Marine Vessel Smoke Emissions in Hong Kong and the Pearl River Delta

Final Report

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March 2012

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ACKNOWLEDGEMENT

The authors of this Study are extremely grateful to Civic Exchange for their sponsorship, and to Christine Loh and Mike Kilburn in particular as strategic advisor and project manager, respectively, of a trio of studies that examine ship emissions, health impacts and policy implications in the Pearl River Delta, under support from the Rockefeller Brothers Fund. Last but not least, the authors also want to pay tribute to the Marine Department and the Environmental Protection Department for their long-standing support in terms of data provision and expertise advice.

1. INTRODUCTION

Background

In the last decade, there has been a growing consensus on the impact of toxic ship exhaust emissions on public health and the need to clean-up the shipping sector. International agencies such as the International Maritime Organization (IMO) is steering its member states towards tighter fuel standards and engine regulations under Annex VI to the International Convention for the Prevention of Marine Pollution from Ships (MARPOL VI). Likewise, government agencies and port authorities, regional or local, are gearing up for comprehensive strategies to reduce not just ship emissions, but in some jurisdictions also port-side emissions. Port cities along the west coast of the United States (US), notably Los Angeles and Long Beach, and the sister ports of Seattle, Tacoma and Vancouver in the Puget Sound region, have been leading the way in developing incentive programmes, regulation and regional collaboration. Ports in Europe are following suit, under the direction of the European Union.

Under the international regulatory regime, the emission control area (ECA) is getting serious attention. Ships operating inside an ECA are required by IMO regulation to comply with a higher marine fuel standard. At the time of writing, the fuel sulphur cap for an ECA is 1%, which will be further tightened to 0.1% in January 2015. The North American ECA, covering waters adjacent to the Pacific coast, the Atlantic/Gulf coast and the eight main Hawaiian Islands, was officially designated by the IMO in March 2010 and will become enforceable in August 2012. It is the world’s third ECA after the ECAs in the Baltic Sea area and the North Sea area in Europe. There is also the fourth ECA – an extension of the North American ECA, covering waters within 50 nautical miles (nm) of the Commonwealth of Puerto Rico and the US Virgin Islands, which is expected to come into force in January 2014.

Unlike their American and European counterparts, Asia’s ports have been far less responsive in cleaning-up, but the pressure and the real need to take action is perhaps the greatest. Asia is fast becoming the engine of the world’s economic growth and trade expansion. With nine of the world’s top ten container ports located in Asia, it is evident that the environmental footprint of the shipping and port sector must be reduced to prevent escalating health and well-being impacts on people living and working close to maritime activities. Zooming into Hong Kong and the Pearl River Delta (PRD), the need for urgent action is greater still as over 10% of the world’s container throughput each year are handled in this small area with a population of about 40 million.

Scientific evidence is key to raising industry and public awareness and to drive policy change. Lau et al. (2004, 2005) estimated that about 3.8 million Hong Kong residents living close to the Kwai Chung Container Terminals are affected by ship and port-related emissions, which is high in sulphur dioxide (SO_2) and other toxic substances. This is supported by findings of a recent study for the Environmental Protection Department (EPD) of the Hong Kong Special Administrative Region Government (the EPD Study) on marine vessel emissions inventory in Hong Kong (Ng, Lin et al., 2012) which confirms that (i) ocean-going vessels (OGV) are a major source of air pollution in Hong Kong, (ii) container ships are the top emitters, contributing about 80% of the OGV emissions, (iii) about 30% to 40% of OGV emissions are produced at berth, and (iv) Kwai Chung Container Terminals and other major berthing locations are ship emissions hot spots in Hong Kong, as shown in Figure 1 below.

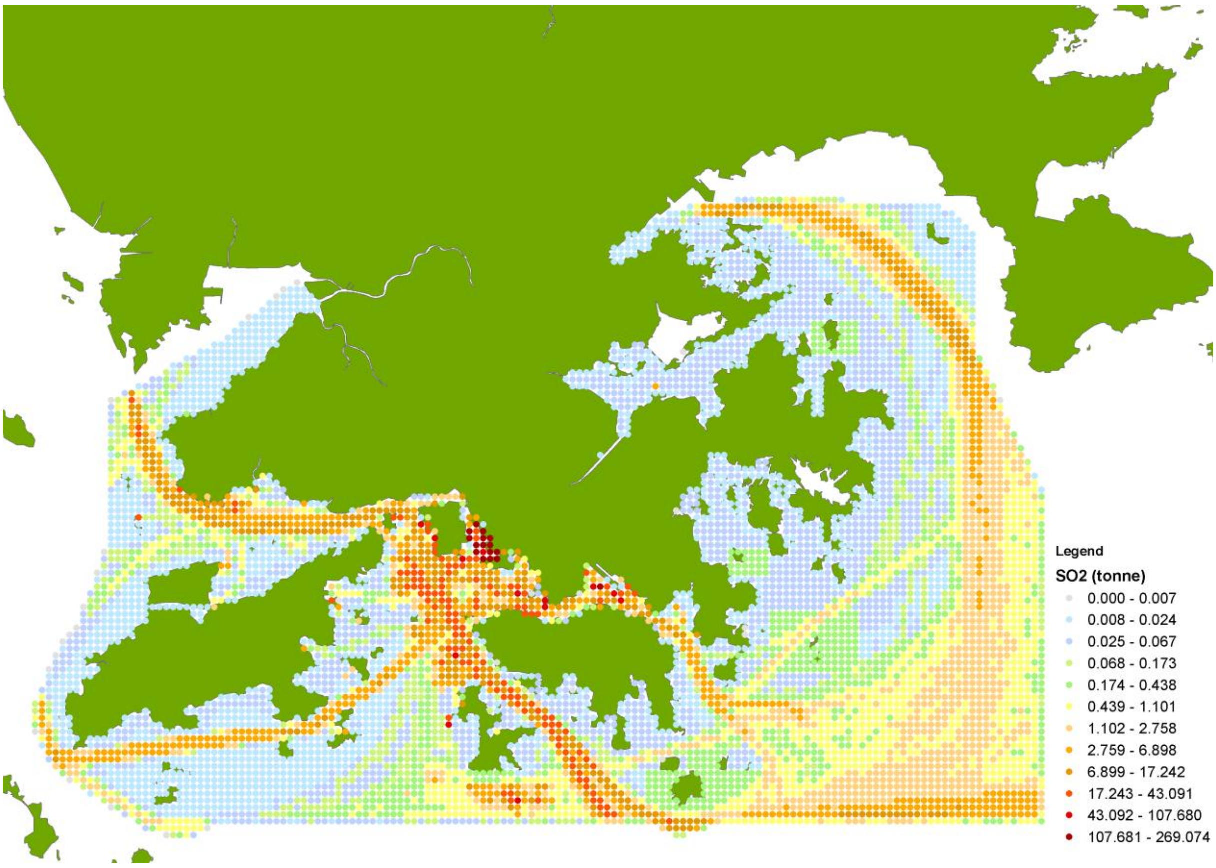

Figure 1 Spatial distribution of ship SO_2 emissions in Hong Kong, 2007

Source: Ng, et al., (2012)

Figure 1 only shows the pattern of emissions inside Hong Kong waters. Emissions levels at Yantian and Shekou, two major ports in Shenzhen which are located just outside Hong Kong waters, which is beyond the scope of the EPD Study, are not included on the map. However, with the high intensity of ship movements to the two Shenzhen ports, the level of ship emissions is expected to be comparable to Kwai Chung Container Terminals, and have a significant adverse air quality and public health impacts on the local communities, as well as on Hong Kong. In other words, only a marine vessel emissions inventory that covers *both* Hong Kong *and* the PRD would provide a full picture of ship exhaust emissions and their environmental consequences, as well as the much needed evidence to drive ship emissions reduction policies in this region as a whole.

Study Objectives and Scope of Work

To this end, Civic Exchange commissioned a Study in 2010 with the aim of filling this information gap. Specifically, the objectives of the Study are (i) to estimate marine vessel emissions in the PRD; (ii) to estimate the impact of these on air quality in the PRD and the associated health risks imposed on people living in this region; and (iii) to prepare groundwork for the establishment of an ECA in the PRD region.

Under the broad study objectives, the Atmospheric Research Center of the Fok Ying Tung Graduate School, the Hong Kong University of Science & Technology (HKUST) was tasked to carry out the following: (i) using 2008 as the base year, to compile an emissions inventory for OGVs consisting of sulphur dioxide (SO_2), nitrogen oxides (NO_X), volatile organic compounds (VOC), carbon monoxide (CO), and particulate matter (PM_{10} and $PM_{2.5}$) in the PRD, covering sea area up to 100 nm from Hong Kong; (ii) to produce emission maps showing the spatial distribution of marine vessel emissions in the PRD; (iii) to demonstrate the impact of marine vessel emissions on air pollution levels in the PRD with the help of an air dispersion model; and (iv) to estimate emissions reduction benefits of several selected marine vessel emissions control strategies. The findings of the four tasks listed above will be documented in this Report. In parallel, the School of Public Health of the University of Hong Kong was tasked to study the health risks of ship emissions on the PRD population. These will be reported in a separate document.

2. RESEARCH METHODOLOGY

Methodology

There are two common approaches to developing an emissions inventory for ships, namely the fuel-based approach and the activity-based approach. The choice between the two is mostly determined by the level of details expected for the inventory and the availability of data. Ng, et al. (2012) took the more detailed activity-based approach to compile a detailed marine vessel emissions inventory for Hong Kong. In short, emissions of a specific air pollutant during a single voyage is a function of the installed power and fractional load of the equipment (main engine, auxiliary engine, and boiler) during different vessel operation modes (cruising, fairway cruise, slow cruise, maneuvering, and hotelling); time in different modes; and emission factors derived in units of works. For the purposes of consistency, the same approach was taken in this Study to estimate ship emissions in the PRD for 2008. The general equation for emissions estimation is as follows:

$$\textit{Total Emissions}_{(pollutant)} = \sum \textit{Emissions}_{(pollutant,\ activity\ mode,\ equipment)}$$

$$\textit{Emissions}_{(pollutant,\ activity\ mode,\ equipment)} = P \times FL \times T \times EF$$

where P is the installed power of equipment;
FL is fractional load of equipment in a specific mode;
T is operation time-in-mode; and
EF is fractional load emission factor of equipment.

One major breakthrough in Ng, et al. (2012) was the use of Automatic Identification System (AIS) data to (i) estimate main engine load factor based on actual vessel speed data embedded in the vessel track data captured by Marine Department's radar system; and (ii) plot emission maps based on the same vessel track information. For the former, AIS data allows the estimation of main engine load factor down to operation mode, vessel type and deadweight tonnage levels. This is a substantial improvement over past practice, which assumed a uniform load factor for vessels under the same operation mode. For the latter, emission maps add a new spatial dimension to the inventory by identifying major emission hot spots and corridors, which in turn provide scientific evidence for informing policy decisions. Both methods were also employed in this Study.

Data Requirements and Data Source

A broad range of information was required for this Study, namely (a) vessel call information, (b) vessel characteristics data, (c) vessel activity and movement information, (d) engine activity information, (e) fuel quality information, and (f) emission factors.

Vessel call and vessel activity/movement information were collected mainly from the Hong Kong Special Administrative Region (HKSAR) Marine Department (MD), either through published statistical reports or web-based information available on MD's website. In addition, a full year of vessel track data for 2008 was obtained from MD for detailed analysis and emissions estimation.

Vessel characteristics data covers (i) vessel registration information (e.g. vessel name, IMO number and call sign); (ii) construction information (e.g. keel laid data, launch data and delivery date); (iii) vessel class information (e.g .main vessel type and vessel sub-type); (iv) vessel size information (e.g. gross register tonnage and deadweight tonnage); (v) main engine information (e.g. number of engine, model, make, builder, engine speed, engine type and total engine power); and (vi) auxiliary engine and boiler information if available. Most of this information was extracted from Lloyd's Register of Ships (LRS).

Engine activity information is important for estimating emissions. As explained above, the main engine load factor of an individual ship at a particular location (as a vessel track data point at 30-second intervals) were determined by the actual vessel speed provided by AIS and the maximum speed obtained from LRS, using the following equation based on the Propeller Law:

$$\textit{Load Factor} = (\textit{Actual Speed}/\textit{Maximum Speed})^3$$

Auxiliary engine load factor, however, cannot be derived directly from the vessel track data. Reference was made to Starcrest Consulting Group (2009) for auxiliary engine default loads. The same also applied to boiler default loads. Similarly, as there are no locally derived emission factors for the estimation of ship emissions, emission factors used in this Study were based on ICF International (2009) and Starcrest Consulting Group (2009).

With respect to fuel quality information, it was assumed in this Study that OGVs with a total main engine power of 1,100 kW or above would use heavy fuel oil (HFO) and the rest would use marine diesel oil (MDO) or marine gas oil (MGO). Sulphur contents of HFO used by OGVs were assumed to be 2.83%, 2.64% and 2.77%, respectively for main engine, auxiliary engine and boiler. Sulphur content of MDO/MGO was assumed to be 0.5%.

