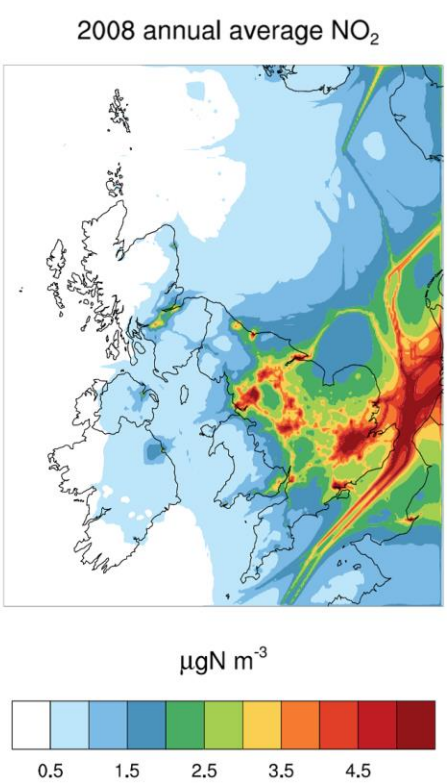
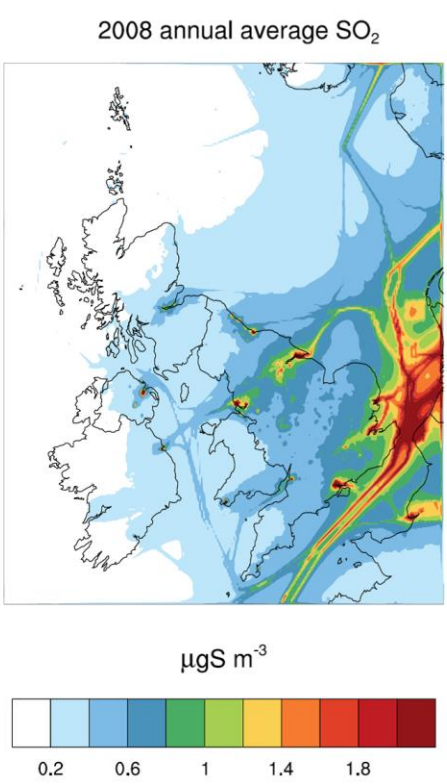
AIR QUALITY EXPERT GROUP

Impacts of Shipping on UK Air Quality





Prepared for:

Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland

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This is a report from the Air Quality Expert Group to the Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland, on the impact of shipping on UK air quality. The information contained within this report represents a review of the understanding and evidence available at the time of writing.

United Kingdom air quality information received from the automatic monitoring sites and forecasts may be accessed via the following media:

Freephone Air Pollution Information Service	0800 556677
Internet	http://uk-air.defra.gov.uk

PB14466

Terms of reference

The Air Quality Expert Group (AQEG) is an expert committee of the Department for Environment, Food and Rural Affairs (Defra) and considers current knowledge on air pollution and provides advice on such things as the levels, sources and characteristics of air pollutants in the UK. AQEG reports to Defra's Chief Scientific Adviser, Defra Ministers, Scottish Ministers, the Welsh Government and the Department of the Environment in Northern Ireland (the Government and devolved administrations). Members of the Group are drawn from those with a proven track record in the fields of air pollution research and practice.

AQEG's functions are to:

- Provide advice to, and work collaboratively with, officials and key office holders in Defra and the devolved administrations, other delivery partners and public bodies, and EU and international technical expert groups;
- Report to Defra's Chief Scientific Adviser (CSA): Chairs of expert committees will meet annually with the CSA, and will provide an annual summary of the work of the Committee to the Science Advisory Council (SAC) for Defra's Annual Report. In exception, matters can be escalated to Ministers;
- Support the CSA as appropriate during emergencies;
- Contribute to developing the air quality evidence base by analysing, interpreting and synthesising evidence;
- Provide judgements on the quality and relevance of the evidence base;
- Suggest priority areas for future work, and advise on Defra's implementation of the air quality evidence plan (or equivalent);
- Give advice on current and future levels, trends, sources and characteristics of air pollutants in the UK;
- Provide independent advice and operate in line with the Government's Principles for Scientific Advice and the Code of Practice for Scientific Advisory Committees (CoPSAC).

Expert Committee Members are independent appointments made through open competition, in line with the Office of the Commissioner for Public Appointments (OCPA) guidelines on best practice for making public appointments. Members are expected to act in accord with the principles of public life.

Further information on AQEG can be found on the Group's website at:
https://www.gov.uk/government/policy-advisory-groups/air-quality-expert-group

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Acknowledgements

The Air Quality Expert Group would like to acknowledge the following individuals and organisations for their help in the preparation of this report:

Dr Massimo Vieno and other staff at the NERC Centre for Ecology & Hydrology

Contents

Executive Summary

Shipping is a growing sector but one of the least regulated sources of emissions of atmospheric pollutants. Shipping makes significant contributions to emissions of nitrogen oxide (NO_x) and sulphur dioxide (SO_2) gases, to primary $PM_{2.5}$ and PM_{10} (particulate matter, PM with diameter less than 2.5 micrometres and 10 micrometres respectively), which includes emissions of black carbon (Table ES1), and to carbon dioxide. Chemical reactions in the atmosphere involving NO_x and SO_2, and ammonia (NH_3) gas emitted from land sources (principally associated with agriculture), lead to the formation of components of secondary inorganic particulate matter. These primary and secondary pollutants derived from shipping emissions contribute to adverse human health effects in the UK and elsewhere (including cardiovascular and respiratory illness and premature death), as well as environmental damage through acidification and eutrophication.

Geographical area	Year	Pollutant			
		NO_x	SO_2	Primary $PM_{2.5}$	Primary PM_{10}
'Extended Europe' domain	2009	23%	16%	7.9%	5.5%
UK National Atmospheric Emissions Inventory domain	2011	45%	40%	21%	15%
	2020	73%	14%	21%	15%

Table ES1: Annual shipping emissions expressed relative to annual anthropogenic land-based emissions for a European-scale domain and a UK-scale domain. The data are illustrative since quantitative comparisons between shipping and land emissions depend on the exact geographical areas being considered (Full details on emissions are given in Section 3).

The relative contribution of emissions from shipping is greater in the vicinity of the UK than across other areas of Europe because of the UK's location adjacent to major shipping lanes and its major port activities.

Projections that take account of current legislation on shipping emissions and growth in shipping activity indicate increased emissions of NO_x from shipping in 2020 but substantial decreases in SO_2 emissions and moderate decreases in PM_{10} emissions.

Recommendations

Emissions and inventories:

The quality of an emissions inventory is limited by the availability of up to date vessel movement data. AQEG recommends that a bottom-up inventory of the type developed by Entec for 2007 should be undertaken using spatially-resolved movement data providing details of vessel type, engine power, movement type and auxiliary engines. AQEG recommend that this process should be repeated every five years.

The new inventory would permit verification of the current National Atmospheric Emissions Inventory (NAEI) approach of using DfT ports data as proxies for trends in movement data.

For the purposes of use by the modelling community, the inventory should include temporal variability (e.g. monthly) in shipping emissions, ship funnel release characteristics and primary PM speciation, including black carbon.

The inventory should also be of high spatial resolution (1 km ×1 km) around all major port areas. It may be possible to obtain data from local air quality assessments that can contribute to the emission estimates included in the national emission maps generated in the NAEI programme.

AQEG recommends that direct measurements of emission factors for ship engines are required to understand the relationship between primary PM emissions and fuel sulphur content. This will allow inventories and air quality models to capture the effect on PM emissions of current and future legislation on fuel sulphur content with more certainty and the impact of fuel quality and exhaust abatement on emissions of PM components, including black carbon.

Regulatory compliance:

The effectiveness of current regulations on marine fuel sulphur content around UK waters needs to be verified. The MARPOL agreement and EU Sulphur Content in Marine Fuels Directive apply in different ways in different sea areas around the UK coast (Emission Control Areas, ECAs and non-ECAs) and to different vessel and movement types (passenger and non-passenger vessels, at sea and at berth). Therefore AQEG recommends that quantitative knowledge of the type and quality of fuels that ships are actually using around the UK coast is obtained to allow a suitably accurate determination of SO_2 and PM emissions and the accompanying spatial variability.

Measurements:

To observe and model future trends, including the impact of changes in SO_2 concentration due to shipping emission reductions (from 1% to 0.1% fuel sulphur, S content), AQEG recommends enhancing the monitoring capability at some sites (e.g. Lullington Heath) with higher specification pulsed UVF instruments that have lower limits of detection than the current SO_2 instrument. AQEG also recommends that concentrations are archived at shorter than hourly time resolution, e.g. 5 min, in order further to help analyses that can distinguish ship signatures from background. The advantages of the Lullington Health site include existing infrastructure, co-located NO_x measurements and continuity with a historic time series. It is recommended that consideration also be given to adding BC monitoring to this site.

AQEG recommends that enhanced measurements of atmospheric concentrations are accompanied by local meteorological measurements of similar time resolution, in particular wind speed and direction, to aid source apportionment to maritime sources.

Modelling:

The fulfilment of recommendations made in respect of improving shipping emissions inventories will be of direct benefit to the modelling of the effects on air quality and deposition of shipping emissions at all modelling spatial and temporal scales. On completion of this

inventory AQEG recommends that model simulations are undertaken to determine current and future impacts of shipping on air quality and deposition across a range of spatial scales. This should include both local dispersion models and regional atmospheric chemistry transport models. Receptor modelling studies may also play a role in quantifying the impacts of shipping on current air quality.

Links between air quality and climate change:

AQEG recommends that projections of air pollutant emissions are developed which are consistent with projections of radiative forcing emissions from shipping (greenhouse gases and black carbon) so that policies addressing climate and air quality impacts are harmonised. The projections needs to take into account future growth in shipping activities around the UK coast as well as the impacts of policies and measures that affect emissions, such as abatement technologies, fuel efficiency improvements and the use of alternative fuels.

Scope of the report

In compiling this report, AQEG were asked to address the following set of questions.

1. What are the quantitative impacts of shipping on UK air quality, including deposition to the UK? Is there any evidence of air quality exceedances being driven predominantly by shipping emissions?

No air quality management area currently in place in the UK is related to shipping, which indicates that no Local Authority currently assesses that air quality exceedances are being driven predominantly by local shipping emissions.

Model simulations suggest substantial impacts of shipping emissions on UK air quality on an annual-average basis.

UK-scale modelling attributes ~0.6 μg m^{-3}, equivalent to approximately 6% of UK population-weighted background $PM_{2.5}$, to emissions from shipping. This is about one-quarter of the UK background $PM_{2.5}$ that is derived from non-UK emissions. The greatest impact of shipping on background $PM_{2.5}$ is from the emissions of SO_2 and NO_x precursors to secondary inorganic $PM_{2.5}$ rather than through the direct emission of primary $PM_{2.5}$; modelling attributes 0.1 μg m^{-3} of UK population-weighted background $PM_{2.5}$ to primary shipping emissions and 0.5 μg m^{-3} to secondary inorganic $PM_{2.5}$ (0.22 and 0.29 μg m^{-3} from shipping SO_2 and NO_x emissions, respectively).

Close to ports, the contribution of shipping to $PM_{2.5}$ is greater than the UK average because of the increased contribution from shipping primary $PM_{2.5}$.

The UK population-weighted secondary inorganic $PM_{2.5}$ derived from shipping emissions is estimated to decrease slightly in the future, to 0.47 μg m^{-3} in 2020 and to 0.39 μg m^{-3} in 2030. The reductions in secondary inorganic $PM_{2.5}$ due to the projected large decreases in shipping SO_2 emissions are to some extent negated by the projected increases in shipping NO_x emissions.

Modelling indicates that 0.54 and 1.24 μg m^{-3} of UK population-weighted background NO_x derives, respectively, from local and regional shipping sources, which correspond to 2.0% and 4.6% of background NO_x. The contributions from shipping to background NO_x and SO_2 over the UK are greatest towards the south and south-east coast of England but also extend well inland, particularly for SO_2.

In recent years shipping emissions have contributed around 20% of the deposition of oxidised S and oxidised nitrogen (N) in the UK. In both cases, the shipping emissions contribute about 40% of the deposition that arises from non-UK emissions. The absolute and relative amounts of S and N deposition derived from shipping are not geographically homogeneous; they are greatest along the south and east coasts of the UK, particularly around the Thames estuary area.

2. Is there empirical evidence of changes to UK air quality from historic changes to shipping emissions?

Yes, analyses of time-series of measurements of SO_2 concentrations close to a port (Dover) and close to shipping lanes (Lullington Heath) show convincing evidence of a step-change reduction in ambient SO_2 concentrations, for wind directions associated with a shipping source, that is coincident in timing and magnitude with the reductions that would be expected from the introduction in 2006/7 of legislation on maximum sulphur content in shipping fuel used within the North Sea and English Channel.

No equivalent legislative measures have yet been enacted to reduce emissions of NO_x and PM from shipping.

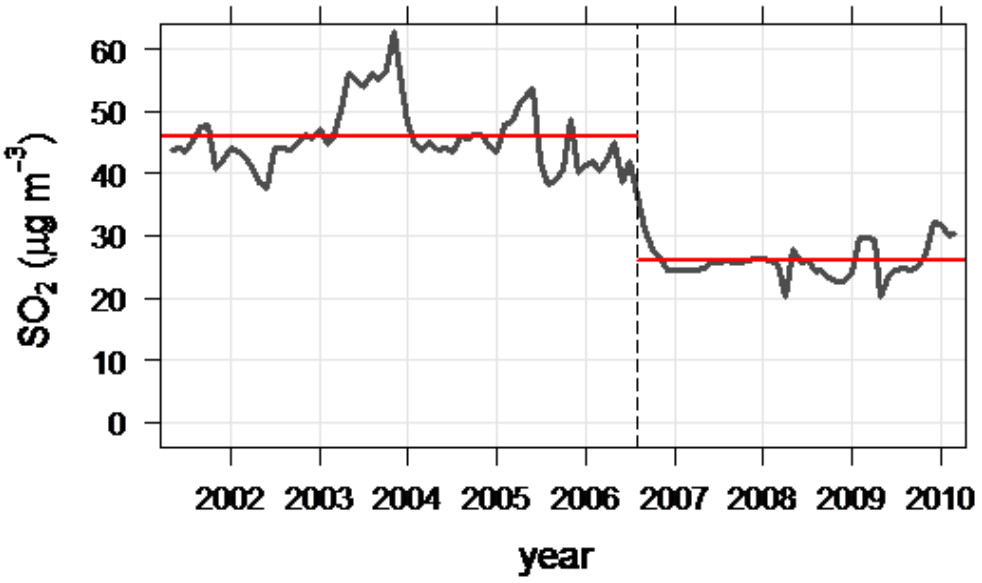


Figure ES1: The observed step-change in SO_2 concentrations at Dover, coincident in timing with regulations reducing the maximum amount of sulphur in ship fuel used in the North Sea and English Channel. The observations have been adjusted to remove the impact of variations in weather conditions on the trend in concentrations. See Section 4.1 for full details.

3. Are current measurement strategies sufficient to identify shipping emissions trends going forward?

No, even at the current monitoring location anticipated to have greatest influence from shipping (Lullington Heath), detection of SO_2 is close to current instrument limit of detection. Future source apportionment via measurements of the influence of shipping on air quality on land requires suitably placed monitoring sites (e.g. close to shipping lanes or ports) with instrumentation of low limit of detection (for SO_2, NO_x and black carbon) and high time resolution (e.g. 5 min), together with coincident meteorological measurements. Such monitoring sites, along with a suitable dispersion model, may allow the influences of individual ships to be determined.

4. What are the requirements and challenges for shipping emissions inventories?

The current method for calculating spatially disaggregated emissions in the National Atmospheric Emissions Inventory uses port data as proxies for trends in movement data together with a spatial distribution from a bottom-up inventory compiled in 2007. As spatial patterns in emissions are likely to be changing there is a necessity to update this inventory in the near future. Other factors which limit the accuracy of the current inventory include the lack of detailed emission factors relating emissions, particularly of particle components, with fuel quality for different engine types and exhaust abatement technologies.

A number of remote sensing approaches show promise for contributing to derivation and validation of shipping NO_x and SO_2 emission inventories. These include enhancement of satellite instrumentation and retrieval algorithms, airborne differential optical absorption spectroscopy, and UV cameras to image SO_2 in individual ship emission plumes.

5. Are considerations of the UK climate and air quality impacts of shipping integrated?

No; controls on air pollutants from shipping were initially addressed by the International Maritime Organisation (IMO) independently of consideration of emissions of radiative forcing agents (greenhouse gases, PM and PM precursors). Controls on greenhouse gases were not addressed until 2011 when the Marine Environment Protection Committee of the IMO adopted additional measures to go into Annex VI of MARPOL with new sections on 'Regulations on energy efficiency for ships.'

It is important that holistic consideration is given to how shipping emissions of all climate forcing reagents may change as shipping emissions are mandated to change. There are clearly air quality benefits which arise from the reductions in sulphur emissions but there is trade-off against reductions in sulphate aerosol and the associated increase in radiative forcing. The reductions in sulphur content require additional activity at the refinery and are therefore also associated with a potential increase in CO_2 emissions. However, improvements in energy efficiency should provide air quality and climate win-win solutions, assuming that the methods adopted do not lead to increases in NO_x emissions.

Ships also emit black carbon and unlike long-lived greenhouse gases the climate impacts of the short-lived climate pollutants like black carbon are greater nearer to areas of higher emission. There is currently no regulation specifically addressing black carbon from ships.

1 Introduction

Shipping is dependent on fossil-fuel combustion, but it is one of the least regulated anthropogenic emission sources and is a growing sector. Shipping makes significant contributions to emissions of atmospheric pollutants, to NO_x and SO_2 gases and to primary particulate matter, in particular. As with emissions from other combustion sources, shipping emissions contribute to adverse human health effects (including cardiovascular and respiratory illness and premature death) and to environmental damage through acidification and eutrophication.

A recent European Environment Agency report on the 'Impact of international shipping on European air quality and climate forcing' has summarized estimates for the contributions to global NO_X, SO_2 and $PM_{2.5}$ emissions from shipping globally as: 10 – 20% (NO_X), 10 – 25% (SO_2) and 15 – 25% ($PM_{2.5}$) (EEA, 2013). The details for one set of estimated emissions for 2009 from sea and land areas in Europe are given in ***Table 1***. The geographical coverage of the EMEP (European Monitoring and Evaluation Programme) 'extended Europe' domain over which these data apply is shown in ***Figure 1***. The data in ***Table 1*** show that, averaged across the whole of this extended Europe domain, emissions at sea in 2009 comprised 19% of all emissions of NO_x, 12% of all emissions of SO_2, and 7.3% and 5.2% of all emissions of $PM_{2.5}$ and PM_{10}, respectively. Of course the relative contribution of shipping emissions varies geographically with proximity to the coast and to ports. Globally, it is estimated that nearly 70% of ship emissions occur within 400 km of the coast (Endresen et al., 2003) but within European waters there is greater proximity of emissions to the coast. According to Hammingh et al. (2012), 89% of North Sea ship emissions are within 50 nautical miles of the coast and 97% are within 100 nautical miles.

Emissions of NO_x from international maritime transport in European waters are projected to increase and could be equal to land-based sources by 2020 onwards (EEA, 2013), but SO_2 emissions in European waters will continue to decrease owing to legislation on the sulphur content in fuel. It is expected that these sulphur standards will also lead to a decrease in emissions of $PM_{2.5}$. The set of estimates given in ***Table 1*** indicate that NO_x emissions at sea may increase to 27% of all anthropogenic emissions across the extended Europe domain in 2030 whilst shipping contribution to SO_2, $PM_{2.5}$ and PM_{10} emissions decrease to 2.8%, 2.2% and 1.5%, respectively, of all emissions in this region.

The EEA (2013) report included European-scale model simulations that indicate substantial contribution of shipping emissions to $PM_{2.5}$, SO_2, NO_2 and O_3 over European land areas (***Figure 2***). Other modelling work has shown that, in northern Germany and Denmark in summer, contributions from shipping emissions may increase sulphate, nitrate and ammonium aerosol concentrations in these regions by more than 50% (Matthias et al., 2010).

The EEA report also noted that the pan-European knowledge and observation base needs to be improved to provide a more complete picture. The review of available observation data shows that there are relatively few measurement data available to attribute the contribution of ship emissions to local air pollution.

In this report AQEG has sought to complement the EEA (2013) report to provide a UK perspective to the impact of shipping on UK air quality. The five general areas the report addresses are:

> What are the quantitative impacts of shipping on UK air quality, including deposition to the UK? Is there any evidence of air quality exceedances being driven predominantly by shipping emissions?
>
> Is there empirical evidence of changes to UK air quality from historic changes to shipping emissions?
>
> Are current measurement strategies sufficient to identify shipping emissions trends going forward?
>
> What are the requirements and challenges for shipping emissions inventories?
>
> Are considerations of the UK climate and air quality impacts of shipping integrated?

In summarising evidence that addresses these questions this report first considers the regulatory framework, followed by sections on emission inventories, measurements and modelling, and concludes with a discussion on air quality and climate change issues.

