Ship engine exhaust emissions in waters around Australia – an overview

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Abstract

Shipping is a major process link in the Australian economy, with 753 Mt of international exports worth $202 billion passing through Australian ports in 2008-2009. However there is limited knowledge about both the emissions from ships in coastal regions and ports in Australia and the effects of these emissions on air quality in the surrounding coastal and portside urban regions. This issue is of growing significance because of the increased regulation of land based emissions and the limited regulation of shipping emissions. These coastal and in port emissions, when advected over land cause deterioration in air quality particularly of atmospheric aerosol that affects human health. Furthermore, the coastal emissions that can be subsequently advected over land are not generally considered in Australian studies, in spite of them being much larger than in-port emissions. An overview is presented of the causes of ship exhaust emissions, their controls and regulation, and the methodologies used to estimate emissions inventory databases. It is suggested that the Australian methodology for estimating ship emissions be updated, airshed shipping emissions for all significant Australian ports and coastal shipping emissions be estimated, and the health effects assessed.

1. Introduction

Fossil fuel combustion contributes to both greenhouse climate forcing and urban and regional air pollution. As land based emissions from fossil fuel combustion become more regulated and reduced the net impact of marine emissions from ship engine fossil fuel combustion increases both relatively and absolutely because of the growth in international trade and shipping and limited regulation of shipping emissions. There have been a number of excellent studies during the last decade unravelling the issues surrounding ship emissions, their impact on the atmosphere, and scenarios of these for the coming decades (Corbett and Koehler 2003; Corbett *et al*. 2007; Dalsoren *et al*. 2007, 2009, 2010; Endresen *et al*. 2003, 2007; Eyring *et al*. 2005a, 2005b, 2010; Fuglestvedt *et al*. 2009; Paxian *et al*. 2010). The study of Dalsoren et al. (2009) includes emission estimates from ports, and the NO_2 and SO_2 emissions from some Australian ports are visible on global maps of these emissions.

The key influences of shipping engine exhaust on the atmosphere are through:

(a) the radiative balance of the atmosphere through

- the greenhouse gases CO_2, CH_4, N_2O, and tropospheric O_3 (via NO_x)
- radiatively active and cloud modifying particles (via SO_2, NO_x and directly emitted particles)
- the complex chemistry that connects these (via NO_x).

(b) the chemistry and biogeochemistry of the environment, including the introduction of nitrogen and sulfur gases into the remote oceanic environment and the impact of these on atmospheric chemistry and marine life

(c) human health when the mixture of SO_2, NO_x, volatile organic compounds (VOCs), and particles from ship engine exhaust is chemically transformed in the atmosphere and advected over land where it adds to the existing pollutant exposure.

As Australian ports handled 753 Mt of international exports worth $202 billion dollars in 2008-2009 (BITRE 2010), shipping is a significant part of the Australian economy and the issue of understanding and quantifying ship emissions within Australian ports is significant for Australia.

In this paper we discuss:

(a) the physico-chemical causes of ship engine exhaust emissions,

(b) methods for estimating ship engine exhaust emissions,

(c) the sources of uncertainties in these emissions,

(d) current emissions estimates for shipping in the Australian region and compare the magnitudes with estimates of emissions from other sources, and

(e) the environmental impacts of ship engine exhaust emissions, particularly those related to human health.

We do not discuss ballasting and fugitive losses (particularly VOCs) from loading and unloading, nor emissions from incinerators on ships.

Prior discussion of this issue in Australia includes: (a) Davies and Holly (2009) have presented an analysis of shipping emissions and the limitations of Australian shipping inventory procedures for Port Botany, NSW; (b) The NSW Department of Environment and Climate Change released an inventory of ship emissions for the four major NSW ports for the calendar year 2003 (DECC 2007), and (c) the Australian House of Representatives Standing Committee on Infrastructure, Transport, Regional Development & Local Government, in their 2008 Inquiry into coastal shipping policy and regulation, recommended a study on the magnitude and location of significant pollution from ship emissions in Australia.

2. Ship Exhaust Emissions Into the Atmosphere

Emissions to the atmosphere in ship engine exhaust including CO_2, CO, VOCs, SO_2, Particles and NO_x will be reviewed here. Other emissions in ships exhaust including PAHs, Metals, Dioxins and HCB have been reviewed elsewhere (Cooper 2005; Cooper 2003; Maldanova *et al* 2009) and will not be reviewed here. Ship emissions of climatically active constituents will be addressed in a companion paper.

2.1 Vessels, their engines and fuels

The classification of ships, their engines and the fuel they use is central to the estimation of ship emissions and so is briefly described first.

2.1.1 Vessels

Ocean Going Vessels (OGV) can be broadly categorised as: Bulk Carrier, Container, Cruise, General Cargo, Roll on – Roll off Cargo, Tanker, Vehicles Carrier and Naval. Container vessels generally carry high value goods and tend to have the highest main engine power and transit speeds. Bulk Carriers and General Cargo vessels tend to have lower powered engines for a given vessel size. Port Vessels include Tugs and Dredges.

Global ship numbers and types of engines are listed in Table 1. Most ships using Australian waters are not registered in Australia. To illustrate ship numbers relevant to Australia, total calls to Australian ports by the various categories of ships are listed in Table 1.

Table 1 Global numbers of ships and engine types and Australian Port Calls

<table>
<tr><th colspan="2">Ship Type</th><th>Global Engine Type [a]</th><th>Global No.[b]</th><th>Australian Port calls 2008/9 [c]</th></tr>
<tr><td rowspan="9">Ocean Going Vessels (OGV)</td><td>Bulk Carrier</td><td>SSD 91%
MSD 6%</td><td>12,930</td><td>9906</td></tr>
<tr><td>Container</td><td>large ships
SSD 100%
smaller ships
SSD 55%
MSD 45%</td><td>4138</td><td>5621</td></tr>
<tr><td>Cruise</td><td>MSD 100%</td><td>499</td><td>491</td></tr>
<tr><td>General Cargo</td><td>SSD 55%
MSD 32%</td><td>18,475</td><td>6138</td></tr>
<tr><td>Roll on – Roll off Cargo</td><td>SSD 11%
MSD 77%</td><td>1711</td><td>(included in General Cargo)</td></tr>
<tr><td>Tanker</td><td>SSD 91%
MSD 6%</td><td>12,528</td><td>3428</td></tr>
<tr><td>Vehicles Carrier</td><td>SSD, MSD</td><td>735</td><td>1166</td></tr>
<tr><td>Naval</td><td>MSD,HSD,GT</td><td>19,646</td><td>328</td></tr>
<tr><td>Tugs</td><td>MSD,HSD</td><td>12,330</td><td>na</td></tr>
<tr><td>Dredges</td><td>MSD,HSD</td><td>1206</td><td>na</td></tr>
</table>

notes:

[a] Engine Type is from Corbett and Koehler for the global fleet (Corbett and Koehler 2003)

[b] Global numbers are for 2004 and are sourced from Table A1-8 of the IMO ship greenhouse emissions study 2009 (Buhaug et al 2009), except “Naval” which comes from Corbett and Koehler (2003)

[c] Australian Port calls are for 2008/9 from Ports Australia (2011)

SSD Slow Speed Diesel, MSD Medium Speed Diesel, HSD High Speed Diesel, GT Gas Turbine

2.1.2 Engines and boilers

There are three different sources of emissions generated by fossil fuel combustion on board vessels. The primary source is the main engine(s) of the ship which provide(s) its propulsive power. The two other sources are the auxiliary engines and boilers used to provide electrical power and heat. The main propulsion engines consume the most fuel while vessels are at sea. Auxiliary engines and boilers run both while vessels are at sea and also at berth. Electricity, generated by the auxiliary engines, is used for lighting, cooking, air conditioning, heating, pumps, auxiliary blowers, bow thrusters, control systems, cargo handling, etc. Oil fired boilers are used for hot water, fuel heating, cargo heating, steam driven cargo pumps, etc.

