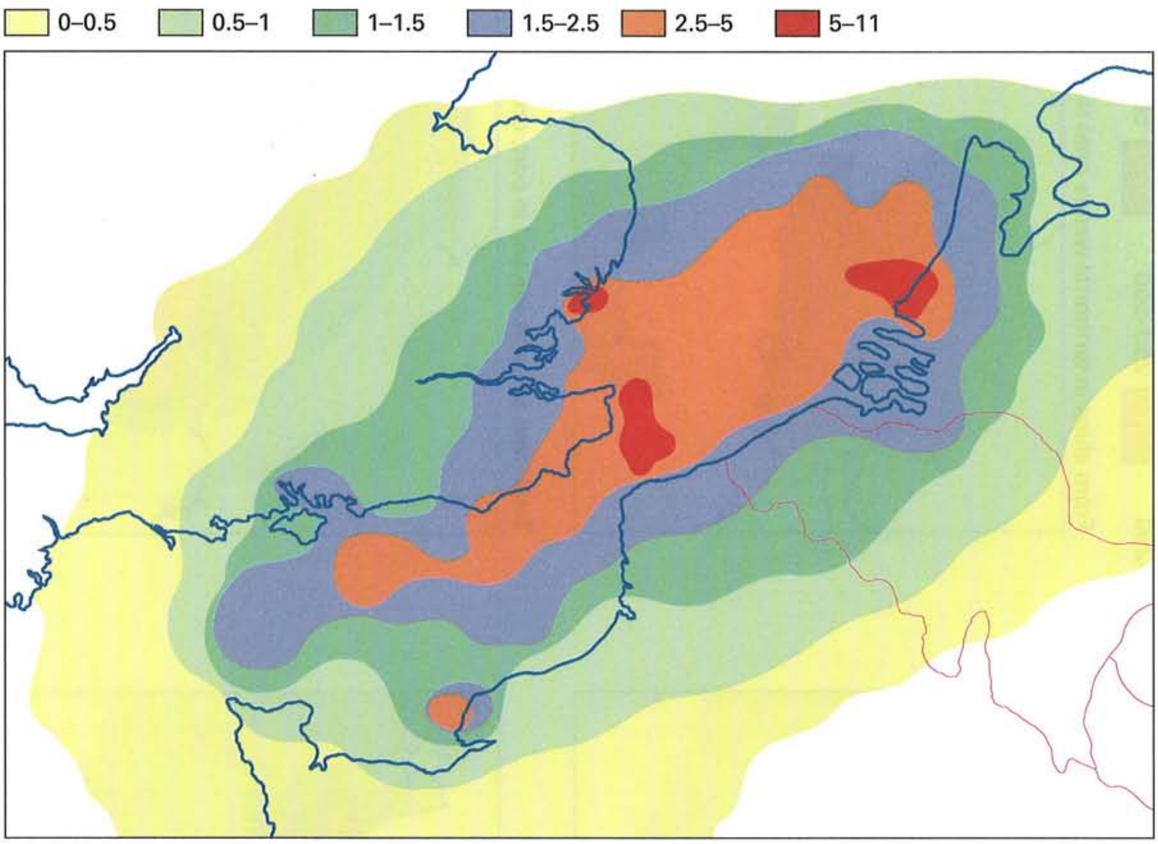
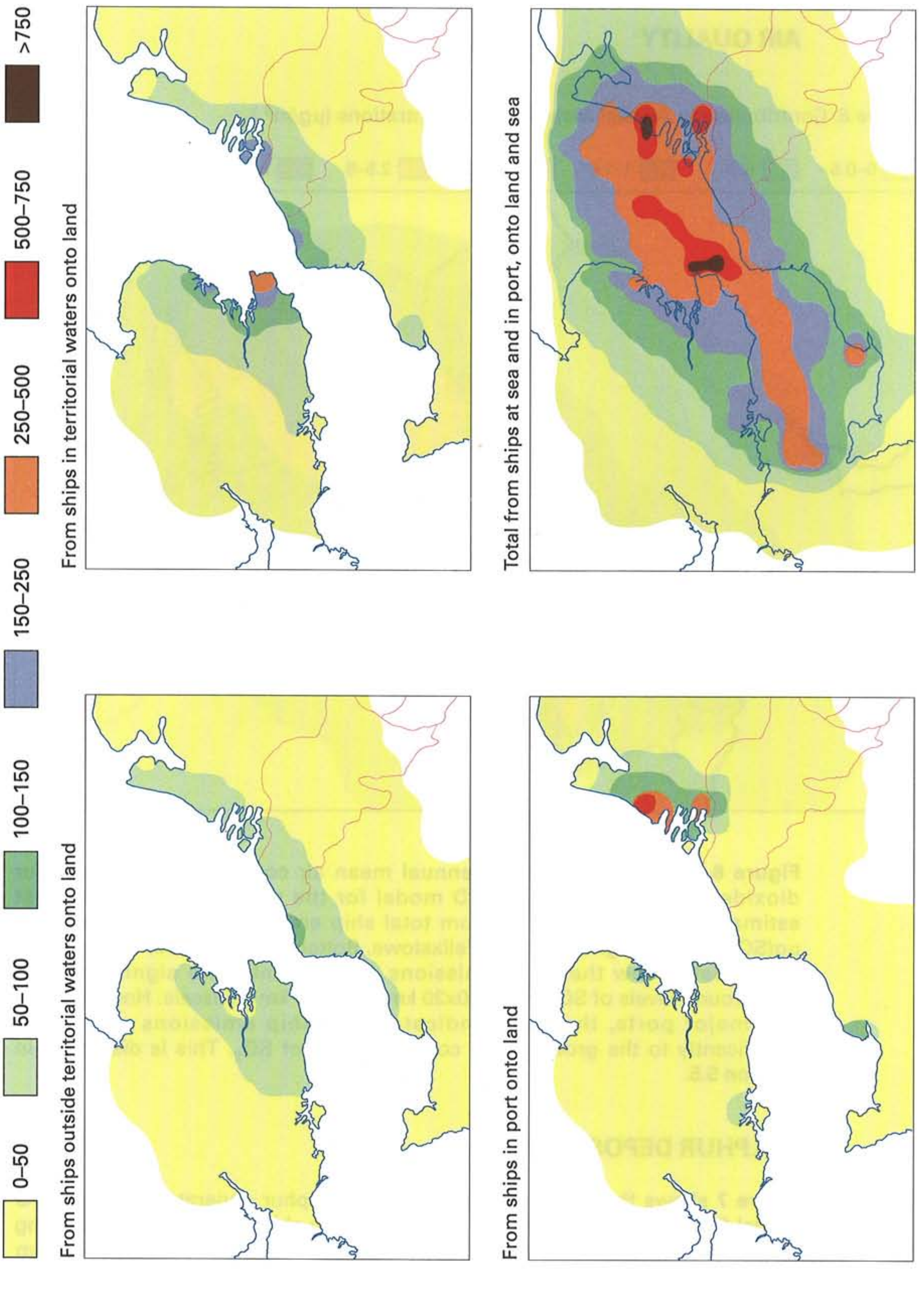


