ESTIMATING THE DISPERSION OF SHIPPING EMISSIONS FROM FREMANTLE PORT, WESTERN AUSTRALIA

by

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I declare that this thesis is my own account of my research, unless otherwise stated. It contains as its main content work which has not previously been submitted for a degree at any tertiary institution.

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ABSTRACT

Fremantle Port is Western Australia's largest general cargo port and has experienced more than 10,660 ship visits since 2011. The burning of marine fuels, however, significantly affects air quality in nearby areas. As there are no air pollution monitoring stations in Fremantle, the impact of emissions from Fremantle port is largely unknown. There is one air pollution modelling study for Fremantle Port (Rolfe, 2016), which was carried out with AERMOD, a steady-state Gaussian plume dispersion model, known to have limitations in its applicability for use in coastal areas. As part of the Rolfe (2016) study, an hourly emissions inventory was created using publicly available data, but the sensitivity of AERMOD to key assumptions and parameters used in developing the inventory were not tested. Therefore, the aims of this thesis were to 1) repeat the study by Rolfe (2016) in order to carry out a sensitivity study on key assumptions and parameters used in the calculation of the emission inventory, and 2) compare the steady-state Gaussian plume model, AERMOD, versus a Lagrangian puff model, CALPUFF, which is more suitable for use in coastal regions. Results showed that, amoung the several parameters tested, AERMOD was highly sensitive to driving meteorology and ship stack height. Meteorology over water and shorter stack heights resulted in the highest concentrations. Regulatory exceedances of the 1 hour average for SO_2 occurred for several simulations. CALPUFF concentrations were higher than AERMOD's for the maximum 1 hour averages and annual averages, but lower

than AERMOD's for the maximum 24 hour averages. A caveat of this study is that the simulated concentrations could not be evaluated due to a lack of air pollution monitoring stations near Fremantle port. As AERMOD was highly sensitive to ships stack height, future air pollution modelling studies require actual ship stack height data in order to more accurately simulate concentrations.

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Dr Simon Petersen created the original emission inventory from Fremantle Port ship movement data, which was a huge undertaking. Dr Petersen also modified the emission inventory used for the sensitivity tests in this thesis.

Methodology used in this thesis was adopted from Dr Robin Smit, who also kindly provided advice on cruise ship fuel efficiency.

Fremantle Ports provided ship movement data for Fremantle Port, detailed maps and permission to use the data.

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ABBREVIATIONS

AERMOD American Meteorological Society and United States Environmental Protection Agency Atmospheric Dispersion Model

CALPUFF California Puff Model

GUI Graphical user interface

HSD High speed diesel

IMO International Maritime Organization

MDO Marine diesel oil

MSD Medium speed diesel

NEPM National Environmental Protection (Ambient Air Quality) Measure

NO_x Nitrogen oxides

NO_2 Nitrogen dioxide

PM Particulate matter

$PM_{2.5}$ Particulate matter (diameter up to 2.5 micrometers)

PM_{10} Particulate matter (diameter up to 10 micrometers)

SECA Sulfur emission control area

SO_2 Sulfur dioxide

SSD Slow speed diesel

STEL Short-term exposure limit

RO Residual Oil

WRF Weather Research and Forecasting Model

CHAPTER 1
INTRODUCTION

1.1 The global shipping industry and Fremantle port

International shipping is an important part of global trade and economies worldwide (Nast, 2013), allowing for the transport of people, consumer goods, materials and food (Alderton and Winchester, 2002; Nast, 2013). Currently, shipping is responsible for 90% of international trade (Alderton and Winchester, 2002; Nast, 2013). In Australia, sea transport is relied upon for 99% of all exports (Australian Government, Department of Infrastructure and Regional Development, 2017). Within the 2013/2014 financial year, 5,499 ships made a total of 28,714 calls to Australian ports (Bureau of Infrastructure, Transport and Regional Economics, 2015). Fremantle port is Western Australia's largest general cargo port and has been operating since 1897 (Fremantle Ports, 2016). Fremantle port is located along the south-west Western Australian coast, approximately 11 km south of Perth as shown in Fig. 1.1.

Emissions from the burning of marine fuels significantly affect air quality, particularly in coastal areas (Corbett et al., 2007; Jayaram et al., 2011). Ship emissions contribute to global background levels of nitrogen and sulfur (Corbett and Fischbeck, 1997). According to Corbett et al. (2007), ship emissions account for 15% of nitrogen oxides (NO_x) and between 5 and 8% of sulfur oxides. Ships

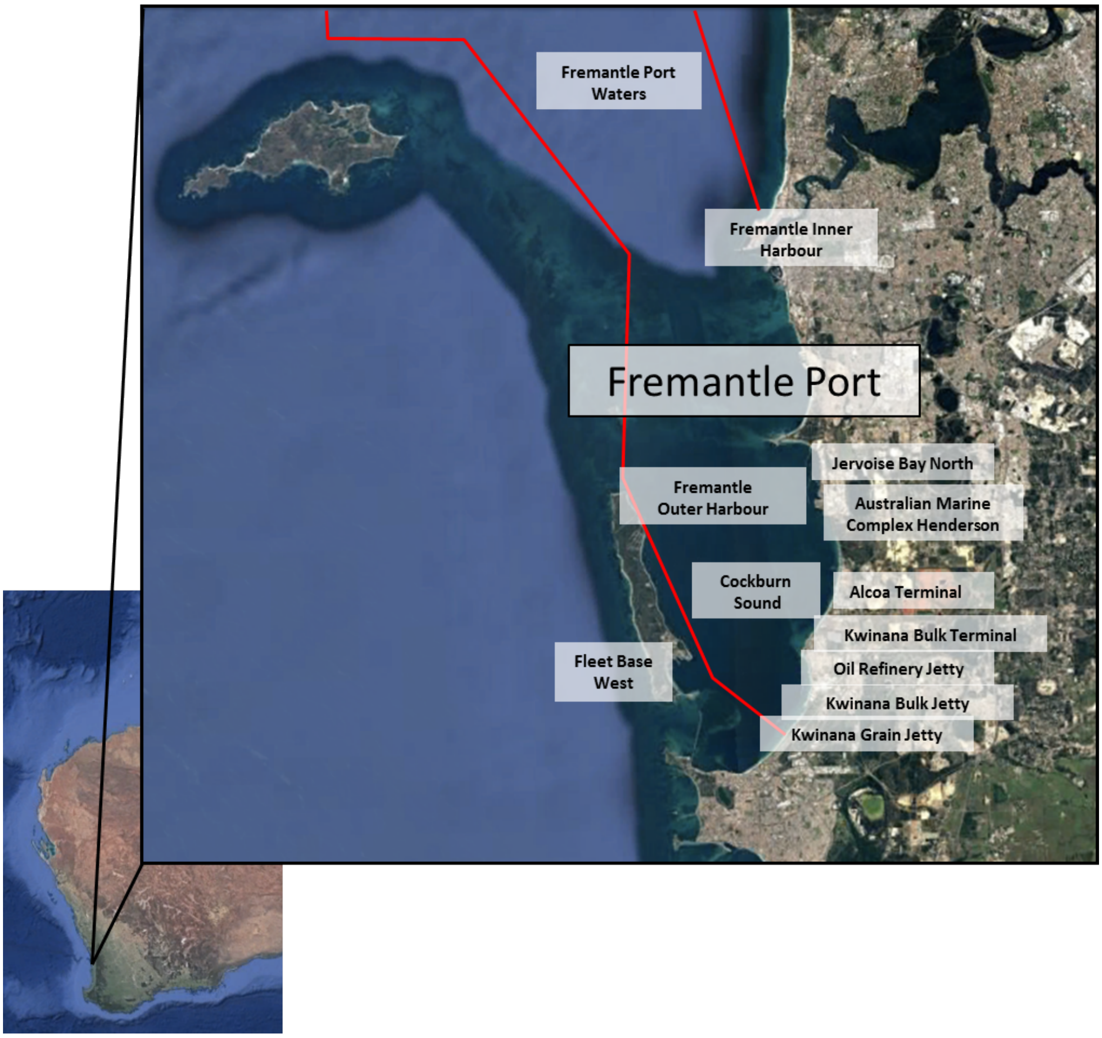

Figure 1.1: Satellite image of Western Australia showing the location of Fremantle port. The red line delineates Fremantle port waters.

are also estimated to emit between 0.9 and 1.7 million tons of particulate matter (PM) annually (Corbett et al., 2007; Moldanová et al., 2009). Locally, NO_x, sulfur dioxide (SO_2) and PM from ship emissions can negatively impact air quality around harbours (Moldanová et al., 2009). This can be detrimental to human health. For example, there is a correlation between long-term exposure to SO_2 and respiratory problems in humans (Abdul-Wahab et al., 2012; Thepanondh et al., 2015), cardiovascular-related hospital emissions and deaths (Sunyer et al., 2003). Corbett et al. (2007) suggest that PM from ship emissions accounts for approximately 60,000 cardiopulmonary and lung cancer deaths globally each year.

While the shipping industry benefits the Australian economy, there has been little inquiry into ship emissions in Australian waters (Goldsworthy and Goldsworthy, 2015). Consequently, the effect of such emissions on air quality in nearby areas is uncertain (Goldsworthy and Goldsworthy, 2015). In 2016, Fremantle ports noted 5 locally recorded smoke/soot related complaints resulting from ships berthed at Fremantle port (Fremantle Ports, 2016). Considering nearly 70% of ship emissions occur within 400 km of land, there is a need to quantify these emissions in the interest of human health (Moldanová et al., 2009). This can be achieved using air pollution dispersion models, which are powerful tools for evaluating the dispersion of pollutants such as SO_2, NO_x, and PM (Chang and Hanna, 2004; Abdul-Wahab et al., 2010, 2011; Langner and Klemm, 2011; Thunis et al., 2012; Gulia et al., 2015).

1.2 Air pollution dispersion models

Air pollution dispersion models take as input various meteorological parameters, such as wind speed, wind direction and temperature, as well as emission rates of air pollutants to simulate the dispersion of these pollutants (Scire et al., 2000; Pacific Environmental Services, 2004). Air pollution dispersion models are widely used for the regulation of industrial emissions and in lieu of air pollution monitoring stations (Zou et al., 2010; Langner and Klemm, 2011; De Visscher, 2013). These models are also used to:

1. Predict the possible impacts of existing (Abdul-Wahab et al., 2011; De Visscher, 2013) and new industrial or mining operations (Fisher et al., 2003; Abdul-Wahab et al., 2010; Chusai et al., 2012);

2. Determine the source of an unknown air pollutant i.e. a retrospective study (Fisher et al., 2003);

3. Determine the emission reductions required to remain compliant with regulations (De Visscher, 2013);

4. Determine the effectiveness of pollution control measures (McNair et al., 1996);

5. Carry out prospective studies (Zou et al., 2010), such as epidemiological studies (Chen et al., 2012); and

6. Provide effective and fast response in emergency situations, for example accidental leaks of a toxic gas (Cui et al., 2011; De Visscher, 2013).

1.3 Dispersion modelling for the port of Fremantle

Rolfe (2016) has carried out the only dispersion modelling study for estimating the dispersion of shipping emissions in Fremantle port. As there are no air pollution monitoring stations in Fremantle, one aim of the study was to determine where such stations would be best situated in order to efficiently measure air pollution levels in Fremantle. To carry out this study, Rolfe (2016) used the American Meteorological Society and United States Environmental Protection Agency Atmospheric Dispersion Model (AERMOD; Pacific Environmental Services, 2004), a commonly used regulatory air pollution dispersion model in Australia (Environmental Protection Authority Victoria, 2014). Fig. 1.1 shows Fremantle port including port waters (red line), inner and outer harbours and berth locations. Rolfe (2016) focussed on shipping emissions for the period 1st July 2011 to 30th June 2012 as this was the financial year the Department of Environmental Regulation chose for the Perth air emission inventory, currently being developed (Rolfe, 2016). The study simulated the dispersion of SO_2, nitrogen dioxide (NO_2), $PM_{2.5}$ and PM_{10} as these are the most important air pollutants to human health as discussed in the literature on the impacts of shipping emissions in coastal communities (Bailey and Solomon, 2004; Corbett et al., 2007; Winebrake et al., 2009; Tzannatos, 2010).

To estimate ship emissions, Rolfe (2016) needed ship specifications. The most commonly used source is the Lloyd's register (IHS, 2017), however access to the register requires paid subscription. Hence Rolfe (2016) carried out their study using only publicly available ship movement data within Fremantle port, ship and engine specification and fuel information. Rolfe (2016) used this information to create a shipping emission inventory, based on methods from Smit et al. (2016) for the 2011/2012 financial year, which was used as input to the AERMOD air pollution dispersion model.

Rolfe (2016) found that in general, the maximum 24 hour and annual average air pollution levels simulated by AERMOD from ships servicing Fremantle port were relatively low, with no major adverse effects on ambient air quality. However, there was one exceedance of regulatory standards for the maximum 1 hour average for SO_2 as defined by the National Environmental Protection Measure (NEPM). The maximum 1 hour average NEPM standard for SO_2 is 524 μg m^{-3} (Australian Government, Department of the Environment and Energy, 2013), and Rolfe (2016) simulated concentrations at 734.5 μg m^{-3}. This exceedance occurred when many large ships were berthed in Fremantle port simultaneously. Rolfe (2016) simulated the dispersion of SO_2, NO_2 and PM for Fremantle port using only 1 air pollution dispersion model, AERMOD, and sensitivity tests to assess assumptions made in the calculation of the emission inventory were not carried out. Considering results from the study by Rolfe (2016) cannot be verified with air pollution observations and it is the only study of its kind carried out at Fremantle port, it is important to further investigate the concentration of pollutants simulated by AERMOD, in particular the exceedances of NEPM standard concentrations for regulatory purposes and in the interest of human health.

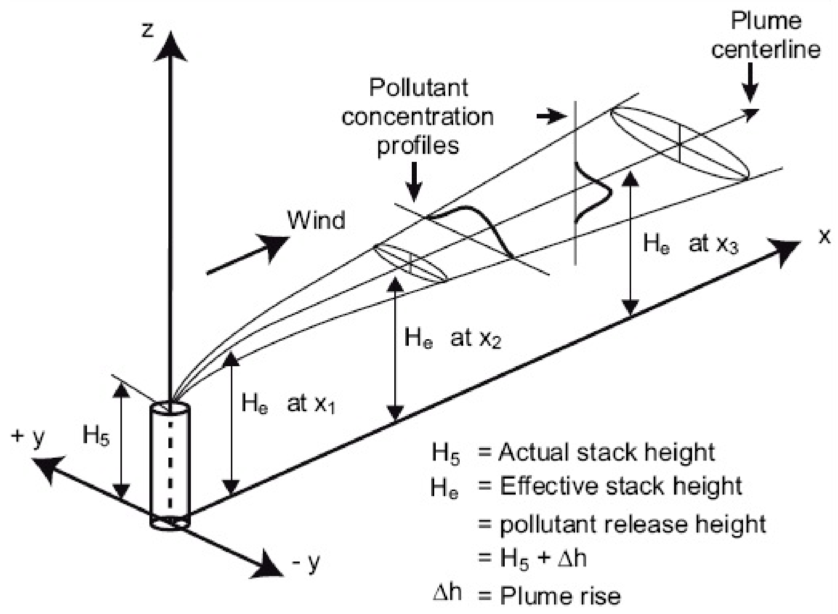

Figure 1.2: Schematic of Gaussian plume dispersion (Schulze and Turner, 1996).

1.3.1 AERMOD overview and limitations

AERMOD is a Gaussian plume model. Gaussian refers to the normal distribution, commonly known as the bell-shaped curve (D'Abreton, 2011) as illustrated in Fig. 1.2. In reality, pollutant concentrations will not always follow a Gaussian distribution due to simplified model physics, and random turbulence in the atmosphere affecting the dispersion of air pollutants (Arya, 1999). However, observations have shown that the average concentration over time will resemble a Gaussian distribution in the horizontal and vertical dimensions (Venkatram, 2008). As a result, a Gaussian model is only a representation of the dispersion of air pollutants modelled and cannot predict the dispersion of pollutant concentrations beyond an average. The AERMOD User Guide recommends AERMOD for use in the near-field, within 50 km from the source (Pacific Environmental Services, 2004).

AERMOD is a steady-state model, meaning it is driven with meteorology at a single point rather than taking into account variations in atmospheric conditions across the geographical area of interest to be modelled, referred to as the receptor domain (Arya, 1999). Therefore, AERMOD assumes atmospheric conditions to be homogeneous across the receptor domain and as such, spatial and temporal atmospheric information can be lost (Fox, 1984; Cimorelli et al., 2004). This is an inherent limitation of AERMOD, affecting its ability to handle complex terrain, or meteorological phenomena associated with coastlines (Walter et al., 1995; Brode, 2008). For example, the recirculation of air pollution via the sea breeze is a common phenomenon in coastal cities (Yimin and Lyons, 2003; Levy et al., 2009; Russo et al., 2016). As AERMOD assumes a homogeneous meteorological domain, if the wind velocities change within the period of travel of a plume across the domain, then the fate of emission concentrations is not likely to be accurately simulated. More specifically, as AERMOD has no memory of the previous hour's dispersion, if the pollutants travel to the boundary of the receptor domain and after this time the wind direction changes, pollution recirculation will not be simulated.

Another limitation of the steady-state atmosphere assumed by AERMOD is its inability to distinguish varying meteorology over land versus over water. Atmospheric turbulence is higher over land than over water due to larger diurnal fluctuations in near-surface temperature over the land than over a body of water, such as the ocean (Arya, 1999). Increased turbulence results in greater mixing and lower air pollutant concentrations over land compared to over water, where less turbulence results in reduced dilution of air pollutants and consequently higher concentrations (Hanna et al., 1985). AERMOD can be driven with either meteorology over land or meteorology over water, but not both simultaneously. As part of the study by Rolfe (2016), AERMOD was operated with two separate sets of meteorological data, one taken over land and one taken over water, in order to quantify the differences arising from driving meteorology. As Fremantle is situated in a coastal position, neither of these meteorological conditions alone is representative of the meteorology of Fremantle in reality. Therefore, the inherent limitation of the steady-state assumption limit AERMOD's applicability in simulating dispersion for coastal regions (Walter et al., 1995).

To overcome limitations of a steady-state model such as AERMOD, Lagrangian puff models have been developed, which take as input, meteorology across the receptor domain, rather than at a single point. One such model is the California Puff Model (CALPUFF; Scire et al., 2000).

1.3.2 CALPUFF

CALPUFF is one of the most commonly used regulatory non-steady state, Lagrangian puff models in Australia. Non-steady-state conditions include inhomogeneous spatial meteorological conditions, calm winds, stagnation and terrain or coastal influences including fumigation (Scire et al., 2000). Lagrangian refers to tracking the motion of an emitted puff of pollutant (Lyons and Scott, 1990). A Lagrangian observer will follow a puff as it is transported through the atmosphere and dispersion parameters, such as atmospheric conditions and pollutant concentrations, are evaluated at the location of the puff (Lyons and Scott, 1990)

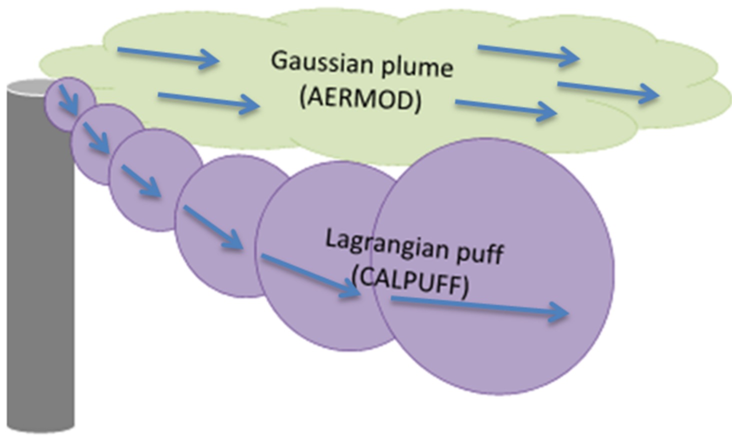

Figure 1.3: A schematic representation demonstrating the homogeneous atmosphere assumed by a Gaussian plume model versus the heterogeneous atmosphere of a Lagrangian puff model. Adapted from Lagzi et al. (2011).

as illustrated in Fig. 1.3. Therefore, CALPUFF requires meteorological information at every point on the receptor domain, making simulations of air pollutant dispersion more likely to be accurate than simulations from a steady-state model such as AERMOD. As a result, CALPUFF can simulate the dispersion of pollutants near a coastline when sea-breeze recirculation occurs, whereas AERMOD is likely to be less accurate (Fisher et al., 2003). As CALPUFF is not limited by a steady-state field, less spatial and temporal information is lost due to the steady-state assumptions of a model such as AERMOD. Therefore, CALPUFF can be applied on spatial scales of tens of metres to hundreds of kilometres and is applicable to situations that include complex terrain, such as coastal regions (Scire et al., 2000).

Hall et al. (2000) argue that the differences between different model outputs may be of equal (if not greater) importance than absolute accuracy of individual models for regulatory purposes and hence inter-model comparisons are important. Several studies have analysed CALPUFF's ability to estimate emission dispersion around coastal locations and areas under the influence of a water body (Elbir, 2003; Indumati et al., 2009; Abdul-Wahab et al., 2010; MacIntosh et al., 2010; Abdul-Wahab et al., 2011; Cui et al., 2011) with varying results. Fewer studies have focussed on AERMOD's ability in similar situations. While research has been conducted that compares pollutant dispersion simulations of AERMOD versus CALPUFF around coastal locations (Fisher et al., 2003; Tartakovsky et al., 2013; Obaid et al., 2014; Rood, 2014; Thepanondh et al., 2015; Tartakovsky et al., 2016), some studies recommended AERMOD over CALPUFF as the most accurate model (Tartakovsky et al., 2013; Thepanondh et al., 2015; Tartakovsky et al., 2016), and others recommended CALPUFF over AERMOD (Fisher et al., 2003; Obaid et al., 2014; Rood, 2014). These studies were also conducted overseas, in meteorological and terrain conditions that vary markedly from Western Australia. As a result, there is no clear guidance from the literature as to which model should be used for coastal situations. Boylan and Russell (2006) argue that the evaluation of air pollution dispersion models should be carried out on a case-by-case basis. It is therefore important to compare AERMOD and CALPUFF in their estimation of the dispersion of pollutants in Fremantle port.

1.3.3 Emission inventory of Rolfe (2016)

Irrespective of which air pollution dispersion model is used, an accurate emission inventory is critical in order to accurately simulate the dispersion of air pollutants. Models require emission inventories for each species of interest with a high level of accuracy (Taghavi et al., 2005). Data quality is critical for model analysis as the quality of the input data directly affects the quality of the model output.

Rolfe (2016) compiled a ship emission inventory for Fremantle port for the period 1st July 2011 to 30th June 2012 in order to specify emission sources and emission rates as required by AERMOD (Rolfe, 2016). The emission rates are required in the form of hourly pollutant emissions from each pollutant source (SO_2, NO_2 and PM) specified (Pacific Environmental Services, 2004). In order to create the hourly emissions file, an inventory of fuel consumption for the period of interest is required and this was compiled using publicly available ship movement data, provided by the Fremantle port Authority (Rolfe, 2016). The ship movement data consisted of ship transit between berth and anchor locations (transect segments) as well as length of time at each berth and anchor location (Rolfe, 2016) which are illustrated in Fig. 1.1.

Using information from the publicly available ship movement data, Rolfe (2016) adopted a method by Smit et al. (2016) to estimate fuel consumption for each ship listed in the ship movement data. The methodology from Smit et al. (2016) was used as it draws on fuel consumption information that is publicly available (Georgakaki et al., 2005; Hulskotte and Denier van der Gon, 2010) and also draws on information from a study focussed on the port of Brisbane (Goldsworthy and Goldsworthy, 2013). Rolfe (2016) argues that Australian based shipping studies were more relevant as opposed to studies conducted internationally, which may focus on ship types that vary from Australian vessels, where waters are subject to different emission standards to Australia and fuel standards are also different to those in Australia.

From the fuel consumption inventory, Rolfe (2016) calculated the emission inventory using emission factors from Goldsworthy and Goldsworthy (2013). Endresen et al. (2005) conducted a global review of sulfur content in marine fuels and showed that emission factors proposed by Goldsworthy and Goldsworthy (2013) were in the middle range of global fuel sulfur content, which varies internationally and affects levels of pollutants in ship emissions (Aliabadi et al., 2016). The emission factors from Goldsworthy and Goldsworthy (2013) were broken into categories for engine type (main and auxiliary), fuel type (residual oil and marine diesel oil) and engine load (small speed diesel, medium speed diesel and fast speed diesel) and Rolfe (2016) applied these to the 25 ship movement transects within port waters and the 41 berth and anchor locations at Fremantle port as illustrated in Fig. 1.1 (Rolfe, 2016).

Rolfe (2016) did not carry out a sensitivity analysis of the parameter values (Georgakaki et al., 2005; Hulskotte and Denier van der Gon, 2010; Goldsworthy and Goldsworthy, 2013) or methods (Smit et al., 2016) used to create the emission inventory used as input for AERMOD. Considering Rolfe (2016) used methods and data from several international and inter-state studies (Georgakaki et al., 2005; Hulskotte and Denier van der Gon, 2010; Goldsworthy and Renilson, 2013) to create the fuel consumption inventory, it is important to test the model's sensitivity to changes in the inventories to determine whether such changes significantly affect pollutant concentrations, particularly exceedances above regulatory standards (National Environmental Protection Council, 2017). Therefore, an investigation into the sensitivity of the model to such modification is required, particularly if this affects Fremantle ports' compliance with NEPM standards.

1.4 Research aims

Rolfe (2016) is currently the only study that focusses on the dispersion of air pollution from ships servicing Fremantle port (Rolfe, 2016). Considering Fremantle port is the largest general cargo port in Western Australia (Fremantle Ports, 2016) and the emissions from ships can cause a variety of adverse health effects in humans (Sunyer et al., 2003; Corbett et al., 2007; Abdul-Wahab et al., 2012; Thepanondh et al., 2015), there is a need to further investigate the dispersion of these pollutants in the interest of human health. The study by Rolfe (2016) used AERMOD to simulate the dispersion of pollutants from ship emissions from Fremantle port, which has inherent limitations as a result of the steady-state assumption. Furthermore, the sensitivity of AERMOD to changes in parameter values and methods used in the emission inventory is unknown.

Considering the above limitations to the study by Rolfe (2016) and lack of comparable studies for shipping emissions from Fremantle port, the aims of this thesis are to:

1. Assess the sensitivity of AERMOD to changes in parameter values and methods used in the emission inventory developed by Rolfe (2016); and
2. Compare the Gaussian plume model, AERMOD to the Lagrangian puff

model, CALPUFF to investigate if a Lagrangian model results in different concentration fields to a Gaussian model in a coastal region such as Fremantle.

CHAPTER 2
METHODS

To investigate AERMOD's sensitivity to changes in the emission inventory, and compare AERMOD versus CALPUFF, the study by Rolfe (2016) was repeated to provide "control" simulations. Rolfe (2016) found large differences in AERMOD simulations with meteorology over land versus water and 20 m versus 30 m stack heights. Therefore, it was necessary to carry out 4 control simulations. To operate both AERMOD and CALPUFF, meteorological data and an hourly emission inventory for the period of interest were required. The following section describes methods used for obtaining the meteorological data and the emission inventory of Rolfe (2016). A brief description of AERMOD and CALPUFF set up is also provided and changes to the emission inventory as part of the sensitivity tests carried out are described.

2.1 Meteorological inputs

Meteorological inputs required by both AERMOD and CALPUFF include hourly data, which describe the vertical profile of the atmosphere (Pacific Environmental Services, 2004). From this atmospheric profile, the atmospheric stability is determined, which is largely responsible for atmospheric turbulence and is crucial in the dispersion of air pollutants (Sturman and Tapper, 2006). Dispersion models such as AERMOD, which take as input meteorology from a single point, can be operated with observations using meteorological stations and atmospheric soundings (e.g., Kumar et al., 2006; Simpson et al., 2007; Gibson et al., 2013). However, these observations are rarely available for the region of interest, at a high enough frequency (ideally, hourly data), and over the duration of the study. Hence, it is common to drive AERMOD with meteorology derived from regional atmospheric modelling systems (e.g., Kesarkar et al., 2007; Boadh et al., 2015). With Lagrangian models such as CALPUFF, which take as input meteorology over the entire computational domain, meteorology from regional atmospheric models is almost always needed (Scire et al., 2000).

Due to a lack of surface meteorological data as well as atmospheric sounding observations in Fremantle, Rolfe (2016) used meteorology generated by the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) as input to AERMOD. The WRF model is one of the most widely used regional atmospheric modelling systems, and can be used for a very wide range of applications, including simulations at the sub-kilometre scale to large scale atmospheric simulations of several kilometres (Skamarock et al., 2005). Rolfe (2016) chose WRF as it has been extensively used and evaluated against temperature and precipitation observations for the south west of Western Australia (Andrys et al., 2015; Kala et al., 2015a), and additionally, several air quality studies have successfully used meteorology from the WRF model as input to AERMOD and showed that WRF simulated winds, air temperature, and boundary layer depths compare well with observations (e.g., Kesarkar et al., 2007; Boadh et al., 2015). Similarly, several studies have successfully used WRF-derived meteorology for CALPUFF simulations (e.g., Yim et al., 2007; Abdul-Wahab et al., 2010; Prueksakorn et al., 2014).

The WRF simulations used by Rolfe (2016) were from WRF v3.3 and consisted of four nested domains as shown in Fig. 2.1. The resolution of the 4 domains were 22.5 km, 7.5 km, 2.5 km, and 833 m respectively, as shown in Fig. 2.2. Rolfe (2016) evaluated wind speed and direction simulations from the WRF simulations as the winds are one of the key drivers of atmospheric dispersion. This is illustrated in Fig. 2.3 showing wind roses from wind observations at Naval Base (Fig. 2.4) and those simulated by WRF from the closest model grid point to the station. The figure shows a very good overall comparison between observed and WRF simulated winds. Rolfe (2016) extended this analysis to 4 other meteorological stations (Jandakot, Perth airport, Perth Metro and Swanbourne; Fig. 2.4) and showed similarly good comparisons on both annual and seasonal time scales. However, WRF had a tendency to overestimate the maximum wind speed by 1 to 5 m s^{-1}. Given these differences, Rolfe (2016) carried out some sensitivity tests by varying the wind speeds by up to ± 10%, and showed that this did not significantly influence AERMOD simulated concentrations.

Since Rolfe (2016) already evaluated the WRF simulated winds against observations and tested the sensitivity of AERMOD to WRF simulated wind speeds, no further evaluation or sensitivity testing of WRF was carried out. This thesis makes use of the exact same WRF-derived meteorological input files used by Rolfe (2016) over land and water for all AERMOD simulations. Meteorology was extracted from the same WRF simulation outputs, across the CALPUFF domain for the CALPUFF simulations, described later in Section 2.4.

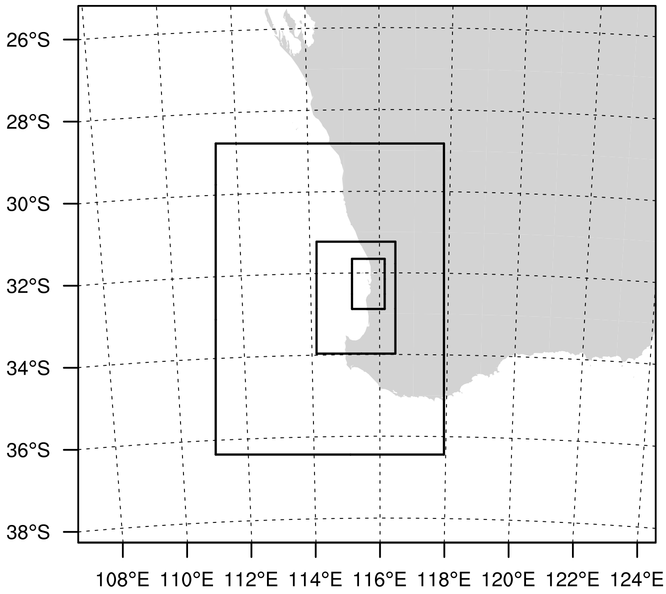

Figure 2.1: Nested model domain configuration used by Rolfe (2016).

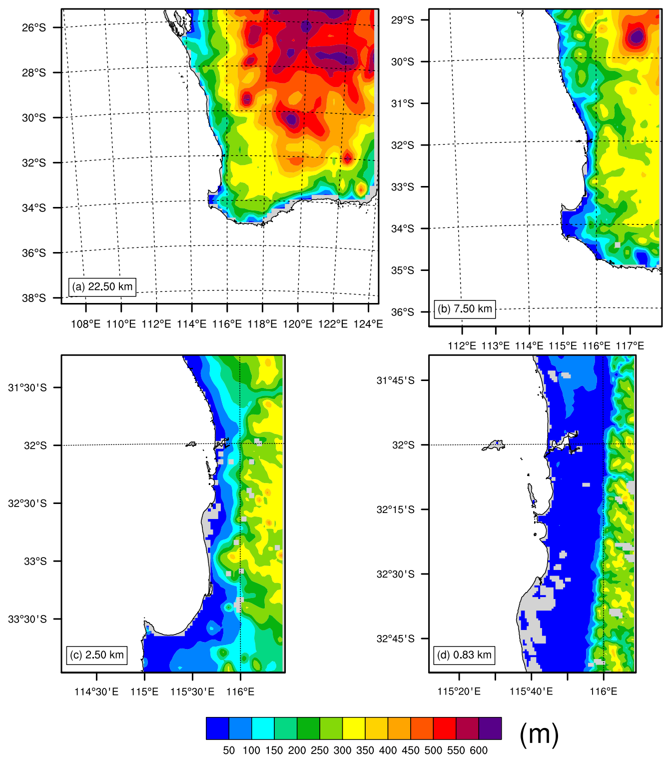

Figure 2.2: Model topography used for each nest shown in Fig. 2.1 (Rolfe, 2016).

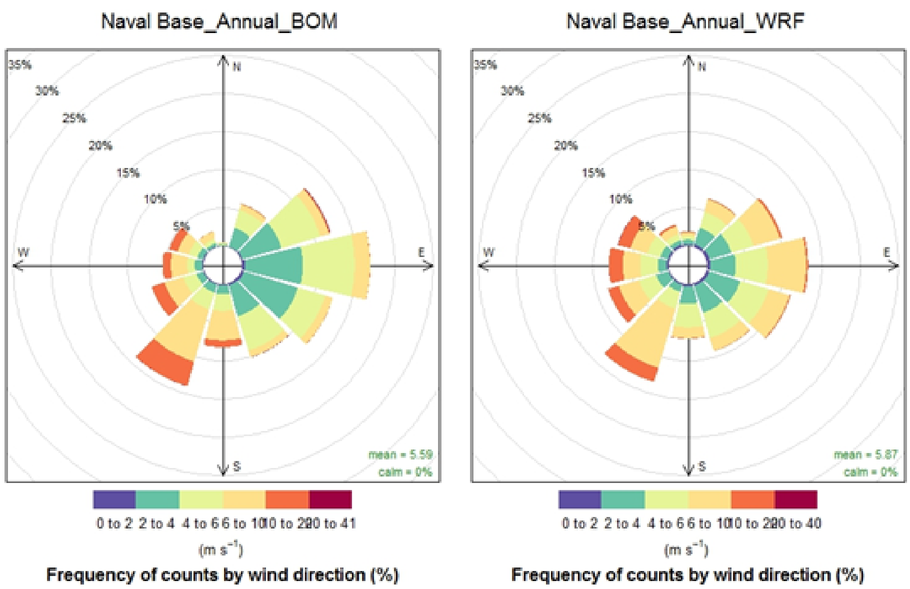

Figure 2.3: Annual wind roses generated by Rolfe (2016), from wind observations at Naval Base (left) and those simulated by WRF at the closest grid point to the station (right).

