Shipping fuel consumption and emissions modelling in fourteen port areas

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Abstract

A new empirical shipping (exhaust) emission model has been developed by DES that uses available input data on local shipping movements. The model first estimates fuel consumption by marine fuel type and ship type, and subsequently uses fuel-based emission factors (g/kg fuel) to estimate emissions (NO_x, SO_2, PM_{10}, V, Ni, PAHs, CO_2, etc.). The structure of the model is based on an extensive literature review and model parameters have been calibrated using a ship energy balance approach. The ship fuel (and emissions) model has been set up in a modular fashion, so that default model parameter values can be readily changed to incorporate updated information or to reflect different assumptions, and can be readily used in "what-if" scenario modelling. For example, it can be used to assess the impacts of reduced fuel sulphur content on ship emissions and local air quality. This paper presents the results of emissions modelling (greenhouse gases and air pollutants) for fourteen port areas in Queensland, Australia.

Introduction

Shipping is a significant source of air pollution and greenhouse gas emissions. Ships use large diesel engines that run on heavy bunker fuels, generally without emission controls. Overseas studies have consistently found that ships have significant effects on local air quality in and around port areas (e.g. EEA, 2013). Corbett et al. (2007) estimated that 3-8 per cent of global $PM_{2.5}$ related mortalities are attributable to marine shipping, but the current health impact for Australia is unclear. Until recently, ships have not been subject to local or national emission control measures and policies in Australia. However, shipping impacts have received increasing scrutiny by regulators in Australia as a consequence of nuisance complaints in for instance Sydney harbour.

The local situation will largely determine the impact of shipping emissions on local air quality. This study has conducted a local assessment for the state of Queensland in Australia. The objective of this research project is to accurately and efficiently estimate fuel use and emissions for a broad range of air pollutants for individual ships operating in strategic port areas over a full year (2015).

Figure 1: 40,542 GT Container ship in Port of Brisbane.

Ship activity data

Ship activity data are obtained from processed and verified Automatic Identification System (AIS) data. AIS is a Very High Frequency (VHF) radio broadcasting system, which enables AIS equipped vessels and shore-based ground stations to send and receive identifying information. This is known as terrestrial AIS data. In Australia, the Australian Maritime Safety Authority (AMSA) collects comprehensive AIS data. Specially equipped satellites can also record the same AIS data. AIS is a mandatory collision avoidance system on ships larger than 300 gross tonnes. Each ship transmits a signal giving details regarding the ship's identity, type, position, course, (spot) speed and other safety-related information at frequent intervals. Unique Mobile Maritime Service Identity (MMSI) numbers are sent in the AIS messages.

A data clean-up process was developed to verify data quality, plug data gaps, correct errors (e.g. locational data) and apply statistical data processing techniques. R code was developed to check, correct and impute AIS data using the following steps:

- extract AIS data for each individual ship
- re-order data using date-time stamps
- convert latitude/longitude to UTM X-Y coordinates
- add distance travelled
- add (travel) speed and acceleration
- outlier detection and removal
- impute missing location and speed data

Outliers are associated with locational errors and are flagged as data points with an absolute acceleration larger than 0.15 m/s^2 and a vessel speed larger than 1.15 times the service speed. Service speed is defined as the speed which a ship is stated to be capable of maintaining at sea in normal weather and at normal service draught.

AIS data gaps are addressed in the following fashion. A complete time-series is created for each ship using 1-minute time steps to identify where ship data are missing. For data gaps of less than or equal to 2 hours duration, UTM coordinates are linearly interpolated in space (i.e. time-steps of equal distance) using the last and first available UTM coordinates at either end of the gap. For data gaps larger than 2 hours and ships > 300 GT, a similar spatial interpolation is applied, on the condition that the vessel remains in the same 1×1 km grid cell and that the last and first recorded speeds at either end of the gap are less than 2.5 km/h. The inclusion of these large data gaps is important because it ensures that time periods with berth/anchorage are captured in the emissions estimation. It is noted that tugs, yachts and dredgers are excluded from this interpolation. Finally, a T4253H filter (Velleman, 1980) is applied to remove noise and unrealistic variations in speed. Ship speeds less than 0.5 km/h are set to zero.

A detailed ship information database was purchased from IHS Markit (previously Lloyds Register). These data provide accurate and detailed information on each ship that operated in Queensland waters in 2015.

The final result is a database with complete time-series information for each individual ship journey, containing ship characterisics and speed (one-minute time steps) in Queensland port areas in 2015. Journeys include all operating modes for ships: berth, anchor, manoeuvring and transit. Visualisation examples of processed AIS data are shown later in the paper (Figure 3 and 4).

Ship fuel use and emission modelling

A new ship (exhaust) emissions model has been built for the research objective. It is based on extensive review of published research, as well as collection of available data. The model first estimates fuel consumption by marine fuel type (three classes) and ship type (ten classes) at a high resolution, and then uses fuel-based emission factors (g/kg fuel) to estimate emissions for a broad range of pollutants.