Figure 6 shows the estimated annual mean air concentrations of sulphur dioxide generated by the OCPD model for the study area. The highest estimated air concentrations from total ship emissions of 5.5, 5.2 and 4.5 $\mu g(SO_2)/m^3$ are in grids close to Felixstowe, Rotterdam and Dover respectively. These data show that ship emissions do not contribute significantly to background levels of SO_2 at the 20x20 km or 25x25 km gridscale. However, in a few major ports, the study indicates that ship emissions contribute significantly to the ground level concentrations of SO_2. This is discussed in **Section 5.5.**

5.2. SULPHUR DEPOSITION

Figure 7 shows the estimated depositions of sulphur generated by the OCPD model for the study area. The contribution from ships at sea, ships operating within 12 nm of the shore (territorial waters) and ships in-port are shown separately in order to appreciate the relative importance of each of these categories to the total deposition from ships.

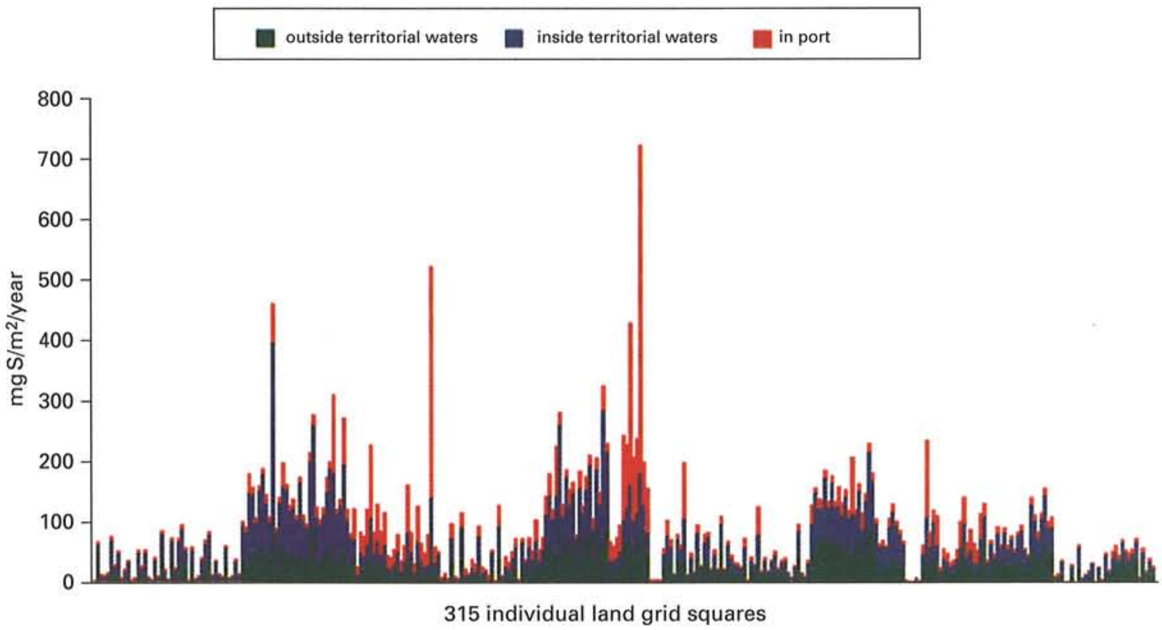
Figure 7: Contribution of ships to sulphur deposition (mg/(S)/m^2/year)



The highest levels of deposition are in the grids close to Rotterdam/Eurooport, Antwerp and the Calais/Dover Straits. Rates of deposition from total ship emissions are estimated by the OCPD model as 732, 528 and 465 mg/m^2/year respectively.