Cruise ships have relatively high electrical loads to supply passenger needs. The statistics concerning the power and usage of auxiliary engines and boilers on ships are limited.

Diesel engines are used for propulsion in virtually all ships because of their high thermal efficiency. They can be categorised into Slow Speed Diesel (SSD) and Medium Speed Diesel (MSD). The essential differences are in the methods for gas exchange (2 stroke vs 4 stroke), the geometry of the piston/crankshaft arrangement, the configuration of the fuel injectors, the in-cylinder gas motion and the number of revolutions per minute (rpm) of the crankshaft.

SSD use a 2 stroke cycle, have cylinder bore up to 1 m, piston stroke up to 3m, power up to 90MW and rated engine speed of 60 - 300 rpm, In general, SSD are the most fuel efficient, but produce the most NOx. The MSD use a 4 stroke cycle, have cylinder bore and piston stroke up to 0.6m, power up to 25MW and rated engine speed of 300 - 1000 rpm. For the purpose of establishing emissions inventories, it is usual to distinguish between SSD and MSD. Auxiliary engines are generally MSD.

Gas turbines have a high power to weight ratio, but use a more expensive fuel. Therefore gas turbines are generally limited to high performance Naval vessels. LNG carriers may use steam turbines, partly powered by cargo boil-off. The current trend in LNG carriers is to use dual fuel diesel engines utilising LNG boil-off, or to use SSD operating on Residual Oil (RO) and to reliquefy the LNG boil-off during the voyage.

A very small proportion of ship engines run on natural gas, either in dual fuel diesel engines or gas only spark ignition engines, although the number of ships powered by LNG is likely to increase due to increasing restrictions on ship engine exhaust emissions in Europe and North America. The trend is to store the fuel in liquid form (LNG), although the MV Accolade operates out of Adelaide on compressed natural gas.

Steam turbines, though once common in ships, are now seldom in use apart from LNG carriers. Two Australian coastal vessels currently use steam turbines powered by coal, but they are to be phased out.

2.1.3 Fuels

Most ship engines and boilers burn Residual Oil (RO). The fuel is derived from the residue from the crude oil refining process. The residue is highly viscous and is composed of very large molecules of high aromaticity, including asphaltenes. Lighter product is added to the residue to reduce the viscosity and to assist the fuel to ignite when injected into the diesel engine combustion chamber. The sulfur content of RO used in ships is typically in the range 2.0% to 3.5% with a global average around 2.6% on a mass basis (IMO 2011). In some markets in the Middle East and Asia, RO of significantly higher sulfur content dominates (Lucas 2011). Many of the ships visiting Australia will purchase fuel from these markets and RO sold in Australia tends to be of higher sulfur content than the global average, so the average fuel sulfur content in Australia is likely to be higher than the global average. RO fuel is relatively inexpensive and as fuel costs are around 60% of total ship operating costs, RO is the economically desirable fuel. RO is purified continuously on-board and the resulting sludge may be disposed of by incineration or discharged into shore facilities where available. Discussion of the emissions associated with on-board incineration is beyond the scope of this paper.

The imposition of restrictions on fuel sulfur content and type in the Baltic Sea, North Sea, EU ports and the Californian coast has led to relevant ships carrying more than one type of fuel.

Marine Distillate (MD) is slightly less dense and significantly less viscous than RO. Sulfur content of MD can be between 0.1% and 1.5%. Local Australian surveys have shown average sulfur content of 0.5% for MD. Ships using MD will most likely carry it into Australian waters. In Australia, MD is not generally available as a distinct fuel type, and ships purchasing MD will generally be supplied Ultra Low Sulfur Diesel ULSD. Sulfur content of ULSD is 0.001%.

Liquefied natural gas (LNG) fuel used in shipping is indistinguishable from that used in terrestrial applications. The fuel has the advantage of containing negligible sulfur and a lower carbon content than diesel fuel. Further, natural gas engines produce greatly reduced quantities of NOx and particles compared with diesel engines.

2.2 The production of exhaust gases and particles in marine engines

CO_2, CO, CH_4, VOCs: The combustion process in diesel engines is very efficient, and the thermal efficiency is high, over 50% for the largest marine engines. Around 99.5% of the hydrocarbons in the fuel are oxidised in the combustion forming CO_2 and H_2O. Thus fuel consumed is a direct measure of CO_2 emission. A small amount of the fuel is unburnt and partially burnt. A partially burnt component is present as CO in the exhaust. The other partially burnt and unburnt but high temperature transformed fuel emerges in the exhaust as CH_4, other gaseous organic compounds (VOCs) and particles.

SO_2: The SO_2 in ship exhaust is formed directly from oxidation of sulfur in the fuel. It is generally assumed that all fuel sulfur is oxidised. Therefore the SO_2 emissions are a direct result of the product of the fuel consumed times the fuel sulfur content.

Particles: The presence of a fuel rich core in the burning fuel spray within the engine combustion zone results in fuel vapour being pyrolised in the absence of oxygen and the production of accumulation mode (around 0.5 μm diameter) and coarse mode (around 5 μm diameter) particulate matter. (Maldanova et al 2009, Fridell et al 2008). RO fuel also produces char and char mineral particles (around 0.2 μm to 5 μm) from incomplete combustion of the heavier components of the fuel, and from the alkali earth metal components of the fuel. The high sulfur content of RO leads to high levels of aqueous sulphate particles. Nuclei mode nanoparticles (around 0.01 μm diameter) are formed when volatile components of the exhaust condense in the exhaust system and atmosphere. They include hydrocarbons and aqueous sulphates.

NO_x: High NO_x and particulate emissions are inherent in the diesel engine combustion process. The high flame temperatures and high oxygen availability which lead to efficient combustion also result in high NO production. NO is mainly formed around the periphery of the burning fuel spray from the combination of oxygen and nitrogen at high temperature in the combustion air, primarily through the Zeldovich mechanism. A small proportion of the NO is produced in the combustion zone from fuel nitrogen. The slow rotational speed of marine diesel engines allows more time for NO to form (Goldsworthy 2002). SSD produce more NO_x than MSD for the same power output.

2.3 Emission control technologies

There is already significant scientific and technological work available on methods to reduce exhaust emissions from ships. The key pollutants that currently can be addressed are VOCs, SO_x, NO_x and particles.