2.2 Hourly emission inventory

Both AERMOD and CALPUFF require hourly emission rates from each source within the receptor domain. This thesis used the emission inventory developed by Rolfe (2016). In order to compile the emission inventory, Rolfe (2016) created a fuel consumption inventory using publicly available information obtained from Fremantle port for the period of 1st July 2011 to 30th June 2012. Methodology for calculation of the fuel consumption for ships were adopted from Smit et al. (2016) who drew on research by Hulskotte and Denier van der Gon (2010) and Georgakaki et al. (2005) for fuel consumption information. Using this, the hourly emission inventory was created for Fremantle port. This required emission factors for each air pollutant species (SO_2, NO_2, $PM_{2.5}$ and PM_{10}) specific for each engine type, fuel type and engine load. Emission factors were used

Figure 2.4: Map showing the locations of the 5 meteorological stations used to compare meteorological observations to to WRF meteorology (Rolfe, 2016).

Table 2.1: Emission factors (g kg^{-1} fuel used) from Rolfe (2016) for SO_2, NO_x, $PM_{2.5}$ and PM_{10}, obtained from Goldsworthy and Goldsworthy (2013). (RO is residual oil, MDO is marine diesel oil, SSD is slow speed diesel, MSD is medium speed diesel and HSD is high speed diesel).

			$\mathbf{SO_2}$	$\mathbf{NO_x}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
Main engine	RO	SSD	52.82	92.82	6.72	7.28
		MSD	53.02	65.12	5.14	6.65
	MDO	SSD	9.78	91.89	1.51	1.68
		MSD	9.76	64.39	1.41	1.51
		HSD	9.76	58.54	1.41	1.51
Auxiliary engine	RO	MSD	52.86	64.76	5.81	6.34
	MDO	SSD	9.77	64.06	1.34	1.47
		HSD	9.77	54.38	1.34	1.47
Auxiliary boiler	RO	-	52.79	6.89	4.43	4.82

as suggested by Goldsworthy and Goldsworthy (2013), who assumed a sulfur content of 2.7% for residual oil and 0.5% for marine diesel oil as shown in Table 2.1. The emission inventory includes hourly emission rates for each ship within the receptor domain in g s^{-1} (Rolfe, 2016), as required by AERMOD and CALPUFF.

2.3 AERMOD

2.3.1 Model set up

The AERMOD set up for the control simulations was identical to that used by Rolfe (2016). However, Rolfe (2016) used the commercial graphical user interface (GUI) provided by Lakes Environmental to operate AERMOD, which is only available by purchase. Hence for this thesis, AERMOD was operated through the command line using a manually written input file shown in Fig. A.1 in Appendix A. The receptor domain was set up to cover approximately 50 km^2 between 31.86° South, 115.50° East to 32.26° South, 115.99° East. 21 by 21 receptors were used, 2.28 km apart in the east-west direction, and 2.24 km apart in the north-south direction covering the receptor domain evenly, as shown in Fig. 2.5. This produced a relatively low resolution receptor domain of 441 receptors over a large area encapsulating the entirety of Fremantle port including inner and outer harbours and ship routes within port waters.

Ships at berth and anchor locations were modelled as point sources and ships moving along transect routes were modelled as area sources as shown in Fig. 2.6. In order to simulate the effects of building downwash, stationary ships were represented as buildings 100 m long, 30 m wide and 18 m high. Parameters of ship exhaust were taken from Mason et al. (2008) and are outlined in Table 2.2.

2.3.2 Sensitivity tests

To assess the sensitivity of AERMOD to the emission inventory (research aim 1), several parameter values and methods were tested as outlined in Table

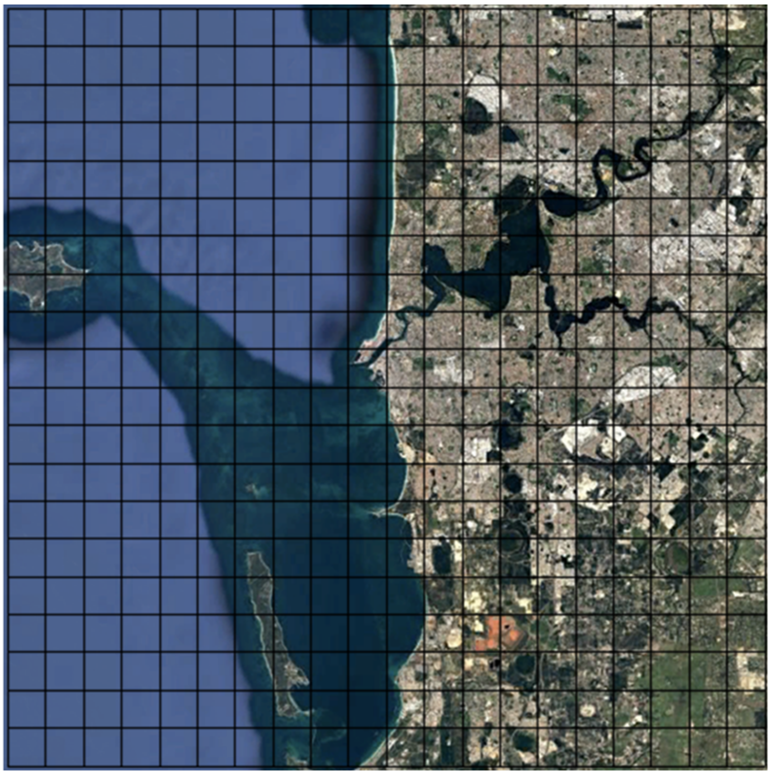

Figure 2.5: AERMOD receptor domain used by Rolfe (2016), and used in this thesis for testing the sensitivity of AERMOD to the emission inventory. 21 by 21 receptors were used covering an area of approximately 50 km^2, with spacing of 2.28 km apart in the east-west direction and 2.24 km apart in the north-south direction.

Table 2.2: Ship exhaust parameters (Mason et al., 2008)

Stack height:	20 m or 30 m
Stack diameter:	0.8 m
Stack velocity:	25 m s^{-1}
Stack gas exit temperature:	282°C (515.15 K)

Figure 2.6: Fremantle port berth and anchor locations, and transect segments within port waters. The yellow lines (S1 to S22) denote ship transect routes and remaining locations denote berth and anchor points (Rolfe, 2016).

Table 2.3: Summary of AERMOD sensitivity tests carried out.

Experiment ID	**Emission factors**	**Cruise ship fuel efficiency**	**Modifier values**	**Building downwash**
Control	Table 2.1	0.0328 kg hr^{-1}	92%	ON
1a	Table 2.1-10%	0.0328 kg hr^{-1}	92%	ON
1b	Table 2.1+10%	0.0328 kg hr^{-1}	92%	ON
2	Table 2.1	0.0165 kg hr^{-1}	92%	ON
3	Table 2.1	0.0328 kg hr^{-1}	85%	ON
4	Table 2.1	0.0328 kg hr^{-1}	92%	OFF

2.3. AERMOD simulations were carried out for each species, for each change of the emission inventory as summarised in Table 2.3. Each sensitivity test was also simulated with combinations of meteorology over land versus water, and 20 m versus 30 m stack heights. An additional simulation was carried out for each pollutant, testing AERMOD's sensitivity to building downwash (experiment ID 4).

1. **Assessment of emission factors for fuel with a modification of ±10% sulfur content (experiments 1a and 1b in Table 2.3)**

   Many elements can change ship emission factors such as engine load, fuel type and emission abatement technology (Hulskotte and Denier van der Gon, 2010; Aliabadi et al., 2016). However, one of the most important elements is the sulfur content used in fuel (Aliabadi et al., 2016), as a lower sulfur content results in lower emission factors (Celo et al., 2015).

The International Maritime Organization (IMO) specifies sulfur emission control areas (SECA) in place in the Northern Hemisphere, but not in Australian waters (International Maritime Organization, 2017a). Within these SECA, the sulfur content of marine fuels is limited to 0.1%. In Fremantle port waters, where there are no such restrictions, the sulfur content of marine fuel can be as high as 3.5% (BP Australia Pty Ltd, 2012; Rolfe, 2016).

There is little literature on emission factors for fuel with 0.1% sulfur content (Zetterdahl et al., 2016). The few studies that do focus on reduced sulfur emission factors suggest different values (Eyring et al., 2005; Buhaug et al., 2009; Lindstad et al., 2015; Winnes et al., 2016; Zetterdahl et al., 2016). Each study categorised the emission factors based on different fuel types, ship types and engine loads, none of which matched the categorisation used in Rolfe (2016). Hence there is no clear guidance on what emission factors to use (Walsh and Bows, 2012).

Given that Rolfe (2016) found exceedances of SO_2 above the regulatory standards, it is important to test the sensitivity of AERMOD to emission factors for SO_2. When there is no clear guidance on absolute values for sensitivity testing, it is a common approach within the meteorological and climate sciences to vary a parameter by $\pm$ some percentage (usually, between 5 to 25%) to quantify the sensitivity of the model to that parameter (e.g,. Miao et al., 2003; Zhang et al., 2013; Kala et al., 2014, 2015b).

Table 2.4: Emission factors (g kg^{-1}) for SO_2 used in Rolfe (2016) and the emission factors reflecting ±10% used for sensitivity testing in this thesis. (RO is residual oil, MDO is marine diesel oil, SSD is slow speed diesel, MSD is medium speed diesel and HSD is high speed diesel; *Goldsworthy and Goldsworthy, 2013.)

			GG(2013)*	**Minus 10%**	**Plus 10%**
Main engine	RO	SSD	52.82	47.53	58.10
		MSD	53.02	47.71	58.32
	MDO	SSD	9.78	8.80	10.75
		MSD	9.76	8.78	10.73
		HSD	9.76	8.78	10.73
Auxiliary engine	RO	MSD	52.86	47.57	58.14
	MDO	SSD	9.77	8.79	10.74
		HSD	9.77	18.79	10.74
Auxiliary boiler	RO	-	52.79	47.51	58.06

Therefore, this thesis tested values equal to minus (experiment 1a) and plus (experiment 1b) 10% of the control emission factors of Rolfe (2016). Table 2.4 outlines emission values for SO_2 used in the study by Rolfe (2016) and ±10% of the control emission factors. The modified emission factors for NO_x and PM can be found in Tables C.1, C.2 and C.3 in Appendix C.

2. **Assessing the fuel efficiency value for Australian cruise ships (experiment 2 in Table 2.3)**

Rolfe (2016) simulated the fuel consumption of ships at anchor and berth using Equation 2.1 from Smit et al. (2016).

$$f_{\mathrm{bAE}}, f_{\mathrm{bAB}}, f_{\mathrm{aAE}}, f_{\mathrm{aAB}} = \frac{a_{\mathrm{b}} GT}{1000 p \Delta t} \tag{2.1}$$

where:

$\mathbf{f_{bAE}}$ is fuel consumption in the auxiliary engine at berth (kg)

$\mathbf{f_{bAB}}$ is fuel consumption in the auxiliary boiler at berth (kg)

$\mathbf{f_{aAE}}$ is fuel consumption in the auxiliary engine at anchor (kg)

$\mathbf{f_{aAB}}$ is fuel consumption in the auxiliary boiler ar anchor (kg)

$\mathbf{a_b}$ is fuel per hour as a function of ship type (kg hr^{-1})

GT is individual ship gross tonnage (obtained from Fremantle port data)

p is fuel type per engine type (Hulskotte and Denier van der Gon, 2010)

Δ **t** is the time in mode (hr)

Rolfe (2016) used values for fuel use per hour (a_b) as a function of ship type and ship size as proposed by Hulskotte and Denier van der Gon (2010). However, the value for cruise ships came from a Copenhagen study by Saxe and Larsen (2004), where visiting cruise ships differ from those visiting Australian ports. A number of large cruise ships and vehicle carriers that enter Australian waters were not included in Saxe and Larsen (2004), so these ships would have been under-represented in the emission inventory of Rolfe (2016). Therefore, a larger value for cruise ship fuel efficiency was used in Rolfe (2016) (determined by personal communications with an expert consultant, Dr Robin Smit), to more accurately reflect fuel use in Australian-servicing cruise ships.

The value from Saxe and Larsen (2004) was 0.0165 kg hr^{-1} and the value used by Rolfe (2016) was nearly double at 0.0328 kg hr^{-1}. However, Rolfe (2016) did not test the effect of doubling this value. Therefore, to test the sensitivity of AERMOD to changing the cruise ship fuel efficiency, the original value from Saxe and Larsen (2004) of 0.0165 kg hr^{-1} was used in this thesis to compare concentrations to those simulated with the higher value of 0.0328 kg hr^{-1} used by Rolfe (2016) to determine if changing this value affected NEPM exceedances.

3. **Assessing the modifier values for calculating fuel consumption during transit for main and auxiliary engines (experiment 3 in Table 2.3)**

Rolfe (2016) used formulae from Smit et al. (2016) for calculating fuel consumption during transit as specified in Equations 2.2, and 2.3 below.

$$f_{\mathrm{tME}} = \varphi_1 f_{\mathrm{ss}} (\frac{v}{v_{\mathrm{ss}}})^3 \rho \Delta d \tag{2.2}$$

$$f_{\mathrm{tAE}} = \varphi_2 f_{\mathrm{ss}} \rho \Delta d \tag{2.3}$$

where:

$\mathbf{f_{tME}}$ is fuel consumption in the main engine during transit

$\mathbf{f_{tAE}}$ is fuel consumption in the auxiliary engine during transit

$\varphi_{\mathbf{1,2}}$ are modifier values

$\mathbf{f_{ss}}$ is fuel consumption at service speed

$(\frac{v}{v_{\mathbf{ss}}})^{\mathbf{3}}$ is a modifier term for fuel consumption

ρ is the proportion of fuel used

$\Delta\ \mathbf{d}$ is the total distance travelled by the ship

When a ship is in transit, both the main engine (ME) and auxiliary engines (AE) are operating at some load (Smit et al., 2016). Combined engine load during transit as suggested by Georgakaki et al. (2005) is equal to 85%. However, a survey for the port of Brisbane revealed a that more accurate value is 92% (Goldsworthy and Renilson, 2009) and this was used in the study by Rolfe (2016). The modifier value, φ_1 (which is equal to 1.001), adjusts the main engine load to 85% and φ_2 (which is equal to 0.084) adjusts the auxiliary engine load to 8% in transit to reflect the 92% combined engine load as proposed by (Goldsworthy and Renilson, 2009).

To test the sensitivity of AERMOD to engine load, and whether changing engine load affected NEPM exceedances, in this thesis AERMOD was operated with combined engine loads of 85% as originally proposed by Georgakaki et al. (2005) and the control from Rolfe (2016). Both sets of engine loads are listed in Table 2.5.

4. **Sensitivity to building downwash (experiment 4 in Table 2.3)**

The presence of buildings can affect the dispersion of pollutants by bringing

Table 2.5: Table showing different engine loads suggested in the literature and used in this thesis to assess the impact on air pollution dispersion.

	Main engine	**Auxiliary engine**	**Combined**
(Georgakaki et al., 2005)	85%	5%	85%
(Goldsworthy and Renilson, 2009)	85%	8%	92%

the pollutants toward the ground due to the airflow around the building, called building downwash (Canepa, 2004). This is important in air pollution dispersion as the ground level pollution can be increased due to this building "wake" effect (Canepa, 2004). To assess the sensitivity of AERMOD to building downwash, 4 more simulations were carried out using meteorology over water and stack heights at 20 m and 30 m, with building downwash turned off. This was simulated for each species to assess if these impacts are significant enough to affect NEPM standards.

2.3.3 Sensitivity tests with a higher resolution receptor domain

Rolfe (2016) found an exceedance of the NEPM standard for the maximum 1 hour average for SO_2 in Fremantle inner harbour. However, Rolfe (2016) did not carry out additional simulations with a higher resolution receptor domain over the area of exceedance. Based on the AERMOD sensitivity test results, further AERMOD simulations were carried out in order to investigate these exceedances. These simulations focussed on Fremantle inner harbour covering an area from 32.03° South, 115.72° East to 32.07° South and 115.77° East as shown in Fig.

Figure 2.7: High resolution domain over Fremantle inner harbour used to model the location of the exceedance of the NEPM maximum 1 hour average concentration for SO_2 simulated by AERMOD. The figure shows the location of 400 receptors spaced 250 m apart.

2.7. This covered approximately 25 km^2 with 400 evenly spaced receptors, every 250 m as opposed to the receptor spacing of 2.28 km apart in the east-west direction and 2.24 km apart in the north-south direction for the larger AERMOD domain of Rolfe (2016). The rationale for this was that the higher resolution receptor domain around the region of exceedance allows for a much better spatial understanding of the exceedance.

2.4 CALPUFF

The receptor domain for the CALPUFF simulations were based on the results of the AERMOD sensitivity simulations. Since exceedances of the NEPM standards with AERMOD were further explored with the higher resolution receptor domain focussed on the inner harbour (Fig. 2.7), the CALPUFF receptor domain was also set up to be as close as possible to the AERMOD higher resolution domain rather than the original domain of Rolfe (2016). CALPUFF simulations used the control emission inventory only and 20 m stack heights as CALPUFF was not subject to sensitivity tests due to time constraints.

CALPUFF was set up in an identical manner to AERMOD. However, the computational input required by CALPUFF is more detailed and time consuming than AERMOD (Fisher et al., 2003; Abdul-Wahab et al., 2010; De Visscher, 2013; Rood, 2014). CALPUFF set up consists of 18 “input groups” (Scire et al., 2000), compared to the 5 pathways required by AERMOD, which provide more options for pollution dispersion such as puff splitting and deposition etc. A complete description of the CALPUFF input file is provided in Fig. B.1 in Appendix B.

To summarise, CALPUFF was operated once only for each pollutant over the high resolution receptor domain over Fremantle inner harbour (Fig. 2.7). The CALPUFF simulations were compared to the equivalent high resolution simulations by AERMOD, which showed exceedances of the NEPM standards.

Table 2.6: NEPM Ambient Air Quality Standards (μg m^{-3}) for SO_2, NO_2, $PM_{2.5}$ and PM_{10}.

Averaging period	$\mathbf{SO_2}$	$\mathbf{NO_2}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
1 hour	524	226	-	-
24 hours	209	-	25	50
1 year	52	56	-	-

2.5 National Environmental Protection (Ambient Air Quality) Measure

To analyse AERMOD and CALPUFF's concentrations of SO_2, NO_2, $PM_{2.5}$ and PM_{10} for shipping emissions in Fremantle port, the simulated highest concentrations were compared to the National Environmental Protection (Ambient Air Quality) Measure. NEPM standards for ambient air quality consist of a 1 hour average, 24 hour average and annual average concentration (National Environmental Protection Council, 2017). These are shown in Table 2.6 for comparison with AERMOD and CALPUFF simulated concentrations. The NEPM standards also have maximum allowable exceedances for the maximum 1 and 24 hour averages, as shown in Table 2.7.

Finally, although Rolfe (2016) simulated an exceedance of the maximum 1 hour average for SO_2, further analysis of subsequent highest concentrations were not carried out. Therefore, this thesis will also investigate 2nd and subsequent highest concentrations to assess if any exceeded NEPM standards, and if

Table 2.7: NEPM maximum allowable exceedances for SO_2, NO_2, $PM_{2.5}$ and PM_{10}.

Averaging period	$\mathbf{SO_2}$	$\mathbf{NO_2}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
1 hour	1 day/year	1 day/year	-	-
24 hours	1 day/year	-	5 days/year	5 days/year
1 year	none	none	none	none

so, whether or not these exceedances occurred above the maximum number of allowable exceedance days.

CHAPTER 3
RESULTS

The following section presents results from the 4 control simulations (meteorology over land versus water and 20 m versus 30 m stack heights). Results from the sensitivity tests for AERMOD are then presented followed by results from simulations with the higher resolution receptor domain for both AERMOD and CALPUFF. The analysis focusses on exceedances of the NEPM standards (Tables 2.6 and 2.7).

3.1 AERMOD control simulations

The control simulations for this thesis had to be repeated due to the unavailability of the AERMOD GUI used by Rolfe (2016). Since the latter found exceedances with meteorology over water and 20 m stack heights, the first part of the analysis focusses on this set up as illustrated in Figs. 3.1, 3.2 and 3.3, which show concentrations across the receptor domain for the 1 hour average, 24 hour average and annual average concentrations. Figures for the control with meteorology over land and stack height at 30 m are shown in Appendix D. The dispersion of all 4 pollutants reflects the berth and anchor locations in the inner harbour (at Fremantle) and outer harbour (at Rockingham) as well as ship routes within port waters to the north west of Fremantle, which are shown in Fig 2.6

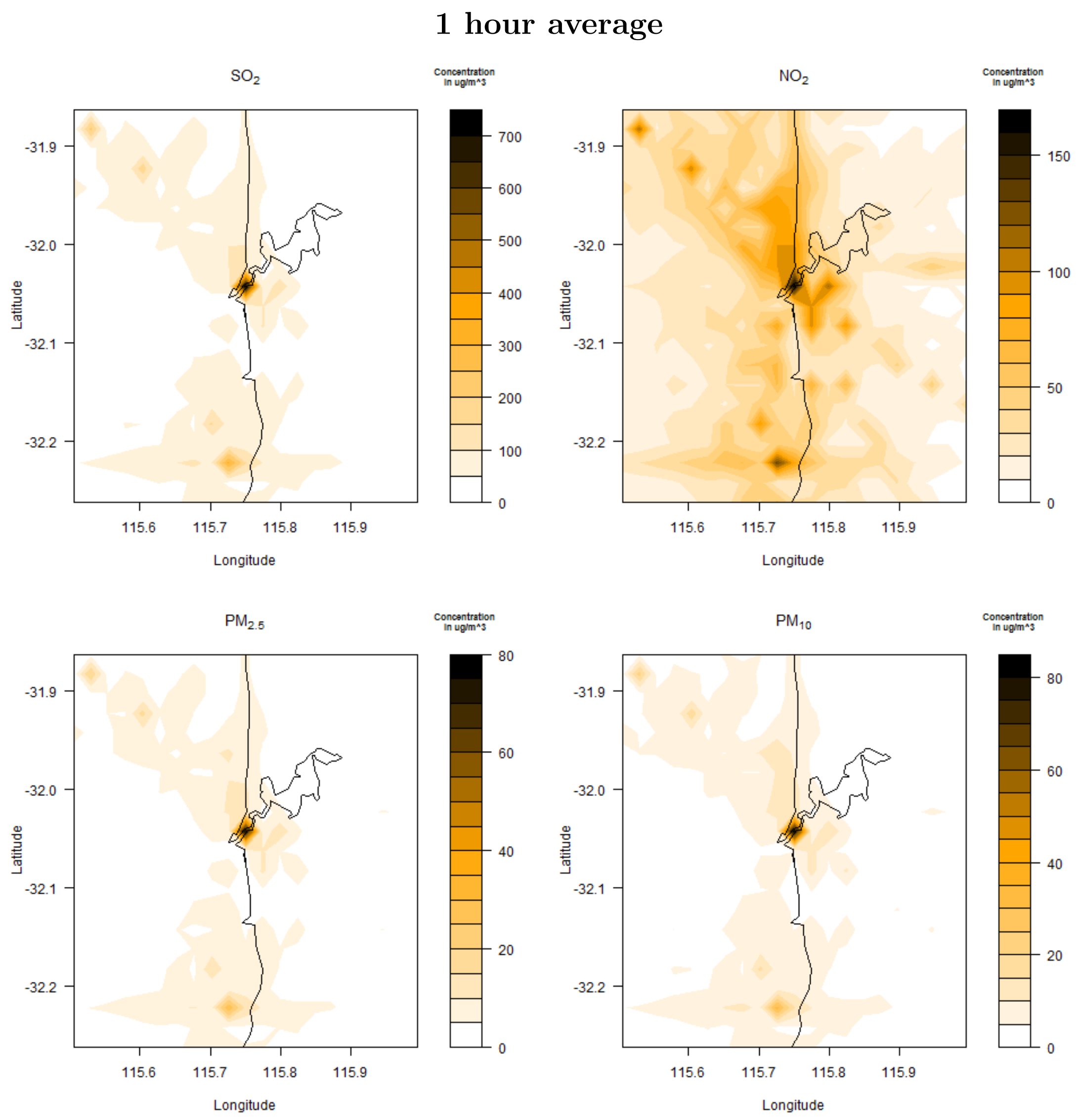

Figure 3.1: 1 hour average concentrations simulated by AERMOD for the control simulation with meteorology over water and ship stack height at 20 m.

and are similar to results from Rolfe (2016).

Having shown that the overall spatial distribution of contours is similar to Rolfe (2016), the following results focus on highest concentrations simulated by AERMOD. Table 3.1 shows absolute concentrations simulated by AERMOD with meteorology over water and 20 m and 30 m stack heights. Model results

24 hour average

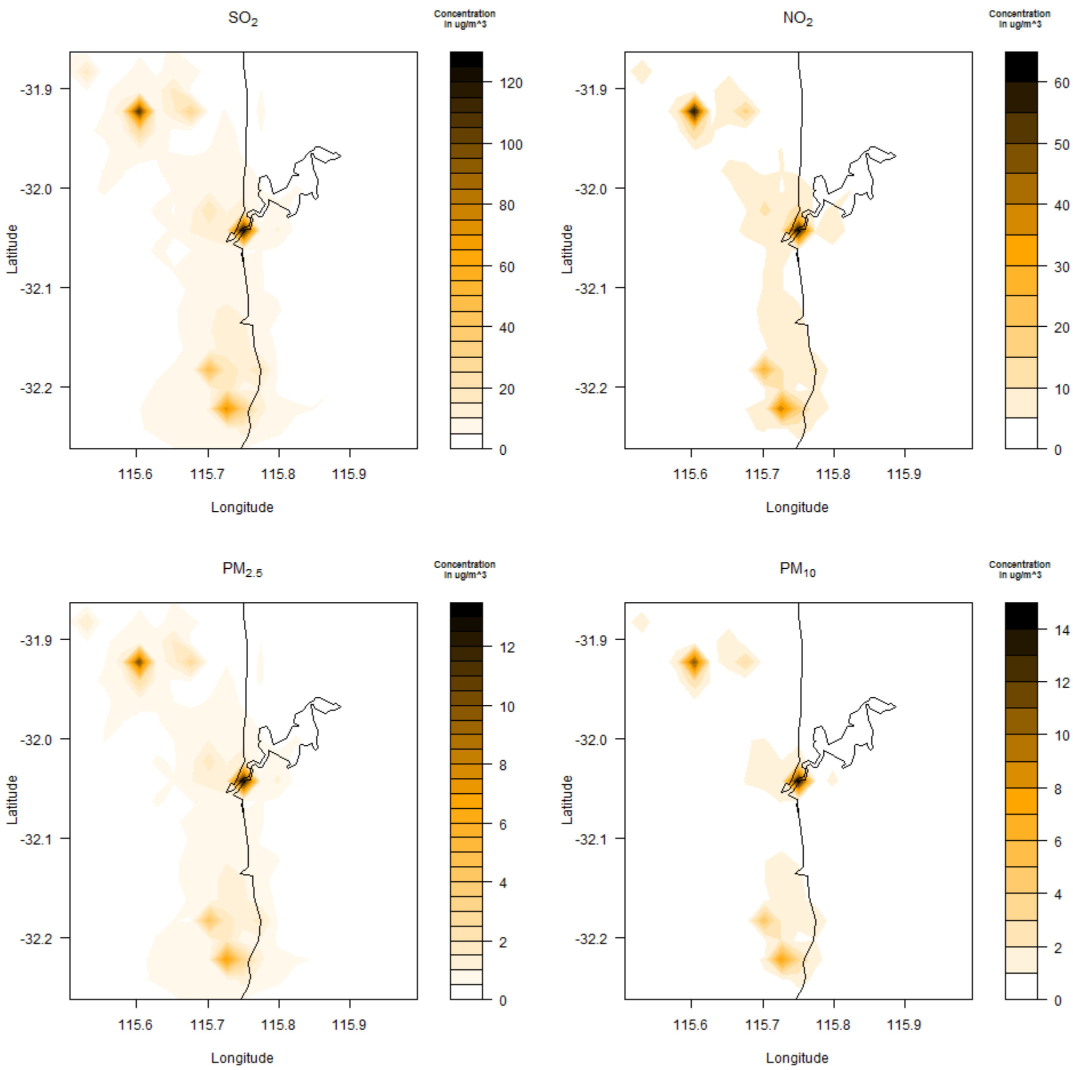

Figure 3.2: 24 hour average concentrations simulated by AERMOD for the control simulation with meteorology over water and ship stack height at 20 m.

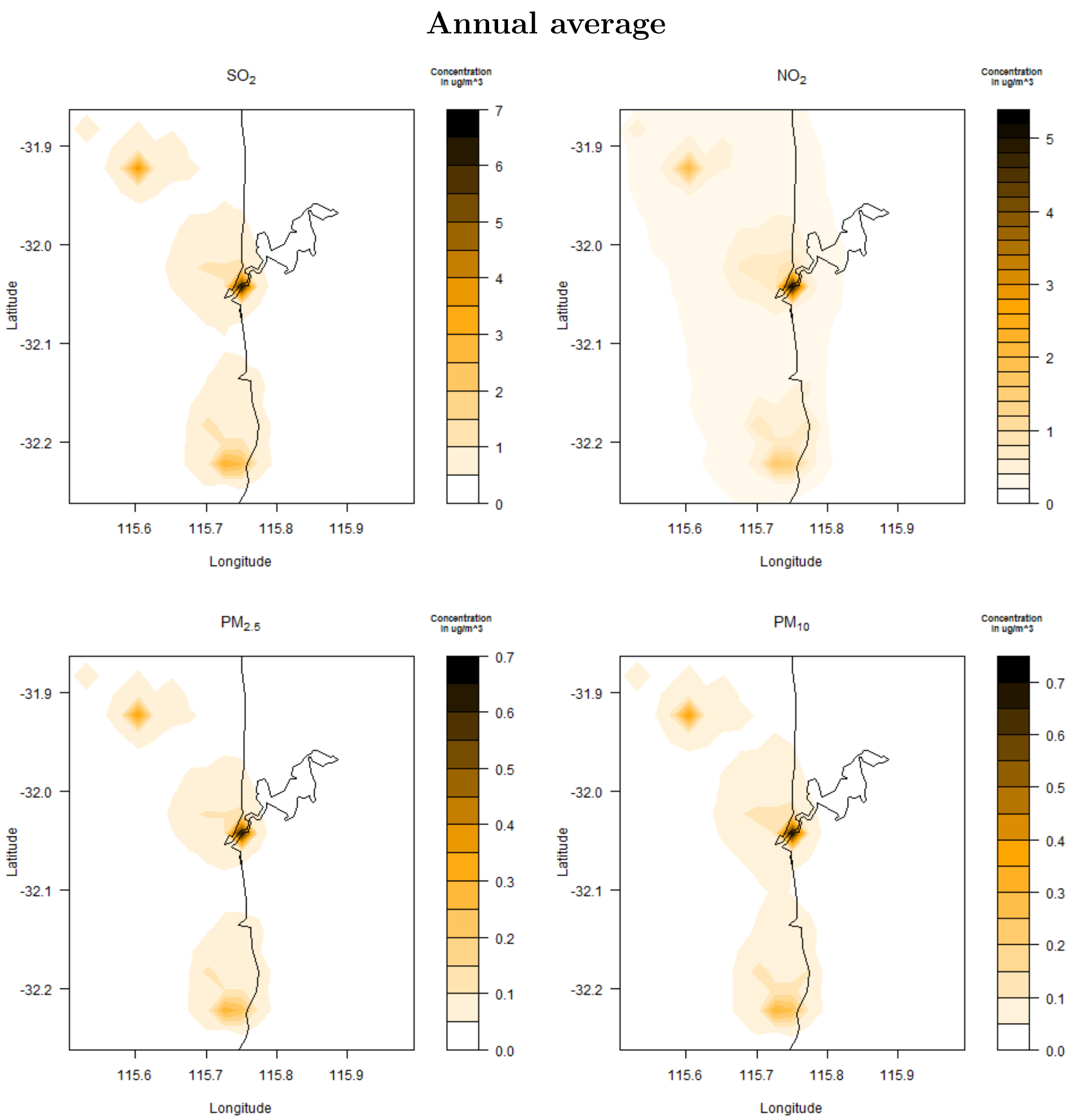

Figure 3.3: Annual average concentrations simulated by AERMOD for the control simulation with meteorology over water and ship stack height at 20 m.

Table 3.1: Concentrations (μg m^{-3}) simulated by AERMOD for the control simulations with meteorology over water, 20 m and 30 m stack heights. (NEPM exceedances are shown in red and the amount by which it is exceeded follows in parentheses.)

Stack height	**Averaging period**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
20 m	1 hour	734.5 (210.5)	167.2	-	-
	24 hours	127.3	-	13.4	14.6
	1 year	6.50	5.35	0.65	0.71
30 m	1 hour	634.5 (110.5)	163.1	-	-
	24 hours	112.2	-	11.8	12.8
	1 year	5.71	4.73	0.57	0.63

for the control simulations are displayed in tables that reflect the averaging periods for NEPM air quality standards and exceedances are shown in red. Where exceedances do occur, the difference between the NEPM standard and the simulated concentrations are shown in parentheses. With meteorology over water, the concentrations for the maximum 1 hour average for SO_2 were 734.5 μg m^{-3} for a 20 m stack height and 634.5 μg m^{-3} for a 30 m stack height. Both of these concentrations exceed the NEPM standard of 524 μg m^{-3} by more than 100 μg m^{-3}. However, a taller stack height of 30 m compared to 20 m reduced concentrations overall, but the concentration remained above the NEPM standard. No exceedances occurred for NO_2, $PM_{2.5}$ or PM_{10}.

Table 3.2: Concentrations (μg m^{-3}) simulated by Rolfe (2016) with meteorology over water, 20 m stack heights for all pollutants and 30 m stack heights for SO_2. (NEPM exceedances are shown in red and the amount by which it is exceeded follows in parentheses.)

Stack height	**Averaging period**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
20 m	1 hour	734.5 (210.5)	167.2	-	-
	24 hours	127.3	-	13.4	14.6
	1 year	6.50	5.00	0.65	0.72
30 m	1 hour	635.0 (111)	not simulated		
	24 hours	112.0	not simulated		
	1 year	5.71	not simulated		

To ensure that the control simulations are identical to that of Rolfe (2016), Table 3.2 shows absolute concentrations simulated by Rolfe (2016) with the AERMOD GUI and meteorology over water. The values were identical except for small differences of less than 1 μg m^{-3} between concentrations for the annual averages of NO_2 and PM_{10} with a 20 m stack height. These small differences may be due to minor differences in model parameter options invoked by the AERMOD GUI used by Rolfe (2016), and are unlikely to affect the overall results of this thesis.

Table 3.3 shows absolute concentrations simulated by AERMOD in this thesis with meteorology over land and 20 m and 30 m stack heights. With meteorology over land, concentrations were lower as compared to meteorology over water. Similar to results discussed earlier, an increase in stack height reduced concentrations for all pollutants. The maximum 1 hour average for SO_2 was 307.8 μg m^{-3} for both stack heights, which does not exceed the NEPM standard of 524 μg m^{-3}. NEPM standards were not exceeded for any pollutant with meteorology over land. These results show that concentrations are strongly dependent on the meteorology used as input to AERMOD.