3. 2008 SHIP EXHAUST EMISSIONS INVENTORY

Ocean-going vessel emissions inside Hong Kong waters

OGV arrivals and transit vessels

According to government statistics, there were 35,850 OGV calls to Hong Kong in 2008. In addition, there were also 14,540 transit vessels that passed through Hong Kong waters to their destination port. (MD, 2009)

Emissions by vessel type

OGV emissions inside Hong Kong waters in 2008 is summarized by vessel type in Table 1. The numbers include emissions produced by vessels that called at the port of Hong Kong and transit vessels. Container vessel were the top emitters, contributing 12,568 tonne of SO_2, 14,114 tonne of NO_X, and 1,449 tonne of PM_{10}. Cruise ship was the second largest emitter, responsible for 1,853 tonne of SO_2, 1,894 tonne of NO_X and 205 tonne of PM_{10}.

Table 1 OGV emissions (tonne) inside Hong Kong waters by vessel type, 2008

Vessel Type	SO_2	NO_X	PM_{10}	$PM_{2.5}$	VOC	CO
A. Chemical Carrier/Tanker	71.5	69.2	7.7	7.1	2.7	6.1
B. Conventional Cargo Vessel	386.0	404.3	43.9	40.4	15.3	34.8
C. Cruise/Ferry	1,853.2	1,894.4	205.2	188.8	66.3	154.7
D. Dry Bulk Carrier	513.4	498.9	53.9	49.6	19.1	44.3
E. Fishing/Fish Processing Vessel	0.8	2.2	0.1	0.1	0.1	0.2
F. Fully Cellular Container Vessel	12,568.2	14,113.9	1,449.4	1,333.5	616.4	1,431.5
G. Gas Carrier/ Tanker	64.8	58.2	6.9	6.4	2.1	4.7
H. Lighter/ Barge/ Cargo Junk	0.0	0.0	0.0	0.0	0.0	0.0
I. Oil Tanker	537.8	354.3	45.4	41.7	13.4	31.8
J. Pleasure Vessel	4.1	4.1	0.5	0.4	0.1	0.3
K. Roll On/Roll Off	112.2	128.0	13.1	12.1	4.7	10.9
L. Semi-container Vessel	8.6	8.3	1.0	0.9	0.4	0.8
M. Tug	144.3	146.2	17.3	15.9	5.4	11.8
N. Others	224.4	218.5	25.9	23.8	7.6	17.1
Total	16,489.3	17,900.7	1,870.3	1,720.7	753.6	1,749.1

In terms of percentage share, container vessel produced 76% of SO_2, 79% of NO_X and 78% of total PM_{10} emissions from OGVs in Hong Kong waters. The corresponding shares of cruise ship were 11% for SO_2, NO_X and PM_{10}, respectively. Adding oil tanker, conventional cargo vessel and dry bulk carrier to container vessel and cruise ship, the top five emitters contributed 96% of SO_2, 97% of NO_X and 96% of PM_{10} in 2008 inside Hong Kong waters. (Figures 2 to 4)

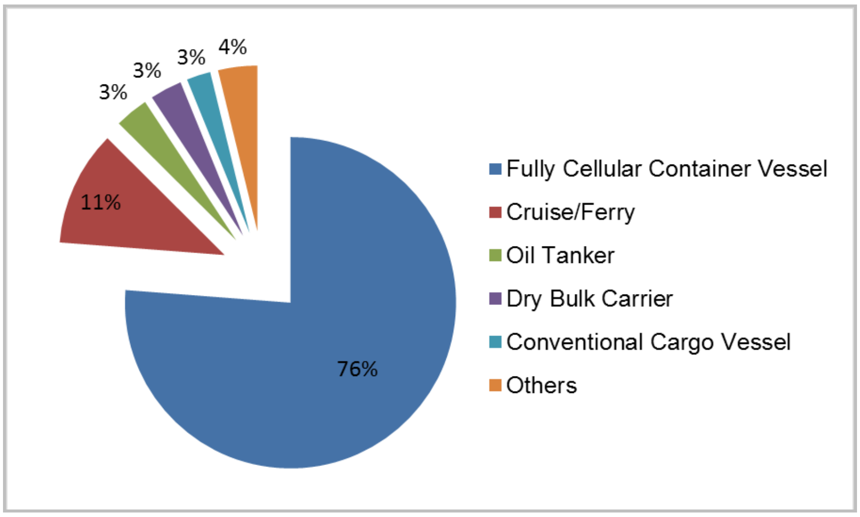

Figure 2 OGV SO_2 emissions (%) in Hong Kong waters by vessel type, 2008

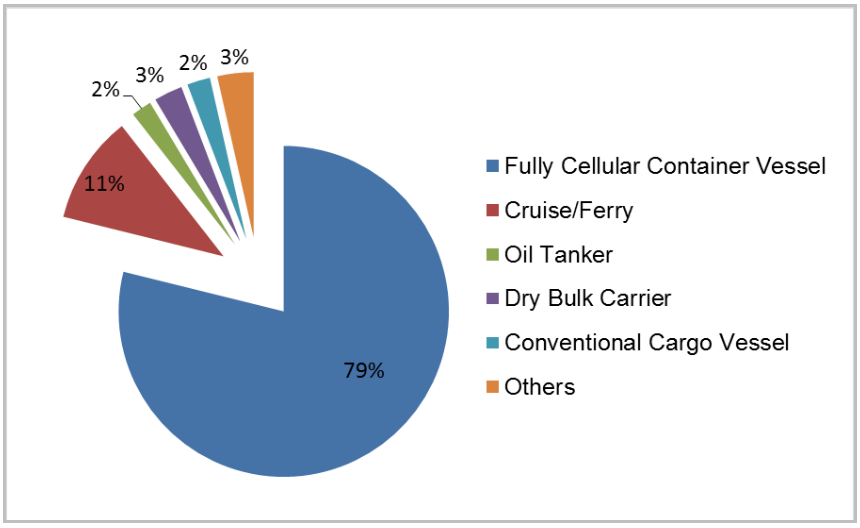

Figure 3 OGV NO_X emissions (%) in Hong Kong waters by vessel type, 2008

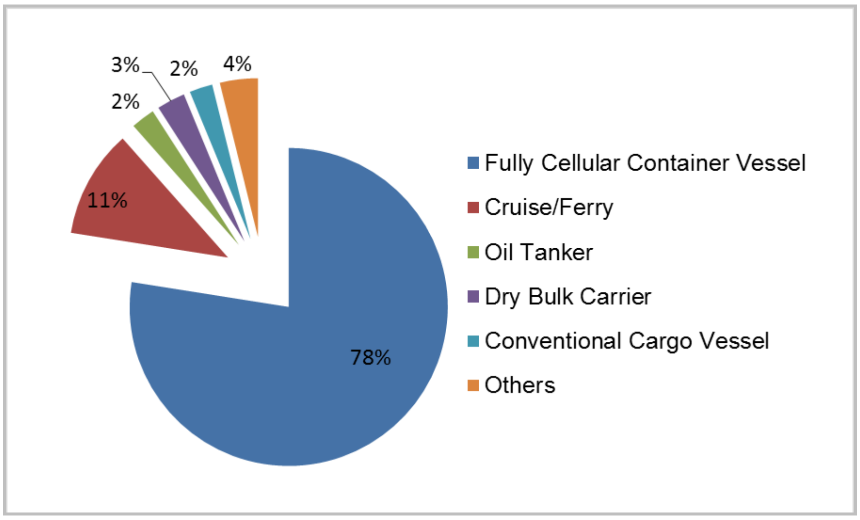

Figure 4 OGV PM_{10} emissions (%) in Hong Kong waters by vessel type, 2008

Emissions by operation mode

Table 2 below summarizes OGV emissions inside Hong Kong waters by operation mode. It is apparent that emissions during hotelling and slow cruise modes was the most significant. For SO_2, emissions produced during hotelling and slow cruise were 41% and 34%, respectively. For NO_X, the corresponding percentages were 29% and 42%, and for PM_{10}, the percentages were 33% and 40%. (Figure 5)

Table 2 OGV emissions (tonne) inside Hong Kong waters by mode, 2008

Vessel Type	SO_2	NO_X	PM_{10}	$PM_{2.5}$	VOC	CO
Cruise	0	0	0	0	0	0
Fairway Cruise	2,384.7	3,261.1	279.6	257.2	113.3	299.0
Slow Cruise	5,650.4	7,482.8	746.2	686.5	366.4	822.6
Maneuvering	1,704.9	2,018.1	226.3	208.2	111.6	215.7
Hotelling	6,749.4	5,138.7	618.2	568.8	162.4	411.7
Total	16,489.3	17,900.7	1,870.3	1720.7	753.6	1,749.1

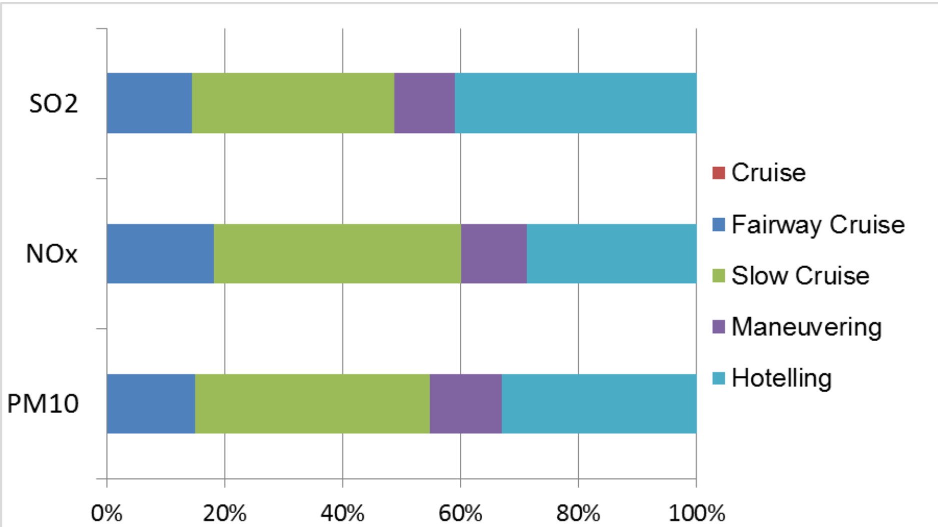

Figure 5 OGV emissions (%) inside Hong Kong waters by mode, 2008

Ocean-going vessel emissions outside Hong Kong waters

Emissions by vessel type

Emissions from OGVs outside Hong Kong waters but within the study area (that is, PRD waters) was much greater in quantity due to the larger area and the longer operation time in general. Apart from vessels that called at Hong Kong and transit vessels that passed through Hong Kong waters, there were also vessels that sailed into the study area without entering Hong Kong waters. These emissions were listed in Table 3 by vessel type.

Table 3 OGV emissions (tonne) outside Hong Kong waters but within the study area by vessel type, 2008

Vessel Type	SO_2	NO_X	PM_{10}	$PM_{2.5}$	VOC	CO
A. Chemical Carrier/Tanker	1,243.0	1,424.6	149.1	137.2	56.3	126.2
B. Conventional Cargo Vessel	3,679.7	4,481.4	453.0	416.8	170.9	384.9
C. Cruise/Ferry	1,832.1	1,959.7	218.3	200.8	75.6	166.0
D. Dry Bulk Carrier	7,140.2	9,170.4	871.7	802.0	344.7	786.8
E. Fishing/Fish Processing Vessel	7.7	22.2	1.0	0.9	0.9	1.9
F. Fully Cellular Container Vessel	100,910.8	134,527.5	11,688.4	10,753.4	4,729.4	12,410.8
G. Gas Carrier/ Tanker	538.2	508.0	59.8	55.0	18.3	40.8
H. Lighter/ Barge/ Cargo Junk	0.0	0.0	0.0	0.0	0.0	0.0
I. Oil Tanker	6,252.7	6,611.3	653.9	601.5	242.2	599.5
J. Pleasure Vessel	0.3	0.1	0.0	0.0	0.0	0.0
K. Roll On/Roll Off	1,183.3	1,542.0	151.3	139.2	59.8	134.4
L. Semi-container Vessel	438.0	578.5	45.2	41.6	18.0	55.7
M. Tug	454.6	476.3	55.0	50.6	17.1	38.3
N. Others	1,749.7	2,110.3	216.2	198.9	75.4	169.2
Total	125,430.4	163,412.4	14,563.0	13,397.9	5,808.4	14,914.3

Once again, container vessels were the largest emitters, contributing 100,911 tonne of SO_2, 134,528 tonne of NO_X and 11,688 tonne of PM_{10}. Unlike the pattern in Hong Kong waters, dry bulk carriers were the second largest emitter, producing 7,140 tonne of SO_2, 9,170 tonne of NO_X and 872 tonne of PM_{10}. Cruise ships were the fifth largest emitter outside Hong Kong waters.