Table 1: *Estimated emissions (ktonnes) for 2009 and 2030 of gases and primary PM from sea and land areas within the extended European domain. Source: Hammingh et al. (2012), which draws on data from the Centre for Integrated Assessment Modelling (CIAM) and the International Institute for Applied Systems Analysis (IIASA).*

2009	**NO_x**	**SO_2**	**CO**	**VOC**	**NH_3**	**Prim. $PM_{2.5}$**	**Prim. PM_{10}**
European seas	3,260	2,015	345	142	0	238	251
- North Sea	*472*	*177*	*82*	*14*	*0*	*25*	*26*
- Baltic Sea	*340*	*109*	*40*	*15*	*0*	*15*	*16*
- Atlantic	*747*	*535*	*36*	*34*	*0*	*61*	*64*
- Mediterranean & Black Seas	*1,701*	*1,194*	*188*	*80*	*0*	*137*	*144*
EU27 + NO + CH [1]	9,393	5,139	23,123	8,508	3,844	1,441	2,120
- UK	*1,244*	*439*	*1,961*	*848*	*311*	*79*	*128*
Rest of EMEP extended Europe domain[2]	4,638	9,733	40,875	3,658	2,109	1,560	2,455
Total (sea & land)	17,291	16,887	64,343	12,308	5,953	3,239	4,826
European seas as % of land-based	**23%**	**16%**	**0.5%**	**1.2%**	**0**	**7.9%**	**5.5%**
European Seas as % of total EMEP	**19%**	**12%**	**0.5%**	**1.2%**	**0**	**7.3%**	**5.2%**
UK land as % of total EMEP	*7.2%*	*2.6%*	*3.0%*	*6.9%*	*5.2%*	*2.4%*	*2.7%*
2030	**NO_x**	**SO_2**	**CO**	**VOC**	**NH_3**	**Prim. $PM_{2.5}$**	**Prim. PM_{10}**
European seas	3,171	405	339	295	0	62	66
- North Sea	*446*	*15*	*76*	*9*	*0*	*13*	*14*
- Baltic Sea	*228*	*11*	*40*	*33*	*0*	*4*	*5*
- Atlantic	*762*	*116*	*36*	*76*	*0*	*14*	*14*
- Mediterranean & Black Seas	*1,735*	*264*	*188*	*177*	*0*	*31*	*33*
EU27 + NO + CH [1]	4,444	2,382	15,306	6,037	3,759	1,017	1,674
- UK	*506*	*160*	*1,372*	*674*	*294*	*48*	*98*
Rest of EMEP extended Europe domain[2]	4,337	11,587	41,728	3,060	2,540	1,760	2,713
Total (sea & land)	11,952	14,374	57,373	9,392	6,299	2,839	4,453
European seas as % of land-based	**36%**	**2.9%**	**0.6%**	**3.2%**	**0**	**2.2%**	**1.5%**
European Seas as % of total EMEP	**27%**	**2.8%**	**0.6%**	**3.1%**	**0**	**2.2%**	**1.5%**
UK land as % of total EMEP	*4.2%*	*1.1%*	*2.4%*	*7.2%*	*4.7%*	*1.7%*	*2.2%*

[1] NO = Norway; CH = Switzerland.

[2] extends to north Africa, Turkey, Caucasus, Central Asia and parts of the Russian Federation, see ***Figure 1***.

***Figure 1**: The EMEP 'extended Europe' domain. The region defined by EMEP as Atlantic is in white, as North Sea is in cyan, as Baltic Sea is in yellow, as Mediterranean Sea is in blue, and as Black Sea is in red. Note that the EMEP grid has 50 km spatial resolution so grids encompassing coast will contain both land and sea.*

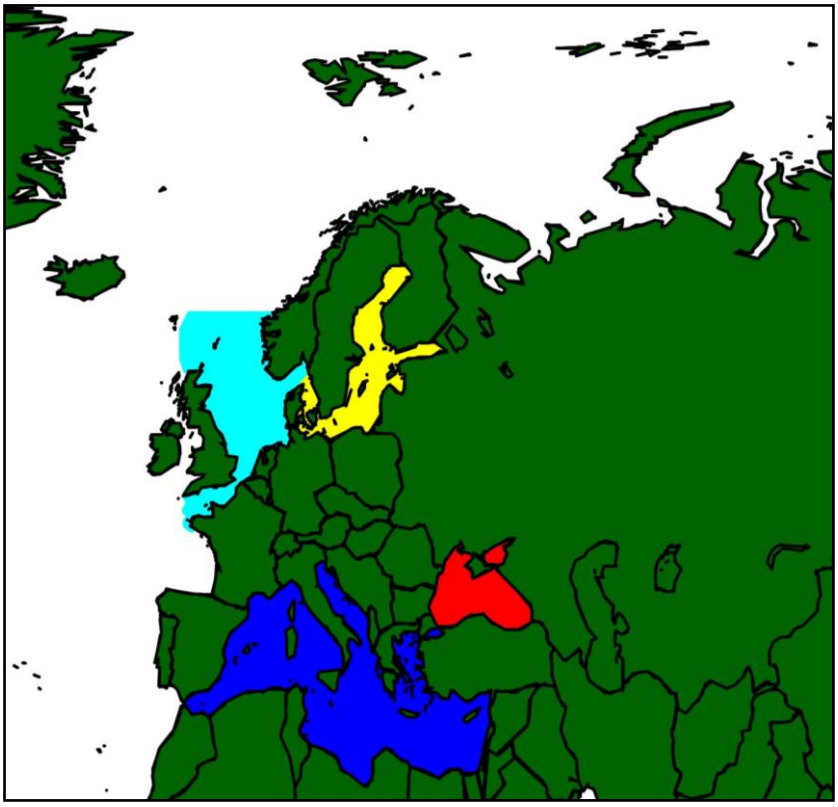
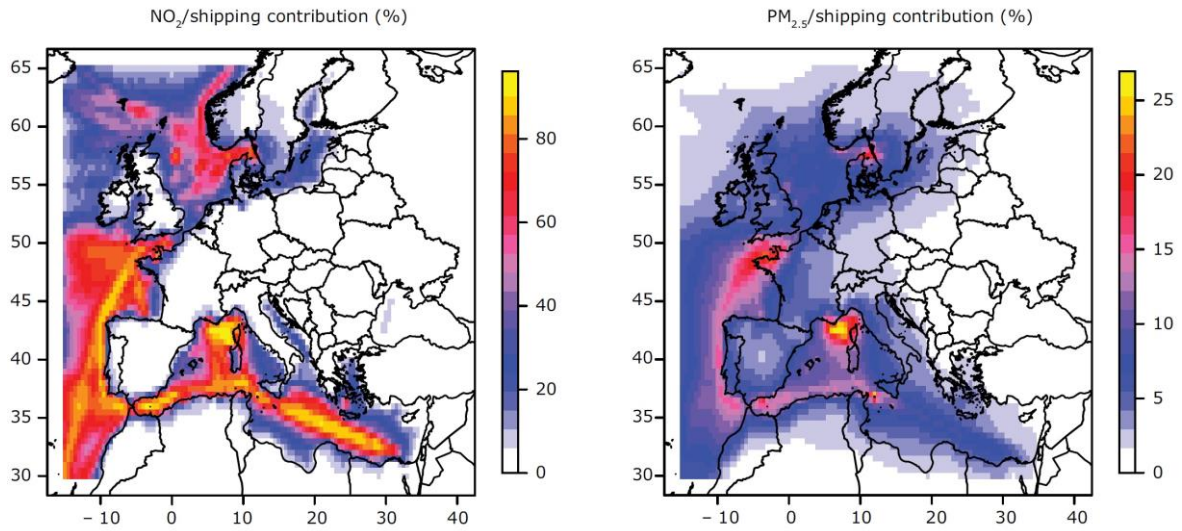


***Figure 2:** Modelled relative contribution of international shipping emissions (in %) on annual mean surface NO_2 (left) and $PM_{2.5}$ (right) concentrations in 2005 (EEA, 2013).*



2 The Regulatory Framework

Fuel costs constitute a large proportion of shipping costs (up to 50% (EEA, 2013)), leading to strong economic incentives for operators to increase fuel efficiency; this may reduce emissions without requiring regulation. However the same incentive applies to the use of residual fuel oils with relatively high sulphur contents, which are cheaper than distilled fuel oils with lower sulphur contents. Hence regulation is required to limit the air pollution generated by shipping, and the principal regulatory approaches have focused on reducing sulphur content in marine fuels. The air quality effects of shipping in waters around the UK are regulated by both the International Maritime Organization (IMO) and the EU. An overview of the timeline for maximum permitted sulphur content in shipping fuel in different locations is given in ***Table 2***.

Table 2: *Overview of International Maritime Organization (IMO) and EU standards and enforcement dates for the maximum sulphur (S) content in the shipping fuel used whilst in the indicated locations (in parts per million by mass of S).*

	IMO		**EU**	
Non-SECA[1]	2005	45,000 (4.5%)		
	2012	35,000 (3.5%)	As IMO	
	2020 [4]	5,000 (0.5%) [4]	As IMO	
SECA[1]	2007 (Nov)	15,000 (1.5%)	2007 (Aug)	15,000 (1.5%)
	2010 (Jul)	10,000 (1%)	As IMO	
	2015	1,000 (0.1%)	As IMO	
Passenger ships[2]	–	–	2006 (Aug)	15,000 (1.5%)
	–	–	2015	1,000 (0.1%)
Vessels at berth and on inland waterways	–	–	2010	1,000 (0.1%)
Inland waterway only vessels[3]	–	–	2011	10 (0.001%)

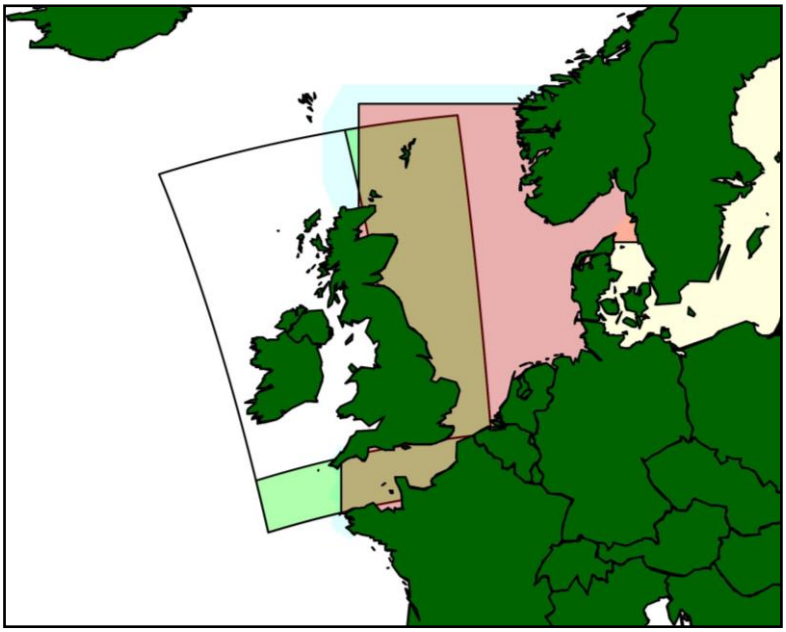
[1] SECA = North Sea and English Channel sulphur emission control area.
[2] Operating on regular services between EU ports.
[3] Recreational craft and non-sea going vessels subject to EU directive emission limits.
[4] Subject to a feasibility review in 2018.

Within the framework of the International Convention for the Prevention of Pollution from Ships (MARPOL) developed by the IMO, Annex VI contains the Regulations for the Prevention of Air Pollution from Ships[1]. Annex VI was originally created in 1997 and came into force in 2005, setting a global cap of 4.5% on the sulphur content of marine fuels. Amendments to Annex VI came into force in 2010 setting a further reduction in the global limit to 3.5% from January 2012 and 0.5% from January 2020 subject to a feasibility review in 2018. Fuel oils with higher sulphur content may be used in combination with equivalent exhaust sulphur reduction technologies such as scrubbers.

[1]http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx

Marine 'Emission Control Areas' (ECAs) can be defined for the purposes of reducing SO_x, NO_x and/or particles, with lower limits on fuel sulphur content and engine emission rates for these areas. In Europe, the North Sea and Baltic Sea are defined as Annex VI Emission Control Areas for SO_x but so far no ECAs have been defined for NO_x or PM. The geographical coverage of the North Sea and Baltic Sea Sulphur Emission Control Areas (SECAs) are illustrated by the red and light yellow shaded areas in ***Figure 3***, respectively. The North Sea SECA includes the English Channel. The sulphur limit for fuels used in SECAs was set at 1.5% in effect from November 2007 in the North Sea area, further reduced to 1.0% from July 2010.

Figure 3: *Geographical boundaries of various areas of the seas around the British Isles defined in legislation or for emissions or modelling purposes. The North Sea Sulphur Emission Control Area (SECA) is in red and the Baltic Sea SECA is in light yellow. The EMEP North Sea area is in light blue, the EMEP Baltic Sea area is light yellow, and the EMEP Atlantic area is white (but note that the EMEP Atlantic area extends over a much larger area than shown here, see* ***Figure 1****). The CMAQ-UK domain is defined by the black, approximately rectangular outline around the British Isles, with the CMAQ-UK North Sea and English Channel area within this domain coloured in green, or in brown where it overlaps with the North Sea SECA.*



Annex VI also specifies limits on NO_x emissions for new or reconditioned marine engines with power output over 130 kW. From 2011 onwards modest emissions reductions apply to all ships in this category; however the most significant reduction in NO_x emission limits do not come into effect until 2021, and then only apply to ships operating in NO_x ECAs.

In 2011, Annex VI was extended to include 'Regulations on energy efficiency for ships' (Chapter 4), which came into force in 2013. This sets a requirement for energy efficiency for new or significantly modified ships over 400 Gross Tonnage, and obliges all ships to have a 'Ship Energy Efficiency Management Plan' (SEEMP).

All EU member states with significant coastlines are parties to MARPOL Annex VI. Most non-EU European countries are also signatories, for example Norway and the Russian Federation.

Of other countries whose shipping is most likely to influence air quality in the UK, Iceland is the most notable non-signatory to the convention.

The EU Sulphur Content of Marine Fuels Directive (2005/33/EC) sets the same limits on the sulphur content of marine fuels used in SECAs as MARPOL Annex VI, but adopts the earlier date for its implementation as 11 August 2007. In addition it goes further by setting:

- a 1.5% sulphur limit for fuels used by passenger ships on regular services between EU ports, from 11 August 2006;
- a 0.1% sulphur limit on fuel used by inland waterway vessels and by ships at berth in EU ports, from 1 January 2010. The limit for ships at berth only applies to ships at berth for more than 2 hours. In practice, this is usually implemented by switching off main engines and running auxiliary engines using lower sulphur fuel or by using shoreside electricity while at berth.

The Sulphur Content of Marine Fuels Directive (SCMFD) has a specific definition of inland waterway vessels. However, the EU Fuel Quality Directive 2009/30/EC sets a much more stringent limit on the sulphur content of fuel used by inland waterway vessels not at sea and recreational craft. This limit is set at 10 ppm (0.001%) from January 2011, in line with the limit on fuels used by other types of non-road mobile machinery.

A recent revision of the SCMFD (2012/33/EU) matches the provisions of the revised MARPOL Annex VI, with a fixed time-scale for the lowest sulphur fuel limit of 2020, and a lower sulphur content limit for fuels used in combination with scrubber technology. The revised SCMFD adopts the MARPOL Annex VI global limit of 0.5% sulphur content from 1 January 2020, with a much tighter limit of 0.1% applying in SECAs from 1 January 2015.

For recreational craft (hull length up to 24 m), emission limits for NO_x, total suspended particles (TSP), CO and VOC are specified in EU directive 2003/44/EC. Emissions from recreational craft may be locally significant, but are of lesser overall concern than emissions from commercial shipping as they generally use distilled fuels with relatively low sulphur contents.

There is no current provision under MARPOL Annex VI or the EU directives for specific emissions controls in the Irish Sea other than for passenger vessels on regular service between EU ports and the sulphur limit on ships at berth. The sulphur content for ships operating in this non-SECA territory are limited by the global MARPOL Annex VI limits.

3 Shipping Emissions Inventories

There are two primary sources of data for compiling inventories of shipping emissions: ship movement data and emissions modelling.

Ship movement data usually has a lower threshold of ship size included, for example Lloyd's Marine Intelligence Unit records movements of commercial ships above 100 gross tonnage, while the Automatic Identification System (AIS), which reports ship position information automatically, is only mandatory for ships greater than 300 gross tonnage. The geographical coverage of the data may be limited; for example in 2007 AIS did not cover the port of Stranraer, which also had little representation in the Lloyd's dataset as most of the movements were domestic. Each dataset excludes certain categories of ships and/or movements such as domestic ferries, tugs, research or naval vessels. Movement data may not include details of routes, particularly for movements which start and end at the same port, such as fishing activities. Vessel speed may not be reported, leading to difficulties in assessing engine power for calculating emissions. The details of ship activities within a port, such as manoeuvring using main engines or lying at berth using only auxiliary engines, may not be specified.

Emissions modelling for ships requires data or assumptions about the number, type and power output of ship engines, both main engines used for propulsion and auxiliary engines used for electricity generation. The type of fuel used in each engine, with associated sulphur content, also affects the emission rates, and may not be known with accuracy. Any use of abatement technology to reduce emissions while continuing to use heavier fuels should be considered, though at present there is very little available data.

Projecting ship emissions for future years requires assumptions to be made about both changes in ship movements, driven largely by global, regional and local economic considerations, and changes in ship emissions due to changes in fleet and responses to regulation such as changes in fuel use.

Entec carried out a series of studies of emissions from shipping around the UK for Defra between 2008 and 2010. The base year for these studies was 2007, and the emissions were calculated on a 5 km × 5 km grid in the EMEP polar stereographic projection. The area covered was within a 200 nautical mile buffer including an additional area in the North Sea roughly up to the coast of Denmark. Lloyd's and AIS ship movement data for 2007 were used with projections for earlier and later years. Emissions were calculated by vessel category, with assigned engine characteristics and fuel types. Emission factors based on measurements made on the international fleet in 1990 - 1995 (Lloyd's Register Engineering Services) and on the Swedish fleet in 1993 - 1996 (IVL Swedish Environmental Research Institute) were used, with adjustments for changes in technology and fuel sulphur content appropriate for 2007. Evaporative emissions of VOCs are not included in this inventory.

The current NAEI produces national figures on total shipping emissions using methods specified in international reporting guidelines. This imposes some restrictions on what emissions are and are not included. The figures which make up the inventory developed for complying with international inventory reporting requirements must be based on national marine fuel statistics. This means the 'official' (compliance) inventory for UK shipping emissions is more a reflection of the amount of emissions the UK is responsible for through

supplying the fuel, rather than the amount of emissions occurring within a defined geographical area.

Following inventory reporting guidelines to the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the national inventory includes total emissions only from domestic shipping. These are defined as movements from one UK port to another (or the same) UK port and are based on the Entec estimates for domestic shipping in 2007. Various port and fishing industry statistics are used as proxies to estimate activities and hence emissions for other years and account is taken of the sulphur content of marine fuel relevant to the vessel movement type. The NAEI also uses supplementary emission factors from the EMEP/EEA Emissions Inventory Guidebook for pollutants not covered by Entec. Separate methods are used to estimate total emissions from activities not included in the Entec study which must be included in the UK's national totals. These include naval shipping, emissions from inland waterways, recreational craft, service craft (e.g. tugs and dredgers) and other small vessel movements in estuaries, as well as emissions between UK ports and UK Overseas Territories and from UK fishing vessels operating in waters outside the Entec study area (e.g. off the coast of Greenland) using fuel sourced in the UK. The calculation methods are described in detail in the NAEI annual reports (Passant et al., 2013) and in Walker et al. (2011).

Emissions from international shipping movements are reported separately as a 'Memo Item' in accordance with CLRTAP reporting guidelines and are derived from the balance in total fuel sales, i.e. the difference between the total marine fuel consumption as reported in UK national energy statistics and the fuel calculated for domestic shipping. Fuel-based emission factors implied by Entec for international vessel movements are used. In effect, these emissions are more a reflection of the amount of bunker fuels supplied by UK sources for international movements and may not bear any relation to emissions from vessel movements themselves around UK waters. For example, they would not capture emissions from transit vessel passing though UK waters and not stopping at UK ports.

The NAEI separately produces a gridded emission dataset covering all shipping movements by redistributing the Entec inventory from a 5 km × 5 km EMEP projection to a 1 km × 1 km OS GB projection by area-weighted average of 1 km × 1 km cells which are in the sea. The gridded emissions data available on the NAEI website cover all shipping movements and are not constrained by the CLRTAP reporting guidelines. This is to make them more suitable for use in air pollution models. Emissions for different years are scaled from the Entec gridded data using the same proxies used for the national totals described above. The gridded emissions are also scaled up to account for the vessels not included in Entec's study and the effect of the SECA is taken into account when defining the SO_2 factor to be used for different movements and sea territories.

The NAEI 1 × 1 km gridded emissions are made available only for the most recent inventory year. The improvements made to the mapping procedures are not applied to gridded data sets developed for previous years. However, for regional-scale modelling activities being carried out using the CMAQ-UK model (a version of the USEPA's Eulerian chemistry-transport model optimised for UK applications), the NAEI is developing a series of consistent maps covering all shipping vessel emissions around UK waters from 2005 to 2011, taking into account the introduction of marine fuel regulations and SECAs. For the purpose of this modelling work, the NAEI 1 km × 1 km maps for shipping around the UK waters have been re-projected onto a

CMAQ-UK shipping inventory grid, at 10 km × 10 km, whose geographical extent is outlined in ***Figure 3***.

When reporting shipping emissions to the United Nations Economic Commission for Europe (UNECE) for EMEP, only domestic shipping emissions must be reported by countries as gridded (spatially distributed) emissions, as is the case for national totals, while international shipping emissions are reported by individual countries as a total for the country as a 'memo item'. The EMEP emissions data includes maps of international marine emissions for European waters based on Lloyds Register data, but this does not cover the Mediterranean, Baltic or inland waters. The emission rates per fuel consumption of bunker fuel oil and marine diesel oil for international shipping are based on the Entec calculations for most standard pollutants (NO_x, VOC, SO_x, PM_{10}, $PM_{2.5}$), while emission rates for domestic shipping using gasoline are based on Winther and Nielsen (2006). Emission rates specified by engine and fuel type are based on Entec calculations except for recreational boats where Winther and Nielsen (2006) data are again used. Fugitive emissions of VOCs from shipping are reported under a different category (NFR category 1.B.2.a.v Distribution of oil products).