Table 3.3: Concentrations (μg m^{-3}) simulated by AERMOD for the control simulations with meteorology over land, 20 m and 30 m stack heights.

Stack height	**Averaging period**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
20 m	1 hour	307.8	139.6	-	-
	24 hours	119.4	-	11.2	12.2
	1 year	7.00	5.98	0.70	0.78
30 m	1 hour	307.8	132.6	-	-
	24 hours	119.4	-	11.2	12.2
	1 year	5.80	5.00	0.58	0.63

Table 3.4 shows absolute concentrations simulated by Rolfe (2016) with the AERMOD GUI and meteorology over land. None of the concentrations for any pollutants exceed NEPM standards. The maximum 1 hour average for SO_2 was 241.5 μg m^{-3}. This differs from the 307.8 μg m^{-3} shown in Table 3.3 in this thesis. Concentrations from Rolfe (2016) for meteorology over land are lower than con-

centrations simulated in this thesis. The control simulations were independently repeated by a third party (Dr Peter Rye) in order to determine the source of the discrepancies between this thesis and Rolfe (2016) for meteorology over land, and results for the third party matched those from this thesis. It was also noted that concentrations for $PM_{2.5}$ and PM_{10} of Rolfe (2016) were erroneous whereby $PM_{2.5}$ exceeded PM_{10} with meteorology over land (Table 3.4). As $PM_{2.5}$ is a subset of PM_{10}, it can never exceed the concentration of PM_{10}. This was most likely a typographical error and explains some of the differences for PM concentrations with meteorology over land. The remaining discrepancies can only be explained by the use of the AERMOD GUI by Rolfe (2016) versus the command line in this thesis.

Table 3.4: Concentrations (μg m^{-3}) simulated by Rolfe (2016) with meteorology over land, 20 m and 30 m stack heights.

Stack height	**Averaging period**	$\mathbf{SO_2}$	$\mathbf{NO_2}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
20 m	1 hour	241.5	139.6	-	-
	24 hours	71.10	-	7.32	6.39
	1 year	7.02	6.01	0.70	0.57
30 m	1 hour	not simulated			
	24 hours	not simulated			
	1 year	not simulated			

3.2 AERMOD sensitivity testing

For the remainder of the results section (unless otherwise specified), tables display the experiment concentration minus the equivalent control concentration, followed by the percentage difference in parentheses. If the simulated concentration exceeded NEPM standards, the amount by which is displayed below in red.

1. **Sensitivity to fuel emission factors (experiment 1a and 1b in Table 2.3)**

   Table 3.5 shows differences in concentrations of AERMOD simulations with minus 10% emission factors and the control. All concentrations showed a decrease from the control simulations by approximately 10%, consistent with expectations. Although concentrations with meteorology over water were lowered with this emission inventory, the maximum 1 hour average for SO_2 still exceeded the NEPM standard for both stack heights. However, the maximum 1 hour average for SO_2 with 20 m stack heights was only 137.1μg m^{-3} above the NEPM standard, which is a large reduction from the equivalent control concentration of 210.5 μg m^{-3} above the NEPM standard. Similarly, for a stack height of 30 m, the maximum 1 hour average for SO_2 exceeded the NEPM standard by only 47.1 μg m^{-3}. This approximately halved the exceedance for the equivalent control, which was 110.5 μg m^{-3} above the NEPM standard. With an emission inventory using emission factors minus 15% of the control and a 30 m stack height, this maximum 1 hour average for SO_2 would likely have been below the NEPM standard.

Table 3.5: Concentrations (μg m^{-3}) for experiment 1a (emission factors -10%) minus the control simulated by AERMOD for all combinations of meteorology and ship stack height. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	$\mathbf{SO_2}$	$\mathbf{NO_2}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
Water	20 m	1 hr	-73.5 (-10.0%)	-2.50 (-1.5%)	-	-
			137.1			
		24 hr	-12.7 (-10.0%)	-	1.30 (-10.0%)	-1.50 (-10.0%)
		1 yr	-0.70 (-10.0%)	-0.50 (-9.8%)	-0.07 (-10.3%)	-0.07 (-10.4%)
	30 m	1 hr	-63.5 (-10.0%)	-5.40 (-3.3%)	-	-
			47.1			
		24 hr	-11.2 (-10.0%)	-	-1.20 (-10.0%)	-1.30 (-10.0%)
		1 yr	-0.60 (-10.3%)	-0.50 (-9.9%)	-0.06 (-10.3%)	-0.07 (-10.4%)
Land	20 m	1 hr	-30.8 (-10.0%)	-2.70 (-1.9%)	-	-
		24 hr	-11.3 (-9.5%)	-	-1.10 (-10.0%)	-1.20 (-10.0%)
		1 yr	-0.72 (-10.2%)	-0.60 (-10.1%)	-0.07 (-10.2%)	-0.08 (-10.3%)
	30 m	1 hr	-30.8 (-10.O%)	-4.70 (-3.5%)	-	-
		24 hr	-11.3 (-9.5%)	-	-1.10 (-10.0%)	-1.20 (-10.0%)
		1 yr	-0.60 (-10.3%)	-0.50 (-10.2%)	-0.06 (-11.3%)	-0.07 (-10.3%)

Table 3.6 shows differences in concentrations of AERMOD simulations with plus 10% emission factors and the control. As expected, results for AERMOD simulations with emission factors plus 10% of the control emission inventory produced concentrations slightly higher than the control with an increase of approximately 10%. The higher emission factors had a lesser effect on NO_2 with maximum 1 hour averages showing an increase from the control of no more than 1.1%. The maximum 1 hour average for SO_2 with meteorology over water exceeded the NEPM standard by 284.0 μg m^{-3} for a 20 m stack height and 174 μg m^{-3} for a 30 m stack height. Even with the increase in emission factors, the maximum 1 hour average for SO_2 did not exceed the NEPM standard with meteorology over land. With meteorology over land and a 20 m stack height, the concentration was still below the NEPM standard. Again, this shows that the influence of meteorology over land versus water is significant enough to affect AERMOD's simulations of NEPM exceedances.

2. **Sensitivity to cruise ship fuel efficiency (experiment 2 in Table2.3)**
   Table 3.7 shows differences in concentrations simulated by AERMOD for experiment 2 (cruise ship fuel efficiency) and the control. Generally the concentrations for the sensitivity test (a_b of 0.0165 kg hr^{-1}) were lower than equivalent concentrations in the control simulations (a_b of 0.0328 kg hr^{-1} for Australian cruise ships). With meteorology over water differences between experiment 2 and the control varied in magnitude depending on stack height. With a 20 m stack height, experiment 2 had the largest differences with a 78.6% decrease from the control for the maximum 1 hour average for

Table 3.6: Concentrations (μg m^{-3}) for experiment 1b (emission factors +10%) minus the control simulated by AERMOD for all combinations of meteorology and ship stack height. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
Water	20 m	1 hr	73.5 (10.0%)	0.50 (0.3%)	-	-
			284.0			
		24 hr	12.7 (10.0%)	-	1.30 (10.0%)	1.50 (10.0%)
		1 yr	0.60 (9.7%)	0.50 (9.0%)	0.06 (9.7%)	0.07 (9.6%)
	30 m	1 hr	63.5 (10.0%)	3.30 (2.0%)	-	-
			174.0			
		24 hr	11.2 (10.0%)	-	1.20 (10.0%)	1.30 (10.0%)
		1 yr	0.60 (9.6%)	0.40 (9.0%)	0.06 (9.6%)	0.06 (9.5%)
Land	20 m	1 hr	30.8 (10.0%)	1.60 (1.1%)	-	-
		24 hr	12.6 (10.5%)	-	1.10 (10.0%)	1.20 (10.0%)
		1 yr	0.68 (9.7%)	0.60 (9.4%)	0.07 (9.7%)	0.07 (9.7%)
	30 m	1 hr	30.8 (10.0%)	3.50 (2.6%)	-	-
		24 hr	12.6 (10.5%)	-	1.10 (10.0%)	1.20 (10.0%)
		1 yr	0.60 (9.7%)	0.50 (9.4%)	0.06 (9.7%)	0.07 (9.6%)

SO_2. This large reduction resulted in a concentration 366.9 μg m^{-3} below the NEPM standard.

With meteorology over water and a 30 m stack height, the maximum 1 hour average for SO_2 was only lowered from the control by 9.8%, and remained above the NEPM standard by 48.4 μg m^{-3} (shown in red in Table 3.7). With meteorology over land, differences were less significant for NO_2 and PM. However, for SO_2 concentrations were again dependent on stack height. A 20 m stack height reduced SO_2 concentrations by up to 53.8% for the maximum 1 hour average, but had no effect for concentrations with a 30 m stack height. As concentrations for the control with meteorology over land did not exceeded NEPM standards, neither did concentrations with meteorology over land in experiment 2 as concentrations were lower than the control.

3. **Sensitivity to modifier values for calculating fuel consumption (experiment 3 in Table 2.3)**

Table 3.8 shows differences in concentrations simulated by AERMOD for experiment 3 (modifier values for calculating fuel consumption) and the control. With meteorology over water, the concentrations for SO_2 were strongly dependent on stack height. With a 20 m stack height, concentrations were lowered from the control by as much as 77.3% for the maximum 1 hour average and did not exceeded the NEPM standard. For 30 m stack heights, the lower engine load had a negligible effect on concentrations. The

Table 3.7: Concentrations (μg m^{-3}) for experiment 2 (cruise ship fuel efficiency) minus the control simulated by AERMOD for all combinations of meteorology and ship stack height. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
Water	20 m	1 hr	-577.5 (-78.6%)	-24.0 (-14.3%)	-	-
		24 hr	-38.1 (-29.9%)	-	-3.00 (-22.3%)	-3.2 (-22.1%)
		1 yr	-1.20 (-18.0%)	-0.20 (-3.3%)	-0.10 (-8.7%)	-0.10 (-7.9%)
	30 m	1 hr	-62.1 (-9.8%)	-20.6 (-12.6%)	-	-
			48.4			
		24 hr	-0.80 (-0.7%)	-	-1.40 (-11.8%)	-1.50 (-11.6%)
		1 yr	-0.40 (-7.5%)	-0.20 (-3.6%)	-0.10 (-8.7%)	0.0 (-7.8%)
Land	20 m	1 hr	-165.4 (-53.8%)	3.30 (2.3%)	-	-
		24 hr	-31.2 (-26.1%)	-	0.0 (0.0%)	0.10 (0.8%)
		1 yr	-1.10 (-15.2%)	0.10 (1.7%)	0.0 (-6.6%)	0.0 (-6.0%)
	30 m	1 hr	0.0 (0.0%)	-1.50 (-1.2%)	-	-
		24 hr	1.10 (0.9%)	-	0.0 (0.0%)	0.10 (0.8%)
		1 yr	-0.30 (-6.0%)	-0.30 (-6.0%)	0.0 (-7.0%)	0.0 (-6.3%)

maximum 1 hour average for SO_2 remained above the NEPM standard by 110.5 μg m^{-3} (shown in red in Table 3.8). For NO_2 and PM the reduced engine load had little to no effect on concentrations with meteorology over water. With meteorology over land, again the effect of lower engine load on concentrations of SO_2 depended on stack height. The maximum 1 hour average for SO_2 with 20 m stack heights was reduced by 53.8% from the control. However, with a 30 m stack height, the lower engine load had no effect on concentrations of SO_2. Again, a lower engine load had little to no effect on concentrations of NO_2 and PM regardless of stack height. Concentrations with meteorology over land did not exceed NEPM standards, as they were lower than the control.

4. **Sensitivity to building downwash (experiment 4 in Table 2.3)**

   The building downwash feature was assessed with meteorology over water and stack height at 20 m versus 30 m. Simulations were not carried out with meteorology over land as previous sensitivity test results had shown lower concentrations with meteorology over land, and the focus of this test was to assess if turning building downwash off affected NEPM exceedances. Results for this experiment are shown in Table 3.9. Turning downwash off resulted in lower concentrations compared to the equivalent control simulations for all pollutants. Downwash had the largest effect on the maximum 1 hour averages for SO_2 for both stack heights, with reductions of 47.6% for 20 m stack heights and 50.3% for 30 m stack heights. Both of these concentrations were below NEPM standards. All other concentrations were also lower than the equivalent control concentrations with downwash turned on. Therefore AERMOD is sensitive to building downwash.

Table 3.8: Concentrations (μg m^{-3}) for experiment 3 (modifier values for calculating fuel consumption) minus the control simulated by AERMOD for all combinations of meteorology and ship stack height. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
Water	20 m	1 hr	-567.5 (-77.3%)	0.0 (0.0%)	-	-
		24 hr	-38.0 (-29.9%)	-	0.01 (0.1%)	0.01 (0.1%)
		1 yr	-0.91 (-13.9%)	1.13 (2.4%)	0.01 (1.8%)	0.01 (1.7%)
	30 m	1 hr	0.0 (0.0%)	0.0 (0.0%)	-	-
			110.5			
		24 hr	0.07 (0.1%)	-	0.01 (0.1%)	0.01 (0.1%)
		1 yr	0.10 (1.8%)	0.13 (2.7%)	0.01 (2.0%)	0.01 (1.9%)
Land	20 m	1 hr	-165.4 (-53.8%)	3.26 (2.3%)	-	-
		24 hr	-31.1 (-26.1%)	-	0.11 (1.0%)	0.11 (1.0%)
		1 yr	-0.68 (-9.7%)	0.10 (1.7%)	-0.05 (-7.0%)	-0.05 (-6.0%)
	30 m	1 hr	0.0 (0.0%)	10.2 (7.7%)	-	-
		24 hr	1.19 (1.0%)	-	0.11 (1.0%)	0.11 (1.0%)
		1 yr	0.08 (1.4%)	0.10 (2.0%)	0.01 (1.6%)	0.01 (1.5%)

Table 3.9: Concentrations (μg m^{-3}) for experiment 4 (building downwash turned off) minus the control simulated by AERMOD with meteorology over water and 20 m and 30 m stack heights. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	SH	AP	SO_2	NO_2	$PM_{2.5}$	PM_{10}
Water	20 m	1 hr	-349.8 (-47.6%)	-23.6 (-14.1%)	-	-
		24 hr	-16.2 (-12.7%)	-	-2.97 (-22.3%)	-3.25 (-22.3%)
		1 yr	-2.73 (-42.0%)	-2.84 (-53.1)	-0.30 (-46.0%)	-0.33 (-46.1%)
Water	30 m	1 hr	-319.4 (-50.3%)	-20.7 (-12.7%)	-	-
		24 hr	-1.02 (-0.9%)	-	-1.38 (-11.8%)	-1.52 (-11.8%)
		1 yr	-1.93 (-33.9%)	-2.59 (-54.9%)	-0.22 (-38.4%)	-0.24 (-38.5%)

To summarise the sensitivity tests, in nearly all cases, meteorology over water for all experiments resulted in exceedances of the maximum 1 hour average for SO_2 regardless of which emission inventory was used. The only exceptions to this were with experiments 2 (cruise ship fuel efficiency) and 3 (modifier values for calculating fuel consumption), where the combination of meteorology over water and a 20 m stack height with these 2 emission inventories reduced the maximum 1 hour average for SO_2 to below NEPM standards. AERMOD is also sensitive to building downwash with meteorology over water, simulating an exceedance of the 1 hour average for SO_2 with the building downwash turned on for both stack heights, and no exceedances with the building downwash turned off. None of the NEPM standards were exceeded with meteorology over land.

Upon inspection of the ship movement data for Fremantle port in the 2011/2012 financial year, the exceedances of the maximum 1 hour average for SO_2 across all experiments occurred at the same time and in the same location. None of the NEPM standards were exceeded for any other pollutant.

3.2.1 Exceedances of standards by first, second and subsequent highest concentrations

As discussed in Section 2.5, NEPM standards have a maximum allowable number of exceedance days, shown in Table 2.7. The 1 and 24 hour averages for SO_2 and NO_2 may be exceeded on 1 day per year and the 24 hour averages for PM may be exceeded on 5 days per year. AERMOD simulated concentrations above NEPM standards for the maximum 1 hour average for SO_2 for several experiments with meteorology over water and stack heights at 20 m and 30 m. To assess if emissions from Fremantle port occurred on a number of days above the maximum allowable exceedance days, second highest to sixth highest concentrations were calculated for those model simulations that exceeded NEPM standards. This is illustrated in Tables 3.10 and 3.11 showing the highest and second highest concentrations respectively, simulated by AERMOD for all model simulations with maximum 1 hour exceedances of SO_2. The third highest to sixth highest concentrations are shown in Tables F.1 to F.4 in Appendix F. The tables show the absolute concentrations in red followed by the amount by which it exceeds the NEPM standard of 524 μg m^{-3} in parentheses.

For the highest concentrations, all exceedances occurred on the 17th February 2012 at 5pm as shown in Table 3.10. This exceedance matches the exceedance reported in Rolfe (2016). During this time, 3 large ships were berthed in Fremantle inner harbour, which contributed to the emissions and were likely responsible for the exceedance. The second highest concentrations for SO_2 ranged from 124.9 μg m^{-3} to 36.5 μg m^{-3} above the NEPM standard (Table 3.11). Some of these simulated exceedances occurred on the 26th April 2012 making the number of exceedance days 2, which exceeds the number of maximum allowable exceedance days of 1. The remaining simulated exceedances occurred on the 17th February 2012 at 4pm, the hour before the first highest exceedance. Table 3.12 shows the simulated number of days the maximum 1 hour average for SO_2 was exceeded for each AERMOD simulation in total. On several accounts this was up to 3 days in the year (experiments 1a and 1b).

3.3 AERMOD simulations focussing on Fremantle inner harbour

Nearly all AERMOD simulations with meteorology over water resulted in exceedances of the maximum 1 hour average concentration for SO_2. Therefore, AERMOD was re-run with a smaller domain with higher receptor resolution in order to investigate these exceedances at a finer scale, as shown in Fig. 2.7. Due to the relatively coarse receptor domain used by Rolfe (2016) of just under 2.5 km between each receptor, highest concentrations may have been dispersed, but not simulated by AERMOD. The 4 control simulations where therefore repeated, and used the control emission inventory from Rolfe (2016) with meteorology over land versus water and 20 m versus 30 m stack heights.

Table 3.10: 1st highest concentrations (μg m^{-3}) simulated by AERMOD for all combinations of meteorology and stack heights for the maximum 1 hour average for SO_2. (MET is meteorology and SH is stack height.)

Experiment ID	MET	SH	1st highest concentrations	Date and time	No. ships contributing
Control	Water	20 m	734.5 (210.5)	17th Feb 2012 5pm	3
Control	Water	30 m	634.5 (110.5)	17th Feb 2012 5pm	3
1a	Water	20 m	661.1 (137.1)	17th Feb 2012 5pm	3
1a	Water	30 m	571.1 (47.1)	17th Feb 2012 5pm	3
1b	Water	20 m	808.0 (284.0)	17th Feb 2012 5pm	3
1b	Water	30 m	562.2 (38.2)	17th Feb 2012 5pm	3
2	Water	30 m	572.4 (48.4)	17th Feb 2012 5pm	3
3	Water	30 m	634.5 (110.5)	17th Feb 2012 5pm	3

Table 3.11: 2nd highest concentrations (μg m^{-3}) simulated by AERMOD for all combinations of meteorology and stack heights for the maximum 1 hour average for SO_2. (MET is meteorology and SH is stack height.)

Experiment ID	**MET**	**SH**	**2nd highest concentrations**	**Date and time**	**No. ships contributing**
Control	Water	20 m	589.9 (65.9)	17th Feb 2012 4pm	3
Control	Water	30 m	none	-	-
1a	Water	20 m	560.5 (36.5)	26th April 2012 11pm	5
1a	Water	30 m	560.5 (36.5)	26th April 2012 11pm	5
1b	Water	20 m	648.9 (124.9)	17th Feb 2012 4pm	3
1b	Water	30 m	562.2 (38.2)	26th April 2012 11pm	5
2	Water	30 m	none	-	-
3	Water	30 m	572.4 (48.4)	26th April 2012 11pm	5

Table 3.12: Number of days each AERMOD simulation exceeded the maximum 1 hour average for SO_2 for the period 1 July 2011 to 30 June 2012. Where the NEPM standard is exceeded on more than 1 day in the year the number of days is highlighted in red.

Experiment ID	**Meteorology**	**Stack height**	**Number of days**
Control	Water	20 m	1 day
Control	Water	30 m	1 day
1a	Water	20 m	3 days
1a	Water	30 m	3 days
1b	Water	20 m	3 days
1b	Water	30 m	3 days
2	Water	30 m	1 day
3	Water	30 m	2 days

Table 3.13: Summary of experiments and AERMOD model set up for the small, high resolution domain over Fremantle inner harbour for each pollutant (SO_2, NO_2, $PM_{2.5}$ and PM_{10}; MET is meteorology and SH is stack height).

Experiment ID	**MET**	**SH**	**Cruise ship efficiency**	**Modifier values**	**Building downwash**
Control	water & land	20 & 30 m	0.0328 kg hr^{-1}	92%	ON
2	land	20 m	0.0165 kg hr^{-1}	92%	ON
3	land	20 m	0.0328 kg hr^{-1}	85%	ON
4	water	20 & 30 m	0.0328 kg hr^{-1}	92%	OFF

2 sensitivity experiments were carried out based on results from the larger model domain simulations. These assessed experiments 2 (cruise ship fuel efficiency) and 3 (modifier values for calculating fuel consumption), using meteorology over land and 20 m stack heights summarised in Table 3.13. These experiments were used as the test focussed on whether the higher resolution receptor domain would affect the simulated highest concentrations, where the lower resolution receptor domain may have been too coarse to show maximum concentrations. The final simulation repeated experiment 4 with building downwash turned off, meteorology over water and 20 m and 30 m stack heights.

1. **Control simulations with the high resolution receptor domain (experiment 1 in Table 3.13).**

   Figs. 3.4, 3.5 and 3.6 show concentrations distributions for the 1 hour, 24 hour and annual averages respectively, with meteorology over water and stack height at 20 m. Contour plots for the remainder control simulations (meteorology over land and stack height at 30 m) are shown in Appendix E. For all simulations with the control emission inventory, pollutant dispersion was most concentrated in the inner harbour, approximately at berth locations 10, 12 and H, which are shown in Fig. 3.7. Fig. 3.8 shows that these 3 berth locations (10, 12 and H) had the highest number of berthed ships throughout the 2011/2012 financial year. Fig. 3.9 shows the total annual emissions of SO_2 for each berth location in the inner harbour and is consistent with the contour plots, showing high emissions for berths 10, 12 and H. Interestingly, berth F also showed high emissions over the 2011/2012 financial year despite the low number of ships berthed there throughout the year.

Table 3.14 shows the absolute concentrations over Fremantle inner harbour simulated by AERMOD for the control simulations with the high resolution receptor domain. With this receptor domain nearly all maximum 1 hour and 24 hour averages for all pollutants exceeded NEPM standards. Maximum 1 hour and 24 hour concentrations for SO_2 exceeded NEPM standards by as much as 1656 μg m^{-3} for the control simulation with meteorology over water and 20 m stack heights. All maximum 1 hour averages of NO_2 and all maximum 24 hour averages for $PM_{2.5}$ exceeded NEPM standards. This high number of exceedances is most likely due to the high resolution receptor domain. The berth locations are approximately 250 m apart (Fig. 3.7),

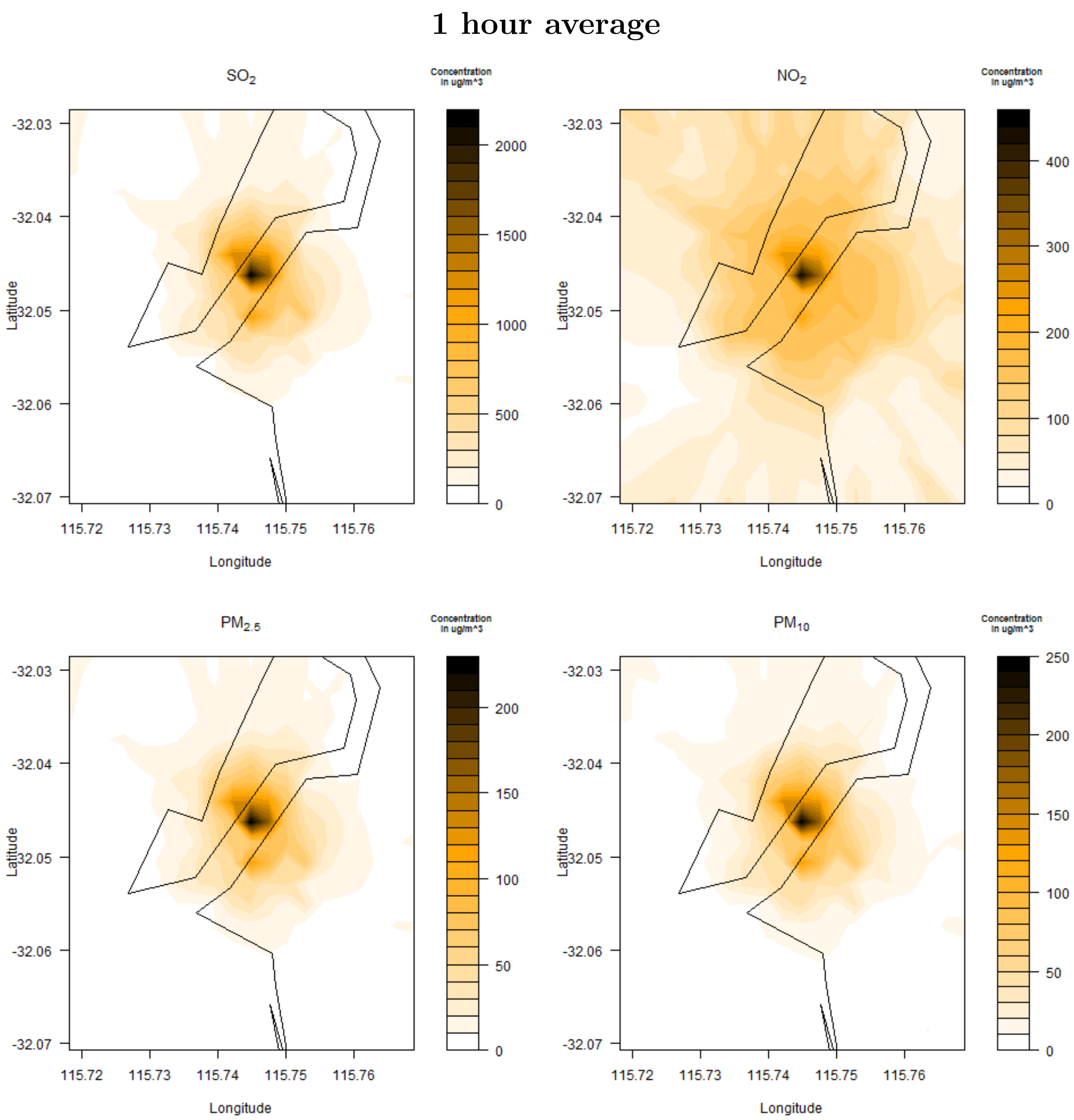

Figure 3.4: 1 hour average concentrations over Fremantle inner harbour simulated by AERMOD for the control simulation with meteorology over water and stack height at 20 m.

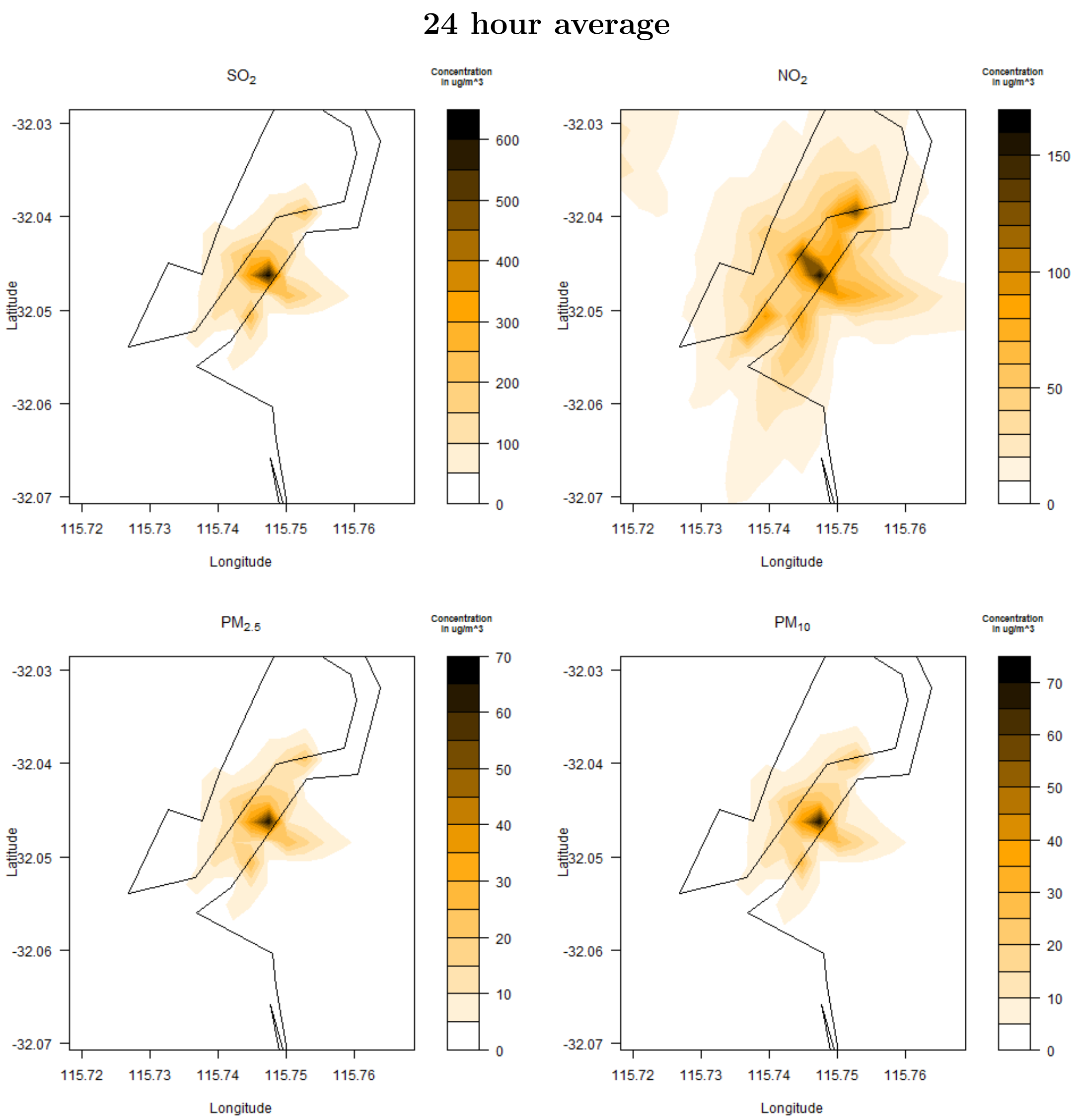

Figure 3.5: 24 hour average concentrations over Fremantle inner harbour simulated by AERMOD for the control simulation with meteorology over water and stack height at 20 m.

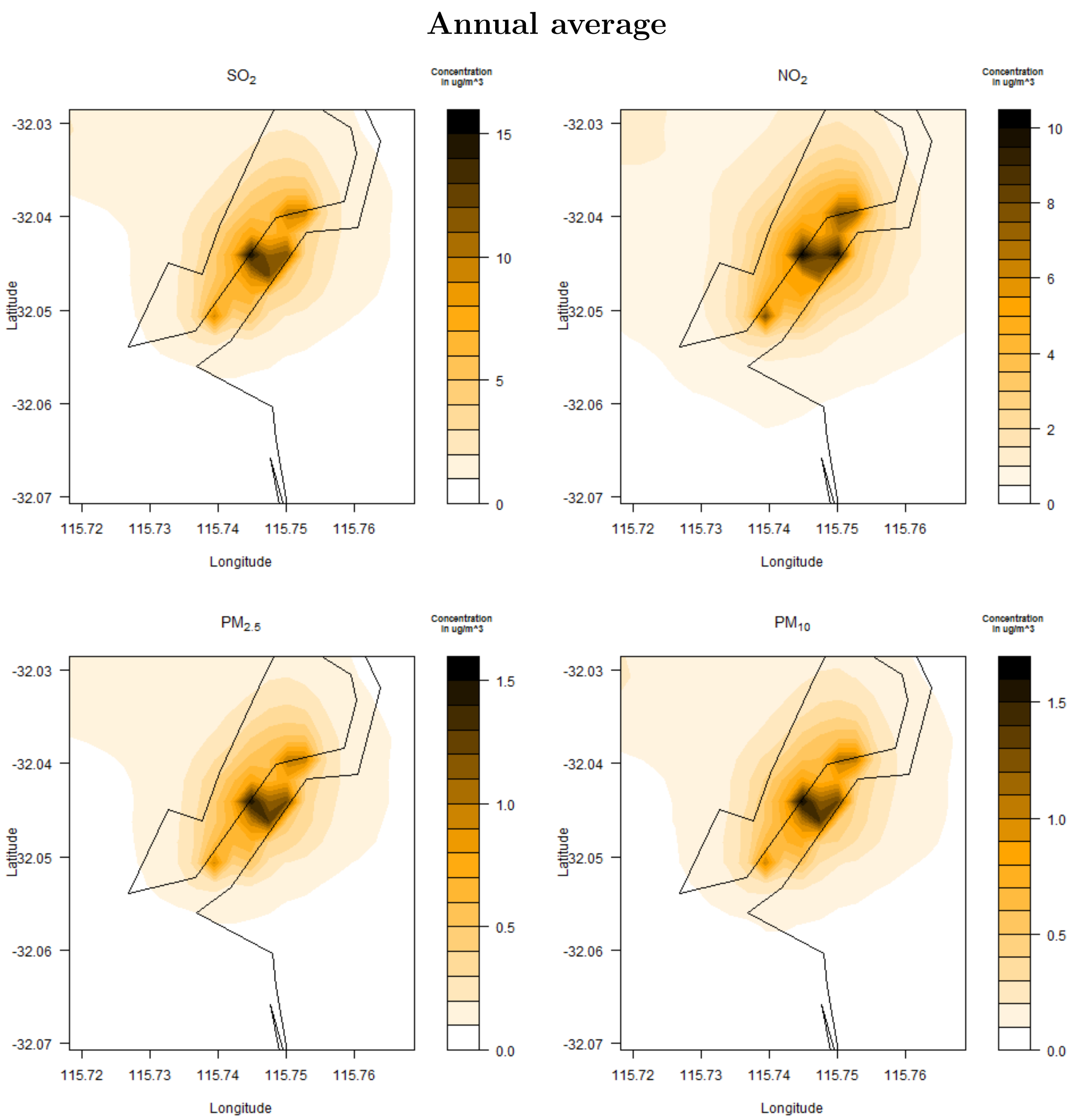

Figure 3.6: Annual average concentrations over Fremantle inner harbour simulated by AERMOD for the control simulation with meteorology over water and stack height at 20 m.

Figure 3.7: Map of Fremantle inner harbour showing berth locations. (Rolfe, 2016).