In terms of percentage share, container vessel accounted for 80% of SO_2, 82% of NO_X and 80% of PM_{10} outside Hong Kong waters but within the study area in 2008. The shares of dry bulk carrier and oil tanker were 6% and 5% for SO_2, 6% and 4% for NO_X, and 6% and 4% for PM_{10}. The same top five emitters accounted for a combined 95% of SO_2, 96% of NO_X and 95% of PM_{10}. (Figures 6 to 8)

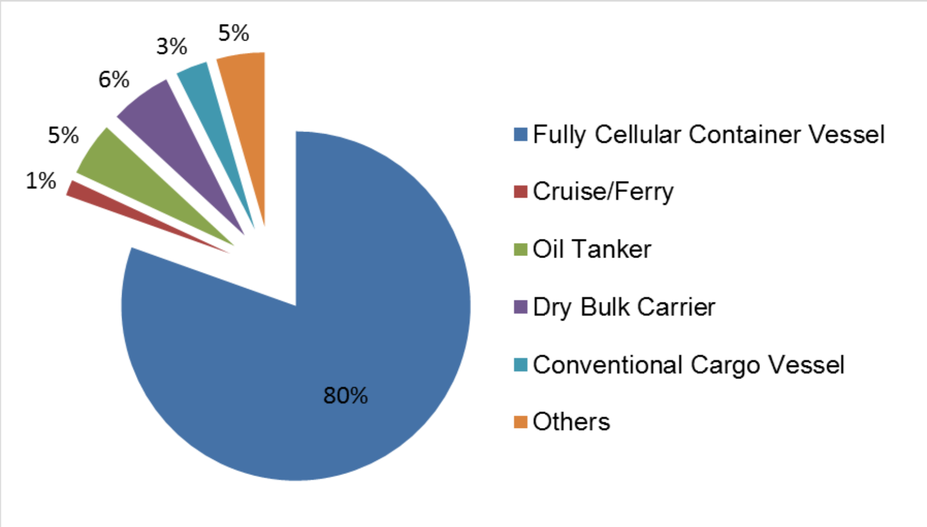

Figure 6 OGV SO_2 emissions (%) outside Hong Kong waters by vessel type, 2008

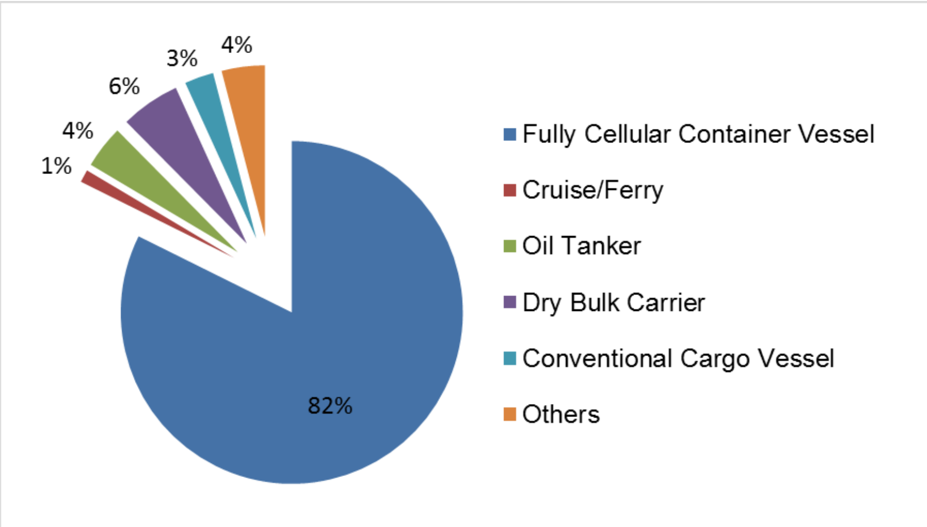

Figure 7 OGV NO_X emissions (%) outside Hong Kong waters by vessel type, 2008

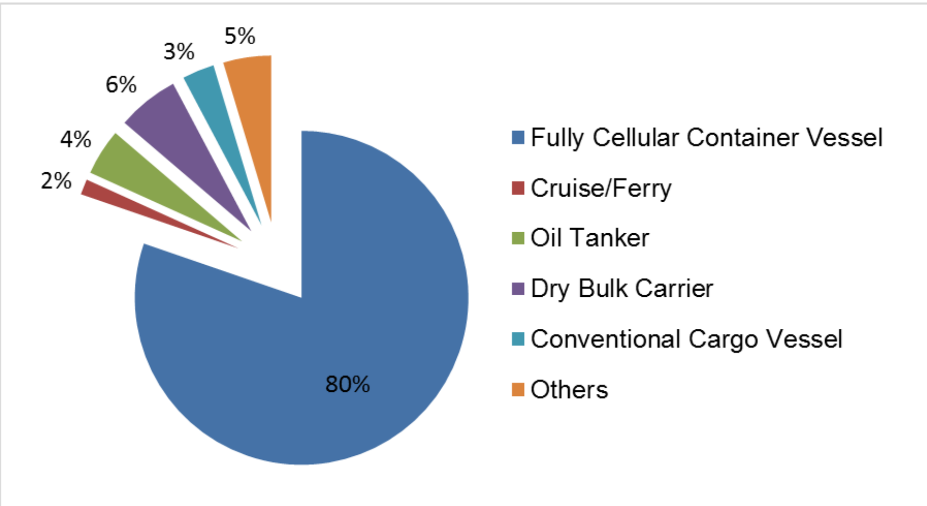

Figure 8 OGV PM_{10} emissions (%) outside Hong Kong waters by vessel type, 2008

Emissions by operation mode

The emissions pattern by operation mode for vessels outside Hong Kong waters was very different from that of vessels operating in Hong Kong waters. Table 4 shows that the cruise mode was the dominant mode in terms of emissions, contributing 89,024 tonne of SO_2, 122,892 tonne of NO_X and 10,411 tonne of PM_{10}. In terms of percentage share, cruise mode was responsible for 71% of SO_2, 75% of NO_X and 71% of PM_{10} emissions. The corresponding shares by slow cruise were 16%, 17% and 18%, respectively. (Figure 9)

Table 4 OGV emissions (tonne) outside Hong Kong waters but within the study area by mode, 2008

Vessel Type	SO_2	NO_X	PM_{10}	$PM_{2.5}$	VOC	CO
Cruise	89,024.3	122,891.7	10,411.1	9,578.2	4,269.0	11,331.5
Fairway Cruise	0.0	0.0	0.0	0.0	0.0	0.0
Slow Cruise	20,391.6	27,323.6	2,594.2	2,386.7	1,056.8	2,443.8
Maneuvering	4,416.3	5,034.4	538.7	495.6	221.3	480.3
Hotelling	11,598.2	8,162.7	1,018.9	937.4	261.4	658.7
Total	125,430.4	163,412.4	14,563.0	13,397.9	5,808.4	14,914.3

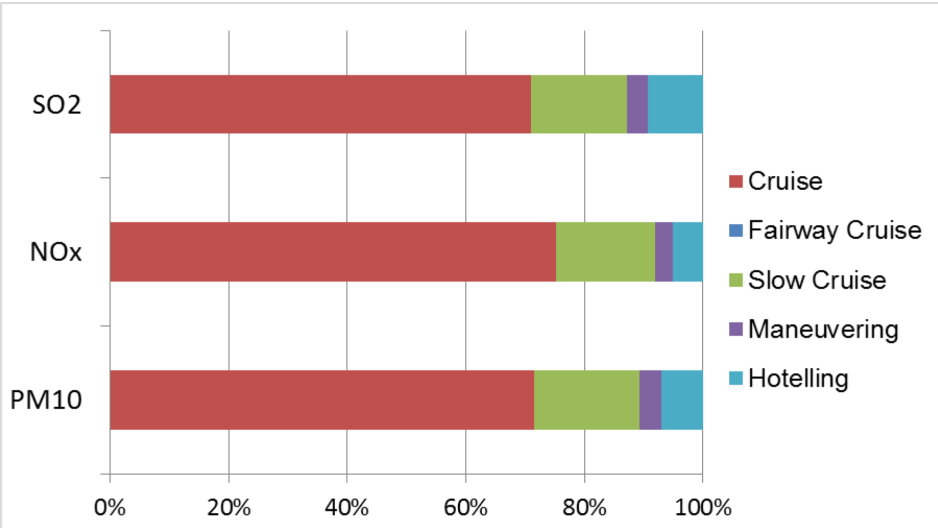

Figure 9 OGV emissions (%) outside Hong Kong waters by mode, 2008

Spatial Distribution of Ship Emissions

The spatial distribution of marine vessel emissions for 2008 was plotted with a 500 meter resolution over the study area, based on the full year vessel track data provided by MD. However, the vessel track data only covers the area about 50 to 60 nm from Hong Kong. In order to complete the emission maps for 100 nm from Hong Kong, vessel tracks (and emission tracks) were extended. As most vessels are operating in cruise mode 50 to 60 nm from Hong Kong, emission values of the grid points along the vessel track data boundary was used for the extension. In the following explanation, the emission maps of SO_2 are used for demonstration purpose, as SO_2 is strongly associated with ship emissions.

Figure 10 below shows the spatial distribution of OGV emissions in the study area. Major emission hot spots are located at Kwai Chung Container Terminals, Yantian and Shekou. The emission corridors in orange also depict the main fairways leading to the port of Hong Kong, Yantian and Shekou. There is also an emission track that goes from the west of Lantau Island all the way up the Pearl River Estuary to Guangzhou.

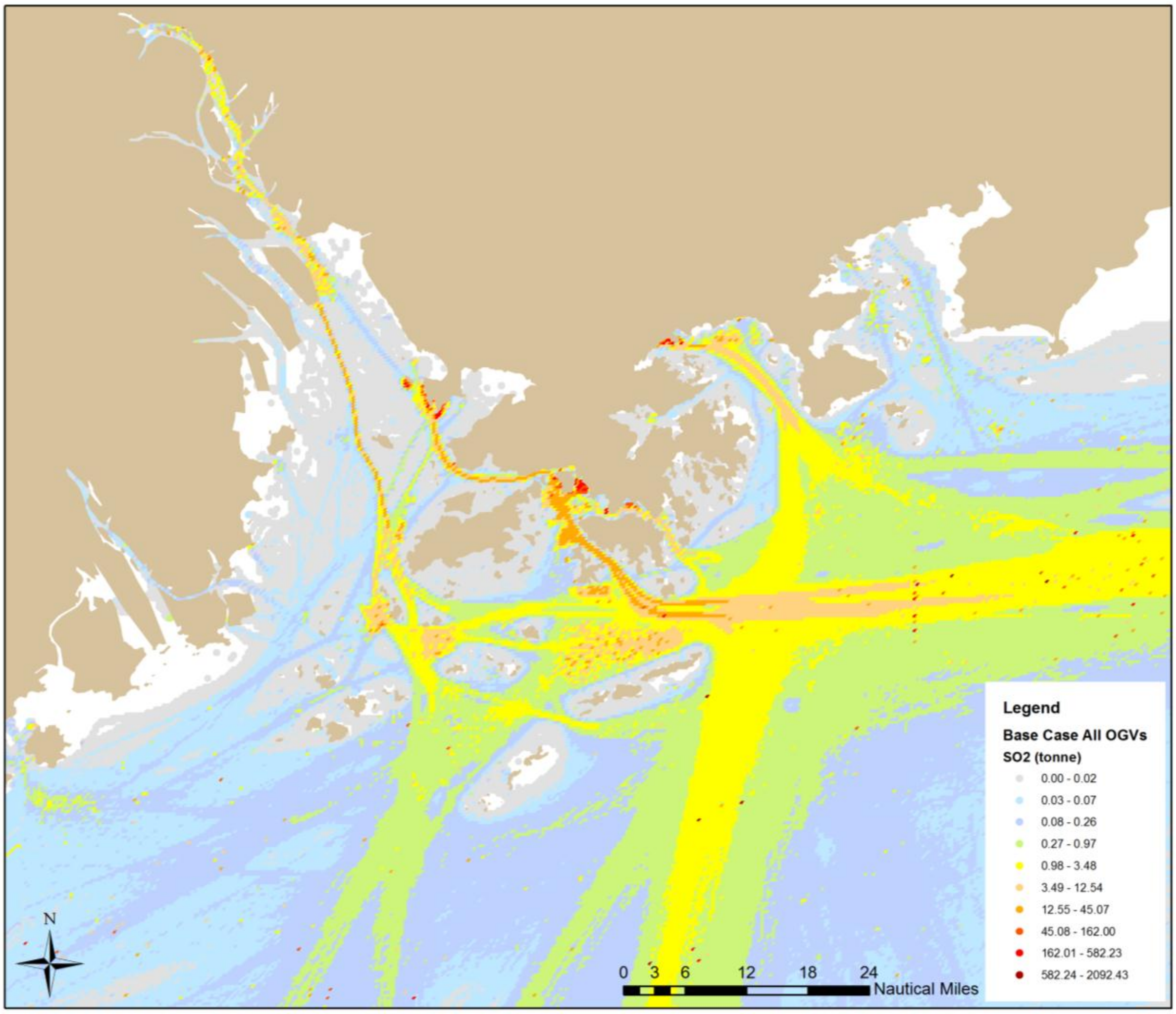

Figure 10 Spatial distribution of OGV SO_2 emissions by 500 meter resolution, 2008

Figures 11 and 12 show a close-up of emissions distribution container vessel and cruise ship inside Hong Kong waters and in adjacent areas. For container vessels, other than the at-berth emission hot spots, there is a major corridor from east to west leading to East Lamma Channel, and another one from south to north approaching Yantian. It is also important to note that vessel movements directly from the Pearl River Estuary to Shekou are limited (as shown by the light blue colour), probably due to the shallow approach to the port. As a result, lots of vessels destined to Shekou will take transit through Hong Kong for the deeper channels, which in turn leads to a higher level of emissions between Ma Wan Fairway and Urmston Road (in orange colour). (Figure 11)