3.1 Uncertainties in shipping emissions inventories

The uncertainties in emission inventories for shipping have not been quantified. The figures reported by the NAEI to comply with national inventory reporting requirements of the UNECE CLRTAP are likely to be reasonably accurate because they are based on marine fuel consumption statistics given in the Department for Energy and Climate Change (DECC) publication "*Digest of UK Energy Statistics*". However, there is far greater uncertainty on how fuel consumption is broken down between domestic and international shipping. This is important because only the domestic shipping emissions are included in the national inventory totals.

Currently, the only way of separating domestic and international shipping emissions for the UK is by using detailed vessel movement data and fuel consumption and emission factors such as that undertaken by Entec. The report by Entec (2010) gave a detailed qualitative assessment of the uncertainties in their inventory of UK shipping emissions. Around 10 different sets of information that were used to develop the inventory were considered and the overall magnitude of the uncertainty ranked low (<10%), medium (10-30%) or high (>30%) for each one. One of the main considerations was the completeness of the vessel movement data in the Lloyd's MIU database. The main issue was the capturing of movements by small vessels less than 100 gross tonnage. Entec addressed this by uplifting the dataset on the basis of DfT's port statistics. This had the effect of increasing fuel consumption and emissions by approximately 10%.

Independently of the Entec study, the NAEI made an estimate of emissions from vessels categorised as "inland waterway" vessels, but which included small fishing, recreational and service vessels operating in estuaries close to shore (Walker et al., 2011). The possibility of a small overlap in vessel coverage between the NAEI inland waterways study and the Entec shipping study leading to a small double-count in emissions for these small vessels operating in river estuaries could not be discounted. The reconciliation with published fuel consumption statistics compensates for this in the national inventory totals.

Other parameters that were given a high or medium uncertainty ranking were:

- Installed main engine power for different vessel categories;
- Installed auxiliary engine power for different vessel categories; and
- Emission factors for manoeuvring and at berth.

It is impractical to compile a bottom-up inventory using detailed vessel movement data every year. Instead, DfT maritime and port statistics are used as proxies to backcast and forwardcast activities from the 2007 base year and assumptions are made about changes to emission factors. This introduces significant further uncertainties in the inventories for other years, however the Entec inventory for 2007 remains at the heart of inventories for all other years, including those addressed by Entec and subsequently by the NAEI.

Other areas of inventory uncertainty may impact on ability to model and understand the impacts of shipping emissions on air quality. These are:

- *Emission near major ports* – the uncertainty in the inventory in specific areas, for example near major ports, may be higher than the overall uncertainty in emissions within a sea territory. The NAEI is currently investigating developing more spatially-resolved shipping emission inventories around some major UK ports taking into consideration specific port activity data, the port configuration and shipping lanes and making use of automatic identification system (AIS) observations.
- *Compliance with fuel regulations* – assumptions are made that all ships comply with relevant regulations on fuel sulphur content in SECAs, but this needs to be independently verified. Although current inventory verification work showed consistency between trends in emissions and ambient SO_2 concentrations likely to be influenced by shipping (e.g. at the port of Dover), the question is whether this can be assumed over wider sea areas.
- *Temporal variability in shipping emissions* – there are no known data available to develop hourly profiles of shipping emissions from the annual emission rates developed by the inventories. Unlike many land-based activities such as power generation and road traffic, there is unlikely to be a regular pattern of vessel movement by time of day, day of the week or month. Activities are more likely to be driven by the state of the tide which will vary around the coast as well as weather conditions. Therefore a pattern developed for one year may not be applicable to another. Real-time satellite data and port timetables may provide some evidence for developing profiles for specific years and sea areas
- *Effect of reduced sulphur content on primary PM emissions* – current factors for PM are based on high sulphur content fuels with empirically-derived relationships between PM emissions and S-content at the high end of the sulphur content range. It is more uncertain how PM emission factors will change for lower sulphur content fuels, particularly at the sub-0.5% level, as well as for alternative fuels such as LNG.
- *Emission projections* – future emission projections will always be more uncertain than base year inventories. The major uncertainty is how activity levels will change in the future. Current projections assume a 1% per annum growth rate in shipping activities, but this depends on global economic conditions.

Overall, one might consider the uncertainty in emission inventories to be higher than land-based sources such as road transport, power generation and other major point sources, but lower than uncertainties in for example more diffuse emission sources in industry, commerce and agriculture. Shipping does have the advantage that shipping lanes are fairly well-defined, so for regional scale modelling, inventories may be adequate, notwithstanding the issues raised above. Although current inventories may still not have sufficient spatial resolution near major port areas where the air quality impacts of shipping activities are more pronounced, the locations of ports are at least known and there is potential for deriving higher quality inventories. In that situation, the uncertainty in the shipping inventory could be at least as good as the inventory for local road traffic where emission factors and fleet mix is more variable.

3.2 Contribution of shipping to UK Emissions

An inventory for shipping emissions will clearly depend on the geographical boundaries of the sea territories and what shipping activities are included and excluded from the inventory. An indication of the contribution of shipping to emissions at the European scale, in the EMEP extended Europe domain, is given in ***Table 1*** in the Introduction. This section discusses the estimated contribution of shipping to UK emissions.

The Entec inventory provides, subject to the uncertainties described above, an estimate of shipping emissions within 200 nautical miles of the UK coast with an additional area in the North Sea, but is only available for 2007 and excludes some activities such as military. The NAEI 'official' (compliance) inventory provides a consistent time-series trend in emissions, but is more a reflection of the amount of emissions the UK is responsible for, through the supply of fuel, rather than the amount of emissions occurring within a defined geographical area. For regional-scale modelling with CMAQ-UK the NAEI has developed a consistent time-series of gridded inventory data on a 10 km × 10 km grid covering all vessel movements within an area shown in ***Figure 3***.

The emissions of shipping around UK waters is compared in ***Table 3*** for inventories developed for 2007 using the three approaches. For the purposes of comparisons, the shipping emissions for the three approaches are also presented as a percentage of the NAEI emissions from land-based sources. The land-based emissions refer to all emissions reported by the NAEI 'inland', and include emissions from vessels on rivers and canals and small recreational craft.

The shipping emissions within the large sea area covered by the Entec domain were a high percentage relative to total land-based emissions in 2007: 70% for SO_2, 66% for NO_x, but less for primary PM_{10} and $PM_{2.5}$ emissions (27% and 38%, respectively). The proportion of shipping emissions within the NAEI CMAQ-UK shipping domain relative to land-based emissions are smaller (41% and 38% for SO_2 and NO_x, respectively) than the emissions from the Entec domain, but it is worth pointing out how much of these emissions occur within the English Channel and North Sea areas alone, reflecting the proportionately higher levels of activities occurring in these sea areas. For example, SO_2 emissions from ships within the English Channel were 19% the magnitude of all UK land-based emissions in 2007, and 18% the magnitude of all UK land-based NO_x emissions (***Table 3***). The UK 'compliance' inventory figures for shipping, referring to the emissions arising from fuel supplied by the UK, are smaller than either the Entec or NAEI CMAQ-UK shipping domain emissions. This implies that much of the emissions from shipping in UK waters are from vessels using fuels sourced overseas.

Table 4 shows similar data to ***Table 3*** but for 2011, rather than 2007. There are no Entec shipping inventory data for 2011. In terms of tonnes emitted, the emissions from both shipping and land-based sources were lower in 2011 than in 2007. The reduction in SO_2 and PM emissions from shipping is mainly due to the introduction of tighter marine fuel regulations as well as changes in marine activities. Despite these reductions the proportion of shipping emissions within the NAEI CMAQ-UK shipping domain relative to land-based emissions remained about the same in 2011 as in 2007 for SO_2, $PM_{2.5}$ and PM_{10} (40%, 21% and 15%, respectively). For NO_x the proportion of shipping emissions relative to land-based emissions increased to 45% in 2011 from 38% in 2007. The disconnect between the fuel-based 'compliance' inventory figures and that based on shipping activities means that comparing the changes in the fuel-based inventory figures is less meaningful.

Table 3: *Shipping emissions (in ktonnes) in UK waters for 2007 calculated for different sea areas and their comparison with UK land-based emissions for 2007. The Entec emissions refer to estimates based on shipping movements within 200 nautical miles of the UK coast on an area defined in the EMEP 5 km × 5 km grid. The 'NAEI UK total shipping (fuel-based)' emissions refer to emissions from ships in 2007 using fuel sourced in the UK. These represent the "official" UK reported inventory of shipping emissions for 2007 reported by the NAEI in 2014 following international reporting guidelines and exclude emissions from transient vessels not fuelling in UK ports. NAEI (CMAQ-UK shipping grid) emissions refer to emissions from all vessels operating in a sea area around the UK shown in Figure 3. These are taken directly from the Entec inventory, but laid on a 1 km × 1 km grid within a smaller geographical boundary specifically for regional scale modelling. This was developed by the NAEI for scaling to other years.*

Inventory	**NO_x**	**SO_2**	**Prim. PM_{10}**	**Prim. $PM_{2.5}$**
Entec (200 nautical mile EMEP 5 km × 5 km grid): all vessels	929	397	35.6	33.7
NAEI (CMAQ-UK 1 km × 1 km shipping grid): all vessels operating within an area defined for CMAQ regional modelling	540	234	21	19
NAEI (CMAQ-UK shipping grid) - English Channel: all vessels operating within the English Channel mapped on the CMAQ grid	*247*	*106*	*9*	*9*
NAEI (CMAQ-UK shipping grid) - North Sea: all vessels operating within the North Sea mapped on the CMAQ grid	*215*	*82*	*6*	*5*
NAEI UK total shipping (fuel-based): emissions only from vessels using fuel sourced in the UK	277	153	17	16
NAEI UK total land-based emissions: emissions from all land-based sources, but including vessels on inland waterways	1410	564	130	88
Shipping as % NAEI UK land-based emissions				
Entec (200 nautical mile EMEP grid)	66%	70%	27%	38%
NAEI (CMAQ-UK shipping grid)	38%	41%	16%	22%
NAEI (CMAQ-UK shipping grid) - English Channel	*18%*	*19%*	*7%*	*10%*
NAEI (CMAQ-UK shipping grid) - North Sea	*15%*	*15%*	*4%*	*6%*
NAEI UK total shipping (fuel-based)	20%	27%	13%	18%

Table 4: *Shipping emissions (in ktonnes) in UK waters for 2011 calculated for different sea areas and their comparison with UK land-based emission for 2011. The 'NAEI UK total shipping (fuel-based)' emissions refer to emissions from ships in 2011 using fuel sourced in the UK. These represent the "official" UK reported inventory of shipping emissions for 2011 reported by the NAEI in 2014 following international reporting guidelines and exclude emissions from transient vessels not fuelling in UK ports. NAEI (CMAQ-UK shipping grid) emissions refer to emissions from all vessels operating in a sea area around the UK shown in Figure 3. These are derived from the Entec inventory, but scaled to 2011 based on UK port activities and laid on a 1 km × 1 km grid within a smaller geographical boundary specifically for regional scale modelling.*

Inventory	**NO_x**	**SO_2**	**Prim. PM_{10}**	**Prim. $PM_{2.5}$**
NAEI (CMAQ-UK 1 km × 1 km shipping grid) – all vessels operating within an area defined for CMAQ regional modelling	448	150	17	16
NAEI (CMAQ-UK shipping grid) - English Channel: all vessels operating within the English Channel mapped on the CMAQ grid	*197*	*68*	*8*	*7*
NAEI (CMAQ-UK shipping grid) - North Sea: all vessels operating within the North Sea mapped on the CMAQ grid	*183*	*46*	*5*	*5*
NAEI UK total shipping (fuel-based): emissions only from vessels using fuel sourced in the UK	283	93	18	17
NAEI UK total land-based emissions: emissions from all land-based sources, but including vessels on inland waterways	991	371	111	77
Shipping as % NAEI UK land-based emissions				
NAEI (CMAQ-UK shipping grid)	45%	40%	15%	21%
NAEI (CMAQ-UK shipping grid) - English Channel	*20%*	*18%*	*7%*	*9%*
NAEI (CMAQ-UK shipping grid) - North Sea	*18%*	*12%*	*4%*	*6%*
NAEI UK total shipping (fuel-based)	29%	25%	16%	22%

The data in ***Table 3*** and ***Table 4*** demonstrate the much greater proportions of shipping emissions around the UK relative to UK land-based emissions than those averaged across Europe as a whole (detailed in ***Table 1***), as expected given the UK's location adjacent to major shipping lanes and its major port activities. ***Table 1*** indicates that in 2009 Europe-wide shipping emissions of SO_2, NO_x $PM_{2.5}$ and PM_{10} were on average 16%, 23%, 7.9% and 5.5% of the Europe-wide land-based emissions of these gases, whilst ***Table 4*** indicates that in 2011 shipping emissions of SO_2, NO_x $PM_{2.5}$ and PM_{10} around the UK were 40%, 45%, 21% and 15% of the UK land-based emissions of these gases.

Table 5 shows the corresponding NAEI CMAQ-UK shipping domain and land-based emissions projected to 2020. Here, only data from the NAEI CMAQ-UK gridded domain (rather than the fuel-based compliance inventory) can be shown. The table also shows projected emissions for land-based sources using the latest emission projections from the NAEI based on DECC's UEP48 energy projections. ***Table 5*** shows a 10% increase in shipping NO_x

emissions in 2020 relative to 2011, based on assumed increases in shipping activities of 1% per annum, but an 83% reduction in shipping SO_2 emissions and a 12% reduction in shipping PM_{10} and $PM_{2.5}$ emissions mainly due to further reductions in fuel sulphur content necessary to comply with MARPOL regulations in SECAs and non-SECAs. ***Table 5*** also demonstrates that, with land-based NO_x emissions expected to decrease with introduction of tighter regulations on emissions from various sources, the importance of shipping to NO_x emissions in the NAEI CMAQ-UK shipping domain increases markedly from 45% relative to UK land-based emissions in 2011 to 73% in 2020 if no measures are introduced to reduce shipping NO_x emissions. For SO_2, the magnitude of shipping emissions in the CMAQ-UK domain relative to UK land-based emissions falls from 40% in 2011 to 14% in 2020, assuming the MARPOL regulations on fuel-sulphur content are successfully implemented. Again, the much greater impact of shipping compared with land-based emissions within the UK geographic area is evident for these future projections to 2020 than for the European-scale projections for 2030 given in ***Table 1***.

Table 5: *Shipping emissions (in ktonnes) in UK waters projected to 2020, calculated for different sea areas and their comparison with UK land-based emission for 2020. NAEI (CMAQ-UK shipping grid) emissions refer to emissions from all vessels operating in a sea area around the UK shown in Figure 3. These are derived from the Entec inventory, but scaled to 2020 assuming a 1% per annum growth in shipping activities and implementation of all MARPOL and EU shipping regulations and laid on a 1 km × 1 km grid within a smaller geographical boundary specifically for regional scale modelling. NAEI emission projections for land-based sources in 2020 are based on the DECC UEP48 energy projections and implementation of all currently agreed emission legislation.*

Inventory	**NO_x**	**SO_2**	**Prim. PM_{10}**	**Prim. $PM_{2.5}$**
NAEI (CMAQ-UK 1 km × 1 km shipping grid) – all vessels operating within an area defined for CMAQ regional modelling	491	26	15	14
NAEI (CMAQ-UK shipping grid) - English Channel: all vessels operating within the English Channel mapped on the CMAQ grid	*216*	*11*	*7*	*6*
NAEI (CMAQ-UK shipping grid) - North Sea: all vessels operating within the North Sea mapped on the CMAQ grid	*200*	*6*	*4*	*4*
NAEI UK total land-based emissions: emissions from all land-based sources, but including vessels on inland waterways	631	188	101	70
Shipping as % NAEI UK land-based emissions				
NAEI (CMAQ-UK shipping grid)	73%	14%	15%	21%
NAEI (CMAQ-UK shipping grid) - English Channel	*32%*	*6%*	*7%*	*9%*
NAEI (CMAQ-UK shipping grid) - North Sea	*30%*	*3%*	*4%*	*5%*

4 Inferences from measurements of the impacts of shipping emissions on UK air quality

In the UK there have been relatively few locations where measurements have been made specifically to assess the impacts of shipping in port areas on air quality. There are now no air quality management areas (AQMAs) in place related to shipping, although the AQMA at Dover, which was for SO_2, was only recently lifted. This suggests that no Local Authority currently assesses that air quality exceedances are being driven predominantly by local shipping emissions.

Long-running air quality monitoring sites with continuous monitors where it would be expected that shipping emissions might have an impact include Lullington Heath which is 5 km from the south coast of England, and the black carbon site at Goonhilly on the Lizard. Each of these sites is discussed below. Other measurements which can give indications of the impact of shipping emissions on the UK include time series of particle sulphate, and satellite observations. These are also discussed.

4.1 Analysis of SO_2 measurements at Dover

A study has been undertaken to understand better whether the planned reductions in the sulphur content of marine fuel used by ships has resulted in the expected reductions in ambient SO_2 concentrations close to the port of Dover. Dover was chosen because it has a relatively long time-series of ambient measurements of SO_2 at two sites at or near the port and the size of shipping activity means that the port's effect on ambient SO_2 concentrations should be relatively large. The study analysed the ambient SO_2 data to 'remove' the effect of inter-annual differences in meteorology and compared the trends in the processed ambient data with trends in shipping emissions implied by the assumptions used in the NAEI based on the introduction of lower sulphur fuel. The locations of the two SO_2 monitoring sites and the met site in relation to the port are shown in ***Figure 4***. The Langdon Cliff SO_2 measurements ceased in 2010 and the Dover Docks measurements started in 2006.

Figure 4: *The area around Dover docks showing the two SO_2 monitoring sites and the Langdon Bay met site. The latter is at an altitude of 117 m.*

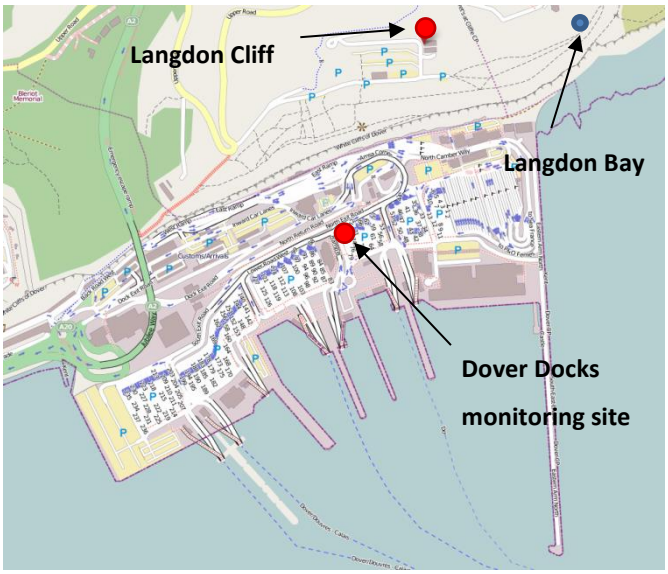


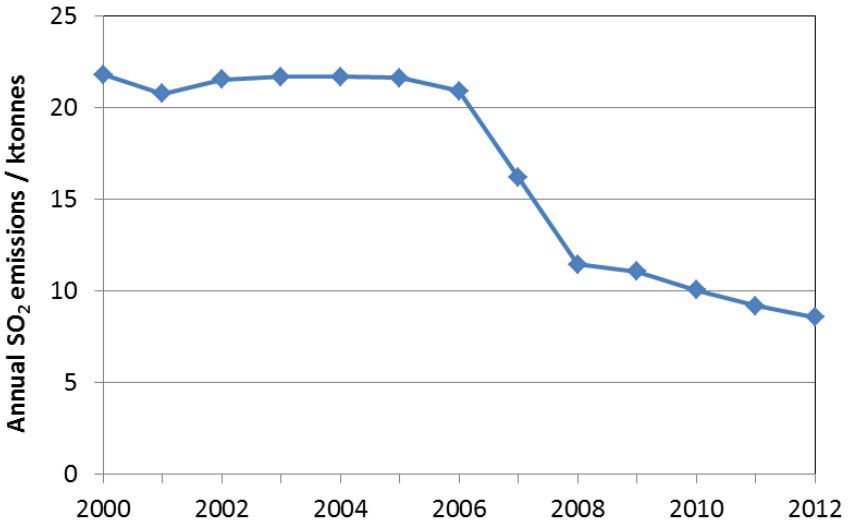
Figure 5 shows a time-series of the inventory of annual UK shipping emissions of SO_2 from 2000 to 2011 derived from the bottom-up methodology based on shipping movement and port statistics. The plot refers to domestic shipping emissions, but the same trend would be expected for all shipping emissions around Dover. The reduction from 2006 reflects in large part the establishment of restrictions of SO_2 emissions in the North Sea and English Channel SECA (from August 2007),and the restrictions on sulphur used by passenger ships on regular services between EU ports (from August 2006). The largest rate of decline occurs between 2006 and 2008 amounting to around a 45% reduction in SO_2 emissions from pre-2006 levels.

Passenger ferries are a significant part of the shipping activities at Dover Port and according to the Port of Dover authorities[2] the ferries operate to a short turnaround time, being in and

2 http://www.doverport.co.uk/_assets/client/images/collateral/environmental%20Bulletin%20web%20version.pdf

out of the port relatively quickly. This means the 0.1% sulphur limit will not apply to ferry operations at the port, but will apply to other vessels such as cargo and cruise vessels which dock at port for longer.

