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STUDY OF THE CUMULATIVE IMPACTS OF AIR EMISSIONS IN THE MURUJUGA AIRSHED

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STUDY OF THE CUMULATIVE IMPACTS OF AIR EMISSIONS IN THE MURUJUGA AIRSHED

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LIST OF ACRONYMS AND ABBREVIATIONS

AIS	Automatic Identification System (for marine vessels)
AMSA	Australian Maritime Safety Authority
AOD	Aerosol optical depth
ARL	Air Resources Laboratory of NOAA
BCs	Boundary Concentrations
BTEX	Benzene, toluene, ethylbenzene and xylene
BTX	Benzene, toluene and xylene
CAM-chem	NCAR Community Atmosphere Model with Chemistry
CAMx	Comprehensive Air quality Model with extensions
CCRS	Coarse Crustal Particulate Matter > 2.5 µm and < 10 µm
CEDS	Community Emissions Data System
CO	Carbon Monoxide
COPERT	Computer Programme to calculate Emissions from Road Transport
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DoT	Western Australian Department of Transport
DWER	Department of Water and Environmental Regulation
ESRL	Earth Systems Research Laboratory
EPA	Western Australian Environmental Protection Authority
EDGAR	Emissions Database for Global Atmospheric Research
FCRS	Fine Crustal Particulate Matter < 2.5 µm
FINN	Fire Inventory from NCAR
GEOS	Goddard Earth Observing System
GDAS	GFS Data Assimilation System
GFS	Global Forecasting System
GOES	Geostationary Operational Environmental Satellite
H1MDA1	Highest daily maximum 1-hour average in the year
H1MDA4	Highest daily maximum 4-hour average in the year
H1MDA8	Highest daily maximum 8-hour average in the year
Hg	Mercury
Hg^0	Elemental gaseous mercury
Hg^2	Oxidised gaseous mercury
HGP	Particulate mercury
HG2P	Mercury adsorbed to particulate
HG2PC	Mercury adsorbed to carbonaceous particulates
HNO_3	Nitric Acid
ICs	Initial Concentrations
LSM	Land Surface Model
mb	millibars
meq	milliequivalent (of an ion)

MDA1	daily maximum 1-hour average
MDA4	daily maximum 4-hour average
MDA8	daily maximum 8-hour average
MEGAN	Model of Emissions of Gases and Aerosols from Nature
MODIS	Moderate Resolution Imaging Spectroradiometer
MOZART	Model for Ozone and Related chemical Tracers
m	metre
MB	Normalised Mean Bias
MPE	Model Performance Evaluation
MSKF	Multi-Scale Kain Fritsch
NAAQS	National Ambient Air Quality Standard
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environment Prediction
NCL	NCAR Command Language
NDAS	NAM Data Assimilation System
NH_3	Ammonia
ng	Nano grams
NME	Normalised Mean Error
NAAQS	National Ambient Air Quality Standard
NO	Nitric Oxide
NOAA	National Oceanic and Atmospheric Administration
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_X	Oxides of Nitrogen
O_3	Ozone
PBL	Planetary Boundary Layer
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter < 2.5 µm
PM_{10}	Particulate Matter < 10 µm
PM_{coarse}	$PM_{10} - PM_{2.5}$
PNO_3	Particulate Nitrate
ppb	parts per billion (1 in 10^9)
ppm	parts per million (1 in 10^6)
ppt	parts per trillion (1 in 10^{12})
PSO_4	Particulate Sulphate
RMSE	Root Mean Squared Error
SO_2	Sulphur Dioxide
SO_X	Oxides of Sulphur
SRTM3	Shuttle Radar Topography Mission (terrain data)

µg	microgram
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UTC	Coordinated Universal Time
VKT	Vehicle kilometres travelled
VOCs	Volatile Organic Compounds
WRF	Weather Research and Forecasting

EXECUTIVE SUMMARY

Background

Murujuga (the Dampier Archipelago, including the Burrup Peninsula and the population centres of Dampier and Karratha and surrounding areas) contains unique ecological and archaeological areas of national and international heritage value including areas of significant cultural and spiritual significance to Aboriginal people.

Murujuga is also home to industry that contributes to the local and state economy and provides employment in the area. In response to concerns that industrial emissions may be affecting the areas of cultural significance, several scientific studies assessing potential impacts have been conducted for the region.

The Western Australian Department of Water and Environmental Regulation (DWER), commissioned Ramboll Australia Pty Ltd (Ramboll) to undertake a study on the cumulative impacts of air emissions within the Murujuga airshed including air emissions from existing and proposed future industries, shipping, and aggregated sources in the Pilbara region.

Scope and Methods

Ramboll used the CAMx air quality model, which includes photochemistry of the atmosphere, to evaluate air concentrations and deposition for these pollutants:

- Nitrogen dioxide (NO_2);
- Ozone (O_3);
- Sulphur dioxide (SO_2);
- Carbon monoxide (CO);
- Ammonia (NH_3);
- Volatile organic compounds (VOCs), including benzene, toluene, ethylbenzene, and xylene (BTEX);
- Particulate matter as PM_{10} and $PM_{2.5}$;
- Chemical constituents of PM including ammonium nitrate and ammonium sulphate;
- Urea dust; and
- Inorganic Mercury (Hg).

A complete emission inventory of all sources was necessary to conduct photochemical modelling. The following emissions sources were included:

- Industrial emissions sources;
- Mobile sources including:
    - Commercial shipping and recreational boating;
    - On-road and off-road mobile vehicles;
    - Airports; and
    - Railways.
- Domestic and commercial sources including:
    - Recreational boats
    - Aerosols and solvents;
    - Cutback bitumen
    - Gaseous fuel combustion;
    - Liquid fuel combustion (domestic);
    - Portable fuel containers (domestic and public open space);
    - Gaseous and solid fuel combustion (domestic);

    - Surface coatings (domestic, commercial and industrial);
    - Industrial solvents;
    - Automotive fuel retailing; and
    - Motor vehicle refinishing.
- Biogenic sources including:
    - Vegetation;
    - Wind blown dust;
    - Bushfires; and
    - Oceanic Sources (Sea salt and dimethyl sulphide).

The CAMx modelling considered three scenarios in order to assess current industry emissions (Scenario 2 – Scenario 1) and anticipated emissions of future industry expansion (Scenario 3 – Scenario 2), namely:

- **Scenario 1** - All emissions, including natural, domestic and commercial sources, but excluding the point and area sources for heavy industry including railways and shipping in the region.
- **Scenario 2** - Scenario 1 plus the point and area sources for heavy industry including railways and shipping in the region.
- **Scenario 3** - Scenario 2 plus proposed future emissions (2030) from all sources.

A base year of 2014 was chosen for the modelling because it has meteorology that is typical of recent years and was not an extreme year. The CAMx modelling uses meteorology from a weather model (WRF) and background air quality from a global air quality model (CAM-chem). CAMx is a grid model, meaning that it represents the atmosphere as a system of inter-connected grid boxes, also called grid cells. The grid cell size is what determines how finely the model can resolve space. The CAMx model has 1.33 km grid cells (meaning 1.33 km by 1.33 km squares) over Murujuga and the adjacent area. The model also has a 4 km resolution grid covering a wide portion of the Pilbara.

CAMx model results for Scenario 2 were compared with available air monitoring data for 2014. The comparison indicated reasonable agreement with the measurements at Burrup Road, Dampier, and Karratha noting the following:

- There is a high NO_2 model bias at Burrup Road and Dampier. The bias at Burrup Road is likely due to the model not having a fine enough resolution to resolve the source-receptor relationships at this location. The bias at Dampier is likely due to influence from the characterisation of shipping and industry emissions in the region.
- Ozone concentrations at Dampier and Karratha correlate closely with observed concentrations and have little bias.
- There was good agreement between modelled and measured distributions of benzene, toluene, and xylene concentrations, especially for higher concentrations (around the 90_{th} percentile).
- Modelled 24-hour average $PM_{2.5}$ and PM_{10} concentrations agree fairly well with observations in Dampier although the 1.33 km model resolution is insufficiently fine to resolve details of the source-receptor relationships.

Results

A summary of the results for Scenario 2 and Scenario 3 includes the following:

- Analysis of source contributions to the predicted ground level concentrations of benzene, toluene and xylene emissions in the Murujuga airshed indicate that the majority contribution is from industry near or on the Burrup Peninsula.
- Exceedances of the benzene standard were predicted for Scenario 2, however these exceedances were predicted to occur at or near industrial facilities and no exceedances were predicted at sensitive receptor locations, including Dampier and Karratha.
- Future industry benzene emissions increased but concentrations remained well below the guideline at sensitive receptor locations, including Dampier and Karratha.
- SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and NH_3 peak ground level concentrations are centred at industrial facilities near or on the Burrup Peninsula, showing that industrial sources and shipping contribute to air emissions in the area, but with total air concentrations for these compounds remaining below current air quality standards except for PM_{10} and $PM_{2.5}$ at sensitive receptor locations, including Dampier and Karratha.
- Industry GLCs contribute from 3.7% to 15.5% of annual average PM_{10} and 6.3% to 18.4% of annual average $PM_{2.5}$ in Scenario 2. Future industry GLCs contribute only around 1% to 2% to annual average PM_{10} in Scenario 3. Contributions to annual average $PM_{2.5}$ in Scenario 3 are negative or zero likely due to decreases in secondary $PM_{2.5}$ precursor emissions.
- Estimated background (Non-industrial) PM_{10} dust concentrations contribute 23-29 µg/m^3 (85-96%) to the annual average and 85-95 µg/m^3 (92-99%) in maximum 24-hr concentrations (although the maximum 24-hr dust and maximum 24-hr total PM_{10} could have occurred on different dates). Dust sources alone (i.e., crustal material from categories 1 and 2 above) contribute approximately 66-73% of the annual average PM_{10} and 79-86% of the maximum 24-hr PM_{10} concentrations.
- Background (Non-industrial) $PM_{2.5}$ dust concentrations contribute 4.6-5.8 µg/m^3 (82-94%) to the annual average and around 16-17 µg/m^3 (82-94%) in maximum 24-hr concentrations. Dust sources alone (i.e., crustal material from categories 1 and 2 above) contribute approximately 31-44% of the annual average $PM_{2.5}$ and 66-74% of the maximum 24-hr $PM_{2.5}$ concentrations.
- For several short-term air quality metrics (i.e., MDA1) industry emissions are a large contributor indicating that the highest short-term ground level concentration episodes tend to occur when industrial emissions are high.
- Offshore SO_2 and NO_2 concentrations show strong influences from shipping emissions.
- Future annual maximum daily 1-hour average (MDA1) NO_2 were predicted to decrease by -13.6 ppb near Dampier which likely results from Woodside's intention to reduce NO_X emissions from the Karratha Gas Plant by 40% by the end of 2030 as part of the North West Shelf Project Extension Proposal (Woodside, 2019).
- Future MDA1 SO_2 concentrations decrease offshore by up to 86 ppb due to the introduction of International Maritime Organisation (IMO) regulations that limit the fuel-sulphur content for marine vessels.
- NO_X emissions from industry result in the suppression of O_3 near Dampier.
- Future industry emissions tend to increase O_3 but O_3 concentrations in all scenarios are below air quality standards.
- Future industry emissions increase MDA8 CO by 359 ppb near the Yara Ammonium Nitrate Plant.

A summary of the deposition rates from Scenario 2 and Scenario 3 includes the following:

- HNO_3, NO_2, and total N deposition amounts are higher over land than over water because HNO_3 and NO_2 dissolves into water.
- Particulate nitrate (PNO_3) is a small contributor to total N deposition because it deposits more slowly than HNO_3 and NO_2.

- PSO_4, SO_2, and S deposition occur mostly offshore near Dampier and over land near Dampier, showing that most of the deposition is coming from shipping and industrial plants in the area.
- Almost all N and S deposition comes from the industrial emissions sources in the region.
- Scenario 2 deposition of total N at Burrup Road is higher than measurements recorded from 2012–2014 suggesting that NO_X emissions from industry and/or shipping may be over-estimated in Scenario 2.
- Industry contributions to N deposition are expected to increase in the future with the largest increase occurring near Burrup Road.
- Industry contributions to S deposition are expected to decrease in the future as a result of the introduction of IMO regulations that limit fuel-sulphur content for marine vessels.
- Hg deposition values are low and there is little change expected in the future.

Recommendations

Ramboll recommends that any future work prioritise the following recommendations:

- The outcomes from the assessment indicate a high bias for NO_2 at the Burrup Road and Dampier monitors. Whilst this may have been a function of the resolution of the modelling, analysis of the plots indicates significant contributions from other sources such as railways and shipping emissions in the region of which there was a degree of uncertainty related to emissions estimates. A more detailed characterisation in the quantity and temporal variation of emissions from these operations would likely enhance the outcomes of the assessment. The use of plume in grid modelling should also be investigated to assist in resolving the NO_2 bias near industrial emissions sources.
- Emissions data from some industry sources were derived from NPI estimates. There are varying levels of uncertainty in the emissions factors often used to derive emissions reported in the NPI. Emissions estimates presented in the publicly available NPI database are also presented for a whole facility which may not allow for accurate distribution and parametisation of emissions from individual sources. More detailed characterisation of emissions from some industry sources in the Burrup peninsula would assist in reducing potential uncertainty.
- Shipping emissions could be further refined by utilising an un-anonymised private AIS dataset with additional vessel detail for all shipping movements in the region instead of the composite approach using the CEDS database and the publicly available AIS dataset from AMSA. The current assessment used AIS records which do not provide unique vessel identification information. With access to vessel identities, vessel-specific characteristics can be accessed through cross referencing with vessel characteristics databases (e.g., IHS Markit or Clarkson). These specifications can provide a much more accurate depiction of vessel emissions. The AIS data assessment can also be expanded to include transiting emissions to provide a uniform approach for estimating vessel emissions within the model domain. Additionally, further details on specific fuel use at individual ports or terminals could be taken into consideration to more accurately refine emissions factors. Such information may be gleaned from port- or terminal-specific emission reduction or fuel use programs.
- It should be noted that it would be difficult to completely match shipping emissions of SO_2 for 2014 data as discussion with Pilbara Ports Authority (PPA) indicates that some ships fuel switch from high to low sulphur fuel at the request of some of the onshore operators but that fuel-switching was not enforceable and so was done on an ad-hoc basis. The introduction of the lower sulphur limits in fuel by the IMO will reduce some of the uncertainty in the future.
- Predicted deposition of pollutants in some grid cells located in close vicinity to each other, displayed a higher degree of variability than would be expected which was likely a function of the landuse maps utilised in the study. Development of more accurate landuse maps would likely result in improved performance related to deposition, particularly in coastal areas.

CONTENTS

1. INTRODUCTION

1.1 Background

Murujuga (the Dampier Archipelago, including the Burrup Peninsula and the population centres of Dampier and Karratha and surrounding areas) is a low-lying, rocky peninsula that includes areas with protection as a National Heritage Place and National Park. It contains unique ecological and archaeological areas of national and international heritage value including areas of significant cultural and spiritual significance to Aboriginal people, particularly due to the large collections of rock art in the form of petroglyphs, standing stones, and other cultural sites such as foraging areas, ceremonial sites and hunting areas. Vegetation with heritage value is also found on the Burrup Peninsula with some trees providing medicine for colds and flus, shade for shelter and ceremonial tools (MAC, 2016).

Murujuga is also home to industry that contributes to the local and state economy and provides employment in the area. In response to concerns that industrial emissions may be affecting the areas of cultural significance, a number of scientific studies assessing potential impacts have been conducted in the region over the past 15 years.

The Western Australian Department of Water and Environmental Regulation (DWER) has commissioned Ramboll Australia Pty Ltd (Ramboll) to undertake a study on the cumulative impacts of air emissions within the Murujuga airshed including air emissions from existing and proposed future industries, shipping, and aggregated sources in the Pilbara region. The Murujuga airshed as assessed in this study is presented in Figure 1-1.

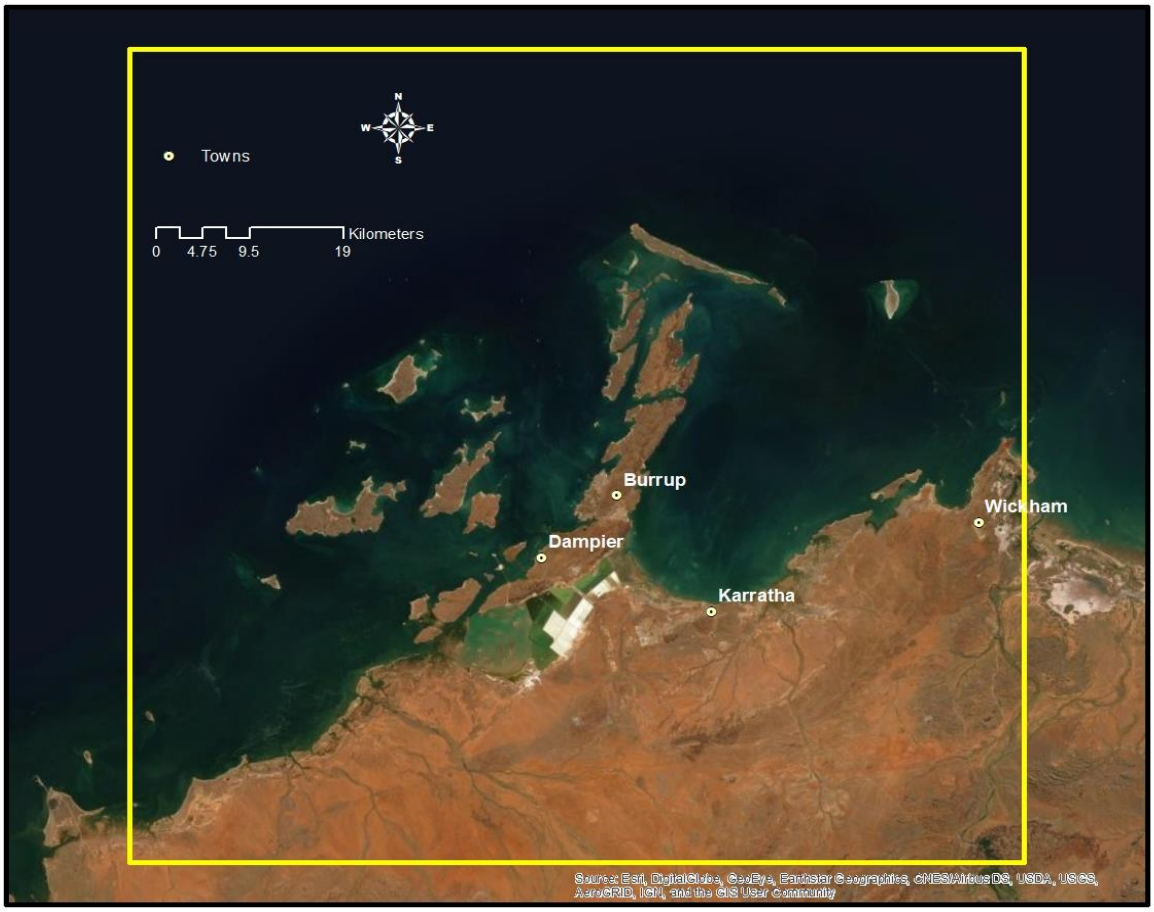


Figure 1-1: Extent of the Murujuga airshed

1.2 Scope of Work

In order to assess air quality in the region, the DWER required that air dispersion modelling be undertaken using an appropriate air dispersion model for the following air pollutants of concern:

- Nitrogen dioxide (NO_2);
- Ozone (O_3);
- Sulphur dioxide (SO_2);
- Carbon monoxide (CO);
- Ammonia (NH_3);
- Volatile organic compounds (VOCs), including benzene, toluene, ethylbenzene, and xylene (BTEX);
- Particulates (as PM_{10} and $PM_{2.5}$), including ammonium nitrate, ammonium sulphate and urea dust; and
- Mercury (Hg).

The following emissions sources were included in the modelling:

- Industry Sources;
- Marine shipping;
- Road vehicles;
- Railroads;

- Aircraft;
- Sub-threshold industry, such as petrol service stations and panel beaters, which are industries that are exempt from reporting their air emissions to relevant jurisdictions as part of the National Pollutant Inventory (NPI);
- Bushfires; and
- Natural sources including vegetation and soils (biogenic), lightning, sea salt spray, and dust.

Air dispersion modelling was completed for three scenarios, namely:

- **Scenario 1** - All emissions, including natural, domestic and commercial sources, but excluding the point and area sources for heavy industry including railways and shipping in the region.
- **Scenario 2** - Scenario 1 plus the point and area sources for heavy industry including railways and shipping in the region.
- **Scenario 3** - Scenario 2 plus proposed future emissions (2030) from all sources.

The air dispersion modelling was used to obtain predicted maximum ground level concentrations (GLCs) for the air emissions of concern at Karratha, Dampier, Hearson Cove and Deep Gorge/Ngajarli for each of the three scenarios. For each air emission of concern in each individual scenario, the following was provided:

- Highest predicted maximum GLC within the model grid(s); and
- Location of predicted GLC contour lines within the Murujuga airshed.

Model predicted GLCs for NO_2, O_3, SO_X as SO_2, CO, and PM_{10} and $PM_{2.5}$ are compared with the relevant criteria in the National Environment Protection Measure (NEPM) ambient air quality standards. Predicted GLCs for NH_3, VOCs including BTEX, and Hg are compared with the relevant criteria in the Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales (NSW EPA, 2016) and the National Environment Protection (Air Toxics) Measure (for BTEX only). Model predictions were used to determine whether there are likely to be any exceedances of applicable criteria at Karratha, Dampier, Hearson Cove, Deep Gorge/Ngajarli or elsewhere within the model grids.

In addition, model predicted deposition to the ground (the surface) is analysed to provide information on the deposition of acid gases and particles NO_2, SO_2, total oxidised N, total oxidised S, ammonium nitrate, Hg, and urea dust on the Murujuga grids.

1.3 Report Organisation

The report is organised as follows. Section 2 reviews the assessment criteria such as the air quality standards for the air emissions of concern. Section 3 meteorological modelling conducted using the Weather Research and Forecasting (WRF) model to prepare input data for the air dispersion modelling. Section 4 presents a summary of ambient air quality monitoring undertaken at monitoring stations within the Murujuga airshed for a number of pollutants of interest in 2014, the modelled year. Section 5 describes the development of emission inventories for all sources and scenarios. Section 6 describes the air dispersion modelling conducted using the Comprehensive Air quality Model with extensions (CAMx) including model configuration and the results for each scenario.

2. ASSESSMENT CRITERIA

2.1 Ambient Air Quality

Table 2-1 contains the relevant criteria for the air emissions of concern assessed in the air dispersion modelling. The standards are based on the Australian National Environmental Protection (Ambient Air Quality and Air Toxics) Measure (NEPM) and values outlined by the NSW EPA and the World Health Organisation (WHO).

Table 2-1 Ambient Air Quality NEPM Particulate Standards

Pollutant	Averaging Period	Unit	Ambient Air Concentration	Reference
NO_2	1-hour	ppb	80	(NEPC 2021)
	Annual	ppb	15	(NEPC 2021)
O_3	8-hour	ppb	65	(NEPC 2021)
SO_2	1-hour	ppb	100	(NEPC 2021)
	24-hour	ppb	20	(NEPC 2021)
CO	8-hour	ppb	9,000	(NEPC 2016)
Ammonia	1-hour	ppb	460	(NSW EPA 2017)
Particles as PM_{10}	24-hour	µg/m^3	50	(NEPC 2016)
	Annual	µg/m^3	25	(NEPC 2016)
Particles as $PM_{2.5}$	24-hour	µg/m^3	25	(NEPC 2016)
	Annual	µg/m^3	8	(NEPC 2016)
Mercury (inorganic)	1-hour	(µg/m^3)[1]	2	(NSW EPA 2017)
	Annual	(µg/m^3)[1]	0.2	(WHO 2003)
Benzene	1-hour	ppb	9	(NSW EPA 2017)
	Annual	ppb	3	(NEPC 2011)
Toluene	1-hour	ppb	89	(NSW EPA 2017)
	24-hour	ppb	1,000	(NEPC 2011)
	Annual	ppb	100	(NEPC 2011)
Xylene	1-hour	ppb	41	(NSW EPA 2017)
	24-hour	ppb	250	(NEPC 2011)
	Annual	ppb	200	(NEPC 2011)

Notes:

1. Referenced to 0ºC, and 101.3 kPa

It should be noted that on the 18th of May 2021, the National Environment Protection Council (NEPC) modified ambient standards for a number of pollutants, based on international guidance (NEPC, 2021). Following public consultation federal Ministers agreed to several changes to the AAQ NEPM including:

- significantly strengthening the NO_2 reporting standards for 1-hour NO_2 to 80 ppb from 120 ppb;
- significantly strengthening the SO_2 reporting standards for 1-hour and 24-hour SO_2 to 100 ppb and 20 ppb as well as removing the annual SO_2; and

- Removal of the 1-hour and 4-hour O_3 averaging periods to align the standards with the recent health evidence and for consistency with many international agencies.

The implemented changes bring forward standards initially proposed for 2025 (NEPC, 2021). The National Environment Protection Council (NEPC) is still planning to further modify ambient standards in 2025, based on international guidance. Changes are expected for O_3, SO_2, and $PM_{2.5}$. Where applicable, predicted and monitored concentrations outlined in this assessment have been assessed against the current and proposed future standards.

Table 2-2 presents the proposed criteria variation for the air emissions of concern for this assessment (NEPC 2019; NEPC 2016).

Table 2-2 Proposed Variations in Ambient Air Quality NEPM Standards

Pollutant	Averaging Period	Units	Current NEPM Standards	2025 Proposed Future NEPM Standards	Reference
O_3	8-hour	ppb	65	To be reviewed	(NEPC 2021)
SO_2	1-hour	ppb	100	75	(NEPC 2021)
Particles as $PM_{2.5}$	24-hour	$\mu g/m^3$	25	20	(NEPC 2016)
	Annual	$\mu g/m^3$	8	7	(NEPC 2016)

2.2 Acidic Deposition

There are no accepted or commonly applied standards for assessing deposition of acidic air pollutants on land surfaces or on sensitive receptors such as the Burrup Peninsula Aboriginal rock art. While this assessment report provides results for acidic deposition, no assessment, or commentary is provided about the potential impacts on areas of sensitivity such as the rock art. In this case, model results for deposition were provided primarily for comparisons with results obtained from measurements.

Air dispersion models calculate surface deposition for airborne substances using an airborne concentration near ground-level, a deposition velocity for the substance of interest, and other parameters (Seinfeld and Pandis, 2016). These parameters are difficult to accurately quantify, and therefore the standards for deposition have greater uncertainties than the standards based on airborne concentrations only.

3. WEATHER RESEARCH AND FORECASTING METEOROLOGICAL MODELLING

3.1 Introduction

Murujuga is located in the Pilbara region of Western Australia. The Pilbara region is characterised by very hot summers, mild winters and low and variable rainfall. It is classified as hot desert in northern and inland areas and hot grasslands in the north-west (DPIRD, 2020). During summer and early autumn (December to March), average daily temperatures exceed 30°C across the region, with average daily maxima exceeding 35°C from October to March. In northern inland areas, such as Marble Bar, average maxima exceed 40°C during summer and temperatures exceeding 45°C are common.

During the winter months (June to August), average temperatures are around 20°C across the region. Coastal areas have a smaller annual temperature range compared to inland areas, and winter temperatures rarely drop below 10°C. Except for the upland areas of the Hamersley Ranges and south-eastern inland areas, there is minimal risk of frost.

The predominant wind directions at the base of the Burrup Peninsula (Karratha Aero) can be seen in the windrose plots in the next section. The mean wind speed ranges from about 5 to 5.5 m/s, with few calms. Lower wind speeds tend to come from the South or Southwest, and higher wind speeds from the West or East-to-Northeast.

Annual rainfall declines from 300–350 millimetres (mm) in the north-east to less than 250 mm in the south and west. Elevated areas in the Hamersley Ranges average more than 500 mm. Rainfall is greatest during summer and autumn and least during winter and spring. Rainfall in the eastern Pilbara is most influenced by tropical and monsoonal drivers, which are predominantly active in summer and autumn. Rainfall in the western Pilbara is also influenced by southern mid-latitude drivers, such as frontal systems, during autumn and winter.

Tropical cyclones cause the most extreme rainfall events and generate 25–34% of the total annual rainfall near the Pilbara coast and as much as 21% up to 450 km inland. Tropical cyclones contribute from 0% to 86% of summer rainfall in the north-west.