Ship classification

The main ship types considered in the model are:

- ‘bulk carrier’
- ‘container’
- ‘cruise ship’
- ‘general cargo’
- ‘reefer’
- ‘roro’ (roll-on-roll-off)
- ‘tanker (oil)’
- ‘tanker (other)’
- ‘vehicle carrier’
- ‘other’

Ship engine type is broadly defined as:

- Main engine (‘ME’), auxiliary engine (‘’AE’) and boiler (‘BL’).
- Slow speed (‘SS’), medium speed (‘MS’) and high speed (‘HS’) diesel engines, or gas/steam turbines (‘GAS’/‘STM’).
- International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI NO_x emission certification limits, which relate to year of vessel construction, i.e. ‘pre-control’ (< 2000), ‘Tier I’ (2000-2010) and ‘Tier II’ (2011+).

Regarding fuel type, marine fuel oils can be split into numerous categories based on e.g. their origin and viscosity. For the model they are classified as follows:

- ‘RO’ – (intermediate) residual fuel oil (50-810 centistokes, 0.5-5.0% sulphur).
- ‘MD’ – marine distillates, which can be further classified into marine diesel oil (‘MDO’, 5.5-50 centistokes, typically 1.0% and maximum 2.0% sulphur) and marine gas oil (‘MGO’, 1-5.5 centistokes, typically 0.1-0.5% and maximum 1.5% sulphur).
- ‘ULSD’ – ultra-low sulphur diesel (typically 10 ppm S).

The different classes of main ship type, engine type and fuel type lead to a large number of combinations, and therefore create a high level of model complexity. However, certain combinations will dominate ship activity. For instance, large ships are primarily powered by diesel propulsion systems and are usually fuelled by residual oil (RO).

RO is a low-grade fuel that includes high concentrations of impurities such as sulphur, ash, asphaltenes, and metals. Marine distillate oils (MD) are more refined fuels, but due to their higher cost, they are generally only used for small, medium-speed diesel engines, such as auxiliary engines for port activities, and for main engines when manoeuvring in harbour areas.

The main engines that propel moving ships are primarily powered by slow (SS, 2-stroke, typically GT ≥ 2500 and ≤ 150 RPM) and medium speed diesel (MS, four-stroke, typically GT < 2500 and 150-1000 RPM) engines that combust residual oil (RO) or marine distillate (MD). High-speed diesel (HS, 4 typically GT < 2500 and ≥ 1000 RPM) engines are primarily used on smaller vessels. Other engine configurations exist, such as liquefied natural gas (LNG) powered vessels, steam turbines and gas turbines although their numbers are significantly lower.

Fuel use algorithms

Apart from some cases where power cables from land-based sources are connected and used on-board vessels in port, ships are generally self-sufficient regarding energy supply. The majority of large ships shut down their main engines when in port, only relying on their auxiliary engines/boilers for necessary on-board electric power and heat (steam) production. Electric power is typically used for cargo refrigeration, air conditioning, cranes and control systems on-board, while steam is used for heating fuel oil, running cargo pumps, tank cleaning and for heating accommodation units.

Different ship types have different ways of using their engines/boilers, especially during harbour visits. Electricity requirements vary depending on the type of the ship. The energy demand of a large cruise ship with more than a thousand air-conditioned cabins is considerably different from that of a bulk carrier. On the other hand, crude oil tankers typically have large boiler systems for warming their cargo, and all ships using fuel oil have some boiler capacity for heating their fuel to obtain desired viscosity.

Fuel use is dependent on actual power demand on-board a ship. However, real world power requirement on-board a ship can vary substantially and power demand is therefore difficult to quantify accurately. In essence, there is no generic and simple relationship between the actual on-board power demand delivered by the different combustion systems and other variables (e.g. vessel speed), that would be accurate for individual ships at all times of operation.

However, for ship emission modelling in (several) large areas and over long periods of time (year) a reasonable and feasible approach is required. Following earlier work by other researchers (e.g. Georgakaki et al., 2005; Hulskotte and Denier van der Gon, 2010), generic empirical relationships, were used in this work. The use of generic relationships for shipping fleets in a large (port) areas over a long period of time is warranted as it is expected that prediction errors for individual vessels will tend to offset each other and average out, leading to robust and relatively accurate emission predictions.