A detailed analysis has been made of all of the OCPD land grid squares (some 315 in the study area) in order to compare the relative contributions from ships in port, in territorial waters and outside territorial waters. These data are shown in **Figure 8** below.

Figure 8: Source Contributions to Total Deposition from Ships



For **In port** emissions:

- The highest rate of deposition is 549 mg/m^2/yr in the grid square including Rotterdam.
- In 3 grid squares deposition exceeds 200 mg/m^2/yr.
- A total of 10 grid squares have depositions in excess of 100 mg/m^2/yr.
- They contribute about 75% of the deposition from ships in the two grid squares, close to Rotterdam/Eurooport and Antwerp, that receive the highest deposition from ships.

For emissions from **within territorial waters:**

- The highest rate of deposition is 308 mg/m^2/yr in the grid including Dover and Ramsgate.
- In 2 grid squares deposition exceeds 200 mg/m^2/yr.
- A total of 15 grid squares have depositions in excess of 100 mg/m^2/yr.
- They contribute up to 66% of deposition from ships in the grid squares close to the busiest shipping lanes.

For emissions from **outside territorial waters:**

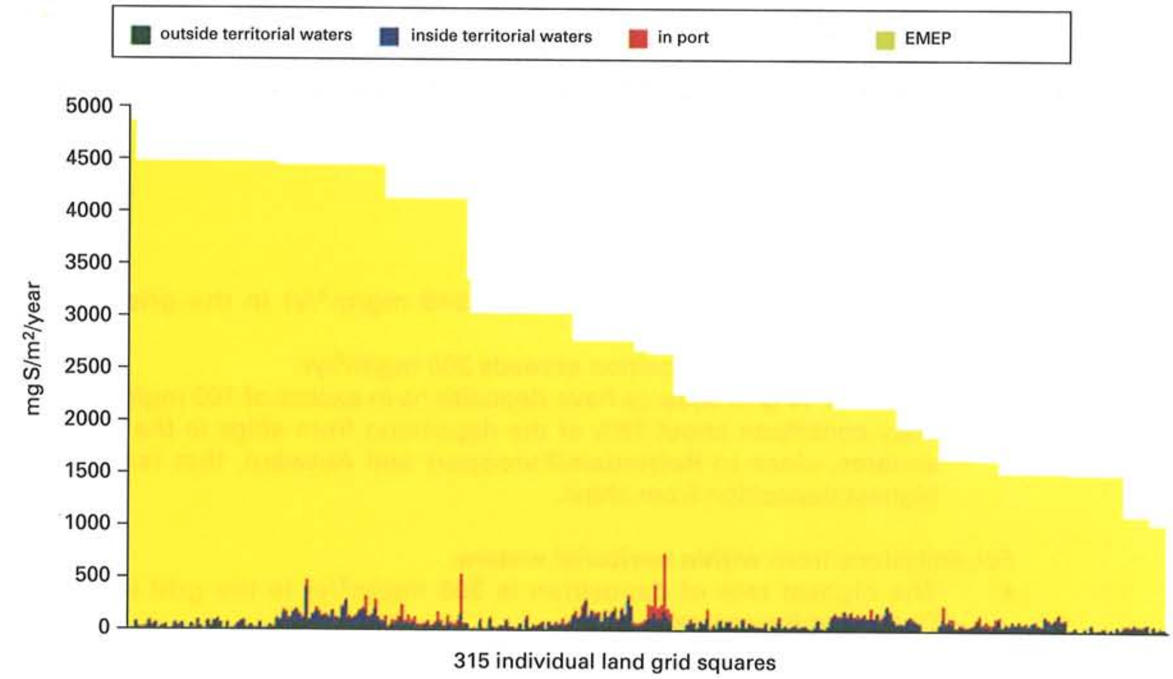
- The highest rate of deposition is 101 mg/m²/yr in the grid square including Dunkirk.
- In only 1 grid square does deposition exceed 100 mg/m²/yr.
- They contribute less than 50% of deposition from ships in all the grid squares analysed.