3.2 Meteorological Data

Meteorological monitoring data from the last 10 years was sourced from the Bureau of Meteorology (BoM) for the stations within the study area, as depicted in Figure 3-1. Wind roses were generated for the stations with data from the entire monitored period (example 10-year wind rose for Karratha Airport station in Figure 3-2 and for each year (example annual wind roses for Karratha stations in Figure 3-3 to look for abnormal years to discard. Analysis of the wind roses indicated that 2014 was a representative year, with overall close-to-average rather than extreme meteorological conditions when compared to the 10-year average.

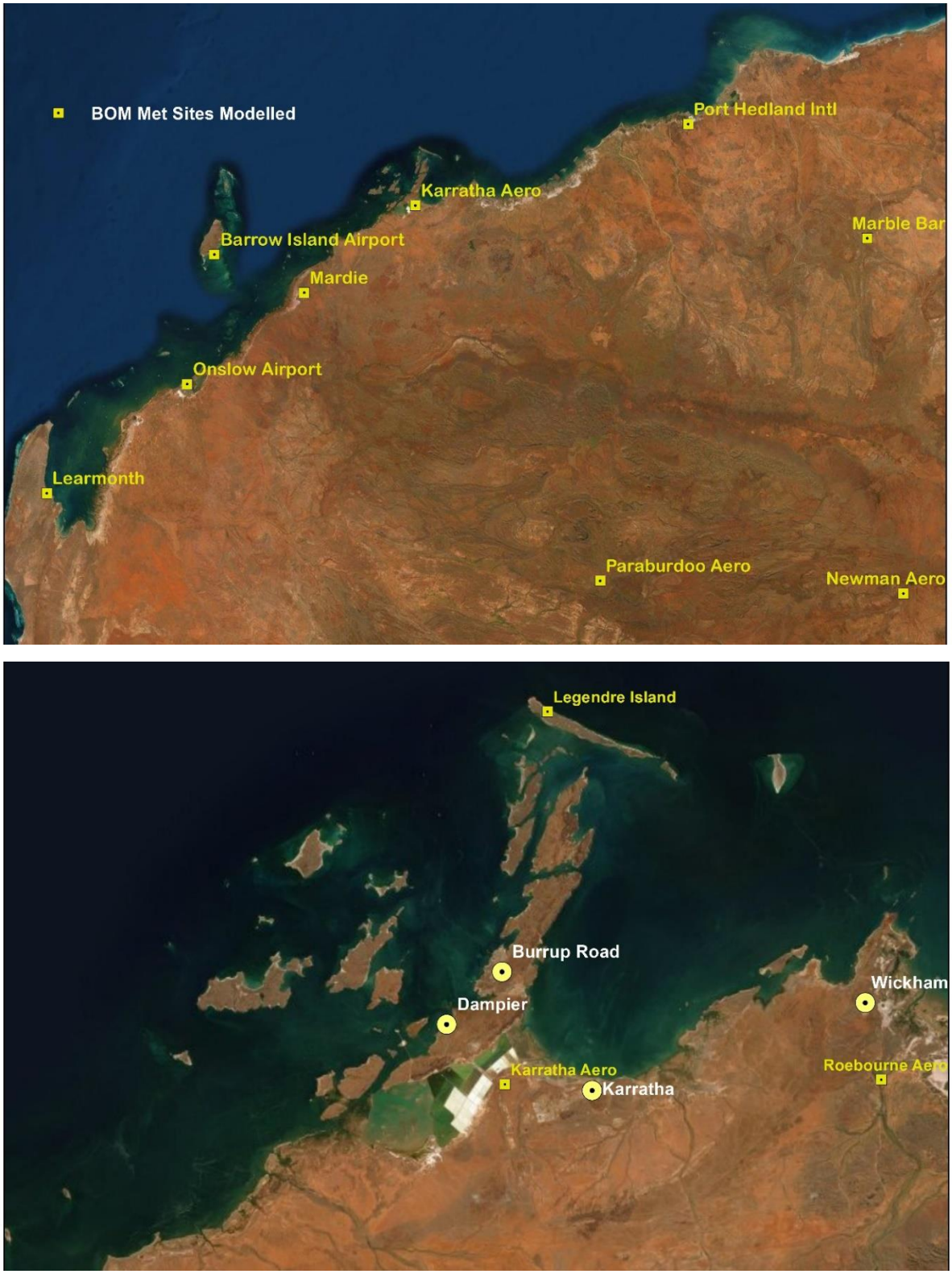


Figure 3-1: Meteorological Stations

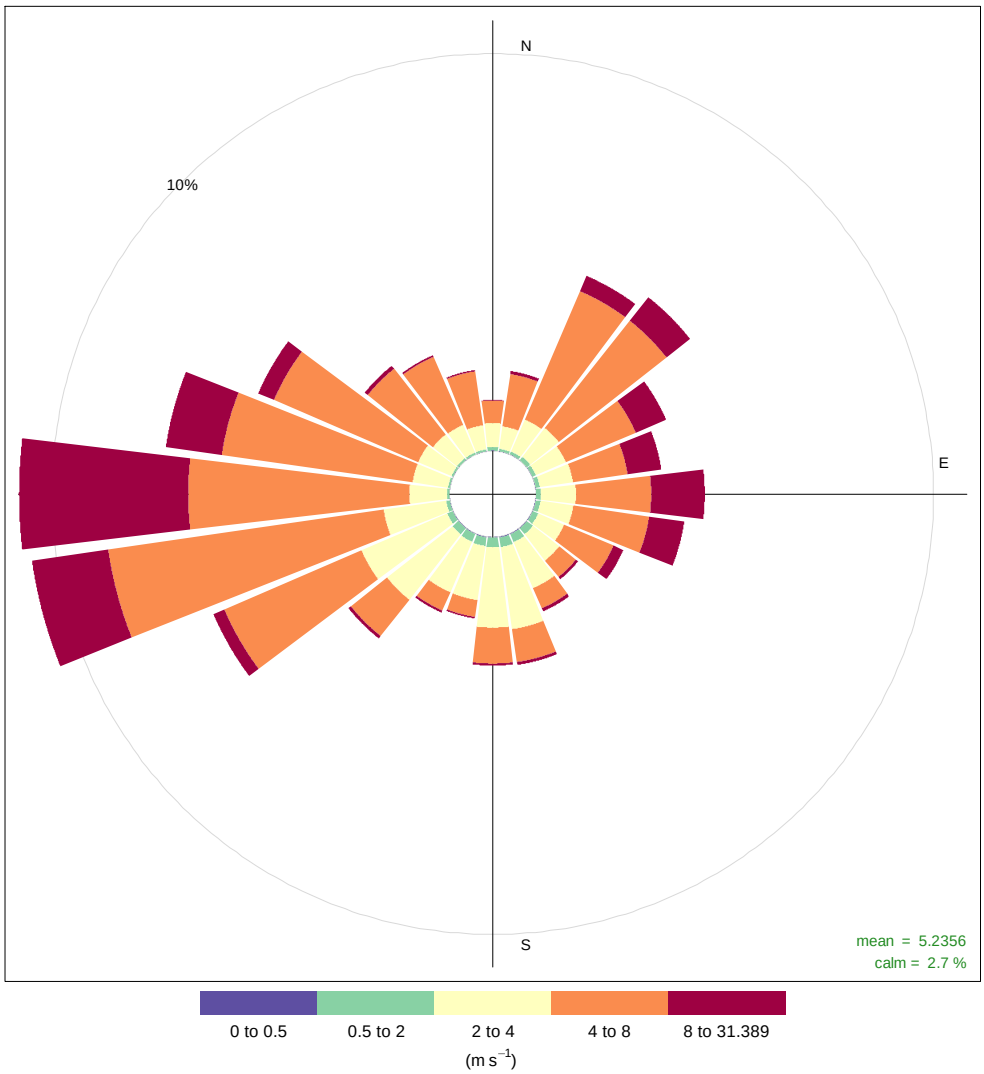


Figure 3-2: Karratha Airport Meteorological Station Wind Rose (2010-2019)

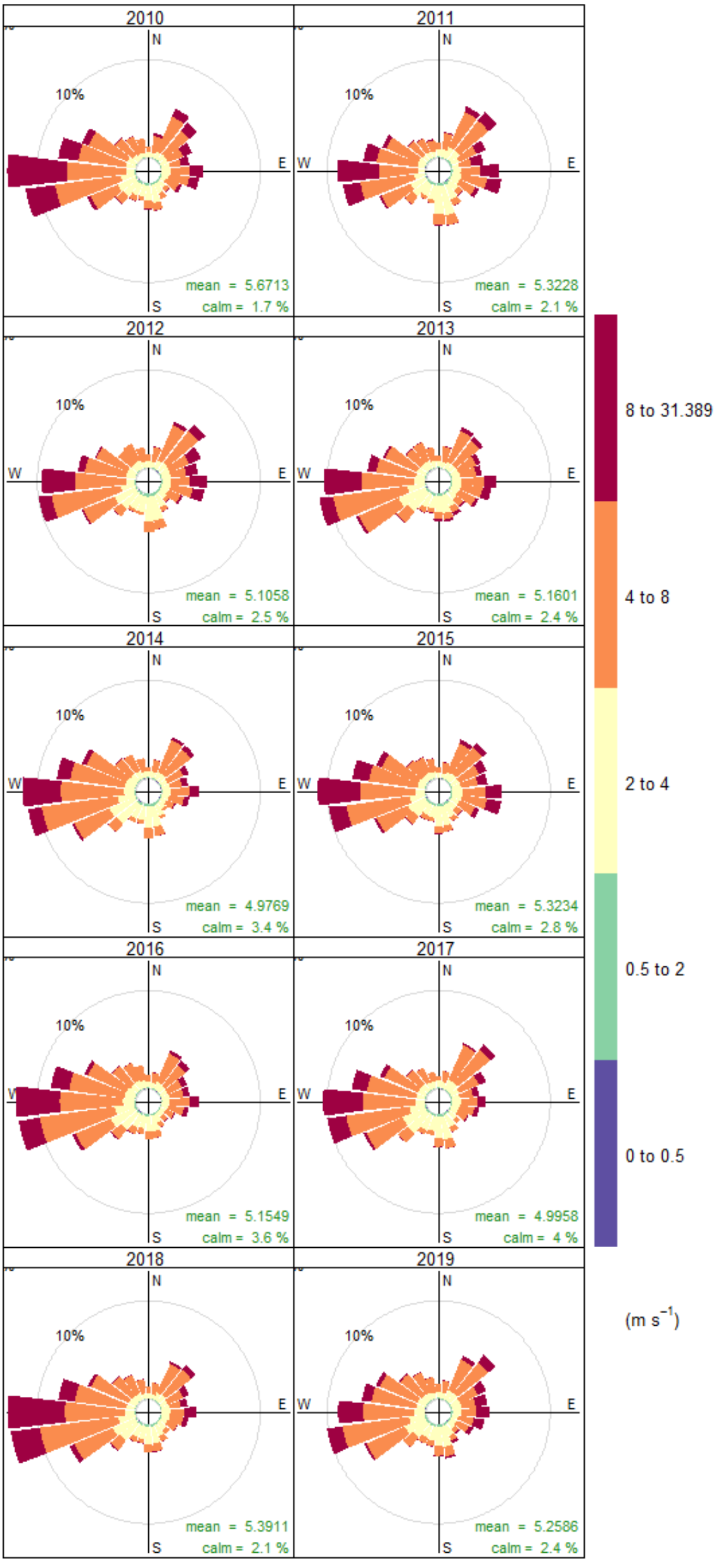


Figure 3-3 Karratha Airport Meteorological Station Annual Wind Roses (2010-2019)

3.3 Meteorological Model Selection

The WRF model is a regional meteorological model that relies on state-of-the-art physics and parameterisations to solve for 4-D meteorological fields. It is widely used in regional air quality assessments to provide meteorological inputs to dispersion and atmospheric chemistry models. After a WRF simulation is complete, interface software can be used to translate WRF meteorological output to the format required by the ultimate air quality model. The most recent version of WRF (NCAR, 2018; Skamarock et al., 2008), version 4.1.3, was used to generate gridded meteorology fields for input into CAMx. This includes version 4.1 of the WRF Pre-processing System (WPS), which generates the initial and boundary conditions for WRF.

3.4 WRF Modelling Domain

Selecting an optimised set of domains focused on the region of highest concern helps streamline the meteorological modelling process. The WRF modelling domains were chosen based on the intended CAMx modelling domain, local terrain, WRF input data resolution, and computational resource considerations. The extent of all four modelling domains can be seen in Figure 3-4, with the outer domain including Indonesia to the north and New Zealand to the south-east.

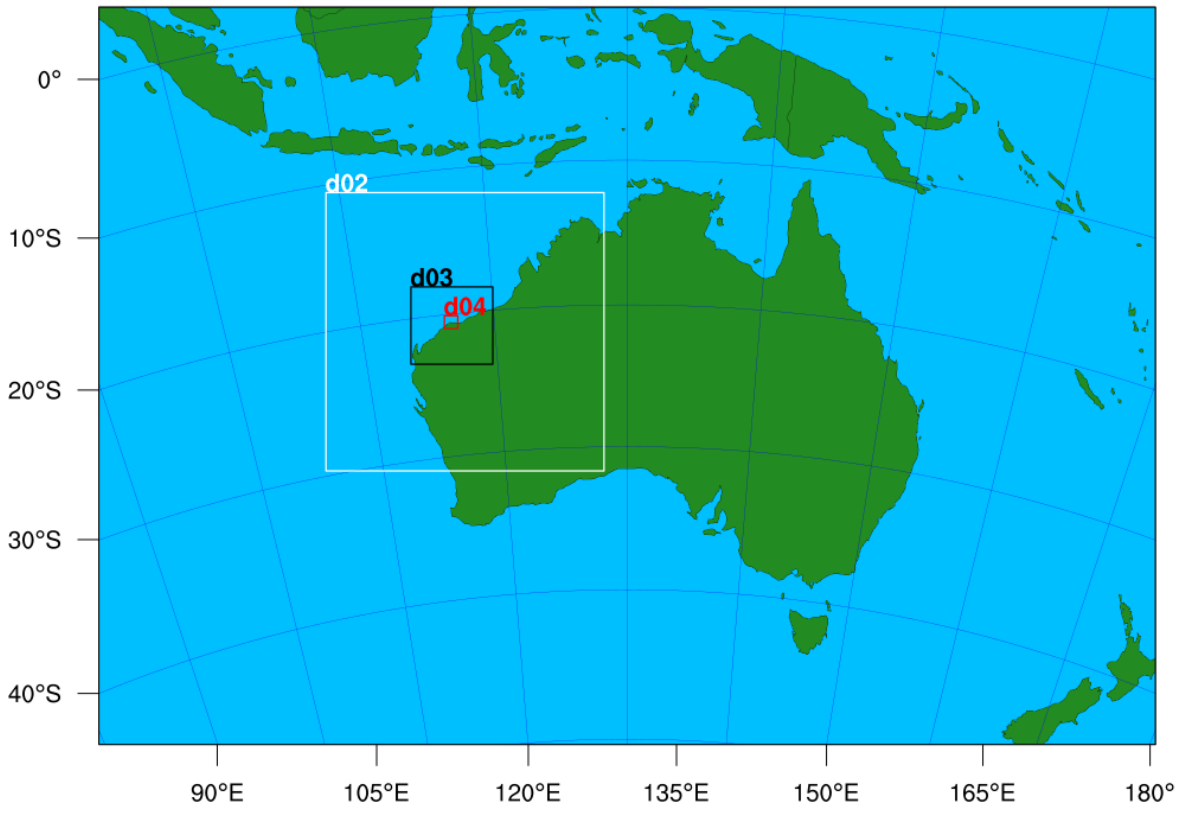


Figure 3-4 WRF Modelling Domains

3.4.1 Horizontal Modelling Domains

The WRF modelling domains are slightly larger than the 4 km and 1.33 km CAMx modelling domains seen in Figure 6-1 and Figure 6-2. The first few "edge" points of a nested WRF domain are not considered valid due to the numerical techniques that supply the boundary conditions for

the nested domain from the coarser domain. As a result, the WRF domains are 5 points larger on each side than the CAMx domains.

3.4.2 Vertical Layer Structure

The vertical layer structure used for this modelling is presented in Table 3-1. Packing the layers near the surface helps resolve the lowest part of the atmosphere, where much of the chemical transformations occur. A surface layer of about 20 metres provides this high resolution without leading to vertical instability model errors that can sometimes occur in high-resolution WRF runs over complex terrain.

Table 3-1: Vertical Layer Structure

Level	eta	Pressure (mb)	Height (m)	Mid Height (m)	dz (m)
0	1.0000	1000	0.0		
1	0.9975	998	20.4	10.2	20.4
2	0.9950	995	40.8	30.6	20.4
3	0.9920	992	65.4	53.1	24.6
4	0.9890	990	90.1	77.7	24.6
5	0.9860	987	114.7	102.4	24.7
6	0.9830	984	139.5	127.1	24.8
7	0.9800	981	164.3	151.9	24.8
8	0.9760	977	197.5	180.9	33.2
9	0.9700	972	247.4	222.5	50.0
10	0.9610	963	322.8	285.1	75.4
11	0.9510	953	407.2	365.0	84.4
12	0.9400	943	500.8	454.0	93.6
13	0.9280	932	603.9	552.3	103.1
14	0.9160	920	708.0	655.9	104.1
15	0.9030	908	822.0	765.0	114.0
16	0.8890	895	946.1	884.1	124.2
17	0.8750	881	1071.8	1009.0	125.7
18	0.8500	858	1300.1	1185.9	228.3
19	0.8200	829	1580.8	1440.5	280.8
20	0.7800	791	1967.6	1774.2	386.8
21	0.7400	753	2369.8	2168.7	402.1
22	0.7000	715	2788.7	2579.2	418.9
23	0.6600	677	3226.1	3007.4	437.4
24	0.6200	639	3683.8	3454.9	457.7
25	0.5800	601	4164.1	3923.9	480.3
26	0.5400	563	4669.7	4416.9	505.6
27	0.5000	525	5203.7	4936.7	534.0
28	0.4500	478	5917.1	5560.4	713.4
29	0.4000	430	6690.5	6303.8	773.4

Level	eta	Pressure (mb)	Height (m)	Mid Height (m)	dz (m)
30	0.3500	383	7536.4	7113.5	846.0
31	0.3000	335	8472.3	8004.4	935.8
32	0.2500	288	9522.5	8997.4	1050.2
33	0.2000	240	10724.1	10123.3	1201.6
34	0.1500	193	12136.7	11430.4	1412.6
35	0.1000	145	13866.9	13001.8	1730.1
36	0.0600	107	15621.6	14744.2	1754.7
37	0.0270	76	17503.4	16562.5	1881.8
38	0.0000	50	19594.2	18548.8	2090.8

3.4.3 WRF Boundary and Initial Conditions Datasets

WRF relies on other meteorological model or re-analysis output to provide initial and boundary conditions (IC/BC). Based on Ramboll's previous experience for similar modelling efforts using WRF, Ramboll has decided to use the first guess fields from the European Centre for Medium-Range Weather Forecasts Re-analysis product (ERA5). The initialisation fields are used both to initialise the model and for analysis nudging on the outer three domains, which guides the model to best match the observations. These fields are objectively re-analysed using observational data from meteorological towers, upper air soundings, etc. and subsequently processed to the resolution of each WRF grid using the OBSGRID program. Although both ERA5's objective analysis procedure and OBSGRID use the same observational meteorological data as is used to evaluate WRF outputs, both are subject to the limitations of grid resolution and potential conflicts with the first-guess field. The verification against observations is really an assessment of the entire process from ERA5 to WRF. Additionally, the spatial distance over which an observation has influence in e.g. ERA5 is purposely set to influence several grid cells. This is intended to lead to neighbouring stations showing similar performance.

3.5 WRF Inputs and Options

Physics Options: The initial physics options selected for this WRF simulation are presented in Table 3-2. The selections are based on the local terrain and weather patterns, as well as Ramboll's experience in optimising WRF for similar modelling campaigns.

Table 3-2: Physics Options

Physics Scheme	Option
Longwave Radiation	RRTMG
Shortwave Radiation	RRTMG
Microphysics	Thompson
Cumulus Parameterisation	Multi-scale Kain-Fritsch for all domains
Planetary Boundary Layer (PBL)	Yonsei University scheme (YSU)
Land surface Model (LSM)	Unified Noah
Surface Layer	Monin-Obukhov

Water Temperature Inputs: The water temperature data was taken from the Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature (SST) Analysis product, available from the Jet Propulsion Laboratory's Physical Oceanography Distributed Active Archive Center.

Topographic Inputs: Topographic information for all domains was integrated using the latest WRF Global Elevation model developed by the United States Geological Survey (USGS). The DWER had mentioned that more accurate results were previously obtained using WRF-Hydro, or the WRF Hydro ArcGIS toolkit. The WRF-Hydro website lists three options for terrain data.[1] Two of the options (NHD Plus and STATSGO) only cover the U.S. The third option (HydroSHEDS) relies on the 1-second resolution Shuttle Radar Topography Mission (SRTM3) data for terrain data. Geosciences Australia has produced a smoothed SRTM3[2] product for the continent (DEM-S) and a hydrologically enforced version (DEM-H) that are available on the ELVIS[3] server.

Both DEM-S and DEM-H data were downloaded and processed through WRF's geogrid.exe pre-processor. The smoothed (DEM-S) and Hydrologically enforced (DEM-H) versions were identical inside the 1.33 km WRF domain and are shown in Figure 3-5. Figure 3-6 shows the terrain when using the USGS dataset that is distributed with WRF after version 3.6. The USGS dataset that was distributed with WRF before version 3.6 produces quite different terrain (not shown). As can be seen, the terrain from the SRTM-based data is very similar to the newer WRF dataset. As a result, Ramboll used the standard USGS datasets that are distributed with WRF post version 3.6.

[1] https://ral.ucar.edu/projects/wrf_hydro/meteorological-terrain-data
[2] https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/72759
[3] https://elevation.fsdf.org.au/

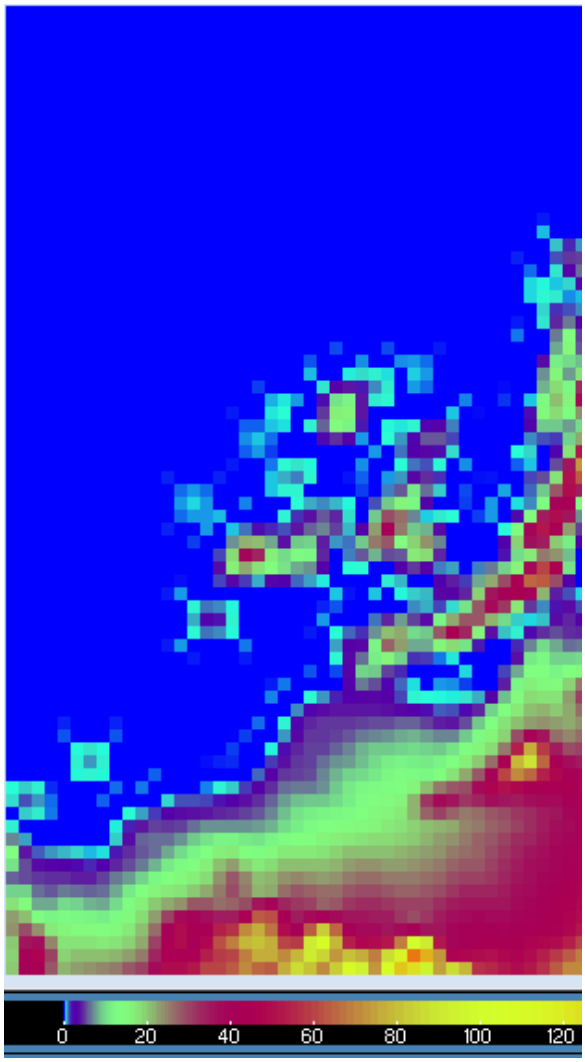


Figure 3-5. Terrain height (m) within the 1.33 km resolution WRF domain using DEM-H or DEM-S SRTM3 data from Geosciences Australia

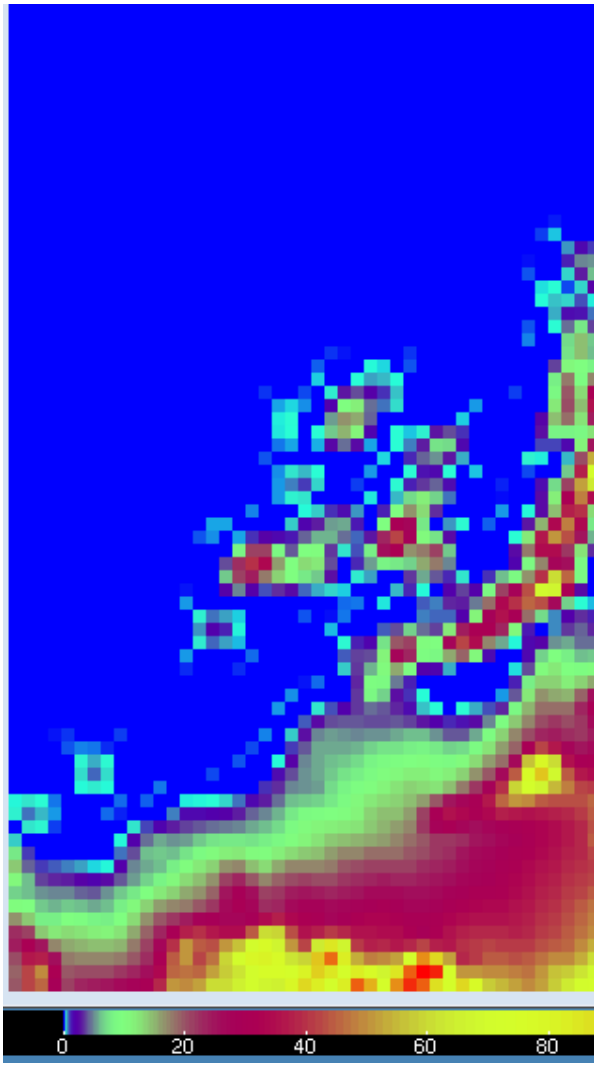


Figure 3-6. Terrain height (m) within the 1.33 km resolution WRF domain using the USGS data distributed with WRF after version 3.6

Vegetation Type and Land Use Inputs: Vegetation and land use information were developed using USGS's most recently-released Moderate Resolution Imaging Spectroradiometer (MODIS) 20-class datasets provided with the standard WRF distribution. The spatial resolutions used for each WRF domain match those of the topographic inputs. The shrub land-use category in WRF's LANDUSE.TBL file was altered to use a non-seasonally varying roughness length of 0.4 m, and an Albedo of 0.2, following Pacific Environment Limited's *Pilbara Strategic Environmental Assessment – Cumulative Air Quality Assessment*[4] (2015).

Time Integration: Third-order Runge-Kutta integration was used.

Diffusion Options: Horizontal Smagorinsky first-order closure with sixth-order numerical diffusion and suppressed up-gradient diffusion.

[4] https://www.bhp.com/-/media/bhp/regulatory-information-media/iron-ore/western-australia-iron-ore/0000/report-appendices/160316_ironore_waio_pilbarastrategicassessment_state_appendix9.pdf

3.6 WRF Model Performance Evaluation

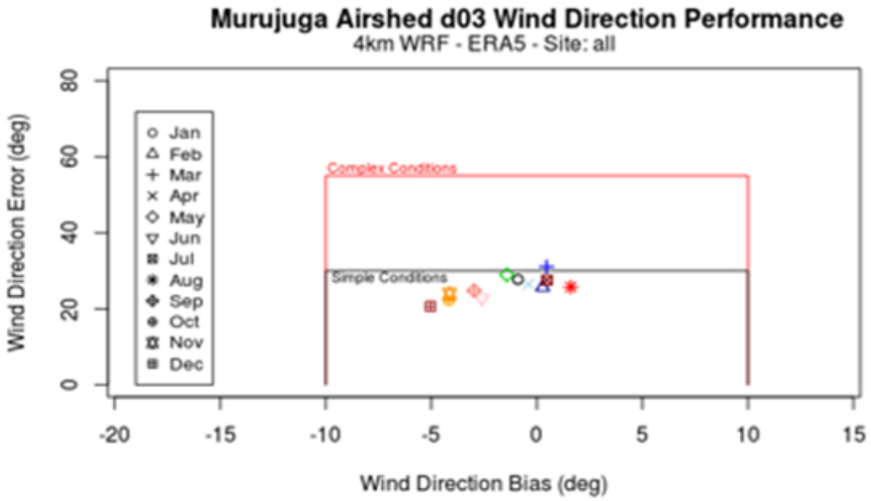
To evaluate WRF performance, Ramboll used the National Climatic Data Center's (NCDC) Integrated Surface Hourly dataset (DS3505), supplemented by local observations available from BoM. The DS3505 dataset is a quality-controlled dataset with global coverage. Performance statistics will be compared to established performance benchmarks to understand how good or poor the results are relative to other model applications.