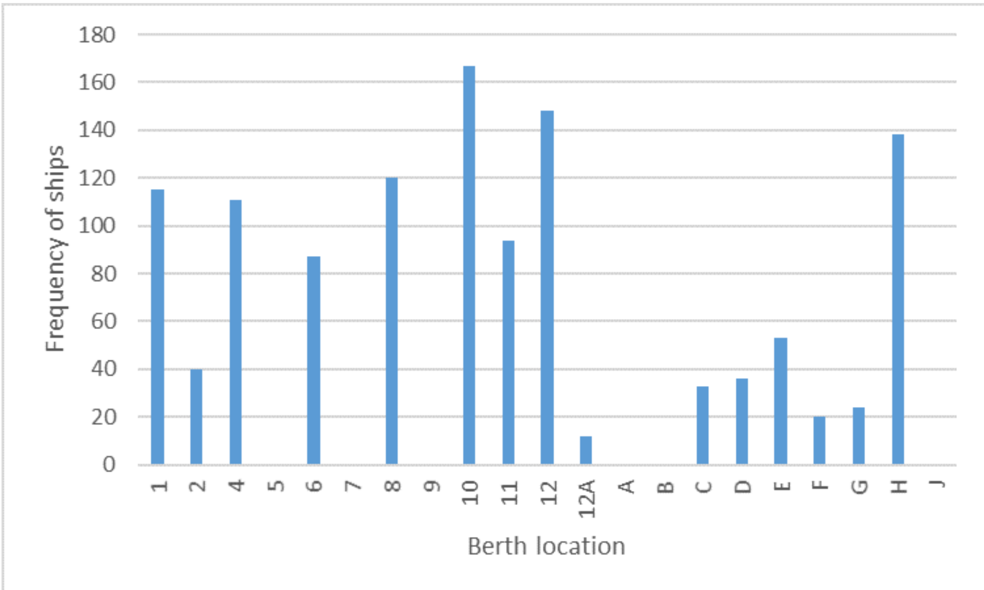

Figure 3.8: Histogram showing the number of ships berthed at each location in Fremantle inner harbour for the 2011/2012 financial year.

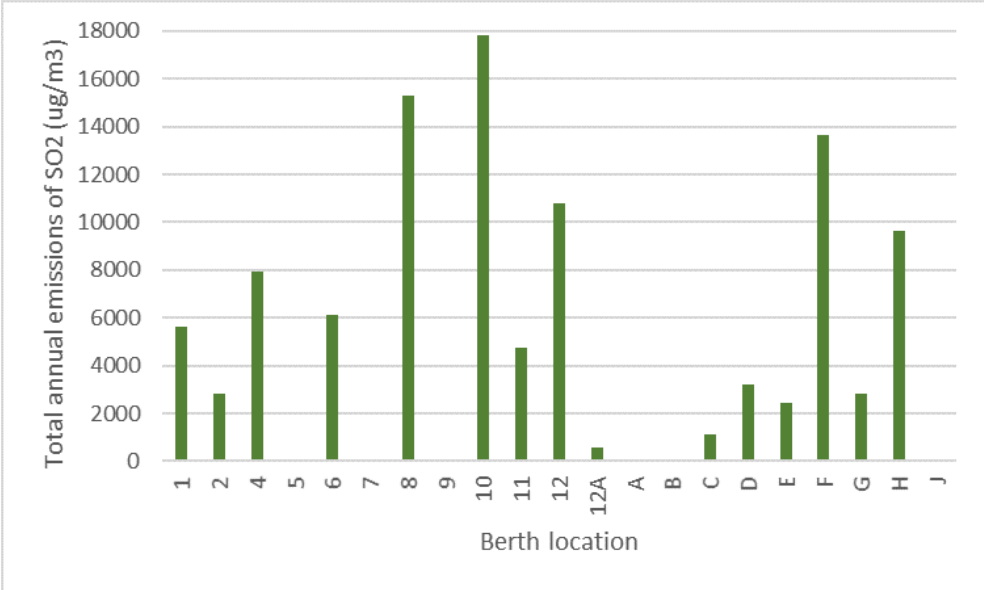

Figure 3.9: Histogram showing the total annual emissions at each location in Fremantle inner harbour for the 2011/2012 financial year.

which is the same as the resolution of the receptor domain (Fig 2.7). This means that each receptor is placed roughly "on top" of ships berthed in the inner harbour and simulated concentrations will be high. However, no annual averages exceeded NEPM standards.

Concentrations with meteorology over water were higher than concentrations with meteorology over land. Similarly, stack heights of 20 m had higher concentrations than stack heights of 30 m. Although meteorology over land and stack height at 30 m did not affect concentrations enough to bring them below NEPM standards, both factors still had a significant effect on concentrations by reducing them substantially, as shown in Table 3.14.

Table 3.14: Absolute concentrations (μg m^{-3}) simulated by AERMOD over Fremantle inner harbour for the control simulations with the higher resolution receptor domain and all combinations of meteorology and stack height. (NEPM exceedances are shown in red and the amount by which it is exceeded follows in parentheses; MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
Water	20 m	1 hr	2179.8 (1655.8)	442.1 (216.1)	-	-
		24 hr	624.7 (415.7)	-	65.6 (40.6)	71.5 (21.5)
		1 yr	15.2	10.3	1.50	1.60
	30 m	1 hr	1592.4 (1068.4)	323.0 (97.0)	-	-
		24 hr	378.1 (169.1)	-	39.7 (14.7)	43.3
		1 yr	10.2	7.77	1.01	1.11
Land	20 m	1 hr	1700.5 (1176.5)	344.8 (118.8)	-	-
		24 hr	514.7 (305.7)	-	54.0 (29) (29.0)	58.9 (8.90)
		1 yr	23.8	15.2	2.35	2.56
	30 m	1 hr	1296.6 (772.6)	262.9 (36.9)	-	-
		24 hr	380.3 (171.3)	-	39.9 (14.9)	43.5
		1 yr	14.9	11.1	1.48	1.61

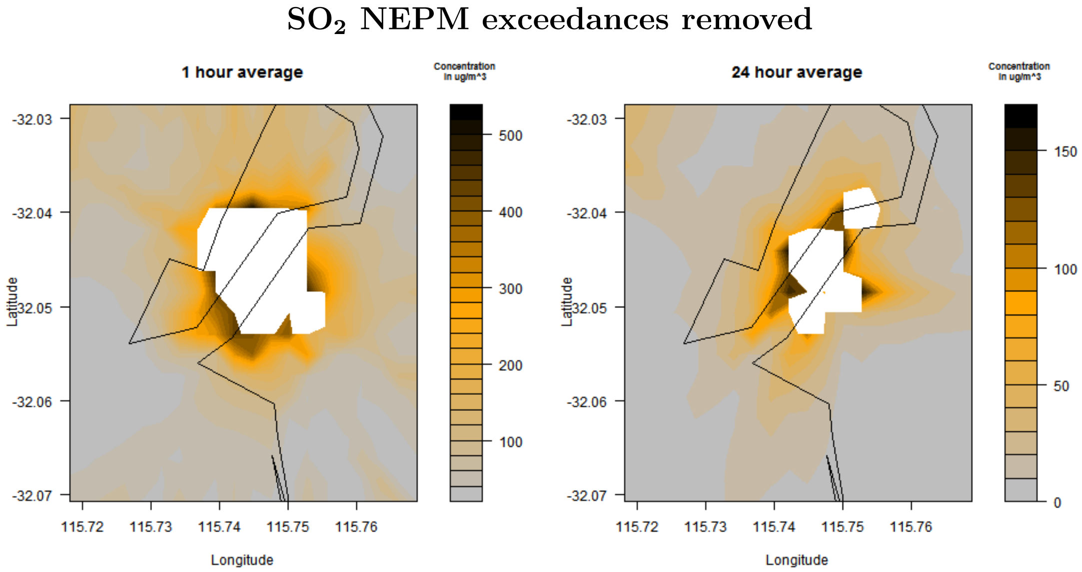

Figure 3.10: 1 hour and 24 hour average concentrations for SO_2 with NEPM exceedances removed over Fremantle inner harbour simulated by AERMOD for the control simulation with meteorology over water and stack height at 20 m.

Fig. 3.10 shows the 1 hour averages and 24 hour averages for SO_2 with the high resolution domain with concentrations above the respective NEPM standards removed. These contour plots demonstrate the area of exceedance over Fremantle inner harbour shown by the white space. The exceedance area covers most of the inner harbour for the 1 hour averages, extending over land either side of the harbour. The exceedance area for the 24 hour averages cover port waters in the inner harbour and extends slightly over land and berth 12A.

2. **Sensitivity to cruise ship fuel efficiency (experiment 2 in Table 3.13) with the high resolution receptor domain**

Table 3.15: Concentrations (μg m^{-3}) over Fremantle inner harbour for experiment 2 (cruise ship fuel efficiency) minus the control simulated by AERMOD with meteorology over land and stack height at 20 m. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
Land	20 m	1 hr	-844.1 (-49.6%)	-136.5 (-40.0%)	-	-
			332.4			
		24 hr	-224.8 (-43.7%)	-	-25.4 (-47.1%)	-27.7 (-47.1%)
			80.9		3.60	
		1 yr	-0.34 (-1.4%)	-0.18 (-1.2%)	-0.04 (-1.7%)	-0.04 (-1.5%)

Table 3.15 shows the differences in concentrations simulated by AERMOD over Fremantle inner harbour between experiment 2 and the control. Concentrations were greatly reduced from the equivalent control for all pollutants by up to nearly half for the maximum 1 hour average for SO_2, but the maximum 1 and 24 hour averages remained above NEPM standards. The annual average for NO_2 was reduced by 40.0% from the control bringing it below the NEPM standard. Similarly, the maximum 24 hour average for PM_{10} was reduced by 47.1% from the control and did not exceed the NEPM standard. The maximum 24 hour average for $PM_{2.5}$ however, remained above the NEPM standard. No annual averages exceeded NEPM standards.

3. **Sensitivity to modifier values for calculating fuel consumption (experiment 3 in Table 3.13) with the high resolution receptor domain**

   Table 3.16 shows the differences in concentrations simulated by AERMOD over Fremantle inner harbour between experiment 3 and the control. Changing the modifier values to reflect a combined engine load of 85% compared to 92% from Rolfe (2016) had little to no effect on concentrations compared to the control simulations with differences less than 1%. The only exception to this was for the maximum 1 hour average for NO_2 which showed an increase of 29.6% from the control, increasing the concentration to 220.7 μg m^{-3} above the NEPM standard, compared to 118.8 μg m^{-3} above the NEPM standard for the control simulation. As a result, the maximum 1 and 24 hour averages still exceeded the NEPM standards as well as the maximum 24 hour averages for PM. None of the annual averages exceeded NEPM standards for any pollutant.

In summary, simulations in the inner harbour of Fremantle port, with the high resolution receptor domain, resulted in exceedances of the 1 and 24 hour averages with meteorology over land and stack height at 20 m (Table 3.16). However, operating AERMOD with the low resolution domain only resulted in the maximum 1 hour average for SO_2 above the NEPM standard, and all other concentrations were below the NEPM standards (Table 3.8). This shows that the low resolution domain was too coarse to capture the highest concentrations simulated by AERMOD. It is also evident that NO_2 is sensitive to the modifier values for calculating fuel consumption, as

Table 3.16: Concentrations (μg m^{-3}) over Fremantle inner harbour for experiment 3 (modifier values for calculating fuel consumption) minus the control simulated by AERMOD with meteorology over land and stack height at 20 m. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	SH	AP	SO_2	NO_2	$PM_{2.5}$	PM_{10}
Land	20 m	1 hr	0.0 (0.0%)	101.9 (29.6%)	-	-
			1176.5	220.7		
		24 hr	0.06 (0.0%)	-	0.01 (0.0%)	0.01 (0.0%)
			305.8		29.0	58.9 (8.9)
		1 yr	0.09 (0.4%)	0.12 (0.8%)	0.01 (0.5%)	0.01 (0.4%)

the maximum 1 hour average exceeded the NEPM standard and was much larger than the equivalent control simulation.

4. **Sensitivity to building downwash (experiment 4 in Table 3.13) with the high resolution receptor domain**

Figs. 3.11, 3.12 and 3.13 show the concentrations across the receptor domain for building downwash turned on minus building downwash turned off over Fremantle inner harbour with the high resolution receptor domain for the 1 hour averages, 24 hour averages and annual averages respectively. The differences in concentrations were largest over berth locations E and F for the 1 hour averages (Fig. 3.11). With building downwash turned off, distances the concentrations travelled from the source was greater for all pollutants than with building downwash turned on (shown by the light orange colour covering the majority of the domain).

A similar pattern is shown in Fig. 3.12, where the largest differences for the 24 hour averages for all pollutants was over berth locations E, F, and also 8 and 12. Operating AERMOD with building downwash off again resulted in pollutants travelling further from the source before dispersing to ground level, compared to building downwash turned on. For both the 1 and 24 hour averages, this would be expected as the simulations did not take into account the effect of nearby buildings (i.e. ship bodies), which has the effect of dragging pollutants down to ground level due to building "wake". Therefore, pollutants remain aloft and travel further without the disruption of nearby buildings. For the annual averages shown in Fig. 3.13, the largest differences between building downwash turned on and off occurred over the entire inner harbour and, in particular, berth location 8, where total annual emissions were 15291 μg m^{-3} (Fig. 3.9) for the 2011/2012 financial year.

Table 3.17 shows the differences in concentrations over Fremantle inner harbour with building downwash turned on minus off. All concentrations with the building downwash turned off showed a decrease by as much as 81.7% for the maximum 24 hour averages for all pollutants with 20 m stack heights. These reductions were large enough to bring all concentrations below NEPM standards with only one exception. Although the maximum 1 hour average for SO_2 was reduced by 70.1% with building downwash turned

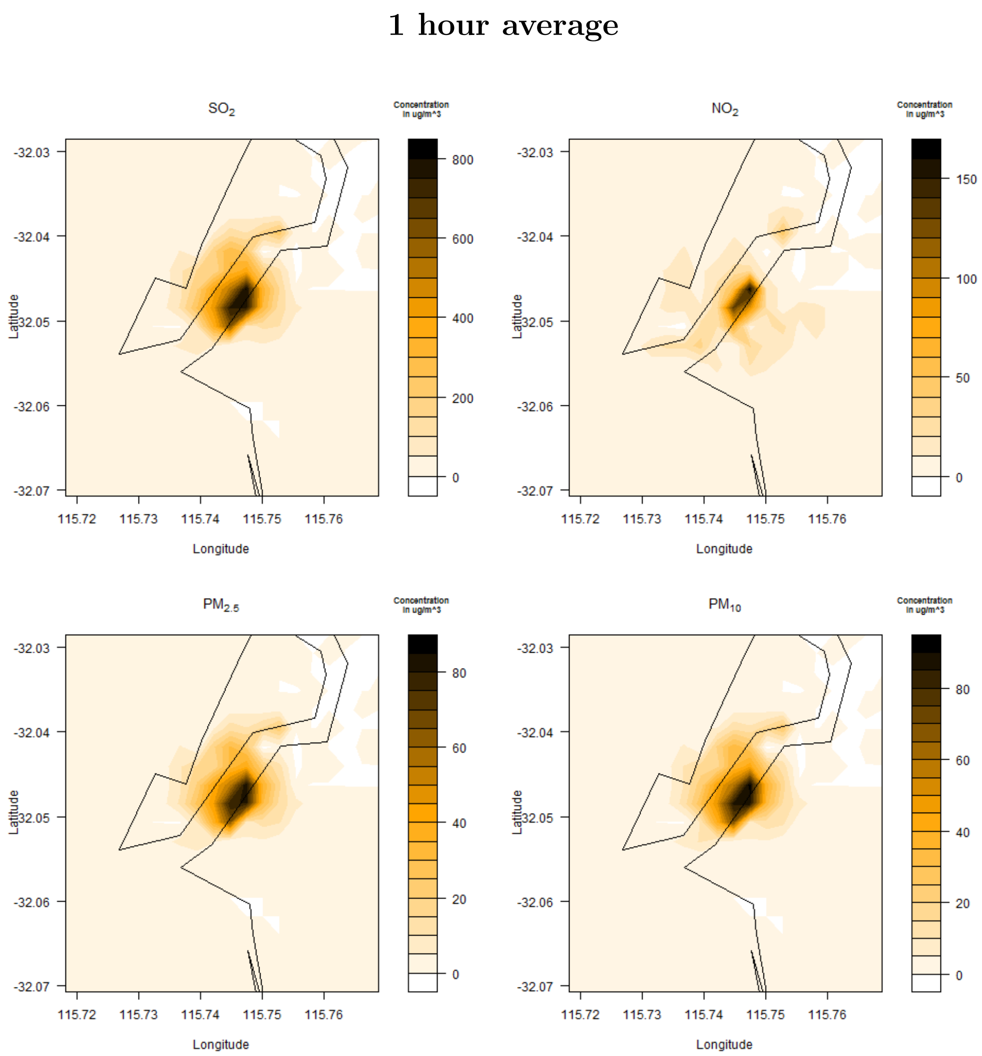

Figure 3.11: 1 hour average concentrations over Fremantle inner harbour for building downwash turned on minus building downwash turned off simulated by AERMOD with meteorology over water and 20 m stack heights.

24 hour average

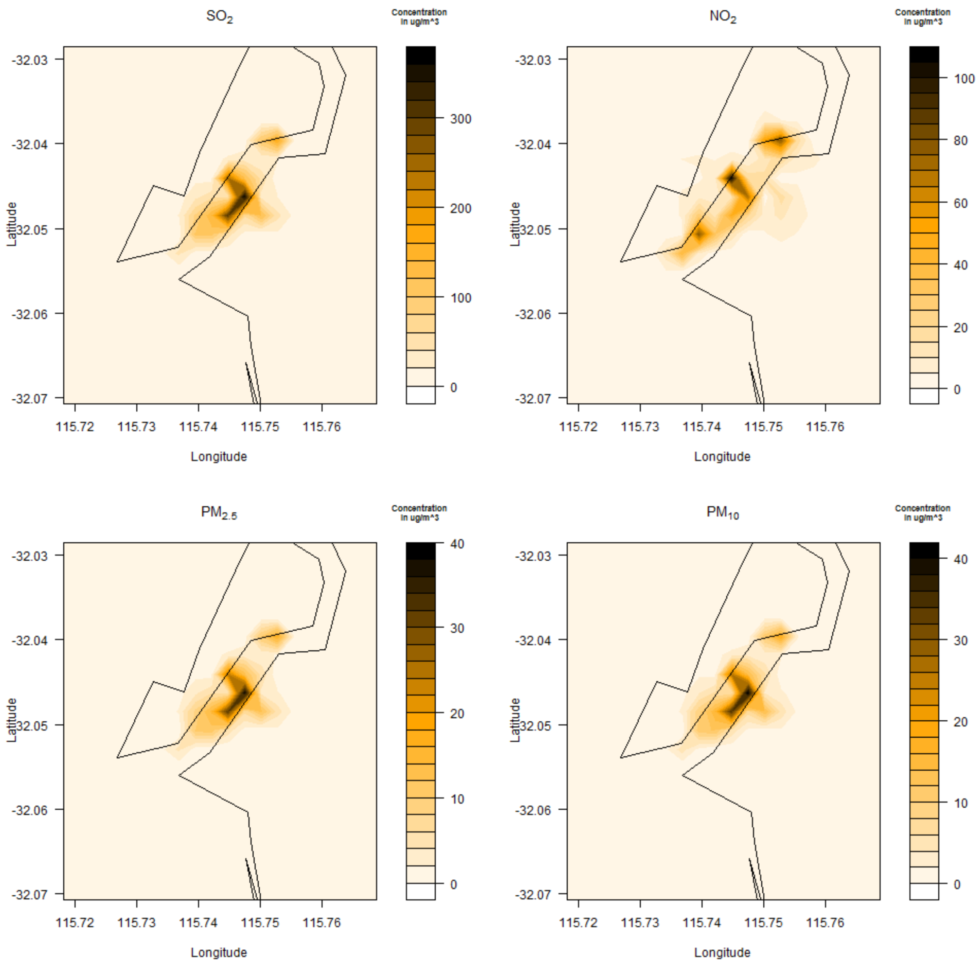

Figure 3.12: 24 hour average concentrations over Fremantle inner harbour for building downwash turned on minus building downwash turned off simulated by AERMOD with meteorology over water and 20 m stack heights.

Annual average

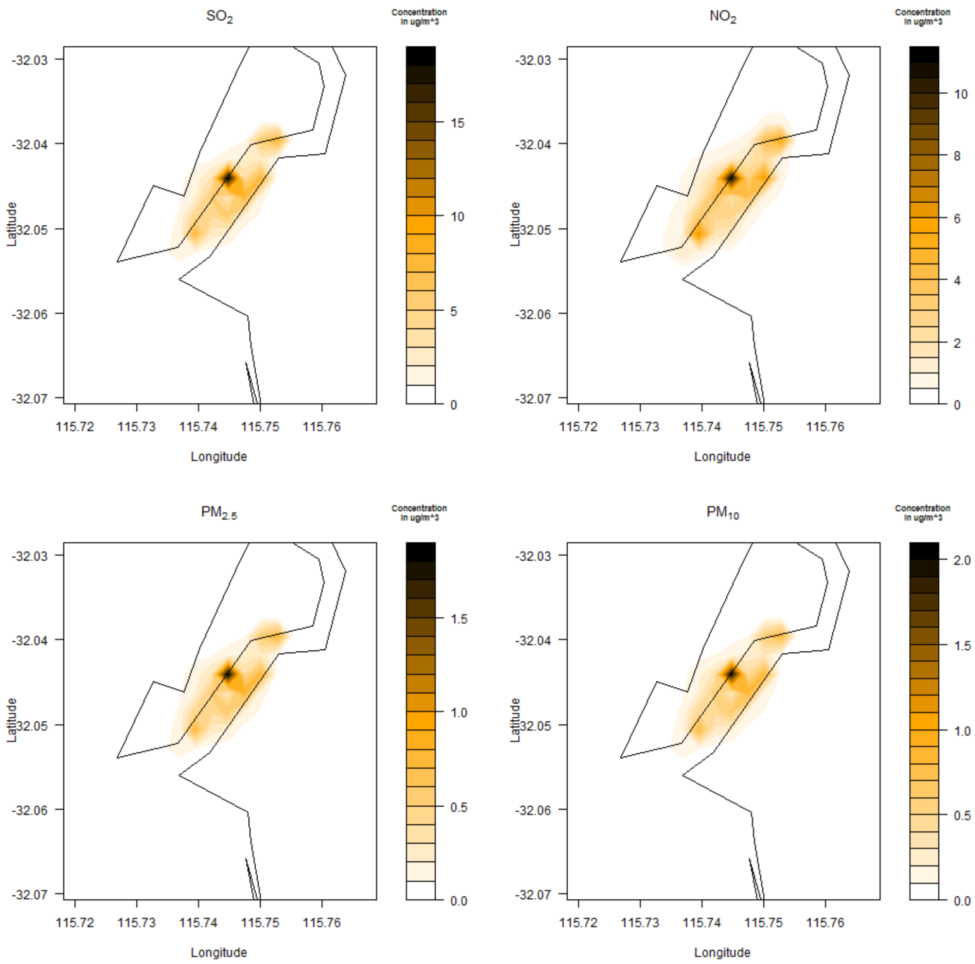

Figure 3.13: Annual average concentrations over Fremantle inner harbour for building downwash turned on minus building downwash turned off simulated by AERMOD with meteorology over water and 20 m stack heights.

off, it still exceeded the NEPM standard of 524 μg m^{-3} by 128.7 μg m^{-3}. However, this is still a large reduction of 1527.1 μg m^{-3} from the simulation with building downwash turned on. The combination of turning downwash off and using stack height of 30 m did reduce the maximum 1 hour average for SO_2 below the NEPM standard.

In summary, AERMOD was sensitive to the building downwash feature over the high resolution receptor domain. Turning downwash off in AERMOD is likely to produce lower concentrations than simulations with downwash turned on.

3.3.1 Exceedances of standards by second highest concentrations

Table 3.18 shows the absolute second highest concentrations that exceeded NEPM standards over Fremantle inner harbour simulated by AERMOD with the high resolution receptor domain. Absolute concentrations are shown in red followed by the amount by which it exceeds the NEPM standard in parentheses. The second highest concentration for the 1 hour average for SO_2 was 1485.4 μg m^{-3} for meteorology over land and 20 m stack heights, and 1686.5 μg m^{-3} for meteorology over water and 20 m stack heights. Second highest concentrations for the high resolution domain reach magnitudes more than 3 times above the NEPM standard for the control simulations with meteorology over water. This may be explained by the high resolution modelling domain, where receptors were placed very close to berth locations in the inner harbour.

Table 3.17: Concentrations (μg m^{-3}) over Fremantle inner harbour for building downwash turned on minus building downwash turned off simulated by AERMOD with meteorology over water and 20 m and 30 m stack heights. (MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
Water	20 m	1 hr	-1527.1 (-70.1%)	-277.9 (-62.8%)	-	-
			128.7			
		24 hr	-510.0 (-81.6%)	-	-53.6 (-81.7%)	-58.4 (-81.7%)
		1 yr	-11.5 (-75.7%)	-7.36 (-71.2%)	-1.14 (-75.7%)	-1.24 (-75.7%)
Water	30 m	1 hr	-1158.4 (-72.7%)	-177.2 (-54.9%)	-	-
		24 hr	-302.2 (-79.9%)	-	-31.7 (-80.0%)	-34.6 (-80.0%)
		1 yr	-7.31 (-71.7%)	-5.45 (-70.1%)	-0.73 (-71.8)	-0.79 (-71.7%)

Table 3.18: 2nd highest concentrations (μg m^{-3}) over Fremantle inner harbour simulated by AERMOD with the high resolution receptor domain for the control emission inventory and all combinations of meteorology and stack height for the 1 hour average for SO_2. (NEPM exceedances are shown in red and the amount by which it is exceeded follows in parentheses; MET is meteorology, SH is stack height, AP is averaging period.)

MET	**SH**	**AP**	**SO_2**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**
Land	20 m	1 hour	1485.4 (961.4)	301.3 (75.3)	-	-
		24 hours	472.9 (263.9)	-	49.6 (24.6)	54.1 (4.10)
	30 m	1 hour	1296.2 (772.2)	262.9 (36.9)	-	-
		24 hours	376.6 (167.6)	-	39.5 (14.5)	43.1
Water	20 m	1 hour	1686.5 (1162.5)	342.1 (116.1)	-	-
		24 hours	521.2 (312.2)	-	54.7 (29.7)	59.6 (9.60)
	30 m	1 hour	1578.9 (1054.9)	320.3 (94.3)	-	-
		24 hours	362.1 (153.1)	-	38.0 (13.0)	41.5

Further highest concentrations were not calculated for the high resolution receptor domain as information regarding the simulated exceedances were already examined for the larger domain, and with receptors placed so close to berth locations it was clear that a large number of the preceding highest concentrations would exceed NEPM standards.

Having presented the control simulations, the AERMOD sensitivity tests for the low resolution receptor domain and the AERMOD simulations for the high resolution domain, the following section presents results from the CALPUFF simulations.

3.4 CALPUFF

CALPUFF was operated with the high resolution receptor domain shown in Fig. 2.7 in order to compare highest concentrations to those from AERMOD simulations. Figs 3.14, 3.15 and 3.16 show the difference in concentrations of the 1 hour averages, 24 hour averages and annual averages respectively, between CALPUFF simulations and AERMOD simulations with meteorology over water. Contour plots for the difference between CALPUFF and AERMOD with meteorology over land, as well as absolute concentrations from CALPUFF are shown in Appendices G and I. The largest differences between AERMOD and CALPUFF occurred over berths E and F in the inner harbour, which is where AERMOD simulated the highest concentrations. Therefore AERMOD and CALPUFF had the largest differences for the maximum concentrations and concentrations closest to the sources (in the very near-field).

1 hour average

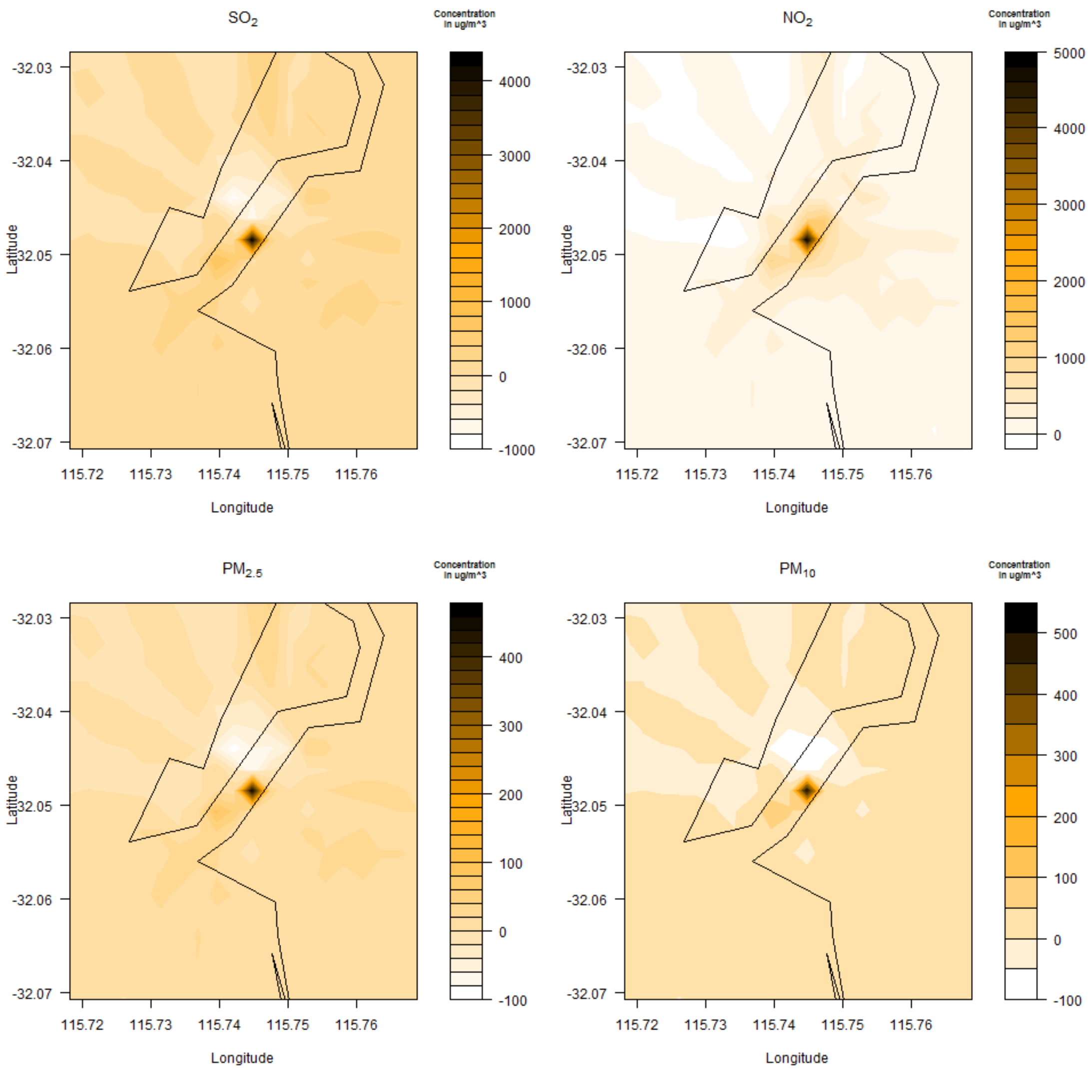

Figure 3.14: 1 hour average concentrations over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over water) for the control emission inventory and 20 m stack heights.

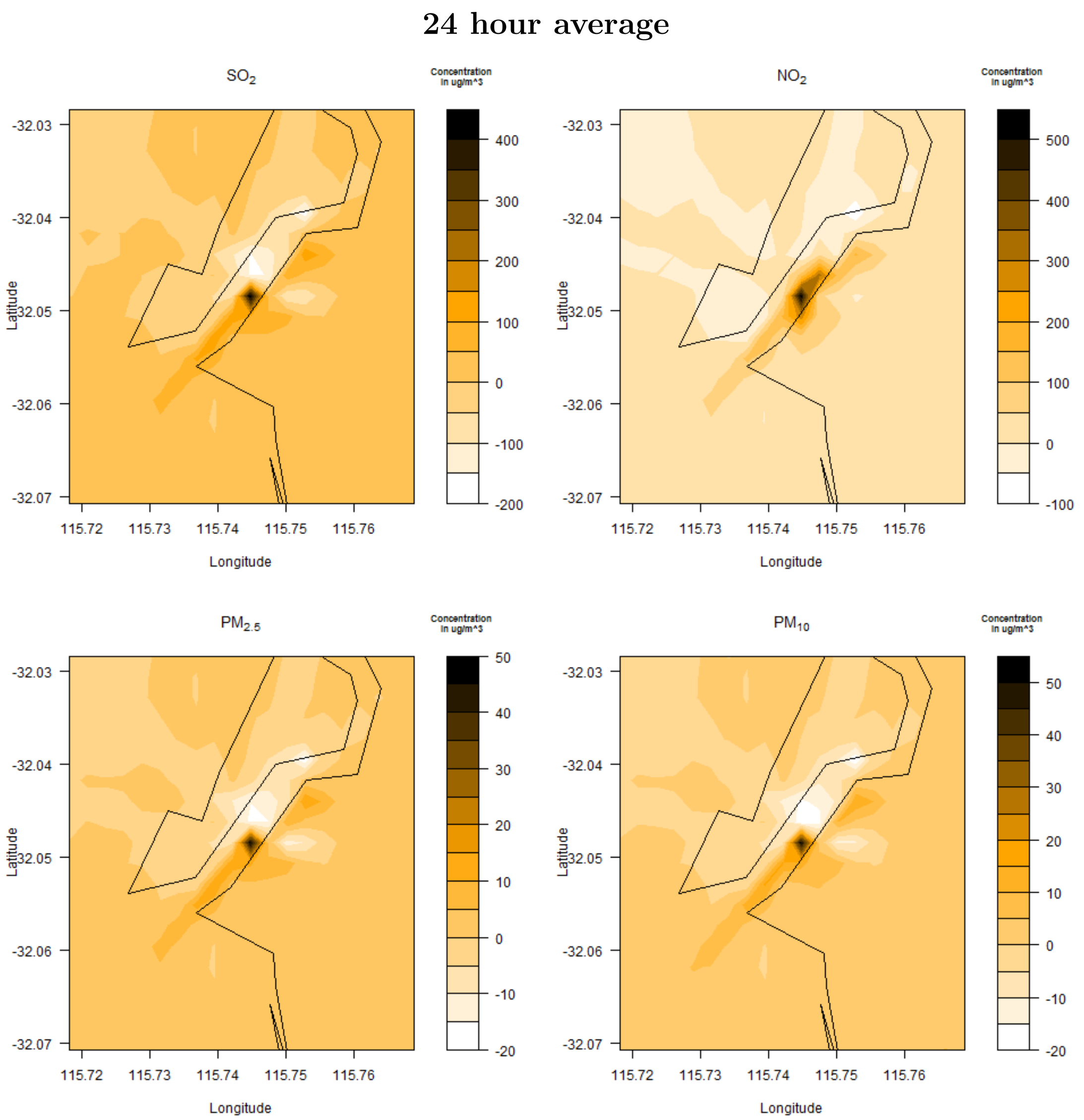

Figure 3.15: 24 hour average concentrations over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over water) for the control emission inventory and 20 m stack heights.