As will be discussed later, a ship energy-balance approach was used to calibrate and expand published empirical functions to better reflect the shipping fleet operating in Queensland waters. As an example, the model formulation is shown for two ship types:

Bulk Carrier

$$F_{ME,x} = 0.271\, S^{0.524}\, \Delta\mathrm{d}\, p_x\, (\nu/\nu_{ss})^3$$

$$F_{boiler} = 0.021\, \mathrm{S}\, \Delta t\, /\, (\tau\, \eta)$$

$$F_{AE1,x} = 0.012\, S^{0.524}\, \Delta\mathrm{d}\, p_x$$

$$F_{AE2,x} = (\psi\, 0.004\, \mathrm{S}\, \Delta\mathrm{t} - F_{boiler})\, p_x$$

where $\psi = 3.262\, (\tau\, \eta\, 0.004\, S\, \Delta t)^{-0.345}$

Cruise ship:

$$F_{ME,x} = 0.257\, S^{0.613}\, \Delta\mathrm{d}\, p_x\, (\nu/\nu_{ss})^3$$

$$F_{boiler} = 0.014\, P\, \Delta t\, /\, (\tau\, \eta)$$

$$F_{AE,x} = 4\, P\, \Delta t\, p_x / (\tau\, \eta), \ldots\ for\ P \leq 2000$$

$$F_{AE,x} = \big(22 - 2.3\, LN(P)\big)\, P\, \Delta t\, p_x / (\tau\, \eta), \ldots for\ P > 2000$$

$F_{ME,x}$ = main engine fuel consumption for machinery/fuel type x (kg)
$F_{AE,x}$ = auxiliary engine fuel consumption for machinery/fuel type x (kg)
$F_{AE1,x}$ = auxiliary engine fuel consumption in transit conditions for machinery/fuel type x (kg)
$F_{AE2,x}$ = auxiliary engine fuel consumption (non-transit) for machinery/fuel type x (kg)
F_{boiler} = auxiliary boiler fuel consumption (kg)
S = vessel size or volume, expressed as (unit-less) gross tonnage (GT)
P = passenger capacity (number of passengers)
ν = actual (average) vessel speed (km/h)
ν_{ss} = vessel service speed (km/h)
Δd = total distance traversed by the ship (km)
Δt = time resolution (h)
η = boiler thermal efficiency (-)
τ = fuel specific lower heating value (MJ/kg)
p_x = proportion of total fuel used by machinery/fuel type x (-)

Full parameterisation of the fuel models for all ship types can be found in DES (2019). These fuel algorithms aim to capture typical fuel consumption rates for different ship classes in four modes of operation, ‘transit’, ‘manoeuvring’, ‘berth’ and ‘anchor’. Fuel rates for moving ships in transit are simulated as a function of ship class, ship size, service speed and actual vessel speed. The predicted fuel rates are expected to be average or typical values, but real world variation will occur, as was discussed before. For instance, weather and sea conditions can significantly alter the power demand in the main engine propulsion system.

The fuel consumption for boilers is dependent on the heat demand on these various systems, and whether the main engine is running (waste heat recovery). The fuel consumption by auxiliary engines and boilers is not dependent on ship movement, but rather on the operational status of the ship (i.e. loading/unloading, operation of cranes, etc.). It is assumed that auxiliary boilers are not in use during transit because (main engine) waste heat boilers are used instead.

Figure 2: 70,285 GT cruise ship leaving Brisbane.

Short-term peaks in power demand are often encountered when bow and stern thrusters are operated during departure from or arrival at a port. Engine loads can change rapidly during manoeuvring operations. Fuel use in manoeuvring conditions are therefore modelled separately.

Fuel rates for stationary ships are simulated as function of e.g. ship class and ship size. Once in port, power requirements for ships are usually less, but can still vary depending on the type of ship activity, e.g. hoteling (berth), cargo refrigeration, and in particular, for self-unloaders, which require energy for loading operations (cargo pumps, cranes). Auxiliary engines are usually used for electric power production, while the main engines are shut down, and the boiler generates steam. The main engine is not used when ships are at berth or at anchorage, except for diesel-electric ships, where main engines may be used to generate auxiliary power.

Cruise ships can be diesel-electric and have relatively high electrical loads to supply passenger needs. For simplicity, it is assumed that cruise ship energy demand can be simulated with the generic fuel algorithms used in this study. However, it is acknowledged that the need for more specific algorithms for cruise ships needs to be explored further. The same can be said for smaller ship types such as tugs, ferries, yachts and dredges. Further research, including collection and analysis of real-world fuel consumption data, for these smaller vessels and possible modification of the generic fuel algorithms is recommended.

Ship energy balance - calibration

A ship energy-balance approach was used to calibrate the fuel algorithms, discussed before, to better reflect the shipping fleet operating in Queensland waters. First, plausible ranges in ship energy use were defined. The IHS database reports Maximum Continuous Rating (MCR) for each ship, which is equivalent to maximum installed engine power. It also reports service speed, which is defined as the speed that the ship is capable of maintaining at sea in normal weather conditions, and at normal service draught. Ships travelling at service speed typically use 80-90% of MCR. This is the first verification point in the energy balance.

Second, plausible ranges of auxiliary engine power were developed using literature review and analysis of the IHS database. The ratios of installed auxiliary engine power to MCR were computed for all ships and plausible ranges were defined as the 10 and 90-percentile values for each ship class. Subsequently these minimum and maximum ratio values were multiplied with reported ranges of auxiliary load factors for different modes of operation.