Emissions of fugitive VOC during transport and handling of crude oil and petroleum products are significant. The loading of petroleum products onto ships from refineries results in emission of the vapours existing in the empty cargo tanks. These can be controlled by vapour recovery techniques (Buhaug et al. 2009).

The control of SO_x emissions can be achieved by switching to lower sulfur fuels. However the impediment to this is the current higher cost of low sulfur fuels. There is also technology involving seawater scrubbers to remove SO_x from the exhaust. The scrubbers will also remove significant amounts of particulate matter (Entec 2010).

NOx emissions may be reduced by either controlling combustion or after-treatment. Methods for reducing combustion temperature include water addition, exhaust gas recirculation (EGR) and injection timing retardation (Goldsworthy 2002; ICCT 2007). The new generation of marine engines use electronically controlled high pressure common rail fuel injection. This allows further optimisation of the combustion process for improved thermal efficiency and reduced NO_x and particles, especially at low loads.

Reduction of NO_x emissions by after-treatment includes the very effective reduction technique, Selective Catalytic Reduction (SCR). Urea is injected into the exhaust stream and when the mixture passes a catalyst, up to 95% of the NO_x is removed. SCR allows engines to be tuned for maximum thermal efficiency, which increases engine-out NO_x (prior to abatement by SCR) but reduces particulate matter (ICCT 2007).

An option for reducing ship emissions in port is to supply shore electricity so that auxiliary generators can be turned off at berth (often called "cold ironing"). However, the net reduction in emissions with cold ironing depends on the emissions generated in production of the shore power.

2.4 Control regulations

Marine activities such as international shipping are regulated by a mixture of the international law of the sea and the law of a particular State. *The United Nations Convention on the Law of the Sea* (UNCLOS) is the cornerstone of international maritime law. Under UNCLOS there is the International Maritime Organization. The primary mechanism for control of exhaust emissions from shipping are by international agreement through the International Maritime Organisation (IMO) MARPOL Annex VI (IMO 2008) covering emissions (a) that take place everywhere at sea (Global) and (b) in special Emission Control Areas (ECA). Australia has ratified MARPOL Annex VI and requires ships operating in Australian waters to comply. The Australian Maritime Safety Authority is the responsible body.

The current global limit on sulfur in marine fuels is 4.5%. Under the revised Annex VI, this limit will fall to 3.5% in 2012, and then to 0.5% in 2020 (subject to a review in 2018).

IMO ECAs can designate limits on fuel sulfur or on NOx emissions, or both. In sulfur ECAs, fuel sulfur content will be reduced to 0.1% by 2015 for all fuel used by ship machinery while in transit and at berth. In NOx ECAs, there are requirements for reduced NOx emissions from new engines. ECAs exist in the Baltic Sea, North Sea, English Channel and the east and west coasts of North America.

The European Union currently limits fuel sulfur content to 0.1% for ships at berth in EU ports. California has placed its own limits on ship fuel sulfur content, whereby ships must burn distillate fuel within 24nm of the coast. In 2012 the maximum fuel sulfur content in Californian waters will be 1% and in 2014 it will reduce to 0.1%. Under the Californian regulations exhaust gas scrubbers cannot be used to achieve equivalent sulfur emissions reductions while continuing to burn RO. In IMO ECAs, scrubbers are allowed.

So far there has been no attempt to regulate ship emissions in Australian waters beyond the global requirements of MARPOL Annex VI, and the necessity for such controls has not been comprehensively examined.

3. The Estimation of Marine Engine and Boiler Emissions

The simplest inventory would be a calculation of a single activity, M (eg kg of fuel combusted by shipping) times an emission factor, E_f (kg of pollutant emitted per kg fuel combusted) to give an estimate of the ship emissions, E. However, more detailed inventories are required because both the relationship of the activity to ship travel and the emission factors vary with ship type, engine type and fuel used. In global inventories, more than 100 categories of ship type and engine are commonly used. The amount of input data available for shipping inventories is limited, so approximations and averages are made regarding both activity and emissions factors that may lead to compromises on accuracy in shipping emissions inventories.

3.1 Inventory methodologies

3.1.1 Main engine emissions algorithm

The detailed inventory approach uses main engine load factors calculated for individual vessels for individual legs of a voyage from a record of the vessel's location at specified times. For each vessel movement between two given waypoints 1 and 2, the locations of the pair of waypoints provides the distance $D_{1,2}$, and the times of departure and arrival of the vessel provides the transit time $T_{1,2}$. These are used to calculate the actual vessel speed $U_{1,2}$ and the activity hours $T_{1,2}$ for the main engine for that movement. The activity associated with ship emissions, E, is the amount of fuel combusted, M. The amount of fuel combusted is related via the fuel type and engine efficiency to the amount of work done by the engine in propelling the ship, W. Propulsive power required, P, is proportional to the cube of the speed. Two key characteristics available for each ship are the main engine "full load power", P_{FL} combined with the vessel speed that corresponds to this engine output, U_{FL}, and specific fuel consumption, SFC, which is mass of fuel burnt per unit of work done by the drive shaft, a measure of the efficiency of the engine. Load factor, L, is the quotient P/P_{FL}. If the emissions factor E_f is given as mass of emissions per mass of fuel combusted, the emissions for a movement are calculated by utilizing equation (1) derived below:

$$U_{1,2} = D_{1,2}/ T_{1,2}, \qquad L = P/P_{FL} = (U_{1,2}/ U_{FL})^3$$

$$W_{1,2} = P_{FL} \text{ x } L \text{ x } T_{1,2}, \quad M_{1,2} = SFC \text{ x } W_{1,2}, \qquad E_{1,2} = E_f \text{ x } M$$

$$\text{Thus} \quad E_{1,2} = E_f \text{ x } SFC \text{ x } P_{FL} \text{ x } (U_{1,2}/ U_{FL})^3 \text{ x } T_{1,2} \tag{1}$$

3.2.2 Auxiliary engine and boiler emissions algorithm

Unlike main engines, there is no rigorous relationship for auxiliary engines and boilers to determine the fraction of installed power which is in use at any time on a vessel. Further, data on installed power are incomplete. Power data are taken from default tables. Actual auxiliary engine power is available by ship type, main engine installed power and operating mode. Generally, default values of actual boiler power are only available by ship type and operating mode (transit, manoeuvring, at berth). Using the same symbols as above where P represents both actual auxiliary engine power, and actual heating power from boiler:

For auxiliary engines and boilers:

$$E = E_f \times SFC \times P \times T \qquad (2)$$

3.2 Emissions factors

There are three fundamental variables (apart from control measures) that affect the emission factor – the engine type, the engine load and the fuel type. For each of the categories formed from these variables, two parameters that define emissions need to be determined. These are the specific fuel consumption and pollutant specific emission factors.

There are many repositories of emission factors. However, such compilations, as listed in the paragraph here are actually second hand accounts of shipping emission factors. Internationally, the IPCC both recommends emission factors in its guidelines for estimating emissions, and their good practice, and has an emissions factor data base (IPCC 2006). The EU has the EMEP EEA data base emission factors (EEA, 2009) and the USA EPA has AP-42, a compilation of emission factors. In Australia there are some NPI emission factors within the emissions estimation handbooks (NPI 1999, 2008). A compilation of recent emission factors is presented for reference in Table 2. The emissions factors in Table 2 have the units g/kWh, which is equivalent to E_f x SFC in equations 1 and 2.