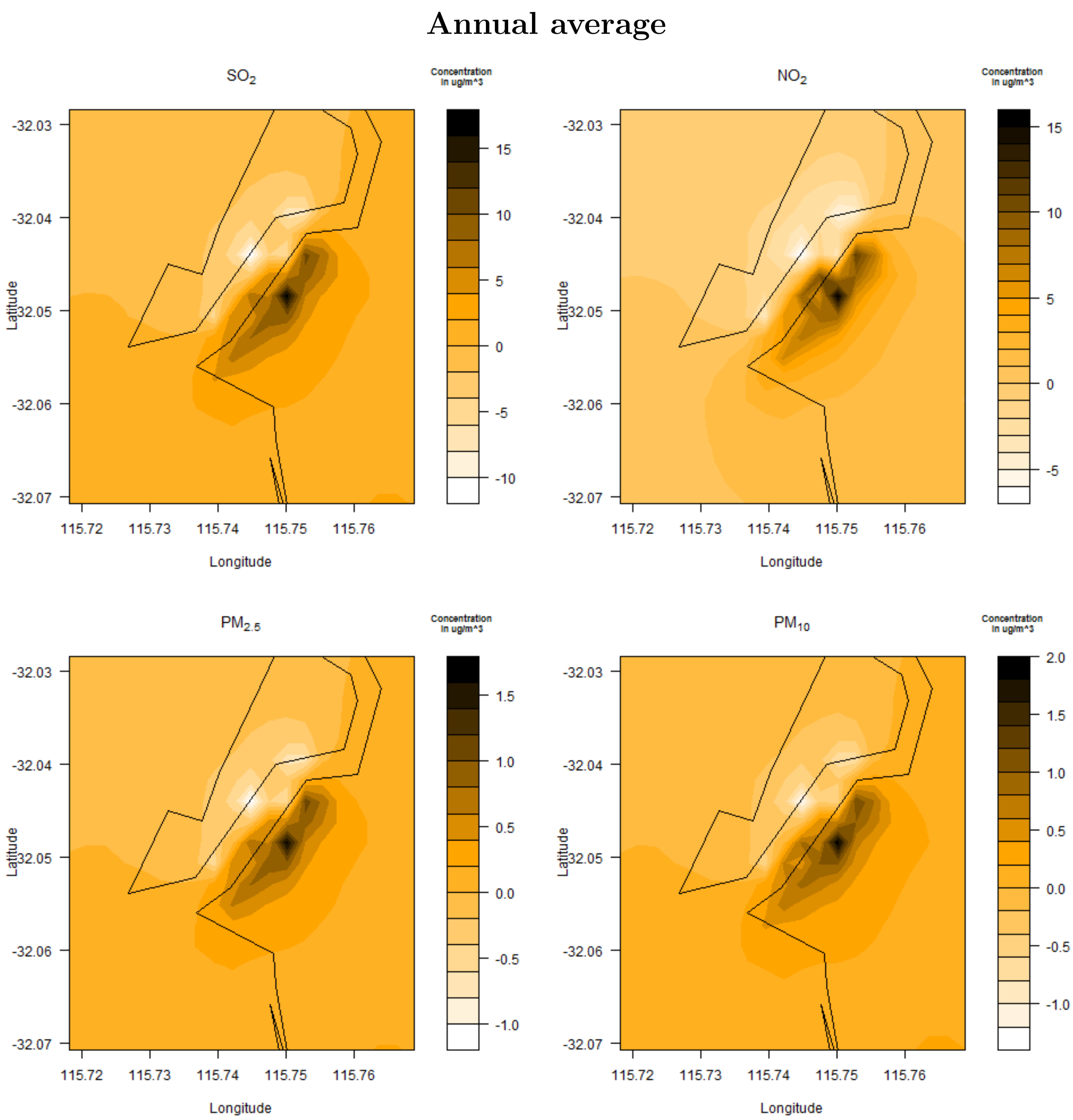

Figure 3.16: Annual average concentrations over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over water) for the control emission inventory and 20 m stack heights.

Table 3.19 shows the difference between CALPUFF concentrations and AERMOD concentrations (with meteorology over water) followed by the percentage difference in parentheses. If the NEPM standard was exceeded, the difference is shown in red. Differences in concentrations between CALPUFF and AERMOD with meteorology over land can be found in Appendix H. CALPUFF concentrations were higher than AERMOD's for the maximum 1 hour and annual averages for all pollutants. The CALPUFF maximum 1 hour average concentration for NO_2 exceeded AERMOD's by 1055.9% and the maximum 1 hour average for SO_2 by 131.3%. As a result, the maximum 1 hour average concentrations from CALPUFF exceeded NEPM standards, by up to 4885.1 μg m^{-3} for NO_2. Although the annual averages were as much as 75.3% above those simulated by AERMOD, none of the annual averages exceeded NEPM standards. Interestingly, the maximum 24 hour averages for all pollutants were simulated to be lower with CALPUFF compared to AERMOD by around 8%, but SO_2 and PM remained above NEPM standards.

Fig. 3.17 shows the 1 hour averages and 24 hour averages for SO_2 with the high resolution domain with concentrations above the respective NEPM standards removed. Similar to the equivalent AERMOD contour plots, these demonstrate the area of exceedance over Fremantle inner harbour shown by the white space. Again, the exceedance area covers a large amount of the inner harbour extending over land either side of the harbour for the 1 hour averages. An area in the north of the plot is also subject to exceed the 1 hour average, suggesting that the receptor domain should have been larger. The area of exceedance is small for the 24 hour averages above berths D, E, F, G and H mostly (i.e. the south side of

Table 3.19: Concentrations (μg m^{-3}) over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over water) with the control emission inventory and 20 m stack heights. (AP is averaging period.)

AP	$\mathbf{SO_2}$	$\mathbf{NO_2}$	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
1 hr	2861.6 (131.3%)	4668.9 (1055.9%)	-	-
	1655.8	4885.1		
24 hr	-53.8 (-8.6%)	-	-5.05 (-7.7%)	-5.73 (-8.0%)
	415.7		40.6	21.5
1 yr	5.36 (35.3%)	7.78 (75.3%)	0.52 (34.3%)	0.67 (40.8%)

the harbour).

To summarise, CALPUFF simulated concentrations larger than AERMOD for both the maximum 1 hour and annual averages for all pollutants. As a result, all 1 hour averages simulated by CALPUFF exceeded NEPM standards. However, the annual averages simulated by CALPUFF remained below NEPM standards. All 24 hour averages simulated by CALPUFF were lower than those simulated by AERMOD, yet remained above the NEPM standards.

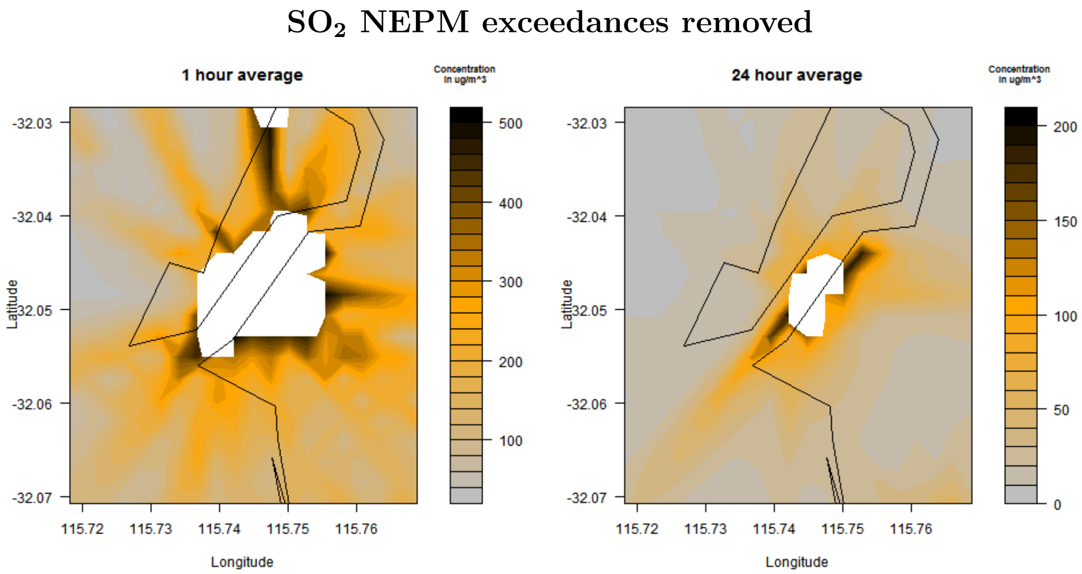

Figure 3.17: 1 hour and 24 hour average concentrations for SO_2 with NEPM exceedances removed over Fremantle inner harbour simulated by CALPUFF for the control simulation with meteorology over water and stack height at 20 m.

CHAPTER 4
DISCUSSION

4.1 AERMOD control simulations

As discussed in Section 3.1, concentrations from the AERMOD control simulations were repeated for comparison against Rolfe (2016). However, concentrations in this thesis were higher than concentrations from Rolfe (2016) with meteorology over land. The only plausible explanation is the use of the AERMOD GUI by Rolfe (2016) versus the command line in this thesis. Regardless of these differences, both sets of concentrations resulted in the same exceedances of NEPM standards for the same pollutant and averaging period. Results from Rolfe (2016) and this thesis showed that maximum 1 hour average concentrations for SO_2 exceeded NEPM standards with meteorology over water, but not with meteorology over land. Therefore, AERMOD is sensitive to the meteorology used as input. The reason for the increase in concentrations with meteorology over water is due to the lower dispersion of pollutants over water compared to over land as discussed in Section 1.3.1, resulting in higher concentrations over water (Hanna et al., 1985; Arya, 1999). AERMOD cannot incorporate meteorology over both land and water over a coastal location, due to assumption of a spatially uniform steady state. As a result, variations from over-water to over-land parts of the domain are not simulated (Pacific Environmental Services, 2004). This accounts for the differences in concentrations with AERMOD operated with meteorology over water and land.

There is little literature exploring the difference in simulated air pollution concentrations over coastal locations using WRF-generated meteorology over land and water to drive AERMOD. Most studies use local meteorological observations (Fisher et al., 2003; Obaid et al., 2014; Thepanondh et al., 2015), or WRF-generated meteorology over land only (Boadh et al., 2015; Madala et al., 2016). The study by Boadh et al. (2015) focussed on the dispersion of pollutants in a coastal city in India using AERMOD and WRF-generated meteorology over land. Boadh et al. (2015) found that AERMOD under-predicted emission concentrations compared to local observations. However, the study was not repeated with WRF-generated meteorology over water so it is unknown if this would have produced higher concentrations. As a result, the Boadh et al. (2015) study and literature in general lacks information regarding AERMOD's performance with meteorology generated over land versus water. Future studies using AERMOD near a coastline requiring model-generated meteorology, should carry out sensitivity tests with meteorology over land versus water as this thesis shows AERMOD's sensitivity to such driving meteorology.

It is ideal to know which model parameters provide the most accurate concentrations. However, when air pollution observations are unavailable, it is important for regulators and decision-makers to know which model parameters result in the highest concentrations, especially if these approach regulatory standards (Obaid et al., 2014). When using AERMOD, the most conservative action in the interest of human health would be to carry out any future modelling at Fremantle port with meteorology over water as this produced the highest concentrations.

With the control simulations, a higher ship stack height of 30 m compared to 20 m resulted in lower pollutant concentrations estimated by AERMOD. This is to be expected based on two explanations. The first is that a higher stack height allows for increased dilution of the pollutant with the surrounding air, hence lowering the concentration (Heckel and LeMasters, 2011). Research by Heckel and LeMasters (2011) focussed on AERMOD's estimation of elemental mercury and also found that a higher stack height resulted in lower ground level concentrations of the pollutant.

Lyons and Scott (1990) offer another explanation, whereby the higher concentrations with shorter stack height is due to the effect of building downwash. As discussed in Section 2.3.2, building downwash involves the region of disturbed airflow around buildings nearby the emission stack. Lyons and Scott (1990) suggest a stack height of 2.5 times the height of the tallest adjacent building in order to avoid this phenomenon occurring. As the bodies of the ships were modelled as buildings to simulate the effect the ship bodies have on the dispersion of pollutants, the theory suggested by Lyons and Scott (1990) could also explain the higher concentrations with lower stack heights.

Although 2 stack heights were tested, it is unlikely that all ships have equal stack heights of 20 m or 30 m. Specific stack heights for ships in Fremantle port were unavailable without subscription to the Lloyd's register and so could not be used in this thesis. Future modelling studies would benefit using exact ship stack heights for accuracy.

4.2 AERMOD sensitivity testing

The sensitivity tests focussed on parameter values and methods used in the emission inventory as well as model set up such as building downwash and stack height.

1. **Assessment of emission factors for fuel with a modification of ±10% sulfur content (experiments 1a and 1b in Table 2.3)**

   Simulations in AERMOD with emission factors -10% of the control emission inventory from Rolfe (2016) resulted in concentrations slightly less than the equivalent control simulation. Unsurprisingly, simulations with emission factors +10% resulted in concentrations slightly higher than the control simulations. These results are intuitive and consistent with findings from Mestl et al. (2013), who found that a lower sulfur content marine fuel resulted in a lower maximum sulfur concentration. Zetterdahl et al. (2016) and Celo et al. (2015) also found that lower sulfur fuel content decreased emissions of SO_2 and $PM_{2.5}$. Although AERMOD results did change depending on the emission factors used, the changes were not large enough to affect NEPM exceedances. The exceedances of the maximum 1 hour averages for SO_2 remained above the NEPM standard even with the 10% reduction in emission factors. Given a slightly larger change in emission factors however, concentrations may have been reduced to below NEPM standards, making AERMOD somewhat sensitive to emission factors.

   Changing the emission factors by ±10% did not represent any real-life reduction in emissions, but was chosen to simply test the sensitivity of AERMOD to such changes due to a lack of clear guidance on emission factors in the literature. Changing the fuel sulfur content in marine fuels to conform to the impending IMO global sulfur cap of 0.5% (International Maritime Organization, 2017a) will likely reduce the maximum 1 hour average for SO_2 below the NEPM standard. Currently, there are few studies that have investigated the emissions from low sulfur content marine fuel. However, Zetterdahl et al. (2016) found that reducing the sulfur content of marine fuel in a ship from 1.0% to 0.1% lowered sulfur emissions by up to 80%, and emissions of PM mass by 67.0%. Similarly, Kotchenruther (2017) found that the same reduction in fuel sulfur content reduced $PM_{2.5}$ emissions by an average of 74.1%. Considering ships in Australia currently use marine fuel with a sulfur content of up to 3.5% (BP Australia Pty Ltd, 2012), a reduction to 0.5% to conform to the IMO global sulfur cap should lower emissions substantially.

Future research should involve simulating the effects of the proposed IMO global sulfur cap of 0.5%, projected to be implemented in 2020 (International Maritime Organization, 2017b). As there is currently little guidance on what emission factors to use reflecting a fuel sulfur content of 0.5%, this will first require research to determine such emission factors for Australian ships.

2. **Assessing the fuel efficiency value for Australian cruise ships (ex-**

periment 2 in Table 2.3)

Simulations with a higher fuel efficiency (a_b of 0.0165 kg hr^{-1}) for cruise ships resulted in lower concentrations than the control. It is expected that ships with a higher fuel efficiency would produce lower emissions than equivalent ships with lower fuel efficiency. However, concentrations from experiment 2 were dependent on the combination of meteorology and ship stack height. The higher cruise ship fuel efficiency had the largest effect on simulations of SO_2 with meteorology over water and stack heights at 20 m. As discussed in Section 4.1, a shorter stack height of 20 m resulted in higher concentrations due to less dilution of the pollutants with surrounding air (Heckel and LeMasters, 2011), and also the effect of building downwash (Lyons and Scott, 1990). Similarly, higher concentrations result from meteorology over water compared to over land. Therefore, results show that the highest concentrations were affected the most by increasing cruise ship fuel efficiency and lower concentrations were affected to a lesser degree. Therefore, the reduction in the maximum 1 hour average for SO_2 (the highest concentration) was large enough to reduce the concentration to below the NEPM standard.

It is important to mention that the fuel efficiency value for Australian cruise ships (a_b of 0.0328 kg hr^{-1}) used in Rolfe (2016) was not determined by the literature or through direct research on Australian cruise ships. Instead it was assumed by an expert consultant, Dr Robin Smit. While the simulations in this thesis show that Australian cruise ships (assumption of an a_b of 0.0328 kg hr^{-1}) produce larger emissions compared to cruise ships in

Copenhagen (a_b of 0.0165 kg hr^{-1}; Saxe and Larsen, 2004), this is not a definitive result. More research is required focussing on the fuel consumption and emissions of cruise ships visiting Australian ports in order to more accurately simulate the emissions from Australian cruise ships.

3. **Assessing the modifier values for calculating fuel consumption during transit for main and auxiliary engines (experiment 3 in Table 2.3)**

AERMOD simulations with a lower combined engine load of 85% proposed by Georgakaki et al. (2005) compared to the 92% combined engine load of Goldsworthy and Renilson (2009) and used by Rolfe (2016) affected the simulation of SO_2 greatly, by lowering emissions by up to more than 70%. The emissions produced by a ship are directly proportional to the amount of fuel burned, so a lower engine load, which burns less fuel than a higher engine load, will result in lower emissions (Ballou et al., 2008). However, these results depended heavily on stack height and to a lesser degree, meteorology. Similar to the results of experiment 2, the combined model set up of meteorology over water and 20 m stack height resulted in the highest concentrations of SO_2, and these emissions were affected to a higher degree than lower concentrations. The maximum 1 hour average for SO_2 with meteorology over water and stack height at 20 m for experiment 3 was reduced to below the NEPM standard. The maximum 1 hour average for SO_2 with meteorology over water but a higher stack height of 30 m, although reduced, remained above the NEPM standard.

Ship engines are usually tuned for maximum speed (i.e. high engine load) as this is the most common engine load condition (Lack and Corbett, 2012). Therefore, ship movement at lower engine loads, such as transit within port waters, is often less fuel efficient and increases engine emissions (Lack and Corbett, 2012). The calculations of the emission inventory in this thesis did not take into account detail such as the tuning of ship engines, and it is important to recognise that the emission inventory and all concentrations are estimations only. However, if the tuning of ship engines optimised transit within port waters (i.e. lower engine loads than maximum speed) then the maximum 1 hour average for SO_2 with stack height at 30 m could possibly be reduced to below the NEPM standard.

One technique to reduce ship emissions, recently explored in the literature, focusses on exhaust scrubbing, which reduces emissions from marine diesel engines. Lack and Corbett (2012) report that using exhaust scrubbing can allow a ship to consume low grade (high sulfur content) fuel and moderate emissions of SO_2. Using exhaust scrubbing with marine diesel oil at a lower engine load in port waters may lower emissions of SO_2 to below NEPM standards close to land and human receptors.

Changes to emissions of NO_2 and PM with the reduced engine load were negligible and none of these concentrations exceeded NEPM standards. However, in the interest of human and environmental health, further reductions in near-port emissions may be desirable. These results show that AERMOD simulations of SO_2 are sensitive to changes in engine load, however AERMOD simulations of NO_2 and PM are not.

Similar to the fuel efficiency for Australian cruise ships, the actual engine load of ships in transit in Fremantle port is unknown. The values used in this sensitivity test were based on research in Europe (Georgakaki et al., 2005) and values used in the control simulations were based on research in the port of Brisbane (Goldsworthy and Renilson, 2009). Therefore, it is unknown which value more closely represents engine load for transit in Fremantle port waters. Further research is required in order to obtain specific values for engine load. Moreover, each category of ship will operate at slightly different engine loads, so this value will always be an estimate unless research is carried out for each individual ship of interest.

4. **Sensitivity to building downwash (experiment 4 in Table 2.3)**

   Turning the building downwash off in AERMOD reduced all concentrations. This is due to the area of "wake" produced downwind from a building, which acts to restrict plume rise and therefore increase concentrations (Cimorelli et al., 2004) by recirculating the pollutants with low ventilation of fresh air (Lyons and Scott, 1990). Experiments by Oettl (2015) also showed higher simulated concentrations of SO_2 when building downwash was utilised. With building downwash turned on in the control simulation, the maximum 1 hour average for SO_2 exceeded the NEPM standard, however with building downwash turned off, this concentration was below the NEPM standard. Therefore, AERMOD is sensitive to the building downwash feature. These findings are consistent with Schulze and Turner (1996), who argue that building downwash in air pollution modelling accounts for 90% of maximum concentrations.

The effect of building downwash is well documented (Lyons and Scott, 1990; Zhang et al., 1996; Canepa, 2004; Schulman et al., 2000; Paine et al., 2016) and should always be used in air pollution dispersion modelling studies. Results in this thesis are consistent with the building downwash effect by showing higher concentrations with downwash turned on lower concentrations with downwash turned off. Therefore, future air pollution modelling studies at Fremantle port should utilise building downwash as it is the most conservative model option, producing the highest concentrations. However, as the building downwash feature in AERMOD was created for buildings, the suitability for use with ship bodies is unknown and in reality the effect of ship-body downwash may vary slightly from buildings, particularly if the ship is in transit.

4.2.1 Simulated exceedances for the low resolution receptor domain

Across all experiments, the maximum 1 hour average concentration for SO_2 was exceeded when AERMOD was operated with meteorology over water, and ship stack heights set at 30 m. The highest 1 hour average for SO_2 across all experiments occurred on the same occasion, on the 17^{th}th of February 2012 at 5pm, in the inner harbour near Cantonment Hill as shown in Fig. 4.1. It occurred when 3 large ships were berthed in the inner harbour, at locations G, 6 and 1 as shown in Fig. 3.7. The ships were a passenger cruise ship, a container ship and a livestock/fodder ship. This exceedance was most likely due to the close berth locations of the 3 ships in the inner harbour.

Figure 4.1: Map of Fremantle inner harbour showing Cantonment Hill in Fremantle where the maximum 1 hour average concentration for SO_2 was exceeded for several experiments with meteorology over water.

For the control simulations and experiment 2, the NEPM standards for the 1 hour average for SO_2 was exceeded on 1 day in the 2011/2012 financial year, which is acceptable according to the NEPM maximum allowable exceedances shown in Table 2.7 in Section 2.5. For the sensitivity tests, the 1 hour average for SO_2 was exceeded on up to 3 days in the year, across several experiments. This is more than the allowable number of exceedance days of 1 per year. The largest number of exceedance days were simulated with increases in emission factors (experiment 1b), meteorology over water and 20 m stack heights as part of the sensitivity testing.

Not all second exceedances of the NEPM standard occurred in Fremantle inner harbour. For several experiments, the second exceedance occurred in the outer harbour near Rockingham at approximately 32.4° South, 117.2° East. This exceedance occurred on the 26$^{\text{th}}$ of April, 2012 at 11 pm, while 5 ships were berthed in the outer harbour. Due to time constraints evaluation of this exceedance could not be carried out with the higher resolution receptor domain over the outer harbour. In order to reduce high levels of emissions at Fremantle port, the port authority should limit the number of large ships berthed simultaneously in the inner and outer harbours.

Although all experiments were based on actual port movement data, the emission inventory was estimated using certain assumptions and parameters values and as a result the concentrations presented in this thesis are estimations only. As there are no air pollution monitoring stations in Fremantle, the concentrations simulated in these experiments cannot be validated with observations. Experiments experienced more than 1 exceedance day when changes to the emission inventory and model set up were tested. These tests where carried out with the intention of assessing AERMOD's sensitivity to assumptions and parameters used to create the emission inventory and whether or not these changes would affect NEPM exceedances. While it was found that some of these tests did affect NEPM exceedances, the concentrations presented in this thesis are estimations only, and are not likely to accurately represent real air pollution concentrations in Fremantle port.

4.2.2 Simulated exceedances for the high resolution receptor domain

With the high resolution receptor domain, the emissions for all pollutants were extremely high and exceeded NEPM standards for the 1 hour and 24 hour averages by more than 1000 μg m^{-3} in some cases. NEPM does not provide clear guidance on the distance from a source from which measurements of air pollutants should be taken. A receptor very close to, or on top of, a source is expected to almost always exceed regulatory standards.

The short-term exposure limit (STEL) for SO_2 is 13,000 μg m^{-3}, based on 15 minute exposure (Coregas, 2008). This converts to approximately 10,000 μg m^{-3} per hour (based on personal communications; Dr Peter Rye). Even with the highest concentrations with meteorology over water and 20 m stack height, the concentrations with the high resolution receptor domain did not approach 10,000 μg m^{-3}. The highest concentration was 2179.8 μg m^{-3}, which is well below the 10,000 μg m^{-3} limit. Therefore, in terms of occupational health and safety of port workers, there is little risk to workers in Fremantle port of exposure to the STEL, based on simulations by AERMOD with the high resolution receptor domain.

4.3 CALPUFF simulations

CALPUFF concentrations were higher than AERMOD's for the maximum 1 hour averages and annual averages, but slightly lower than AERMOD's maximum 24 hour averages for all pollutants. The differences in model output is most likely due to the differences in meteorological input required by AERMOD and CALPUFF as discussed in Sections 1.3.1 and 1.3.2. The steady-state assumption of AERMOD restricts its ability to simulate dispersion of pollutants near a coastline. In comparison, CALPUFF takes into account the heterogeneous meteorology along the coastline and is more likely than AERMOD to be able to simulate the dispersion of pollutants in such conditions. Fig 4.2 shows the wind field generated by WRF for the date and time of the highest exceedance of the 1 hour average for SO_2 (February 17th, 2012 at 5pm). Winds are strongest over the ocean and directly over the inner harbour, shown by the colour contours. Winds are calmer over the land. Therefore, wind speed varied at the time of the exceedance over water and land, demonstrating a heterogeneous wind-field. The wind direction also changes from a south-west direction over the ocean to a west south-west direction over the land. Therefore, wind direction is also changing over the receptor domain. As a result, AERMOD would not have incorporated the heterogeneity of the wind speed and direction into the simulation of air pollution dispersion over Fremantle port.

Similar research comparing concentrations from AERMOD and CALPUFF (Fisher et al., 2003; Dresser and Huizer, 2011; Rood, 2014; Gulia et al., 2015; Hoinaski et al., 2016) found CALPUFF to be the most accurate model when concentrations were compared to air pollution observations. However, Thepanondh

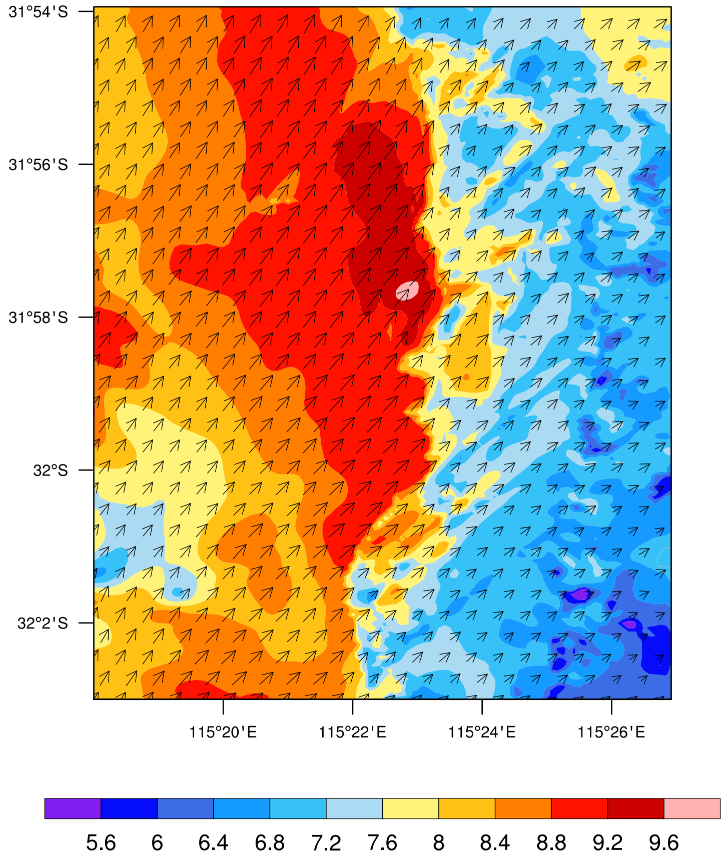

Figure 4.2: Wind field generated by WRF for 17_{th} February 2012 at pm (time of the highest exceedance of the 1 hour average for SO_2). Colour contours denote wind speed (m s^{-1}) and arrows denote wind direction.

et al. (2015) argue that over a coastal location, AERMOD is more accurate in predicting upper levels of SO_2 than CALPUFF, and that CALPUFF is better at predicting annual averages. Abdul-Wahab et al. (2011) found CALPUFF to over-predict concentrations in a coastal location. Similarly, Abdul-Wahab et al. (2010) found that CALPUFF over predicted the 1 hour averages for SO_2 by approximately 20% from observed concentrations. This research suggests that the high CALPUFF concentrations in this thesis may be due to CALPUFF's tendency to over-predict high end concentrations compared to AERMOD near coastal locations. This is consistent with Thepanondh et al. (2015), who suggest that AERMOD is more accurate at predicting extreme high-end concentrations than CALPUFF in a coastal location.

Unfortunately, results from this thesis cannot be compared to observed data due to the lack of air pollution monitoring stations in Fremantle, and can therefore not be evaluated. It would therefore be beneficial that air pollution monitoring stations be installed in Fremantle in high-concentration areas. This is at Cantonment Hill, where the highest concentrations of SO_2 were simulated and near the outer harbour in Rockingham, where some of the second highest concentrations of SO_2 were simulated.

CHAPTER 5
CONCLUSION

The aims of this thesis were to:

1. Assess the sensitivity of AERMOD to changes in parameter values and methods used in the emission inventory developed by Rolfe (2016); and

2. Compare the Gaussian plume model, AERMOD to the Lagrangian puff model, CALPUFF to investigate if a Lagrangian model results in different concentration fields to a Gaussian model in a coastal region such as Fremantle.

The most significant findings of the sensitivity tests were AERMOD's sensitivity to the meteorology used as input and stack height specification. The combination of these parameters also affected concentrations when other sensitivity tests were carried out. For example, changing the Australian cruise ship fuel efficiency and modifier values for calculating fuel consumption had variable effects on concentrations depending on the combination of driving meteorology and stack height. In general concentrations with meteorology over water and shorter, 20 m stack heights were affected to the largest extent when simulations were carried out with changes to assumptions and parameter values used to create the emission inventory. Exceedances of NEPM standards were simulated for the 1 hour average for SO_2 for most experiments.

AERMOD and CALPUFF showed large differences between the maximum 1 hour averages for both SO_2 and NO_2 with CALPUFF simulating the highest concentrations. However, CALPUFF concentrations where slightly lower than AERMOD's for the maximum 24 hour averages.

As the concentrations presented in this thesis are estimations only and rely heavily on assumptions about ship specifications, fuel usage and meteorology, further information is required in order to more accurately simulated air pollution dispersion in Fremantle port:

1. Air pollution observations for Fremantle port are required for evaluating simulated concentrations, such as those in this thesis, and should therefore be installed at high-concentration areas such as Cantonment hill;

2. Information is required regarding ship stack heights specific to ships entering Fremantle port. As AERMOD was sensitive to stack heights, simulations are likely to be more accurate if actual ship stack heights are used:

3. AERMOD was sensitive to the use of building downwash when ships were specified as buildings to simulate the effect of the ship body on pollution dispersion. However, the building downwash feature was created for use with buildings, and it is unknown how effective this feature is when used with ships, particularly when ships are in transit. Therefore, research is required focussing on the effectiveness of AERMOD's building downwash feature with ship bodies as opposed to buildings;

4. Ideally, sensitivity tests would have been performed in this thesis for CALPUFF

as well as AERMOD. However, due to time constraints this was not possible. Further research is required focussing on CALPUFF's sensitivity to parameters values and methods used to create the emission inventory;

5. Finally, although concentrations of SO_2 did not reach the STEL, it is recommended that future air pollution dispersion studies at Fremantle port use CALPUFF over AERMOD, as CALPUFF simulated the highest concentrations for the maximum 1 hour averages. Therefore, in the interest of human health, using CALPUFF would be the most conservative model.

Appendices

APPENDIX A
AERMOD INPUT FILE SET UP

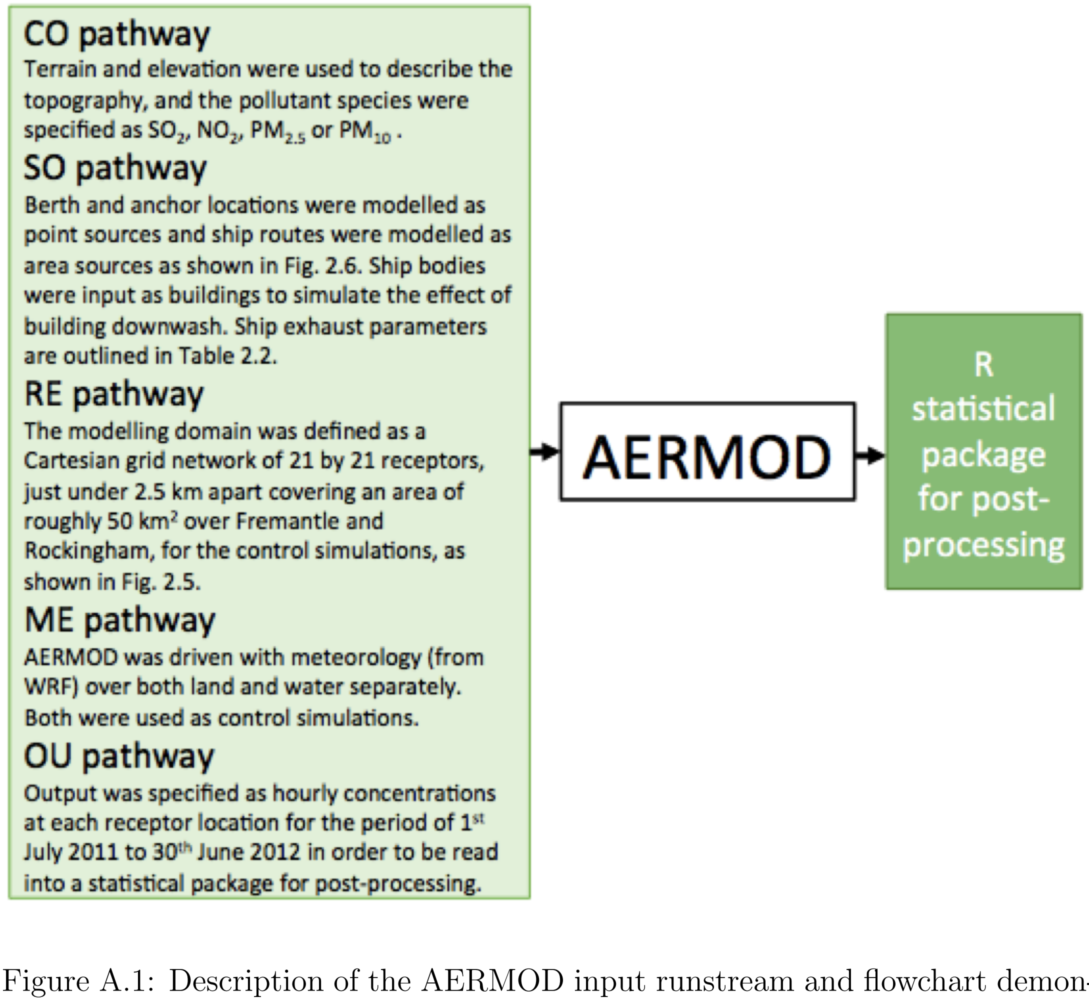

Figure A.1: Description of the AERMOD input runstream and flowchart demonstrating the process of post-processing AERMOD output in R.

Control pathway

The control (CO) pathway is responsible for the modelling options such as the run title, terrain elevation, averaging period used and the pollutant species modelled (Cimorelli et al., 2004). Depending on the pollutant species, the CO pathway was set up as SO_2, NO_2, $PM_{2.5}$ or PM_{10}. For NO_2, the ARM2 option was utilised to evaluate the ratios of NO_2 and NO_x, similar to Rolfe (2016). The default option of including model terrain was used and the population of Fremantle was included to determine the surface roughness.