Analysis at this spatial level shows that in port emissions are responsible for the highest rates of deposition. Deposition from emissions from busy shipping lanes within territorial waters, while not reaching the peak values seen from ships in port, is also substantial in a number of grid squares. The contribution from ships outside territorial waters is much less significant.

5.3. COMPARISON OF OCPD SHIPS' DEPOSITION AND EMEP TOTAL DEPOSITION DATA

The deposition values estimated by the OCPD model have been compared with total depositions calculated by EMEP. Deposition on all 315 OCPD land grid squares from **Figure 8** has been compared with total deposition values for the EMEP grid squares in which they are situated. A graphical representation is shown in **Figure 9.** This figure enables the contribution of ship emissions to be seen in the context of the total deposition from all sources. In reality the total deposition varies across an EMEP gridsquare which would show peaks near large land based point sources, however at present EMEP only produce data with a resolution of 150x150 km.

Figure 9: Comparison of Ship Contribution to EMEP Total Deposition Data



A detailed analysis of these data indicates the following:

- In only 9 of the OCPD grid squares was the total ship contribution to overall total EMEP deposition greater than 10%.
- In the 4 OCPD grid squares with the highest percentage contribution from ships, the most significant source of emissions was from ships in port.

- In the 5 next highest OCPD grid squares, emissions from ships inside the 12 mile territorial limit were the most significant ship source.
- Throughout the study area, the contribution from ships outside the 12 mile limit was less than 5% of the overall EMEP deposition.

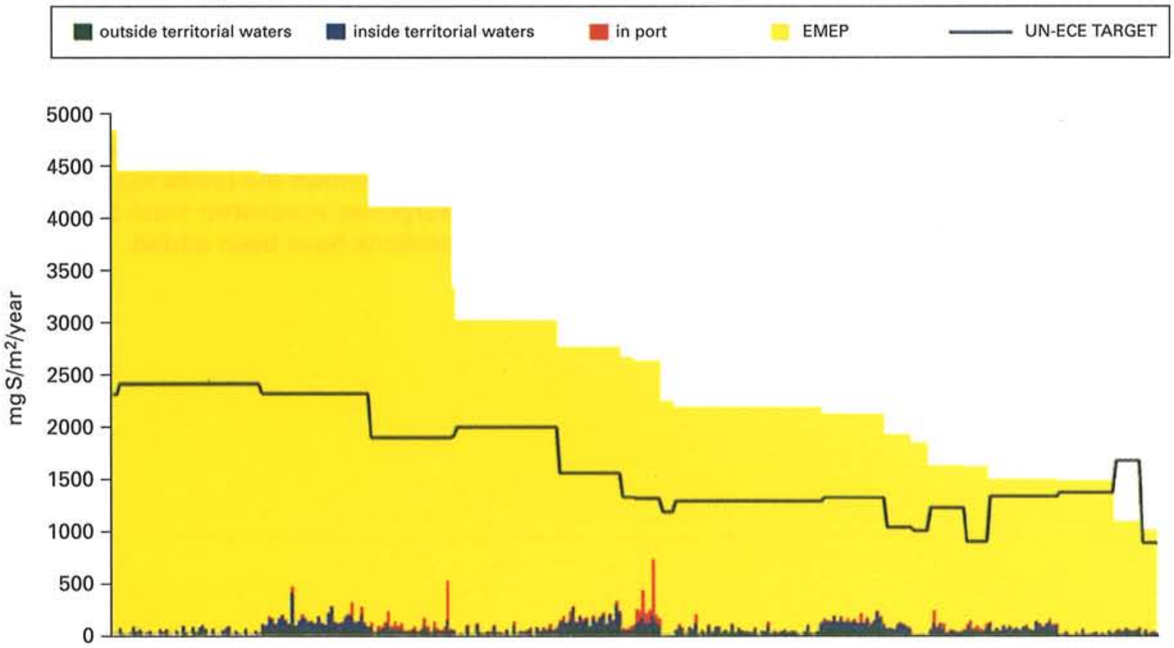
As mentioned above, the total deposition data from EMEP is only provided at a resolution of 150x150 km; when the detailed ship deposition data from the OCPD model were averaged over the land area in a given EMEP gridsquare, the contribution of ships at sea to total EMEP deposition did not exceed 6%. When in-port emissions were included the maximum contribution increased to some 8%.