Subsequently, a typical ship speed-time profile (75 hours), including all four modes of operation (cruising, manoeuvring, berth, anchor), was used to calculate minute-by-minute energy use for individual ships (5,510 vessels in total).

Estimated fuel use (kg/min) was then converted to energy use (kW) using information on the fuel type, lower heating value (LHV, MJ/kg fuel) and engine and fuel type dependent thermal efficiency. Figure 3 shows an example of energy plots constructed for a specific container ship built in 2004 with a direct-drive slow-speed diesel engine, about 53,000 GT, a length of 294m and a service speed of 44 km/h.

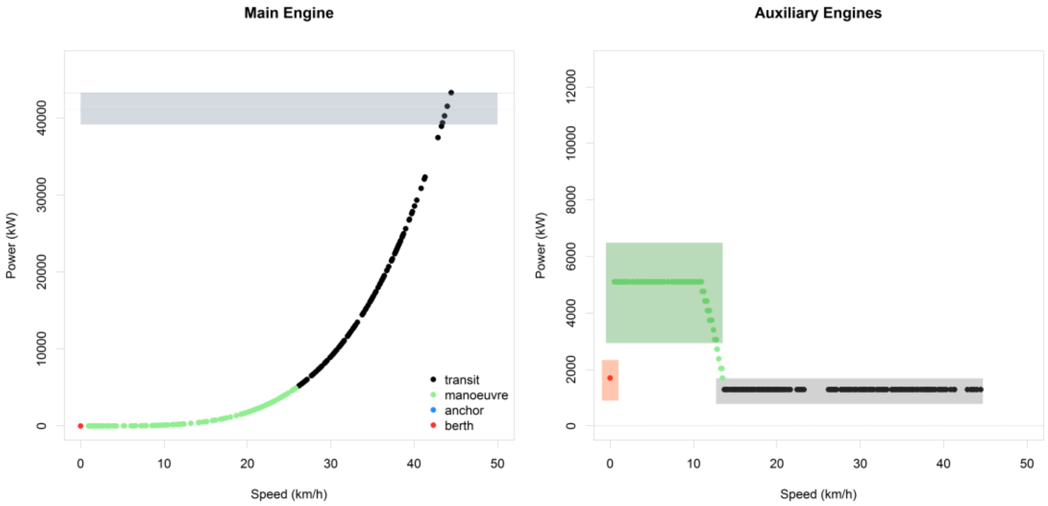

Figure 3: Energy plots for main and auxiliary engines.

The plots show the plausible energy power ranges for specific conditions and for the three engine types. The simulated energy use by the main engine (left plot) at service speed is 5% higher than the average energy use derived from the IHS Markit data. The grey shaded area shows the plausible range of 80-90% of MCR. The simulated energy use falls just outside the plausible range for this vessel. It can be seen that simulated auxiliary engine power (right plot) in transit conditions (grey shaded area), in manoeuvring conditions (green shaded area) and in berth conditions (red shaded area) all fall within the expected and plausible ranges. Note that anchor and berth conditions are assumed to have equivalent auxiliary energy use for this vessel.

Similar plots and associated statistics were computed for all 5,510 vessels for which IHS Markit data are available. An example of the step-wise calibration procedure is shown in Figure 4 for 258 container ships.

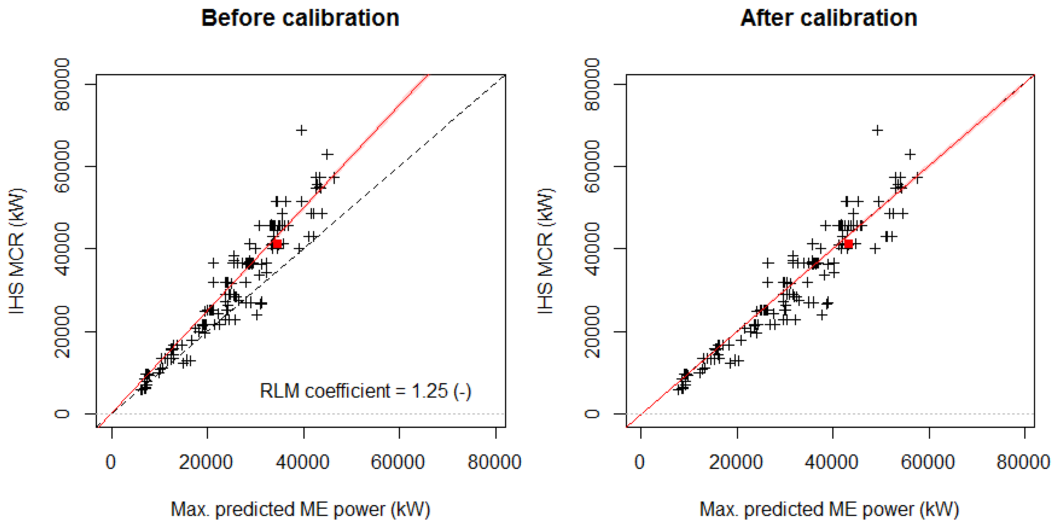

Figure 4: Calibration of main engine fuel algorithm for container ships.