Source pathway

The source (SO) pathway defines the emission source(s) such as the location of the source(s) and the source type (point, area or volume) (Cimorelli et al., 2004). Berth and anchor points were modelled as point sources and transect segments were modelled as area sources. For point sources, ship height, width and angle were entered as buildings in order to simulate the building downwash effect from the ship body. Each ship was assumed to be 100 metres long, 30 metres wide and 18 metres high. Other nearby buildings such as the Fremantle terminal were also included (Rolfe, 2016). In line with Rolfe (2016), parameters for ship exhaust were adopted from research by (Corbett et al., 2007), shown in Table 2.2.

Receptor pathway

The receptor (RE) pathway defines the grid of virtual receptors (Cimorelli et al., 2004). These are the exact locations where AERMOD calculates pollutant concentrations. A Cartesian grid network was used in AERMOD to define the receptor grid of 21 by 21 evenly spaced receptors over an area of approximately 50 km^2 following Rolfe (2016) as show in Fig. 2.5. This covered the area between 31.86° South, 115.50° East and 32.26° South, 115.99° East.

Meteorology pathway

WRF generated meteorology was used in lieu of surface meteorological data as well as atmospheric sounding observations for Fremantle.

Output pathway

The output (OU) pathway specifies the desired format for the model output. The output required for this research consisted of concentrations for each hour over the modelling period for each species. The POSTFILE option was used to create files of hourly concentrations, which could then be exported into a statistical package for post-processing and statistical analyses.

APPENDIX B
CALPUFF INPUT FILE SET UP

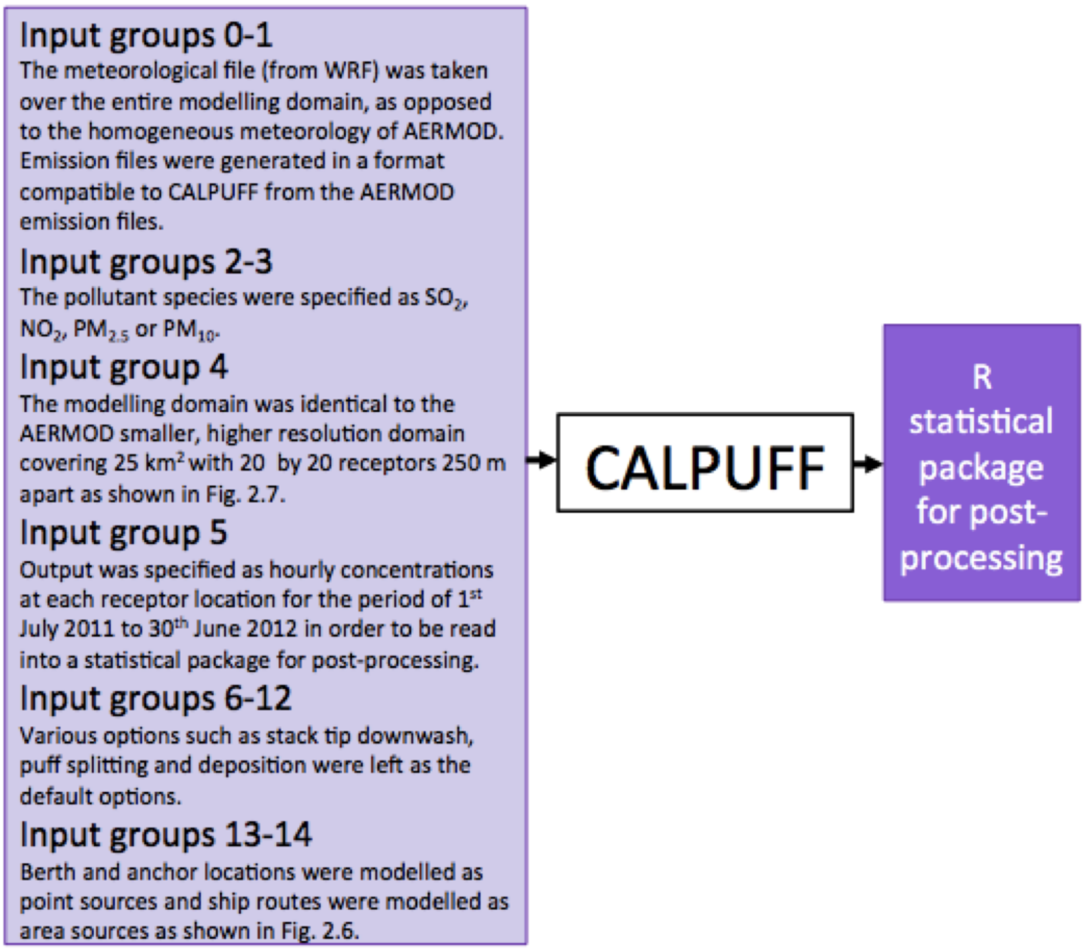

Figure B.1: Description of the CALPUFF input file and flowchart demonstrating the process of post-processing AERMOD output in R.

Input group 0

Input group (IG) 0 specifies input and output file names (Scire et al., 2000). For this study meteorological input data was a CALMET version 6 file. Emissions files were also specified here: point sources for berth and anchor points and area sources for transect segments (equivalent to AERMOD setup). An error file was also specified for output.

Input group 1

In IG1, the user specifies the time period of the meteorological file (see 1.3 for time period) and the number of chemical species to be modelled among other general parameters (Scire et al., 2000).

Input group 2

Technical options are detailed in IG2, such as method for stack tip downwash, building downwash, puff splitting and deposition etc. (Scire et al., 2000). For this thesis, most default options were used with the exception of no chemical transformations modelled.

Input group 3

The species list is entered in IG3 (Scire et al., 2000). Each species were modelled separately.

Input group 4

IG4 controls map projection and grid parameters (Scire et al., 2000). Universal Transverse Mercator map projection was used along with a grid of 100 by 170 cells.

Input group 5

IG5 specifies output options, which were selected as concentrations only.

Input group 6

IG6 determines subgrid scale complex terrain (Scire et al., 2000). This section was left blank as the meteorology contained the required information regarding terrain influences.

Input group 7 - 11

IGs 7 - 11 address wet and dry deposition and chemical transformation (Scire et al., 2000). As none of these options were utilised, these sections were either left blank or as the default options specified by CALPUFF.

Input group 12

Miscellaneous dispersion and computational parameters are found in IG12 (Scire et al., 2000). These were not utilised, so default values were used.

Input group 13

Point source parameters are specified under IG13 (Scire et al., 2000). As the ship emissions were not constant over the modelling period, an external data file of variable emissions was created from emission data obtained from Rolfe (2016) see 2.2. This file was specified in IG 0 and the remainder of IG13 was left blank.

Input group 14

Area source parameters are specified under IG14 (Scire et al., 2000). Similarly to point source emissions, the area sources were detailed in an external data file (specified in IG0) due to the variability in source emissions. This remainder of IG14 was left blank.

15 - 16

IG15 and 16 specify line and volume source parameters (Scire et al., 2000). Line and volume sources were not modelled in this research and so these sections were left blank.

Input group 17

A particular area of interest within the modelling domain that is not covered by a gridded receptor can be specified as a non-gridded (discrete) receptor in IG17 (Scire et al., 2000). However, this option was not utilised and therefore left blank.

APPENDIX C
EMISSION FACTORS USED AS PART OF THE AERMOD SENSITIVITY TESTING

Table C.1: Emission factors (g kg^{-1}) for NO_2 used in Rolfe (2016) and the emission factors reflecting ±10% used for sensitivity testing in this thesis.(RO is residual oil, MDO is marine diesel oil, SSD is slow speed diesel, MSD is medium speed diesel and HSD is high speed diesel; *(Goldsworthy and Goldsworthy, 2013).)

			GG(2013)*	**Minus 10%**	**Plus 10%**
Main engine	RO	SSD	92.82	83.54	102.10
		MSD	65.12	58.61	71.63
	MDO	SSD	91.89	82.70	101.08
		MSD	64.39	57.95	70.83
		HSD	58.54	52.69	64.40
Auxiliary engine	RO	MSD	64.76	58.28	71.24
	MDO	SSD	64.06	57.65	70.47
		HSD	54.38	48.94	59.82
Auxiliary boiler	RO	-	6.89	6.20	7.58

Table C.2: Emission factors (g kg^{-1}) for $PM_{2.5}$ used in Rolfe (2016) and the emission factors reflecting ±10% used for sensitivity testing in this thesis. (RO is residual oil, MDO is marine diesel oil, SSD is slow speed diesel, MSD is medium speed diesel and HSD is high speed diesel; *(Goldsworthy and Goldsworthy, 2013).)

			GG(2013)*	**Minus 10%**	**Plus 10%**
Main engine	RO	SSD	6.72	6.05	7.39
		MSD	5.14	4.63	5.65
	MDO	SSD	1.51	1.39	1.66
		MSD	1.41	1.26	1.55
		HSD	1.41	1.26	1.55
Auxiliary engine	RO	MSD	5.81	5.23	6.39
	MDO	SSD	1.34	1.21	1.47
		HSD	1.34	1.21	1.47
Auxiliary boiler	RO	-	4.43	3.91	4.77

Table C.3: Emission factors (g kg^{-1}) for PM_{10} used in Rolfe (2016) and the emission factors reflecting ±10% used for sensitivity testing in this thesis. (RO is residual oil, MDO is marine diesel oil, SSD is slow speed diesel, MSD is medium speed diesel and HSD is high speed diesel; *(Goldsworthy and Goldsworthy, 2013).)

			GG(2013)*	**Minus 10%**	**Plus 10%**
Main engine	RO	SSD	7.28	6.55	8.01
		MSD	6.65	5.99	7.32
	MDO	SSD	1.68	1.51	1.85
		MSD	1.51	1.36	1.66
		HSD	1.51	1.36	1.66
Auxiliary engine	RO	MSD	6.34	5.71	6.97
	MDO	SSD	1.47	1.32	1.62
		HSD	1.47	1.32	1.62
Auxiliary boiler	RO	-	4.82	4.34	5.30

APPENDIX D
CONTOUR PLOTS FOR AERMOD CONTROL SIMULATIONS WITH LOW RESOLUTION RECEPTOR DOMAIN

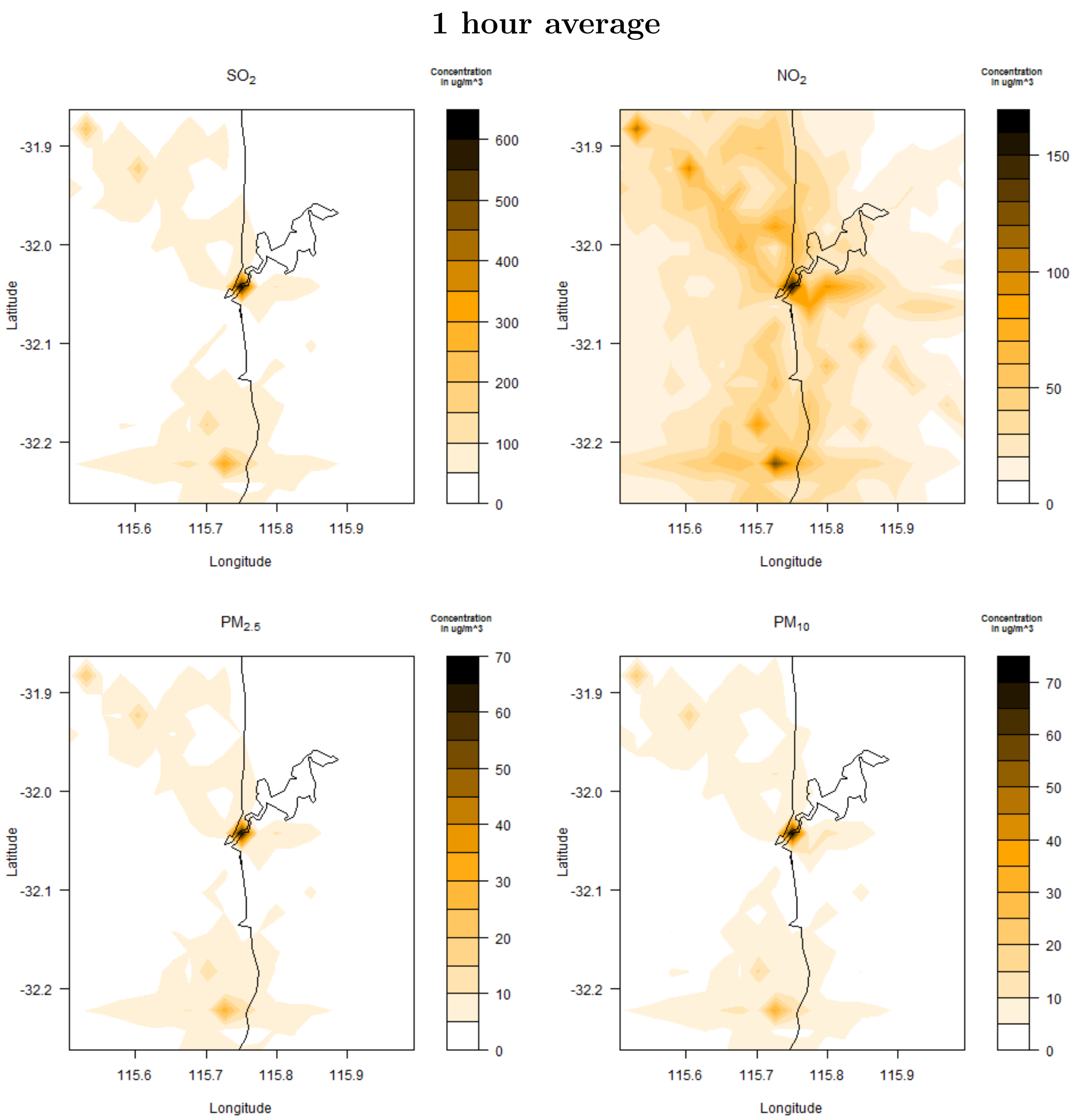

Figure D.1: 1 hour average concentrations simulated by AERMOD for simulations with meteorology over water and ship stack height at 30 m.

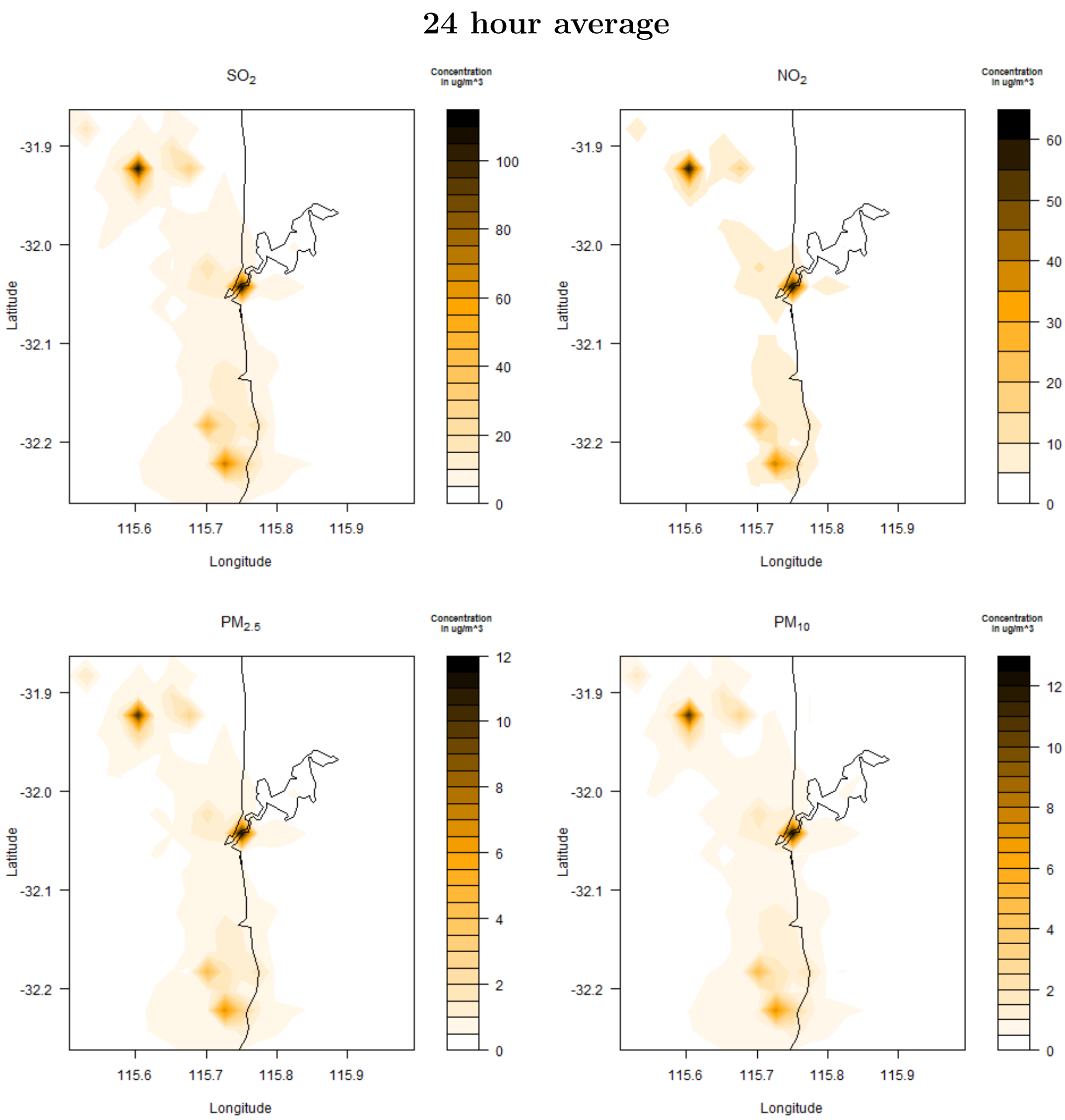

Figure D.2: 24 hour average concentrations simulated by AERMOD for simulations with meteorology over water and ship stack height at 30 m.

Annual average

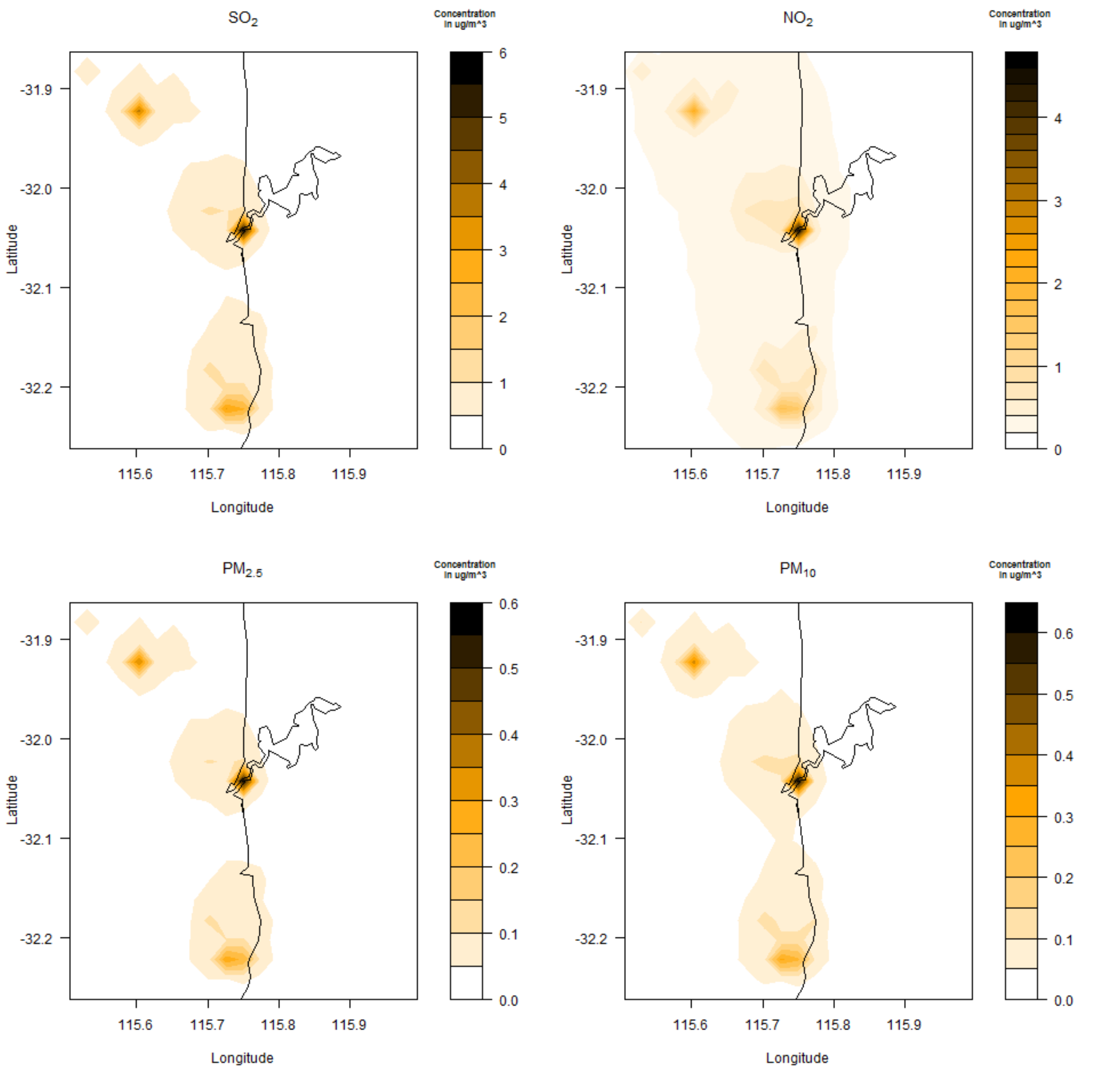

Figure D.3: Annual average concentrations simulated by AERMOD for simulations with meteorology over water and ship stack height at 30 m.

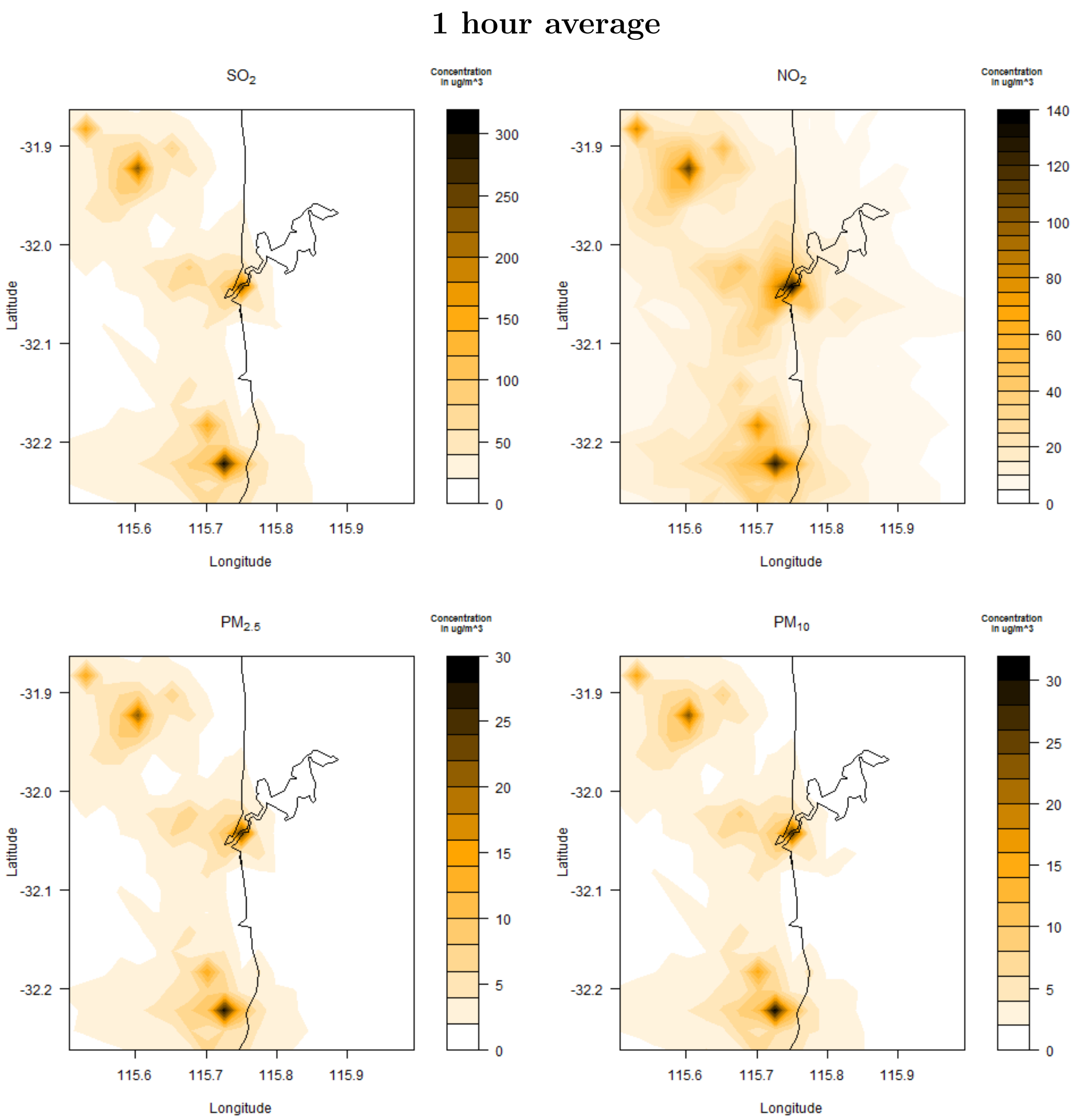

Figure D.4: 1 hour average concentrations simulated by AERMOD for control simulation with meteorology over land and ship stack height at 20 m.

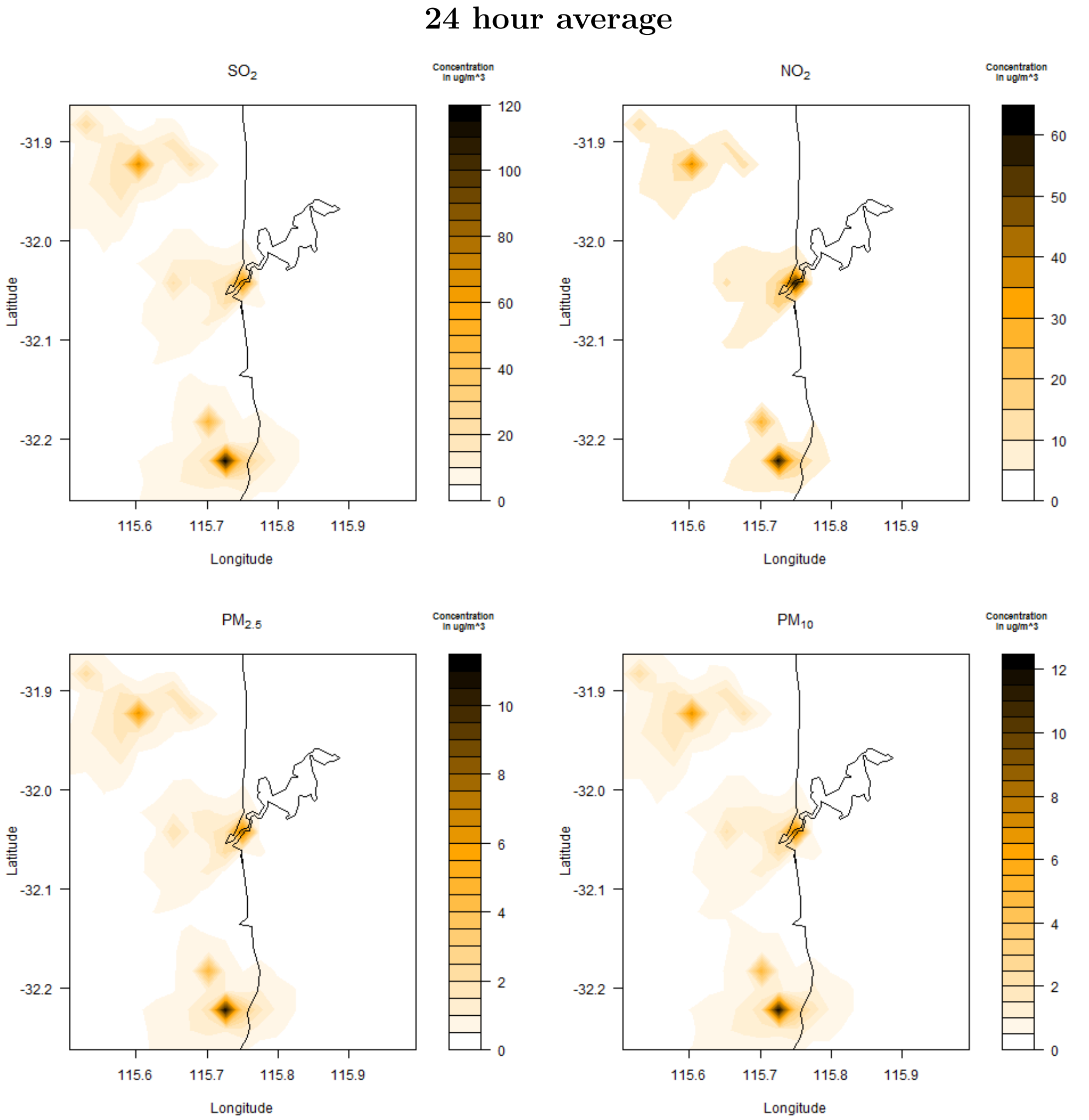

Figure D.5: 24 hour average concentrations simulated by AERMOD for control simulation with meteorology over land and ship stack height at 20 m.

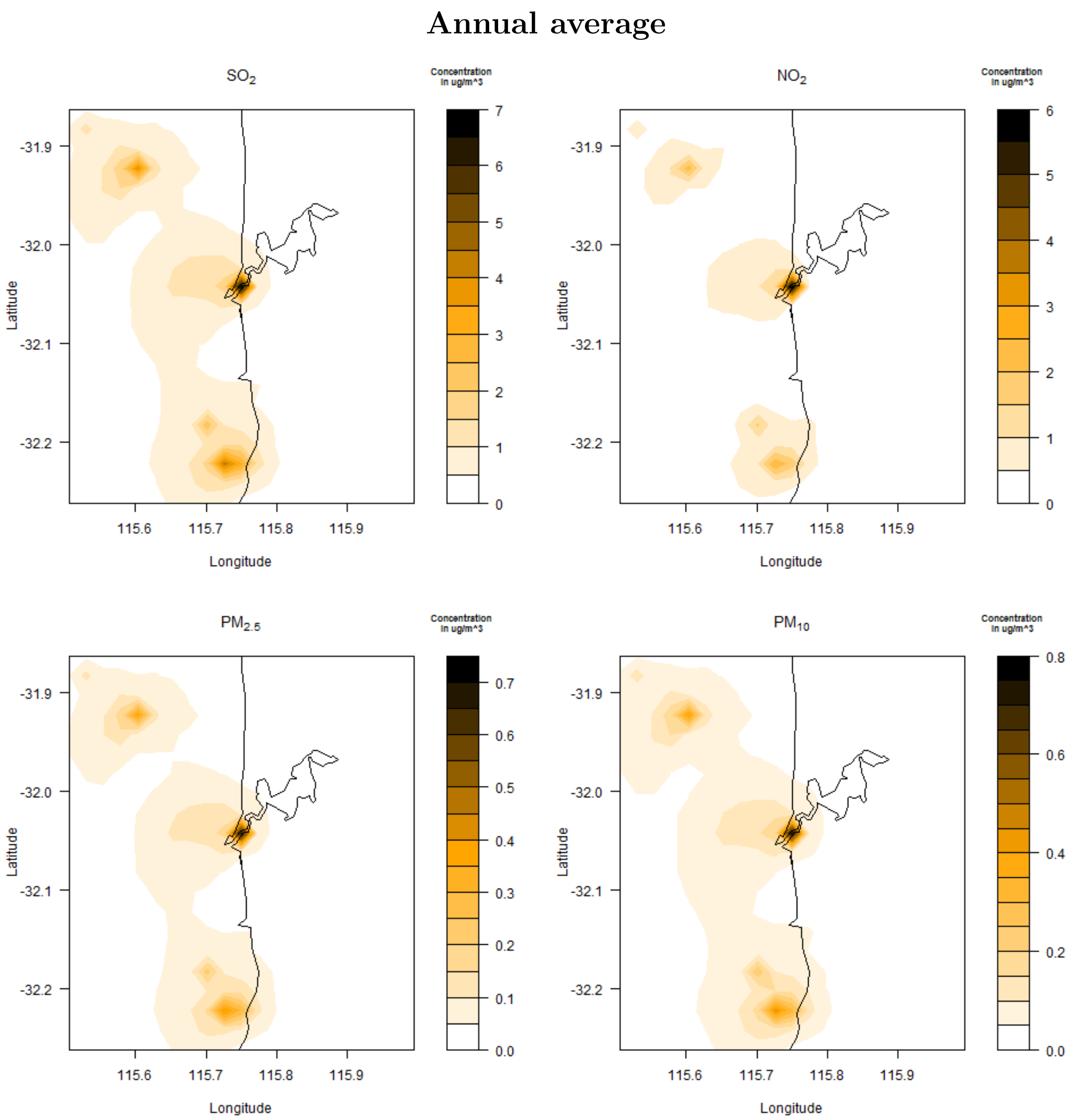

Figure D.6: Annual average concentrations simulated by AERMOD for control simulation with meteorology over land and ship stack height at 20 m.

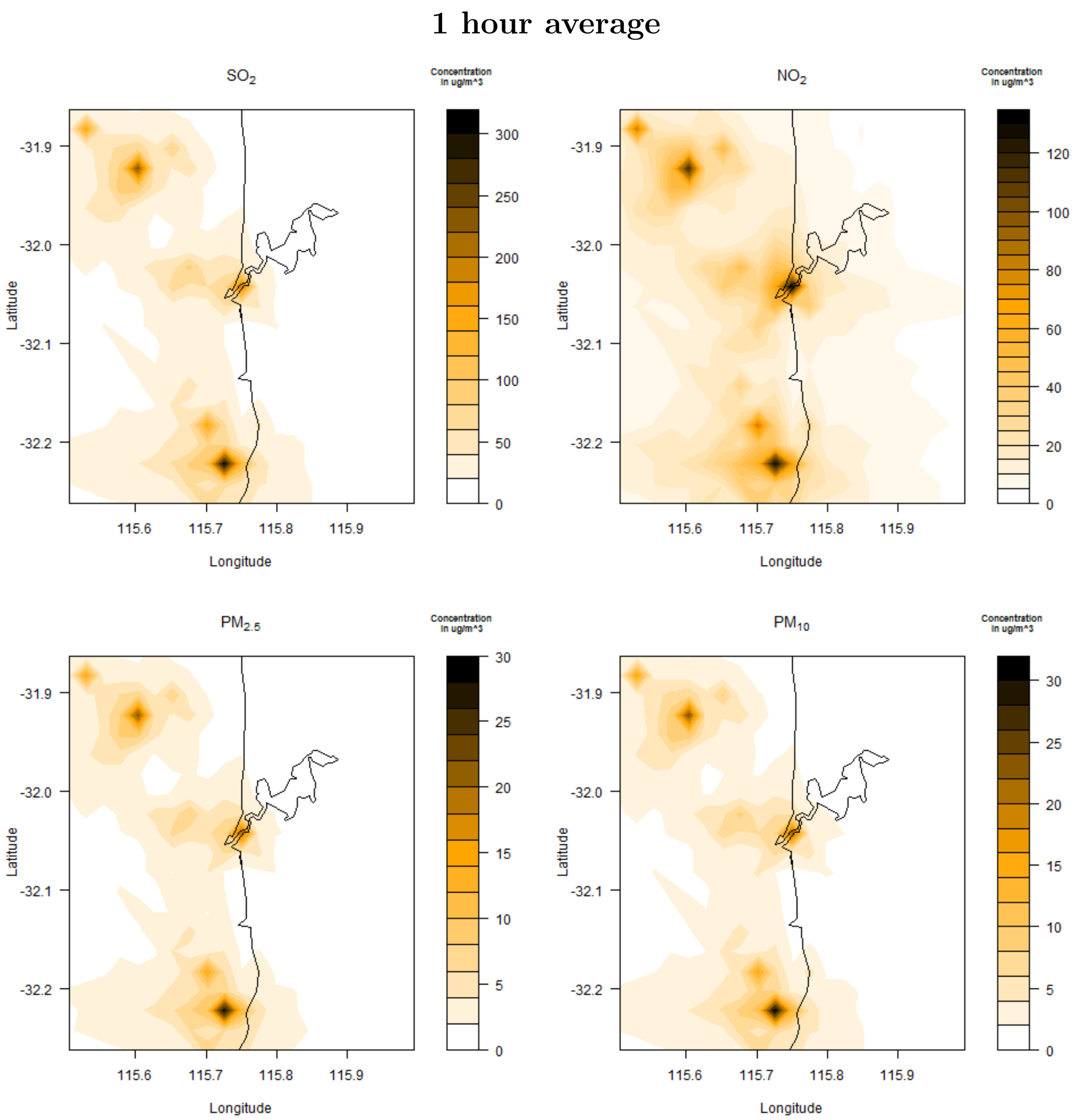

Figure D.7: 1 hour average concentrations simulated by AERMOD for simulations with meteorology over land and ship stack height at 30 m.