In contrast with the apparent confidence of the second hand accounts, it appears that there are limited numbers of actual measurements of ship emissions. Sixty percent of the current gross tonnage of ships in the current fleet was built prior to 2000. Emission measurements of NO_x have been made on only 121 engines built prior to 2000 (Buhaug et al. 2009) The uncertainty appears significant of having measurements on 121 engines, mostly operating out of Europe, representing 60% of the worlds shipping, which are required to represent multiple categories of ship, engine and fuel type. The emission factor data for VOCs and particles are even scantier. The key aspect is that with small data sets, “If the data are non-representative, then statistical analysis will provide an insufficient basis for quantifying either variability or uncertainty in the data.” (Cullen and Frey 1999). There are more extensive test bed measurements of marine engine emissions post 2000 (Buhaug *et al*. 2009).

Table 2 Typical emissions factors for a range of engines and fuel types

(Sources include: Entec et al 2002; Cooper and Gustaffson 2004; Goldsworthy and Renilson 2009; ARB 2008; EPA 2009; Starcrest 2007; ENVIRON and Sylte 2008, NPI 2008, NGA 2008)

Engine type	Fuel type	Emissions factors and specific fuel consumption g/kWh									
		CO_2	CO	VOC	CH_4 (CO_{2e})	SO_2	PM10	PM2.5	NOx	N_2O (CO_{2e})	SFC
SSD Main	RO	603.6	1.38	0.69	0.50	10.5	1.5	1.46	18.1	5.0	195
MSD Main	RO	659.3	1.1	0.57	0.54	11.5	1.5	1.46	14	5.4	213
MSD Aux	RO	702.6	1.1	0.46	0.58	12.3	1.5	1.46	14.7	5.8	227
MSD Aux	MD	661.4	1.1	0.52	1.91	2.2	0.38	0.35	13.9	4.8	217
MSD Aux	ULSD	659.7	1.1	0.52	1.90	0.004	0.38	0.35	13.9	4.8	205
Aux Boiler [a]	RO	348.2	0.07	0.04	0.29	6.1	0.29	0.29	0.77	2.9	112.5
Aux Boiler [a]	MD	337.6	0.07	0.08	0.98	1.1	0.02	0.02	0.74	2.4	112.5
ST Main	RO	897.6	0.2	0.1	0.74	15.7	1.55	0.66	2.1	7.4	290
GT Main	MD	870.4	0.2	0.1	2.5	14.5	0.25	0.25	5.7	6.3	290

[a]For boilers, the energy output represents the energy delivered to the steam/thermal oil (for engines, the energy output represents the energy delivered by the shaft to the propeller or generator).

Main propulsion engine

Aux electrical power generator engine

Aux Boiler oil fired boiler for heating purposes or to drive steam driven cargo pumps

RO Residual Oil, MD Marine Distillate, ULSD Ultra Low Sulfur Diesel

SSD Slow Speed Diesel, MSD Medium Speed Diesel, HSD High Speed Diesel, GT Gas Turbine

The distribution of main engine loads tends to be bimodal - high engine loads during transit and low engine loads during movement in Ports. The majority of the mass of emissions from main engines occur during transit. Studies indicate that emissions factors and specific fuel consumption can increase as engine load decreases, although the trends are not straightforward (Carlton and et al 1995). Therefore a correction may be required to increase the emissions factors of main engines at engine load below 20%. Low speed operation generally occurs close to urban centres, so refinement of emissions factors during low load operation would be beneficial for emissions estimates for Ports.

3.2.1 An example of the variation of NOx emission factor with engine load

To illustrate the changes in the NO_x emission factor with load, measurements made (Goldsworthy unpublished data) of NO_x mass flow rate in the main engine exhaust and NOx emission factor on MV Goliath, a cement carrier sailing between Devonport and Melbourne, are shown in Figure 1. The Goliath has a 5 cylinder slow SSD main engine rated at about 6 MW and operating on RO.

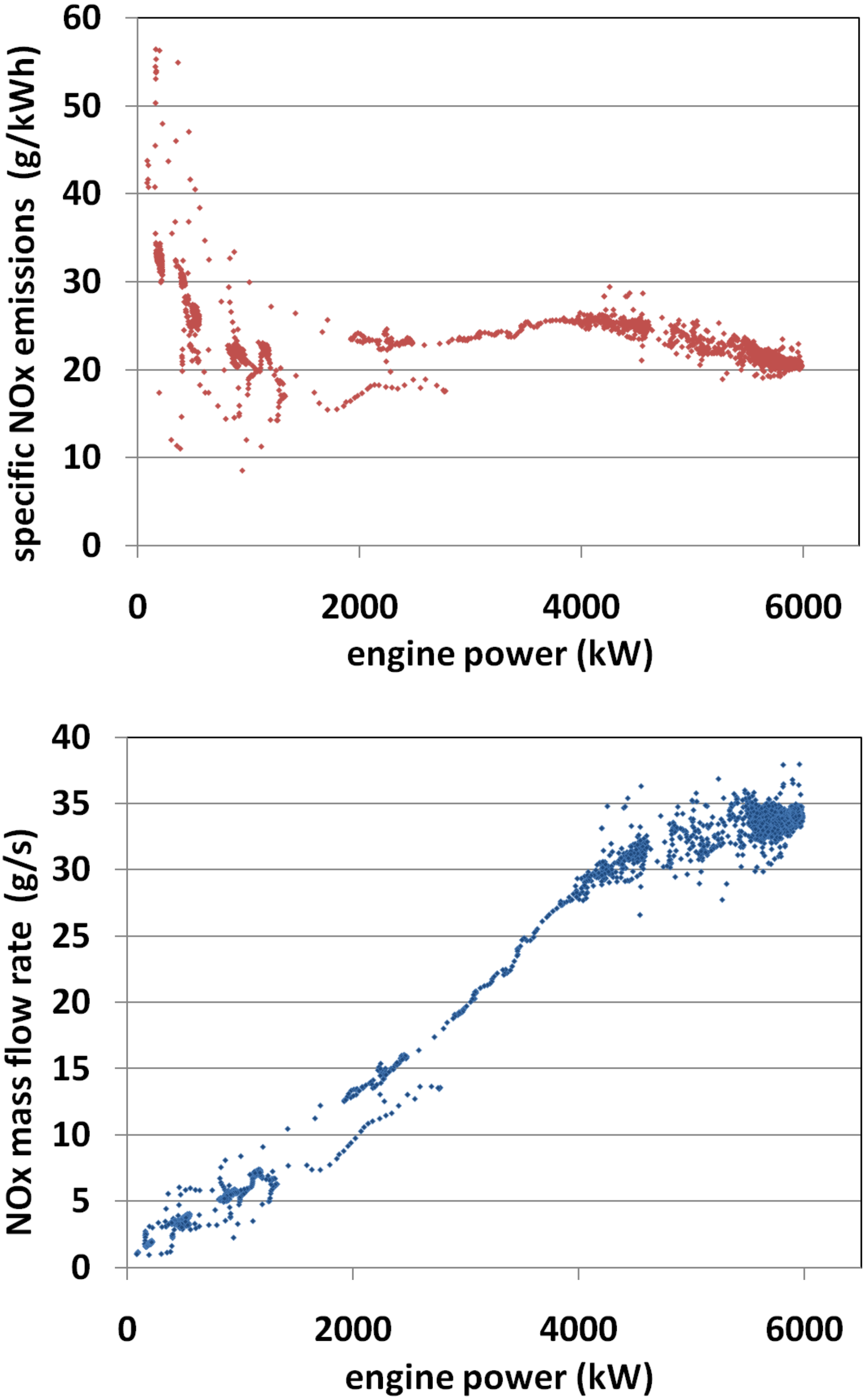

Figure 1 NO_x emission factor (g/kWh) and NO_x mass flow rate (g/s) in the main engine exhaust measured on MV Goliath in passage between Devonport and Melbourne.