5.4. COMPARISON OF OCPD DEPOSITION DATA WITH TARGET LOADS RESULTING FROM SECOND UN-ECE SULPHUR PROTOCOL

The OCPD estimated depositions can also be compared with EMEP figures which reflect the implementation of the recently signed second UN-ECE sulphur protocol aimed at further reductions in SO_2 emissions from land based sources. The commitments made by signatories of this protocol are to be achieved in a staged manner from year 2000-2010. The final "target loads" for each of the EMEP grid squares in the study area have been overplotted on **Figure 9** and given as **Figure 10** below.

Comparison of the deposition from ships with the so-called "critical loads" established under the UN-EMEP is difficult since these have been established on a 150x150 km grid scale on the basis of protecting 95% of the ecosystems in a given grid square. [4] Furthermore, the second sulphur protocol was based on a strategy aimed at reducing the difference between current levels of deposition and the critical load by at least 60 percent . The so-called "60% gap closure". This level of gap closure was set based on a cost-benefit analysis. It

Figure 10: Comparison with Target Loads of Second Sulphur Protocol



is therefore more appropriate to compare the contribution of ship emissions to the resultant "target loads" for the 60 percent gap closure case.

This figure shows that even after the implementation of this new protocol, in the study area, apart from the three grid squares where in-port emissions dominate the contribution from ships, the contribution from all shipping to "target deposition" is 20% or less.

COMPARISON OF OCPD DEPOSITION WITH CRITICAL LOADS FOR THE UK

In the detailed ICCET report [3] for the UK only, the deposition from ships has been produced in the form of "critical load exceedance maps" by the Institute of Terrestrial Ecology, one of the partners undertaking the study on behalf of CONCAWE. For most of the UK part of the study area, the sulphur deposition from ship emissions is less than 10% of the critical load. In small areas where the soil is most sensitive to acid deposition the calculated deposition from ships exceeds 25% of the critical load.

Land based emissions, modelled by HARM, produce significant exceedances in areas of more sensitive soils in south east England. When the ship emissions modelled by OCPD are added, the degree of exceedance is somewhat increased, particularly in those areas where the ship contributions are high in relation to the critical load.