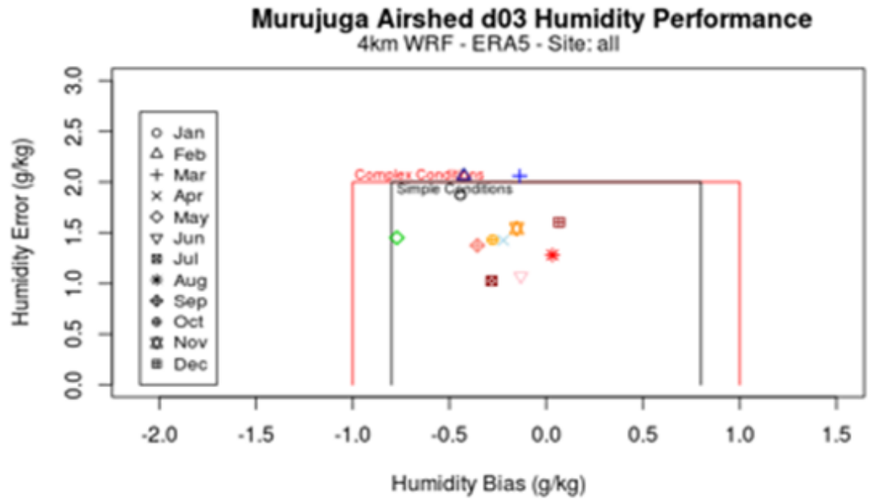
Ramboll used METSTAT (Ramboll Environ, 2015), a publicly available evaluation software that calculates statistical bias and error performance metrics, such as surface winds, temperature, and humidity, in the WRF model output. METSTAT uses performance benchmarks to evaluate a meteorological model simulation for air quality model applications. A series of meteorological model performance benchmarks for simple (Emery et al., 2001) and complex (Kemball-Cook et al., 2005) situations were used to assess performance of the model as demonstrated in Figure 3-7, Figure 3-8 and Figure 3-9. The simple benchmarks were developed by analysing well-performing meteorological model evaluation results for simple, mostly flat terrain conditions and simple meteorological conditions (e.g., stationary high pressure) that were mostly conducted to support air quality modelling studies (e.g., ozone SIP modelling). The complex benchmarks were developed during the Western Regional Air Partnership (WRAP) regional haze modelling and are performance benchmarks for more complex conditions, such as the complex terrain of the Rocky Mountains and Alaska (Kemball-Cook et al., 2005). McNally (2009) analysed multiple annual runs that included complex terrain conditions and suggested an alternative set of benchmarks for temperature under more complex conditions. The purpose of the benchmarks is to understand how good or poor the results are relative to other model applications run for the United States. The evaluation metrics were calculated on hourly, daily, and monthly time frames for wind speed, wind direction, temperature, and humidity at the surface, using all available observational weather data. Information from monitoring undertaken by Woodside in the region was used in the validation. In addition, probability density functions after Perkins (2007) that incorporate Weibull distribution function to fit wind speed rather than a normal distribution were utilised at the request of the DWER.

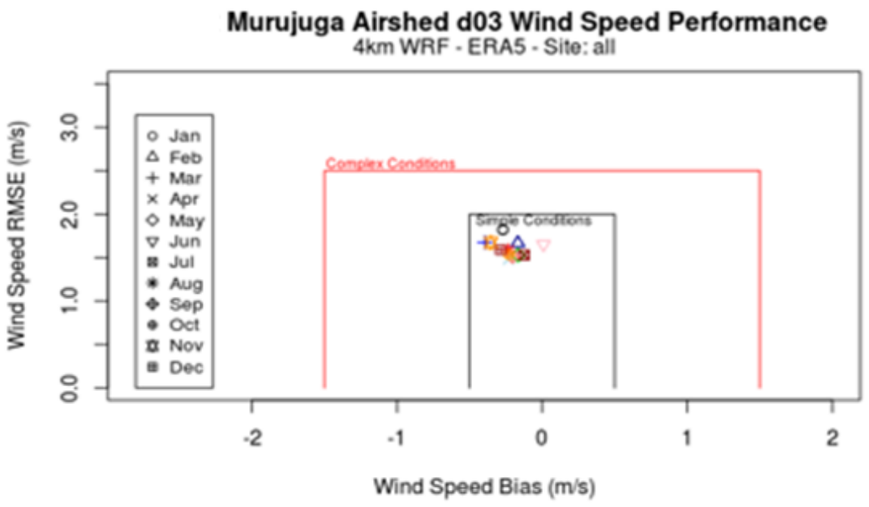
Ramboll used Global Precipitation Measurement (GPM) satellite data from NASA, which is a follow-on to the Tropical Rainfall Measuring Mission (TRMM), to evaluate WRF precipitation performance. GPM has 10 km special resolution and 30-minute temporal resolution. For this reason, WRF was only compared to GPM for the 36 and 12 km domains.

Overall, WRF reproduced the observed surface meteorological variables reasonably well. WRF has a slight negative temperature bias in both the 4 km and 1.33 km domains for both DS3505 and Woodside stations, and a slight positive wind speed bias in the 1.33 km domain for Woodside stations. Although a cursory look using Google Street View of the Woodside sites does not indicate any obvious obstructions, it is possible they suffer from being in the lee of obstructions that are causing the measured winds to be lower. Because the nearby BoM sites have likely been incorporated by ERA5's objective analysis program, they are likely setting the input wind speed for the nearby region (at least one or two ERA5 grid cells, 28 km each). This input of course only *influences* WRF output, it does not fully control WRF output. The three Woodside stations inside the 1.33 km WRF domain are also sited closer to the ocean than the BoM sites, and it is possible that WRF is not resolving the land-sea boundary well enough at a 1.33 km resolution to avoid a bias at these sites.

WRF precipitation measurements were consistent with those taken from GPM.







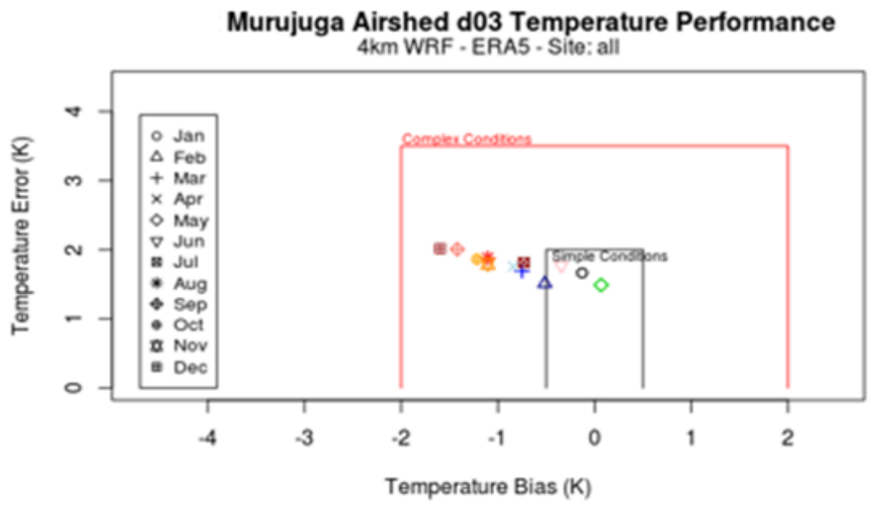
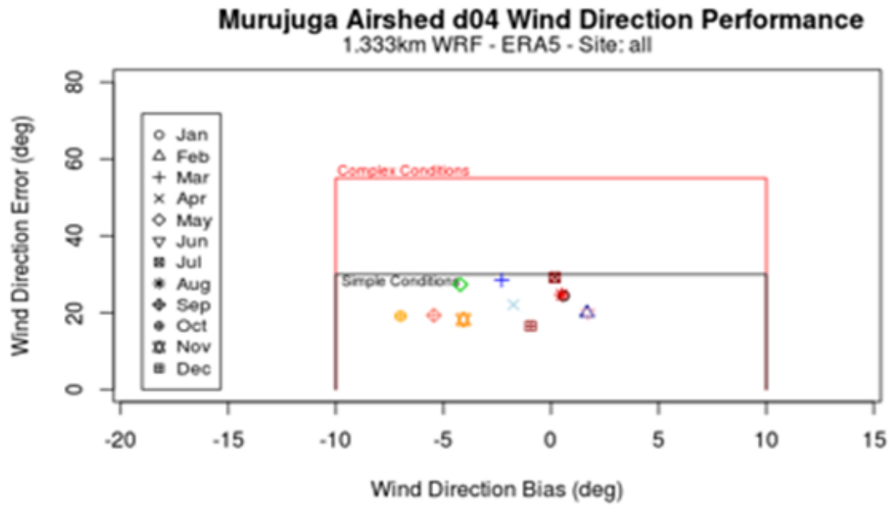
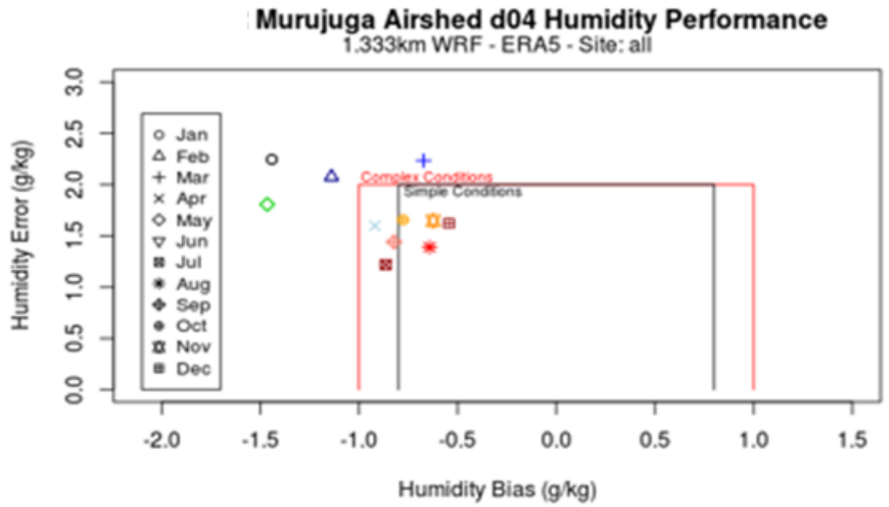
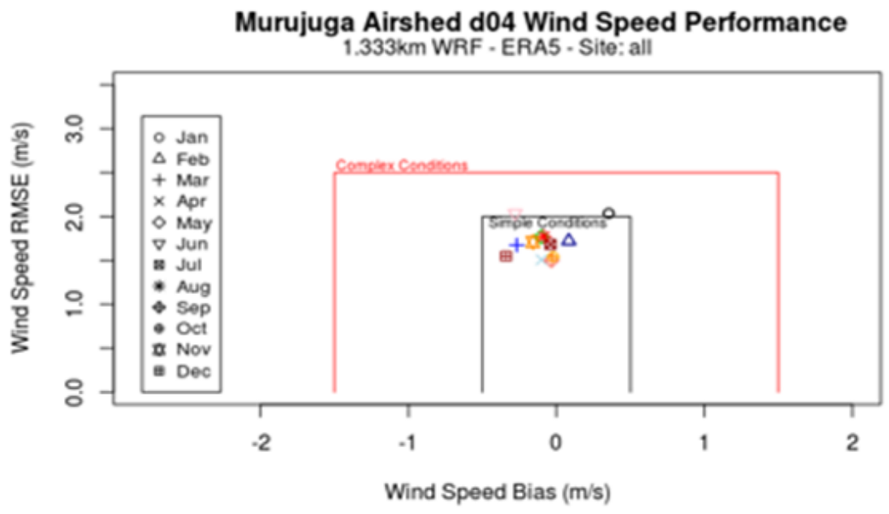


Figure 3-7. METSTAT 4 km domain DS3505 observations







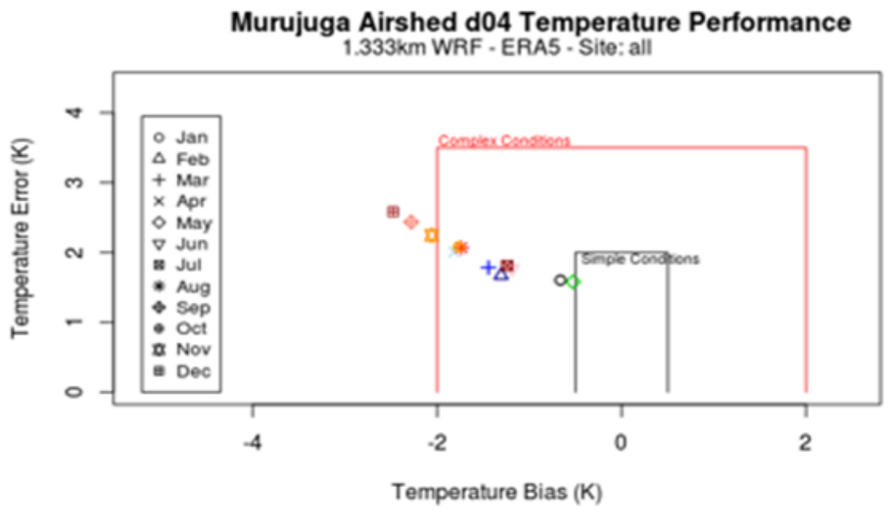
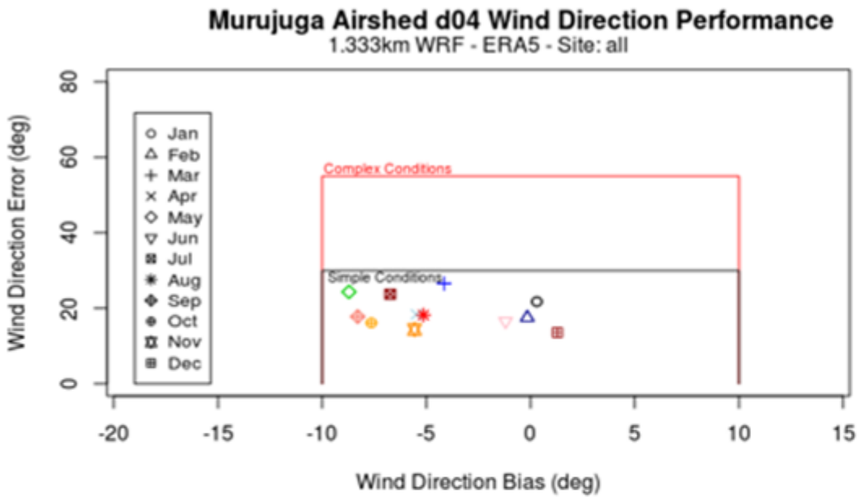
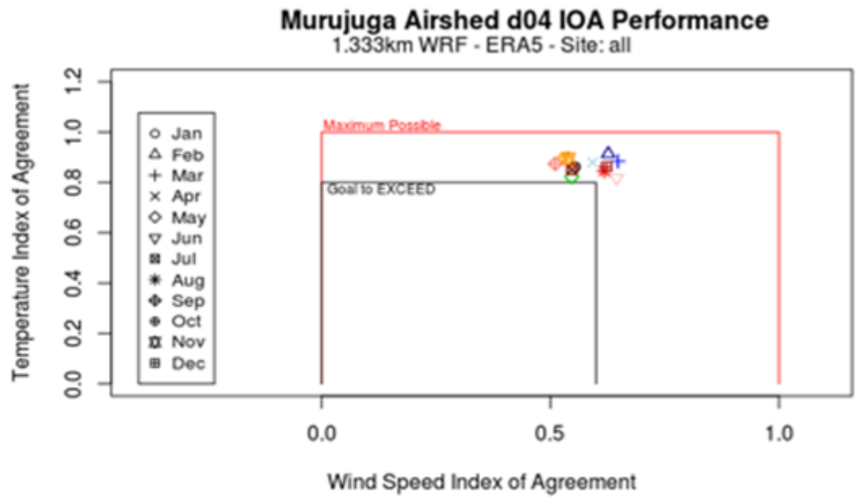
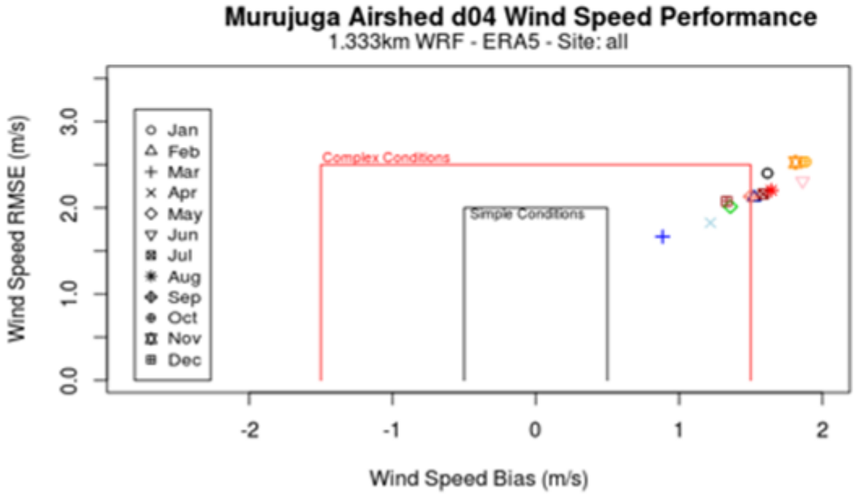


Figure 3-8. METSTAT 1.33 km domain DS3505 observations







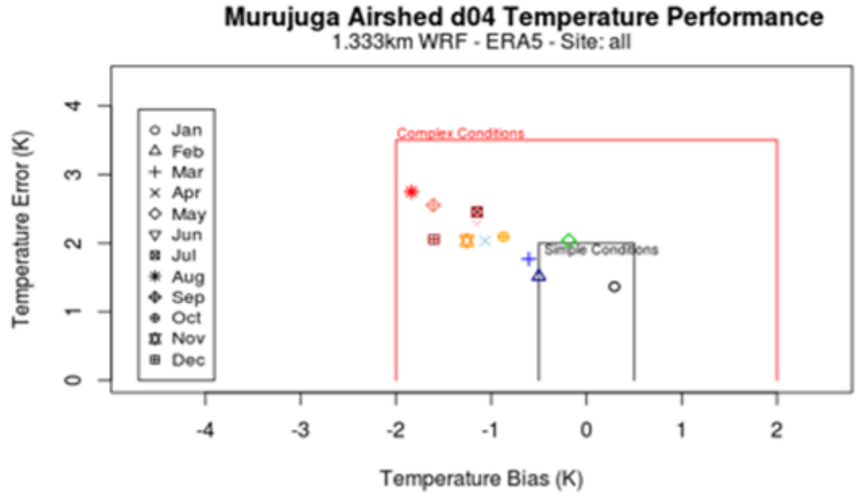


Figure 3-9. METSTAT 1.33 km domain Woodside observations

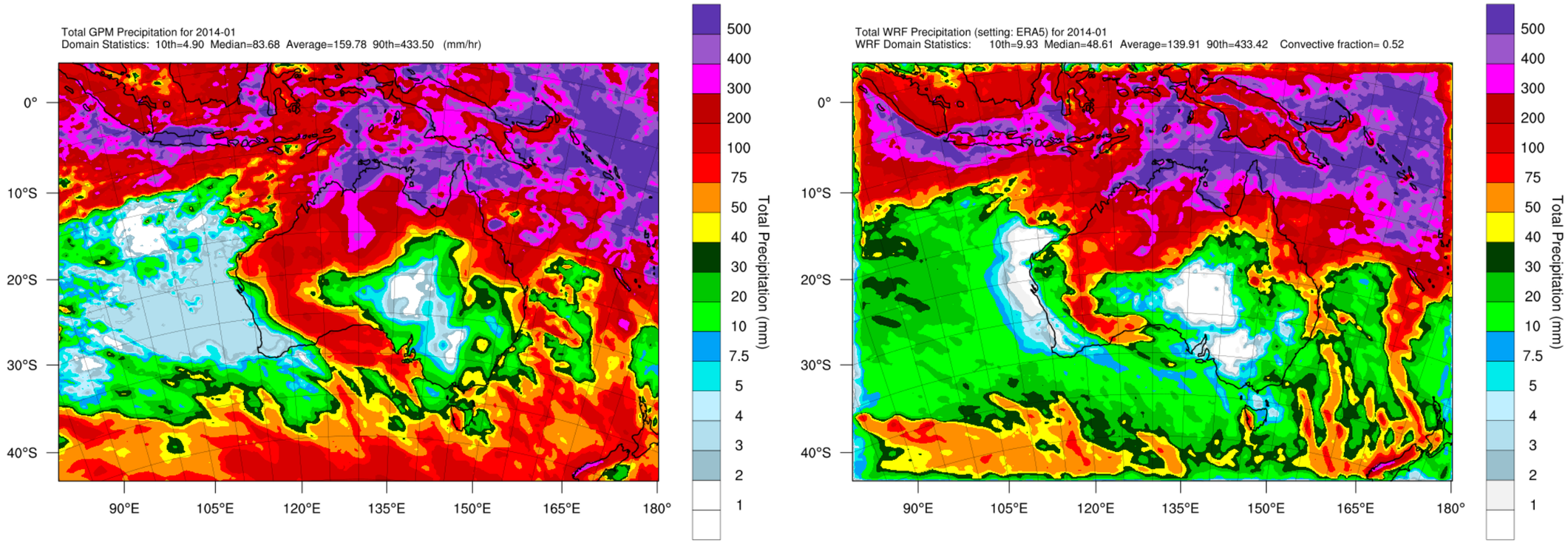


Figure 3-10. 36 km precipitation comparison of GPM (left) and WRF (right) for January 2014

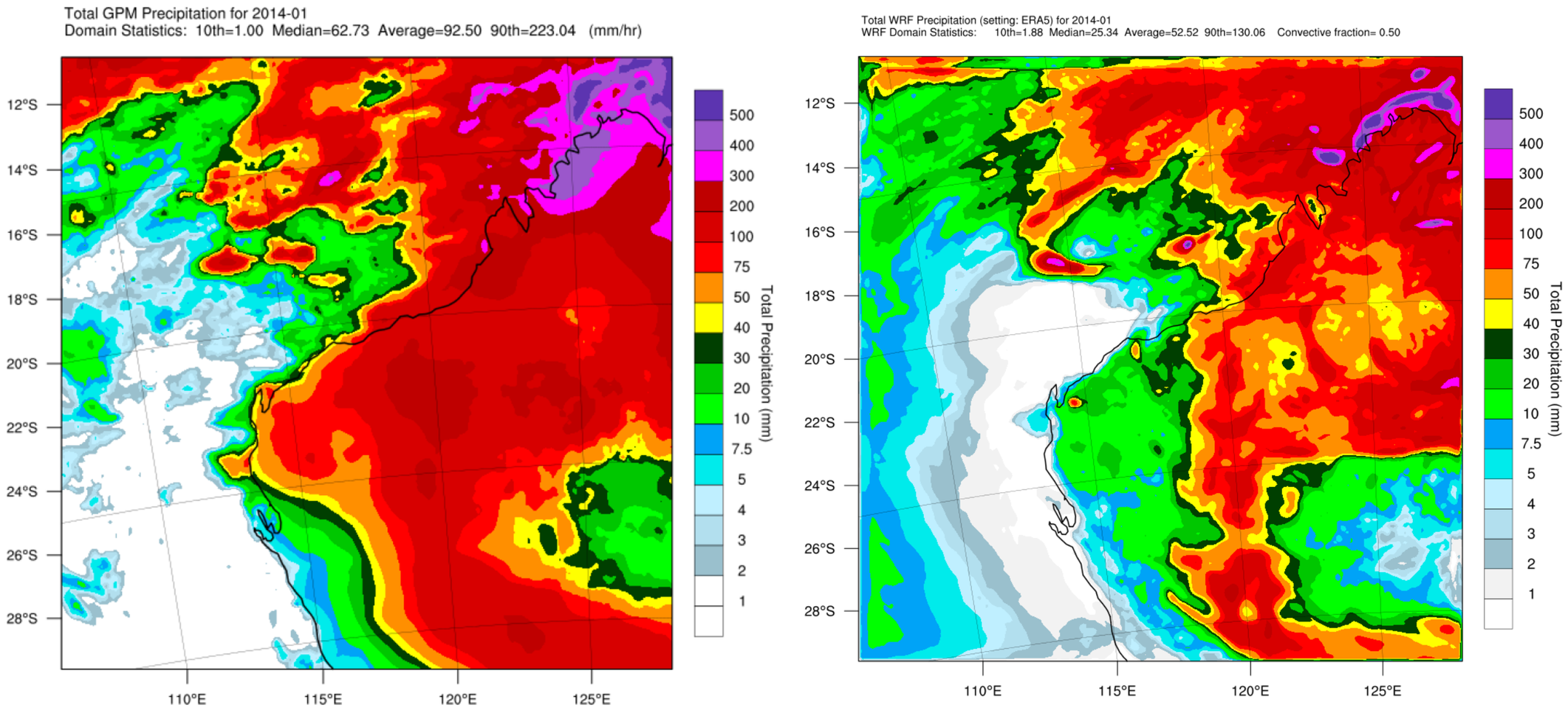


Figure 3-11. 12 km precipitation comparison of GPM (left) and WRF (right) for January 2014

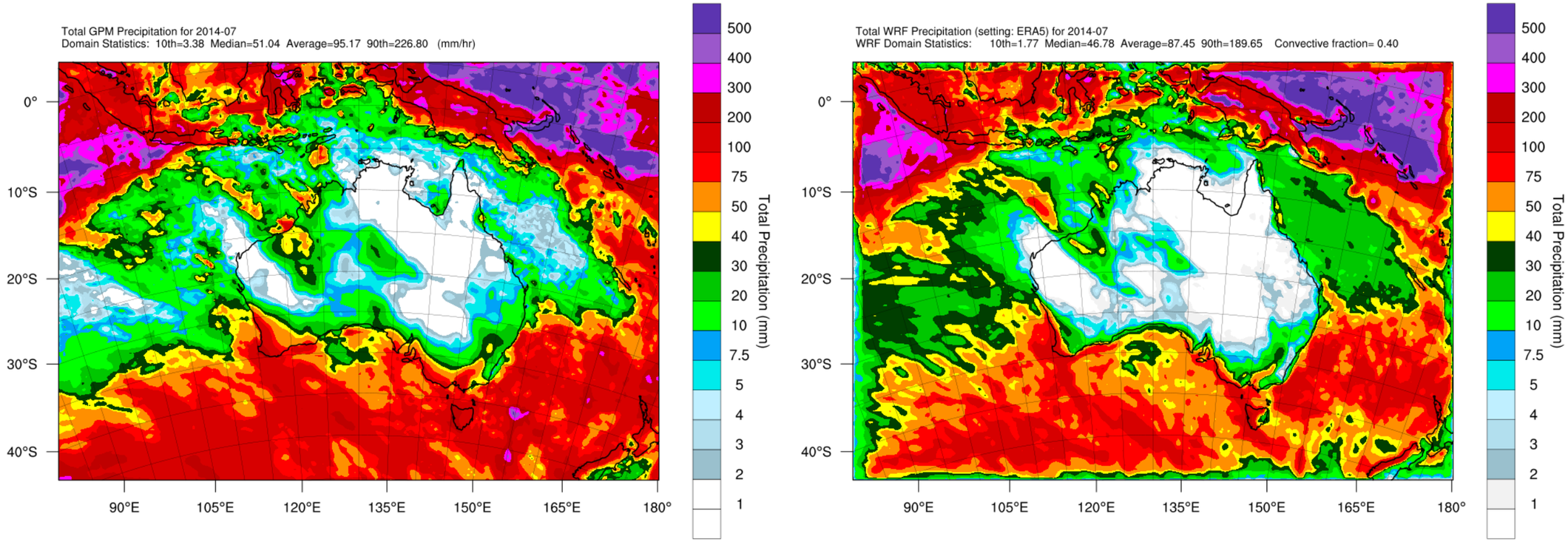


Figure 3-12. 36 km precipitation comparison of GPM (left) and WRF (right) for July 2014