Emissions of CO_2, CO, VOC, NO_x, and O_2 were continuously monitored from the exhaust trunking, along with fuel flow rate and engine power from the ship engine operating system. These parameters allowed calculation of air to fuel ratio, exhaust mass flow rate and NO_x emission factor in g/kWh throughout the voyage, including the transit of Port Phillip Bay and the low load manoeuvring in the Yarra River to and from berth at South Wharf. Emissions were sampled through a heated filter and heated sample line, then passed through a NO_x converter and refrigerated dryer before analysis in an Autodiagnostics 5 gas analyser using an NDIR bench for CO_2, CO and VOC, and electrochemical cells for O_2 and NO. It can be seen that the mass flow rate of NOx varies approximately linearly with engine power. At low engine loads, NO_x mass flow rate decreases but the NO_x emission factor (in g/kWh) increases by approximately 50% and in extreme measurements doubles. Engine powers below 2 MW occurred in the Yarra River and the data show significant scatter due to the varying transient loading conditions during manoeuvring into and out of berth. Thus the assumption of a constant NO_x emission factor introduces an uncertainty into shipping emission estimates particularly for in-port calculations. While the mass flow rate of emissions at low engine load is low compared to high engine load, berths are often located near population centres.

3.3 Australian Shipping Inventories

3.3.1 The National Pollutant Inventory, NPI

There are two manuals that have been prepared for the National Pollutant Inventory (NPI) related to shipping. The Emission Estimation Technique Manual for Aggregated Emissions from Commercial Ships/Boats and Recreational Boats - Version 1.0, (NPI 1999) includes emissions from shipping in harbour transit in shipping channels while docking, and auxiliary engines while loading and ballasting at berth. The Emissions Estimation Technique Manual for Maritime Operations 2008 (NPI 2008) appears to overlap with the previous discussed Manual and covers only the emissions from shipping at berth. A further complication of the NPI is that the emissions from shipping are listed under three headings: Commercial Shipping/Boating [*]; Recreational Boating [*], and Commercial Shipping/Boating and Recreational Boating [*] where the text [*] indicates a diffuse source. In the data subsequently presented here emissions from the category Recreational Boating [*] are not included.

The NPI methodology (NPI 1999) is based on dividing shipping according to gross weight, assuming a standard number of transit hours per port call and using a fixed emission factor per hour of transit. The NPI (NPI 2008) recommends that in the absence of detailed information on individual vessels, a default auxiliary engine actual power of 600 kW can be used. The NPI manual also allows a default fuel usage rate for auxiliary boilers of 0.0125 tonnes per hour for all vessels. There has been no quantification of the uncertainties and biases introduced by the simplifying assumptions used in the NPI methodology.

3.3.2 Other Australian port based inventories

The SKM Port Botany inventory (Davies and Holly 2009) considered emissions from ships at berth and mainly from auxiliary engines. Some account was taken of the use of main engines in port, by assuming two of the ships in port were operating their main engines at any one time. Auxiliary boilers were not considered. Auxiliary engine power of 600 kW for all vessels was assumed, but some allowance was made for different auxiliary powers. The data were utilized for atmospheric concentration estimation of PM_{10}, NO_2 and SO_2 using the models AUSPLUME and CALPUFF.

The NSW Office of Environment and Heritage (OEH) produced a detailed inventory for 2008 for the Greater Metropolitan Region (GMR) which includes Port of Newcastle, Port Jackson, Port Botany, and Port Kembla. This inventory used ship arrival, berthing and departure times, and ship machinery data from Lloyds Register. Main and auxiliary engines as well as boilers were included. Emissions were calculated for ships in transit and berthing.The Port of Brisbane inventory (Goldsworthy and Renilson, 2009) used detailed ship movement data supplied by the port authority.

The ship movement data included an intermediate waypoint between port arrival and berthing, which allowed good differentiation between port transit and manoeuvring operations. Lessons from the Port of Brisbane inventory that can inform national methodology, including the NPI Estimation Technique Manual, are that (a) the default fuel usage rate for auxiliary boilers of 0.0125 tonnes per hour appears to be an overestimate by around 50%, and (b) total emissions during port transit can be greater than emissions while at berth. This is because of the large fuel consumption rate in the main engines during transit. The length and significance of the port transit will depend on the extent of the port boundaries. Those inventories that neglect emissions in transit will substantially underestimate shipping emissions into the airshed.

4. Regional and In-Port Shipping Emissions and Their Environmental Impacts

International studies can inform the Australian regional analysis. The shipping emissions of SO_2 in the Australian region are presented in Figure 2 from global spatially distributed data presented in Wang et al (2008). It is apparent that substantial parts of the shipping emissions in coastal waters around Australia are located such that with typical seasonally prevailing winds, the pollutants from shipping will frequently be carried into the airsheds of major urban population centres including the capital cities of Perth, Melbourne, Sydney and Brisbane. The amounts of selected pollutants emitted over this Australian region from Wang *et al*. (2008), and in Australian Ports and from all sources over Australia, compiled by the National Pollutant Inventory are presented in Table 3. According to these figures, the ship emissions off the coast of Australia are substantially larger than the in-port ship emissions in the NPI. Further, NO_x and SO_x ship emissions whilst at sea are comparable in magnitude with the other national sources. Thus shipping emissions of NO_x and SO_x are potentially significant contributors to the presence of these pollutants in urban airsheds. Only detailed studies will clarify this issue.