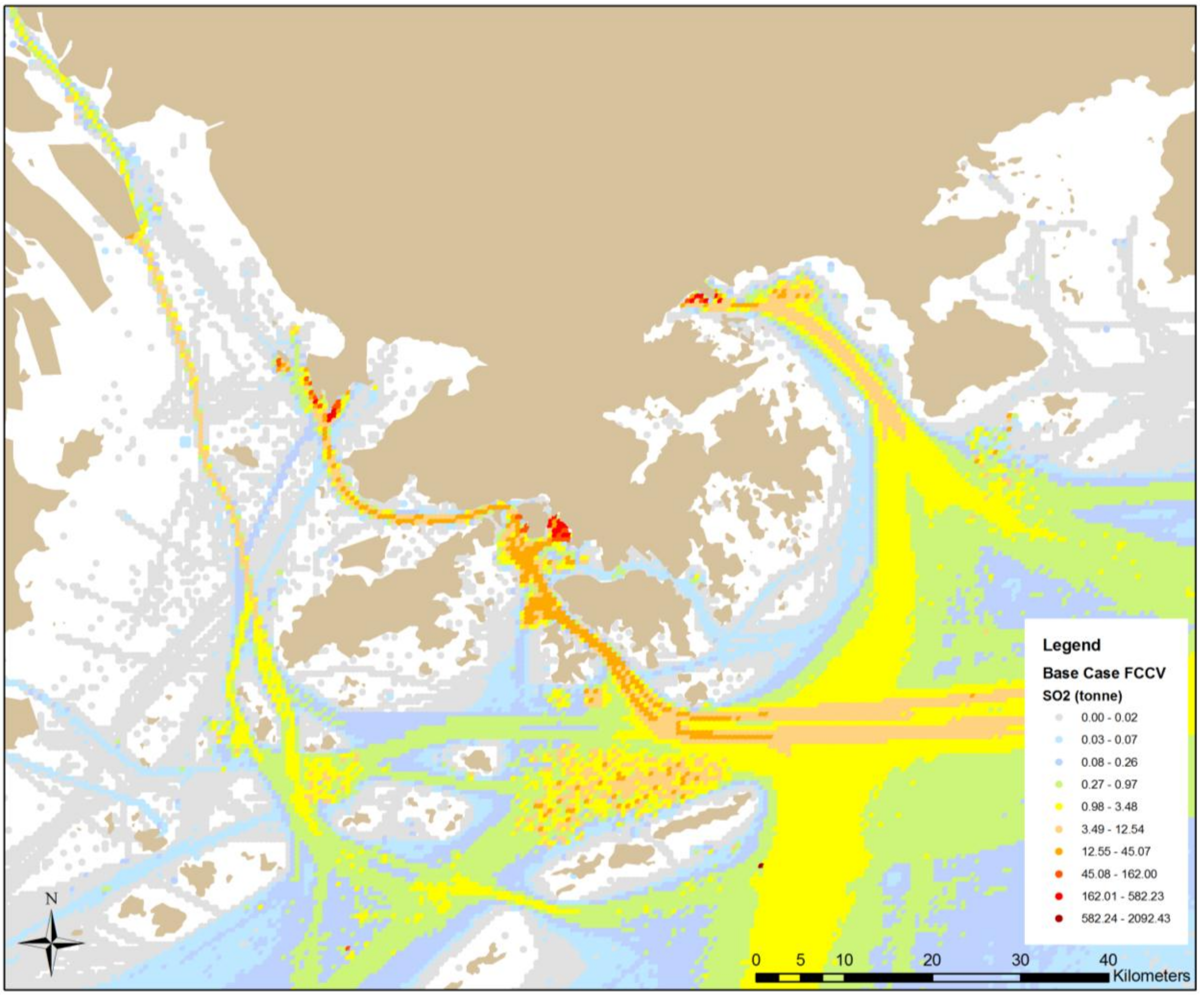

Figure 11 Spatial distribution of container vessel SO_2 emissions by 500 meter resolution, 2008

For cruise ships, the pattern of emissions is directly related to major berthing locations and popular operating routes. The red dots in Figure 12 are Ocean Terminal to the left and the government buoys off Kowloon Bay to the right, both of which are long-term berthing locations for home-based cruise ships. Emission patterns then radiate from Hong Kong to the open sea areas where casino cruises spend most of the time at slow speed or idling between late evening and early morning, before sailing back to port in Hong Kong from the east.

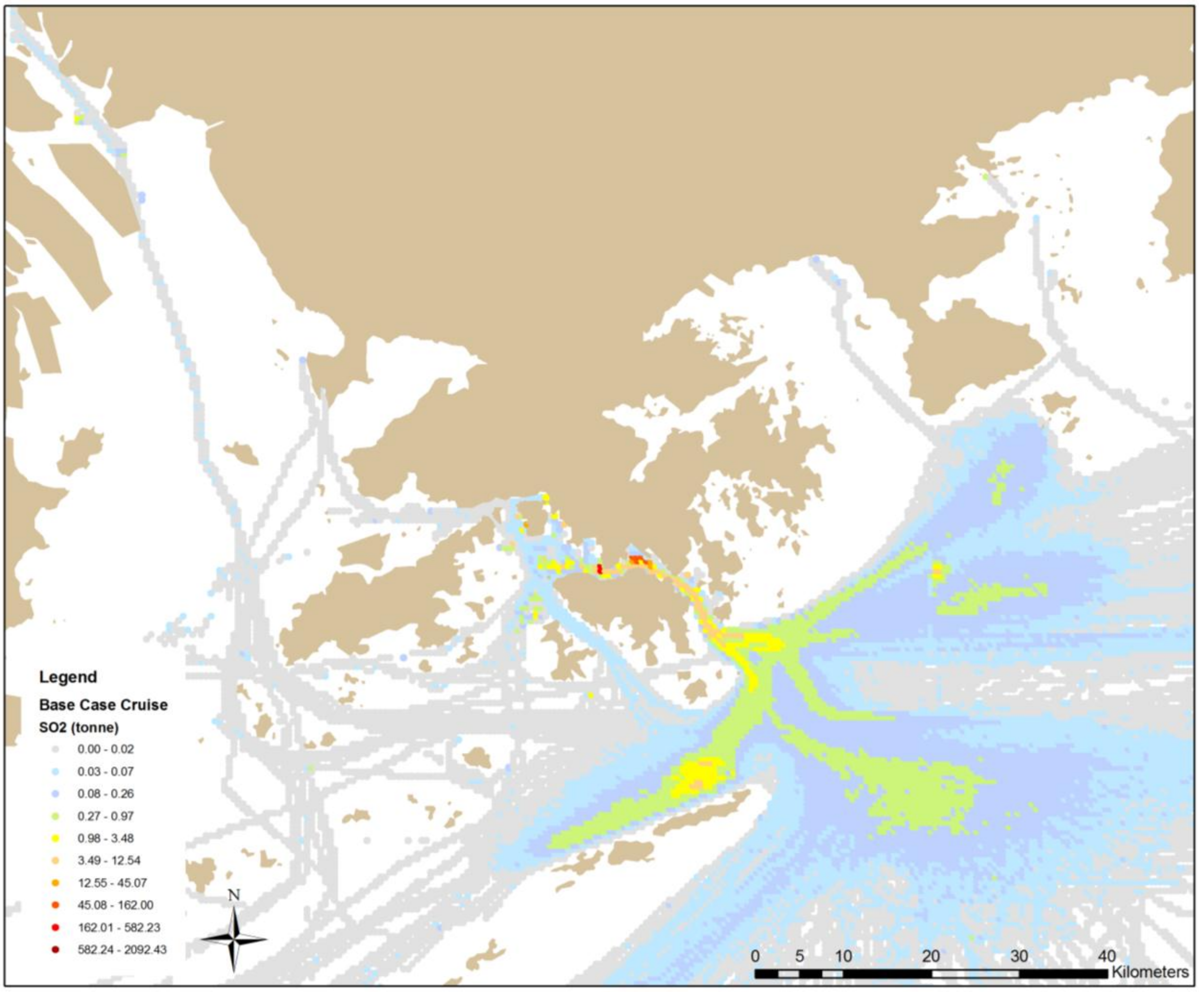

Figure 12 Spatial distribution of cruise ship SO_2 emissions by 500 meter resolution, 2008

4. CONTROL SCENARIOS

In this Study, four different ship emissions control scenarios were considered and their emissions reduction benefits estimated. In the following sections, each scenario will be briefly described and its benefits explained with the help of emission maps with the same colour scale.

Case 1: Switching to 0.5% sulphur fuel at berth inside Hong Kong waters, OGVs only

This control measure follows the Fair Winds Charter (FWC), except that voluntary at-berth fuel switching is made mandatory. The fuel sulphur content requirement at berth is capped at 0.5%. This is slightly different from the FWC as some vessels use distillate fuel with sulphur content as low as 0.1%. Auxiliary engines and boiler of OGVs are expected to switch to low sulphur fuel while alongside.

As the measure is only applicable to OGVs at berth in Hong Kong, emissions reductions are mainly achieved at Kwai Chung Container Terminals, Ocean Terminal, and the anchorage area off Kowloon Bay (from red to dark orange colour). Emission hot spots south and west of Tsing Yi (fuel loading and unloading facilities) also disappeared. (Figures 13 and 14) In addition, ship emissions will drop in the Western Harbour Anchorage, North Lamma Anchorage and South Lamma Anchorage.