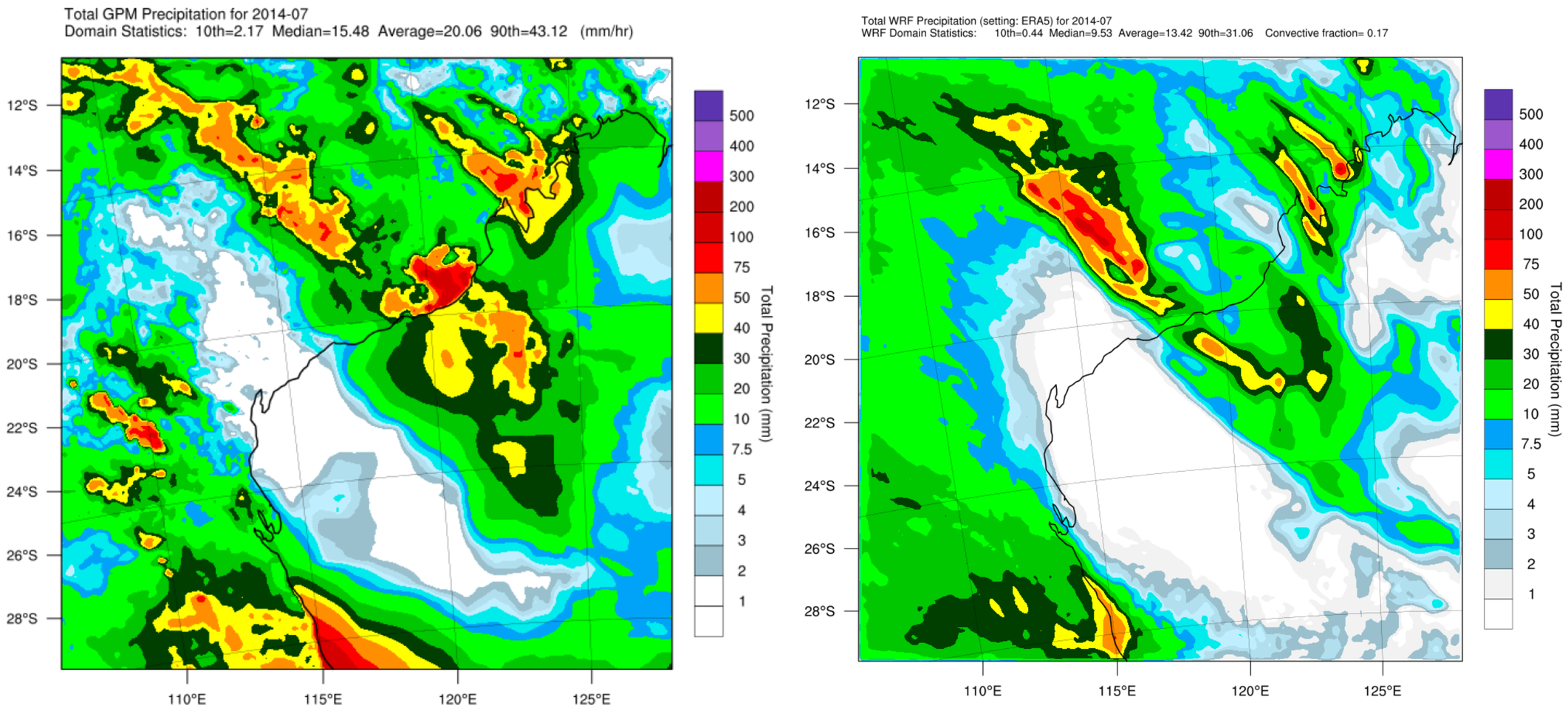
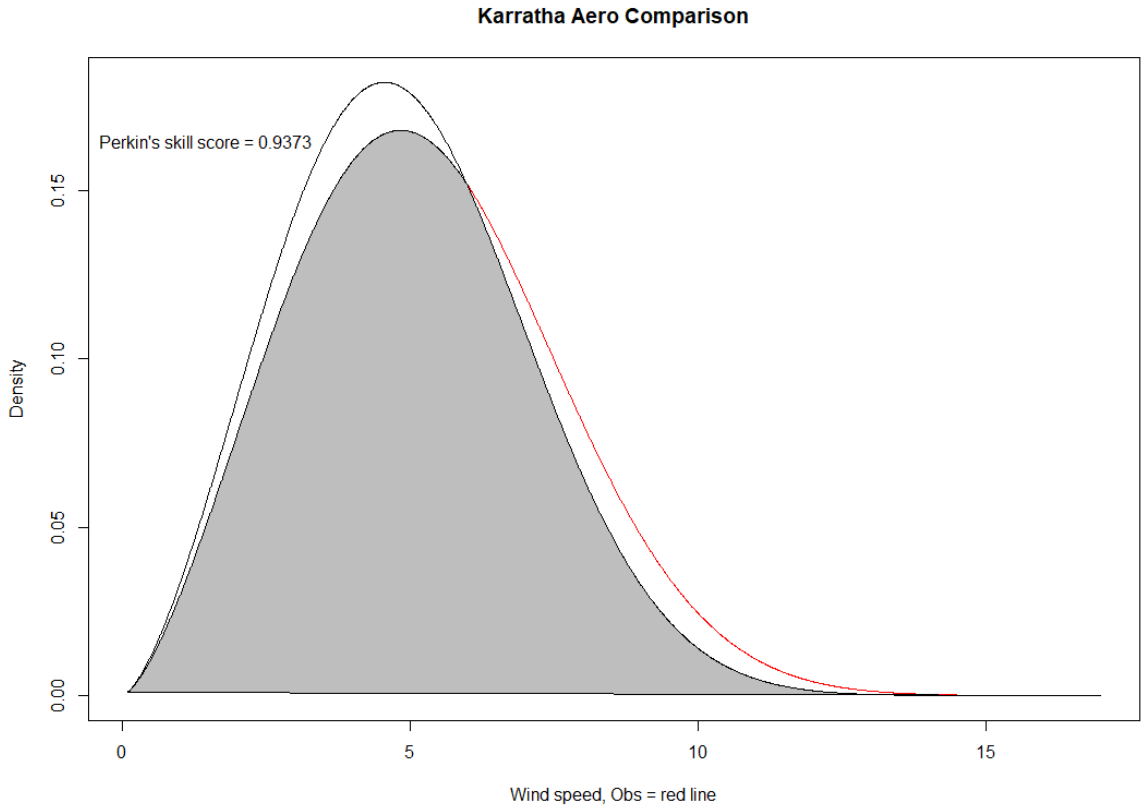
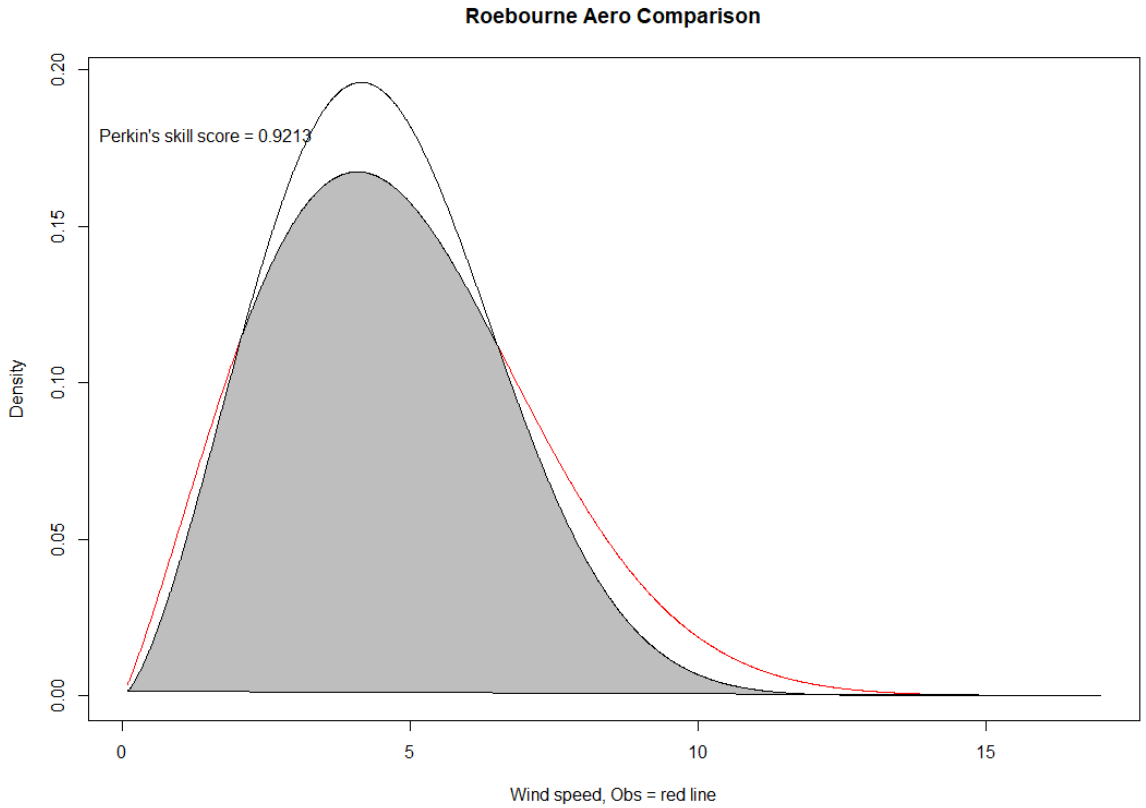


Figure 3-13. 12 km precipitation comparison of GPM (left) and WRF (right) for July 2014


Karratha Aero Comparison
Perkin's skill score = 0.9373
Density
0.00
0.05
0.10
0.15
0
5
10
15
Wind speed, Obs = red line


Roebourne Aero Comparison
Perkin's skill score = 0.9213
Density
0.00
0.05
0.10
0.15
0.20
0
5
10
15
Wind speed, Obs = red line

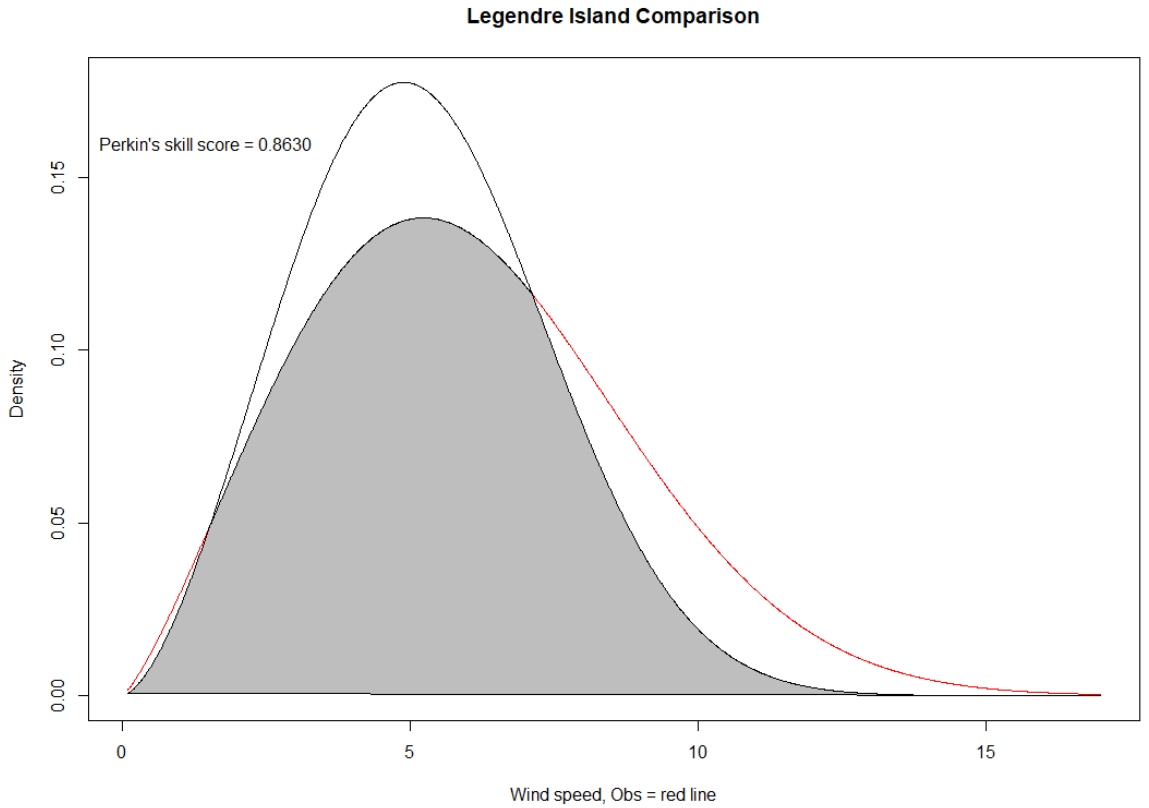
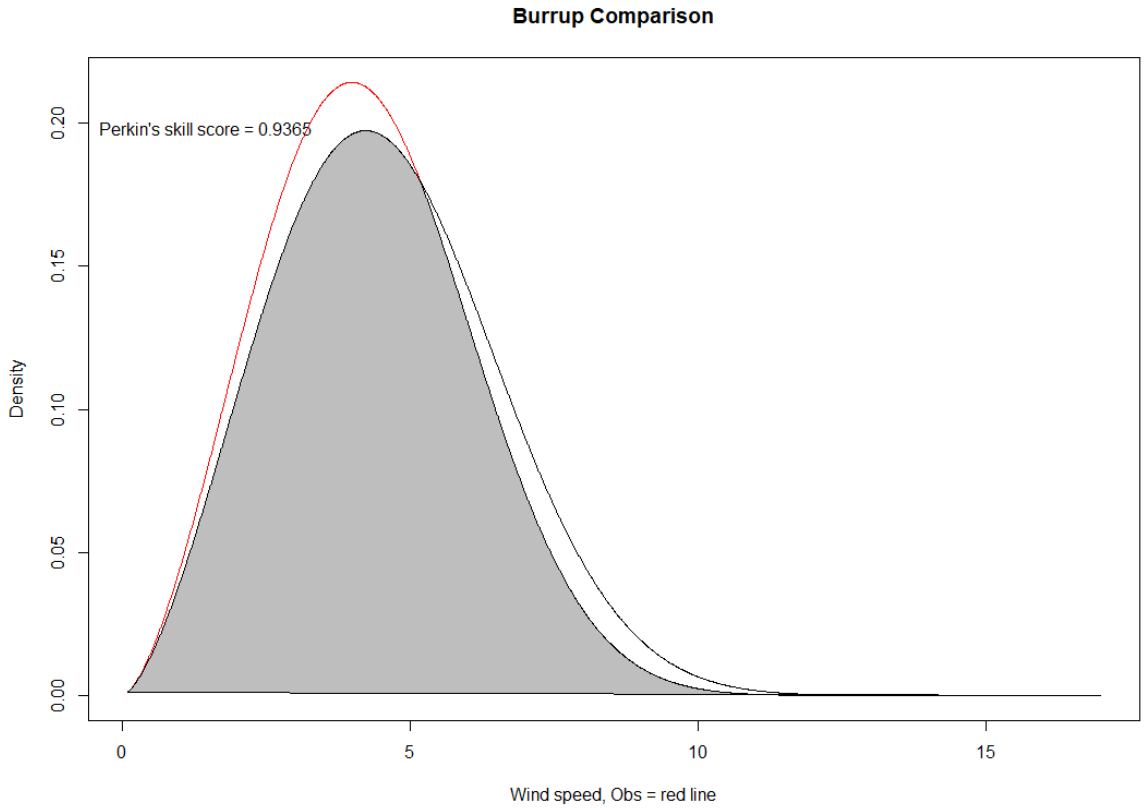
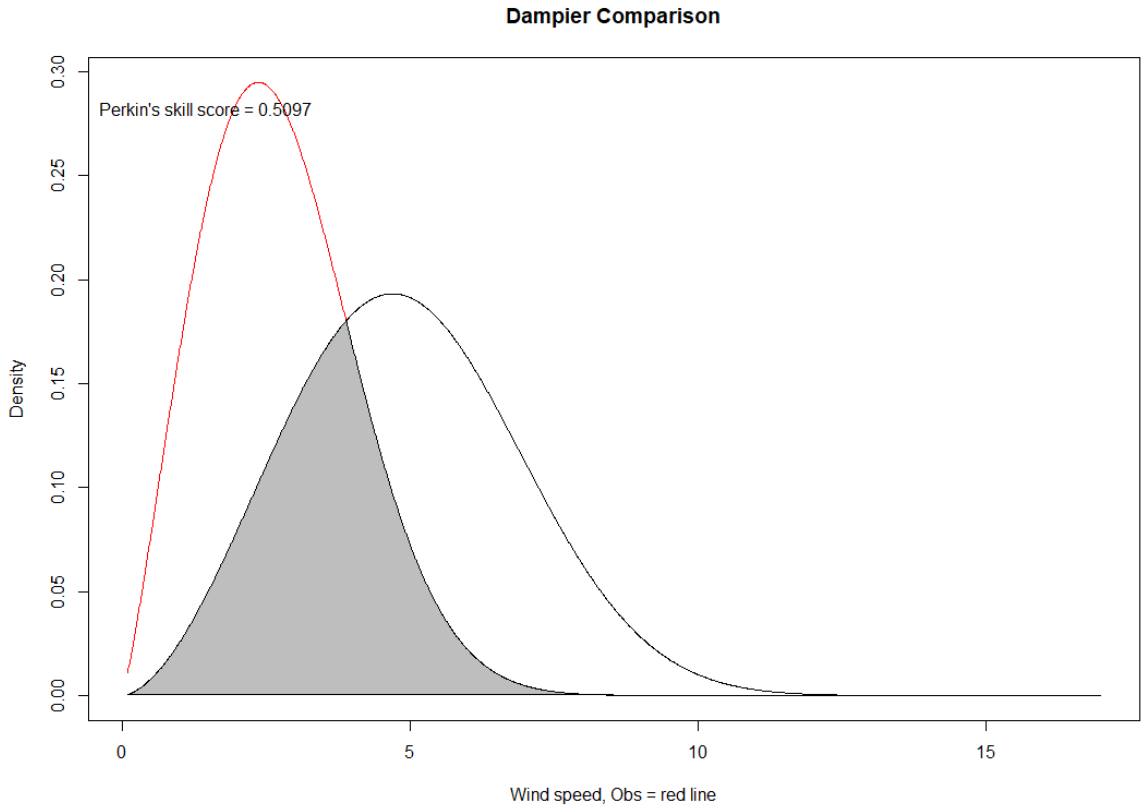


Figure 3-14. Perkins Skill Plots for Bureau of Meteorology Monitoring Stations (Karratha Aero, Roebourne Aero, Legendre Island)


Burrup Comparison
Perkin's skill score = 0.9365
Density
0.00
0.05
0.10
0.15
0.20
0
5
10
15
Wind speed, Obs = red line


Dampier Comparison
Perkin's skill score = 0.5097
Density
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
5
10
15
Wind speed, Obs = red line

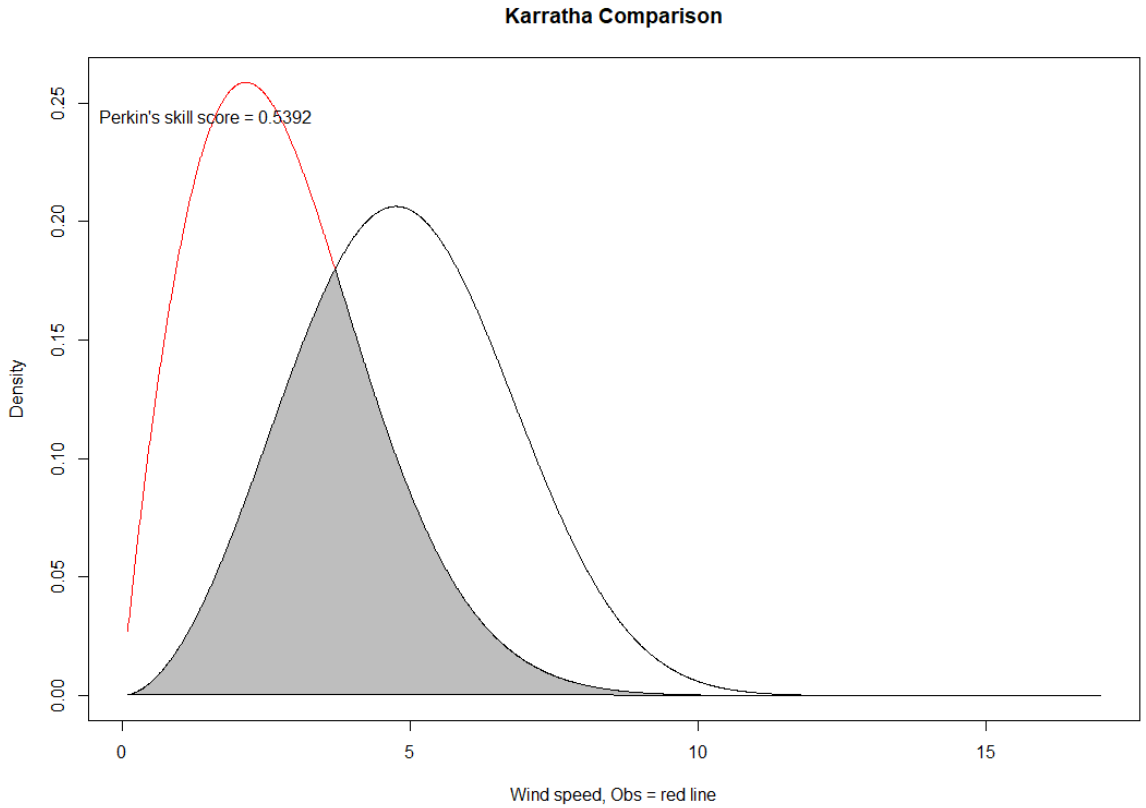


Figure 3-15. Perkins Skill Plots for Woodside Meteorological Monitoring Stations (Burrup, Dampier, Karratha)

4. AMBIENT MONITORING

The Burrup Peninsula comprises multiple industrial facilities emitting a range of compounds. Historical air quality data for both gaseous and particulates for the region were made available for the period 2008 to 2015 from a number of locations including Burrup Road, Karratha and a number of locations in Dampier. The locations of these stations are shown in Figure 4-1. Pollutants monitored at these locations included O_3, NO_X, NO_2, NO, PM_{10}, $PM_{2.5}$ and BTX (benzene, toluene and xylene). Table 4-1 presents a summary of the compounds and the period where monitoring occurred at each of the stations. The following was noted:

- BTX monitoring data was available for the period 2009-2010 from two stations (Karratha and Dampier), and a longer period at Burrup Road (2009 – 2015);
- NO, NO_2, NO_X were monitored for six years (2009 – 2015) at Karratha, Burrup Road and Dampier North;
- Ozone was monitored for six years (2009 – 2015) at the Karratha and Dampier North monitors and for one year at Burrup Road monitor (2009);
- $PM_{2.5}$ was monitored at the Dampier Centre and Karratha monitoring locations in 2014, as well as the Karratha, Burrup Road and the Dampier North monitors in 2012; and
- All Dampier and the Karratha monitoring stations monitored PM_{10} during 2014.

Table 4-1: Historic air quality monitoring data

Location	Pollutants Monitored	Period of Monitoring
Karratha	BTX	2009-2010
	NO_x, NO_2, NO	2009-2015
	O_3	2009-2015
	$PM_{2.5}$	2012
	PM_{10}, $PM_{2.5}$	2014
Burrup Road	BTX	2009-2015
	NO_x, NO_2, NO	2009-2015
	O_3	2009
	$PM_{2.5}$	2012
Dampier North	BTX	2009-2010
	NO_x, NO_2, NO	2009-2015
	O_3	2009-2015
	$PM_{2.5}$	2012
	PM_{10}	2014
Dampier East	PM_{10}	2014
Dampier Centre	PM_{10}, $PM_{2.5}$	2014
Dampier West	PM_{10}	2014

Across the monitoring period, several exceedances of the nominated standards were recorded which were primarily associated with PM_{10} and $PM_{2.5}$. Some exceedances of benzene and the O_3 standards were also noted.

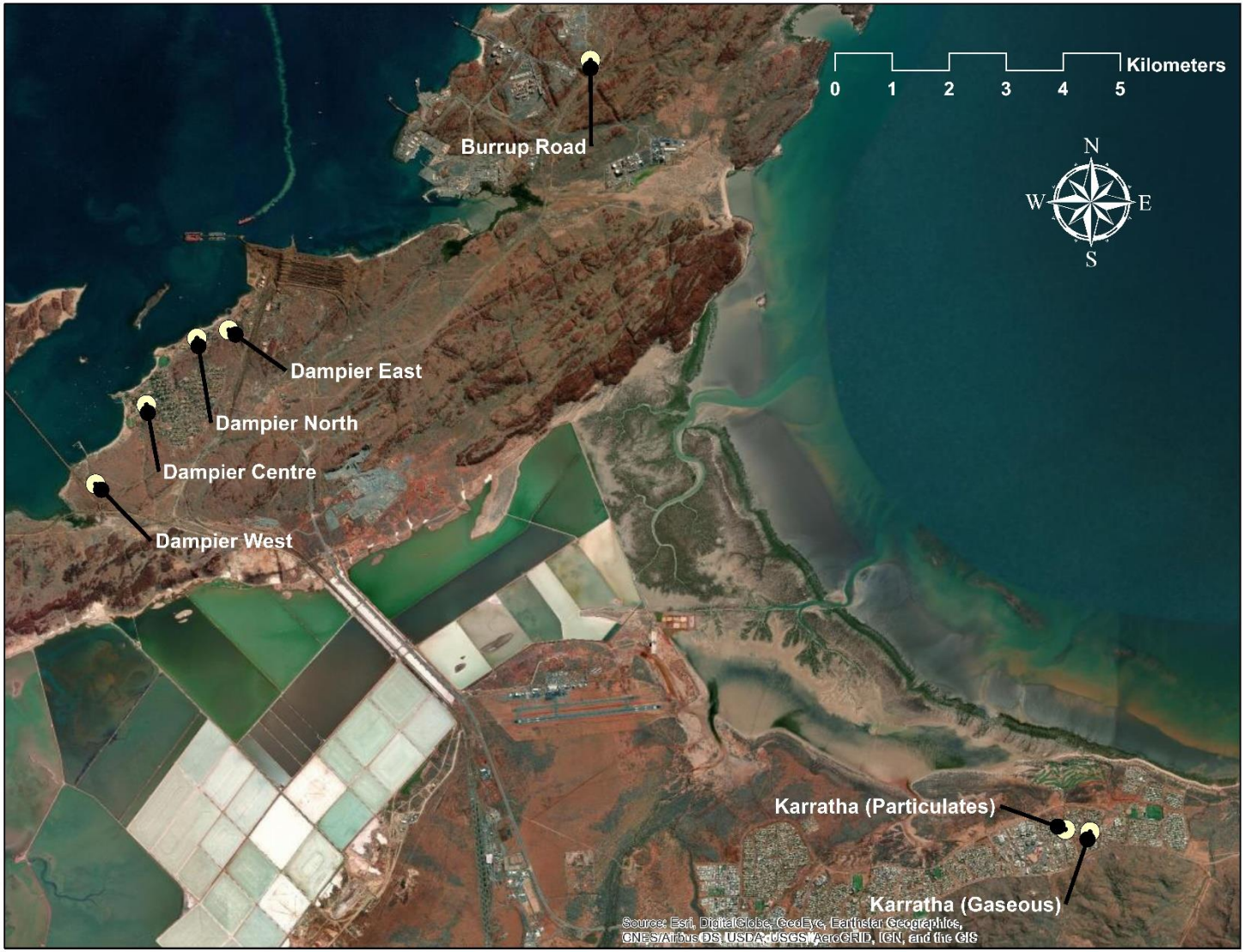


Figure 4-1: Location of Ambient Air Quality Monitoring Sites

4.1 Ambient Monitoring Summary for 2014

4.1.1 Data Capture

Table 4-2 shows the data capture for 2014. Monitors at Karratha and Dampier stations recorded concentrations of NO, NO_2, NO_X, PM_{10}, $PM_{2.5}$ and O_3 with a data capture of between 88-97%. The Burrup Road monitor recorded concentrations of NO, NO_2, NO_X and BTX with a data capture of approximately 95%.

Table 4-2: Data Capture of 2014

Monitoring Station	Pollutant Monitored	Data Capture 2014
Karratha	O_3	93%
	NO_x	94%
	NO_2	94%
	NO	94%
	PM_{10}	96%
	$PM_{2.5}$	96%
Burrup Road	NO_x	94%
	NO_2	94%
	NO	94%
	Benzene	97%
	Toluene	97%
	Xylene	96%
Dampier North	NO_x	92%
	NO_2	92%
	NO	92%
	O_3	93%
	PM_{10}	97%
Dampier East	PM_{10}	97%
Dampier West	PM_{10}	88%
Dampier Centre	PM_{10}	97%
	$PM_{2.5}$	97%

Table 4-3 presents a summary of the maximum monitored gaseous pollutant concentrations for 2014, compared against relevant standards. Monitored concentrations of O_3 concentrations were the highest when compared against the standards (ranging between 57% to 81% of the relevant standard across stations and averaging periods). The maximum monitored concentrations at any station for NO_2 and BTX were 28% and 51% of their respective standards.