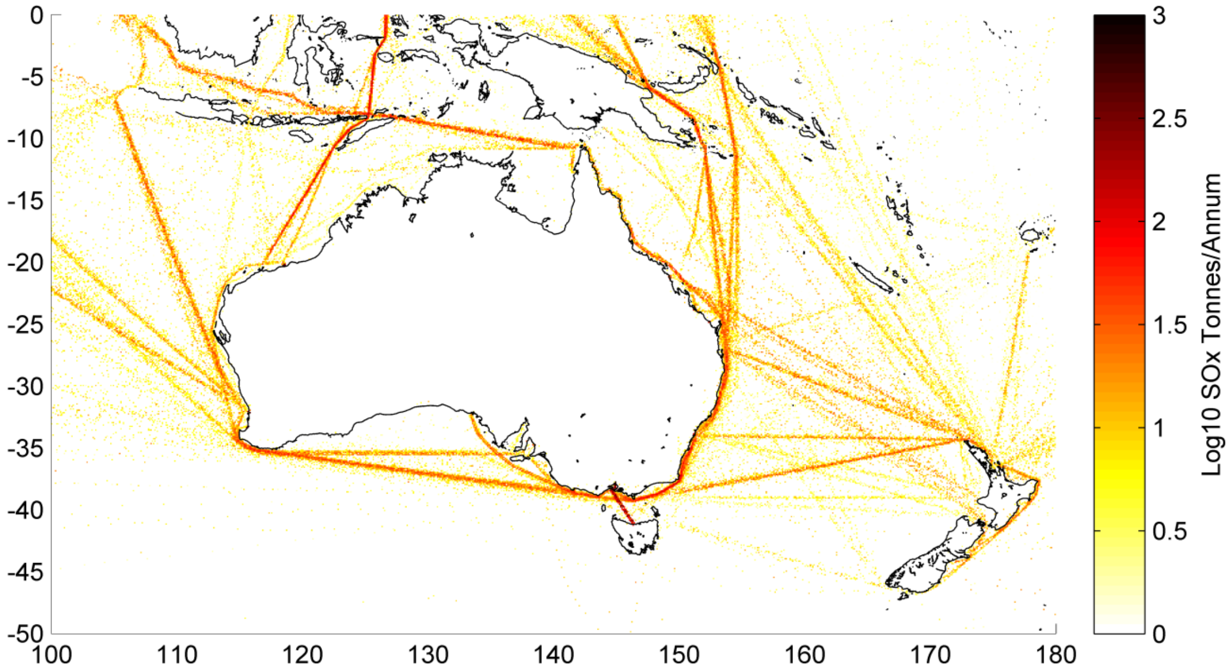

Figure 2 SO_2 emissions from shipping around Australia in 2001 (total emissions in each 0.1x0.1 deg grid cell over 1 year). Data derived from Wang et al (2008): http://coast.cms.udel.edu/GlobalShipEmissions/Inventories/

Table 3 Comparison of Australian regional shipping, in-port shipping, and total anthropogenic emissions in Mt/annum.

	Australian Ship Emissions Mt/annum		Australian total from NPI 2008/9[b] Mt/annum	
	Regional[a]	In-Port[b]	Diffuse [b]	Industrial [b]
CO	0.040	0.014	4.48	0.84
VOC	0.021	0.005	3.06	0.09
SO_2	0.352	0.019	0.072	1.34
PM	0.044	0.003	0.63	0.53
NO_x	0.612	0.034	0.65	0.8

[a]Ship data derived from Wang et al 2008:
http://coast.cms.udel.edu/GlobalShipEmissions/Inventories/
Bounds for Australian totals: 5deg S to 45 deg S, 105deg E to 160 deg E
[b]NPI data for Australia for 2008/9
The NPI diffuse emissions include all transport emissions
The NPI does not include ship emissions outside ports
NO_x as NO_2

Global studies indicate that near land and in ports, shipping emissions of NO_x and SO_x emissions contribute to the formation of photochemical smog and particles. Photochemical smog leads to elevated levels of ozone and production of hazardous organic compounds. Ozone is hazardous to human health and is also a greenhouse gas. As well as affecting air quality, SO_x and NO_x emissions contribute to acid rain and NOx emissions contribute to eutrophication of ecosystems (Buhaug et al 2009; EMEP 2009).

Particles from engine exhausts, especially the finer particles, can lodge in the lungs and move into the bloodstream, leading to cardiovascular and pulmonary disease. Corbett *et al* (2007) estimated accelerated mortality from ship emissions. Their results indicated that particles resulting from ships emissions are responsible for approximately 60,000 premature mortalities annually, mostly near coastlines in Europe, East Asia and South Asia. They also estimated that at current shipping growth rates, annual mortalities could increase by 40% by 2012 in the absence of control measures.

A report published by the US EPA in 2010 (EPA 2010) describes detailed studies of the impact of ship engine exhaust emissions on public health. They estimate that their new regulatory regime involving implementation of an IMO Marpol Annex VI Emission Control Area (ECA) on the North American east and west coasts, and further controls on particle emissions will yield, for example, monetised health benefits of the order of $40 billion to $100 billion annually in 2020. The costs of implementing the policy, which include increased freight charges, are of the order of $3 billion, so the benefit to cost ratio is very high.

There are no integrated studies of the health effects of shipping emissions in Australia.

5. An Outline of a Detailed Ship Emissions Methodology for Australia

The authors consider the Emission Estimation Technique Manual for Aggregated Emissions from Commercial Ships/Boats and Recreational Boats - Version 1.0, (NPI 1999), prepared twelve years ago is outdated. Whilst it was appropriate for that time it now needs updating to take into account improved knowledge of ship emissions. Current international best practice is the detailed emissions inventory introduced in Section 3.2. For individual ports or for the Australian region overall, it is recommended that a detailed methodology is used, as outlined in the following text.

The first requirement is identification of the ship. After a ship identified, its main engine machinery characteristics can be obtained from industry databases such as Lloyd's Seaweb (Lloyds Register Fairplay 2009). A complementary program of in-port ship surveys can provide information and reduce uncertainties in assigning auxiliary engine and boiler power, and fuel type and sulfur content.

The second requirement is for tracking of the vessel movements, for which there are three options. Port authority vessel movement data may give time of arrival at a few key waypoints. Commercially available movement data from Lloyds gives port arrival, berthing and port departure times. Depending on the number of waypoints available, assumptions are made regarding ship speeds on approach to and between waypoints. Examples of such inventories include a number of inventories for US ports (Starcrest 2007; ENVIRON and Sylte 2008), the recent inventory for the Port of Brisbane (Goldsworthy and Renilson 2009), and the NSW Office of Environment and Heritage ship emissions inventory for the NSW Greater Metropolitan Region for 2008. The detailed methodology is also described in EPA (2009) and WPCI (2010).

For a higher level of detail on ship movements, the mandatory Automatic Identification System (AIS) tracks each ship's identity, type, position, course, speed, navigational status (underway, manoeuvring, moored, anchored) and other safety-related information at regular time intervals of less than a minute. Jalkanen et al (2009) used raw AIS data for the Baltic Sea area to track individual vessels and to calculate main engine load factor and thus emissions over a full calendar year. The use of raw AIS data is the most accurate way of tracking vessels because actual vessel speed is available at all times. AIS data in ports are comprehensive. Away from ports, terrestrial AIS receivers may not always track ships. Satellite AIS data, available commercially have good spatial coverage but there are temporal gaps. Route modelling could be used to fill data gaps. The subsequent steps for compiling the inventory involve the use of the emission algorithms and emission factors, discussed in Section 3, to arrive at emissions. An emission inventory constructed on this basis assigns emissions rates with high spatial and temporal resolution, as is required as input for accurate air quality modelling. A comparison of the coverage of this inventory approach with previous methodologies in Australia is presented in Table 4. The table deals only with coverage and does not address the more approximate approaches to emissions estimation utilized in the earlier inventories.