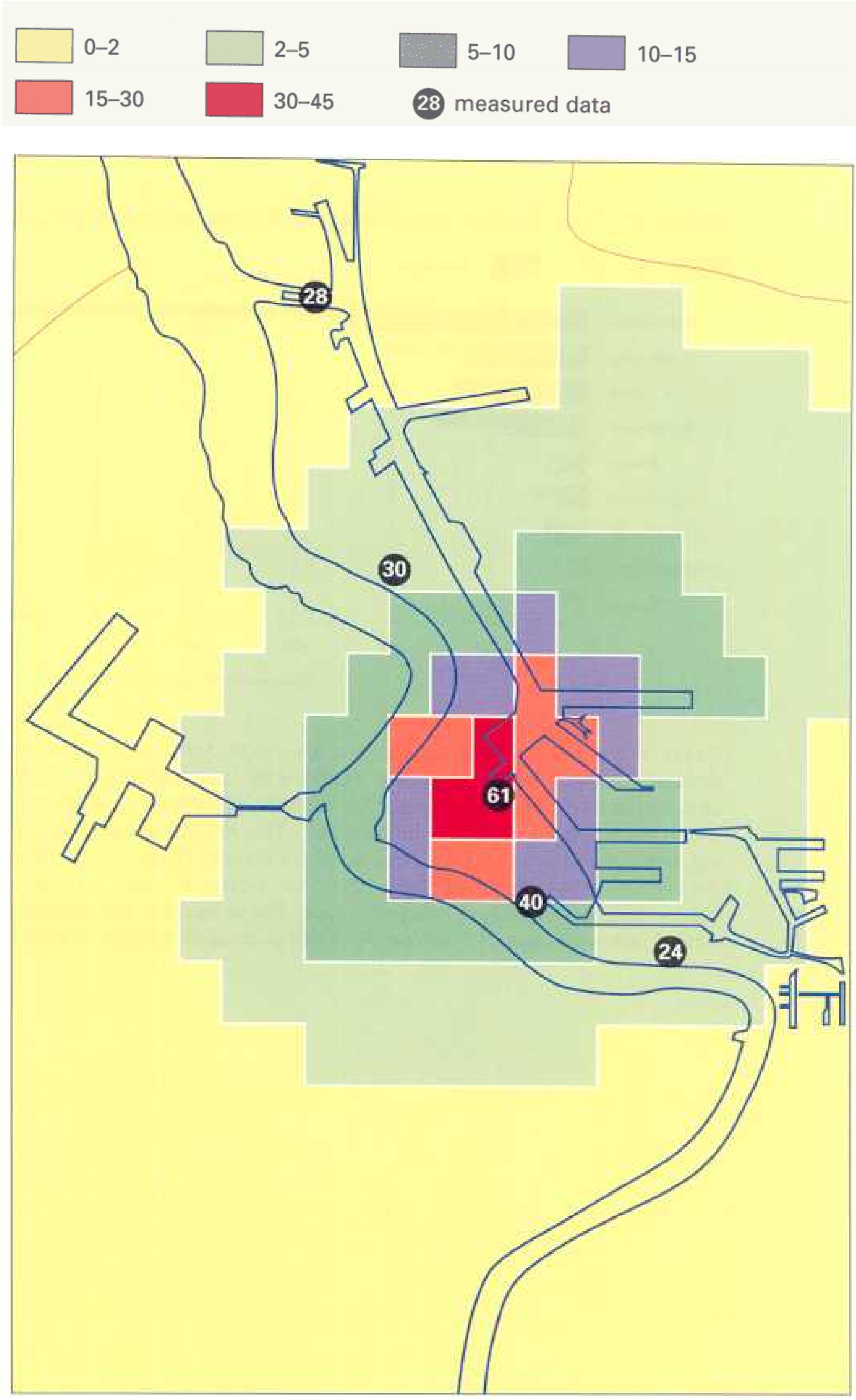
It is difficult to draw general conclusions from this part of the work since critical loads vary significantly across Europe, with generally very low values for the sensitive soils in Scandinavia and relatively high values in Southern Europe. Furthermore, this study area represents one of the most heavily trafficked areas of shipping in the world. In other areas, therefore, ships emissions are likely to result in lower levels of coastal deposition.

FINE RESOLUTION MODELLING OF PORT EMISSIONS

Lowles et al. [3] also modelled each of the 11 major ports on a fine gridscale of about 1x1 km. For convenience total port emissions were represented as a single point source located at the centre of activity of the port.

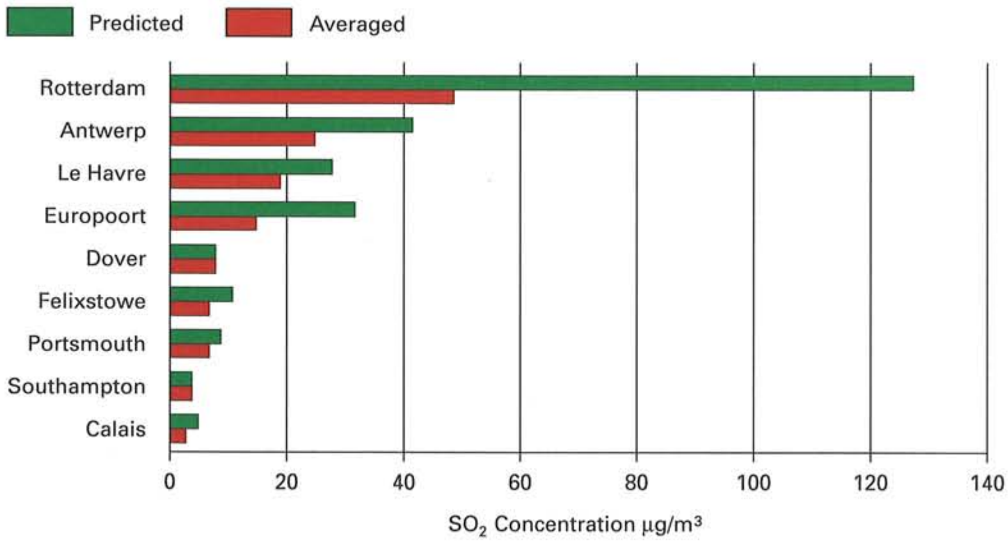
Detailed data on the predicted concentrations of SO_2 from ships for each of the 11 ports are given in the ICCET report. [3] **Figure 11** shows the predicted situation for the port of Antwerp. For comparison purposes measured total SO_2 data (1990 annual means) from fixed monitoring stations have been added.