Figure 5: *Total annual UK domestic shipping emissions of SO_2.*

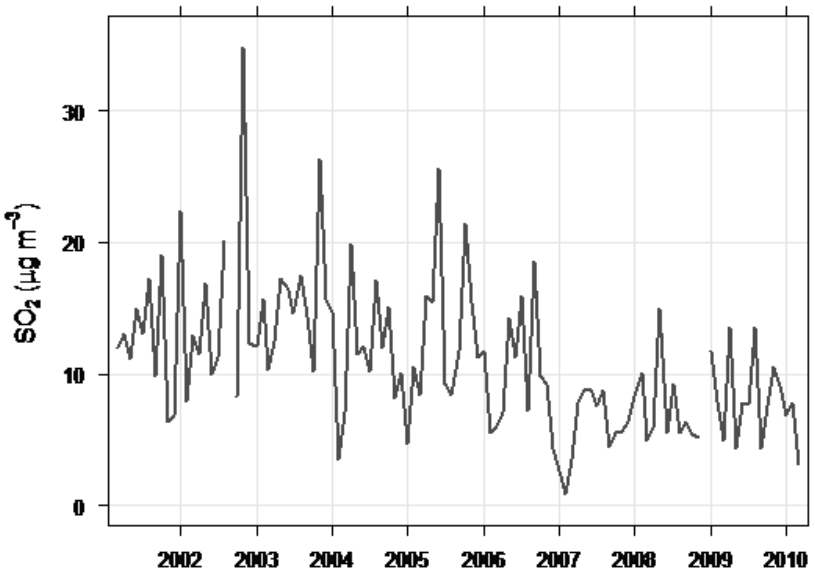


According to the shipping emissions study by Entec (2010), the sulphur content of Residual Fuel Oil used by ships around UK waters before imposition of MARPOL Annex VI limits in 2006 was around 2.7%. If port activities around Dover have been dominated by ferries, this implies that SO_2 emissions might be expected to have fallen around Dover Docks by around 45% between 2005 and 2007 (i.e. from 2.7% to 1.5%) and a further 33% (from 1.5% to 1%) between 2009 and 2010, assuming no change in port activities and overall fuel consumption.

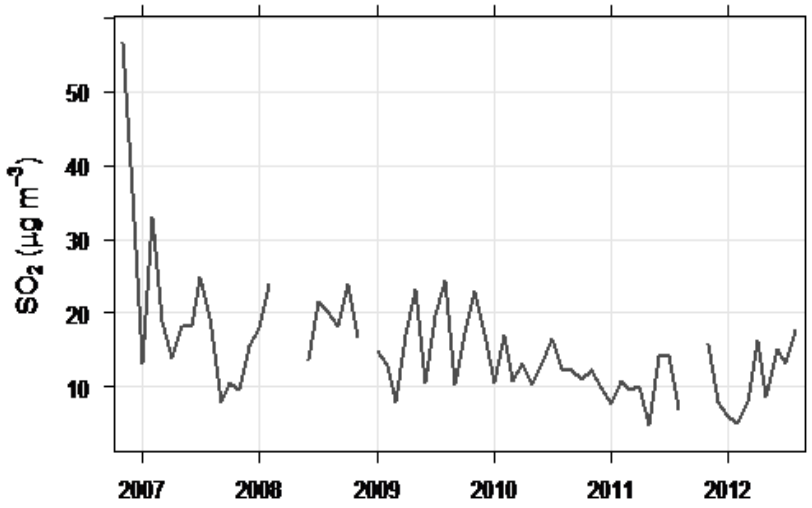
The monthly mean SO_2 concentrations for Langdon Cliff and Dover Docks, ***Figure 6***, show that SO_2 concentrations at Langdon Cliff decreased over the period from 2001 to 2010, but it is not clear what the timing of these changes may have been. Between 2007 and 2012 at Dover Docks, there is less clear evidence of reductions in SO_2 .

Figure 6: *Plot of monthly SO_2 concentrations at (a) Langdon Cliff and (b) Dover Docks.*

a)

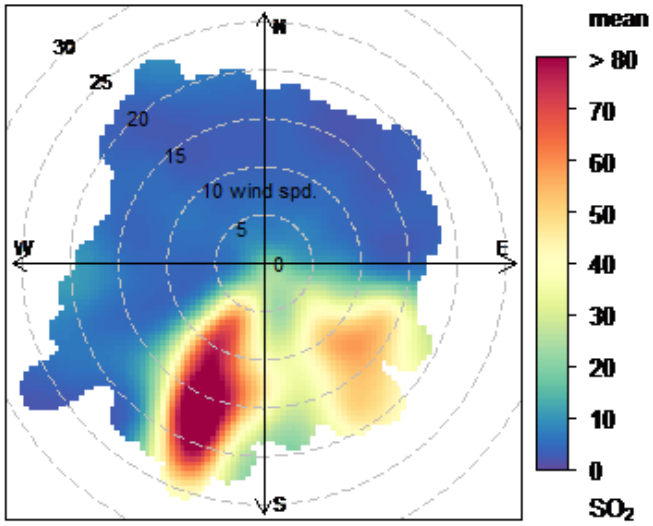


b)



A bivariate polar plot of SO_2 concentrations at Langdon Cliff shows two clear sources to the SSW and SE (***Figure 7***). The high SO_2 concentrations at high wind speeds are indicative of a stack-type emission with strong buoyancy and relatively low height and are consistent with shipping sources. The fact there are two areas of high SO_2 may be indicative of two different activities e.g. ships actually docked and stationary and ships manoeuvring in the harbour.

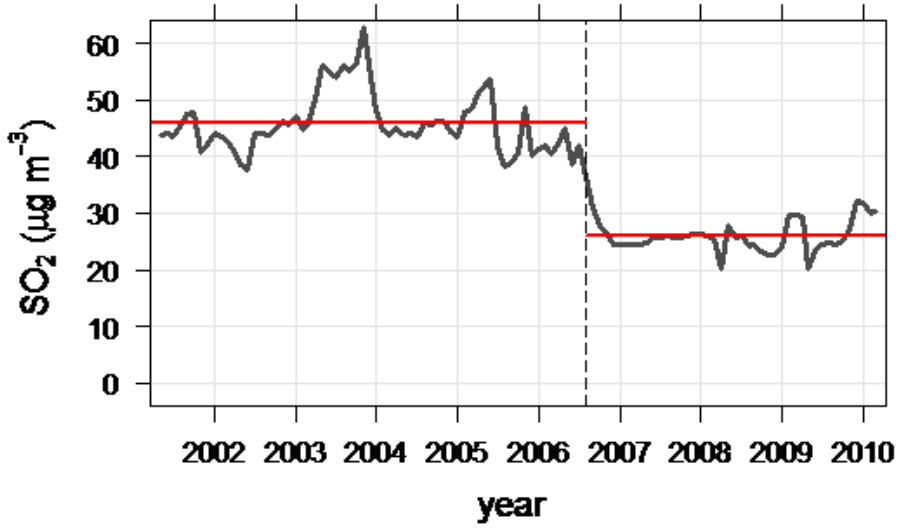
Figure 7: *Polar plot of SO_2 concentrations (µg m^{-3}) as a function of wind speed and wind direction at Langdon Cliff.*



In order to understand how SO_2 has changed more precisely, statistical models have been developed using meteorological data from the nearest Met Office surface site at Langdon Bay. These models describe the concentration of SO_2 in terms of a range of meteorological variables and other variables e.g. hour of day to account for regular temporal variations. Once a satisfactory model has been developed to explain SO_2 concentrations, the models are then run 1000s of times with randomly selected meteorological conditions and the results averaged. This approach has the effect of producing a time series that is not influenced by long-term variations in meteorology – leaving a signal that should be more representative of longer term changes in emissions.

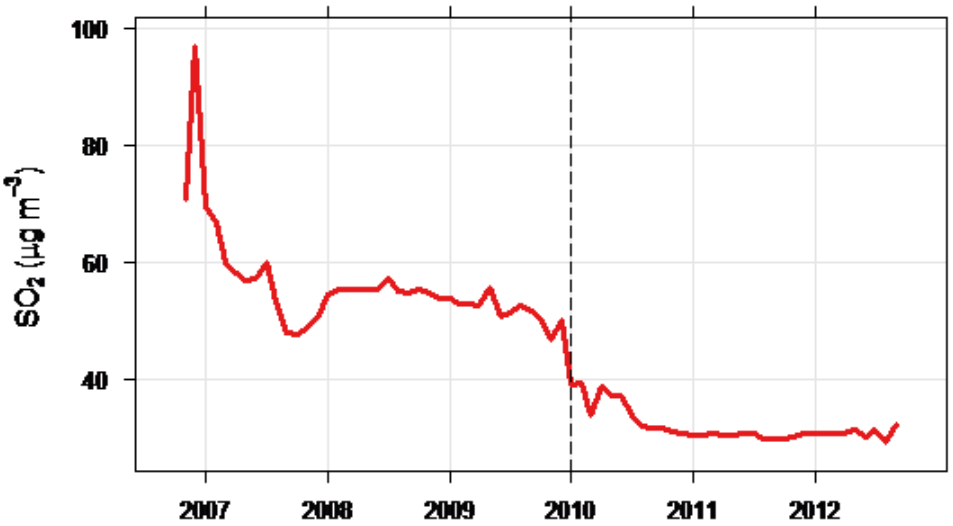
The results of using this model for Langdon Cliff are shown in ***Figure 8***. This time series now shows some periods where SO_2 changed abruptly which are not apparent in ***Figure 6***, in particular the reductions in August 2006. Considering the periods from 2002 to August 2006 and August 2006 to 2010, concentrations of SO_2 have reduced from 46 to 26 µg m^{-3} (a reduction of 44%) consistent with the expectations of the SCMFD on sulphur emissions from passenger ships (2.7% to 1.5% sulphur, i.e. a 45% reduction).

Figure 8: *Time series of SO_2 concentrations for Langdon Cliff removing the effect of long-term changes in meteorology. The dashed line shows August 2006 and the red lines show the mean concentration of SO_2 before and after August 2006.*



The de-trended SO_2 time series for Dover Docks (***Figure 9***) shows a sharp reduction in SO_2 concentrations at the beginning of 2010, from about 50 µg m^{-3} to about 30 µg m^{-3}. This reduction is proportionally broadly consistent with but slightly greater than the reduction from 1.5% to 1.0% sulphur in shipping fuel required by the legislation at this time. The additional reduction in observed SO_2 may be due to the contribution from vessels other than ferries which dock for longer periods of time and are therefore required to use the lower (0.1%) sulphur content fuel from 2010 or else switch off their engines and use shoreside power whilst at port.

Figure 9: *Time series of SO_2 concentrations for Dover Docks removing the effect of long-term changes in meteorology.*

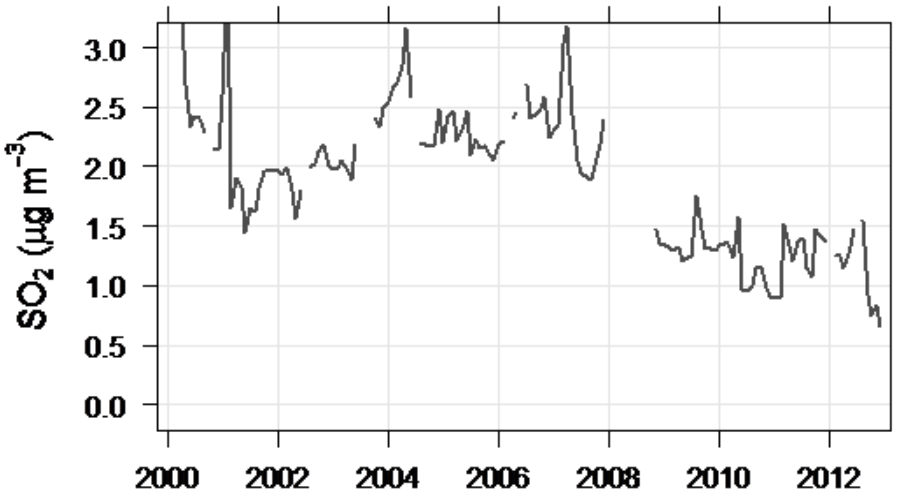


Considering both the Langdon Cliff and Dover Docks time series there is very strong evidence that reductions in fuel sulphur have had a clear and consistent effect on ambient SO_2 concentrations and in a manner consistent with obligations under shipping fuel legislation. The fact that the reductions were abrupt suggests that there was no lag in implementing low sulphur fuels and the large majority of ships complied by the required date.

4.2 Analysis of SO_2 measurements at Lullington Heath

The other site with continuous measurements where ship SO_2 emissions might be detected is Lullington Heath, which is located in a rural location in East Sussex, approximately 5 km from the coast. Unlike the Dover port site, the Lullington Heath site might be expected to show the effects of ships in transit rather than in port and is likely to be dominated by emissions from tankers and container ships. Applying the same techniques to the Lullington Heath hourly time series (for wind directions from 80 to 250 degrees) as those used at Dover yields the time series shown in ***Figure 10***. There is evidence that SO_2 concentrations have decreased, but the timing of the decrease is not certain due to poor data capture in 2008. However, the Lullington Heath data appears consistent with the introduction of the North Sea SECA (including the English Channel) in August 2007. Comparing post-2008 concentrations (1.3 µg m^{-3}) to pre-2008 concentrations (2.3 µg m^{-3}) indicates a reduction in SO_2 concentrations of 43%, which is again consistent with the legislation change for shipping fuel sulphur content in August 2006.

Figure 10: *Time series of SO_2 concentrations at Lullington Heath for wind directions from 80° to 250°, removing the effect of long-term changes in meteorology.*



4.3 Time series of particle sulphate from long-running AGANET sites

Monthly-average concentrations of particle sulphate have been measured using the DELTA annular denuder technique (Sutton et al., 2001) for many years at a number of sites around the UK. Measurements at some sites only began during 2006 so have insufficient measurements from before the dates on which S in supping fuel was reduced to a maximum of 1.5% (Aug 2006 for all passenger ships in EU waters and Nov 2007 for all ships in the SECA) to investigate evidence for a step change in particles SO_4^{2-}. The time series of annual

average SO_4^{2-} shown in ***Figure 11*** is therefore restricted only to those sites with measurements from 2000. ***Figure 12*** shows the absolute and relative reduction in particle SO_4^{2-} at these sites for the period 2008-2012, after the shipping fuel S reductions, compared to the period 2000-2005.

All sites show a decline in SO_4^{2-} reflecting the general decline in S emissions from all sources during this period. Barcombe Mills is the site closest to the south and east coast and is therefore the site that would be expected to be most directly influenced by shipping emissions. Whilst ***Figure 12*** shows that Barcombe Mills has sustained the largest absolute and almost largest relative decreases in particle SO_4^{2-} pre- to post-2006/07 (along with Stoke Ferry and High Muffles, which might also be expected to have some influence from shipping), there is no convincing evidence from either ***Figure 11*** or ***Figure 12*** that these SO_4^{2-} data are picking up a shipping source signature, including in relation to the step-change reduction in shipping fuel S around 2007. At all sites 2003 is an anomalous year, but removing data for 2003 from the pre-2006/07 averaging doesn't make trends any more obvious. It is concluded that the combination of the location of these sites and the monthly averaged nature of the measurements is insufficient for these measurements to be useful for future source apportionment of shipping emissions.

Figure 11: *Time series of annual particle SO_4^{2-} concentrations measured at AGANET sites in operation since 2000. Underlying raw data are monthly averages.*

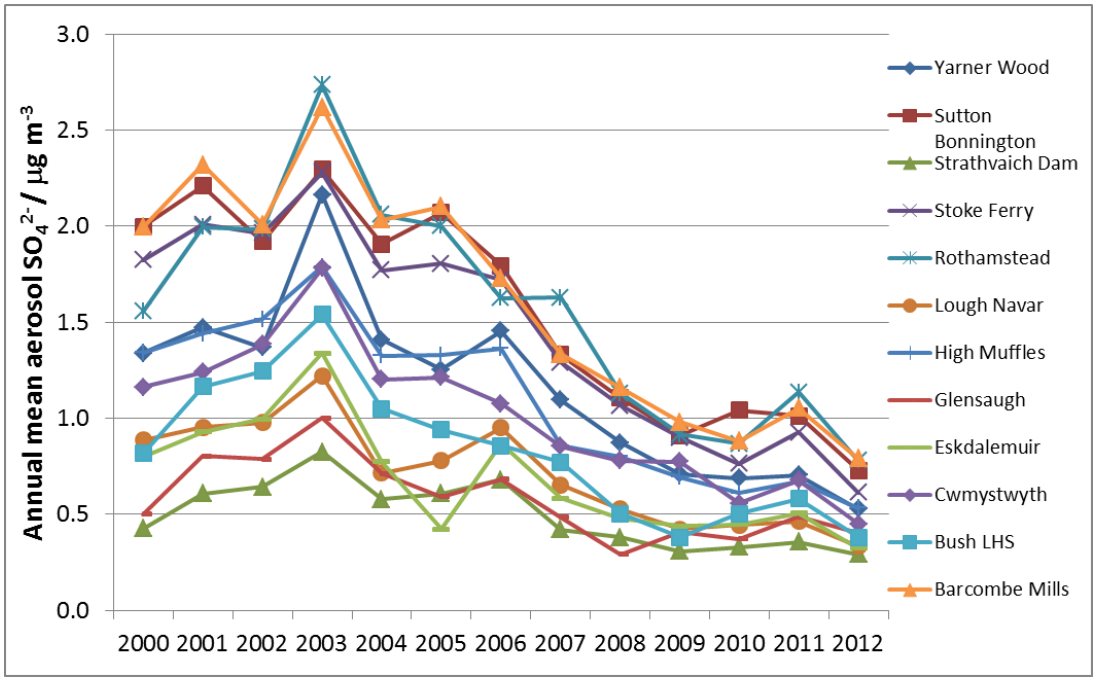
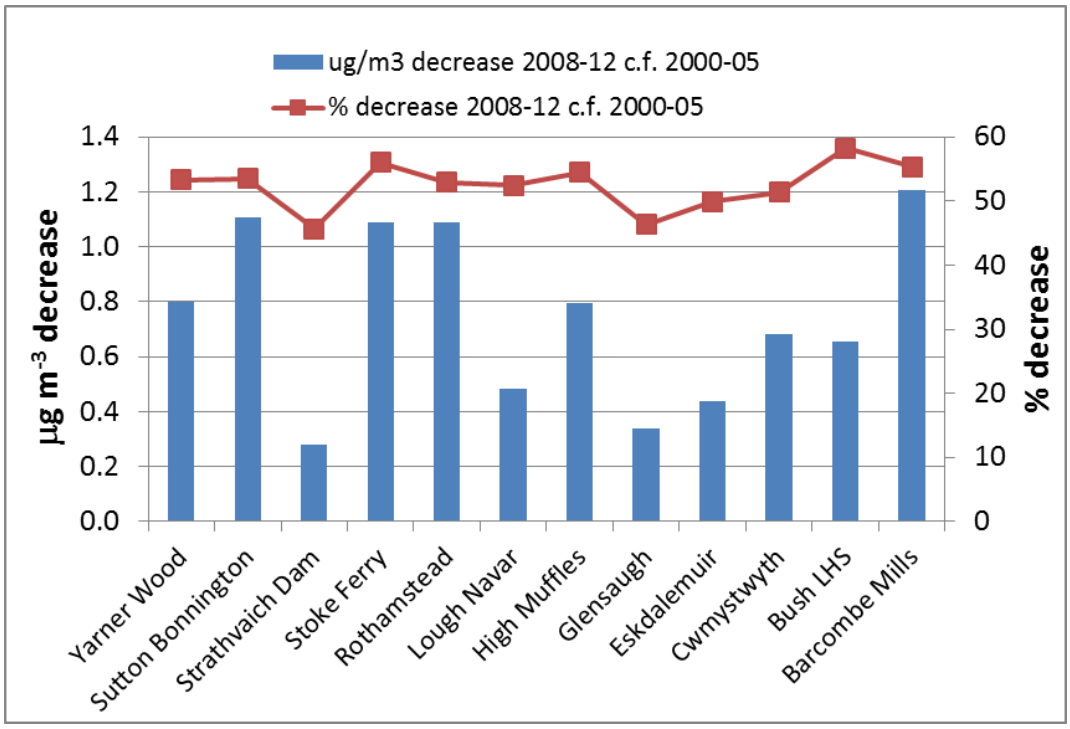


***Figure 12**: The 2008-2012 average versus 2000-2005 average absolute and relative decrease in particle SO_4^{2-} concentrations at AGANET sites with long-running data.*



4.4 Comments on SO_2 measurement capability

4.4.1 Limit of detection

The UV fluorescence instrument used for SO_2 measurement in the AURN has a limit of detection of ~0.9 µg m^{-3} although it is also reported to have detection issues where ambient SO_2 concentrations are close to or less than 2-3 µg m^{-3} (Cape, 2011). To observe changes in SO_2 due to changes in shipping emissions, at locations away from the vicinity of ports, changes of the order of 0.2 µg m^{-3} need to be quantified. The DELTA technique used for SO_2 (and particle SO_4^{2-}) at the AGANET sites has a lower detection limit of 0.03 µg m^{-3} (Sutton et al., 2001), but only yields monthly averages and therefore cannot be used to detect and characterise SO_2 as a function of wind direction or shipping movements. It is noted that the recommendation for improved sensitivity and precision in SO_2 measurement is to contribute to shipping emission apportionment and not because SO_2 concentrations are currently a cause for concern against health-based air quality limit values.