The left plot shows the reported and predicted engine power at service speed. The red square data point reflects the specific container ship that was previously discussed. The initial model parameters appear to generally underestimate main engine power for the fleet of container ships in Queensland waters. A robust linear regression model (RLM) was fitted to estimate a calibration factor for predicted power. In this case, the calibration factor is computed to be 1.25 and used to adjust model parameter values. The result for the calibrated model is shown in the scatter plot on the right. A similar approach was used to adjust the model parameters for other engine types and operating conditions. The calibration procedure is described in detail in DES (2019).

Emission algorithms

An extensive review of published research reports and scientific papers was used to create a set of fuel-based emission factors (g of pollutant per kg of fuel burned) for relevant air pollutants and greenhouse gases. For instance, trace heavy metal content in ship PM emissions is significant. Specific heavy metals such as vanadium, nickel and iron have been reported to be particularly prominent in ship exhaust. Celo et al. (2015) reported a total metal content in $PM_{2.5}$ in the range of 1-4 mass%. Indeed, vanadium concentrations and vanadium-to-nickel ratios have been used to assess and attribute ship emission impacts to local air quality (e.g. Coggon et al., 2012; Zhang et al., 2014). Significant emissions of polycyclic aromatic hydrocarbons (PAHs) from ships, and substantially elevated local concentrations close to ship activity, has attracted research attention (e.g. Moldanova et al., 2010; Pongpiachan et al., 2015). Significant carbonyl emissions have also been reported (Agrawal et al., 2008).

Emission factors, expressed as grams of pollutant per kg of fuel, were generated for a range of pollutants and greenhouse gases, i.e. CO_2, NO_x, SO_2, PM_{10}, $PM_{2.5}$, VOCs, CH_4, N_2O, Pb, As, Ni, V, Mn, Cd, PAHs (sum), benzo(a)pyrene, 1,3-butadiene, benzene, formaldehyde, toluene, xylenes and ethylbenzene. The emission factor values are a function of engine system (ME, AE, BL), engine type (SS, MS, HS, GAS, STEAM), fuel type (RO, MD, ULSD) and MARPOL Annex VI emission certification limit (NO_x only).

These emission factors are combined with estimates of fuel consumption for each minute of individual ship activity. This is done for all ships that operate in a particular port area in a year and emissions are aggregated to give total emission loads. Total emission loads are aggregated at grid cell level and calculated for each hour of the year.

Results

Figure 5 shows the 14 ports for which fuel consumption and emissions were calculated. The emission estimates are based on detailed ship activity data, i.e. minute-by-minute fuel and emissions estimates for each individual ship in all port areas over a full year (2015).

In order to analyse the modelling results, minute-by-minute emission predictions for individual ships have been aggregated to 1 × 1 km grid cells within the port areas and allocated to each hour of the year.

Some examples of gridded emission are shown in Figures 6-9. It is noted that DES (2019) provides these maps for all 14 Queensland ports. Major routes followed by vessel entering, leaving or passing by ports are clearly visible. In general, some ports have significant passing traffic, with vessels that neither anchor nor berth at port but whose emissions are within the emission modelling area. This is the case for e.g. Port of Brisbane, with substantial shipping traffic east of Moreton and Stradbroke Islands. Likewise, Thursday Island experiences substantial ship activity in the northern part of the modelling area. Anchorage and berth areas are clearly discernible in Figure 6-9. For instance, red/orange cells indicate berth areas or anchorage areas where vessels remain stationary, while waiting for the authorisation to berth.

Figure 5: Queensland Ports selected for emission modelling.