Table 4-3: Summary of Maximum Average Concentrations for Gaseous Pollutants in 2014

Pollutant	Monitoring Station	Averaging Period	Standard (ppb)	Max Average Conc. (ppb)	% of Guideline	Reference
NO_2	Karratha	1-hour	80 [a]	33	41%	(NEPC 2021)
	Burrup Road	1-hour	80 [a]	28	35%	(NEPC 2021)
	Dampier North	1-hour	80 [a]	25	31%	(NEPC 2021)
	Karratha	Annual	15 [a]	2	16%	(NEPC 2021)
	Burrup Road	Annual	15 [a]	3	16%	(NEPC 2021)
	Dampier North	Annual	15 [a]	2	16%	(NEPC 2021)
O_3	Karratha	8-hour	65	53	81%	(NEPC 2021)
	Dampier North	8-hour	65	47	72%	(NEPC 2021)
Benzene	Burrup Road	1-hour	9	5	51%	(NSW EPA 2017)
	Burrup Road	Annual	3	0.06	2%	(NEPC 2011)
Toluene	Burrup Road	1-hour	90	6	7%	(NSW EPA 2017)
	Burrup Road	24-hour	1000	1	0.1%	(NEPC 2011)
	Burrup Road	Annual	100	0.06	0.06%	(NEPC 2011)
Xylene	Burrup Road	1-hour	40	8	20%	(NSW EPA 2017)
	Burrup Road	24-hour	250	1	0.27%	(NEPC 2011)
	Burrup Road	Annual	200	0.04	0.02%	(NEPC 2011)

Notes:

a) Monitored concentrations have been compared against values outlined in the recent variation to the NEPM standard criteria (NEPC, 2021). The 1-hour and annual average standards for NO_2 when the monitoring was conducted was 120 ppb and 30 ppb respectively.

Table 4-4 presents the monitored PM_{10} and $PM_{2.5}$ maximum 24-hour average and annual average concentrations for 2014 at the Karratha and Dampier stations. The PM_{10} 24-hour criteria was exceeded at all of the stations, with the highest 24-hour concentrations monitored at Dampier West and Dampier North. The $PM_{2.5}$ average concentrations remained below the standard criteria.

Table 4-4: 2014 PM_{10} and $PM_{2.5}$ average concentrations at each of the monitoring sites.

Pollutant	Monitoring Station	Averaging Period	Guideline (µg/m³)	Max Average Conc. (µg/m³)	% of Guideline	Exceedances (2014)
PM_{10}	Dampier East	24-hour	50	73	147%	Yes – 15 days
		Annual	25	28	112%	Yes
	Dampier West	24-hour	50	84	168%	Yes – 14 days
		Annual	25	24	96%	No
	Dampier North	24-hour	50	80	160%	Yes – 20 days
		Annual	25	29	116%	Yes
	Dampier Centre	24-hour	50	76	153%	Yes – 12 days
		Annual	25	24	97%	No
	Karratha	24-hour	50	74	148%	Yes – 11 days
		Annual	25	23	90%	No
$PM_{2.5}$	Dampier Centre	24-hour	25	17	67%	No
		Annual	8	5	66%	No
	Karratha	24-hour	25	18	71%	No
		Annual	8	5	67%	No

Investigations undertaken to assess contributions from regional sources concluded a high proportion of short-term exceedances were related to high background regional concentrations with some exceedances associated with industry (Hass, 2015). Figures 4-2 to 4-10 present polar plots (average 1-hour concentrations as a function of wind speed and wind direction) for NO_2, O_3, and at Karratha, Dampier and Burrup Road stations, and particulates at the Karratha and Dampier stations.

4.1.2 Karratha

Figure 4-2 and Figure 4-3 present polar plots of 1-hour average concentrations of NO_2 and O_3 respectively at the Karratha monitoring station. The NO_2 1-hour average concentrations presented in Figure 4-2 are less than 15 ppb (<13% of criteria) and do not indicate elevated concentrations from any specific direction.

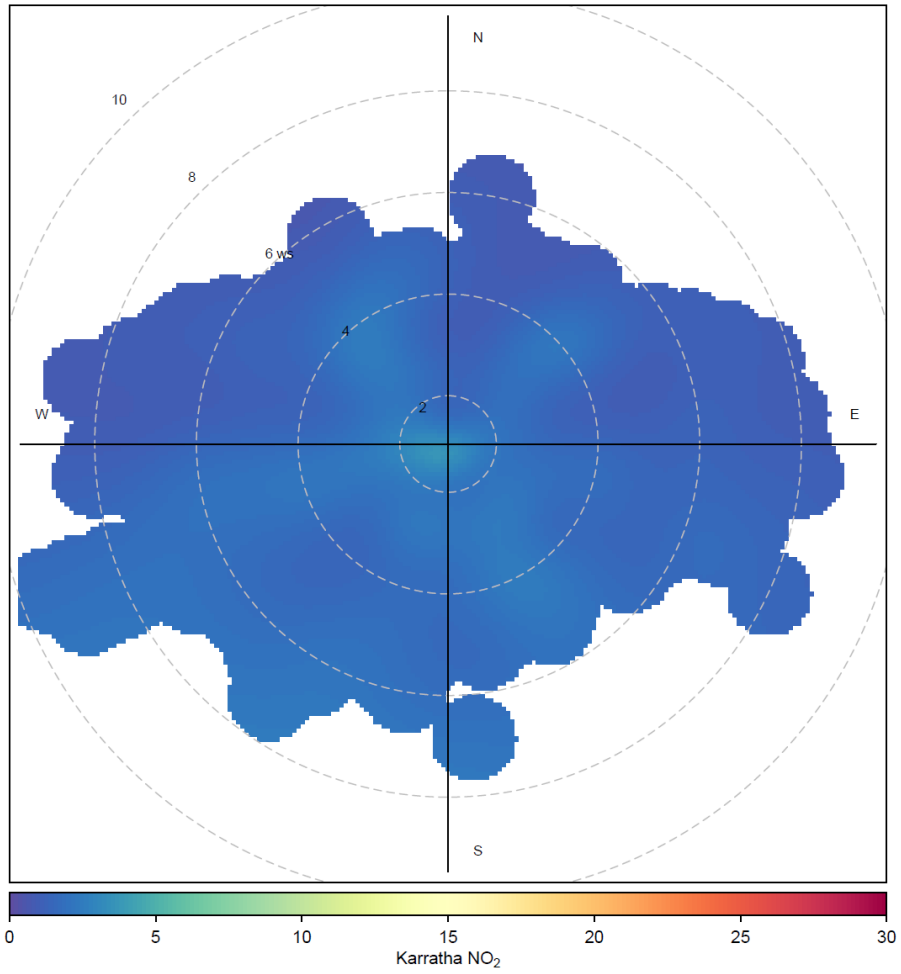


Figure 4-2: Karratha NO_2 Polar Plot (1-hour Averages, ppb) – 2014

Figure 4-3 presents the monitored 1-hour average O_3 concentrations at Karratha and indicates that they were below the applicable standard.

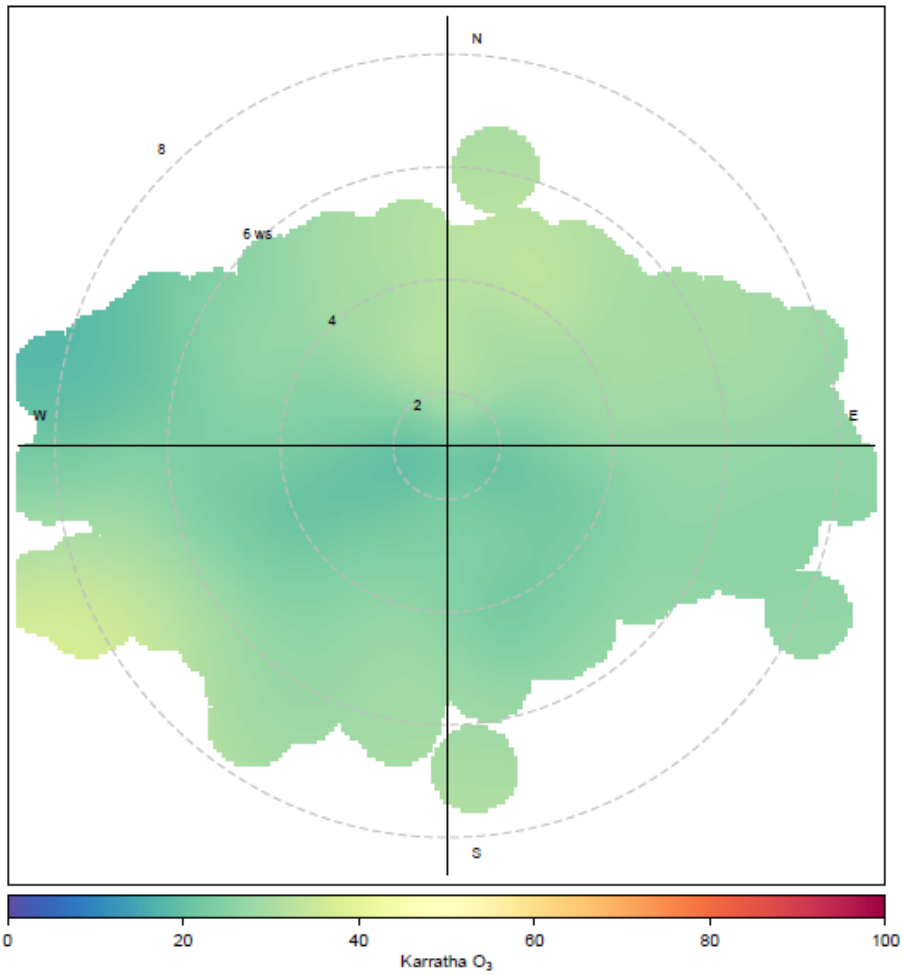


Figure 4-3: Karratha O_3 Polar Plot (1-hour Averages, ppb) – 2014

Figure 4-4 and Figure 4-5 present polar plots of the monitored 95th percentile of 1-hour averages of PM_{10} and $PM_{2.5}$ concentrations at Karratha (Particulates) and indicates high concentrations of PM_{10} (200-300 µg/m^3) tended to occur from a west-south-westerly direction. PM_{10} elevated levels are outside the industry arc of influence and are most likely related to elevated regional levels. $PM_{2.5}$ elevated concentrations of around 10-20 µg/m^3 occur within an arc from the south-west (SW) to the north-east (NE).

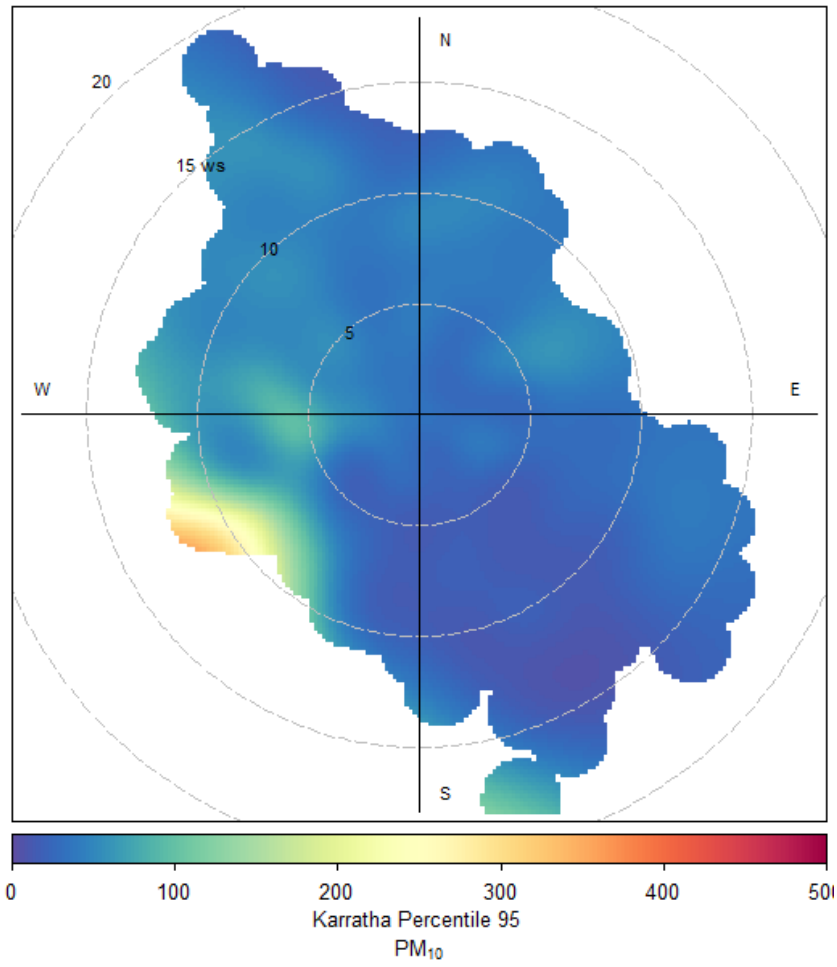


Figure 4-4: Karratha PM_{10} Polar Plot (95th Percentile – 1-hour Averages, µg/m³) – 2014

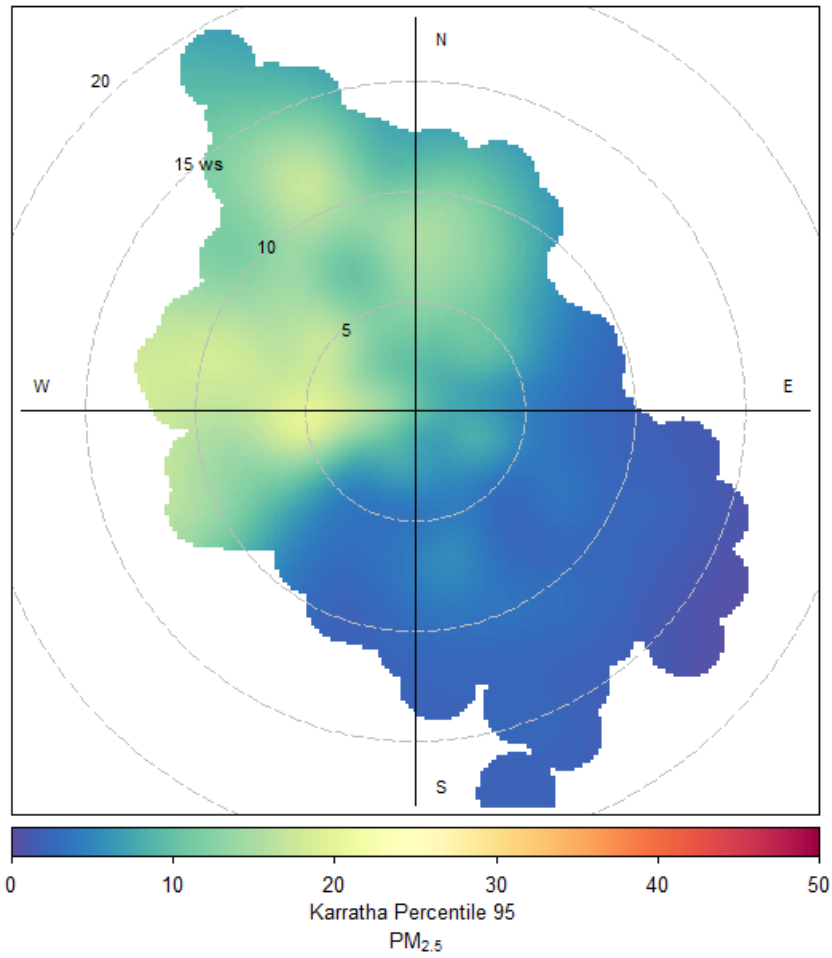


Figure 4-5: Karratha $PM_{2.5}$ Polar Plot (95th Percentile – 1-hour Averages, µg/m³) – 2014

4.1.3 Dampier

Figure 4-6 to Figure 4-7 present polar plots for NO_2 and O_3, respectively at the Dampier North monitoring station. It is noted in Figure 4-6 that elevated NO_2 concentrations tended to occur from the north and south-east (SE). These higher concentrations were likely associated with the industry and potentially shipping in the vicinity.

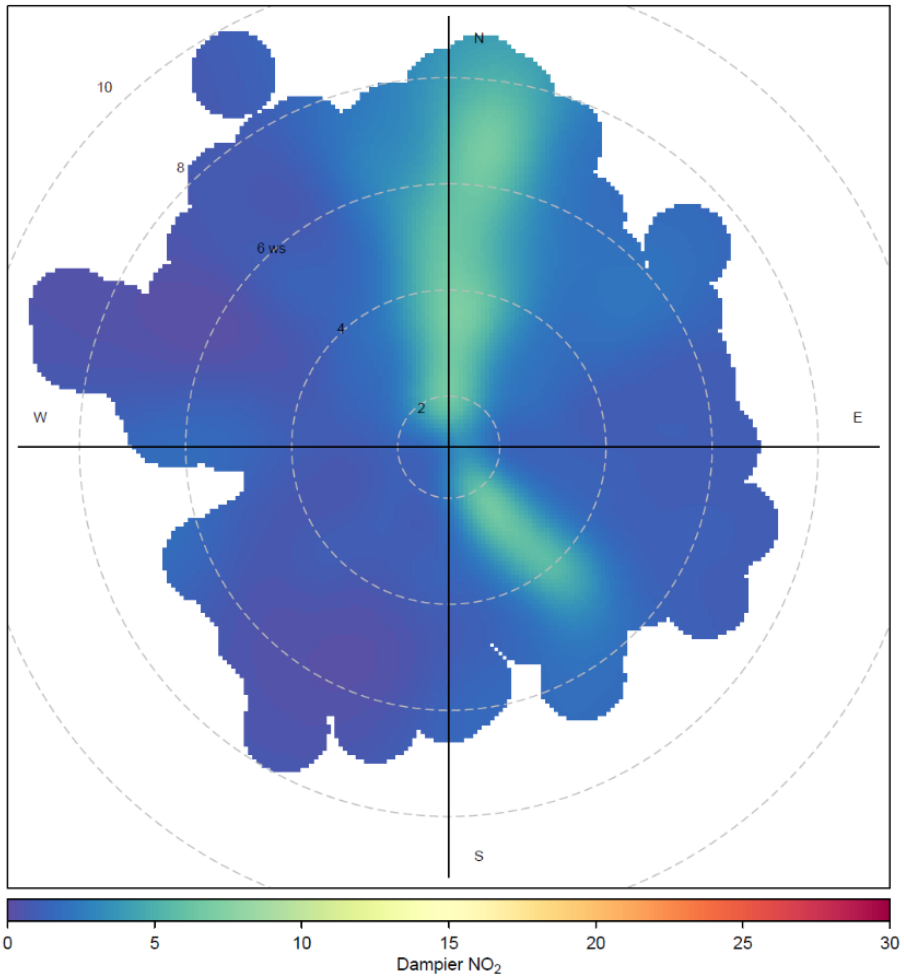


Figure 4-6: Dampier North NO_2 Polar Plot (1-hour Averages, ppb) – 2014

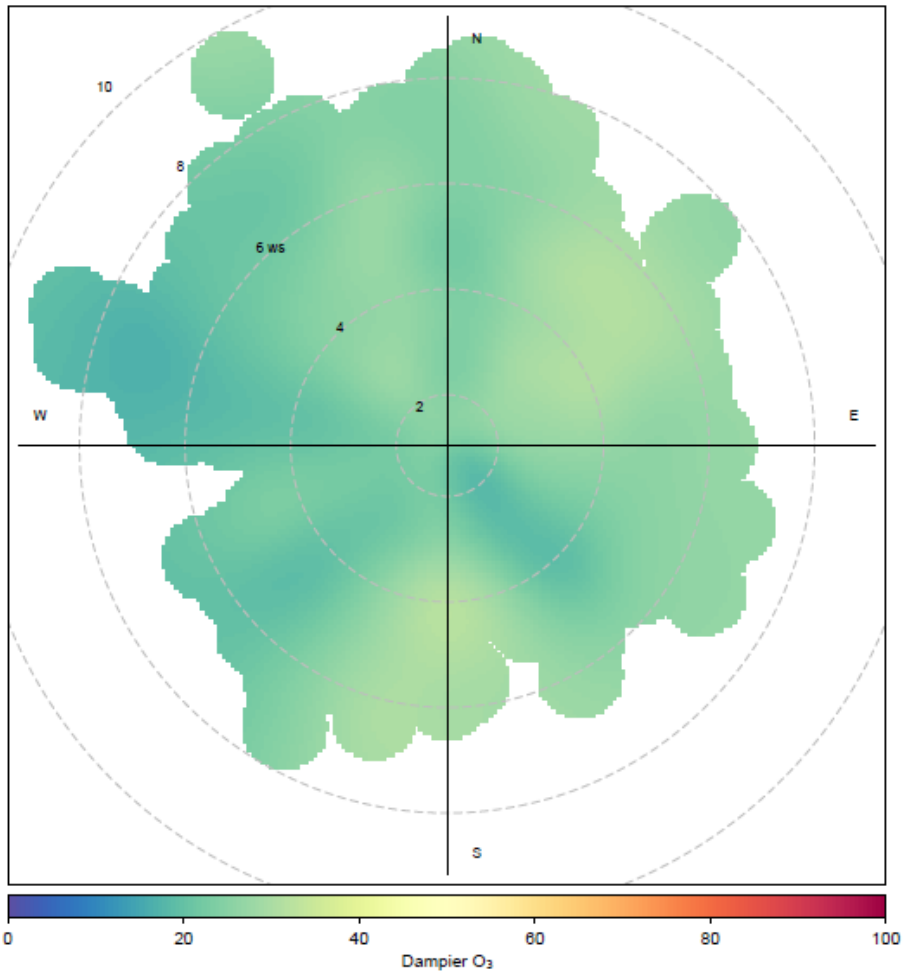


Figure 4-7: Dampier North O_3 Polar Plot (1-hour Averages, ppb) – 2014

Figure 4-8 to Figure 4-12 present polar plots for PM_{10} and $PM_{2.5}$ at the Dampier monitoring stations. Elevated PM_{10} of around 100 to 200 µg/m^3 concentrations occur from the north-east at Dampier East and Dampier North. High concentrations between 20-30 µg/m^3 of $PM_{2.5}$ occur within an arc from the SW to the NE. Analysis of elevated concentrations of particulates indicates they are within the arc of influence of industrial operations in the region.

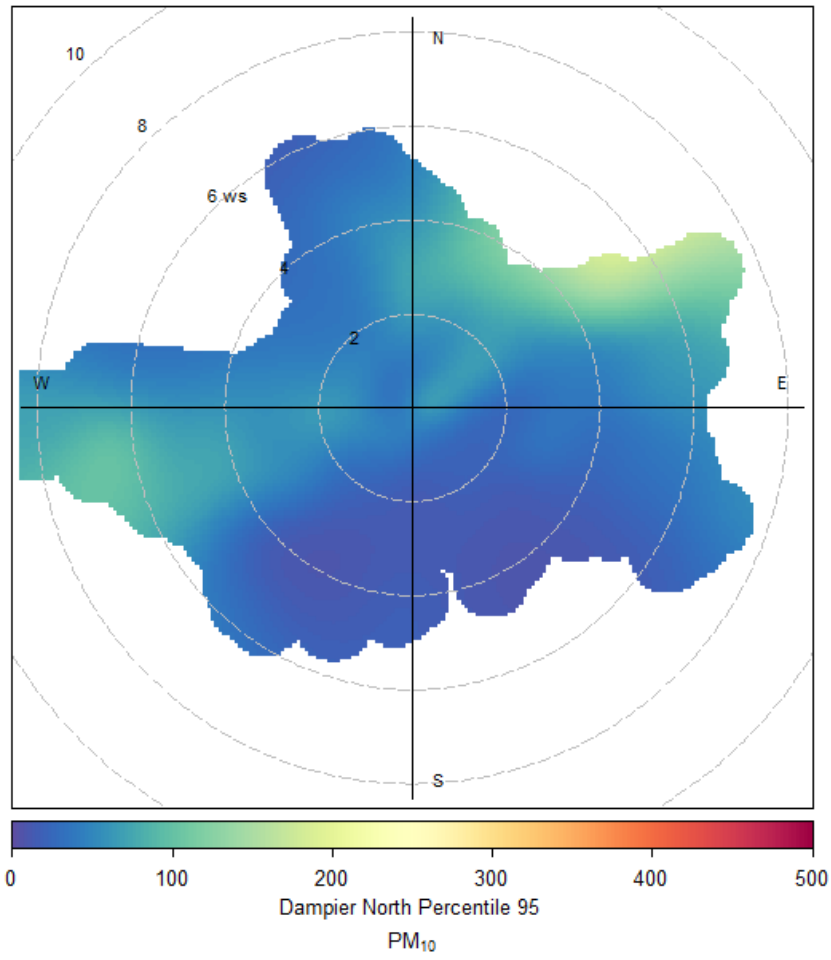


Figure 4-8: Dampier North PM_{10} Polar Plot (95th Percentile – 1-hour Averages, µg/m^3) – 2014

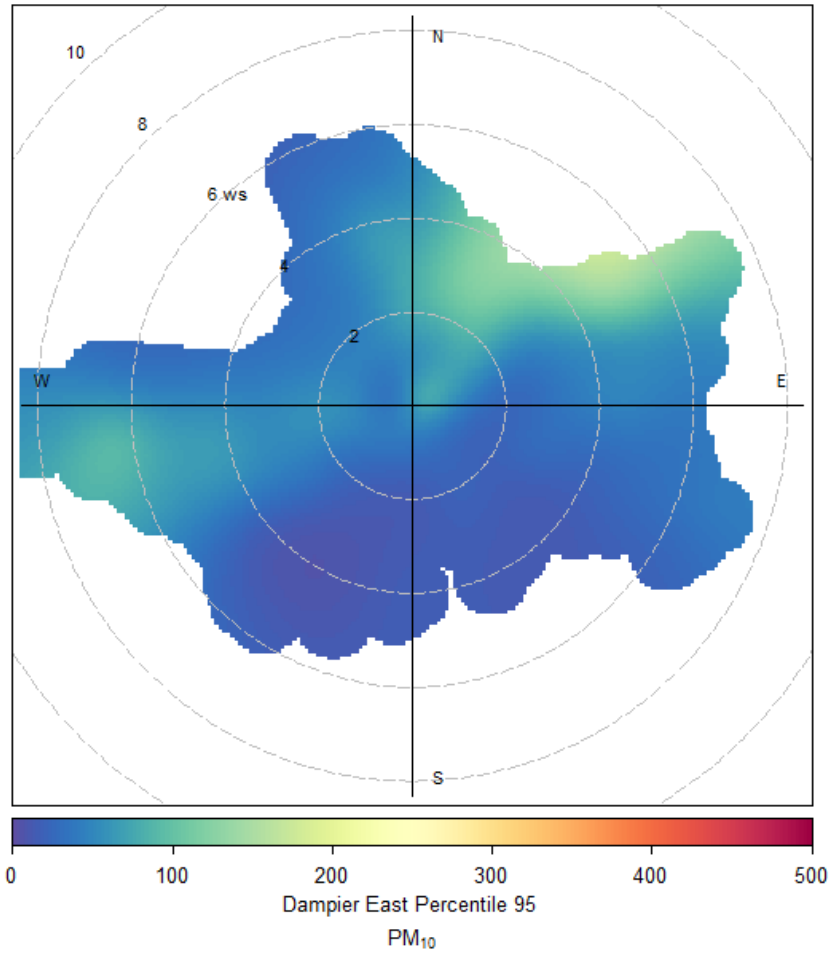


Figure 4-9: Dampier East PM_{10} Polar Plot (95th Percentile – 1-hour Averages, µg/m^3) – 2014