4.4.2 Short term variability in SO_2 concentrations

A further method for assessing the impact of ships on pollutant concentrations is to focus on higher frequency variation in pollutant concentration. Considering the Lullington Heath monitoring site, and by using a dispersion model (in this case ADMS) and making reasonable assumptions about ship speed (~10 knots), it can be determined that the plume from an individual ship in the Channel shipping lanes will show a signature at Lullington Heath for between about 10 and 30 minutes depending on the weather conditions. This shows the advantage of archiving data at high time resolution (e.g. 5 minutes) in order to distinguish ship signatures. In principle, given real time shipping information, such data could be used in

conjunction with a suitable Lagrangian model to determine the specific ship responsible for each signature.

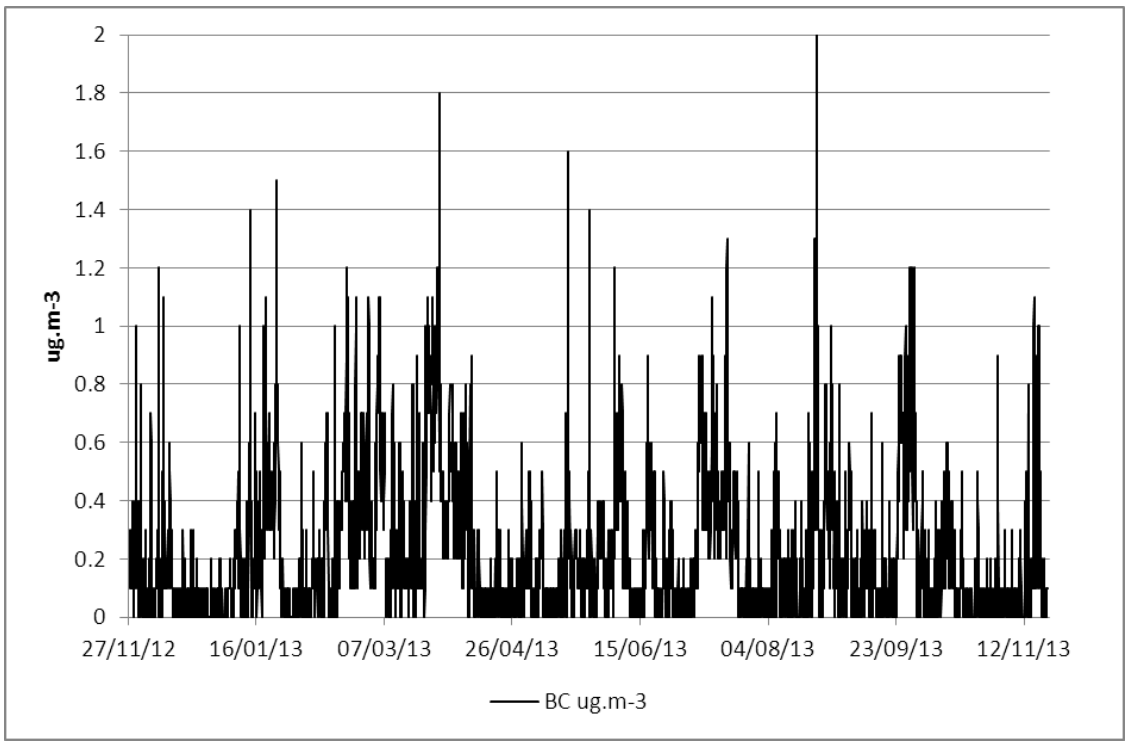
4.5 Analysis of black carbon measurements at Goonhilly

Monitoring of black carbon at Goonhilly, on the Lizard peninsula about 7 km from the coast, was carried out from November 2012 to November 2013. The instrument used was a two channel aethalometer, as used in the Defra black carbon network. The “black carbon” channel measures the absorption by particles sampled on a filter at a wavelength of 880 nm, and is a measure of the quantity of soot in the air. The “UV” channel measures absorption at 370 nm, but these data are not presented here. Further information on the method is contained in the network Annual Reports (e.g. Butterfield et al., 2013).

The site was chosen to investigate shipping emissions as it is typically downwind of busy shipping lanes, while background concentrations were expected to be low.

The time series of the aethalometer black carbon data, shown in ***Figure 13***, is typical of rural network sites, with small spikes in concentration interspersed with prolonged periods of low concentrations. The annual average, 0.22 µg m^{-3}, is similar to that for the most remote rural site in the black carbon network (Auchencorth Moss in Midlothian, ~0.2 µg m^{-3}), and significantly lower than that at the rural site of Harwell in Oxfordshire (~0.5 µg m^{-3}).

Figure 13: *Time series of attenuation-corrected and flow-scaled aethalometer black carbon data for the monitoring at Goonhilly.*



A bivariate black carbon concentration plot as a function of wind speed and direction has been generated to try to discriminate between possible pollutant sources ***Figure 14***. Wind data are taken from the Culdrose Fleet Air Arm Base, located 6.5 km to the NW.

Figure 14: *Pollution wind rose of aethalometer black carbon for the monitoring at Goonhilly.*

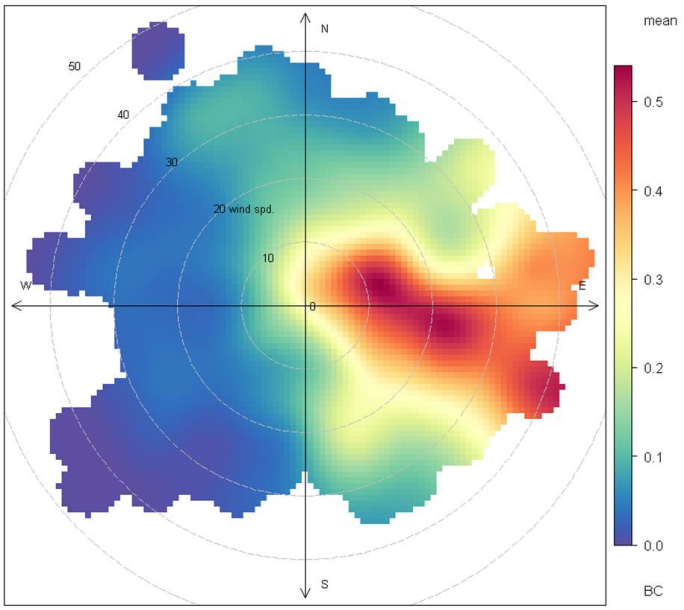


Figure 14 shows that higher concentrations of black carbon tend to occur for wind directions between ENE and ESE at all wind speeds, suggesting a pollution source that is not directly adjacent to the site. If the source was next to the site, higher concentrations at low wind speeds would be expected when there was poor dispersion. The source may be the road 750 m NE of the site, which runs NW to SE. The pollution rose provides strong evidence against significant direct effects from shipping at the site, which would be expected for south-westerly wind directions. The wind rose for the year, ***Figure 15*****,** which shows the frequency with which the wind came from different directions, confirms that south-west winds were relatively common over the year.

Figure 16 shows a potential source contribution function (PSCF) map for black carbon based on back-trajectory analysis. The PSCF gives the probability of high concentrations at the receptor being derived from particular geographical locations backwards along the air mass back trajectory. It is not clear, given the typically low concentrations observed, how much confidence can be assigned to the indicated European source. However, again there is no indication of significant sources in nearby shipping lanes.

The overall conclusion from the analysis of this full year's aethalometer data is that any contribution from shipping to measured black carbon at Goonhilly is very small.

Figure 15: *Wind rose for Culdrose for the period November 2012 to November 2013.*

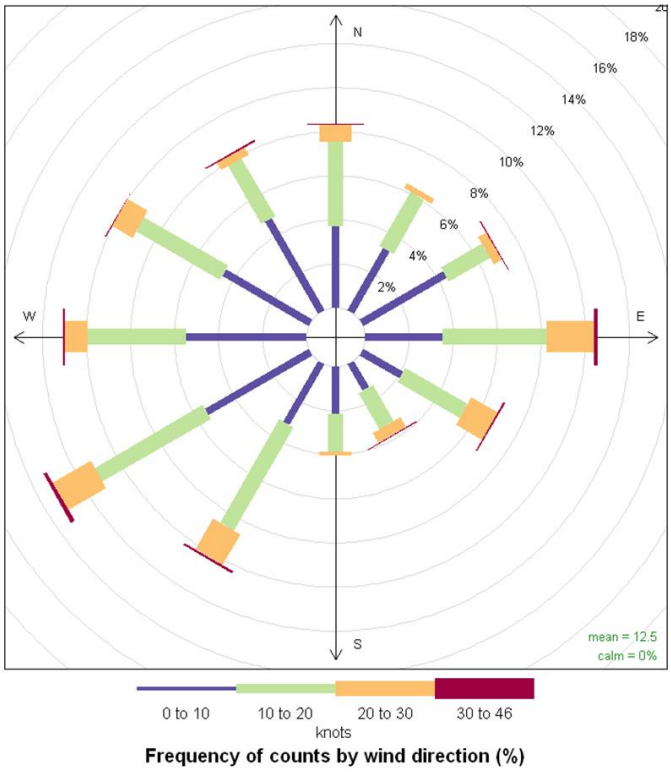
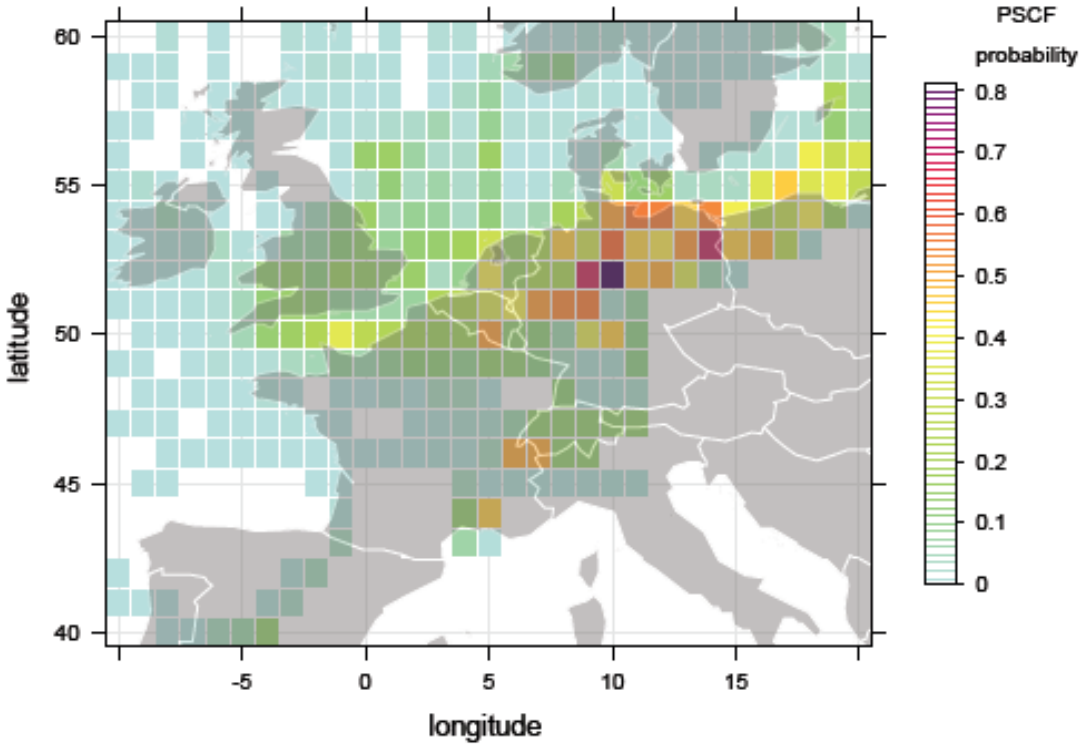


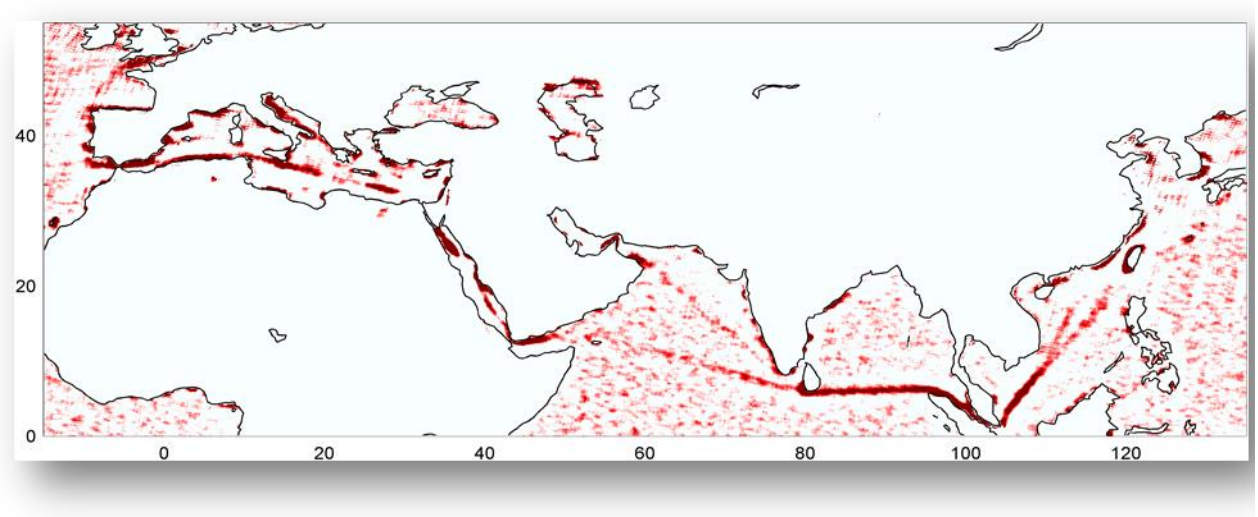
Figure 16: *Potential source contribution function map for black carbon based on back-trajectory analysis.*



4.6 Remote sensing of shipping emissions

Satellite data of tropospheric nitrogen dioxide (Beirle et al., 2004; Richter et al., 2004; Franke et al., 3009) and formaldehyde (Marbach et al., 2009) have been used to quantify shipping emissions. Typical data for NO_2 are shown in ***Figure 17***. Using a six-year record for NO_2 data from GOME, coupled to seasonal differences in wind direction, Beirle et al. (2004), derived a mean lifetime of NO_x in ship exhaust of 3.7 (1.9–6.0) hours in the Indian Ocean. The lifetime calculation was used as the basis for the derivation of shipping emissions estimates in the same area.

Figure 17: *NO_2 from ship emissions from space (courtesy of Stefen Bierle, MPI, Mainz), derived as per Beirle et al. (2004). Displayed data are the differential slant column density which is related to the integrated concentration of NO_2 along the absorption path length.*



De Wildt et al. (2012) used data from four space-borne instruments to observe NO_2 columns from shipping activity in a region stretching from the Mediterranean Sea to the South China Sea. Using data from SCIAMACHY they detected four major shipping lanes: the Mediterranean Sea between Italy and Tunisia, the Red Sea, the Indian Ocean (as reported by Beirle et al. (2004)), and the South China Sea leading northeast from Singapore to Chinese ports. They developed time trends in NO_2 column density from 1996 to 2010 and compared them with trends in shipping cargo volume and international trade volume.

Recently, Vinken et al. (2014) have used comparisons between satellite-observed tropospheric NO_2 columns of the Ozone Monitoring Instrument (OMI) for 2005-2006 with new GEOS-Chem chemistry transport model column simulations to constrain ship NO_x emissions in four European seas (the Baltic Sea, the North Sea, the Bay of Biscay and the Mediterranean Sea). Their results indicated that EMEP emissions in the Mediterranean Sea were too high (by 60%) and misplaced by up to 150 km. However, this discrepancy will have negligible consequence for UK air quality impact. In the North Sea ship track, their top-down emissions amounted to 0.05 Tg N for 2005 (35% lower than EMEP). Increased top-down emissions were found for the Baltic Sea and the Bay of Biscay ship tracks, with totals in these tracks of 0.05 Tg N (131% higher than EMEP) and 0.08 Tg N for 2005 (128% higher than EMEP),

respectively. This study was based on conditions prevailing in 2005-06, but it demonstrates the feasibility for using 'top-down' satellite NO2 observations to derive and validate ship NOx emissions.

Sensitivity for retrieval of surface SO_2 concentrations from satellite is currently considerably less than for NO_2. The UV absorption of SO_2 is strongly dominated by absorptions from stratospheric ozone in the same wavelength region so small uncertainties in the accurate retrieval of O_3 can have significant impact on SO_2 estimates. Furthermore, instrument artefacts may also introduce spectral features that resemble the SO_2 absorption, resulting in bias (Fioletov et al., 2013). Consequently satellite quantification of SO_2 sources has to date largely been confined only to large natural (e.g. volcano) and anthropogenic sources. However, as instrumentation and satellite retrieval algorithms continue to be enhanced, more sensitive and better spatially resolved satellite-derived SO_2 may be expected in the future, which may help with top-down emissions inventory evaluation.

Berg et al. (2012) describe testing of differential optical absorption spectroscopy from an aircraft platform to measure fluxes of both SO_2 and NO_2 from ships in two feasibility studies in the Baltic Sea and the North Sea near Rotterdam. The method uses reflected skylight from the water surface as the light source and a telescope pointed downward at 30° from the horizon. To obtain total mass emission rate, the total integrated mass of retrieved SO_2 and NO_2 across the ship plume is multiplied by the apparent wind, i.e. dilution factor corresponding to the vector between the wind and ship speed.

The use of a fast-sampling ultra-violet imaging camera for the real-time measurement of concentrations and fluxes of SO_2 from stationary and moving large ships has recently been demonstrated (Prata, 2013). This shows promise for tracking of emissions from individual ships and verification of use of low-S fuel in designated areas.

5 Modelling the impacts of shipping emissions on UK air quality

5.1 Introduction

This section presents some recent modelling of the impact of shipping emissions on concentrations of SO_2, NO_x, NO_2 and $PM_{2.5}$ in the UK and on deposition of sulphur and nitrogen. The specific model results presented are those from the Eulerian models EMEP and EMEP4UK and the semi-empirical model PCM. EMEP has a European domain and a horizontal grid size of 50 km with the lowest grid 90 m in height above the ground so it is appropriate for assessing regional but not local impacts. EMEP4UK is nested within EMEP and uses a 5 km horizontal resolution with the same lowest grid height of 90 m; it is therefore able to provide higher resolution concentration patterns but it still has limitations relatively close to sources as highlighted below. PCM has a 1 km horizontal resolution but is limited in its treatment of chemical reactions and spatial and temporal variations in meteorology.

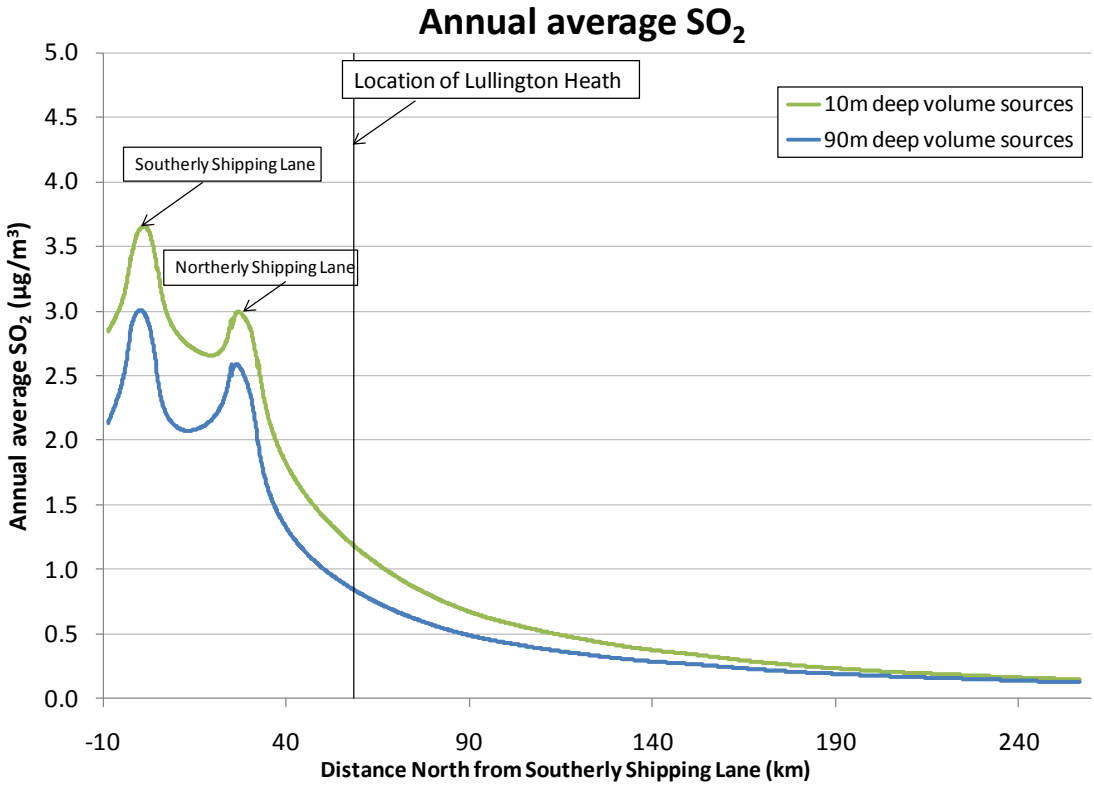
Meteorological patterns are complex close to coastlines due to the strong contrasts in surface roughness, surface heating and sometimes surface elevation (e.g. Hunt et al. 2004). This means that optimum modelling of near-coastal dispersion, as occurs for instance due to ships in the shipping lanes of the English Channel, requires high resolution temporal and spatial data (e.g. from local measurements or a fine scale meteorological model). Such data are not

used by the models described herein, therefore these models are best used for modelling long term average concentrations. Even then the lack of spatial resolution limits the accuracy of the models in predicting concentrations of primary pollutants close to sources. EMEP cannot resolve emissions from shipping lanes whilst EMEP4UK's large vertical grid spacing (lowest grid height 90 m) may result in underestimates of concentrations near sources because of the vertical spreading of emissions this causes.