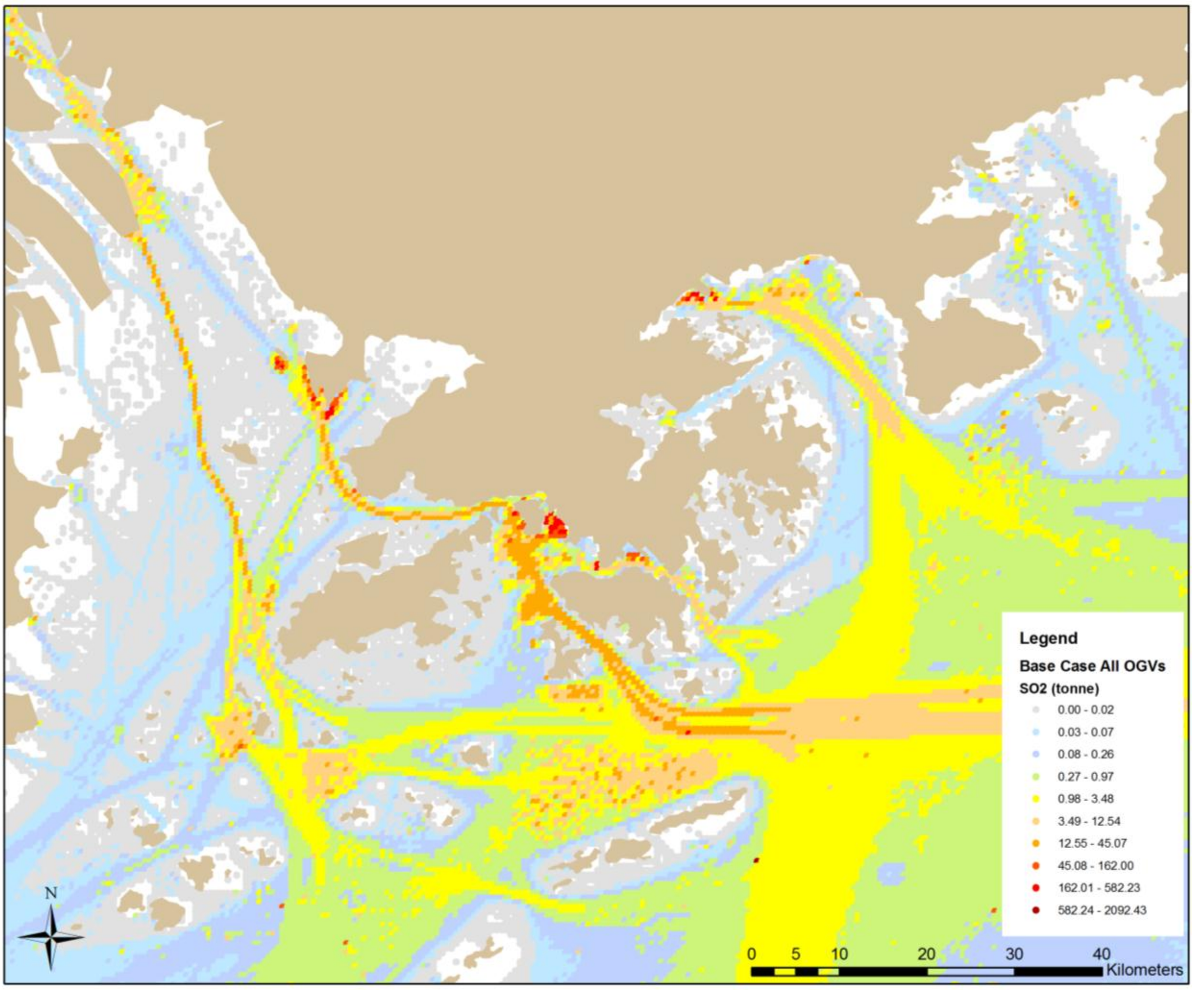

Figure 13 Baseline OGV SO_2 emissions

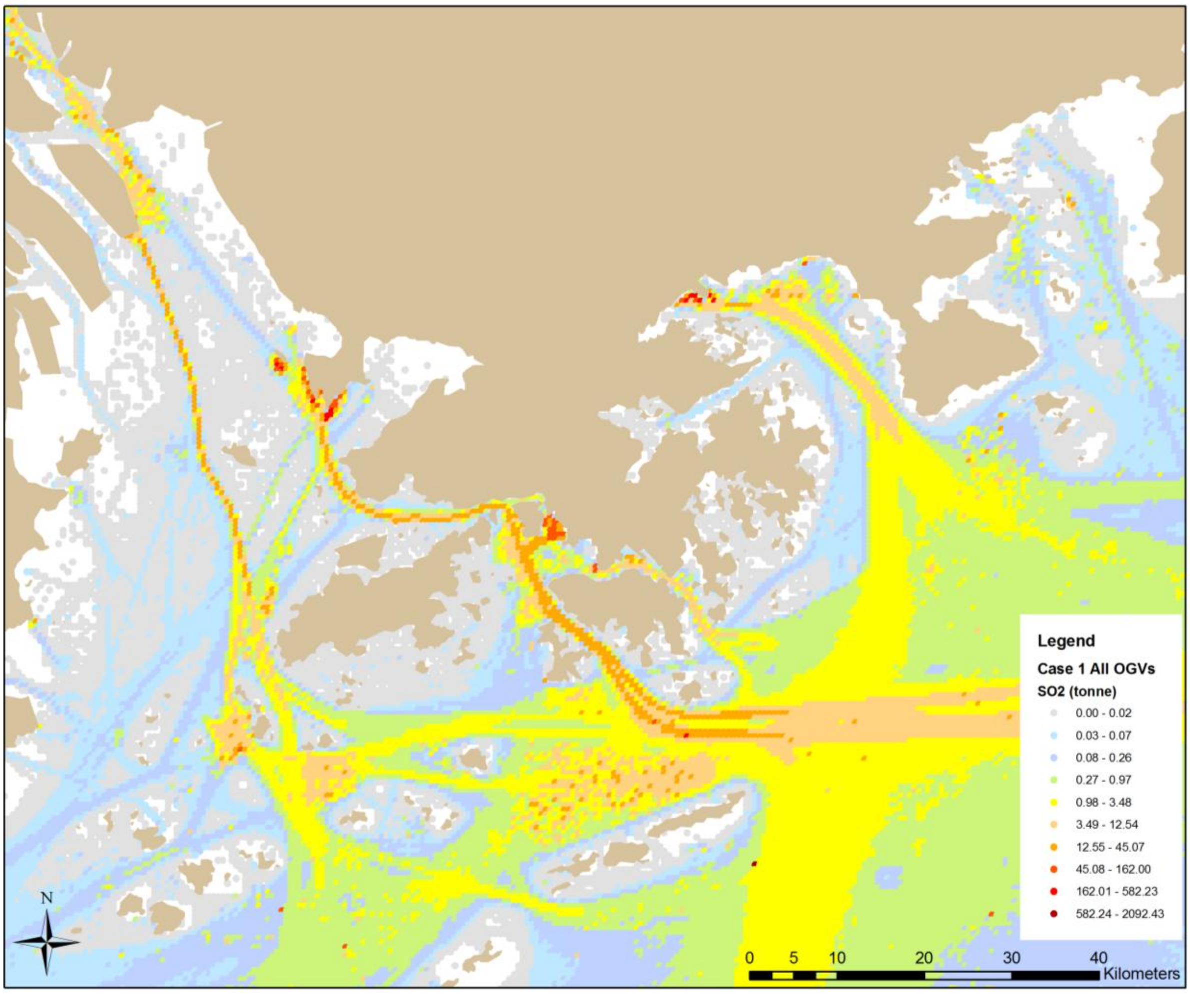

Figure 14 OGV SO_2 emissions under Case 1

Case 2: Switching to 0.1% sulphur fuel inside Hong Kong waters, OGVs only

The second control case requires all OGVs to switch to 0.1% low sulphur fuel inside Hong Kong waters. This represents tighter control over OGV fuel quality as vessels are asked by regulation to burn low sulphur fuel after entering Hong Kong waters. In order to do that, vessels have to start fuel changeover for all their equipment as they approach Hong Kong. Likewise, vessels will only switch back after they exit the boundary of Hong Kong waters.

Comparing Figure 15 with the baseline (Figure 13), it is clear that ship emissions inside Hong Kong waters will be significantly reduced. The gradient of change between Hong Kong waters and its adjacent waters is quite abrupt on the map (without any touch-up work on presentation), but in reality the change will be gradual over space (so is emission level change), as fuel changeover will require a certain period of time determined by differences in fuel temperature, fuel quality and other variations in fuel switching practice.

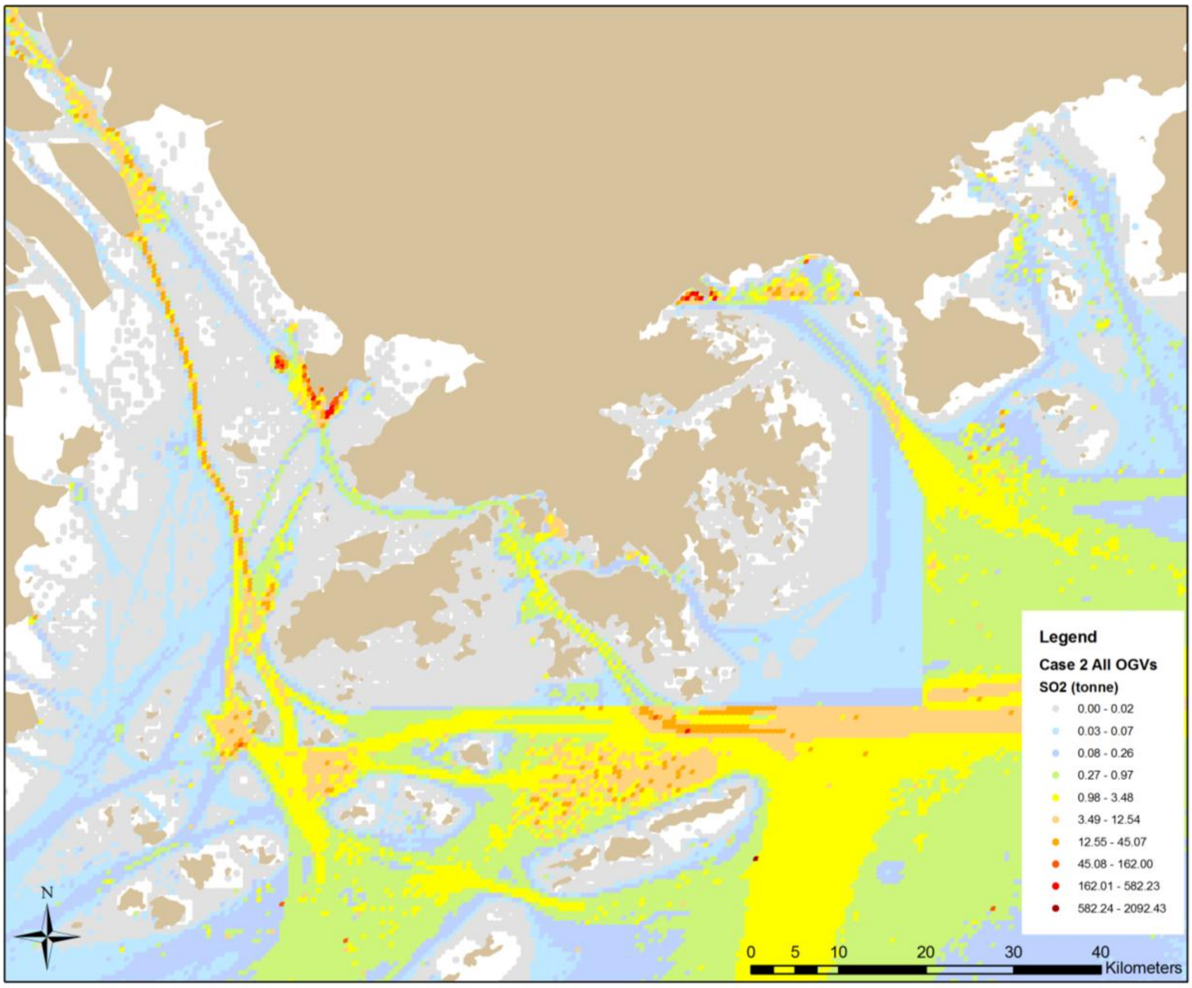

Figure 15 OGV SO_2 emissions under Case 2

Case 3: ECA (all vessels switching to 0.1% sulphur fuel within 100 nm of Hong Kong)

The third case is the establishment of an ECA in PRD waters, assumed to an area up to 100 nm off Hong Kong. All vessels, including OGVs, river vessels (RVs) and local vessels (LVs), will switch to 0.1% low sulphur fuel inside the ECA.

In order to demonstrate the full impact of an ECA on emissions reductions from all vessel types, emissions from river vessels and local vessels that can be tracked by MD's radar system were added back to the baseline emission map. Since smaller vessels without the AIS equipment onboard will not be tracked, emissions as shown on the map are under-estimated. (Figure 16)

Nevertheless, even with a slightly under-estimated baseline, Figure 17 clearly demonstrates that an order-of-magnitude reduction in ship emissions will be achieved under an ECA.

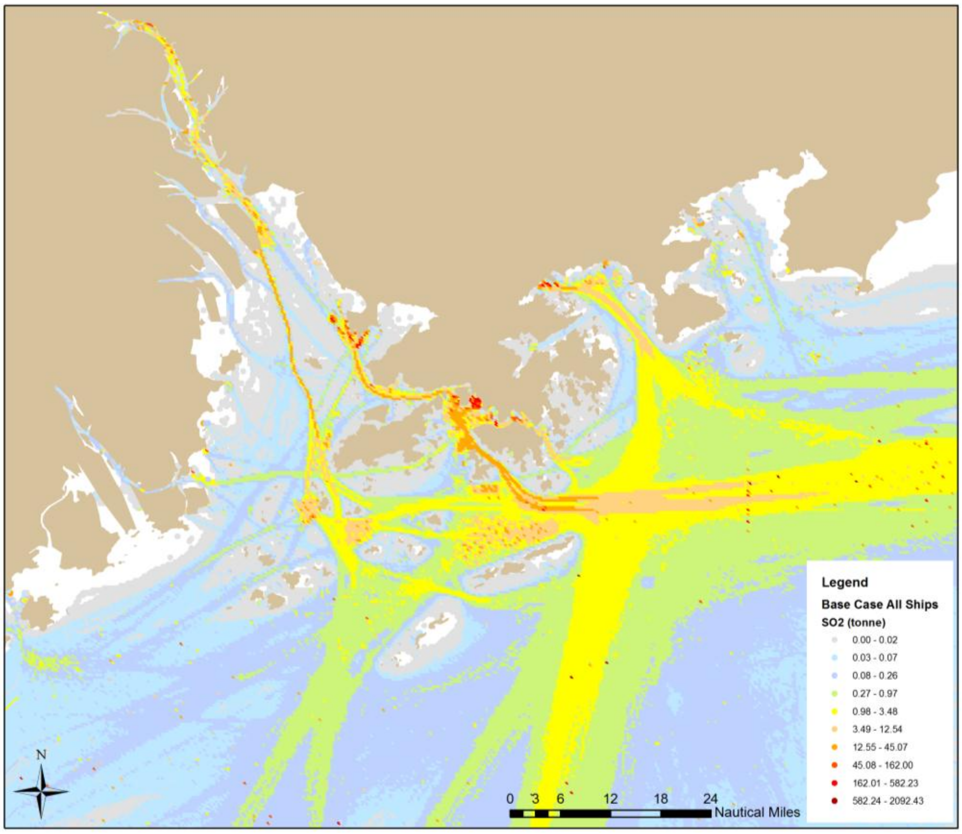

Figure 16 Baseline ship SO_2 emissions including ocean-going, river and local vessels

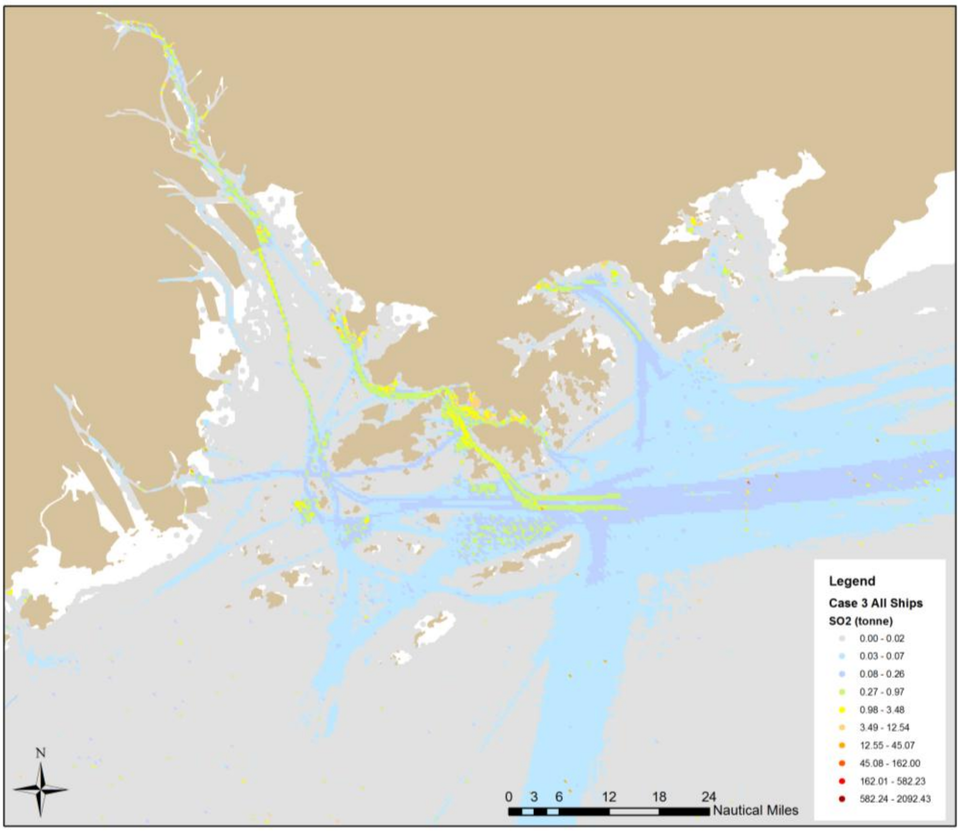

Figure 17 Ship SO_2 emissions under Case 3

Case 4: Vessel speed limit at 12 knots in Hong Kong waters for OGVs

Finally, the fourth control scenario moves from improving fuel quality to improving fuel efficiency. It is commonly agreed that slower vessel speed will significantly reduce fuel consumption and hence reduce emissions. While vessel speed limits are already in force in certain parts of Hong Kong waters, such as Victoria Harbour and East Lamma Channel, it is identified on the emission maps (such as Figure 1) that several emission corridors actually fall outside speed limit zones. For example, there is no vessel speed limit to the northeast towards Mirs Bay and Yantian, as well as between Ma Wan Fairway and Urmston Road. Under this scenario, all OGVs are required to limit their speed to 12 knots.