Table 4 Comparison of coverage of Australian shipping inventory methodologies

Note: this table does not address the level of approximation utilized in the various inventories

Emissions Covered	At Berth	Berthing	In-Port Transit	Coastal
NPI (1999)	Y	Y	Y	N
NPI (2008)	Y	N	N	N
Port Botany (Davis and Holly 2009)	Y	Y	Y	N
GMR Ports NSW (2008)	Y	Y	Y	Y
Port of Brisbane (Goldsworthy & Renilson 2009)	Y	Y	Y	N
This Methodology	Y	Y	Y	Y

The other issue is where should shipping emissions be calculated in Australia? An analysis of shipping statistics (BITRE 2010) indicates that while the main city ports handle the major fraction of container trade, 77% of the weight, 50% of the value of exports and the greater number of ship port visits occurs at Dampier, Port Hedland, Port Walcott, Newcastle, Gladstone and Hay Point. In 2010, 14,199 commercial vessels called at the main city ports of Brisbane, Newcastle, Port Kembla, Sydney, Melbourne, Adelaide and Fremantle, while for all other ports, the total number of ship visits was 13,007. (Ports Australia, 2011) Emissions in all significant ports should be estimated as well as emissions from shipping in coastal waters immediately upwind of significant population areas. Further, ship emissions from the whole region should be estimated for analysis of potential contribution to climate disturbance.

A project is underway at the Australian Maritime College to produce a detailed national ship engine exhaust emissions inventory over the Australian region including all ports, using detailed AIS data for ship movements.

Ship emission inventories, combined with dispersion modelling allow assessment of the impact of ship emissions on air quality in populated regions.

5.1 Uncertainties in emission estimates

A key aspect that makes an estimate useful is a measure of its uncertainty. Cooper (2002) introduced uncertainty estimates to fleet emissions and these uncertainties are subsequently used or acknowledged in the studies of Corbett and Koehler (2003), Entec (2007) and Dalsøren et al. (2007). However the underlying details of the uncertainties calculations were not presented.

Here we consider the uncertainty in emissions of a single ship, as this is the basic unit from which a detailed inventory is built. There are uncertainties associated with its:

1. characteristics, particularly auxiliary power
2. location, speed and operating mode
3. fuel composition

4. fuel consumption per given speed (hull condition, engine maintenance)

5.emission factors (it's an individual ship not a fleet average).

A full uncertainty calculation is not made here, because it can only be done in conjunction with emissions estimates. However some comments can be made. The observed variation in individual NO_x emission factors (see the range of pre 2000 NO_x emission factors in Buhaug *et al*. 2009) and the observed variation in individual samples of the sulfur content of fuel (Buhaug *et al*. 2009), are around ±50% at the 95% Confidence Interval. Therefore, in the first instance, the uncertainties in NO_x and SO_2 emissions of an individual vessel will be greater than ±50% at the 95% Confidence Interval. The uncertainty in the SO_2 emissions can be reduced if the ship undergoes an in-port ship survey. It should be noted that these uncertainties are not entirely random, and therefore do not diminish in the same manner as random statistics with larger sample numbers. Detailed uncertainty analyses should be done with emissions inventory estimates. More detailed information on uncertainty calculations is presented in the IPCC inventory uncertainty guidelines (Penman *et al.* 2000).

6. Conclusions

Near land and in ports, shipping emissions of NO_x and SO_x contribute to the formation of photochemical smog and particles. Shipping is a significant part of the Australian economy and the issue of understanding and quantifying ship emissions within Australian ports and on the coast is significant for Australia. Current estimates of Australian shipping emissions for in-port vessels are typically a fraction of that once the vessel is at sea within the Australian region. These at sea emissions can be advected over coastal population centres. This paper presents an outline of an improved methodology for estimating ship engine exhaust emissions to the atmosphere from in-port vessels and vessels in the Australian region.

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8. References

ARB, 2008, Initial Statement of Reasons for Proposed Rulemaking, Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline, Appendix D Emissions Estimation Methodology for Ocean-Going Vessels, ARB Stationary Source Division, Emissions Assessment Branch, June, 2008

BITRE, 2010, *Australian sea freight, 2008–09*, Bureau of Infrastructure, Transport and Regional Economics (BITRE), Canberra ACT.

Buhaug, Ø., J.J. Corbett, Ø. Endresen, V. Eyring, J. Faber, S. Hanayama, D.S. Lee, D. Lee, H. Lindstad, A.Z. Markowska, A. Mjelde, D. Nelissen, J. Nilsen, C. Pålsson, J.J. Winebrake, W.Q. Wu, and K. Yoshida, 2009, Second IMO GHG study 2009, International Maritime Organization (IMO) London, UK.

Carlton et al, Marine Exhaust Emissions Research Programme, 1995, Lloyd's Register Engineering Services: London

Charlton-Perez, C.L., M.J. Evans, J.H. Marsham, J.G. Esler, 2009, The impact of resolution on ship plume simulations with NO_x chemistry, *Atmospheric Chemistry and Physics*, **9**, 7505-7518.

Cooper, D., 2002, Representative emission factors for use in “Quantification of emissions from ships associated with ship movements between port in the European Community” (ENV.C.1/ETU/2001/0090) prepared for Entec UK Ltd by IVL Swedish Environmental Research Institute Ltd.

Cooper, D. and T. Gustaffson, 2004, Methodology for calculating emissions from ships: 1. Update of emission factors, Swedish Methodology for Environmental Data (SMED). SMHI Swedish Meteorological and Hydrological Institute

Cooper, D.A., 2003, Exhaust emissions from ships at berth, *Atmospheric Environment*, **37**,3817-3830.

Cooper, D.A., 2005, HCB, PCB, PCDD and PCDF emissions from ships, *Atmospheric Environment*, **39**: 4901 - 4912.

Corbett, J., J. Winebrake, E. Green, P. Kasibhatala, and A. Lauer, 2007, Mortality from Ship Emissions: A Global Assessment, *Environmental Science and Technology*, **41**(24), 8512-8518.

Corbett, J.J. and H. Koehler, 2003, Updated emissions from ocean shipping, *Journal of Geophysical Research*, **108(D20)**, 4650, doi:10,1029/2003JD003751. .

Cullen, A.C., and Frey, H.C., 1999, Probabilistic Techniques in Exposure Assessment, Plenum Press, New York.

Dalsøren, S. B., Ø. Endresen, I. S. A. Isaksen, G. Gravir and E. Sørgard, 2007, Environmental impacts of the expected increase in sea transportation, with a particular focus on oil and gas scenarios for Norway and northwest Russia, *Journal of Geophysical Research*, **112**, D02310, doi:10.1029/2005JD006927.

Dalsøren, S.B., M.S. Eide, Ø. Endresen, A. Mjelde, G. Gravir, and I.S.A. Isaksen 2009, Update on emissions and environmental impacts from the international fleet of ships. The contribution from major ship types and ports, *Atmospheric Chemistry and Physics*, **9**, 2171-2194.

Dalsøren, S. B., M. S Eide, G. Myhre, O. Endresen, I. S. A. Isaksen and J. S. Fuglestvedt, 2010, Impacts of the large increase in international ship traffic 2000-2007 on tropospheric ozone and methane. *Environmental Science & Technology*, **44 (7)**, 2482-2489.