As an illustration of the impact of this effect, concentrations of SO_2 due to shipping emissions have been calculated by ADMS with volume sources, first at a height of 25 m and vertical depth of 10 m to represent the range in heights of actual emissions including allowance for plume rise, and secondly using a vertical depth of 90 m so that the source configuration is similar to that used in EMEP4UK.

Figure 18 shows calculated annual average SO_2 for both cases along a south-north transect from the shipping lanes in the English Channel through Lullington Heath to the north. There is gradual convergence of the two solutions but at Lullington Heath the more explicit representation of the ship sources results in concentrations approximately 50% greater than the grid based modelling. Thus it may be expected that EMEP4UK underestimates concentrations of primary pollutants emitted from ships up to10s of kilometres from the shipping lanes. This should be recognised in the discussion of the results of EMEP4UK that follow.

Figure 18: *Annual average SO_2 concentration calculated using ADMS on a north-south transect through Lullington Heath.*



5.1 EMEP source-receptor simulations of shipping contributions to UK air quality nationally averaged

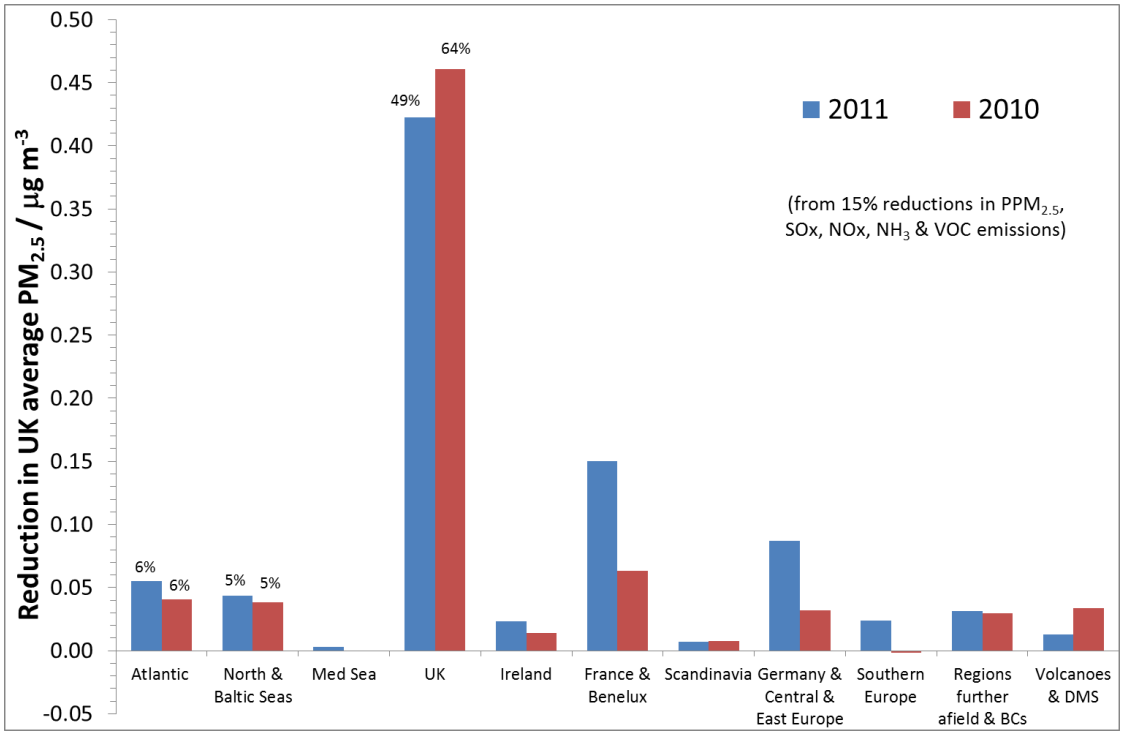
EMEP provides annual source-receptor matrices for a number of air quality concentration and deposition metrics which quantify the impact of a certain emissions reduction in one country or region on the air pollution metric in every other country or region. The data are derived using the current operational version of the EMEP Unified Model (www.emep.int/OpenSource). A number of the designated source regions are marine areas, which therefore provide information of the impact of shipping emissions on UK air quality.

5.1.1 Impact on $PM_{2.5}$

Figure 19 shows the simulated reductions in UK area-averaged surface $PM_{2.5}$ concentration for 2010 and 2011 for 15% reductions in emissions of primary $PM_{2.5}$, SO_x, NO_x, NH_3 and VOC simultaneously. There is inter-annual difference.

The effect of 15% reductions in all the precursor emissions listed in the Atlantic and North & Baltic Seas is to reduce UK area-averaged $PM_{2.5}$ by ~0.08-0.10 µg m^{-3}. Extrapolating a linear relationship implies that shipping emissions contribute ~0.6 µg m^{-3} to area-averaged UK primary and secondary inorganic $PM_{2.5}$. The impact of shipping VOC emissions on organic $PM_{2.5}$ is negligible.

Figure 19: *Reductions in UK-average surface $PM_{2.5}$ (for 2010 and 2011) resulting from 15% reductions in anthropogenic emissions of primary $PM_{2.5}$, SO_x, NO_x, NH_3 and VOC simultaneously, from each of the marine areas or countries/regions indicated. Source of data: www.emep.int/SR_data/sr_tables.html (downloaded November 2013), as calculated with EMEP/MSC-W model rv4 for 2010 and rv4.4 for 2011.*



The % values marked on some of the bars in ***Figure 19*** indicate the fractional contribution to the reduction in modelled UK-average surface $PM_{2.5}$ due to the emissions reduction in that

region relative to the sum of the contributions to reduction in UK-average surface $PM_{2.5}$ due to emissions reductions in all the different countries (and boundary values) within the full EMEP model domain. In 2011, emissions from the North & Baltic Sea and remaining North Atlantic, together contributed 11% of the 51% of the contribution to UK-average $PM_{2.5}$ derived from outside the UK, i.e. these marine areas contributed a 11/51 = 0.22 proportion of the non-UK contribution to UK $PM_{2.5}$. In 2010, emissions from these marine areas together contributed 11% of the 36% (proportionally: 11/36 = 0.31) of the non-UK contribution to UK area-averaged $PM_{2.5}$. The influences of emissions from the Atlantic or from the North & Baltic Seas are roughly equal. The impact of emissions from shipping in the Mediterranean Sea is negligible. Taking the two years of data together suggests that shipping contributed around 11% to UK area-averaged $PM_{2.5}$, which is around one-quarter of the non-UK emissions influence on UK $PM_{2.5}$. However, it should be noted that the simulations tend to underestimate observed $PM_{2.5}$ because not all sources are included, nor absorbed water. Consequently the model-derived 11% contribution to UK $PM_{2.5}$ from shipping is likely an overestimate.

EMEP source-receptor data presented in AQEG (2015) show that, of the inorganic precursor gases, the influence of shipping SO_x on UK $PM_{2.5}$ dominates the influence of shipping NO_x, and that there is no shipping contribution through emissions of NH_3.

The simulations described have perturbed emissions of all precursors simultaneously. The complex atmospheric oxidation and phase-partitioning chemistry may lead to different outcomes if only one gaseous precursor is reduced or if gaseous precursors are reduced in different relative proportions to each other.

5.1.2 Impact on S and N deposition

Figure 20 illustrates the modelled reductions in annual deposition to the UK of oxidised sulphur, oxidised nitrogen and reduced nitrogen for 2011 arising from 100% reductions in emissions of SO_x, NO_x, NH3 and VOC simultaneously, from the North & Baltic Seas, the remaining North Atlantic, and the Mediterranean Sea, in comparison with similar emissions reductions from the UK, Ireland and various groupings of other source countries or geographic areas. Trends for 2010 are similar. (Note the simulations are actually performed for 30% emissions reductions in a given source region and the effect on deposition scaled (by EMEP) by a factor 100/30.) The % values marked on some of the bars in the figure indicate the fractional contribution to the deposition in the UK of the emissions reduction in that region relative to the sum of the contributions to deposition in the UK of emissions reduction in all the different countries (and boundary values) of the full EMEP model domain. Some of the absolute values of reductions in deposition to the UK for 2011 and 2010 are given in ***Table 6***.

Figure 20: *Reductions in annual deposition to the UK in 2011 of oxidised sulphur, oxidised nitrogen and reduced nitrogen from 100% reductions in emissions of SO_x, NO_x, NH_3 and VOC simultaneously from each of the marine areas or countries/regions indicated. Source of data: www.emep.int/SR_data/sr_tables.html (downloaded November 2013), as calculated with EMEP/MSC-W model rv4.4.*

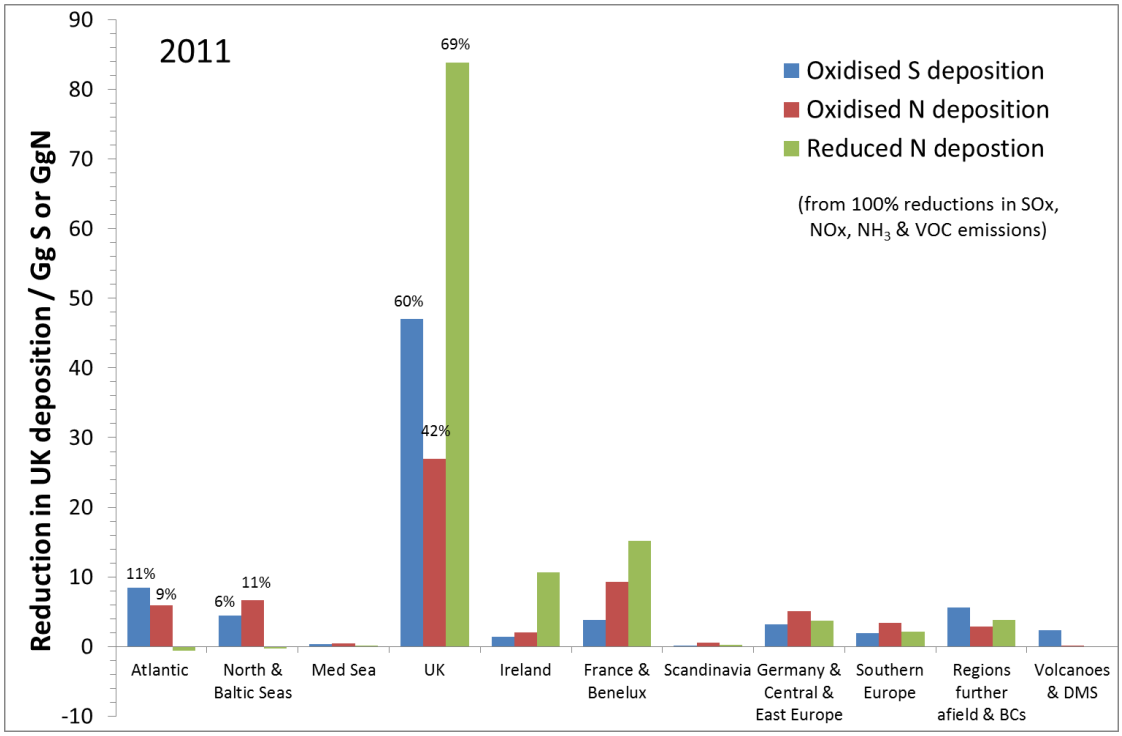


Table 6: *Reductions in annual deposition to the UK from 100% reductions in emissions of SO_x, NO_x, NH_3 and VOC from each of the marine areas indicated, or from the UK. The bottom line of the table is the sum of the reductions in deposition to the UK from emissions reductions in all modelled source regions. Source of data: www.emep.int/SR_data/sr_tables.html (downloaded November 2013), as calculated with EMEP/MSC-W model rv4.4 for 2011 and rv4 for 2010.*

Source region	2011				2010		
	Oxid_S dep / Gg S	Oxid_N dep / Gg N	Red_N dep / Gg N		Oxid_S dep / Gg S	Oxid_N dep / Gg N	Red_N dep / Gg N
Atlantic	8.4	5.9	–0.6		7.0	5.1	–0.3
North & Baltic Seas	4.5	6.7	–0.3		5.9	6.6	–0.2
Mediterranean Sea	0.3	0.5	0.05		0.1	0.1	0.01
UK	47.1	26.9	83.8		52.2	26.7	83.2
TOTAL (all source regions)	78.6	63.3	119		87.7	57.3	107

Figure 20 and ***Table 6*** indicate that, for these years, emissions in the UK were responsible for about 60% of the oxidised S deposition in the UK but that a significant proportion (17% in 2011 and 16% in 2010) derived from emissions from shipping; i.e. shipping emissions contributed about 16/40 = 40% of the non-UK derived S deposition, which is substantially more than any other single country's contribution to UK S deposition. Shipping emissions from the Atlantic collectively had slightly more impact on UK S deposition than shipping emissions from

the North Sea and Baltic Sea (emissions from the Baltic Sea make up only a small proportion of the total impact from these marine areas).

Shipping emissions contributed a somewhat greater proportion to oxidised N deposition in the UK in these years (about 21%), than their contribution to oxidised S deposition (16-17%) (***Figure 20*** and ***Table 6***). This contribution from shipping again represented about 21/55 = 40% of the non-UK contributions to the oxidised N deposition in the UK. (A greater proportion of the oxidised N deposition in the UK was derived from non-UK sources compared with the non-UK derived sources of oxidised S deposition in the UK.) In contrast to the situation for oxidised S deposition, the impact of emissions from the North Sea on UK oxidised N deposition was greater than the impact of emissions from the remaining north Atlantic.

Shipping emissions had a very small impact on UK deposition of reduced N (***Figure 20*** and ***Table 6***), but the direction of impact is for shipping emissions reductions very slightly to increase deposition.

There is negligible impact of emissions from shipping in the Mediterranean Sea to S and N deposition in the UK.

5.2 EMEP4UK modelling of effects of shipping emissions reductions on UK air quality spatially

Simulations have been carried out using the EMEP4UK model of the impact of 30% reduction in emissions of primary-PM, SO_x, NO_x and VOC simultaneously from all shipping everywhere in the EMEP4UK inner domain (the region demarcated by the area shown in the figures that follow). All other emissions were unaltered. Shipping emissions were derived from the ENTEC estimates published on UK Air (ENTEC, 2010). EMEP4UK model version 3.7 was used (Vieno et al., 2010), with 2008 meteorology and emissions. The results derive from previous simulations for Defra and SEPA (Vieno et al., 2012; Laxen et al., 2010).

5.2.1 Impact on SO_2 and NO_2

The modelled 2008 annual average reductions in surface SO_2-S for a 30% reduction in all shipping emissions in the EMEP4UK inner domain is shown in ***Figure 21***. The equivalent for annual average NO_2-N is shown in ***Figure 22***.

Figure 21 shows that the 30% reductions in shipping emissions are simulated to yield in the region of 9 - 15% reductions in SO_2 in many coastal areas of the south and south-east of England, and more in the vicinity of busy ports. Reductions in SO_2 around other coastal areas are in the range 3 - 9%, and even well inland the 30% reductions in shipping emissions reduces the SO_2 by 2 - 4%. The impact of shipping emissions on surface NO_2 is slightly less marked than for SO_2, ***Figure 22***, reflecting the large contribution to NO_2 from land-based transport. Nevertheless, reductions in shipping emissions also lead to clearly discernible reductions in NO_2, in the range 1.5% - 4.5% even inland, but particularly along the south and south-east coast where reductions of NO_2 of up to 15% (up to 2 µg m^{-3} NO_2) are simulated for the shipping emissions reductions of 30%.

***Figure 21*:** EMEP4UK 2008 annual average surface concentration of SO_2-S (left panel) and % and absolute reductions in SO_2-S (centre and right panels) resulting from a 30% reduction in all emissions from all shipping everywhere in the EMEP4UK inner domain. All terrestrial emissions unaltered. Source: M. Vieno (CEH).

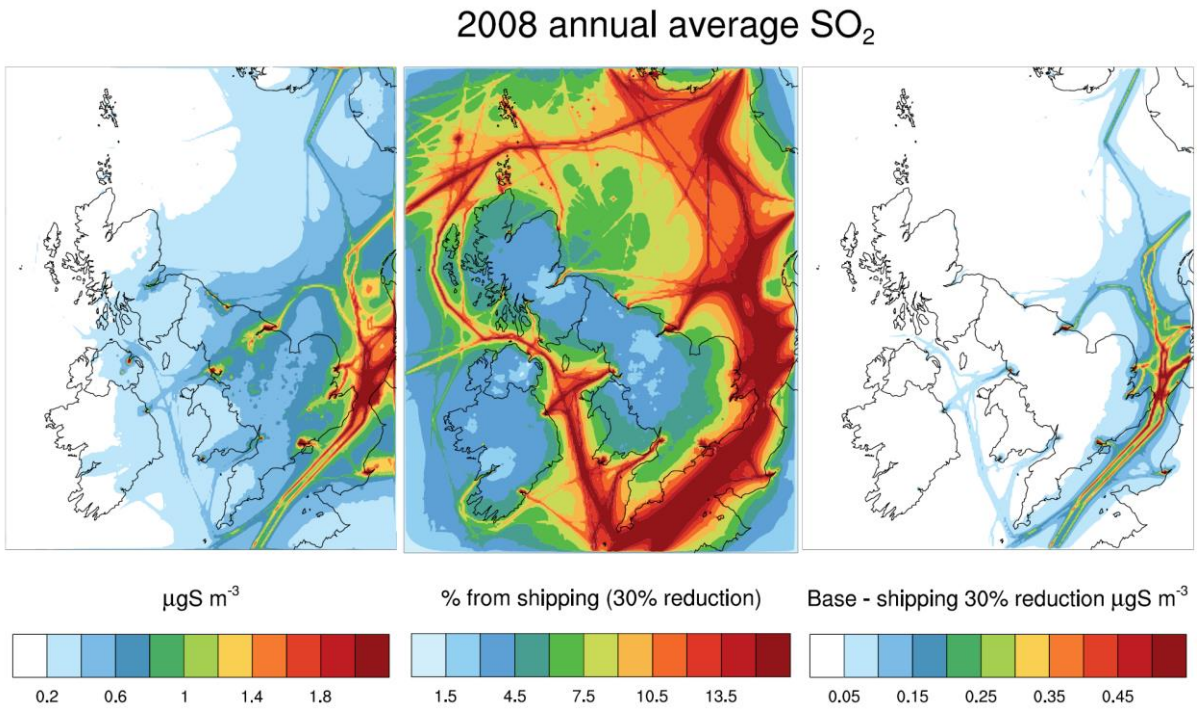
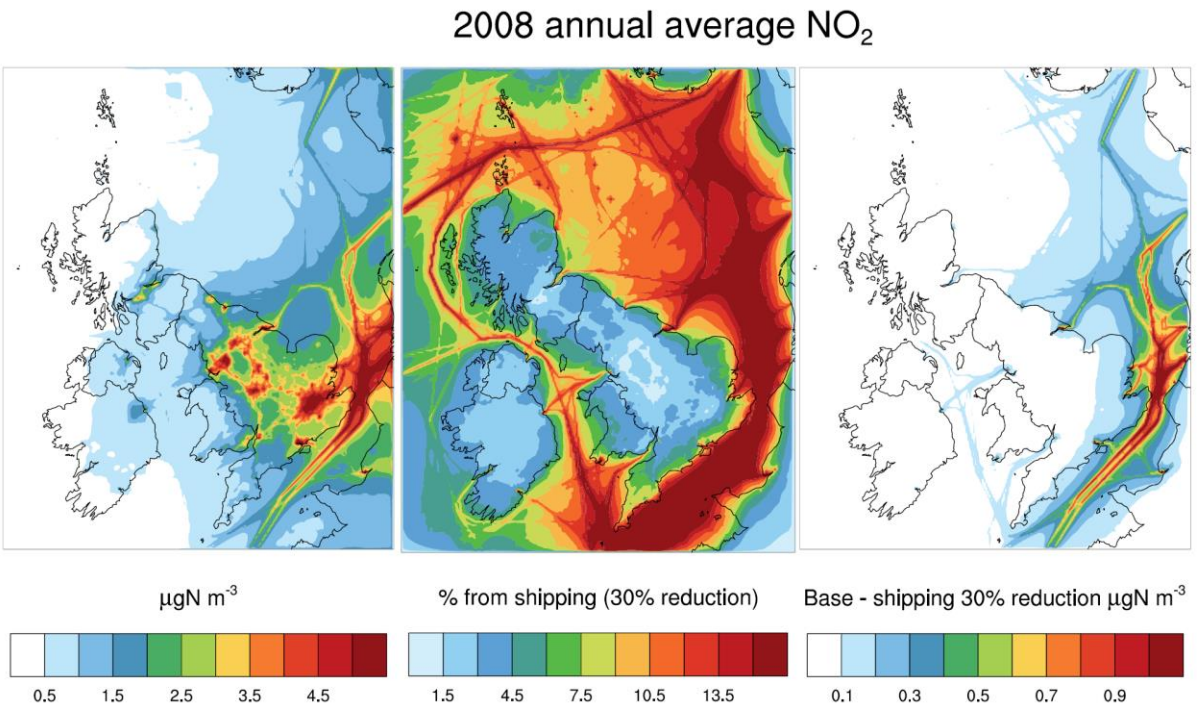