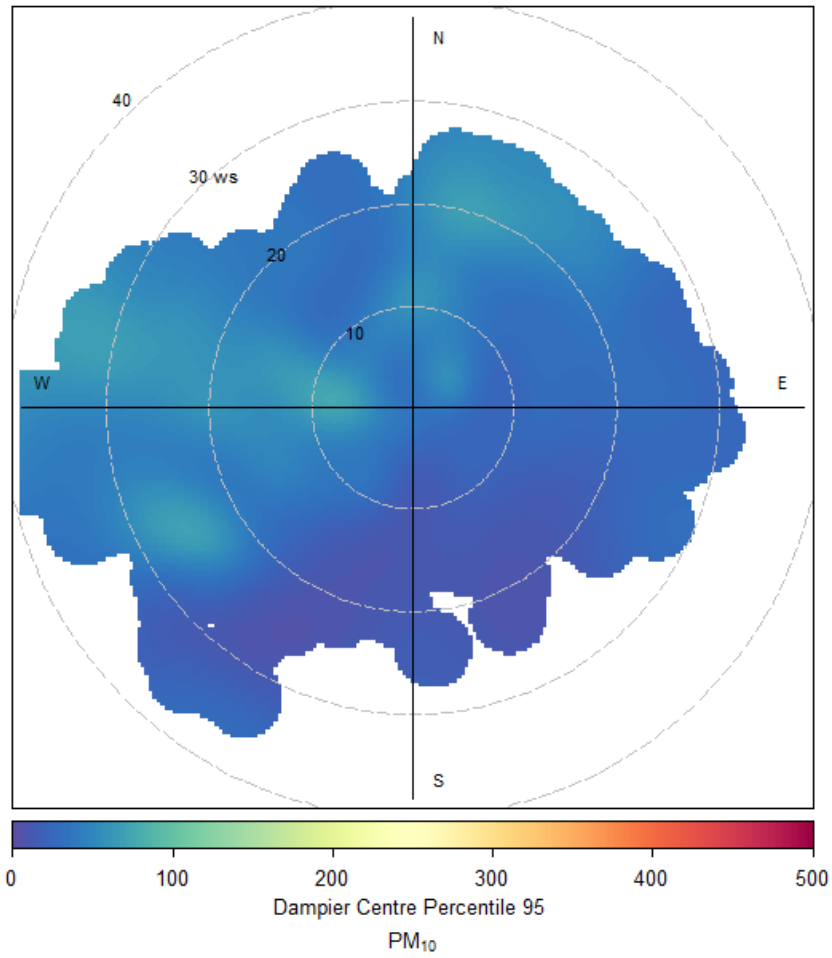


Figure 4-10: Dampier Centre PM_{10} Polar Plot (95th Percentile – 1-hour Averages, µg/m^3) – 2014

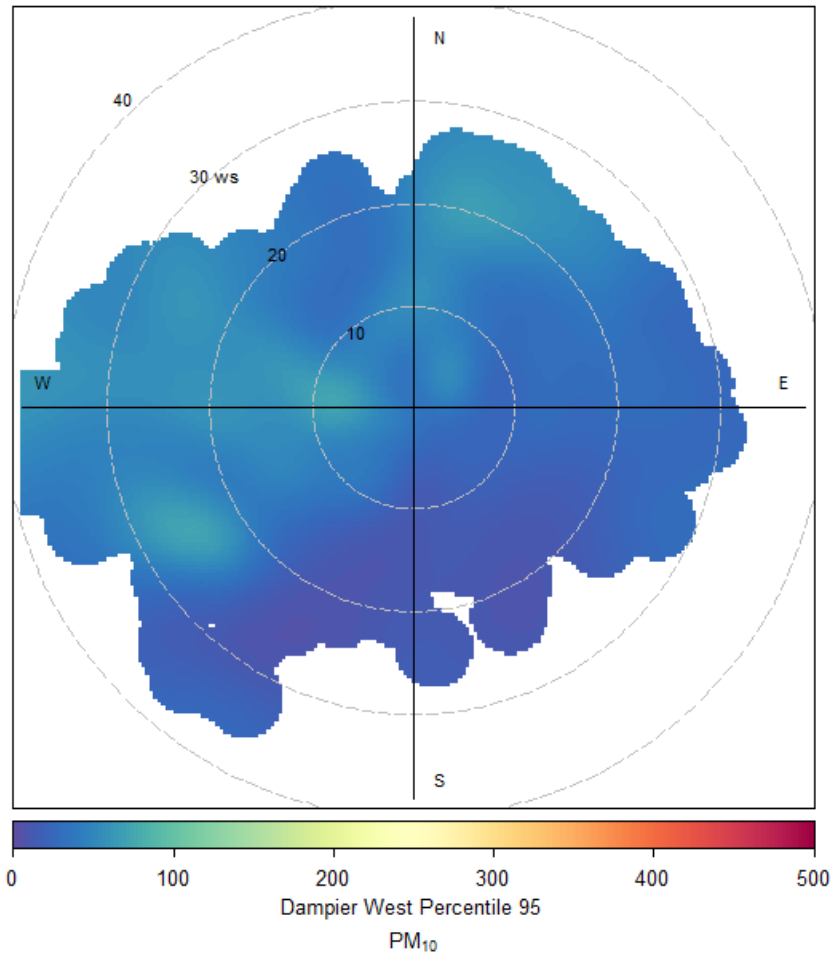


Figure 4-11: Dampier West PM_{10} Polar Plot (95th Percentile – 1-hour Averages, µg/m^3) – 2014

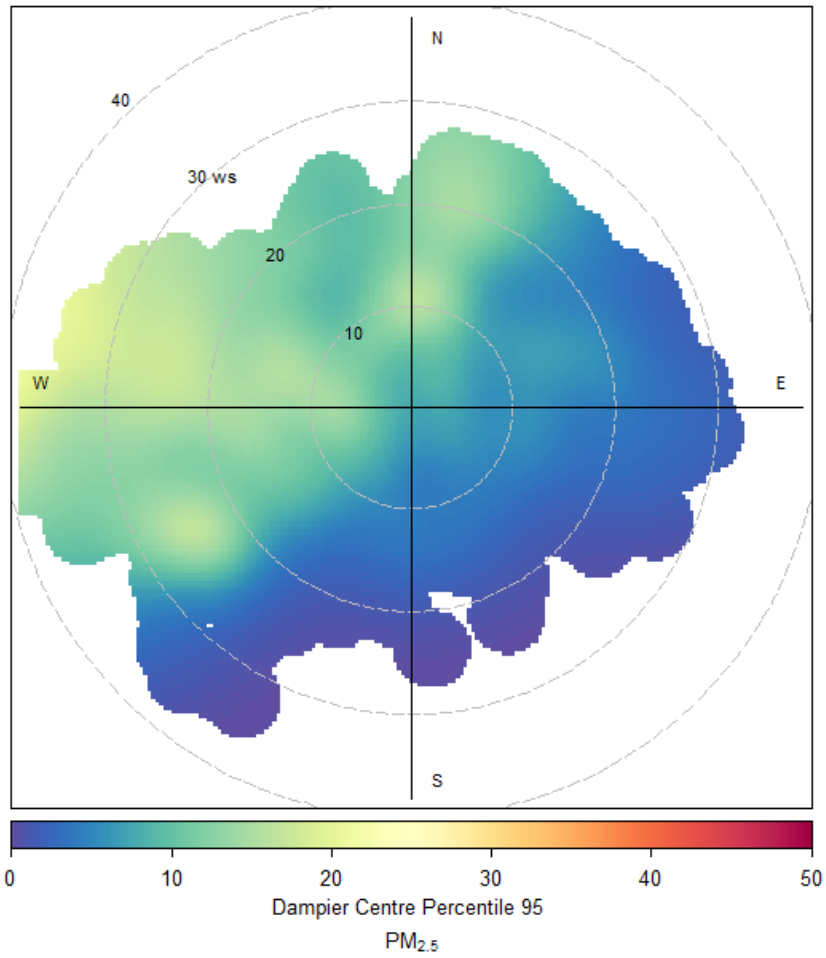


Figure 4-12: Dampier Centre $PM_{2.5}$ Polar Plot (95th Percentile – 1-hour Averages, µg/m³) – 2014

4.1.4 Burrup Road

Figure 4-13 presents 1-hour average NO_2 concentrations at the Burrup Road monitoring station. Elevated concentrations of NO_2 were recorded from the directions of nearby industry. All recorded concentrations were well below the nominated guidelines. Figure 4-14 presents 1-hour average concentrations of the BTX recorded at the Burrup Road monitoring station in 2014. It is noted that maximum concentrations were below relevant criteria, comprising 51%, 7% and 20% respectively (Table 4-3) of the 1-hour criteria for benzene, toluene and xylene.

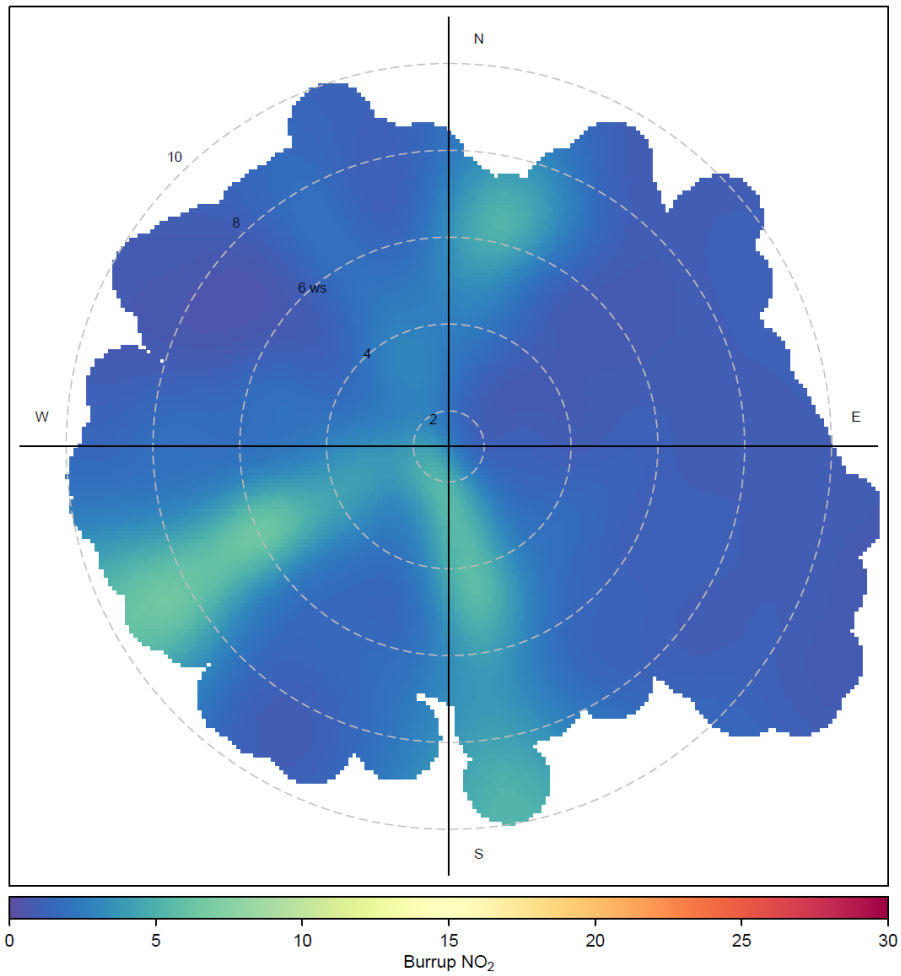


Figure 4-13: Burrup Road NO_2 Polar Plot (1-hour Averages, ppb) – 2014

Figure 4-14: Burrup Road 2014 Time Series Plot BTX

4.1.5 Overall Trends for 2014

Figure 4-15 to Figure 4-18 present the monthly trend of concentrations recorded across the monitoring stations in 2014. It is observed from the NO_2 trend the highest monthly average concentration was recorded at Dampier. Smoothed curve NO_2 concentrations at Dampier and Karratha display unimodal distribution with Dampier peaking in July and Karratha peaking in August. Smoothed curve NO_2 concentrations at the Burrup Road monitor display trimodal distribution with peaks occurring in February, April and the highest concentration in September. The Burrup Road monitor recorded its lowest NO_2 levels in June. Overall, NO_2 concentrations increased in winter and decreased in summer. Figure 4-16 presents O_3 trends at Karratha and Dampier with the highest monitored concentrations at both stations occurring in September.

The particulates trends are depicted in Figure 4-17 and Figure 4-18, PM_{10} and $PM_{2.5}$ concentrations present a unimodal distribution with elevated concentration levels at December, January and November across all the stations.

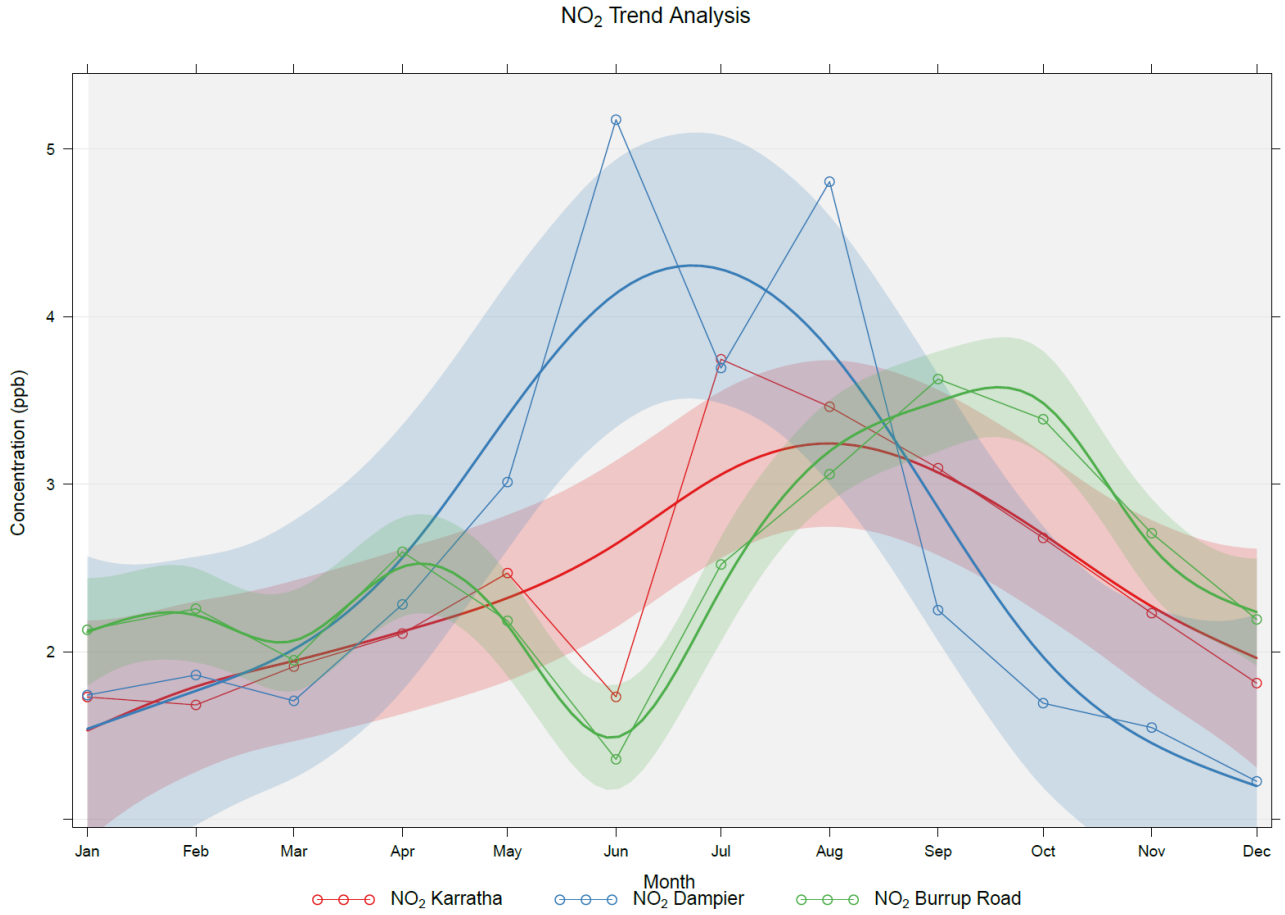


Figure 4-15: Trend for NO_2 Concentrations (2014)

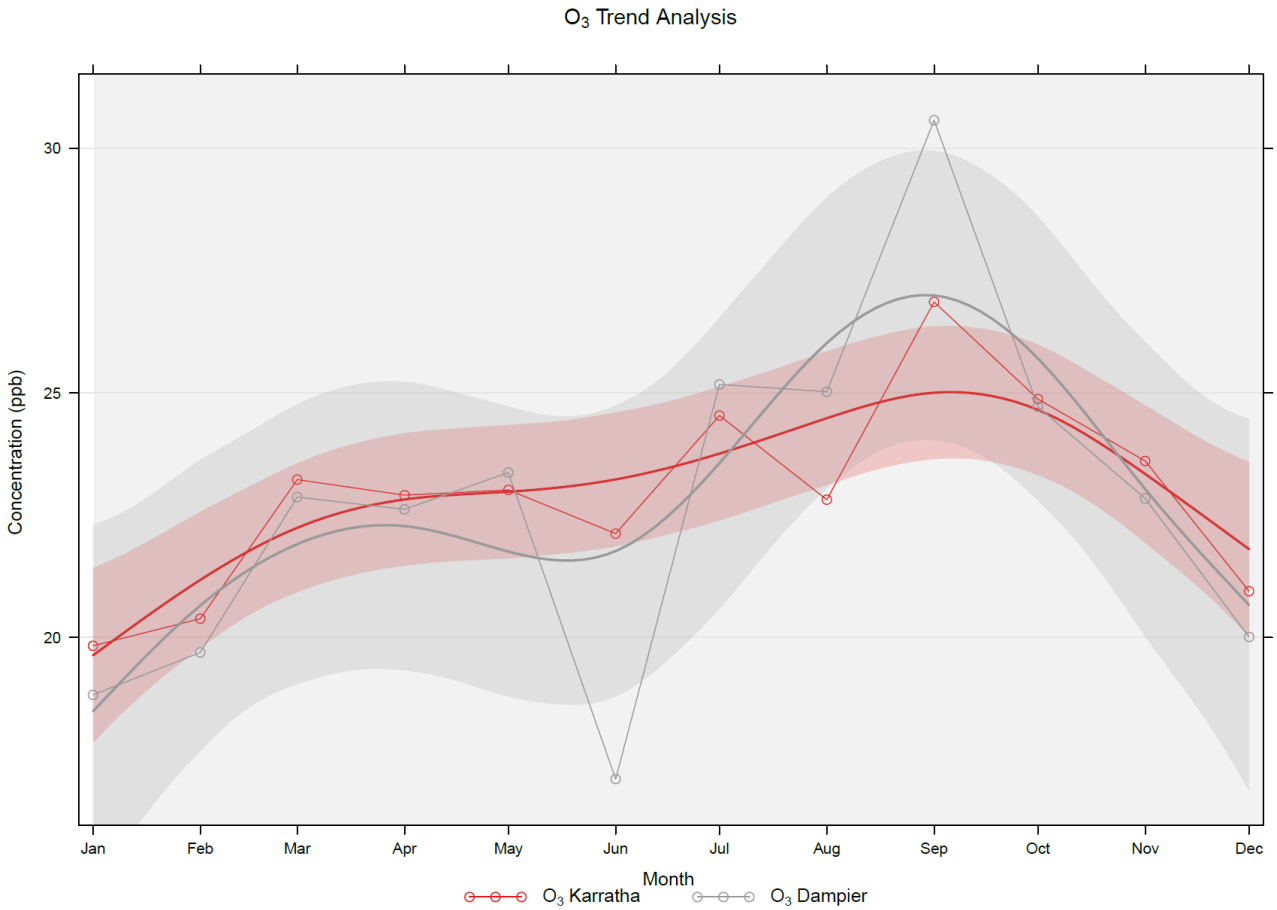


Figure 4-16: Monthly Trend O_3 Concentrations (2014)

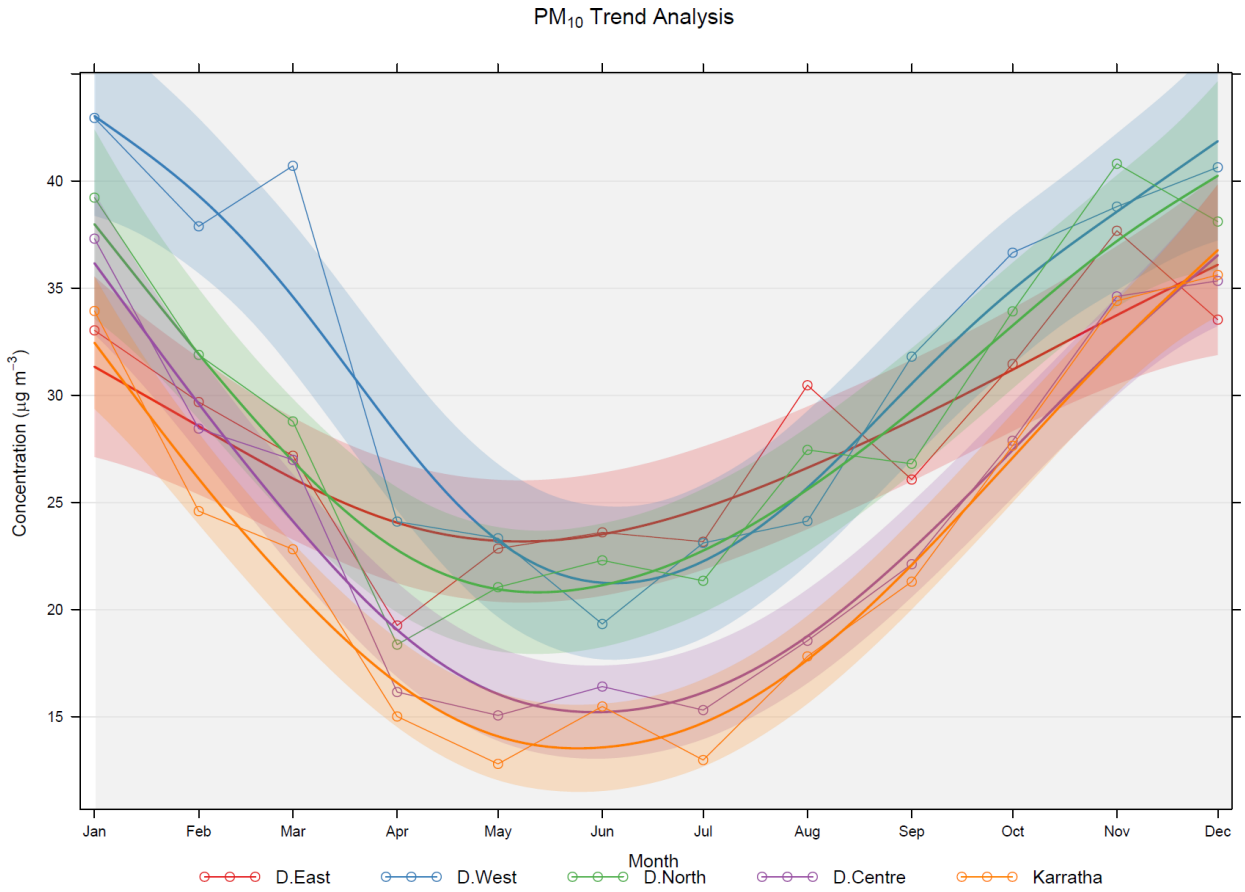


Figure 4-17: Monthly Trend PM_{10} Concentrations (2014)

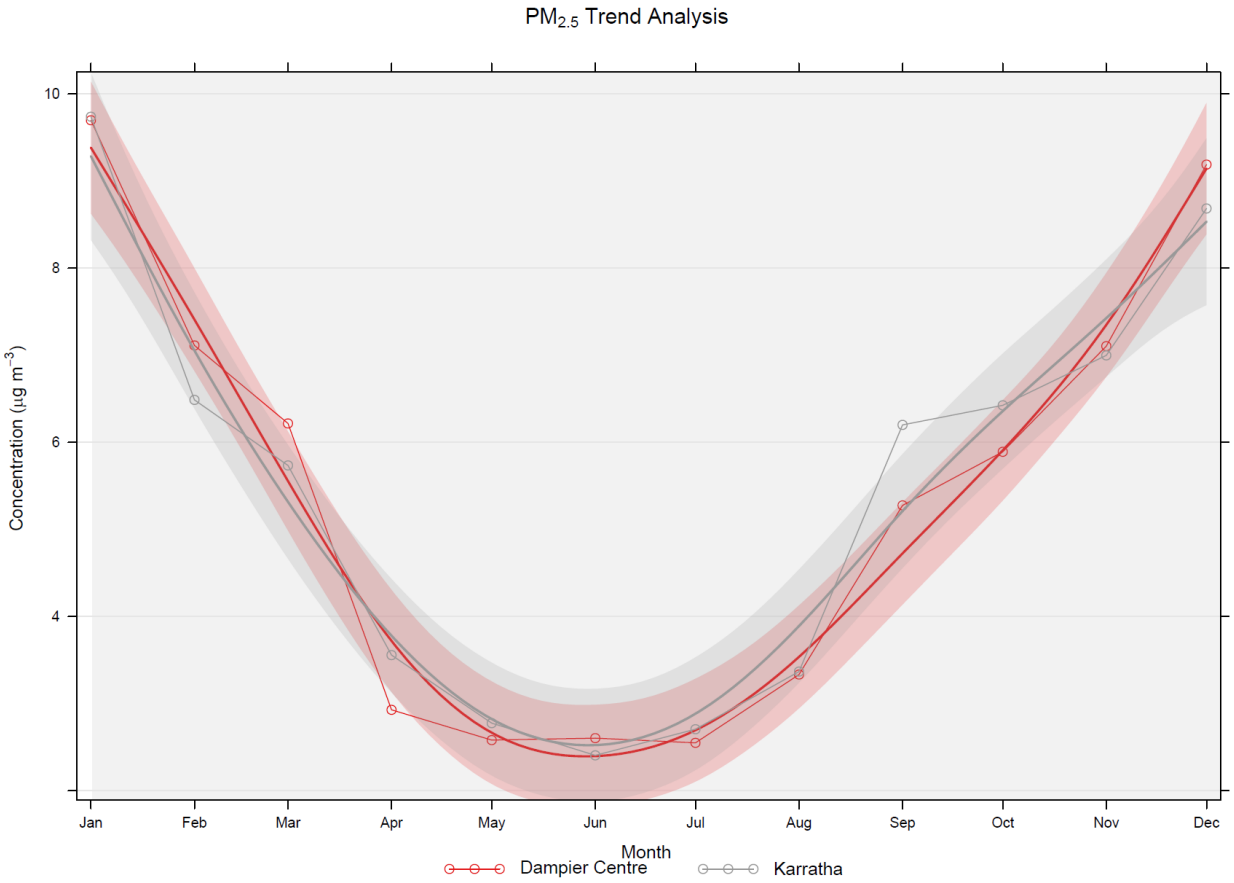


Figure 4-18: Monthly Trend $PM_{2.5}$ Concentrations (2014)

4.2 Acidic Deposition

Total deposition flux of nitrogen and sulphur at a number of measurement sites on the Burrup Peninsula were determined in 2004/2005 and 2007/2008 by calculating the wet and dry deposition of all nitrogen and sulphur species in the gas and aqueous (rainwater) phases. This included NO_2, SO_2, nitric acid and ammonia gases, and some other species in rainwater (Jacobs, 2019a). The study showed that the total wet and dry deposition flux of nitrogen and sulphur ranged from 19.8-31.6 milliequivalents per square metre per year (meq/m^2/yr) over the two monitoring periods from 2004 to 2008. Units of 'meq/m^2/yr' were used to enable comparisons with previous monitoring results. A milliequivalent is one thousandth of a chemical equivalent. An equivalent of an ion is the mass in grams of the ion divided by its molecular weight and multiplied by the charge on the ion (Jacobs, 2019a).

Woodside engaged CSIRO to carry out a study to determine the nitrogen deposition flux (between February 2012 and June 2014) on and around the Burrup Peninsula before and after the commissioning of the Pluto LNG Plant. A summary of results for the ranges of total measured nitrogen (N) and sulphur (S) fluxes is provided in Table 4-5. Inspection of these results indicates they have been reasonably consistent over a long period of sampling (Jacobs, 2019a).

Table 4-5: Summary of Results for Burrup N and S Deposition Monitoring Programs

Monitoring Program	Analyte	Range of Deposition Excl. Background Sites	Dry Deposition NO_2 Fraction
2004–2005 and 2007–2008	Total nitrogen and sulphur	19.8 – 31.6 meq/m2/year	16%-36% of total N & S
2008–2009	Total nitrogen	18.4 – 32.9 meq/m2/year	19%-29% of total N only
2012–2014	Total nitrogen	17.1 – 28.8 meq/m2/year	17%-34% of total N only

5. ATMOSPHERIC EMISSIONS

5.1 Introduction

This section provides details on the estimation of atmospheric emissions for the pollutants of concern within the region of interest for this study.