Figure 18 shows that ship emissions to the east and northeast of Hong Kong has been reduced under the vessel speed reduction scheme. Similarly, ship emissions south of Hong Kong near Po Toi Island and the southeastern water boundary has also be cut.

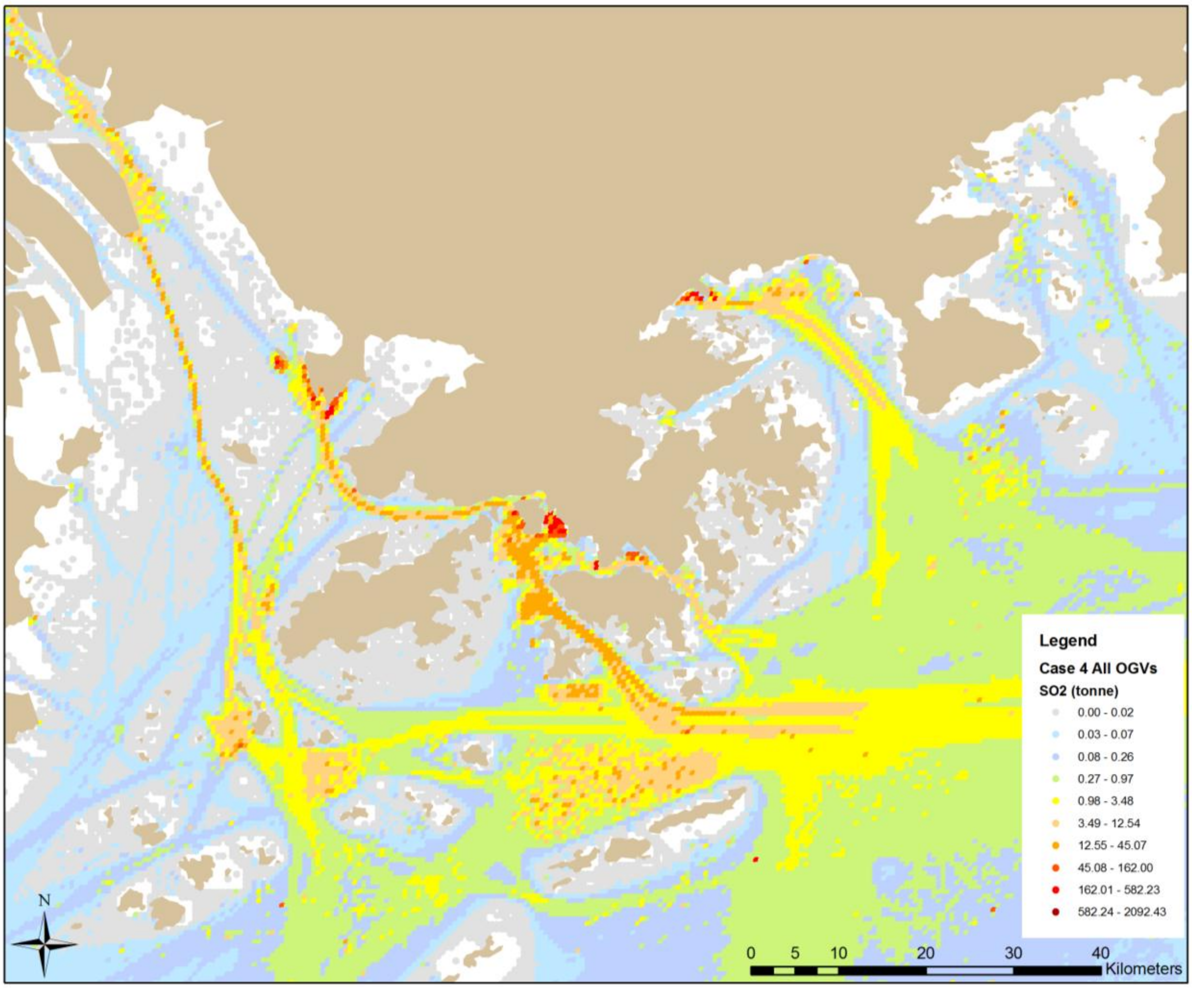

Figure 18 OGV SO_2 emissions under Case 4

Emissions reduction benefits

Table 5 below compares ship emissions reduction benefits achieved through the four control cases within Hong Kong waters and the entire study area.

Table 5 Emissions reduction potential of four control cases for ships in Hong Kong waters and 100 nm from Hong Kong (tonne)

Control Scenarios	SO_2	NO_X	PM_{10}	$PM_{2.5}$	VOC	CO
Hong Kong waters						
Baseline	16,489.3	17,900.7	1,870.3	1,720.7	753.6	1,749.1
Case 1	10,940.4 (66.3%)	17,623.8 (98.5%)	1,393.4 (74.5%)	1,281.9 (74.5%)	753.6 (100%)	1,749.1 (100%)
Case 2	2,880.0 (17.5%)	17,071.6 (95.4%)	502.8 (26.9%)	462.6 (26.9%)	753.6 (100%)	1,749.1 (100%)
Case 3	2,880.0 (17.5%)	17,071.6 (95.4%)	502.8 (26.9%)	462.6 (26.9%)	753.6 (100%)	1,749.1 (100%)
Case 4	14,484.4 (87.8%)	15,139.1 (84.6%)	1,655.8 (88.5%)	1,523.3 (88.5%)	689.8 (91.5%)	1,563.3 (89.4%)
Study area (100 nm)						
Baseline	141,919.7	181,313.1	16,433.2	15,118.6	6,562.0	16,663.4
Case 1	136,370.8 (96.1%)	181,036.2 (99.8%)	15,956.3 (97.1%)	14,679.8 (97.1%)	6,562.0 (100%)	16,663.4 (100%)
Case 2	128,310.4 (90.4%)	180,484.0 (99.5%)	15,065.8 (91.7%)	13,860.5 (91.7%)	6,562.0 (100%)	16,663.4 (100%)
Case 3	7,141.8 (5%)	170,712.3 (94.2%)	2,413.2 (14.7%)	2,220.2 (14.7%)	6,562.0 (100%)	16,663.4 (100%)
Case 4	139,914.8 (98.6%)	178,551.4 (98.5%)	16,218.7 (98.7%)	14,921.2 (98.7%)	6,498.2 (99%)	16,477.6 (98.9%)

(percentage of baseline)

Among the four control cases, the establishment of an ECA (Case 3) is obviously the most attractive one for the entire study area, cutting 95% of SO_2 and about 85% of PM emissions from ships in the PRD waters. In contrast, the other three cases have relatively limited emissions reduction benefits for SO_2, NO_X and PM, and almost no benefit for VOC and CO in a regional context.

However, it must not be overlooked that Cases 1 and 2 will bring significant air pollutant reduction benefits within Hong Kong waters. Table 5 shows that mandatory fuel switching (0.5% sulphur) at berth for OGVs (Case 1) will approximately reduce SO_2 by 33% and PM by 25%. Mandatory fuel switching to 0.1% sulphur in Hong Kong waters for OGVs will bring even greater reduction of SO_2 and PM by over 80% and 70% respectively. On the other hand, setting OGV speed limit to 12 knots in the entire Hong Kong waters will cut SO_2 and PM by 11% to 12%. Significantly, NO_X emissions will also be slashed by 15% in Hong Kong waters, which is unachievable by other control measures that mainly focus on improving marine fuel quality.

5. SHIP EXHAUST EMISSIONS AND AIR QUALITY

The emission maps in the previous chapters show the spatial pattern of ship emissions at source under the base case and the four control cases. To explain the connection between ship emissions and its impact on the population, the next task is to demonstrate the contribution of marine emissions to air quality in Hong Kong and the PRD. To this end, an air dispersion model was used. The model was also used to examine the positive impact of the four control cases on air quality in this region.

The emissions inventory developed in this Study covers six air pollutants. In this Chapter, the impact of ship emissions on ambient SO_2 level in Hong Kong and the PRD will be highlighted for a number of reasons. First, SO_2 is a criteria air pollutant and has significant impacts on human health. Understanding the contribution of marine source to SO_2 and its subsequent effects on air quality is essential for the formulation of appropriate policies in cutting ambient SO_2 level and in protecting public health. Second, SO_2 is a primary pollutant, unlike NO_X and PM_{10} whose formation may involves complex chemical reactions, and its contribution to ambient air quality is easy to model. On the contrary, changes in ambient NO_X and PM_{10} levels related solely to different ship emissions levels is difficult to establish.

Domain setting and configuration

Comprehensive Air Quality Model with Extensions (CAMx) is the air dispersion model selected for this task. It is an Eulerian photochemical dispersion model that allows for integrated "one-atmosphere" assessments of gaseous and particulate air pollution (including ozone, SO_2, $PM_{2.5}$, PM_{10}) over many scales, ranging from a sub-urban to a continental geographic setting.

In this exercise, domain setting was the same as the Pollutants in the Atmosphere and their Transport over Hong Kong model (PATH). PATH system is developed by EPD using a Lambert Conformal Projection system with which α = 15^0 N, β = 40^0 N, center latitude = 28.5^0 N, and center longitude = 114^0 E. The PATH modeling system is related to other independent models. (Figure 19) CAMx, which is designed to unify all the technical features required for a "state-of-the-science" air quality model into a single system, is the core of PATH modeling system. CAMx requires inputs from meteorology fields, pollutant emission rates, initial/boundary conditions and photolysis rate, which were provided respectively by the Fifth-Generation NCAR/Penn State Mesoscale Model (PSU/NCAR or MM5), emission process model (SMOKE), initial and boundary conditions generator, and photolysis rate processor (AHOMAP/TUV).

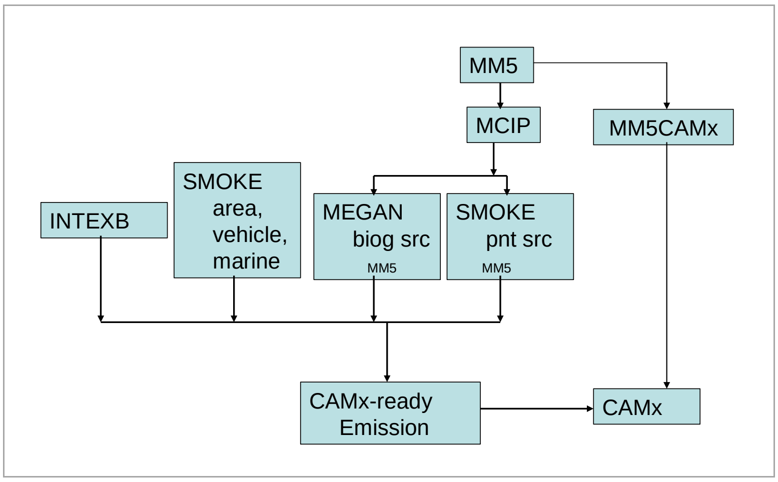

Figure 19 The PATH modeling system

In the PATH system, four nested horizontal domains with grid resolution of 27 km (D1), 9 km (D2), 3 km (D3) and 1 km (D4) are used. In this Study, however, only D2 and D3 were used for simulation based on the geographic coverage of the analysis. The corresponding horizontal grid points (column × row) for D2 and D3 in MM5 and CAMx are 222×162 (D2), 171×129 (D3), and 98×74 (D2), 152×110 (D3), respectively. For the geographic coverage, D2 covers most of south-eastern China including Guangdong Province, Hong Kong and Macau. D3 covers most of Guangdong Province, Hong Kong and Macau. (see Figure 20) In this Study, D2 results were used to provide boundary condition for D3.