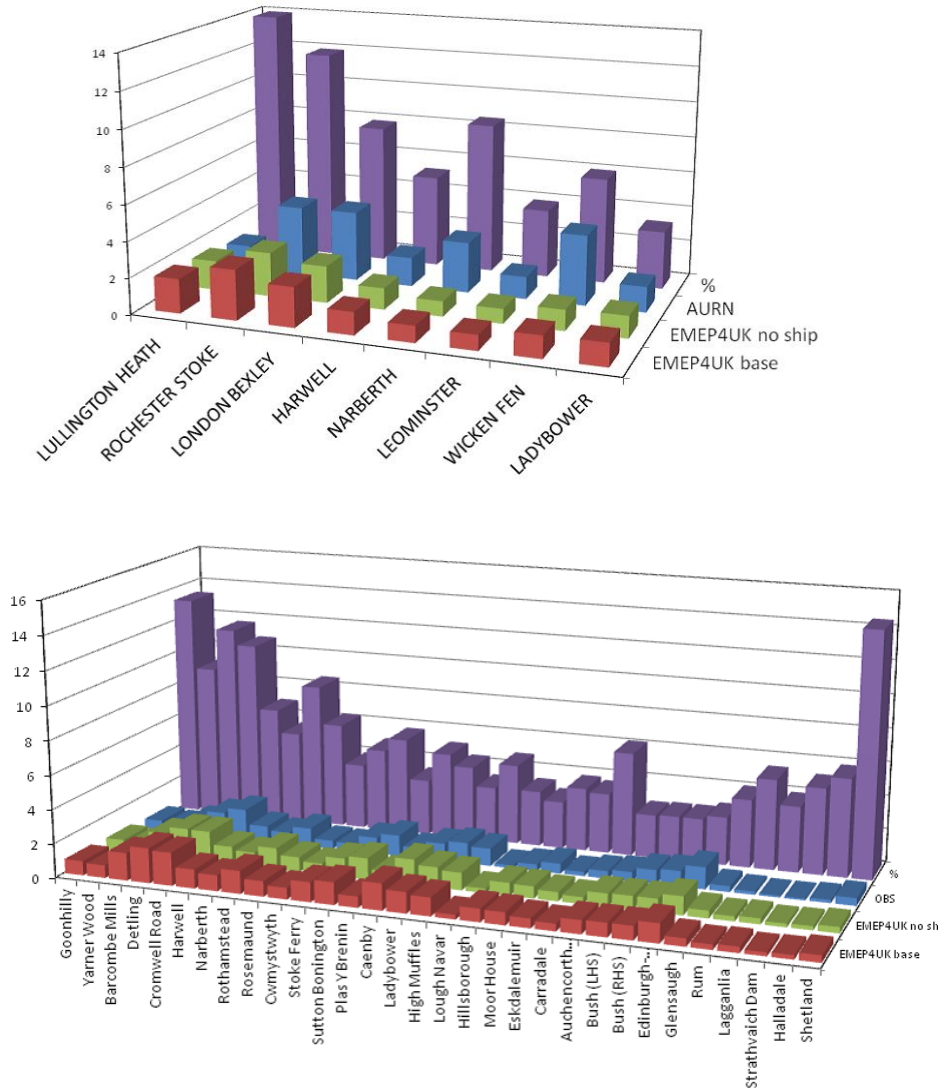
Figure 22: *EMEP4UK 2008 annual average surface concentration of NO2-N (left panel) and % and absolute reductions in NO_2-N (centre and right panels) resulting from a 30% reduction in all emissions from all shipping everywhere in the EMEP4UK inner domain. All terrestrial emissions unaltered. Source: M. Vieno (CEH).*



For illustration of the impact of shipping at locations of UK network sites, ***Figure 23*** shows the % change of SO_2 concentrations for the EMEP4UK 5 km grid squares containing AURN sites that monitor SO_2 in real-time by UV fluorescence and for the grid squares containing AGANET sites yielding monthly average SO_2 via denuder and off-line ion chromatography analysis. The figure shows the generally increasing influence of shipping emissions to SO_2 further south and closer to the Channel. However, there can also be major relative influence of shipping in coastal areas when SO_2 is already low such as around Shetland.

If the relationship between shipping emissions reductions and SO_2 and NO_2 concentrations can be linearly extrapolated then the effect on SO_2 and NO_2 of 100% reductions in all shipping emissions in the modelled inner domain would be approximately three times those observed in ***Figure 21*** and ***Figure 22***. Note that, as discussed at the beginning of Section 5, owing to limitations in modelling at 5 km horizontal resolution in the vicinity of high source regions, concentrations of SO_2 and NO_2 immediately adjacent to major port areas (and, the corollary, the reductions in SO_2 and NO_2 from precursor emission reductions) may be greater than simulated in a 5 km × 5 km grid-square average.

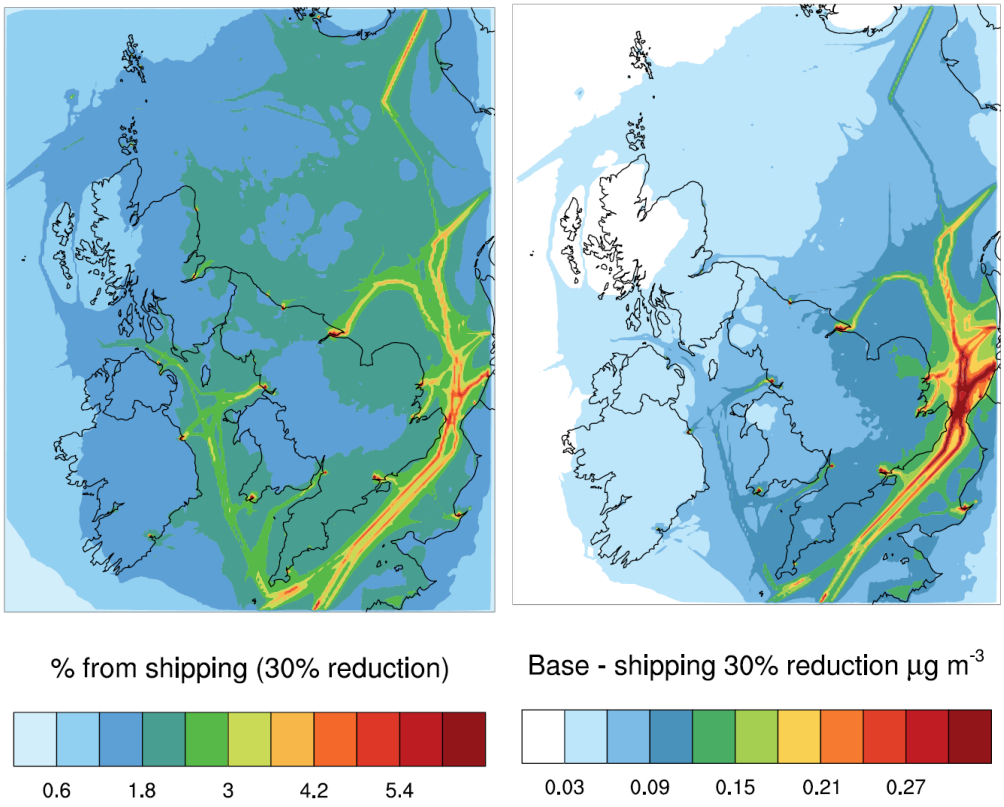
***Figure 23*:** Annual average surface SO_2 concentrations (for 2008) for: upper plot, all available rural and sub-urban AURN sites; lower plot, all available AGANET sites. For both plots, red is the EMEP4UK base run, green the EMEP4UK simulation with 30% shipping emissions reduction, blue the observations (units of μg m^{-3}), and purple the % change in modelled SO_2 for the 30% emissions reductions. The sites are ranked by increasing latitude from left to right in each plot. Source: Vieno et al. (2012).



5.2.2 Impact on $PM_{2.5}$

Figure 24 shows the change in modelled annual average $PM_{2.5}$ for 30% reduction in emissions of primary-$PM_{2.5}$, SO_x, NO_x and VOC simultaneously, from all shipping everywhere in the EMEP4UK inner domain. It should be noted that in these simulations the modelled $PM_{2.5}$ does not include secondary organic aerosol, nor contribution from windblown dusts, wood-burning and forest-fire primary emissions which are now included in more recent EMEP4UK model versions; modelled $PM_{2.5}$ mass also does not include absorbed water. Consequently, the modelled reductions in $PM_{2.5}$ from the reductions in emissions from shipping shown in ***Figure 24*** would in reality be smaller percentages of total $PM_{2.5}$ than shown.

Figure 24**:** *Decreases in EMEP4UK modelled 2008 annual average surface $PM_{2.5}$ (left panel in %, right panel in µg m^{-3}) for 30% reduction in emissions of primary-$PM_{2.5}$, SO_x, NO_x and VOC, simultaneously, from all shipping everywhere in the EMEP4UK inner domain. All terrestrial emissions unaltered. Note that modelled baseline $PM_{2.5}$ does not include all components of $PM_{2.5}$ – see text. Source: M. Vieno (CEH).*



In general, a 30% reduction in all shipping emissions in waters surrounding the British Isles has fairly small impact on modelled $PM_{2.5}$ over UK land, <0.12 µg m^3 in most areas or <0.15 µg m^3 for areas near the southern coast and East Anglia. These absolute reductions correspond to relative reductions in simulated $PM_{2.5}$ of <2.4% in most areas.

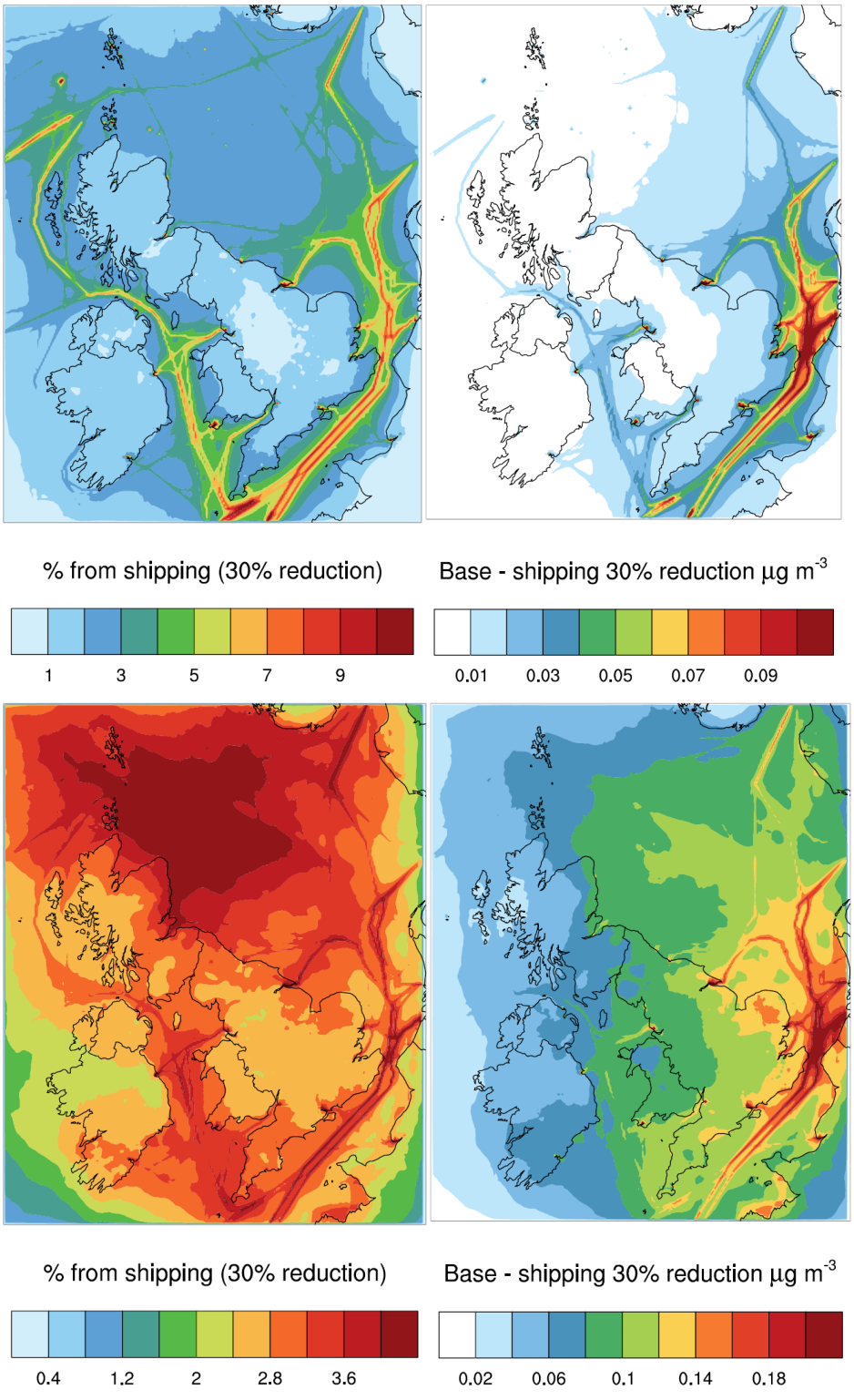
However, much larger $PM_{2.5}$ decreases for shipping emissions reductions are simulated in the vicinity of large ports including Merseyside, Milford Haven, Avonmouth, the Solent, Dover, the Thames estuary, Harwich, the Humber, Teesside, the Forth estuary, Aberdeen and Belfast Loch. Reductions in excess of 0.3 µg m^3 (>6%), are simulated around many of these ports for the 30% shipping emissions reductions.

Figure 25 breaks down the $PM_{2.5}$ results of ***Figure 24*** into the reductions due to primary $PM_{2.5}$ and the reductions due to secondary inorganic aerosol (the sum of NO_3^-, SO_4^{2-} and NH_4^+). The upper row shows that 30% reductions in shipping emissions generally leads to smaller and much more localised reductions in primary $PM_{2.5}$ compared with the reductions in secondary inorganic aerosol (SIA) shown in the lower row. The 30% shipping emissions reductions yields <3% (0.03 µg m^{-3}) reduction in primary $PM_{2.5}$ across the UK, except immediately adjacent to major ports where reductions in primary $PM_{2.5}$ exceed 0.1 µg m^{-3}. In contrast, the 30% shipping emissions reductions leads to >0.08 µg m^{-3} reductions in SIA over the whole of England and

Wales, and to reductions of >0.12 μg m^{-3} over much of south east England and >0.2 μg m^{-3} close to the busiest ports. In general, therefore, across the UK as a whole there is much greater impact of shipping on $PM_{2.5}$ through its emissions of SIA precursors, but close to ports the shipping emissions of primary $PM_{2.5}$ are at least as important as the SIA precursors.

Again, as pointed out in the introduction to this chapter, owing to limitations in modelling at 5 km resolution in the vicinity of very high source regions, concentrations of $PM_{2.5}$ immediately adjacent to port areas and shipping lanes (and, the corollary, the reductions in $PM_{2.5}$ from emissions reductions) will likely be greater than simulated in a 5 km × 5 km resolution model. Also, as before, if the relationship between shipping emissions reductions and $PM_{2.5}$ concentrations is linearly extrapolatable then the effect on $PM_{2.5}$ of 100% reductions in all shipping emissions in the modelled inner domain would be approximately three times those calculated.

***Figure 25**: The left panels are the % reductions and the right panels are the concentration reductions (µg m^{-3}) in 2008 annual average primary $PM_{2.5}$ (upper row) or secondary inorganic aerosol (sum of NO_3^-, SO_4^{2-} and NH_4^+) (lower row) for 30% reduction in emissions of primary $PM_{2.5}$, SO_x, NOx and VOC, simultaneously, from all shipping everywhere in the EMEP4UK inner domain. All terrestrial emissions unaltered. Note different scales between upper and lower rows. Source: M. Vieno (CEH).*



5.2.3 Impact on S and N deposition

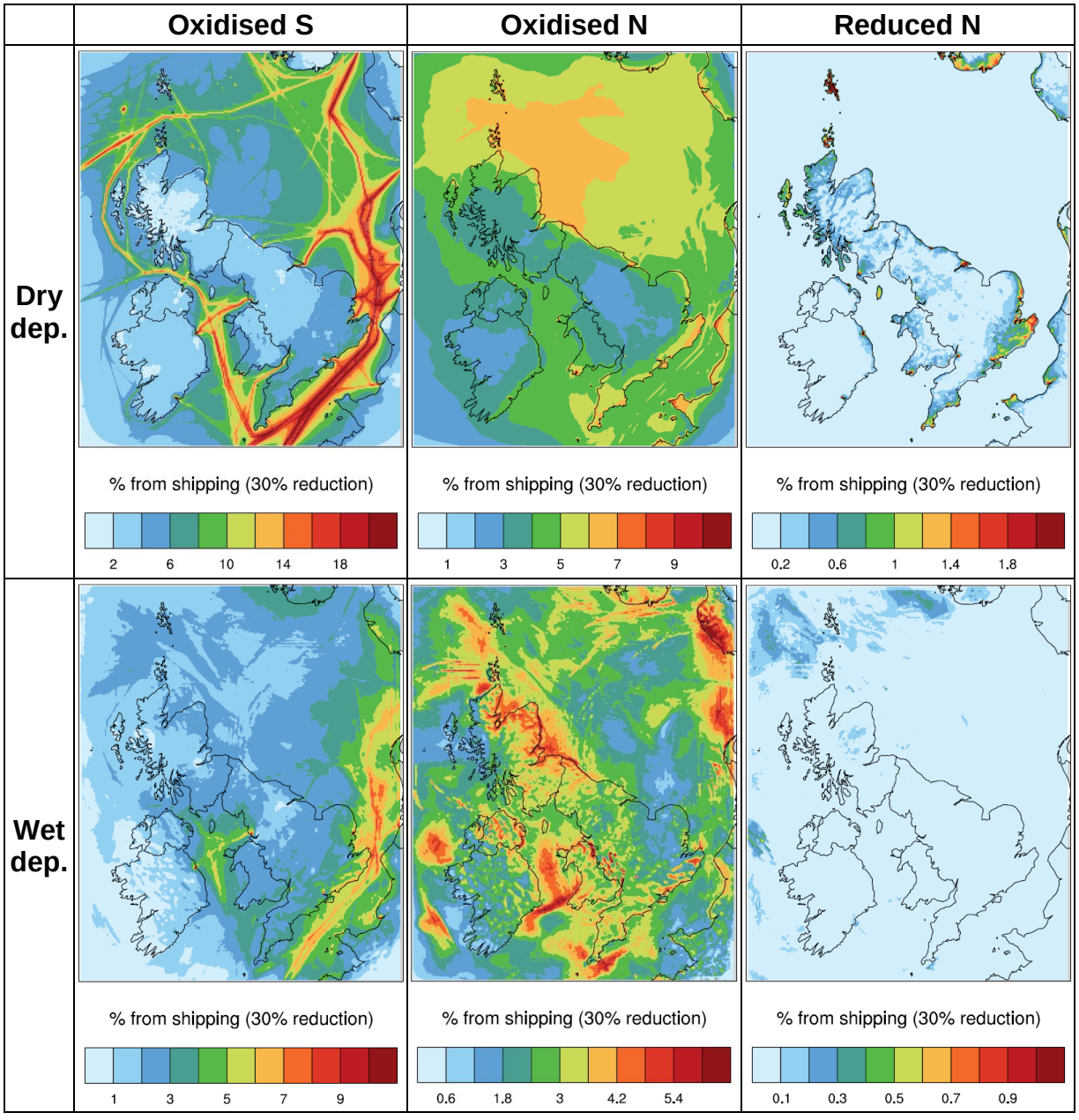
Figure 26 shows the spatial distributions in the % reductions in modelled dry and wet S and N deposition in the UK for a 30% reduction in all shipping emissions in the EMEP4UK inner domain.

The 30% reductions in emissions yield reductions of 2 - 8% in dry deposition of oxidised S across the UK, with increased contribution towards the Channel coast. Reductions in wet deposition across the UK are in the range 1 - 6% again increasing to the south east. Visual inspection of the maps in ***Figure 26*** indicates that on average across the UK the 30% shipping emissions reductions yield approx. 6% reduction in oxidised S (~4% and 2% for wet and dry deposition, respectively); which, with linear extrapolation of the emissions-receptor factor, implies that shipping contributes ~18% to oxidised S deposition in the UK. This estimate is consistent with the estimates of the shipping contribution to UK oxidised S deposition from the European scale modelling described above.

The 30% reduction in shipping emissions yields 2 - 7% reductions in dry deposition of oxidised N, with the highest reductions in this range along the whole of the south and east coasts of the UK (***Figure 26***). The decreases in wet deposition of oxidised N is more geographically variable and in the range 1 - 5% with increasing relative impacts generally to the west and north of the UK. Again by visual inspection of ***Figure 26*** the 30% shipping emissions reductions yield approx. 4% and 3% reductions in dry and wet deposition of oxidised N on average across the UK, which implies a total shipping contribution to UK oxidised N deposition of around 20%.

The impact of the shipping emissions reductions on deposition of reduced N are very small compared with impacts on oxidised N and S.