Air emissions of concern for this study included the following:

- Nitrogen dioxide (NO_2);
- Ozone (O_3);
- Sulphur dioxide (SO_2);
- Carbon monoxide (CO);
- Ammonia (NH_3);
- Volatile organic compounds (VOCs);
- Particulates (as PM_{10} and $PM_{2.5}$), including ammonium nitrate, ammonium sulphate and urea dust; and
- Mercury (Hg).

Emissions of the pollutants were categorised into a number of sources within the region. These sources were defined in the region including the following:

- Industrial emissions sources;
- Mobile sources including:
    - Commercial shipping and recreational boating;
    - On-road and off-road mobile vehicles;
    - Airports; and
    - Railways.
- Domestic and commercial sources including:
    - Recreational boats
    - Aerosols and solvents;
    - Cutback bitumen
    - Gaseous fuel combustion;
    - Liquid fuel combustion (domestic);
    - Portable fuel containers (domestic and public open space);
    - Gaseous and solid fuel combustion (domestic);
    - Surface coatings (domestic, commercial and industrial);
    - Industrial solvents;
    - Automotive fuel retailing; and
    - Motor vehicle refinishing.
- Biogenic sources including:
    - Vegetation;
    - Wind blown dust;
    - Bushfires; and
    - Oceanic Sources (Sea salt and dimethyl sulphide).

In order to derive emissions estimates for use in the modelling, a number of techniques were used including; direct measurement, recognised emissions factors from sources such as the NPI, other emissions databases (CEDS), as well as other publicly available information such as population data and surveys conducted in the region. More detailed explanations on the

techniques used to derive emissions estimates for each source type are provided in the following sections. A summary of the emissions estimates is provided in Table 5-1.

Table 5-1 Summary of Emissions Estimates from All Sources (Tonnes Per Year)

	Industry		Railways		Shipping		Transport		Domestic & Commercial		Natural
	Scenarios 2 (2014)	Scenario 3 (2030)	Scenario 2 (2014)	Scenario 3 (2030)	Scenarios 1 and 2 (2014)	Scenario 3 (2030)	Scenarios 1 and 2 (2014)	Scenario 3 (2030)	Scenarios 1 and 2 (2014)	Scenario 3 (2030)	Scenarios 1,2 (2014) and 3 (2030)
CAMx-4 km Grid											
NOx	51,616	78,946	31,678	43,205	24,568	36,675	961	1,035	459	477	38,311
CO	32,340	50,578	4,020	5,483	1,912	2,854	2,929	3,148	387	403	38,217
Total VOCs	15,144	30,477	1,379	1,880	735	1,097	464	494	888	928	605,467
SOx	1,438	1,452	1,388	1,893	24,786	13,304	11	11	55	57	234
$PM_{2.5}$	1,980	2,792	0	0	3,185	2,842	1,351	1,380	73	76	55,444
PMcoarse	114,056	128,170	745	1,016	0	0	6,093	6,215	0	0	79,014
NH_3	140	405	0	0	0	0	17	18	0	0	411
Hg	0.044	0.043	0	0	0	0	0	0	0	0	0
Urea	0	354	0	0	0	0	0	0	0	0	0
CAMx-1.33 km Grid											
NOx	13,937	12,052	1,765	2,133	4,656	5,773	209	221	173	180	159
CO	13,327	15,968	224	271	350	434	740	784	91	95	125
Total VOCs	6,128	6,433	77	93	139	173	162	171	271	282	4,907
SOx	913	926	77	94	6,288	1,484	4	4	21	22	0
$PM_{2.5}$	212	658	0	0	769	445	254	259	20	21	177
PMcoarse	998	1,121	42	50	0	0	765	780	0	0	855
NH_3	137	402	0	0	0	0	4	4	0	0	0
Hg	0.00023	0.00027	0	0	0	0	0	0	0	0	0
Urea	0	354	0	0	0	0	0	0	0	0	0

5.2 Spatial Limits of Estimates

Estimates of emissions were derived for all nominated sources within the CAMx 4 km domain and CAMx 1.33 km domain as described in Section 6.1.1. The CAMx 4 km domain study area comprises the towns of Karratha, Dampier, Port Hedland, Exmouth, Onslow, Paraburdoo, Pannawonica and Tom Price. The CAMx 1.33 km domain is centred on the town of Dampier and includes, the Burrup Peninsula, the townships of Karratha, Wickham and Roebourne.

5.3 Industrial Sources

5.3.1 Data Collection and Information Sources

Where feasible, detailed emissions information from industry sources operating in 2014 was sought with particular focus on operators in the Murujuga airshed. Where detailed site-specific information was not made available, information was mainly derived from the Australian NPI database. Many facilities report to the NPI on a financial year basis. Where this occurred, industry emissions derived from NPI estimates were averaged across the 2013/2014 and 2014/2015 reporting years. Sources and a description of the sources included in the 2014 inventory are described in Table 5-2 below. Publicly reported NPI data for parameters (e.g particulate ratios) were used to supplement information where site specific operator data was supplied but was not sufficient to derive estimates for all parameters.

Table 5-2 Industrial Emissions Included in Scenario 2

Company	Facility
Alinta Dewap Pty Ltd	Boodarie Gas Fired Power Station
	Port Hedland Power Plant
APA (Pilbara Pipeline) Pty Ltd	PEPL - Alinta Power Station Delivery Meter Station
	PEPL - Stovehill Rd Power Station Delivery Meter Station
	PEPL - Telfer Gas Pipeline Meter Station
APT Management Services Pty Limited	Boodarie Compressor Station
Atlas Iron Limited	Abydos Iron Ore Mine
	Atlas Wodgina Operations
	Mt Dove Iron Ore Mine
	Mt Webber Iron Ore Mine
	Pardoo Operations
ATCO Power Australia (Karratha) Pty Ltd	Karratha Power Station
BGC Contracting Pty Ltd	Elazac Quarry
BHP Billiton Iron Ore Pty Ltd	Marillana Creek - Yandi
	Mining Area C
	Port Operations - Nelson Point & Finucane Island
	Rail Operations Port Hedland
BHP Billiton Petroleum Pty Ltd	Macedon Gas Project
	Pyrenees Venture FPSO
	Stybarrow Venture MV16

Company	Facility
BOC Limited	Karratha AU167
BP Australia Pty Ltd	Air BP Cloudbreak Mine
	AIR BP Karratha
	AIR BP Port Hedland
	Air BP Solomon Mine
	Port Hedland Terminal
Caltex Australia Petroleum Pty ltd	Caltex Port Hedland Terminal
Chevron Australia Pty Ltd	Barrow Island Operations
	Gorgon Operations
	Thevenard Island Operations
Citic Pacific Mining Management Pty Ltd	Sino Iron Project - Mining, Processing & Infrastructure Area
	Sino Iron Project - Port Area
City of Karratha	7 Mile Waste Facility
Dampier Salt Limited	Dampier Salt Operations
	Port Hedland Salt Operations
DBNGP (WA) Nominees Pty Limited	Ashburton Meter Station
	Burrup Meter Station
	Cape Preston Meter Station
	Compressor 1, GGP Interconnect and FRGP interconnect
	Compressor Station 2
	Exmouth Meter Station
	Maitland Meter Station
	MLV 7 Interconnect
	Pluto Meter Station
	Seven Mile Meter Station
Dyno Nobel Asia Pacific Pty Limited	Dyno - Port Hedland
EDL NGD (WA) Pty Ltd	Maitland
Exmouth Power Station Pty Ltd	Exmouth Power Station
Fortescue Metals Group Ltd	Cloudbreak Operations
	Herb Elliott Port Operations
	Kanyirri Fuel Facility Operations
	Solomon Operations
Global Advanced Metals Wodgina Pty ltd	Wodgina Operations
Goldfields Gas Transmission Pty Ltd	GGP. Turee Creek Compressor Station
	GGT, Paraburdoo Delivery/Meter Station
	Paraburdoo Compressor Station
	Wyloo West Compressor Station
	Yaraloola Compressor Station
Hamersley Hms Pty Ltd	Hope Downs 1 Mine

Company	Facility
Hamersley Iron - Yandi Pty Limited	Yandicoogina Mine
	Brockman 2/Nammuldi Mine
	Brockman 4 Mine
	Marandoo Mine
	Mt Tom Price Mine
	Paraburdoo Mine
	Western Turner Syncline Mine
Holcim (Australia) Pty Ltd	Nickol Bay Quarry
	Turner River Quarry
IB Operations Pty Ltd	North Star Operations
Mermaid Marine Australia Ltd	Mermaid Supply and Logistics Base
Mineral Resources Limited	Iron Valley Iron Ore Mine
	Phils Creek Iron Ore Mine
	Poondano Iron Ore Mine
Mobil Oil Australia Pty Ltd	Learmonth Aviation Refuelling Service
Northern Star Resources Ltd	Paulsens Gold Mine
Onslow Electric Power Pty Ltd	Onslow Power Station
Onslow Salt Pty Ltd	Onslow Salt Minesite
Orica limited	Orica Pippingarra ANE
Pilbara Iron Pty Ltd	Cape Lambert Port
	Channar Mine
	Dampier Port
	Dampier Railyard
Pilbara Ports Authority	Port of Port Hedland
Santos Pty Ltd	Armada Claire Operation
	Stag Operations
	Van Gogh Operations
	Varanus Island Operations
	Ningaloo Vision
	Devils Creek Gas Processing Facility
Regional Power Corporation	Karratha Temporary Generation Project
	South Hedland Temporary Generation Power Station
Robe River Mining Co Pty Ltd	Mesa A/Warramboo Mine
	Mesa J/K Mine
	West Angelas Mine
Santos limited	"Mutineer-Exeter"
Shell Aviation Australia Pty Ltd	Shell Barrow Island Airport
	Shell Boolgeeda Airport
	Shell Karratha Airport

Company	Facility
	Shell Paraburdoo Airport
TEC Pipe Pty Ltd	Solomon Power Station
The Pilbara Infrastructure Pty Ltd	Thomas Rail Yard Operations
The Shell Company of Australia Limited	Shell Dampier Terminal
	Shell Paraburdoo Terminal
	Shell Tom Price Terminal
Town of Port Hedland	South Hedland Tip Site
Vermilion Oil & Gas Australia Pty Ltd	Wandoo Offshore Facilities
Viva Energy Australia ltd	Viva Energy/Rio Tinto Dampier Terminal
	Viva Energy/Rio Tinto Paraburdoo Terminal
	Viva Energy/Rio Tinto Tom Price Terminal
	Viva Energy/Rio Tinto West Angelas Terminal
Water Corporation	Karratha #1 WWTP
	Karratha #2 WWTP
	Port Hedland WWTP
	South Hedland WWTP
Wesfarmers Kleenheat Gas Pty Ltd	KHG Port Hedland - Gas
Woodside Energy Ltd	Angel
	Goodwyn Alpha
	Pluto Gas Treatment Plant
	Nganhurra
	Ngujima-Yin
	North Rankin Alpha
	Okha
	Pluto Offshore Platform
	Vincent VNB-H1-ST2
	XNA-01
	Tidepole-2
	Karratha Onshore Gas Treatment Plant
	King Bay Supply Facility
Yara Pilbara Fertilisers Pty Ltd	Ammonia Plant

To identify potential industry sources for the future emissions scenario (i.e. Scenario 3), emissions for all facilities in the study area that reported to the 2017/2018 NPI database (the most recently available at the time of access) were identified. Any known expansion proposals from existing facilities were also incorporated. In addition to existing facilities, emissions from other proposed facilities, were also identified and included where information was available. The following sources of information were utilised to determine future projects:

- The EPA's Status of Active Formal Assessments was accessed to identify projects that have recently been referred to the EPA and are currently under assessment (or the EPA has indicated no assessment is required).

- The EPA's Proposal Search Tool (http://www.epa.wa.gov.au/proposal-search) – was used to obtain approval documentation for current or future proposals that may have an impact on air quality in the Pilbara. For example, Environmental Scoping Documents (ESDs) are available for most recent assessments under Stage 3 of the EPA assessment process which identifies relevant key environmental factors. Only those projects where 'Air Quality' was identified as a key environmental factor, were investigated further.
- For proposals where additional environmental approval documentation (e.g. Environmental Document Review) was publicly available, any information or data relevant to air quality was obtained. Where no additional environmental approval documentation was available, then the ESD or Referral was obtained to provide an indication of the key project characteristics, potential environmental factors, proposed scope of work and potential impacts and mitigation measures.
- DWER licences and works approvals assessments for public comment (https://www.der.wa.gov.au/our-work/licences-and-works-approvals/lwa-applications) were included to identify projects that currently have licenses or works approvals under assessment, relevant to air quality emissions.
- Department of Mines Industry Regulation & Safety (DMIRS) Major Resource Maps (http://dmpbookshop.eruditetechnologies.com.au/product/major-resource-projects-western-australia-2019.do) and Prospect Magazine https://www.dmp.wa.gov.au/Documents/Community-Education/Prospect-Winter-2019.pdf) – to identify future major projects (i.e. 'Committed Projects' and 'Projects Under Consideration') were also reviewed. In some cases, the proposals identified by DMIRS sources are in the early stages of exploration and development and very little information was available.

For some proposals, no information was available other than what was found through a general search engine query (e.g. news articles or investment related reports indicating ownership or funding status). No relevant air quality information was obtained from these sources.

Additional facilities that have begun operations since 2014 as well as proposed operations that were included in the future emissions scenario (Scenario 3) are presented in Table 5-3.

Table 5-3 Industrial Emissions included in Scenario 3

Company	Facility	Status
Australian Terminal Operations Management Pty Ltd	Port Hedland Terminal	Currently Operating
Balla Balla Infrastructure Port	Balla Balla Infrastructure Port	Proposed
Boral Resources (WA) Ltd	Mt Regal Quarry	Currently Operating
	Tabba Tabba	Currently Operating
Chevron Australia Pty ltd	Wheatstone GTP	Currently Operating
	Wheatstone Platform	Currently Operating
DBP Development Group Pty Limited	Ashburton West Lateral	Currently Operating
DDG Fortescue River Pty Ltd	Fortescue River Gas Pipeline	Currently Operating
Fortescue Metals Group Ltd	Solomon Power Station	Currently Operating
Jadestone Energy (Australia) Pty Ltd	Stag Operations	Currently Operating
Orica Australia Pty Ltd	Orica Pippingarra Plant	Currently Operating
Perdaman Industries	Urea Project Proposal	Proposed
Pilgangoora Operations Pty ltd	Pilgangoora Operations	Currently Operating
Roy Hill Infrastructure Pty Ltd	Roy Hill Port (Boodarie)	Currently Operating

Company	Facility	Status
	Roy Hill Rail Terminal Yard	Currently Operating
TEC Hedland Pty Ltd	South Hedland Power Station	Currently Operating
Wesfarmers Limited	Methanol Plant Proposal	Proposed
Wodgina Lithium Pty Ltd	Wodgina Operations	Currently Operating
World Fuel Services (Australia) Pty Ltd	Learmonth Aviation Refuelling Service	Currently Operating
Yara Pilbara Nitrates Pty Ltd	Technical Ammonium Nitrate Production Facility (TANPF)	Currently Operating

5.3.2 Emission Estimation

An estimate of the emissions in Scenario 2 and Scenario 3 from industrial sources that were considered in the study is provided in Table 5-4.

Table 5-4 Emissions Estimates from Industrial Sources

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	51,616	13,937	78,946	12,052
CO	32,340	13,327	50,578	15,968
Total VOCs	15,144	6,128	30,477	6,433
SOx	1,438	913	1,452	926
$PM_{2.5}$	1,980	212	2,792	658
PMcoarse	114,056	998	128,170	1,121
NH_3	140	137	405	402
Hg	0.044	0.00023	0.043	0.00027

5.3.3 Temporal and Spatial Allocation

For most industrial sources, emissions were assumed to be continuous. Additional characterisation of sources on a temporal basis was undertaken for some facilities located near or on the Burrup Peninsula where data was made available. Industry sources with point sources (stacks) that were identified and characterised were located using actual stack locations. Emissions from all other sources were aggregated into the relevant modelling grid cells based on publicly available information regarding the site location.

5.4 Mobile Sources

5.4.1 On-Road Vehicles

For most on-road vehicle sources, emissions were assumed to be continuous. A range of pollutants are emitted during operation including Volatile Organic Compounds (VOCs), oxides of nitrogen (NO_x) and oxides of sulphur (SO_x), lead, particulate matter and trace metals. For this assessment, emission estimates were based on the software package COPERT Australia. The estimated emissions were then spatially allocated based on publicly available GIS data from Main Roads WA. Further details are provided below.

5.4.1.1 Data Collection and Information Sources

COPERT is an acronym for Computer Programme to calculate Emissions from Road Transport. The COPERT Australia (version 1.3) software package was used to estimate the total emissions from on-road vehicles in the region. COPERT is an average speed model commonly used around the world to estimate road traffic emissions on a regional or national level. COPERT Australia was developed specifically for Australia with consideration of local fleet composition and driving characteristics.

COPERT Australia simulates emissions from more than 250 vehicle classifications and a wide range of pollutants and includes all emission types (hot running, cold start, non-exhaust and evaporative). The vehicle classifications are based on a combination of main vehicle type, fuel (petrol, diesel, LPG etc) and Australian Design Rules (ADR) categories. ADRs are national standards for vehicle safety, anti-theft, and emissions that have been adopted in Australia. COPERT Australia accounts for 18 ADR categories.
COPERT Australia requires the following information to generate emissions:

- Meteorological data (temperature and relative humidity);
- Annual fuel consumption by fuel type (petrol diesel, LPG) and fuel specification;
- Vehicle population by
    - Vehicle type (passenger, light commercial, heavy duty trucks);
    - fuel type (petrol, diesel, LPG);
    - vehicle size (engine size, gross vehicle mass);
- For each vehicle group
    - Vehicle kilometres travelled (VKT);
    - Average speed on rural, urban and highways;
    - Average proportion of VKT spent on urban, highway and rural roads; and
    - Fuel tank size, fuel composition/quality and engine technology.

The meteorological data for the study was based on 2014 Bureau of Meteorology (BoM) data recorded at the Karratha Aero monitoring station.

Requests for information on fuel consumption in the Pilbara region in 2014 were made to major fuel distributors operating in the region. Data on fuel consumption was not provided and so a surrogate method to estimate fuel consumption was adopted. The annual fuel consumption data was based on the ABS Survey of Motor Vehicle Use (SMVU), 12 months ending 31st October 2014 and was scaled down to the region of interest based on population (Table 5-5). For Scenario 3, a rate of increase of 6.5%[5] in fuel consumption was adopted based on information outlined within CSIRO (2011).

Table 5-5: COPERT Australia - Fuel consumption

Item description	Value	Reference
Fuel consumption in WA (Million litres, ML)	1,965 (Petrol) 1,882 (Diesel) 131 (LPG)	(ABS, 2015a)
Population in WA – 2014	2,590,000	(ABS, 2015b)
Population – Pilbara Region	52,000	WA Parliamentary Library[6]

[6] Considers the use of alternative fuels including electricity and hydrogen power
[6] https://profile.id.com.au/wapl/population-estimate?WebID=530 (Accessed 19 March 2020)

Item description	Value	Reference
Fuel consumption in Pilbara (Million litres, ML)	39.3 (Petrol) 37.6 (Diesel) 2.6 (LPG)	Downscaled based on population

Vehicle registration information for 2014 was obtained from the WA Department of Transport (DoT). This information included details on total number of vehicles segregated by body type, fuel, age, classification (heavy/light) and post code. This information was categorised to the COPERT vehicle classifications.

Traffic and road network data from Main Roads WA was used to estimate annual Vehicle Kilometres Travelled (VKT). Where no traffic count data exist for a road section, default daily volume was assigned based on the NPI Emissions Report for the Pilbara Airshed (SKM, 2003) (see Table 5-6). For Scenario 3, the total VKT travelled in the region was based on a projected 2% increase in the region surrounding Murujuga airshed (Email communication with Main Roads WA, 27 February 2020).

Table 5-6: Default daily traffic volume

Road Hierarchy	Road Surface	Default daily volume (vpd)
Highway	Sealed	600
Main Road	Sealed	1,000
Main Road	Unsealed	75
Urban Collector	Sealed	2000
Urban Street	Sealed	200
Urban minor street	Sealed	100
Other road	Sealed	25
Other road	Unsealed	10

Speed of vehicles and driving share in urban, rural and highway roads were initially based on Perth Air Emissions Study (DWER, 2018) with the values adjusted iteratively during input data validation (Table 5-7).

Table 5-7: COPERT Australia - vehicle speed and driving share

COPERT Sector	COPERT Sub-sector	Average Speed (km/hr)			VKT Share (%)		
		Urban	Rural	Highway	Urban	Rural	Highway
Passenger Cars	PC-S-petrol	30	75	100	80	15	5
Passenger Cars	PC-M-petrol	30	75	100	80	15	5
Passenger Cars	PC-L-petrol	30	75	100	80	15	5
Passenger Cars	PC-S-diesel	40	80	100	70	25	5
Passenger Cars	PC-ML-diesel	40	80	100	70	25	5

COPERT Sector	COPERT Sub-sector	Average Speed (km/hr)			VKT Share (%)		
		Urban	Rural	Highway	Urban	Rural	Highway
Passenger Cars	PC-LPG	40	80	100	90	10	0
SUV	SUV-C-petrol	30	75	100	80	15	5
SUV	SUV-L-petrol	30	75	100	80	15	5
SUV	SUV-diesel	40	80	100	70	25	5
Light Commercial Vehicles	LCV-petrol	30	75	100	75	20	5
Light Commercial Vehicles	LCV-diesel	46	76	97	65	30	5
Heavy Duty Trucks	MCV-petrol	46	76	97	60	35	5
Heavy Duty Trucks	MCV-diesel	46	76	97	60	35	5
Heavy Duty Trucks	HCV – diesel	46	76	97	60	35	5
Heavy Duty Trucks	AT-diesel	46	76	97	60	35	5
Heavy Duty Trucks	Autogas Trucks	35	75	100	90	10	0
Buses	Bus-L-diesel	46	76	97	60	35	5
Buses	Bus-H-diesel	46	76	97	60	35	5
Motorcycles	4 stroke 250 – 750 cm^2	46	76	97	70	25	5

Data for engine technology was based on the 2010 Australian motor vehicle emission inventory for Western Australia (UniQuest, 2014) and is provided below. The evaporative share for urban, rural and highway share remains the same across all categories and are 90%, 10% and 0% respectively.

Table 5-8: COPERT Australia – Engine technology and evaporative control

COPERT Sector	COPERT Sub-sector	Technology	Tank size (L)	Canister size (L)	Fuel Injection (%)	Evaporative control %
Passenger Cars	PC-S-petrol	ADR00-UNC	50	N/A	1	0
Passenger Cars	PC-S-petrol	ADR27	50	0.38	6	97
Passenger Cars	PC-S-petrol	ADR37-00	50	0.43	33	97
Passenger Cars	PC-S-petrol	ADR37-01	50	1	100	97

COPERT Sector	COPERT Sub-sector	Technology	Tank size (L)	Canister size (L)	Fuel Injection (%)	Evaporative control %
Passenger Cars	PC-S-petrol	ADR79-00	50	1	100	97
Passenger Cars	PC-S-petrol	ADR79-01	50	1	100	97
Passenger Cars	PC-S-petrol	ADR79-02	50	1	100	97
Passenger Cars	PC-S-petrol	ADR79-03	50	1	100	97
Passenger Cars	PC-M-petrol	ADR37-00	65	0.43	81	97
Passenger Cars	PC-M-petrol	ADR37-01	65	1.25	100	97
Passenger Cars	PC-M-petrol	ADR79-00	65	2	100	97
Passenger Cars	PC-M-petrol	ADR79-01	65	2	100	97
Passenger Cars	PC-M-petrol	ADR79-02	65	2	100	97
Passenger Cars	PC-L-petrol	ADR00-UNC	70	N/A	1	0
Passenger Cars	PC-L-petrol	ADR27	70	0.5	8	97
Passenger Cars	PC-L-petrol	ADR37-00	70	0.54	90	97
Passenger Cars	PC-L-petrol	ADR37-01	70	1.25	100	97
Passenger Cars	PC-L-petrol	ADR79-00	70	2	100	97
Passenger Cars	PC-L-petrol	ADR79-01	70	2	100	97
SUV	SUV-C-petrol	ADR00-UNC	65	N/A	1	0
SUV	SUV-C-petrol	ADR37-00	65	0.77	100	97
SUV	SUV-C-petrol	ADR37-01	65	1.25	100	97

COPERT Sector	COPERT Sub-sector	Technology	Tank size (L)	Canister size (L)	Fuel Injection (%)	Evaporative control %
SUV	SUV-C-petrol	ADR79-00	65	2	100	97
SUV	SUV-C-petrol	ADR79-01	65	2	100	97
SUV	SUV-C-petrol	ADR79-02	65	2	100	97
SUV	SUV-C-petrol	ADR79-03	65	2	100	97
SUV	SUV-L-petrol	ADR00-UNC	75	N/A	1	0
Light Commercial Vehicles	LCV-petrol	ADR00-UNC	75	N/A	1	0
Light Commercial Vehicles	LCV-petrol	ADR37-00	75	0.77	95	97
Light Commercial Vehicles	LCV-petrol	ADR79-00	75	2	100	97
Light Commercial Vehicles	LCV-petrol	ADR79-01	75	2	100	97
Light Commercial Vehicles	LCV-petrol	ADR79-02	75	2	100	97
Light Commercial Vehicles	LCV-petrol	ADR79-03	75	2	100	97
Motorcycles	4-stroke 250 - 750 cm^3	Conventional	18	N/A	0	0

Main Roads WA publishes information on traffic studies undertaken across its network (TrafficMap). GIS information is also available on road networks in the region. These together with default daily volumes (Table 5-6) were used to estimate vehicle kilometres travelled. GIS information from Main Roads WA was also used to spatially allocate emissions. It is noted that Main Roads WA adopts a 12 AUSTROADS Vehicle Classification System based on vehicle axle configuration. Of these, Class 1 and Class 2 collectively represent light vehicles with the remaining classes accounting for heavy vehicles.

Total emission rates output by COPERT were split into light and heavy categories to match the description of available spatial data (Main Roads WA) as below:

- Light vehicles include COPERT categories of passenger cars, SUVs and motorcycles; and
- Heavy vehicles include COPERT categories of light commercial, heavy duty and buses.

Further, particulate emissions due to material re-suspension on paved and unpaved roads were estimated. It is acknowledged that emission factors from paved roads include tyre and brake wear in addition to resuspended dust which would result in the doubling up of emissions from tyre and brake wear. However, this will be insignificant compared to the emissions caused due to re-suspended dust on unpaved roads.

Particulate emissions from paved and unpaved roads were estimated using USEPA AP-42 methodologies (USEPA, 2011) (USEPA, 2006) as defined below.

$$EF = k \times (sL)^{0.91} \times (AW)^{1.02}$$

Where

EF	=	emission factor for paved roads (kg/km)
K	=	empirical factors (0.0046 kg/km for PM_{10} and 0.0011 kg/km for $PM_{2.5}$)
sL	=	0.4 g/m^2 default silt loading for low average daily traffic road surface
AW	=	3.1 tonnes, default average weight of vehicle, (NPI, 1999)

$$EF = k \times \left(\frac{s}{12}\right)^{A} \times \left(\frac{AW}{3}\right)^{B} \times \left(\frac{M}{0.2}\right)^{C}$$

Where

EF	=	emission factor for PM_{10} on unpaved roads (kg/km)
K	=	empirical factor (0.733 kg/km for PM_{10} and 0.0773 for $PM_{2.5}$)
s	=	11%, default silt content (NPI, 1999)
AW	=	3.1 tonnes, default average weight of vehicle, (NPI, 1999)
M	=	2% moisture content
A	=	empirical constant (0.8)
B	=	empirical constant (0.4)
C	=	empirical constant (0.3)

The following settings were defined in COPERT Australia.

- Average trip length of 11.4 km (default COPERT setting in lieu of location specific data);
- Average trip time of 0.25 hours (default COPERT setting in lieu of location specific data);
- Statistical fuel correction applied; and
- 2009 fuel effect year.

5.4.1.2 Emission Estimation

The estimated total emissions from vehicles within the study area are detailed in Table 5-9.