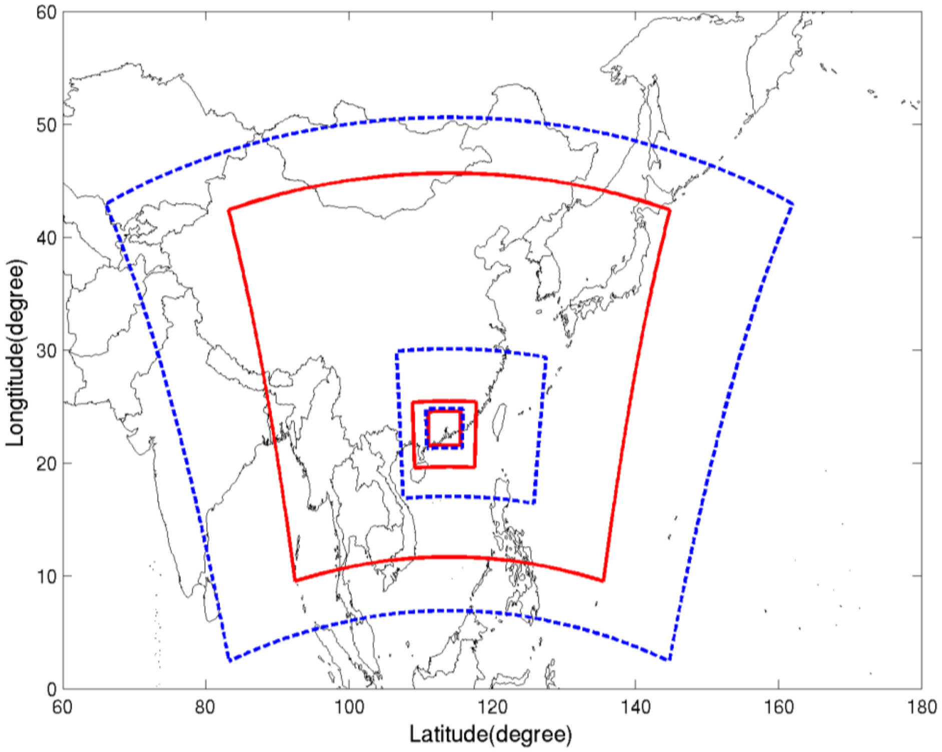

Figure 20 Modeling domains of MM5 (dotted line) and CAMx (solid line)

For vertical structure, MM5 uses the terrain following sigma coordinate with 38 layers in total, which extend from the ground to 50mb pressure level (approximately 20 km above ground). Subsequently, 26 layers were picked from MM5 for CAMx, with all the 20 layers lower than 2 km vertical height being selected.

CAMx inputs

Initial and boundary conditions

Initial and boundary conditions are driving force for CAMx model. Initial condition (ICON) and boundary condition (BCON) for D3 was extracted from D2 AVRG output which represents the hourly average concentration output, whereas BCON for D2 were set as zero, making sure that marine vessels emissions is the only source of SO_2 in the model.

In this Study, the meteorology fields of 2007 were used, as the MM5 data for 2008 (the base year) were not available. Although the hourly wind speed and direction in 2007 and 2008 will be different, the overall patterns are the same. (Figure 21) In general, Hong Kong has the highest wind speed in winter (from October to February) and the lowest wind speed in summer (from April to September) in both 2007 and 2008. The wind speed difference between 2007 and 2008 ranges from about 0.05m/s to 1m/s. These small differences imply that using 2007 meteorology fields is a reasonable surrogate.

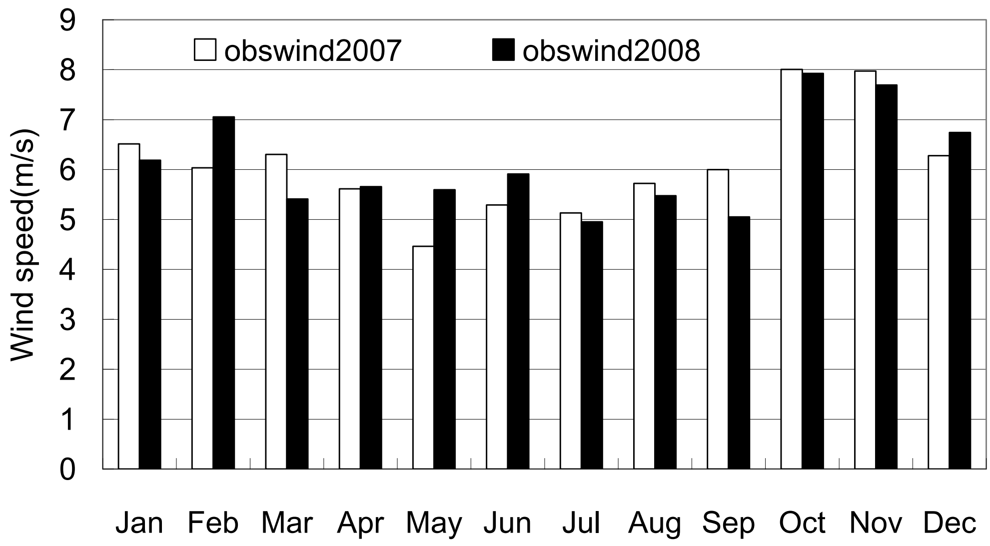

Figure 21 Monthly average wind speed at Waglan Island in 2007 (white bar) and 2008 (black bar)

Meteorological inputs

The meteorological inputs for CAMx, including temperature, wind, pressure, water vapor concentration, vertical diffusion rate, cloud cover, precipitation, and land use information, were generated from MM5. MM5 is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation. In the past decades, it has been widely used for numerical weather prediction (NWP), natural hazard simulation (typhoon), wind energy estimation, and air pollution analysis.

Emissions inputs

The emission file, one of the major inputs for CAMx model, contains emission rate for different pollutants. Each pollutant can be classified as primary or secondary. Usually, primary pollutants are directly emitted from a process, such as SO_2 released from factories or marine vessels. Secondary pollutants are not emitted directly. Rather, they are formed in the air when primary pollutants react or interact. An important example of a secondary pollutant is ground level ozone, which is one of the many secondary pollutants that make up photochemical smog. Some pollutants can be classified as both primary and secondary.

In order to highlight the importance of marine vessels emissions to ambient SO_2 level, all the other emission categories (such as emissions from power plants, motor vehicles and so on) were removed, only keeping emissions coming from marine vessels. Since SO_2 is a primary pollutant, the final ambient SO_2 level output from the model due to marine emissions will be straightforward. However, it must be stressed that for secondary pollutants such as ozone (O_3) and PM, model outputs will be under-estimated. Therefore, it is not recommended to use CAMx model outputs in interpreting the contribution of marine vessels emissions to ambient secondary pollutant levels.

Marine vessels were classified under OGV, RV and LV. Emissions from different vessel classes will have different spatial distributions and plume rise heights. For RV and LV, it was assumed that 80% of the emissions will be released into the second model layer (17m to 35m), while only 20% will be released in the third layer (35m to 55m). For OGV, which is much larger than RV and LV, it was assumed that 80% of the pollutants will be released into the third layer, and 20% into the second layer.

Model results

A basic simulation and four sensitive simulations were carried out by CAMx model to find out the contribution of marine vessels emissions to the ambient SO_2 level in Hong Kong and the PRD, as well as the most effective control policy to reduce ambient SO_2 level. The basic run (the control) made use of the emissions estimates derived from this Study (see Chapter 3), while the four sensitive simulations considered the resultant emissions estimates under different control strategies (see Chapter 4).

Baseline – general observations

Figure 22 provides a map of the PRD region by the 9 prefectures of Dongguan, Foshan, Guangzhou, Huizhou, Jiangmen, Shenzhen, Zhaoqing, Zhongshan and Zhuhai, plus the two Special Administrative Regions of Hong Kong and Macau. On the map, the monthly average SO_2 concentration in micrograms per cubic meter (ug/m^3) for each of the 11 locations in 2008 contributed solely by ship emissions are plotted to show the baseline. It is observed that amongst the 11 locations, (i) Hong Kong's ambient SO_2 level is the most affected by ship emissions, ranging from 5 ug/m^3 in winter to around 13 to 15 ug/m^3 in spring and summer; (ii) ship emissions also contribute to Shenzhen's ambient SO_2 levels with similar seasonal variations, but in a smaller scale than Hong Kong that ranges from 1 to 10 ug/m^3; (iii) Macau also feels the impact of ship emissions produced in this region, despite being a small port. Due to its location in the west PRD and seasonal wind directions, Macau is affected mainly during winter months. Zhuhai, Zhongshan and Jiangmen all have similar seasonal pattern in terms of the contribution of marine source to ambient SO_2 concentrations; and (iv) further inland, the contribution of ship emissions to ambient SO_2 becomes minimal.

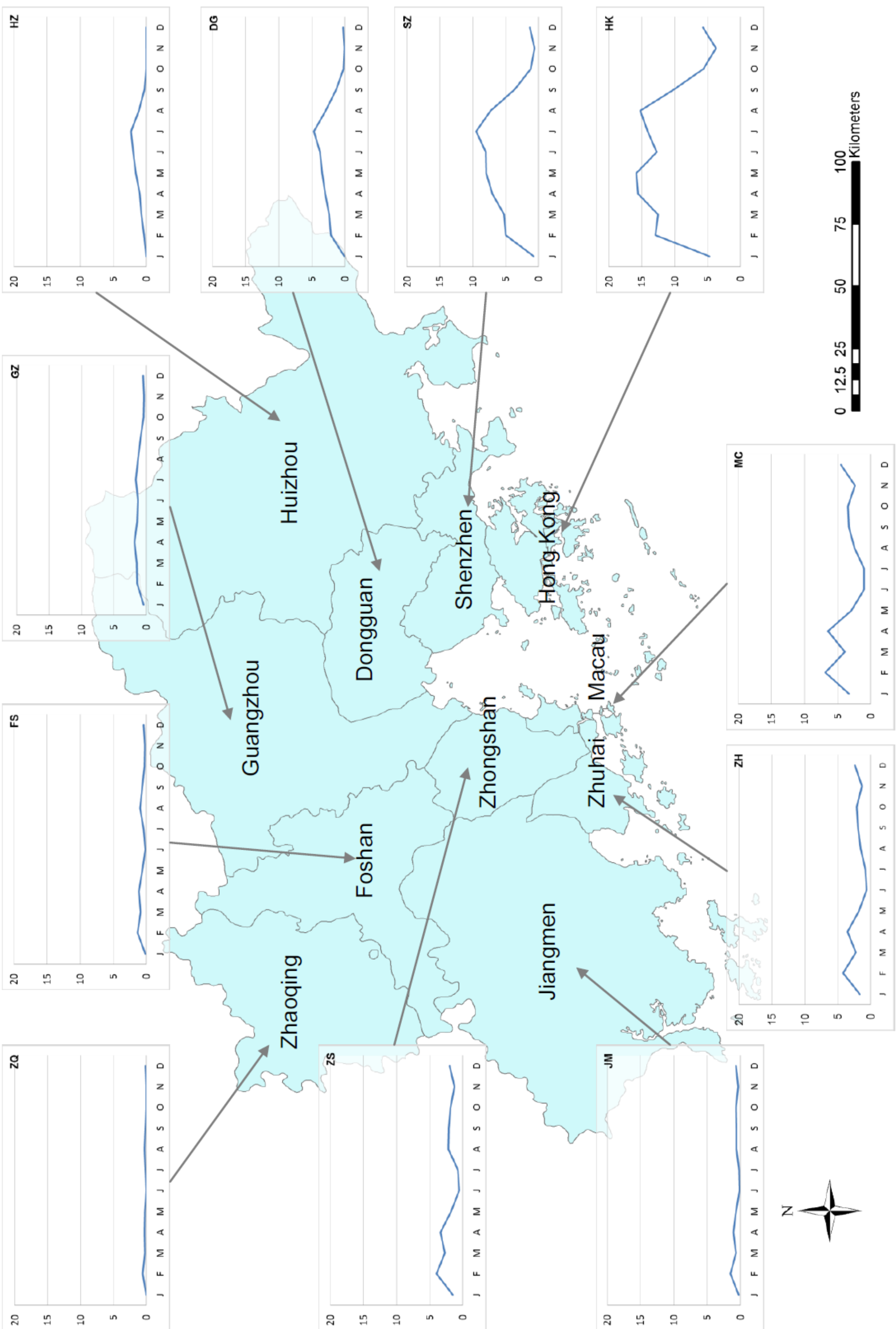

Figure 22 Monthly average concentration of SO_2 (ug/m^3) in the PRD region due to ship emissions, 2008

Baseline – Hong Kong

Figure 23 plots the observed (black bar) and simulated (white bar) average monthly concentrations of SO_2 in Hong Kong in 2008. The observed concentrations were derived from readings recorded at Hong Kong's air quality monitoring stations. According to the figure, monthly average SO_2 concentration level at the monitoring stations ranged between about 13 to 28 $\mu g/m^3$, while the simulated SO_2 concentration ranged from about 4 to 16 $\mu g/m^3$.

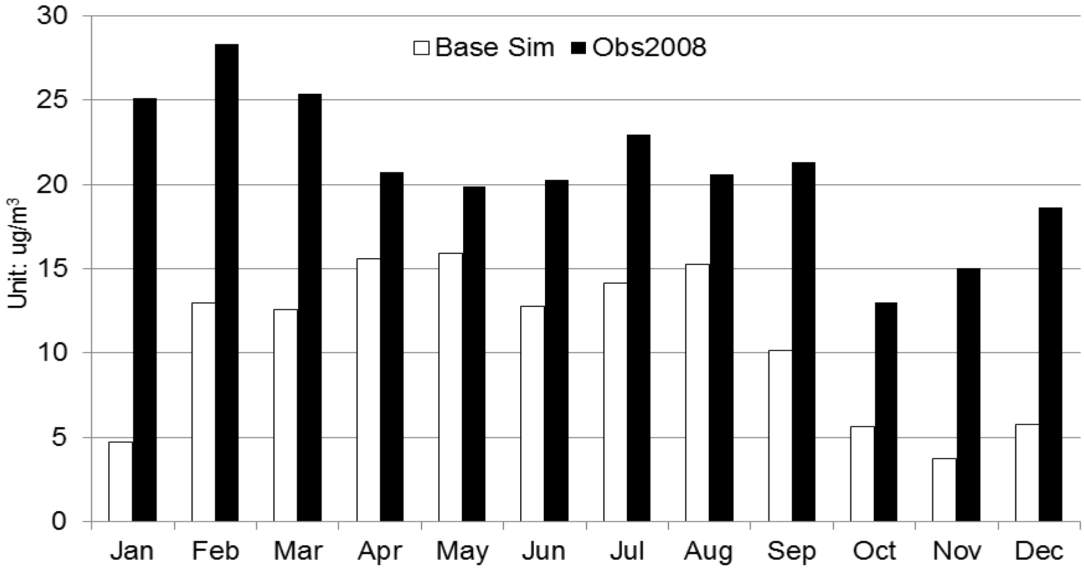

Figure 23 Monthly average concentration of SO_2 in Hong Kong, observed (black) and simulated (white, ship emissions only), 2008.