Figure 26: *% reductions in dry and wet S and N deposition (for 2008) resulting from a 30% reduction in emissions of primary-$PM_{2.5}$, SOx, NOx and VOC, simultaneously, from all shipping everywhere in the EMEP4UK inner domain. All terrestrial emissions unaltered. Note the different scales. Source: M. Vieno (CEH).*



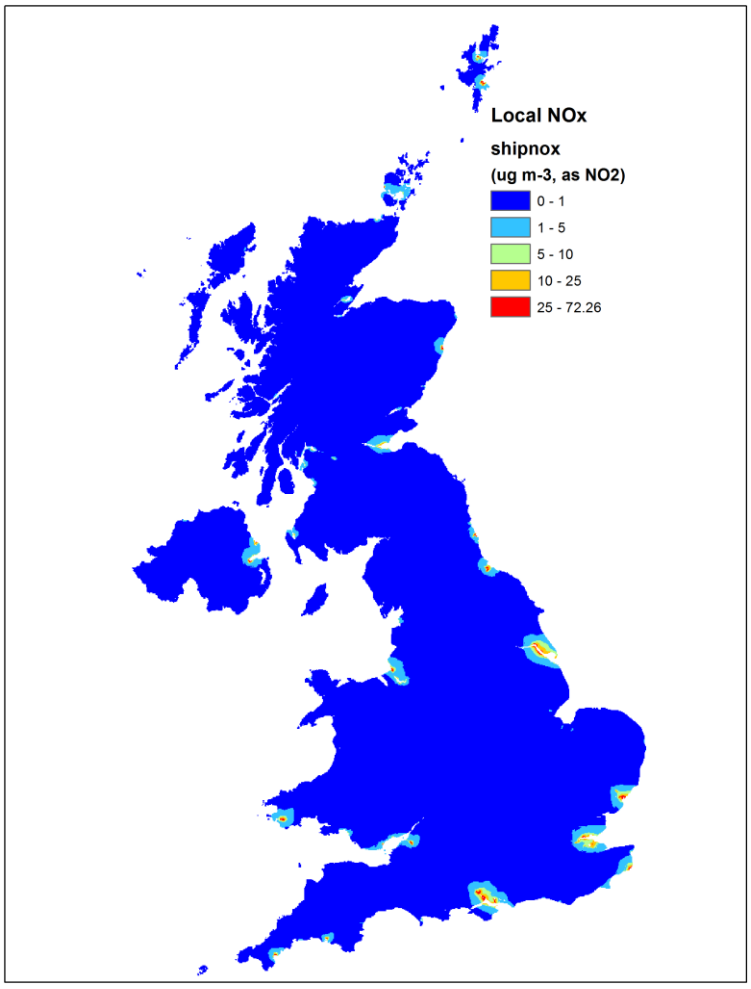
5.3 An assessment of the contribution to ambient NO_x and $PM_{2.5}$ concentrations from shipping emissions using results from the PCM model

The PCM model has been used to assess the contribution to ambient NO_x and $PM_{2.5}$ concentrations across the UK in 2012. This assessment is based on the models used to inform the 2012 assessment of compliance with the limit and target values set out in the Air Quality Directive. The PCM model includes contributions to ambient concentration from a number of separate components and can therefore provide estimates of both the contribution from local emissions and of more distant emissions to the regional background.

5.3.1 Local NO_x

The contribution from local NO_X emissions from shipping from the NAEI has been assessed using dispersion kernels derived from ADMS. These kernels calculate the concentration at a receptor location from emissions within an area of 33 km × 33 km. The UK population-weighted mean annual mean NO_x concentration from these sources is 0.54 µg m^{-3} (2.0% of the total background NO_x from all sources). ***Figure 27*** shows that the highest concentrations from these sources (exceeding 25 µg m^{-3}) are close to busy ports.

Figure 27: *The contribution to annual mean NO_x concentrations in 2012 from local shipping emissions estimated using the PCM model*.



5.3.2 Regional NO_x

Total regional NO_x concentrations within the PCM model are derived by interpolation from concentrations measured at rural monitoring stations. The measured values at the monitoring stations are adjusted prior to interpolation to subtract an estimate of the contribution from local sources. The regional NO_x concentration has been assigned to contributions from UK, rest of Europe and shipping emissions using source apportionment proportions for 50 km grid squares derived using the PPM model (a component of the UKIAM model). ***Figure 28*** shows the spatial distribution of this regional contribution. The UK population-weighted mean annual mean contribution from shipping is 1.24 µg m^{-3} (4.6% of the total background NO_x from all sources, 14.7% of the total regional background). The lower contribution from shipping in the 50 km grid square in Yorkshire is likely to be an artefact of the combination of measurement and model based datasets. This grid square includes emissions from several larger power stations.

The PCM local and regional NO_x results together yield an estimated contribution to population-weighted NO_x (in 2012) of 1.78 µg m^{-3}, or 6.6% of total background NO_x from all sources (***Table 7***). This is compared in ***Table 7*** with an estimated contribution of shipping to UK population-weighted NO_2 of 1.19 µg m^{-3} derived from the EMEP4UK shipping perturbation simulations for NO_2 illustrated in ***Figure 22***. The latter value was obtained by scaling the population-weighted reductions in gridded EMEP4UK surface NO_2 for the 30% shipping emissions reduction simulation by a factor 100/30. The two estimates are reasonably consistent given substantial differences in the two model simulations: the EMEP4UK value is for NO_2 which is a subset of NO_x; the EMEP4UK perturbation reduced shipping emissions only in the EMEP4UK British Isles inner domain and therefore does not estimate the contribution from shipping emissions outside of this domain; the scaling of the EMEP4UK perturbations assumes linearity of the impact of shipping emissions on UK surface NO_2. The two models also simulate different years. Visual inspection of ***Figure 22*** suggests that the 30% shipping emissions reductions leads to an average reduction in spatially-averaged NO_2 across the UK of ~3% (in 2008). Extrapolating this latter value to 100% shipping reductions would give an estimated contribution from shipping to UK NO_2 (in 2008) of very approximately 9%.

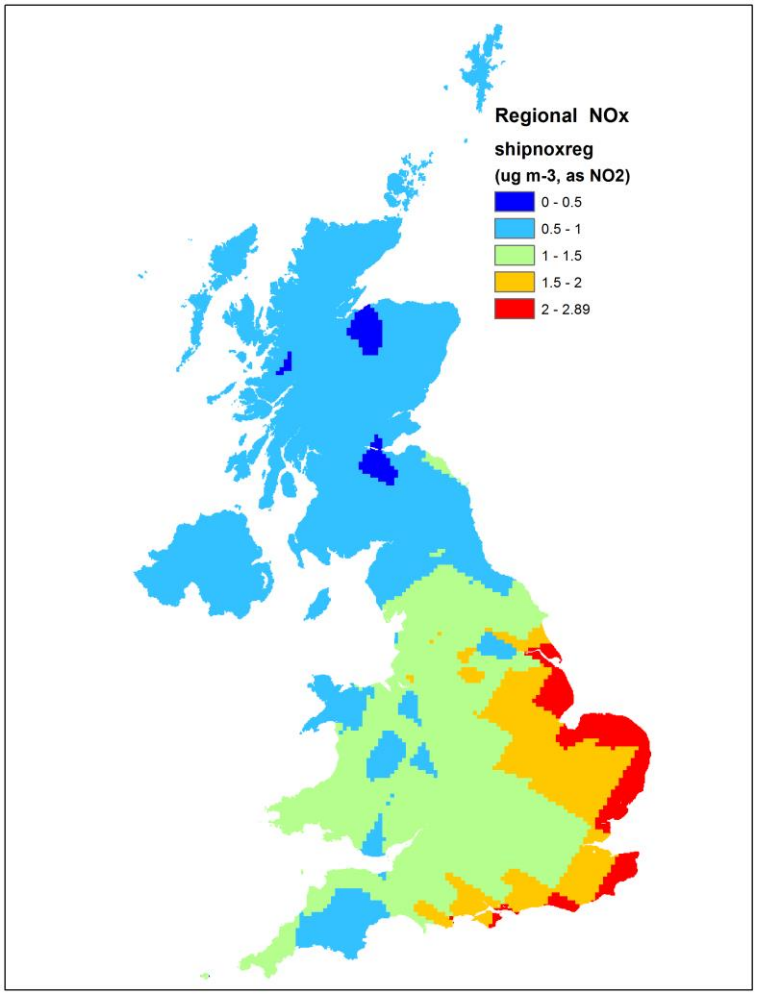
Table 7: *Comparison of EMEP4UK and PCM model estimates of the contributions from shipping emissions to UK annual-average population-weighted NO_2 or NO_x, and to primary, secondary inorganic and total $PM_{2.5}$. Data for EMEP4UK and for PCM are for years 2008 and 2012, respectively.*

	PCM (µg m^{-3})	PCM (% of all sources)		EMEP4UK (µg m^{-3})
NO_2 or NO_x [a]	1.78	6.6%		1.19
Primary $PM_{2.5}$	0.10	1.0%		0.06
local	*0.03*	*0.3%*		
regional	*0.07*	*0.7%*		

SIA $PM_{2.5}$ *shipping SO_2* *shipping NO_x*	0.50 *0.22* *0.29*	4.8% *2.1%* *2.7%*		0.24
Total $PM_{2.5}$	0.60	5.8%		0.30

[a] NO_2 for EMEP4UK and NO_x for PCM

Figure 28: *The contribution to regional annual mean NO_x concentrations in 2012 from shipping emissions estimated using the PCM model*.



5.3.3 Local primary $PM_{2.5}$

The UK population-weighted mean annual mean from shipping emissions is small at 0.03 µg m^{-3} whch represents 0.3% of the total background $PM_{2.5}$ from all sources.

5.3.4 Regional primary $PM_{2.5}$

Regional primary $PM_{2.5}$ is calculated within the PCM model using the TRACK model. A specific estimate of the contribution to the regional background from shipping emissions has not been calculated. The contribution from non-UK SNAP 8 (other mobile sources and machinery) sources is available and this is 0.07 µg m^{-3} as a population-weighted mean (0.7% of the total background population-weighted mean $PM_{2.5}$ from all sources). This estimate is derived from the EMEP emission inventory available from WebDab[3]. The contribution to regional primary $PM_{2.5}$ from shipping is therefore also quite small. This value includes other non-UK sources such as railways and off-road machinery in addition to shipping.

The total PCM estimated contribution of shipping to UK population-weighted primary $PM_{2.5}$ is therefore 0.03 + 0.07 = 0.10 µg m^{-3} (***Table 7***).

5.3.5 Regional secondary $PM_{2.5}$

Regional secondary inorganic aerosol (SIA) PM concentrations within the PCM model are derived by interpolation from measurements of SO_4, NO_3 and NH_4 at rural monitoring stations. Scaling factors are applied to account for bound water, counter ions and size fraction.

Emission sensitivity coefficients derived from the EMEP model can be used to estimate the contributions from shipping emissions of SO_2 and NO_x to total regional SIA $PM_{2.5}$ concentrations shown in ***Table 8*** by setting the emissions from shipping to zero.

Table 8: *Estimates of the contribution to regional $PM_{2.5}$ SIA from shipping emissions in 2012.*

Emissions	Population-weighted annual mean $PM_{2.5}$ (µg m^{-3})	Percentage of UK total background population-weighted annual mean $PM_{2.5}$ SIA
Shipping SO_2	0.22	7%
Shipping NO_x	0.29	9%

Thus the contribution to total UK population-weighted mean annual mean $PM_{2.5}$ from shipping SIA is much larger at 0.50 µg m^{-3} (4.8% of the total background $PM_{2.5}$ from all sources) than the contribution of 0.10 µg m^{-3} from primary PM from shipping (***Table 7***).

Table 7 also presents the estimated contributions from shipping emissions to UK population-weighted primary $PM_{2.5}$, SIA $PM_{2.5}$ and total $PM_{2.5}$ derived from the EMEP4UK simulations of 30% shipping emissions reductions presented in ***Figure 24*** and ***Figure 25*** in Section 5.3. The contributions derived from the EMEP4UK simulations are only about half of those derived from the PCM model. Two reasons for the lower values derived from the EMEP4UK simulations are as follows. Firstly, shipping reductions were applied only to shipping within the inner British Isles domain, but shipping emissions from outside this domain will influence $PM_{2.5}$ concentrations in the UK, particularly concentrations of SIA because of the longer timescales (and hence greater transport distances) for formation of SIA from the gaseous SO_2 and NO_x precursors. As described in Section 5.2, and illustrated in ***Figure 19***, the EMEP source-receptor matrices for sensitivities to emissions reductions suggest that the contribution of

[3] http://www.ceip.at/webdab_emepdatabase/

shipping emissions to UK SIA from marine areas across the whole EMEP domain is ~0.6 µg m^{-3} compared to the 0.3 µg m^{-3} value for population-weighted $PM_{2.5}$ derived from the EMEP4UK model. Secondly, the concentrations of SIA (and thus also to total $PM_{2.5}$) in the PCM include a factor 1.3 to account for water of hydration in the sulphate and nitrate components. This factor was not applied to the EMEP4UK simulations of SIA $PM_{2.5}$ and total $PM_{2.5}$. Further contributors to discrepancies in the two model approaches is the assumption of linearity in the scaling to 100% of the effects on surface $PM_{2.5}$ components from the EMEP4UK 30% reductions perturbations, and the difference in model spatial resolution (5 km for EMEP4UK and 1 km for the PCM).

5.3.6 Projections of shipping contributions to $PM_{2.5}$ in 2020 and 2030

The PCM model has been used to estimate the contribution from shipping emissions to UK population-weighted mean concentration in 2020 and 2030.

Projections of the primary component have been calculated based on projections for 2020 provided by Entec. These projections show an overall decrease in primary $PM_{2.5}$ emissions across the emission inventory domain to 68% of the 2012 level by 2020 (projections beyond 2020 are not available). The magnitude of the reduction varies spatially but the population-weighed mean is dominated by contributions from port areas, where uncertainties in the spatial pattern of emissions at the 1 km × 1 km level have led to the application of a maximum emissions cap within the PCM model. Thus the modelled contribution to ambient $PM_{2.5}$ concentration from primary ship emission is quite insensitive to the overall emission trend leading to a reduction to 0.025 µg m^{-3} in 2020 from 0.027 µg m^{-3} in 2012.

Projections of the contribution to regional secondary $PM_{2.5}$ have been calculated based on emission inventory projections provided by IIASA (PRIMES, 2010). Projections of emissions have been provided separately for the Atlantic and the North Sea, with steeper emission reduction for SO_2 expected in the North Sea. ***Table 9*** shows the resulting emissions reductions that have been used within the PCM model. The North Sea has been assumed to contribute two-thirds of the precursors of UK shipping SIA and the Atlantic one-third.

Table 9: *Relative shipping emissions used within the PCM model (2012 = 1).*

	SO_2	NO_x
2020	0.891	1.127
2030	0.266	1.344

The projections of regional $PM_{2.5}$ SIA are shown in ***Table 10***.

Table 10: *Projections of the contribution to regional $PM_{2.5}$ SIA from shipping emissions.*

Emissions	Population-weighted mean annual mean $PM_{2.5}$ (µg m^{-3}) 2012	Population-weighted mean annual mean $PM_{2.5}$ (µg m^{-3}) 2020	Population-weighted mean annual mean $PM_{2.5}$ (µg m^{-3}) 2030
Shipping SO_2	0.22	0.17	0.05
Shipping NO_x	0.29	0.31	0.34
Total	0.50	0.47	0.39

5.4 Summary of modelling results

Considering the different modelling studies together the following conclusions can be drawn.

Concentrations

- Estimates from European-scale EMEP model simulations suggest that in recent years shipping emissions contribute up to ~11% to area-averaged UK $PM_{2.5}$, corresponding to around one quarter of the concentration of UK $PM_{2.5}$ that is derived from non-UK emissions. The greatest impact of shipping on $PM_{2.5}$ across the UK is through the emissions of secondary inorganic PM precursors rather than the emission of primary $PM_{2.5}$. The PCM model attributes 0.1 µg m^{-3} (equivalent to 1%) of the population-weighted $PM_{2.5}$ to primary shipping emissions (0.03 and 0.07 µg m^{-3} local and regional, respectively) and 0.5 µg m^{-3} (or 5%) to secondary inorganic $PM_{2.5}$ (0.22 and 0.29 µg m^{-3} from shipping SO_x and NO_x emissions, respectively). Close to ports, shipping impacts on $PM_{2.5}$ are much greater than the UK average because of increased contribution from shipping primary $PM_{2.5}$.

- In an assessment for future years, the PCM attributes 0.47 µg m^{-3} of UK population-weighted secondary inorganic $PM_{2.5}$ to shipping in 2020 (0.17 and 0.31 µg m^{-3} from shipping SO_x and NO_x emissions, respectively) and 0.39 µg m^{-3} of UK population-weighted secondary inorganic $PM_{2.5}$ to shipping in 2030 (0.05 and 0.34 µg m^{-3} from SO_x and NO_x emissions, respectively). The estimated shipping attribution to UK population-weighted $PM_{2.5}$ decreases in the future compared with the 2011 value (0.50 µg m^{-3}, previous bullet) but whilst the contribution from shipping SO_x emissions decreases substantially, the contribution from shipping NO_x increases over these projections.

- A simulation of 30% reductions in shipping emissions in the EMEP4UK model yields in the region of 9 - 15% reductions in SO_2 in many coastal areas of the south and south-east of England, and more in the vicinity of busy ports. Reductions in SO_2 around other coastal areas are in the range 3 - 9%, and even well inland the 30% reduction in shipping emissions reduces the SO_2 concentration by 2 - 4%.

- The EMEP4UK modelled impact of shipping emissions on NO_2 is slightly less marked than for SO_2, reflecting the large contribution to NO_2 from land-based transport and industry. Nevertheless, reductions in shipping emissions also lead to clearly discernible reductions in NO_2, particularly along the south and south-east coast. The PCM model indicates that 0.54 and 1.24 µg m^{-3} of UK population-weighted NO_x derives, respectively, from local and regional shipping sources. These concentrations correspond to 2.0% and 4.6%, respectively, of total background NO_x from all sources.

Deposition

- EMEP and EMEP4UK model simulations indicate that in recent years shipping emissions contributed around 20% of the deposition of oxidised S and oxidised N in the UK. In both cases, the shipping emissions contribute about 40% of the deposition derived from non-UK emissions. Contributions from dry deposition exceed those from wet deposition. The absolute and relative amounts of S and N deposition derived from shipping are not geographical homogeneous; they are greatest along the south and east coasts of the UK, particularly around the Thames estuary area.

Current model resolution issues may obscure impacts of shipping close to strong sources of shipping emissions such as busy ports. The EMEP/EMEP4UK models do not simulate source apportionment directly (by 'tagging') but derive source apportionment insight through sensitivity simulations in which emissions of certain pollutants from certain sectors or regions are perturbed. Care is required in interpreting extrapolation of impacts from perturbations to a full source contribution.

There are no modelled trends to compare with available trends in measurements.

In principle there is potential for high temporal resolution dispersion modelling of specific ships.

6 Air quality and climate change issues

Shipping uses diesel engines virtually exclusively, apart from small craft used over short distances near the shore in outboard motors, so the issues of petrol versus diesel which occur in the road vehicle sector are absent.

Controls on air pollutants from shipping have been addressed before; emissions of greenhouse gases by the International Maritime Organisation (IMO) and the regulatory framework is discussed in more detail in Section 2. Controls on the sulphur content of marine fuels were first agreed in IMO within Annex VI of the 'MARPOL' Convention which set a global cap of 4.5% for the sulphur content of marine fuel oil and set provisions for the definition of Sulphur Emission Control Areas (SECAs) where more stringent limits on sulphur emissions would apply. NO_x limits were also set but at a level so lax as not to have any practical effect.

Subsequently, in 2008 Annex VI was revised setting a world-wide limit of 0.5% sulphur in all marine fuels from 2020 (subject to a review in 2018). The global cap was lowered to 3.5% from 2012 and the limit for SECAs was reduced to 1% from July 2011 and 0.1% from January 2015. NO_x limits were strengthened with reductions of 16-22% on the existing 2000 standard by 2011, and a second step of 80% by 2021, this latter limit applying only in designated NO_x-

SECAs. The EU has extended these controls by not only incorporating the Annex VI obligations into EU legislation but also adding a 1.5% limit for all passenger ferries in the EU and a 0.1% limit for vessels at berth which took effect in January 2010. The North Sea and the Baltic have been declared as SECAs.

Controls on GHGs were not addressed in IMO/MARPOL until 2011 when the Marine Environment Protection Committee of the IMO adopted additional measures to go into Annex VI of MARPOL with new sections on 'Regulations on energy efficiency for ships' making mandatory the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan. The EEDI requires a minimum standard of energy efficiency and the intention is to tighten it every 5 years until 2025-2030 when a 30% reduction is mandated over the average efficiency of ships built between 2000 and 2010.

There are clearly air quality benefits which arise from the reductions in sulphur emissions but these have been traded off against reductions in sulphate aerosol and the associated increase in warming. Indeed, it has been noted by some that in large areas of the world's oceans the potential adverse effect on climate will not be offset by any benefits from reduced air pollution. The reductions in sulphur content require additional activity at the refinery and are therefore also associated with a potential increase in CO_2 emissions. However, improvements in energy efficiency from the recent revisions to Annex VI should provide air quality/climate win-win solutions, always assuming that the methods adopted do not lead to increases in NO_x emissions, although the use of technologies such as SCR should allow any NO_x increase to be controlled.

Emissions of black carbon (BC) from ships are also an issue. On a global scale shipping emissions only account for 1-2% of total emissions (Bond et al., 2013, Browse et al., 2013) but unlike the well-mixed GHGs the climate impacts of short-lived climate pollutants like BC are regional, with larger impacts nearer to areas of higher emission. This is of particular concern in the Arctic and other areas of the cryosphere where the deposition of BC on snow and ice can reduce the albedo and add to the direct warming effect of atmospheric BC. Although there is no regulation at present specifically addressing BC from ships, reductions of fuel sulphur will have the effect of reducing particle emissions and current sulphur regulations could reduce the emission factor of BC from ships by anything from 30%-80% (Lack and Corbett, 2012). The effects of SO_2 scrubbing on BC emissions is not well known but it has been suggested (Lack and Corbett, 2012) that this scrubbing of SO_2 from high sulphur residual fuel oil use could result in BC reductions similar to those resulting from switching from residual fuel oil to lower sulphur distillate oil. The improvements in climate warming resulting from these BC reductions will of course be offset by the reduction in sulphate aerosol resulting from the sulphur reductions.

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