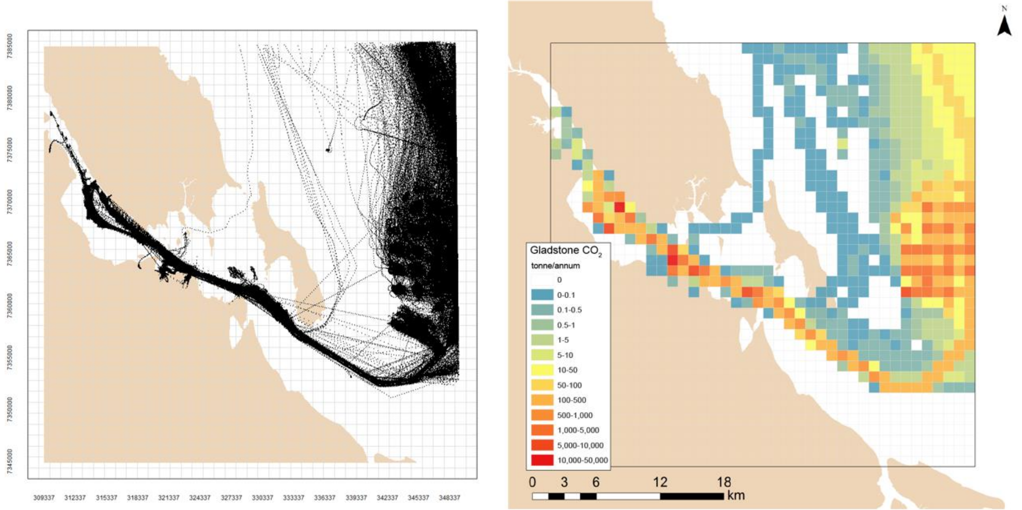

Figure 6: Gladstone – AIS data visualisation (left) and gridded CO_2 emissions (right).

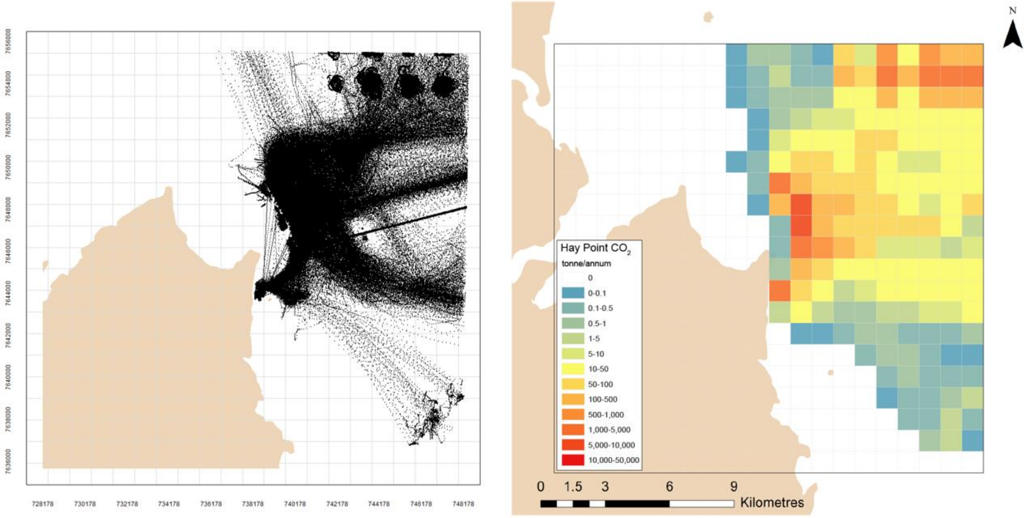

Figure 7: Hay Point – AIS data visualisation (left) and gridded CO_2 emissions (right).

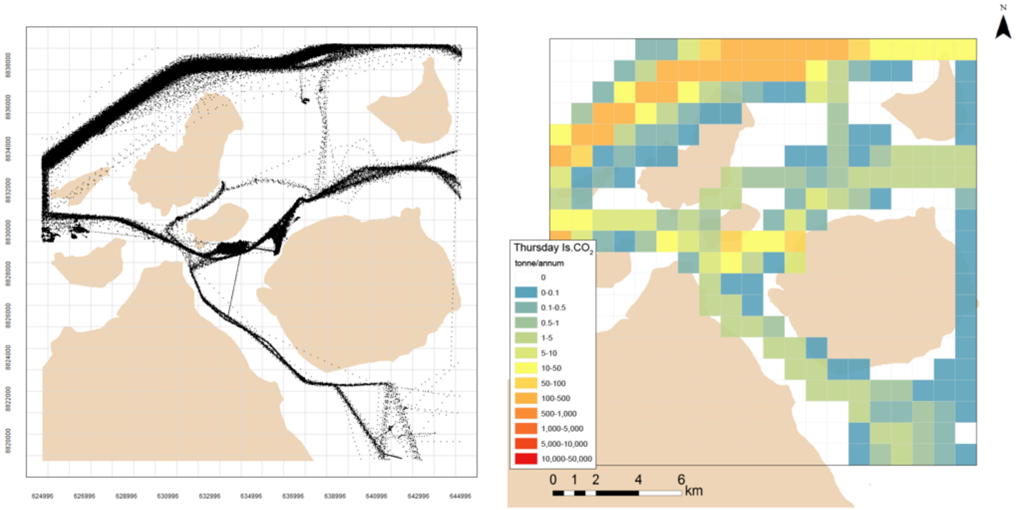

Figure 8: Thursday Island – AIS data visualisation (left) and gridded CO_2 emissions (right).