Monthly variations of the observed SO_2 concentration are evident, with peak concentrations found in the winter month of February and the summer months of July and September. For the simulated SO_2 concentration, peak concentrations are found in April, May, July and August, which do not match exactly with the observed data. The differences between the observed and simulated concentrations range from about 4 to 20 $\mu g/m^3$, with larger difference during winter, and smaller gap in summer. In other words, ship emissions have a greater impact on ambient SO_2 level in Hong Kong during summer, up to about 80%, whereas the contribution of marine sources to SO_2 level is only about 20% in winter. It can be explained by the south and southwesterly wind in summer months against the north and northeasterly wind in winter that carries the pollutants to the west PRD (like Macau) and to the sea.

Control cases – general observations

The respective impact of the four control cases on reducing the contribution of ship emissions to ambient SO_2 concentration in the study area was estimated through the four sensitive simulations. Figure 24 summarizes the results of the four control cases and highlights their air quality improvement potential in January, April, July and October 2008, showing seasonal variations. As expected, the establishment of an ECA (Case 3) will bring most reduction in SO_2 concentrations across the board, because an ECA will cut ship SO_2 emissions in the PRD region by 95% (Table 5). The second most effective control measures among the four to reduce ambient SO_2 level is the mandatory OGV switch to 0.1% sulphur fuel within Hong Kong waters.

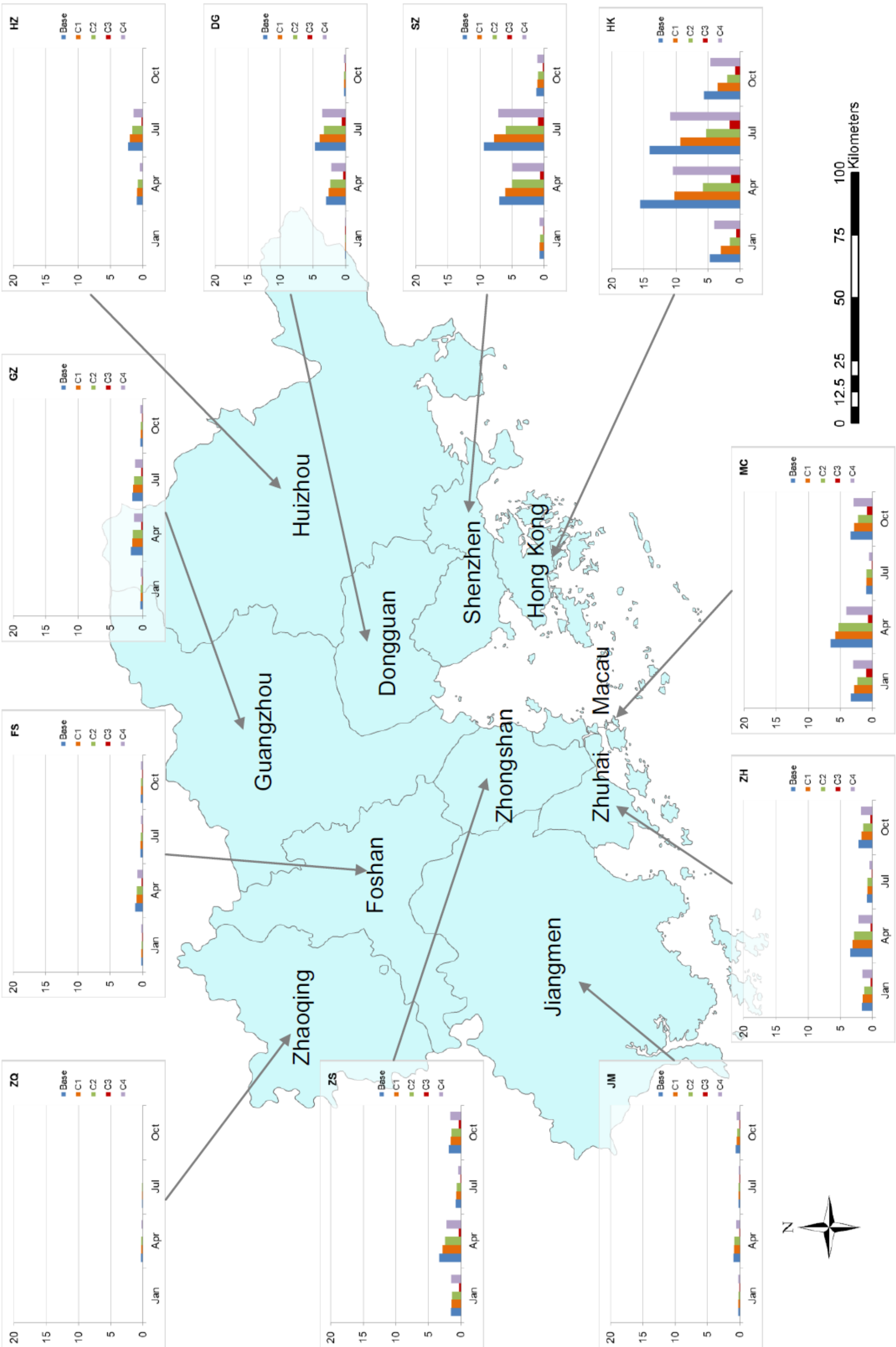

Figure 24 Comparison of seasonal concentration of SO_2 (ug/m^3) in the PRD region under different control scenarios, 2008

Figure 24 also shows that Hong Kong will benefit most from each of the four control cases in terms of the absolute drop in ambient SO_2 concentration due to ship emissions. Improvements are more significant during spring and summer. Shenzhen and Dongguan, both situated immediately north of Hong Kong, will also benefit greatly from the control measures in spring time and summer time. On the other hand, Macau, Zhuhai and Zhongshan, which is in the west PRD, will have most reductions during winter and spring. Understandably, control measures on ship emissions will bring very little improvement in ambient SO_2 concentration to locations further away from the Pearl River Estuary and the busy port cluster of Hong Kong, Yantian and Shekou. Examples include Zhaoqing to the north west, Jiangmen to the west, and Huizhou to the east.

Control cases – Hong Kong

Figure 25 below focuses on Hong Kong and compares the simulated monthly average SO_2 concentration levels under different control scenarios. It is apparent that in terms of emissions reduction potential, Case 3 will bring the most improvement in ambient SO_2 level to Hong Kong, followed by Case 2, Case 1 and Case 4. During spring and summer (from March to August), average SO_2 concentration will be reduced by 4 to 5 ug/m^3 under Case 1 (at-berth fuel switching for OGVs), 7 to 10 ug/m^3 under Case 2 (fuel switching in Hong Kong waters for OGVs), 11 to 14 ug/m^3 under Case 3 (ECA within 100 nm of Hong Kong), and 3 to 5 ug/m^3 under Case 4 (speed reduction to 12 knot for OGVs in Hong Kong waters). The absolute reduction of SO_2 concentration will be much lower during winter months, due to the lower baseline.

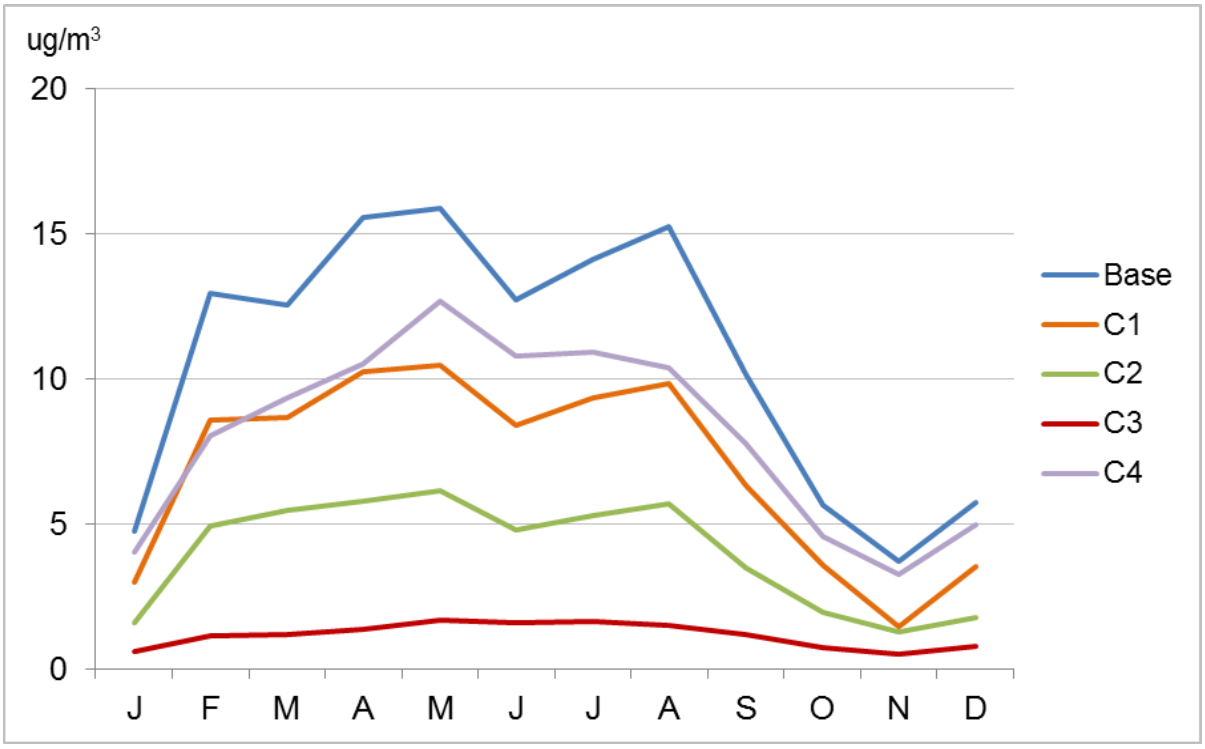

Figure 25 Comparison of monthly average concentration of SO_2 in Hong Kong under different control scenarios, 2008.

6. CONCLUSION

Based on findings of this Study, it is estimated that in 2008, 141,920 tonne of SO_2, 181,313 tonne of NO_X and 16,433 tonne of PM_{10} were emitted from OGVs in the entire study area. Of these, 16,489 tonne of SO_2, 17,901 tonne of NO_X and 1,870 tonne of PM_{10} were produced in Hong Kong waters. This is extremely alarming as a health threat to the population and requires immediate attention from government agencies. As the number of OGV arrivals is expected to grow, same for the number of people living in this region, ship emissions will escalate if control and regulations are not quickly put in place.

Amongst the vessel types, container vessels are the main emitter, accounting for roughly 80% to 83% of OGV emissions in the study area. Contributions from cruise ships, oil tankers and conventional cargo vessels are each responsible for 4% to 6% of emissions.

The study findings also show that in areas closer to the coast, at-berth emissions and emissions during slow cruise are dominant. This is backed up by the emission maps, which confirm that the container terminals in Hong Kong, Yantian and Shekou are the key ship emissions hot spots in this region. Further away from coast, emissions from cruise mode becomes dominant as most vessels are sailing at higher speed in open sea.

Four control measures were introduced and considered in the Study, and their respective emissions reduction benefits were plotted on emission maps against baseline emissions. While an ECA that can cut SO_2 and PM emissions by 95% and 85 % respectively is the stand-out solution, establishing an ECA in this region requires thorough scientific research, lengthy discussion and deliberation among various government agencies and industry representatives, as well as the all-important support from the Central Government and the international community at the IMO. In short, it will at least take years to set up an ECA in the PRD.

Alternatively, the great majority of the practical benefits of an ECA can be achieved in the short to medium term by creating a low emissions zone (LEZ) that replicates the same emissions controls and regulations for all vessels in Chinese territorial waters in and around the PRD. This LEZ would also serve as a useful pilot for collecting the necessary information and driving key supports for the establishment of an ECA in the long run.

Apart from the ECA, the other three strategies explored in this Study will also bring notable reduction of ship emissions in Hong Kong waters and the adjacent port areas of Yantian and Shekou. They should be prioritized and pursued for the short- and medium-term. After all, the ports of Hong Kong and Shenzhen (Yantian plus Shekou) are receiving a significant portion of OGVs and cargoes in the PRD, and their locations also mean that a huge population base will be adversely affected by toxic ship emissions on a daily basis. This paper presents the scientific evidence of ship emissions and its impact on air quality in the PRD. This is the basis on which government agencies in the PRD must act together in tackling growing ship emissions and protecting public health without further delay.

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