Figure 11: Predicted Contribution to Annual Mean Concentrations of SO_2 from Ships in the Port of Antwerp (µg/m³)



Clearly, representing the entire emissions from a port complex as a single point source will tend to overpredict concentrations near to the source. To compensate for this, predicted concentrations of SO_2 have been averaged based on the eight grid squares surrounding the source. The results of this averaging are shown in **Figure 12** below . The predicted concentrations from the modelling results are also shown for comparison purposes. For Antwerp this averaging results in a reduction of the predicted concentration of SO_2 from 41 $\mu g/m^3$ to 24 $\mu g/m^3$.

Figure 12: "Near Source" annual mean concentrations of SO_2 in-port



These initial results indicate that, in the large ports of Rotterdam, Europoort, Antwerp and Le Havre there are likely to be local air quality problems due to ship emissions.given the current European Union lower guide value for annual mean concentration of SO_2 of 40 g/m^3 . The results also show that in the low activity quick turnaround ports, such as Calais, Dover, Felixstowe, Harwich, Southampton and Portsmouth, the contribution of ships to local concentrations of SO_2 is relatively low. These results are consistent with the size of port and type of traffic visiting the port as discussed in **Section 3.3.**

6. RELATIVE COST EFFECTIVENESS OF CONTROLS AT SEA AND IN PORT

The relative size of the contribution of ship emissions to overall land deposition from each source category (in port, within and outside territorial waters) is discussed in **Section 5.** It is also important to understand the relative cost-effectiveness of reducing emissions from these sources. The detailed data generated by both the inventory study and subsequent modelling study enables such an analysis to be made.

The split between emissions of SO_2 from ships in port, within territorial limits (12 nm from the shore) and outside territorial limits within the study area given below:

	Emissions (% Total Ship)
In Port	26.0
Within 12 nm	30.5
Outside 12 nm	43.5

Given these data and detailed data on the contribution to deposition at a given receptor from each of these ship source categories (see **Figure 8**) an assessment of the relative cost-effectiveness for reducing sulphur emissions from ships in these categories can be made. The basis for this analysis is given in **Appendix 1**. It should be noted that this is based on the assumption that the cost of a unit reduction in sulphur emissions is the same whether a ship is in port or at sea.

Using the simple relationship developed in this analysis, together with the deposition data generated by the modelling study for each of the 315 land grids in the study area indicates that:

- For the 4 grid squares with the highest deposition from ships, the relative cost of in-port control is some 10-20% of that for control outside territorial waters and some 15-50% of that for control within territorial waters.
- For the remaining 5 grid squares where ship emissions contribute more than 10% to overall deposition, the relative cost of control within territorial waters is about 30% of that for control outside territorial waters.
- For all land grid squares where the contribution to sulphur deposition from ships is above 100 $mg/m^2/year$, the relative cost for control of ships within territorial waters is about 50% of that for control outside these waters.

7. CONCLUSIONS

The purpose of this report is to present a detailed analysis of the impact of sulphur emissions from ships within the heavily trafficked southern North Sea and Channel as a contribution to the debate on the need to limit the sulphur content of bunker fuels.

Comparing the inventory prepared by Meech with EMEP data indicates that EMEP may underestimate emissions in the southern North Sea by about 50%. In the Channel and Calais/Dover Straights area good agreement was found between the Meech work and EMEP. In the overall study area, the detailed inventory by Meech was some 25% higher than that used by EMEP. These values are in line with previous work done by CONCAWE and do not materially affect the conclusion regarding the relative importance of ship emissions to overall sulphur depositions in Europe as predicted by EMEP.

The study clearly identifies in-port emissions as a significant source of ship emissions in the study area. Ships in port contribute 26% of the total emissions from ships. As a consequence, the data presented show that in the major ports of Rotterdam, Europoort, Antwerp and Le Havre, they make a significant contribution to atmospheric concentrations of sulphur dioxide. In addition, the first three ports also contribute significantly to overall deposition.