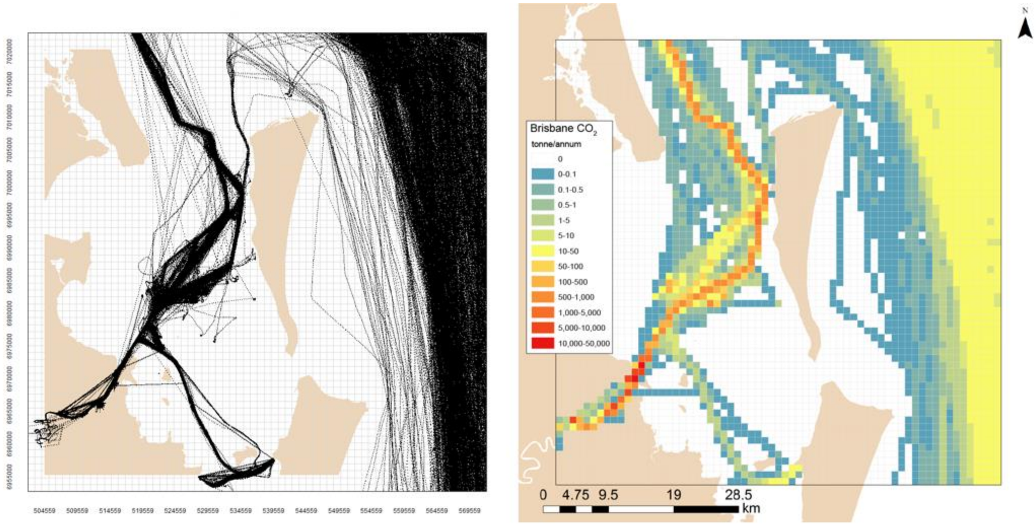

Figure 9: Port of Brisbane – AIS data visualisation (left) and gridded CO_2 emissions (right).

Table 1 presents total emission estimates for a range of selected pollutants and for the fourteen port areas. CO_2 emissions are a good proxy variable for total fuel use. Table 1 shows that Gladstone accounts for approximately 40% of total emissions (with slight variations by pollutant), followed by Port of Brisbane with about 35%, Hay Point with about 10%, and Abbot Point and Townsville both with about 5%.

Table 1: Total emissions by port and by pollutant

Port	CO_2 (tonne)	NO_x (tonne)	SO_2 (tonne)	PM_{10} (tonne)	$PM_{2.5}$ (tonne)	CO (tonne)	VOCs (tonne)	PAHs (tonne)	B(a)P (kg)	Ni (kg)	V (kg)
APT	23,664	372	247	31	28	30	11	121	8	263	616
BND	577	10	7	1	1	1	0	3	0	7	15
CRN	15,196	310	214	31	29	23	9	138	12	185	422
CFL	8,379	197	131	17	16	9	4	56	5	103	231
GLD	198,421	3,385	2,605	345	317	273	102	1,457	116	2,708	6,357
HPT	42,086	649	505	60	55	51	20	224	16	569	1,344
LUC	451	7	5	1	1	1	0	2	0	5	12
MKY	8,447	144	110	13	12	11	4	45	3	109	252
MRN	544	10	6	1	1	1	0	3	0	6	13
POB	155,270	3,042	2,253	303	279	207	84	1,245	103	2,123	4,932
RKH	786	14	11	1	1	1	0	4	0	11	25
THI	7,439	173	115	16	15	9	4	58	5	91	204
TWN	29,426	503	372	45	41	38	15	163	13	368	855
WEI	12,027	194	121	15	14	15	6	63	4	126	293
TOTAL	502,716	9,011	6,702	880	809	668	260	3,585	285	6,672	15,571

APT = Abbot Point, BND = Bundaberg, CRN = Cairns, CFL = Cape Flattery, GLD = Gladstone, HPT = Hay Point, LUC = Lucinda, MKY = Mackay, MRN = Mourilyan, POB = Port of Brisbane, RKH = Rockhampton (Port Alma), THI = Thursday Island, TWN = Townsville, WEI = Weipa.

However, these proportions do not reflect the different sea surface areas within the modelled port areas, which vary from about 200 km^2 (Mourilyan) to 3,300 km^2 (Port of Brisbane). Normalising for sea surface area shows a different picture, and produces the following ranking in terms of the average 'emission intensity', which is expressed as tonne CO_2 per km^2 per year.

- Gladstone: 226 tonne CO_2/km^2.annum
- Hay Point: 152 tonne CO_2/km^2.annum
- Port of Brisbane: 47 tonne CO_2/km^2.annum
- Weipa: 42 tonne CO_2/km^2.annum
- Cairns: 35 tonne CO_2/km^2.annum
- Mackay: 34 tonne CO_2/km^2.annum

- Thursday Island: 32 tonne CO_2/km^2.annum
- Townsville: 32 tonne CO_2/km^2.annum
- Cape Flattery: 27 tonne CO_2/km^2.annum
- Abbot Point: 24 tonne CO_2/km^2.annum
- Other ports : < 3 tonne CO_2/km^2.annum

Further analysis of the shipping activity and emissions data shows that most of the vessels operating in and around Queensland ports are classified as bulk carriers (63%), tankers (13%) and container ships (6%).