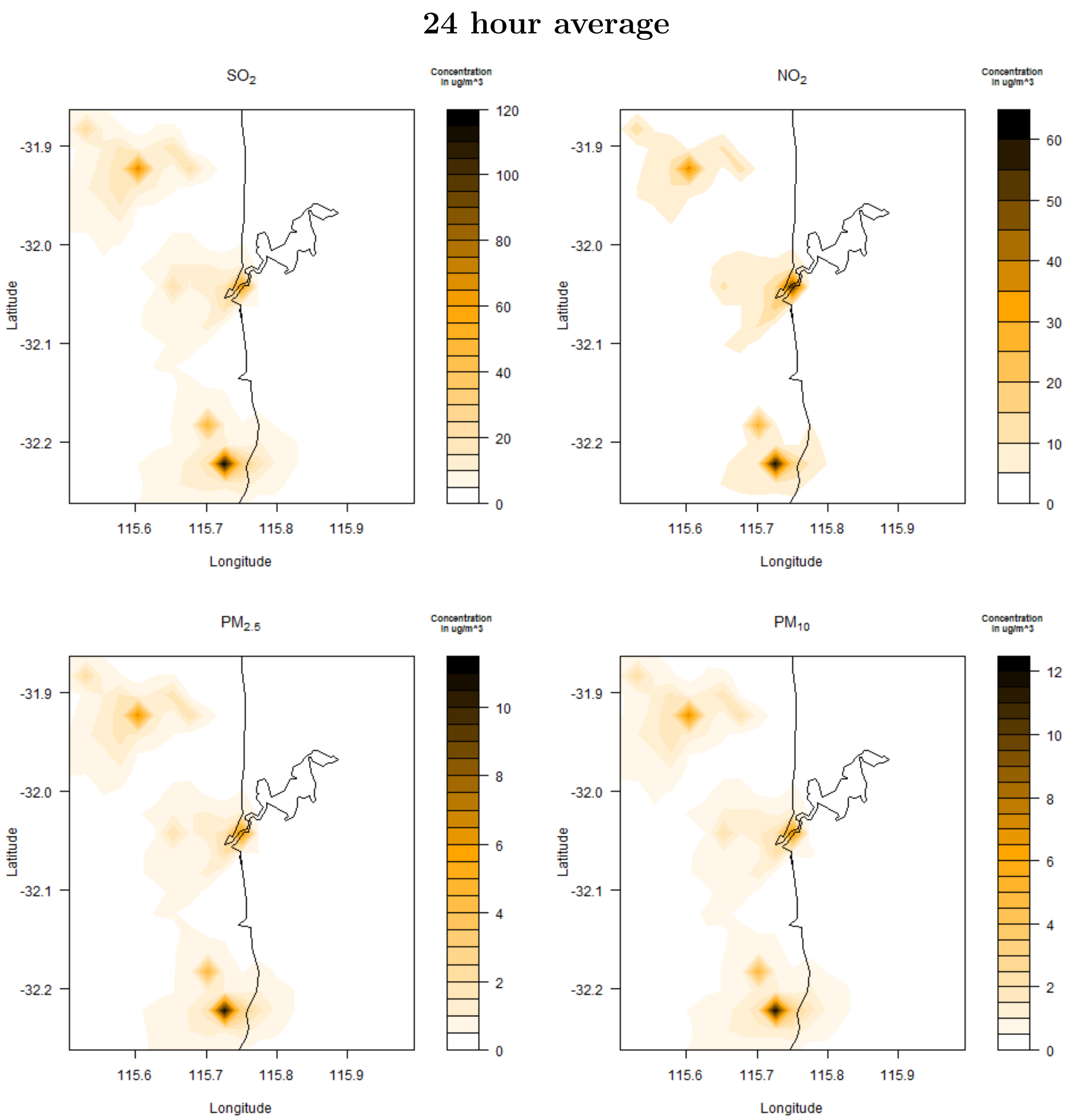

Figure D.8: 24 hour average concentrations simulated by AERMOD for simulations with meteorology over land and ship stack height at 30 m.

Annual average

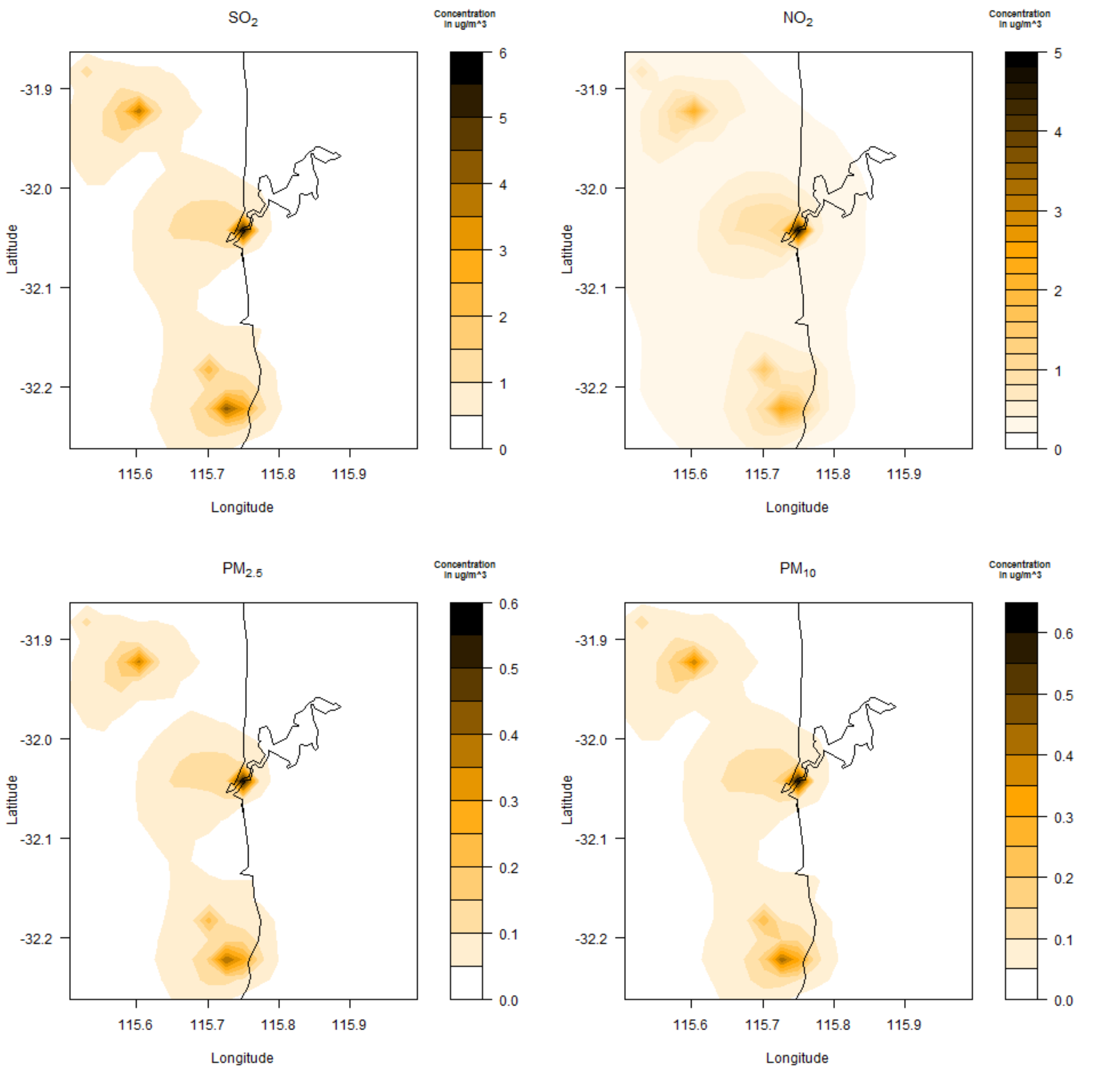

Figure D.9: Annual average concentrations simulated by AERMOD for simulations with meteorology over land and ship stack height at 30 m.

APPENDIX E
CONTOUR PLOTS FOR AERMOD CONTROL SIMULATIONS WITH HIGH RESOLUTION RECEPTOR DOMAIN

1 hour average

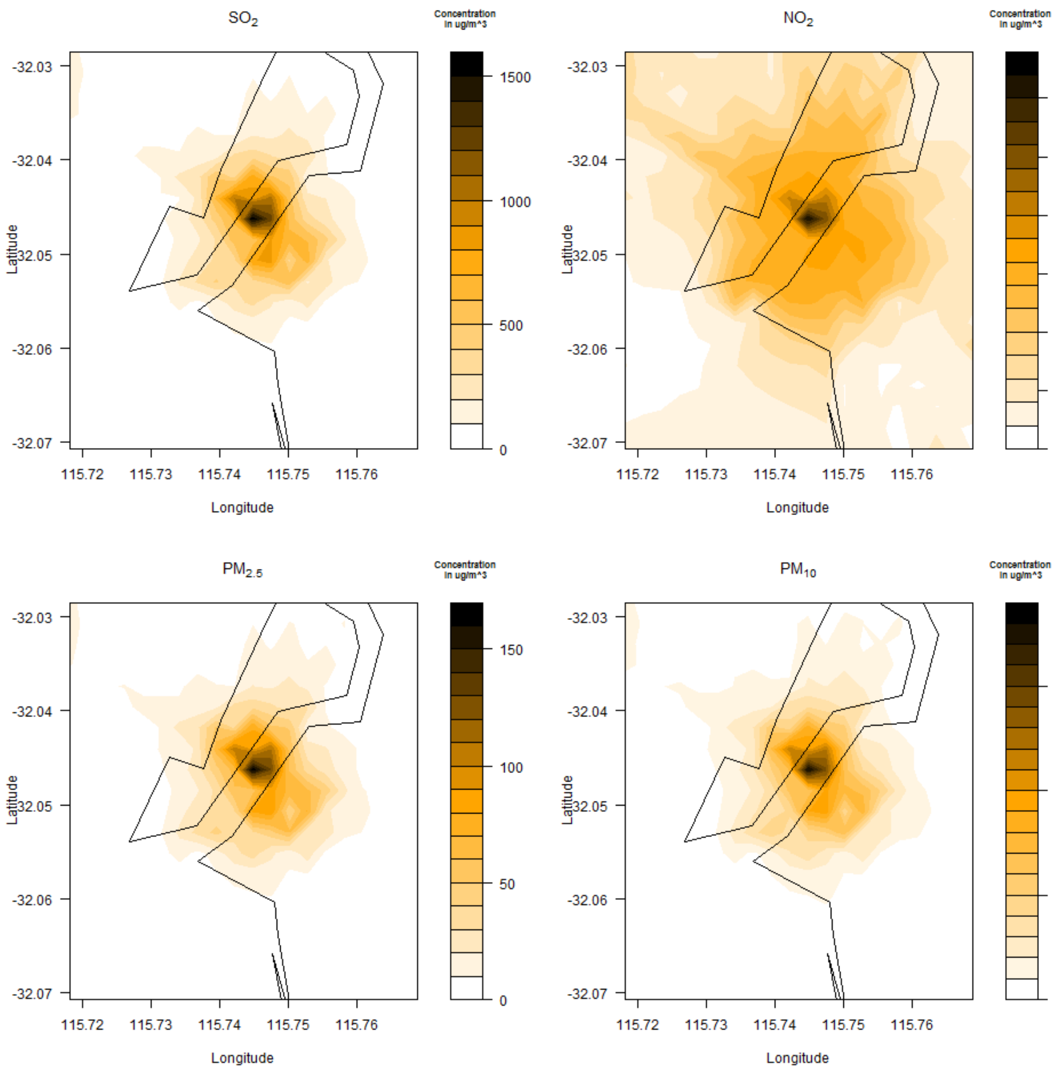

Figure E.1: 1 hour average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over water and ship stack height at 30 m.

24 hour average

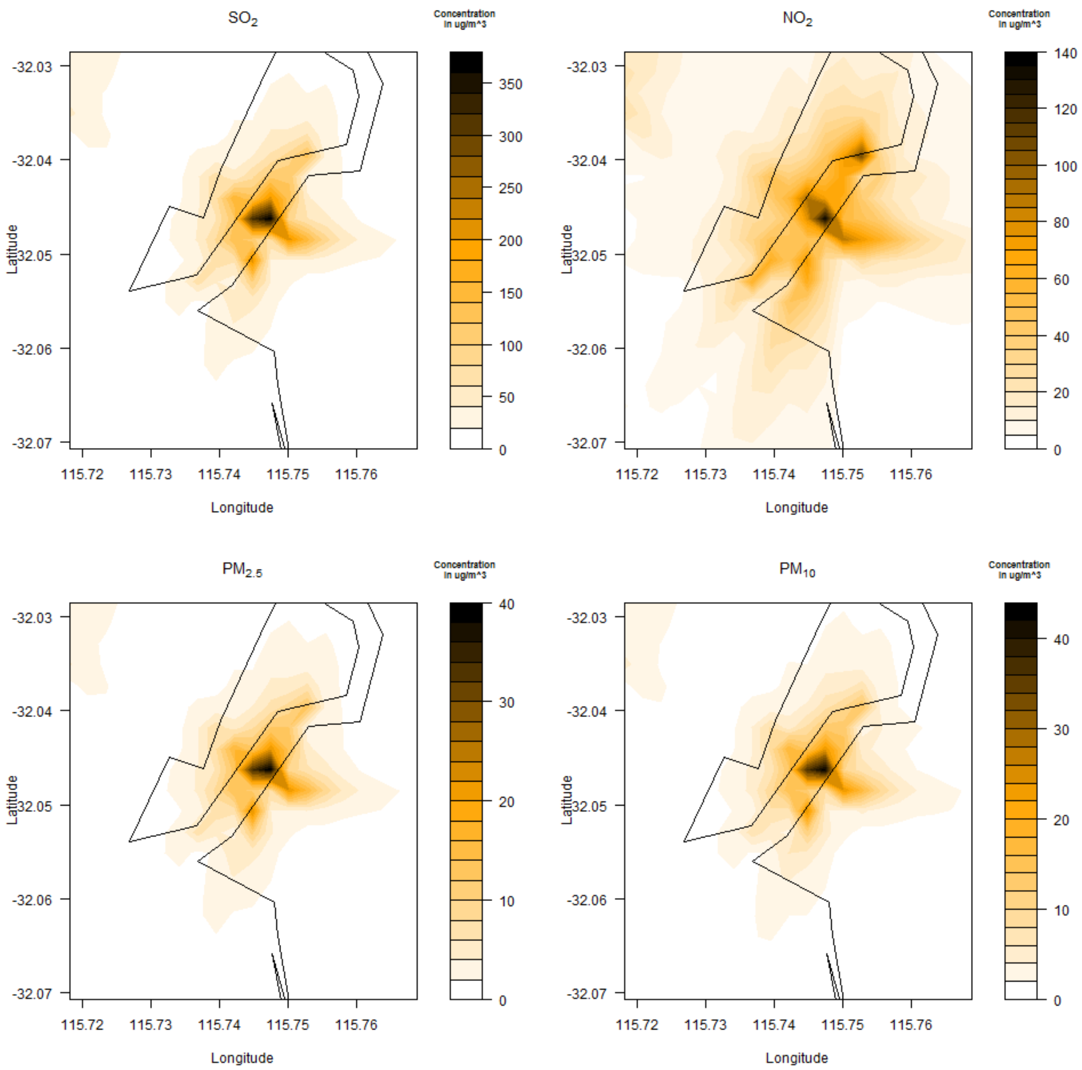

Figure E.2: 24 hour average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over water and ship stack height at 30 m.

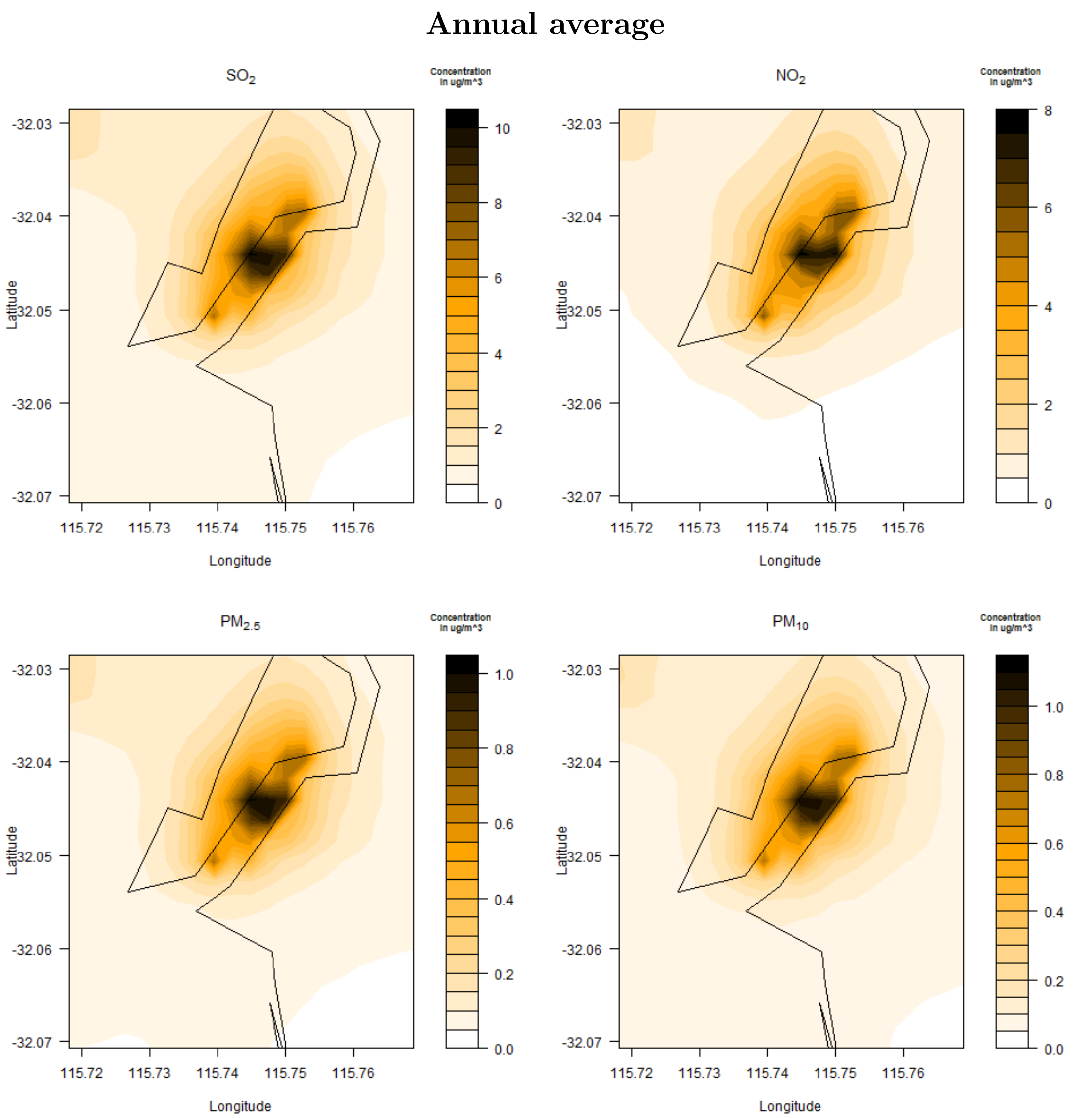

Figure E.3: Annual average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over water and ship stack height at 30 m.

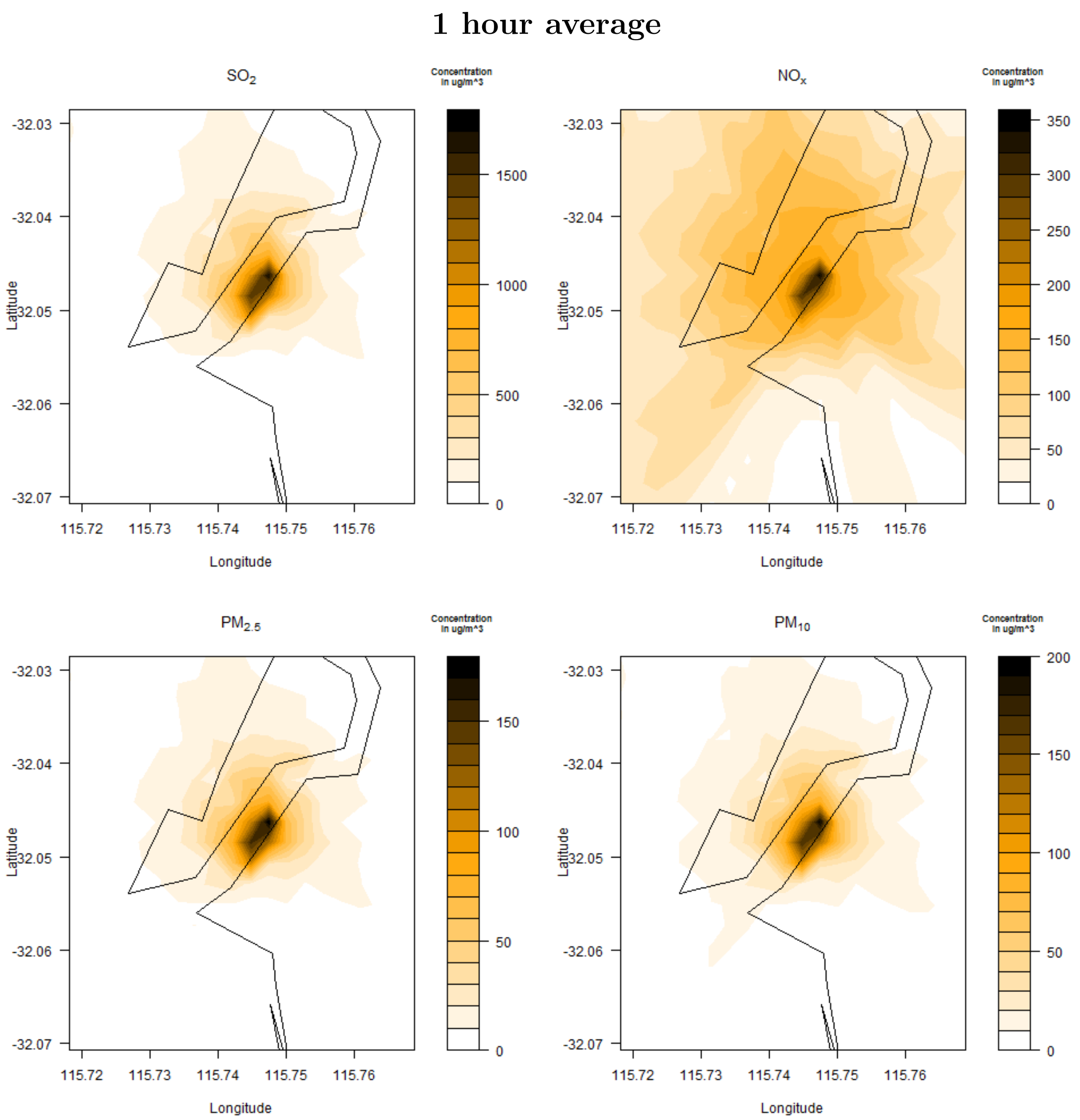

Figure E.4: 1 hour average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over land and ship stack height at 20 m.

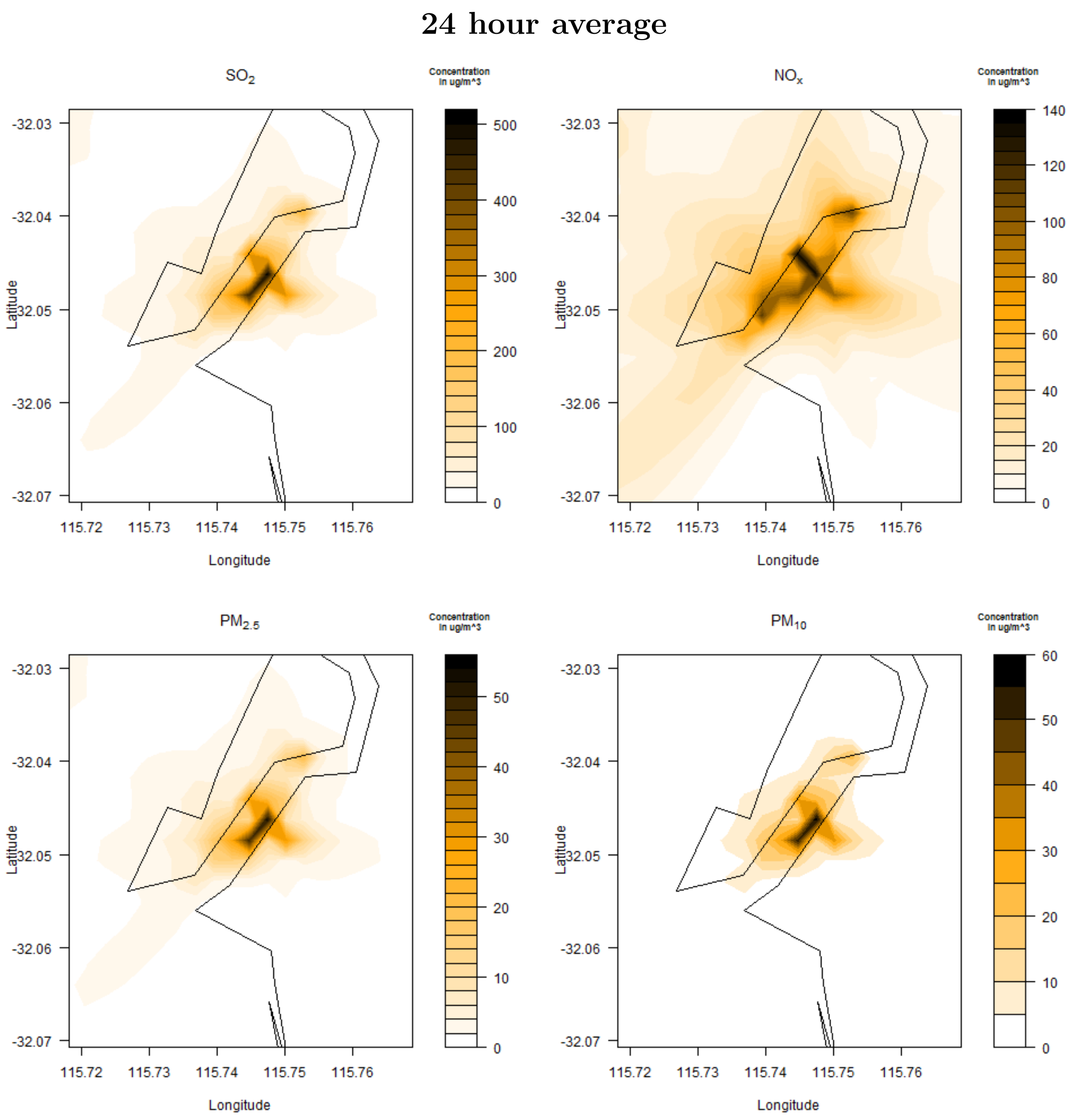

Figure E.5: 24 hour average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over land and ship stack height at 20 m.

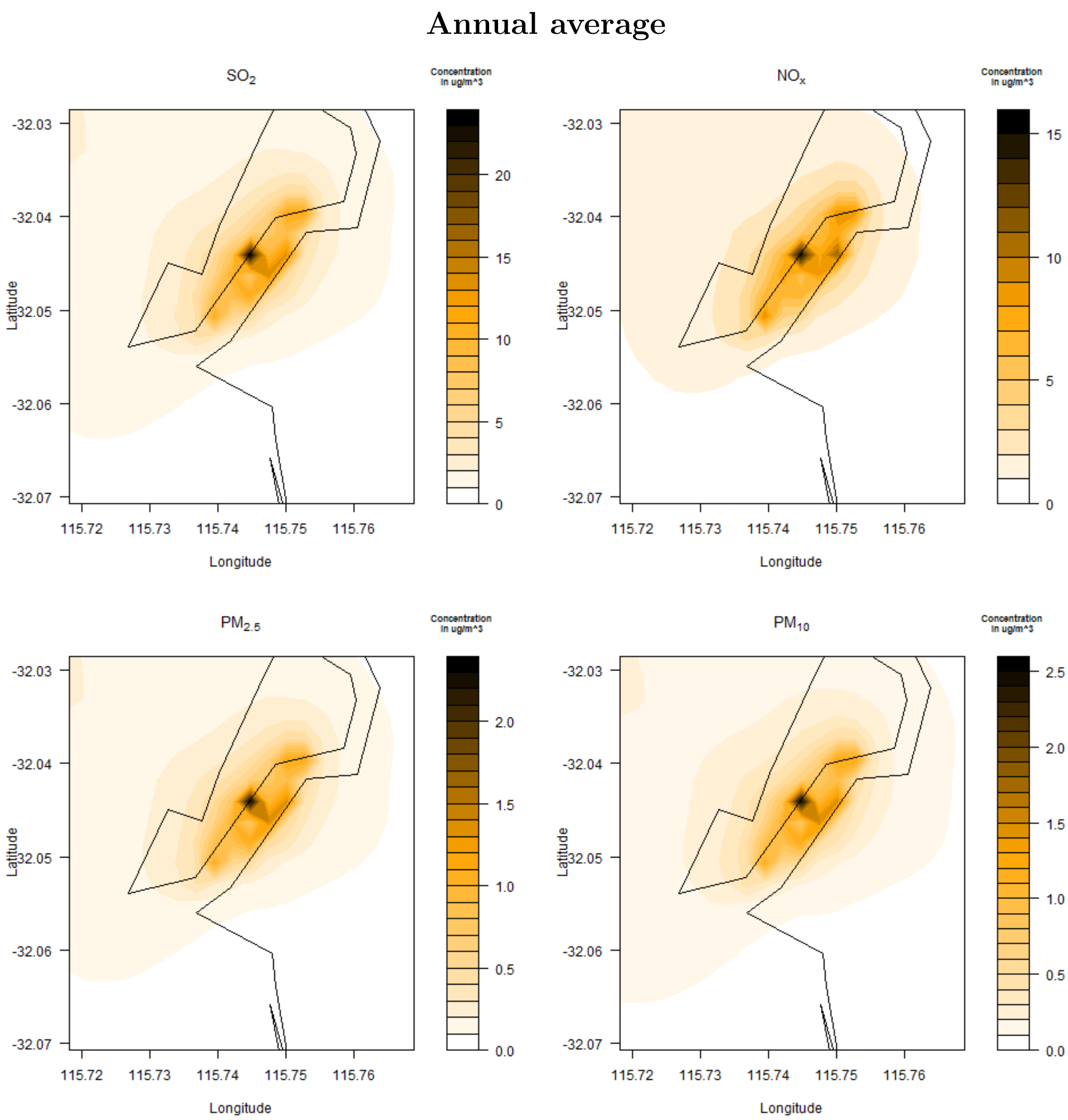

Figure E.6: Annual average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over land and ship stack height at 20 m.

1 hour average

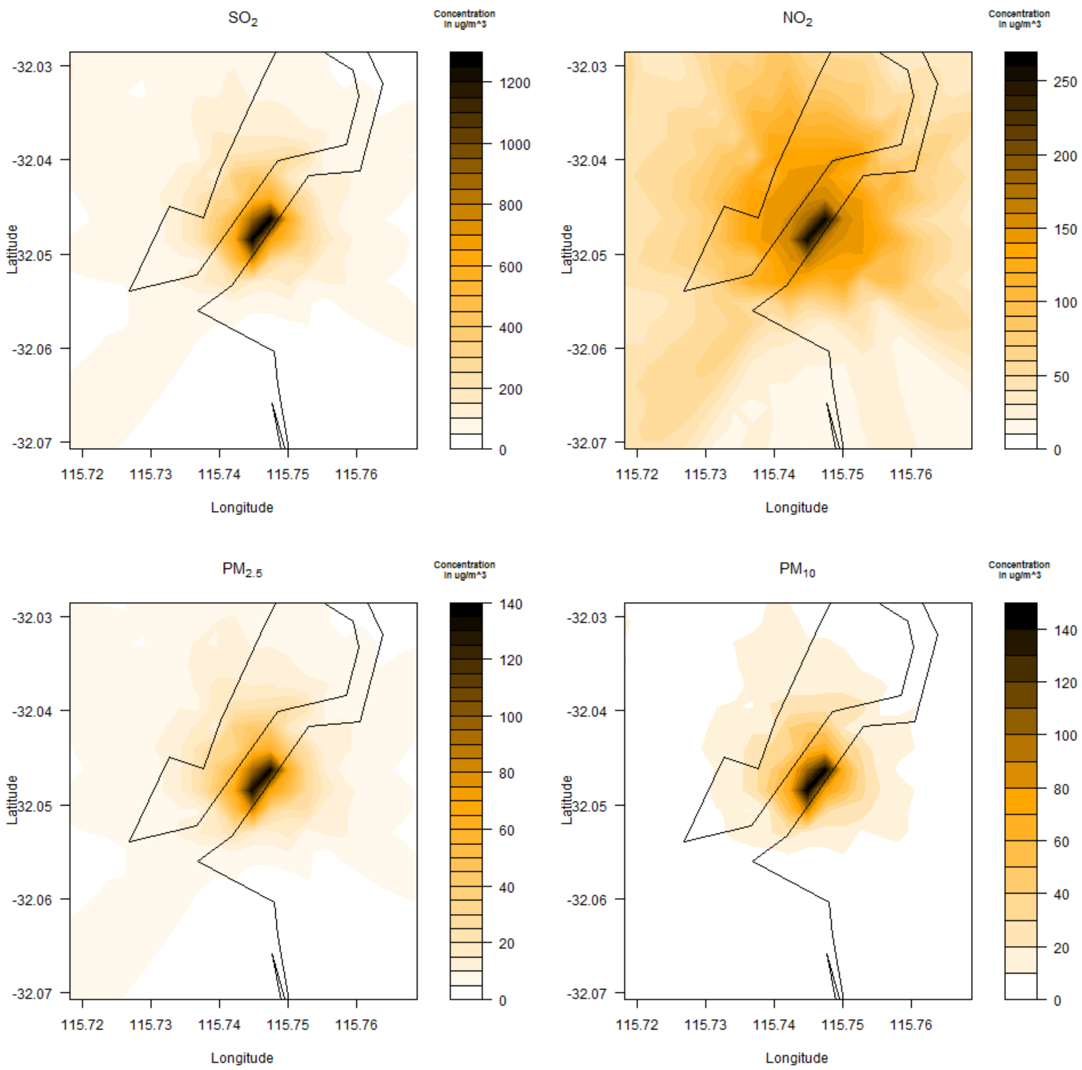

Figure E.7: 1 hour average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over land and ship stack height at 30 m.