Comparison of ship deposition with EMEP total deposition indicates that in only nine out of the 315 land grids squares in the study area does the contribution of ship emissions exceed 10% of the total. In the four grid squares with the highest percent contribution from ships, the dominant source was in-port emissions. In the two grid square with the highest deposition from ships, emissions from the ports of Rotterdam, Europoort and Antwerp alone were found to contribute more to these two squares than all the at-sea movements in the study area.

Given their proximity to land, a higher proportion of in-port emissions deposit on land than emissions from ships at-sea. Therefore, assuming that the costs of reducing sulphur emissions per unit of fuel consumed are constant, it is more cost effective to reduce in-port than at-sea emissions. Based on the study data CONCAWE estimates that for the four grid squares with the highest percent contribution from ships, the relative cost of in-port control is some 10-20% of that for control of ships outside territorial waters (12 mile limit) and some 15-50% of that for control within territorial waters.

In the remaining five grid squares where the contribution of ships to total deposition exceeds 10% the contribution of ships within territorial waters are the most significant source of the ship contribution to overall sulphur deposition on land. For these grid squares, the relative cost of control for ship emissions within territorial waters was found to be some 30% of that for ships outside these waters

The results of this study indicate that even in this highly trafficked area, apart from the four grid squares affected by high in-port emissions and five grid squares affected by ships operating within territorial waters, ships emissions are not a significant contribution to deposition. Throughout the study area, the contribution of ships operating outside territorial waters was less than 5% of total deposition.

In areas where ship emissions contribute most significantly to overall deposition and air quality, the study indicates that emission reduction measures in just four of the major ports (of the 80 ports in the study area) would offer a greater benefit to the environment than the control of all at-sea ship emissions within the study area. Furthermore, the cost of achieving a unit reduction in deposition in such areas through in-port control is some 10-20% of the cost for control of ships operating outside the 12 mile territorial limit.

8. REFERENCES

1. CONCAWE (1993) The European environmental and refining implications of reducing the sulphur content of marine bunker fuels. Report No.1/93. Brussels: CONCAWE.

2. Meech, R (1993) Quantifying marine sulphur emissions in the Southern North Sea and Channel. London.

3. Lowles, I.M. et al (1994). The contribution of sulphur dioxide emissions from ships to coastal acidification. London; Imperial College Centre for Environmental Technology.

4. Iversen, T. et al (1991) Calculated budgets for airborne acidifying components in Europe, 1985, 1987, 1988, 1989 and 1990. EMEP/MSC-W Report 1/91. Technical Report No. 91, Oslo: Det Norske Meteorologiske Institutt.

5. Bremnes, P.K. (1990) Exhaust gas emission from international marine transport. Report No. OR 222955.0001.90. Trondheim: Norwegian Marine Technology Research Institutt (MARINTEK)

APPENDIX 1: METHODOLOGY FOR RELATIVE COST-EFFECTIVENESS

The following basic assumptions have been made in this analysis:

1. Cost-effectiveness is defined as the cost of achieving a unit reduction in sulphur deposition at a given land receptor from a given source or source category.

2. The cost for a unit reduction of emissions at the source is the same for ships sailing outside the 12 nm limit, within it or in-port.

Given this basis the Relative Cost Effectiveness of control between any two of these source categories may be expressed as follows:

$$RCE[sc1/sc2] = \frac{[\$/t_{dep\ n}]_{sc1}}{[\$/t_{dep\ n}]_{sc2}} = \frac{[\$/t_{em\ tot}]_{sc1} \times [t_{em\ tot}\ /t_{\ dep\ n}]_{sc1}}{[\$/t_{em\ tot}]_{sc2} \times [t_{em\ tot}\ /t_{\ dep\ n}]_{sc2}}$$

Where: RCE[sc1/sc2] is the ratio of costs of reducing emissions from source category 1 relative to source category 2 for a unit reduction of deposition at a given receptor.

$[\$/t_{dep\ n}]$ is the cost of reducing emissions from a given source category to give a unit reduction in deposition at a given receptor "n".

$[\$/_{tem\ tot}]$ is the cost of a unit reduction of emissions from a given source or source category.

$[t_{em\ tot/}/t_{dep\ n}]$ is the ratio of the quantity emitted from a given source or source category to the amount received at a given receptor "n".

Since in the case of ship emissions $\$/t_{em\ tot}$ are the same for each source category this simplifies to:

$$RCE[sc1/sc2] = \frac{[t_{em\ tot}]_{\ sc1} \times [t_{dep\ n}]_{sc1}}{[t_{em\ tot}]_{\ sc2} \times [t_{dep\ n}]_{sc2}}$$