The contribution to total emissions roughly follows the proportions of different ship classes in the Queensland shipping fleet, but variations do occur due to differences in the distributions of vessel size, year of manufacture, fuel mix, and actual operating conditions. The contribution of bulk carriers to total emissions is therefore lower than the proportion in the fleet (63%) and varies between approximately 30-45%. In contrast, the contributions of container ships and tankers is higher than would be expected based on the fleet proportions: approximately 10-15% (fleet percentage of 6%) and 20-30% (fleet percentage of 8%), respectively.

Air quality impact assessment

A preliminary assessment of local air quality impacts by ships was conducted for the Australian port areas. Modelled pollutant concentrations ($\mu g/m^3$) were compared with Australian air quality objectives. Contributions to local air concentrations up to 10% of the objective were found for 11 pollutants. Several of these pollutants are (possibly) carcinogenic and there is no safe threshold concentration level. Contributions to local air concentrations up to 50% of the objectives were found for SO_2, NO_2, vanadium, nickel, $PM_{2.5}$, PM_{10}, whereas a higher contribution was found for benzo(a)pyrene. For a more detailed discussion of methods and analysis, the reader is referred to DES (2019).

Conclusion and next steps

This paper presents the results of ship emission modelling, both greenhouse gas emissions and air pollutant emissions, for 14 ports in Queensland. The information is useful to identify ports with a relatively high emission intensity and prioritise possible emission mitigation/reduction actions. The data are available at a very high spatial and temporal (minute-by-minute) resolution, and can be used for e.g. detailed air quality impact (scenario) modelling (e.g. impacts of reduced maximum sulfur content in 2020, impacts of shore power, impacts of emission control technology such as scrubbers and SCR), or for detailed analysis of fleet impacts (e.g. type or age of ships vs. emissions).

The next step and focus of the work is validation of the ship fuel/emission algorithms. This will be achieved through different research programs and partnerships with Australian universities. First, the fuel and emission predictions will be compared with on-board emission measurements for two vessels on different port-to-port trips in Queensland. Second, a measurement program is being rolled out that specifically measures local air quality impacts of ships in the Brisbane port area using a dedicated air monitoring station, and will likely combine this with brief measurement campaigns using UAV (drone) emission measurements and on-board fuel surveys.

References

Agrawal, H., Welch, W.A., Miller, J.W., Cocker, D.R. (2008). Emission measurements from a crude oil tanker at sea, *Environ. Sci. Technol.*, 42, 7098-7103.

Celo, V., Dabek-Zlotorzynska, E., McCurdy, M. (2015). Chemical characterization of exhaust emissions from selected Canadian marine vessels: The case of trace metals and lanthanoids, *Environ. Sci. Technol.*, 49 (8), 5220-5226.

Coggon, M.M., Sorooshian, A., Wang, Z., Metcalf, A.R., Frossard, A.A., Lin, J.J., Craven, J.S., Nenes, A., Jonsson, H.H., Russell, L.M., Flagan, R.C., Seinfeld, J.H. (2012). Ship impacts on the marine atmosphere: Insights into the contribution of shipping emissions to the properties of marine aerosol and clouds, *Atmospheric Chemistry and Physics*, 12 (18), 8439-8458.

Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V., Lauer, A. (2007). Mortality from ship emissions: a global assessment, *Environ. Sci. Technol.*, 41, 8512–8518.

DES (2019). *Simulation and Assessment of Shipping Fuel Consumption and Emissions and their Local Air Quality Impacts – 15 Queensland Strategic Ports*, Queensland Government, Department of Science and Environment, Brisbane.

EEA (2013). *The Impact of International Shipping on European Air Quality and Climate Forcing*, European Environment Agency, Technical report No. 4/2013.

Georgakaki, A., Coffey, R.A., Lock, G., Sorenson, S.C. (2005). Transport and Environment Database System (TRENDS): maritime air pollutant emission modelling, *Atmospheric Environment*, 39, 2357-2365.

Hulskotte, J.H.J., Denier van der Gon, H.A.C. (2010). Fuel consumption and associated emissions from seagoing ships at berth derived from an on-board survey, *Atmospheric Environment*, 44, 1229-1236.

Moldanová, J., Fridell, E., Popovicheva, O., Demirdjian, B., Tishkova, V., Faccinetto, A., Focsa, C. (2010). Characterisation of particulate matter and gaseous emissions from a large ship diesel engine, Atmospheric Environment, 43, 2632-2641.

Velleman, P.F. (1980). Definition and Comparison of Robust Nonlinear Data Smoothing Algorithms, *Journal of the American Statistical Association*, 75 (371), 609-615.

Zhang, F., Chen, Y., Tian, C., Wang, X., Huang, G., Fang, Y., Zong, Z. (2014). Identification and quantification of shipping emissions in Bohai Rim, China, Science of the Total Environment, 497, 570-577.