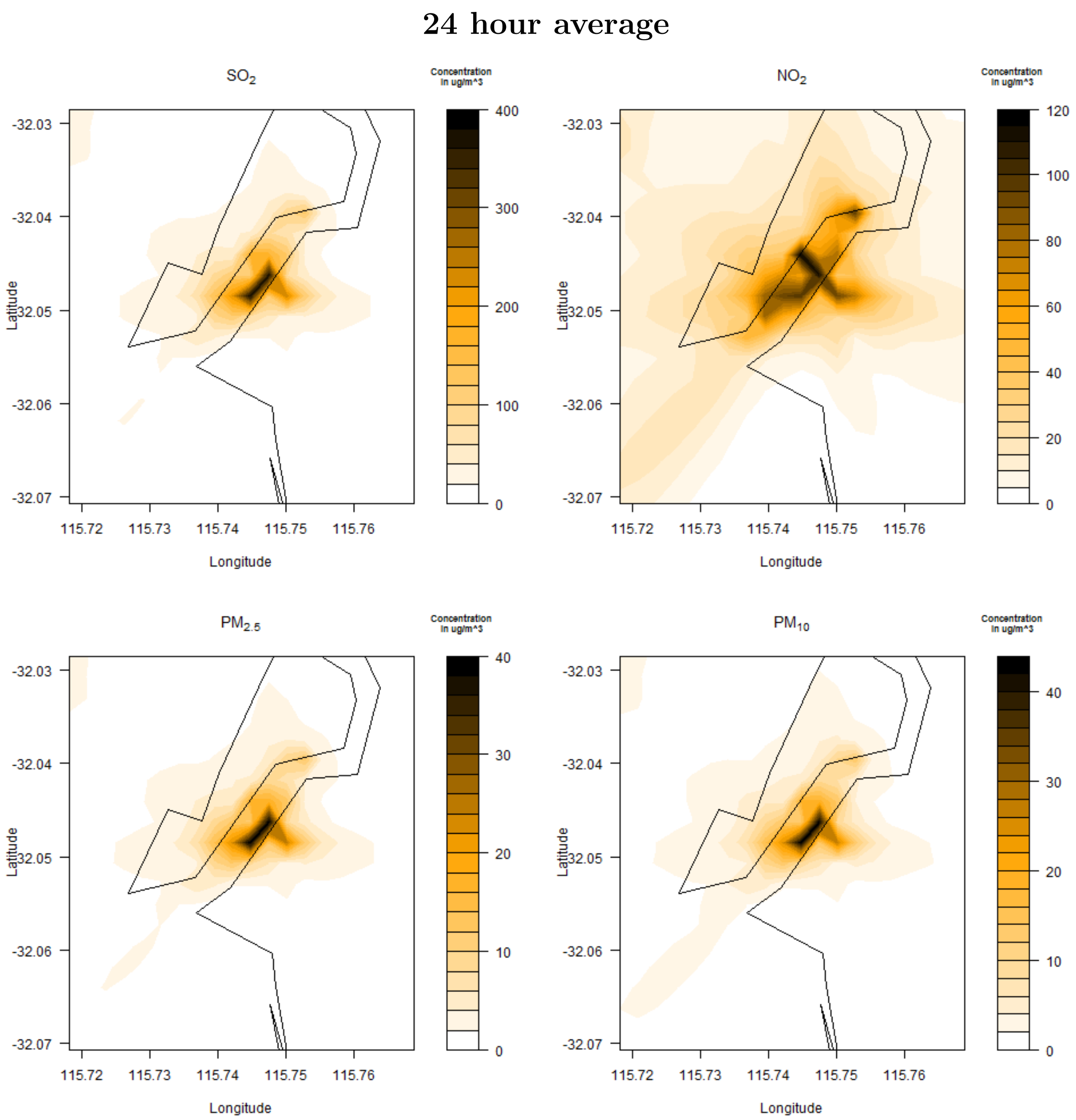

Figure E.8: 24 hour average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over land and ship stack height at 30 m.

Annual average

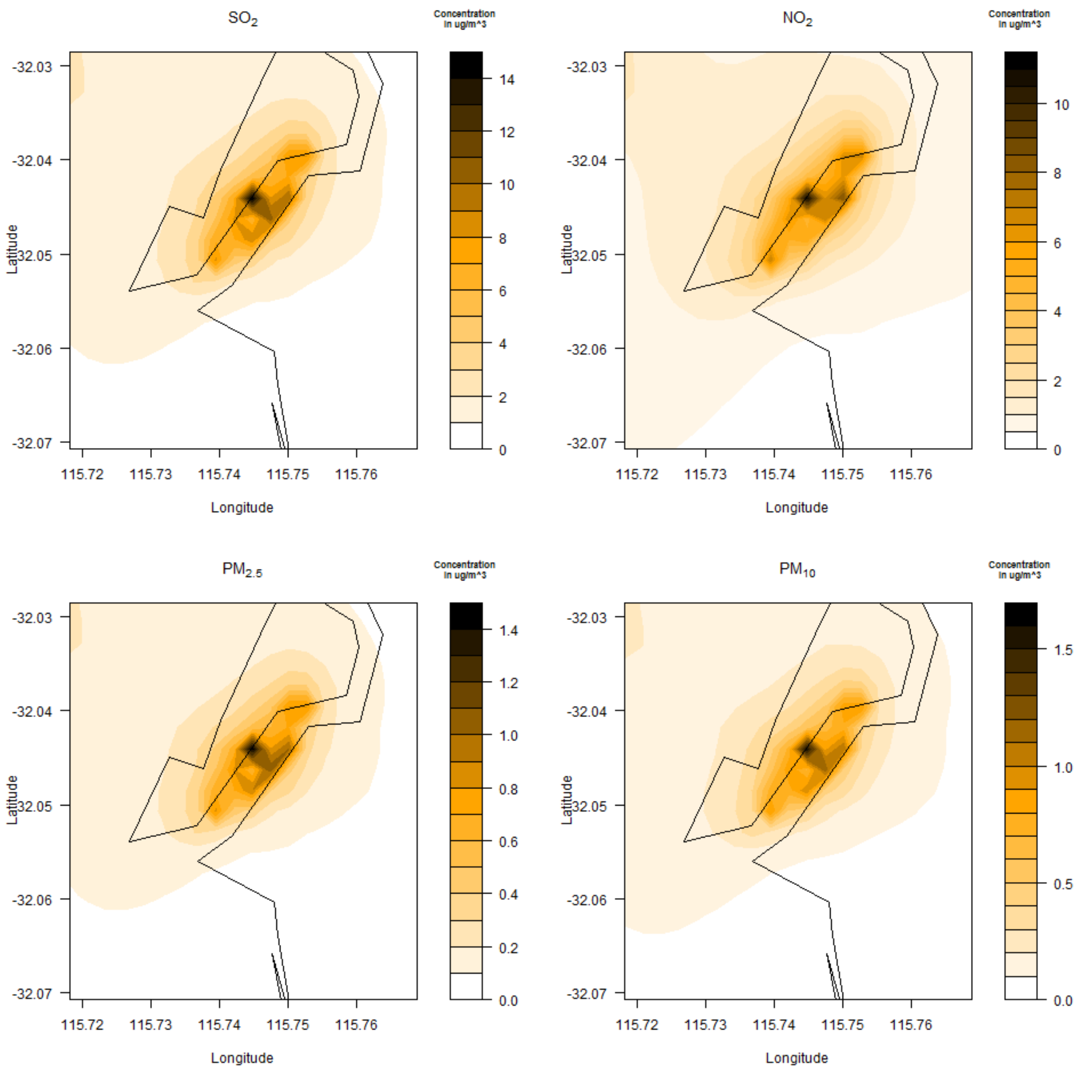

Figure E.9: Annual average concentrations simulated by AERMOD over Fremantle inner harbour for simulations with meteorology over land and ship stack height at 30 m.

APPENDIX F
EXCEEDANCE TABLES (LOW RESOLUTION DOMAIN)

Table F.1: 3rd highest concentrations (μg m^{-3}) estimated by AERMOD for all combinations of meteorology and stack height for the maximum 1 hour average for SO_2. (MET is meteorology and SH is stack height.)

Experiment ID	**MET**	**SH**	**3rd highest concentrations**	**Date and time**	**No. ships contributing**
Control	Water	20 m	578.3 (54.3)	17th Feb 2012 3pm	3
Control	Water	30 m	none	-	-
1a	Water	20 m	542.0 (18.0)	19th Jan 2012 3pm	3
1a	Water	30 m	542.0 (18.0)	19th Jan 2012 3pm	3
1b	Water	20 m	636.1 (112.1)	17th Feb 2012 3pm	3
1b	Water	30 m	551.2 (27.2)	17th Feb 2012 4pm	3
2	Water	30 m	none	-	-
3	Water	30 m	none	-	-

Table F.2: 4th highest concentrations (μg m^{-3}) estimated by AERMOD for all combinations of meteorology and stack height for the maximum 1 hour average for SO_2. (MET is meteorology and SH is stack height.)

Experiment ID	**MET**	**SH**	**4th highest concentrations**	**Date and time**	**No. ships contributing**
Control	Water	20 m	none	-	-
Control	Water	30 m	none	-	-
1a	Water	20 m	530.9 (6.90)	17th Feb 2012 4pm	3
1a	Water	30 m	none	-	3
1b	Water	20 m	562.2 (38.2)	26th April 2012 11pm	5
1b	Water	30 m	546.1 (22.1)	17th Feb 2012 3pm	
2	Water	30 m	none	-	-
3	Water	30 m	none	-	-

Table F.3: 5th highest concentrations (μg m^{-3}) estimated by AERMOD for all combinations of meteorology and stack height for the maximum 1 hour average for SO_2. (MET is meteorology and SH is stack height.)

Experiment ID	**MET**	**SH**	**5th highest concentrations**	**Date and time**	**No. ships contributing**
Control	Water	20 m	none	-	-
Control	Water	30 m	none	-	-
1a	Water	20 m	none	-	-
1a	Water	30 m	none	-	-
1b	Water	20 m	543.3 (38.2)	19th Jan 2012 3pm	3
1b	Water	30 m	543.3 (19.3)	19th Jan 2012 3pm	3
2	Water	30 m	none	-	-
3	Water	30 m	none	-	-

Table F.4: 6th highest concentrations (μg m^{-3}) estimated by AERMOD for all combinations of meteorology and stack height for the maximum 1 hour average for SO_2. (MET is meteorology and SH is stack height.)

Experiment ID	**MET**	**SH**	**6th highest concentrations**	**Date and time**	**No. ships contributing**
Control	Water	20 m	none	-	-
Control	Water	30 m	none	-	-
1a	Water	20 m	none	-	-
1a	Water	30 m	none	-	-
1b	Water	20 m	528.7 (4.7)	17th Feb 2012 2pm	3
1b	Water	30 m	none	-	-
2	Water	30 m	none	-	-
3	Water	30 m	none	-	-

APPENDIX G
CONTOUR PLOTS FOR THE DIFFERENCE BETWEEN AERMOD WITH METEOROLOGY OVER LAND AND CALPUFF SIMULATIONS

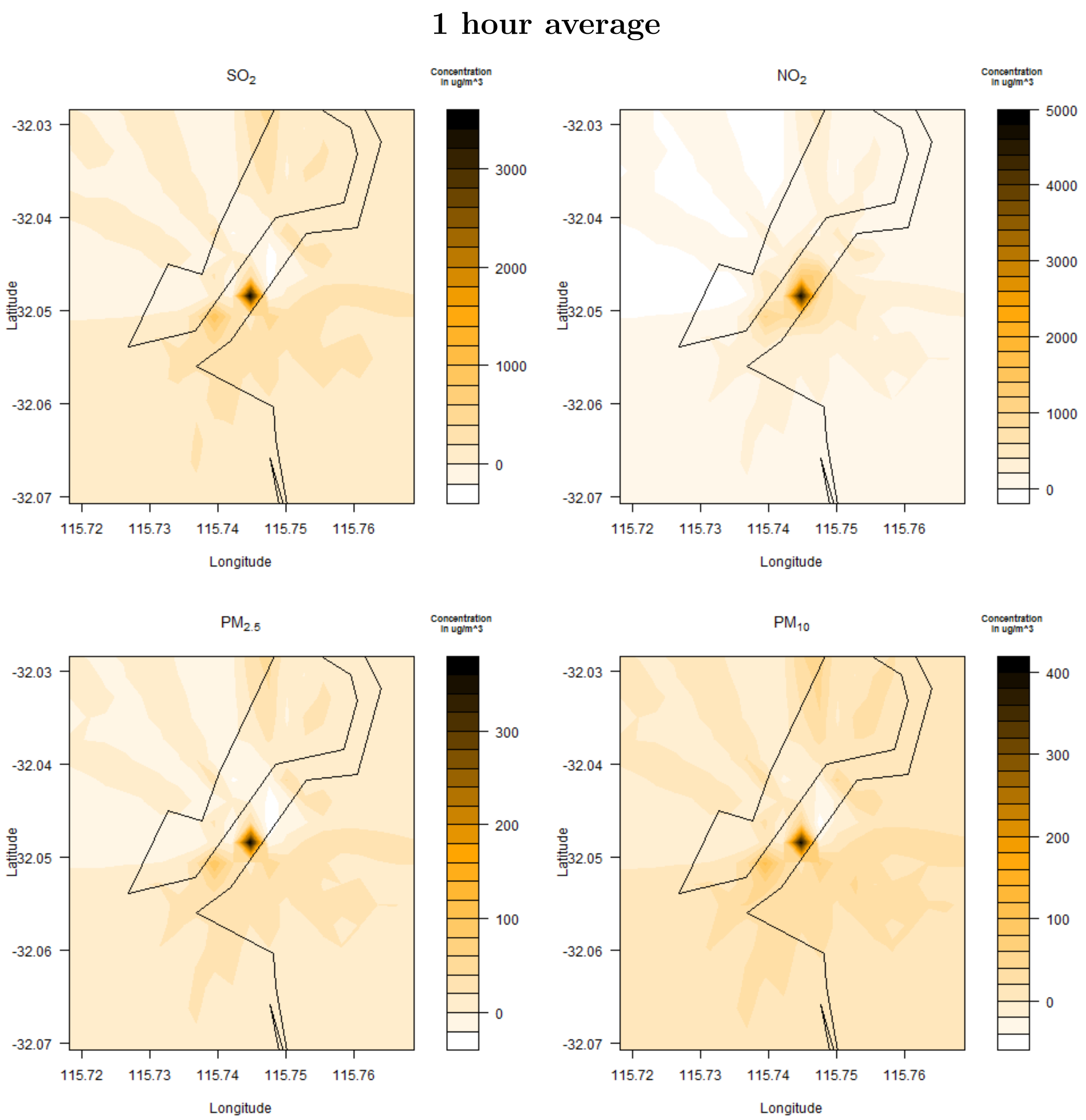

Figure G.1: 1 hr average concentrations over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over land) for the control emission inventory and 20 m stack heights.

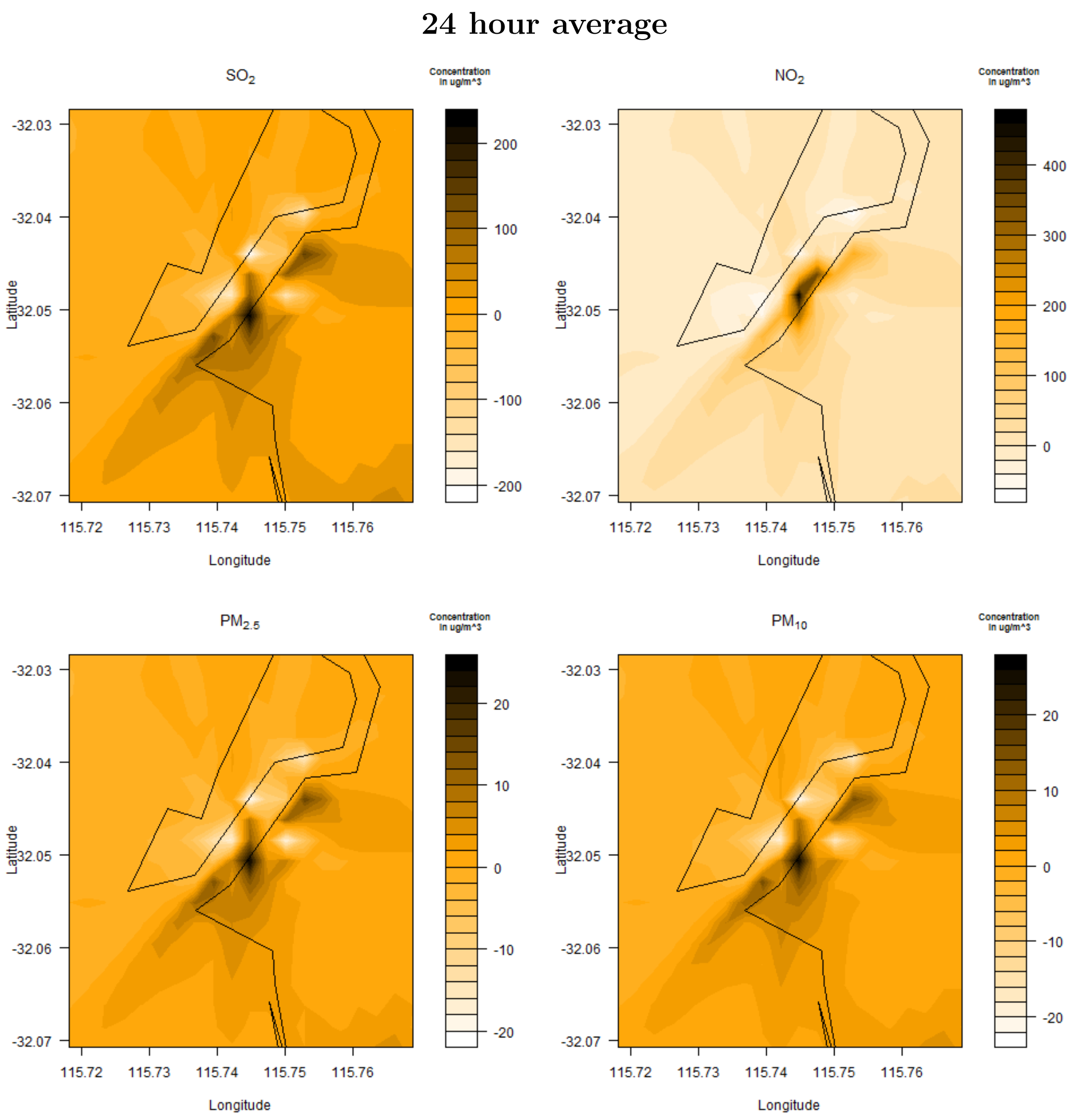

Figure G.2: 24 hr average concentrations over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over land) for the control emission inventory and 20 m stack heights.

Annual average

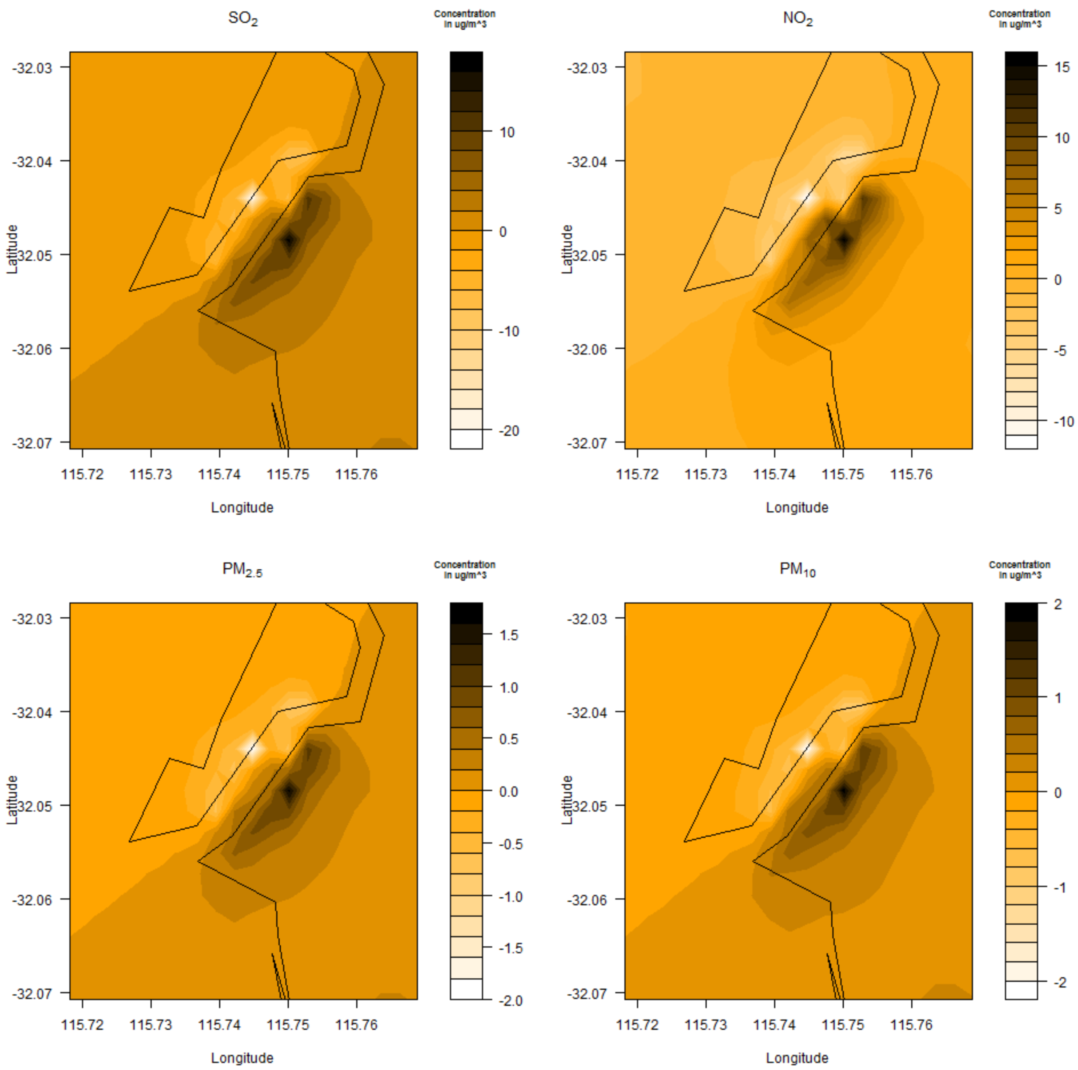

Figure G.3: Annual average concentrations over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over land) for the control emission inventory and 20 m stack heights.

APPENDIX H
DIFFERENCES IN CONCENTRATIONS FOR CALPUFF AND AERMOD WITH METEOROLOGY OVER LAND

Table H.1: Concentrations (μg m^{-3}) over Fremantle inner harbour for CALPUFF minus AERMOD (meteorology over land) with the control emission inventory and 20 m stack heights. (AP is averaging period.)

AP	SO_2	NO_2	$PM_{2.5}$	PM_{10}
1 hr	3340.9 (196.5%)	4766.3 (1382.2%)	-	-
	1176.5	118.8		
24 hr	56.2 (10.9%)	-	6.50 (12.0%)	6.87 (11.7%)
	305.7		29.0	8.90
1 yr	-3.19 (-13.5%)	2.87 (18.8%)	-0.32 (-13.8%)	-0.25 (-9.61%)

APPENDIX I
CONTOUR PLOTS FOR ABSOLUTE CONCENTRATIONS FROM CALPUFF SIMULATIONS

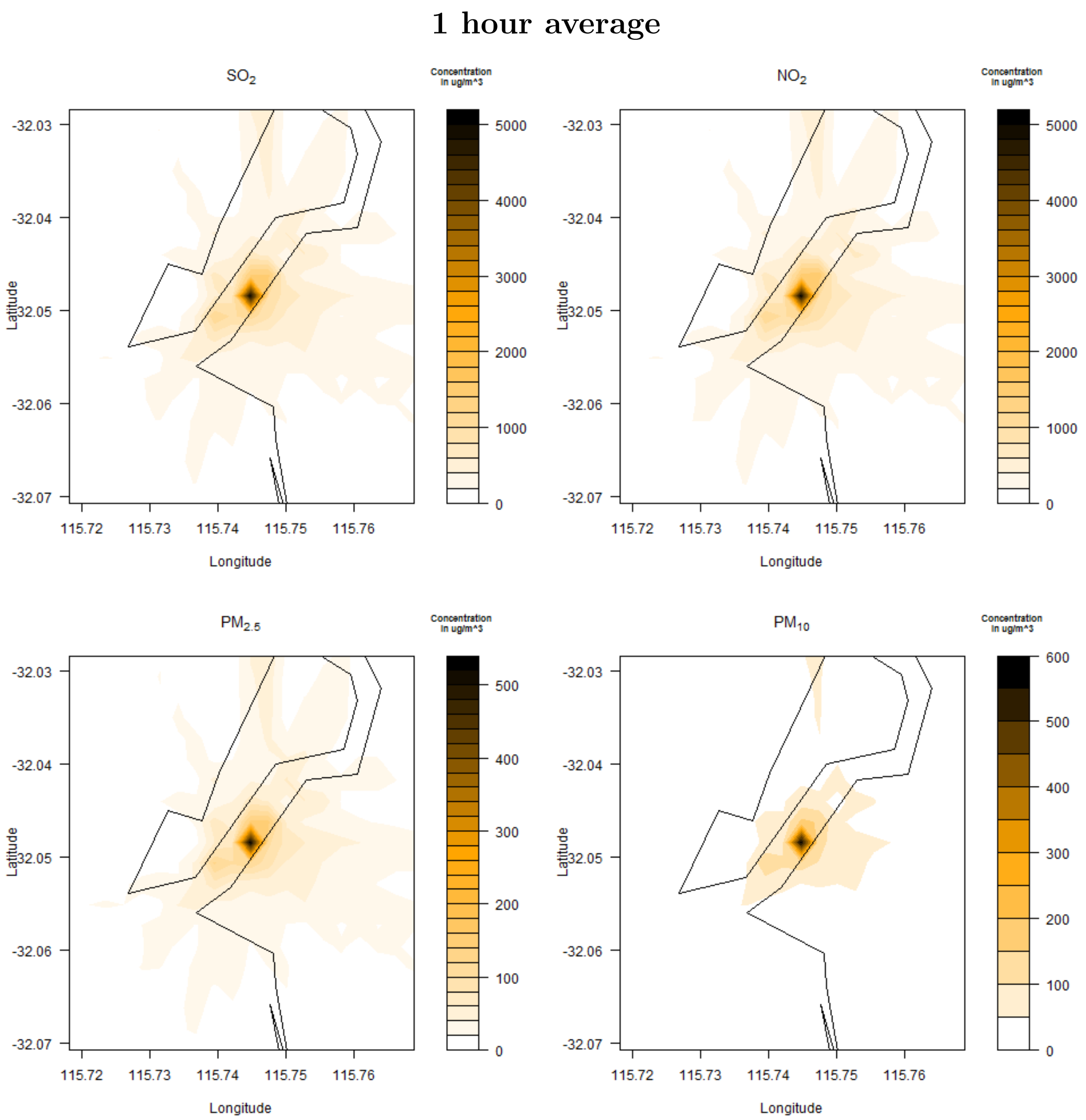

Figure I.1: Absolute 1 hour average concentrations over Fremantle inner harbour simulated by CALPUFF with the control emission inventory 20 m stack heights.

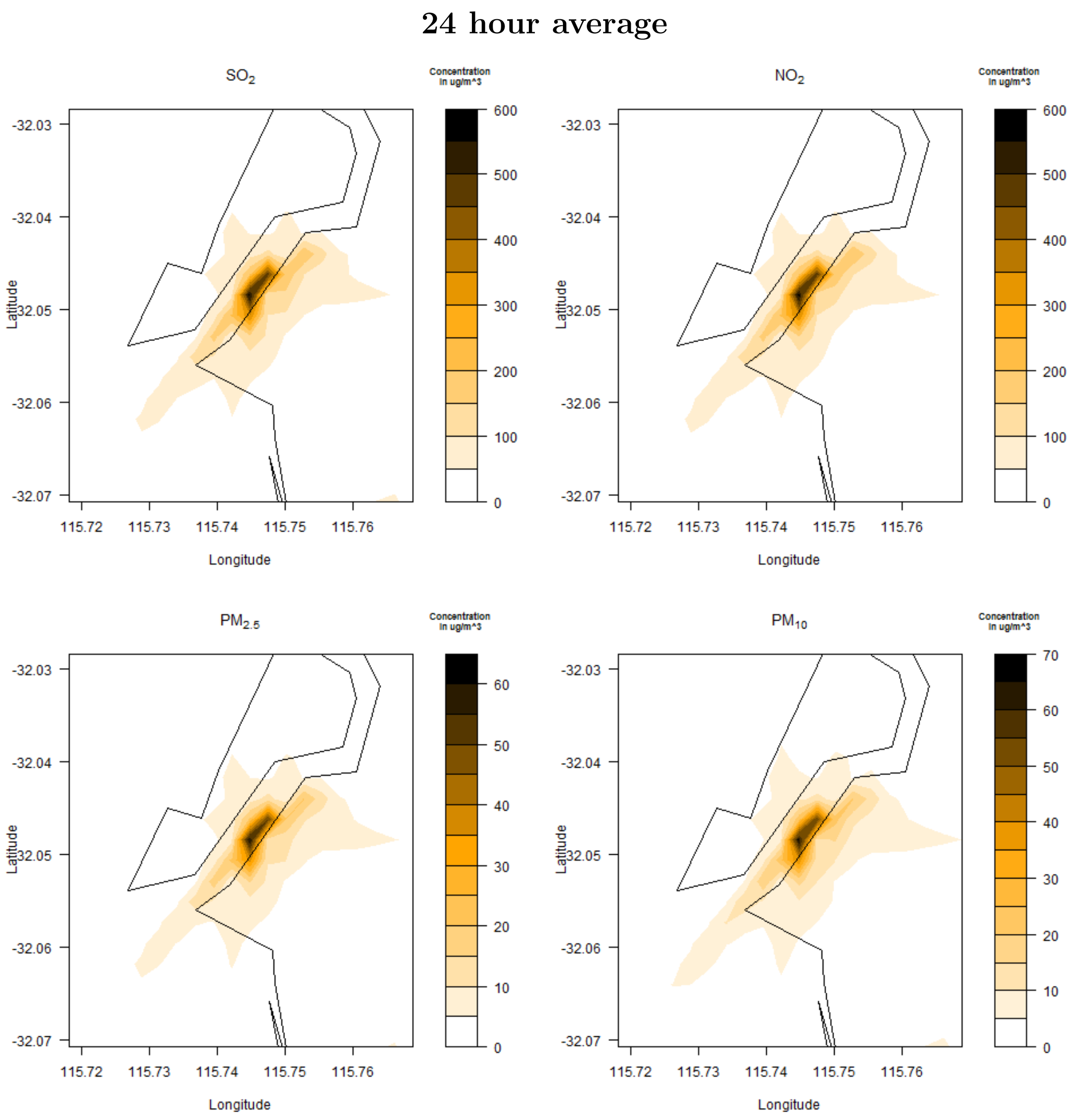

Figure I.2: Absolute 24 hour average concentrations over Fremantle inner harbour simulated by CALPUFF with the control emission inventory 20 m stack heights.

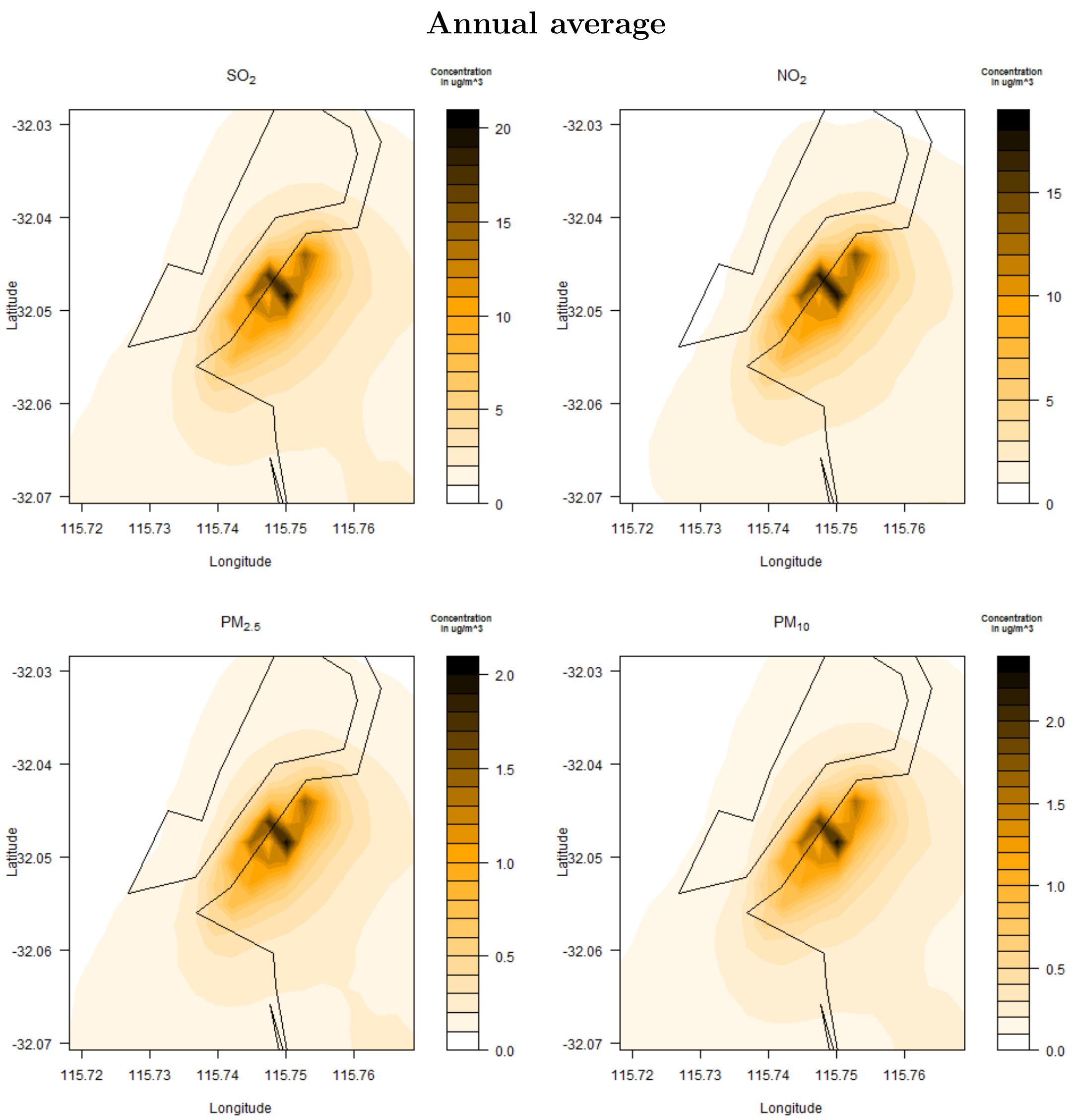

Figure I.3: Absolute annual average concentrations over Fremantle inner harbour simulated by CALPUFF with the control emission inventory 20 m stack heights.

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