Davies, M. and M. Holly, 2009, Ship Emissions from Australian Ports, the Smoking Guns, in 19th International Clean Air and Environment Conference, 2009, Perth.

DECC, 2007, Technical report Number 7, Air Emissions Inventory for the Greater Metropolitan Region of New South Wales, Off-Road Mobile Emissions Module.

EEA, 2009, EMEP/EEA air pollutant emission inventory guidebook, Part B 1-a-3-d-navigation, 2009.

EMEP, 2009, Acidifying and Eutrophying Pollutants, www.emep.int/acidify.html, accessed July 2009.

Endresen, Ø., E. Sorgard, H. Behrens, and P. Brett, 2007, A historical reconstruction of ships' fuel consumption and emissions, *Journal of Geophysical Research*, **112(D12301)** doi:10,1029/2006JD007630.

Endresen, O., E. Sorgard, J. Sundet, S. Dalsoren, I. Isaksen, and T. Berglen, 2003, Emission from International Sea Transportation and Environmental Impact, *Journal of Geophysical Research*, **108(D17)** , 4650, doi:10,1029/2002JD002898..

Entec, C. Whall, D.A. Cooper, K. Archer, L. Twigger, N. Thurston, D. Ockwell, A. McIntyre, and A. Ritchie, 2002, Quantification of Emissions from Ships Associated with Ship Movements between Ports in the European Community, prepared for the European Commission, Entec UK Limited, July 2002,

Entec, 2007, CONCAWE, Ship Emission Inventory - Mediterranean Sea, Final Report, Entec UK Ltd, April 2007,

Entec, 2010, Study to Review Assessments Undertaken of the Revised MARPOL Annex VI Regulations, B. Grebot, T. Scarbrough, A. Ritchie, C. Mahoney, R. Noden, M. Sobey and C. Whall,.

ENVIRON and W. Sylte, 2008, Revised Port of Oakland 2005 Seaport Air Emissions Inventory,

EPA, 2010, United States Environmental Protection Agency, Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder, Federal Register 75(83), 2010.

EPA, 2009, Current Methodologies in preparing Mobile Source Port-Related Emission Inventories – Cargo Handling Equipment, April 2009, ICF Consulting for the Environmental Protection Agency, 2009.

Eyring, V., Koehler, H. W., van Aardenne, J., and Lauer, A., 2005a, Emissions from international shipping: 1. The last 50 years, *Journal of Geophysical Research*, **110**, D17305, doi:10.1029/2004JD005619.

Eyring, V., Koehler, H. W., Lauer, A., and Lemper, B. 2005b, Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050, *Journal of Geophysical Research*, **110**, D17306, doi:10.1029/2004JD005620.

Eyring, V., I.S.A. Isaksen, T. Berntsen, W.J. Collins, J.J. Corbett, Ø. Endresen, R.G. Grainger, J. Moldanova, H. Schlager and D.S. Stevenson, 2010, Transport impacts on atmosphere and climate: Shipping. *Atmospheric Environment*, **44(37),** 4735-4771.

Fridell, E., E. Steen and K. Petersen, 2008, Primary particles in ship emissions, *Atmospheric Environment*, **42(6),** 1160-1168.

Fuglestvedt, J. S., T. Berntsen, V. Eyring, D.S. Lee, R. Sausen and I.S. A. Isaksen, 2009, Shipping emissions: From cooling to warming of climate - and reducing impacts on health. *Environmental Science and Technology*, **43 (24)**, 9057-9062.

Goldsworthy, L., 2002, Design of Ship Engines for Reduced Emissions of Oxides of Nitrogen, in Engineering a Sustainable Future Conference Proceedings, IEAust, Hobart, 2002.

Goldsworthy, L. and M. Renilson, 2009, Waterside Air Emission Inventory for Port of Brisbane 2007/8, 2009. Australian Maritime College, AMC Search - not released publically as at end July 2011.

ICCT, 2007, The International Council on Clean Transportation, Air Pollution and Greenhouse Gas Emissions from Ocean-going Ships: Impacts, Mitigation Options and Opportunities for Managing Growth, A. Friedrich, F. Heinen, F. Kamakate and D. Kodjak, 2007.

IMO, 2008, Annex 13, Resolution MEPC 176(58), Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (Revised MARPOL Annex VI), MEPC 58/23/Add.1, Adopted on 10 October 2008.

IMO, 2011, Sulphur monitoring for 2010, MEPC 62/4.

IPCC, 2006, IPCC Guidelines for National Greenhouse Gas Inventories Volume 2 Energy, 2006.

Jalkanen, J.P., A. Brink, J. Kalli, H. Pettersson, J. Kukkonen and T. Stipa, 2009, A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area, Atmospheric Chemistry and Physics, **9**, 9209-9223.

Lloyd's, 2009, Lloyd's Seaweb Register of Ships online, accessed 2009. http://www.sea-web.com

Lucas, M., 2011, An uncertain future for marine fuels, Motorship.

Maldanova, J., E. Fridell, O. Popovicheva, B. Demirdjian, V. Tishkova, A. Faccinetto, and C. Focsa, 2009, Characterisation of particulate matter and gaseous emissions from a large ship diesel engine, *Atmospheric Environment*, **43**, 2632-2641.

NGA, 2008, Australian Government, Department of Climate Change, National Greenhouse Account (NGA) Factors, Updating and replacing the AGO Factors and Methods Workbook, November 2008.

NPI, 1999, Australian Government Department of the Environment, Water, Heritage and the Arts, National Pollutant Inventory, Emission Estimation Technique Manual for Aggregated Emissions from Commercial Ships/Boats and Recreational Boats - Version 1.0, Environment Australia, 1999, ISBN 0642 648102

NPI, 2008 Australian Government Department of the Environment, Water, Heritage and the Arts, National Pollutant Inventory, Emission estimation technique manual for Maritime operations Version 2.0 July 2008.

Paxian, A., V. Eyring, I.S.A. Isaksen, W. Beer, R. Sausen, C. Wright, 2010, Present-Day and Future Global Bottom-up Ship Emission Inventories including Polar Routes , *Environmental Science and Technology,* **44 (4)**,1333-1339

Penman, J., Kruger, D., Galbally, I. E., Hiraishi, T., Nyenzi, B., Emmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., Miwa, K., and Tanabe, K., editors. (2000). Good practice guidance and uncertainty management in national greenhouse gas inventories [Electronic publication]. Kanagawa, Japan: Intergovernmental Panel on Climate Change. 1 v. http://www.ipcc-nggip.iges.or.jp/public/gp/english/

Ports Australia, 2011, www.portsaustralia.com.au/port_industry/, accessed April 2011.

Starcrest, 2007, Starcrest Consulting Group, Port of Los Angeles Inventory of Air Emissions 2005, 2007

Wang, C., J.J. Corbett and J. Firestone, 2008, Improving Spatial Representation of Global Ship Emissions Inventories, *Environmental Science & Technology*, **42**, 193-199.

WPCI, 2010, World Port Climate Initiative, Climate Footprinting for Ports - Guidance Document, Carbon Footprint Working Group, Port of Los Angeles Lead Port, Starcrest Consulting Group, June 2010.

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