Table 5-9 Emissions Estimates from Vehicles in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	860	135	934	147
CO	2,282	377	2,478	409
Total VOCs	283	54	307	59
SOx	6	1	6	1
$PM_{2.5}$	1,344	243	1,373	248
PMcoarse	6,093	765	6,215	780
NH_3	17	4	18	4

5.4.1.3 Temporal and Spatial Allocation

Emissions were temporally allocated based on hourly averaged traffic volume estimates for weekends/public holidays and weekdays from Main Roads WA. Total emissions from roads were spatially allocated in proportion to the length of unpaved and paved road VKT in each grid cell. On-road vehicle emissions were estimated from the region encompassing five Local Government Areas including Karratha, Port Hedland, Ashburton, East Pilbara, and Exmouth. A layout of the spatial extent and roads considered within the region is detailed in Figure 5-1 and Figure 5-2. The emissions were assigned a temporal variability based on a selection of hourly traffic volumes recorded at selected stations managed by Main Roads WA.

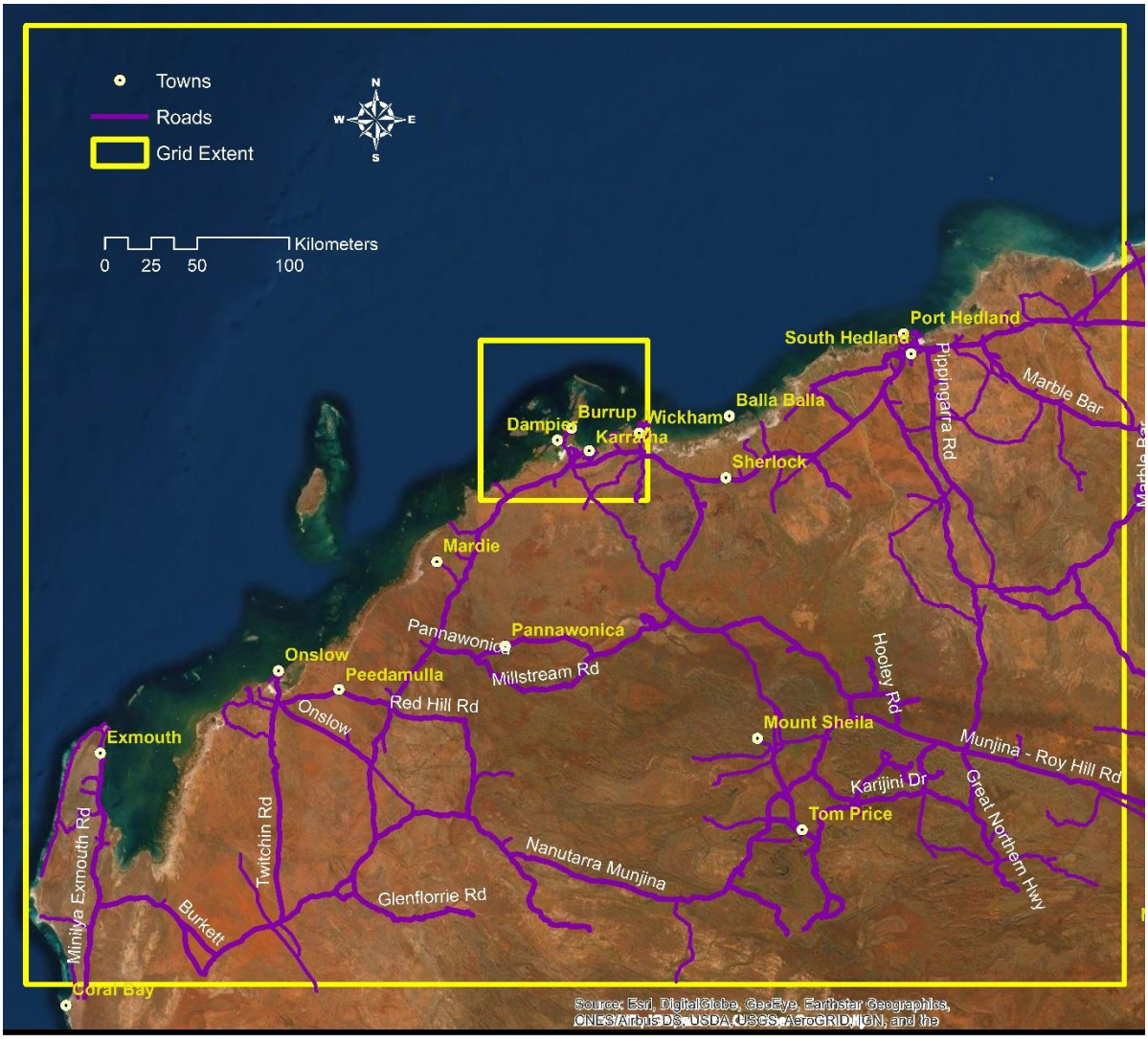


Figure 5-1: Road Network Modelled (4 km Grid)

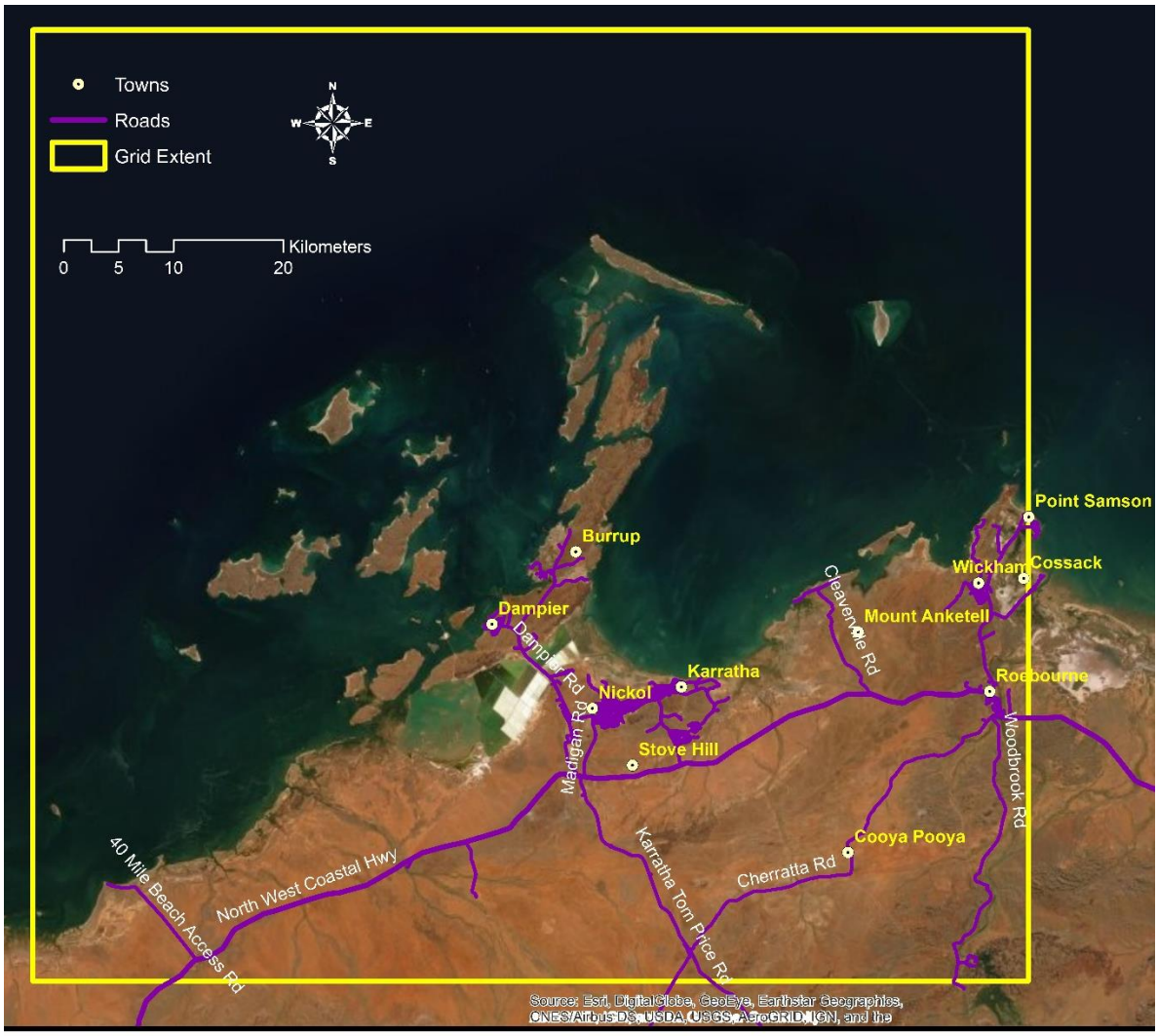


Figure 5-2: Road Network Modelled (1.33 km Grid)

5.4.2 Aircraft

5.4.2.1 Data Collection and Information Sources

Emissions from aircraft were calculated using a methodology derived from techniques outlined in the *NPI Emissions Estimate Technique Manual for Aggregated Emissions from Aircraft Version 2.2* (Environment Australia, 2003) (EET Manual), the International Civil Aviation Organization (ICAO, 2011) and the Guidance on the Determination of Helicopter Emissions (Rindlisbacher, 2015) with modifications to account for availability of data.

Emissions from aircraft were estimated using aircraft movements in the study region within the domains up to a height of 1,000 m. Emissions included in the assessment only include those combustion products from the aircraft engines and do not include vehicles used at the airport, losses from fuel tanks and refueling as these are captured under NPI emissions from these sites.

Emission estimates were made using the following general methodology:

- Locating active aircraft operations within the region;

- Determining the types and quantities of aircraft used for each operation;
- Determining estimates of the time in mode (TIM) for each aircraft type and airport;
- Determining emission rates for each pollutant for each 'flight' mode, i.e. approach, taxi/idle, take off and climb out for each engine type;
- For each flight mode, pollutant and airport the aircraft is in, multiplying the modal emission rate by the time in that mode;
- The emissions per aircraft type were then obtained by multiplying by the number of landings/take-offs at each airport;
- This is then performed for each aircraft type; and
- Summing all the emissions.

Eleven aircraft operations were considered in this study:

- Karratha Airport / Heliport;
- Barimunya Airport;
- Barrow Island Airport;
- Boolgeeda Airport;
- Coondewanna Airport;
- Exmouth Aerodrome;
- Fortescue Dave Forest Airport;
- Learmonth Airport / Heliport;
- Onslow Airport;
- Port Hedland International Airport / Heliport; and
- Solomon Airport.

Data that are required for estimating aircraft emissions in an airshed are as follows:

- The location of airports, runways, landing and approach flight paths, and associated ground movements, in the airshed;
- The number of landing/takeoff (LTO) cycles for each of the aircraft types operating at these airports;
- The prevalence of the different types of engines (and numbers of engines) and Auxiliary Power Units (APUs) used by each aircraft type; and
- The TIM (approach, taxi/idle, takeoff and climbout) for the airport for estimating aircraft engine emissions.

Where contact details were available, airport/heliport operators were contacted to request required data. Of the 18 facilities contacted, only three operations provided data:

- Karratha Airport: Total number of LTO cycles by aircraft type over the 2013/14 and 2014/15 financial years;
- PHI International Helicopters: Total number of LTO cycles and approach, landing, ground, and depart times for 2019 and for March 2014 to December 2014. Split by aircraft type was not available; and
- Learmonth Airport / Heliport: Total number of LTO cycles by aircraft type over the 2014 period.

Aircraft service providers such as Qantas, Virgin, Alliance, Skippers, Polar Aviation and the Flying Doctor Service were also contacted however declined to provide data.

Information on flight schedules and aircraft types for the remaining operations was obtained from either the operator's website or from third party flight tracking websites such as www.Flightradar24.com and www.flightaware.com. Where data was not supplied, the number of LTO cycles per year for each aircraft type was estimated using approximately a week of flight scheduling data based on the availability of public information.

Aircraft engines are of two major types: gas turbine (jet) and reciprocating piston (internal combustion). Engine types and quantities were assumed based on a desktop review of the common engine types used for each aircraft. Each aircraft type was matched with data from the International Civil Aviation Organization (ICAO, 2011) to establish detailed aircraft type, engine and fuel characteristics as well as emissions for an LTO cycle.

Of the 11 aircraft operations considered in the study, only Karratha Airport falls within the 1.33 km inner grid. As such detailed emission estimates (including consideration of TIM) was only possible for Karratha Airport.

Emission factors for the LTO cycles for all airports were derived from estimated plane movements and types and the LTO emissions for compounds outlined in the ICAO database and guidance on the determination of helicopter emissions handbook. Assumptions were made on aircraft types based on data where was not available. For example, no data was available on activity type or frequency for Port Hedland Airport and so estimates were based on the activity and frequency from Karratha Airport and then scaled by publicly available information based on passenger numbers. Default values from the NPI EET Manual were used where engine data was not available. Emissions from APUs were assumed using default values from the EET Manual for each engine type

The Karratha Airport Master Plan & Land Use Plan 2013 - 2033 (Roebourne, 2013) indicated that in 2013 under a high growth scenario, an increase in passenger numbers could be expected at a compound growth rate of 2 percent.

In order to determine emissions for Scenario 3, an analysis of total aircraft movements at Port Hedland and Karratha airports on a year by year basis was undertaken from data obtained from the Department of Infrastructure, Transport, Regional Development and Communications (DITRDC, 2020). The data indicates that since 2014 passenger numbers at both airports have decreased, likely associated with an economic slowdown in industrial activity in the region. If a 2% annual growth rate was applied based on 2019 passenger data, the expected passenger numbers would still be below those modelled in 2014. Lacking a clear basis for estimating future aircraft activity at Karratha and Port Hedland, it was assumed that aircraft activity in 2030 for Scenario 3 would be equal to activity in 2014.

Table 5-10 Aircraft Movements at Karratha and Port Hedland Airports

Airport	Year	Aircraft Movements		
		Inbound	Outbound	Total
Karratha	2014	4,253	4,256	8,509
Karratha	2015	4,010	3,981	7,991
Karratha	2016	3,600	3,544	7,144
Karratha	2017	3,128	3,093	6,221
Karratha	2018	2,995	2,980	5,975

Airport	Year	Aircraft Movements		
		Inbound	Outbound	Total
Karratha	2019	2,996	2,980	5,976
Port Hedland	2014	2,832	2,770	5,602
Port Hedland	2015	2,695	2,640	5,335
Port Hedland	2016	2,528	2,465	4,993
Port Hedland	2017	2,370	2,292	4,662
Port Hedland	2018	2,333	2,298	4,631
Port Hedland	2019	2,432	2,413	4,845

5.4.2.2 Emissions Estimates

An estimate of the emissions in Scenario 2 and Scenario 3 from airports in the study region is provided in Table 5-11.

Table 5-11 Emissions Estimates from Aircraft in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	96.0	71.3	96.0	71.3
CO	106.5	79.8	106.5	79.8
Total VOCs	22.0	25.0	22.0	25.0
SOx	4.4	3.1	4.4	3.1
$PM_{2.5}$	6.5	10.4	6.5	10.4

5.4.2.3 Temporal and Spatial Allocation

All airport emissions were temporally apportioned between 6:00am and 9:00pm based on Karratha Airports operating hours. The estimates of total emissions for the various modes of operation were spatially allocated to the grid cells within which the flight paths (below 1000 m) and associated ground movements would be expected to occur.

5.4.3 Railways

All rail lines within the study area are operated by private mining companies, namely Rio Tinto, FMG, Roy Hill and BHP. The Roy Hill railway was not operating in 2014 but emissions from Roy Hill's operations have been included in Scenario 3. Potential future rail operations in the region also include proposed operations associated with the Balla Balla Resource.

5.4.3.1 Data Collection and Information Sources

Electronic data sets of railways for the operators in the Pilbara were gridded over the domains. Figure 5-3 illustrates railway tracks in the study area. The total length of tracks within the study area is 955 km.

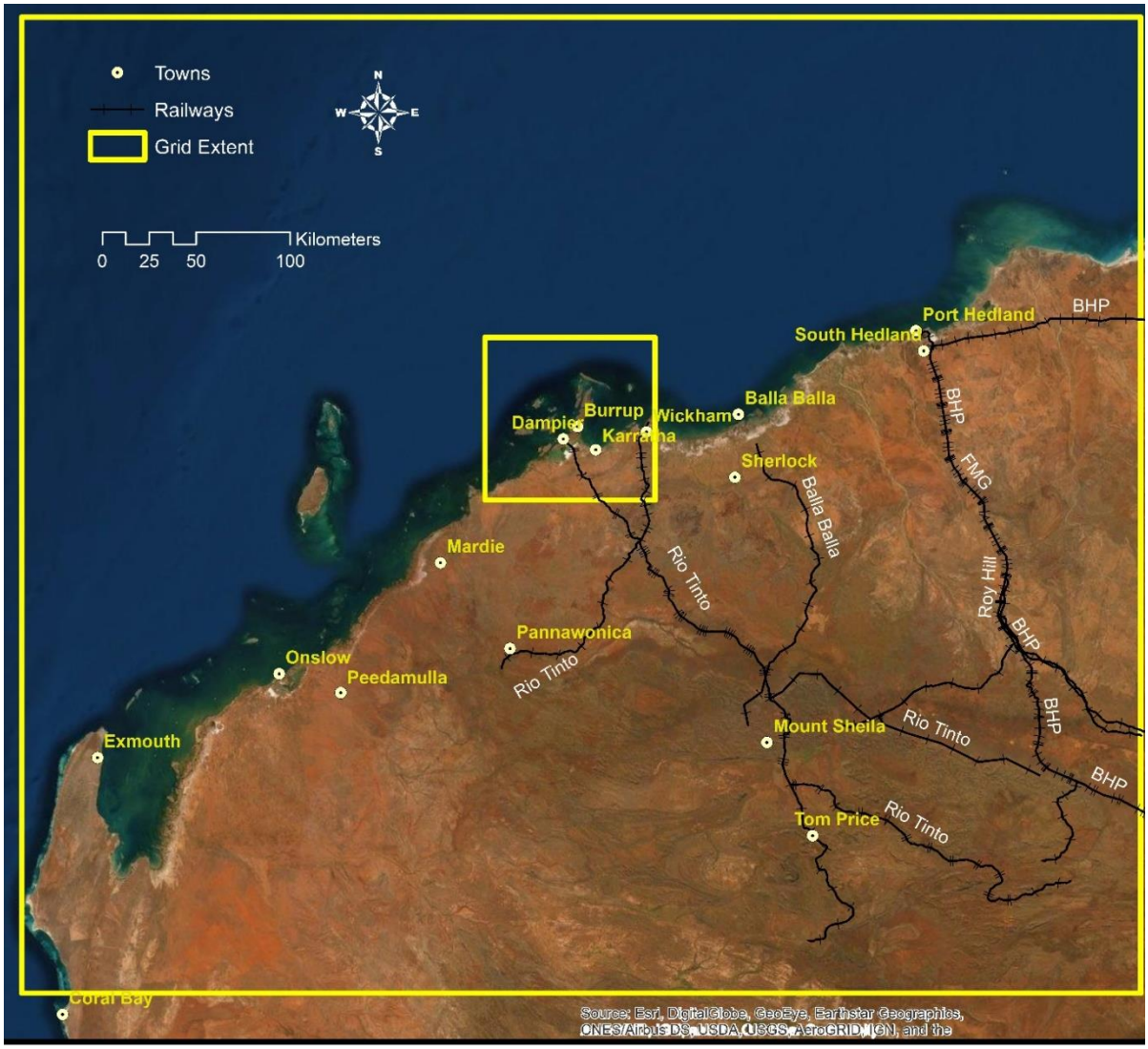


Figure 5-3: Modelled Railways in the Study Area

Requests were made to companies to obtain fuel usage from locomotives however this data was not made available. Data on fuel consumption in 2001 was obtained from (SKM, 2003) and based on publicly available data on production from mine sites, an estimate on an average litres of diesel consumed per tonne/kilometre was derived. This estimate was then applied to all operating facilities in 2014 and scaled based on publicly available production data production and future operational scenarios for Scenario 3.

5.4.3.2 Emission Estimation

Emissions for criteria pollutants and Total VOC's were from trains were estimated using methods outlined in the EET Manual for Aggregated Emissions from Railways (Environment Australia, 1999h). Total estimated diesel consumption for line haul locomotives used to determine emissions are summarised in Table 5-12.

Table 5-12 Total Estimated Diesel Consumption

2014 Estimated Diesel (Million Litres)	2030 Estimated Diesel Million (Litres)
558 ML	748 ML

A summary of total emissions from railways in the study area for Scenario 2 and Scenario 3 are presented in Table 5-13.

Table 5-13 Emissions Estimates from Railways in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenario 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	31,677.7	1,765.4	43,204.5	2,133.4
CO	4,020.1	224.0	5,482.8	270.7
Total VOCs	1,378.7	76.8	1,880.3	92.8
SOx	1,388.2	77.4	1,893.4	93.5
PMcoarse	745.0	41.5	1,016.1	50.2

5.4.3.3 Temporal and Spatial Allocation

Emissions from railways were spatially allocated in proportion to the length of track per grid cell, and the tonnes of ore estimated as being hauled along each section of rail. Emissions were assumed to be temporally spaced evenly across the year assuming operations were occurring 24 hours a day for all days of the year.

5.4.4 Commercial Shipping and Boating

Commercial shipping and boating activities in the study area occur at a number of ports in the region. The ports of the Pilbara are industrial ports, derived from the demand to export mining or resource production.

The ports or major independent private port complexes of the Pilbara include:

- Barrow Island;
- Ashburton;
- Onslow;
- Cape Preston;
- Dampier;
- Port Walcott (Cape Lambert);
- Port Hedland; and
- A number of offshore facilities within the study region that export oil and gas.

Proposed ports for the Pilbara include projects at:

- Cape Preston East for iron ore exports. Located 60 km to the southwest of Dampier; and
- Balla Balla for iron ore exports. A proposed 50 Mtpa trans-shipment port facility 100 km east of Karratha.

5.4.4.1 Data Collection and Information Sources

Vessel activity in the study area was derived from two data sets: 1) the Community Emissions Data System (CEDS) data for transiting vessels and 2) Automatic Identification System (AIS) data for at-berth or at-anchor activities (i.e., speed over ground less than or equal to 1 knot). AIS records are produced by commercial vessels approximately every 30-seconds and provide detailed movement activities (e.g., position, speed over ground, course over ground, draught). AIS was

originally designed to reduce vessel collision incidents, but they've gained traction over the past decade as a tool for improving emission inventory estimates for vessels.

The Australian Maritime Safety Authority (AMSA) provides open access to anonymised AIS records throughout Australia. At-berth and at-anchor emissions relied on the AMSA's 2014 data records for Western Australia. The AIS records include a field that identifies vessel type, which has been used to cross-reference a set of U.S. Environmental Protection Agency (USEPA) default specifications for propulsion engines, auxiliary engines, and boilers.

The CEDS database (Hoesly et al., 2018) provides historical emission estimates for anthropogenic aerosol and precursor compounds are key data needed for Earth system, climate, atmospheric chemistry, and transport models, as well as for economic and energy models. Historical emissions data are used both for general analysis and assessment and also for model validation through comparisons with observations. The CEDS database only provides data for vessels that are underway and so AIS data was used to estimate emissions from stationary vessels at the Port or vessels that were moored offshore.

Future shipping emissions for Scenario 3 were derived by estimating publicly available increases in production from facilities known to utilise shipping in the region and estimates projected by AMSA (2016). Emissions of SO_2 were predicted to decrease based on the implementation of the International Maritime Organisation (IMO) regulations for the reduction of sulphur in fuel for shipping.

5.4.4.2 Emission Estimates

Emissions have been calculated following the methodologies presented in the USEPA's recent draft port-related emissions guidance.[7] The in-use fuel sulphur content is a key distinction between the baseline and future year scenarios. The 2014 baseline scenario assumed a fuel sulphur content of 2.7% and the future year was modelled with a fuel sulphur content of 0.5% - consistent with International Maritime Organization regulations that went into effect on January 1, 2020. A summary of the total emissions from shipping in the study area for Scenario 2 and Scenario 3 is provided in Table 5-14.

Table 5-14 Emissions Estimates from Shipping in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	24,568	4,656	36,675	5,773
CO	1,912	350	2,854	434
Total VOCs	735	139	1,097	173
SOx	24,786	6,288	13,304	1,484
$PM_{2.5}$	3,185	769	2,842	446

5.4.4.3 Temporal and Spatial Allocation

Vessel at-berth and anchoring activity emissions are spatially allocated using the AIS records, which provide geospatial position on a high temporal resolution. The emissions are spatially intersected with both the 4-kilometer and 1-kilometer CAMx modelling grids and summed per grid cell. A depiction of the spatial allocation is shown in Figure 5-4. The emissions are tabulated for

[7] Draft Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emission Inventories, February 2020, U.S. Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YFY8.pdf

full calendar years and are temporally spaced evenly across the year, assuming operations occur 24 hours a day.

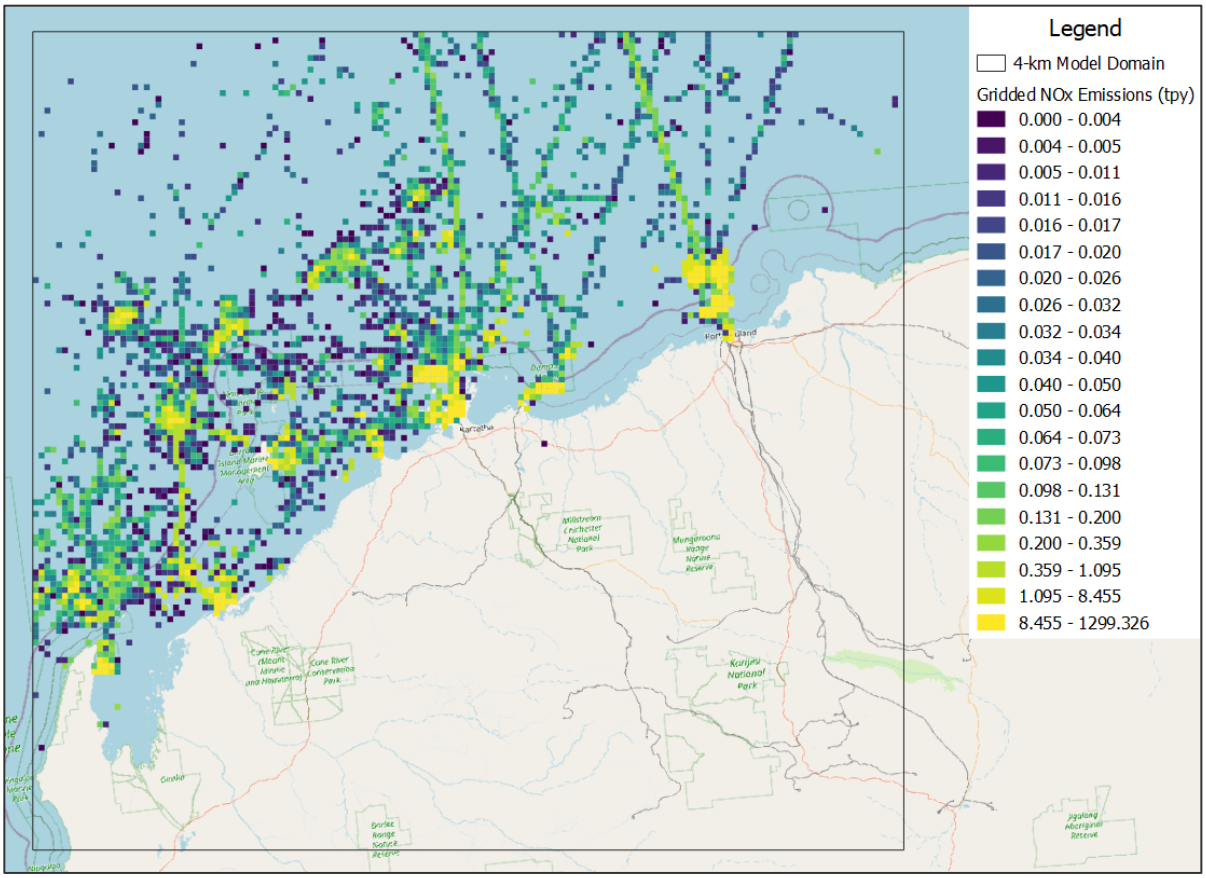


Figure 5-4: Example of the Spatial Allocation of Vessel At-Berth and Anchor Emissions

Whilst data from the AIS was available every 30 seconds, emissions information from CEDS is available on an annualised basis and so to ensure consistency, emissions derived from AIS data were annualised and once merged with emissions derived from CEDS data were assumed to be temporally spaced evenly across each hour of the year. Emissions from the datasets were spatially allocated to each grid cell across the modelling domain.

5.4.5 Recreational Boating

5.4.5.1 Data Collection and Information Sources

An estimate of average fuel consumption for recreational boats in the Pilbara region was derived from a domestic survey conducted in Port Hedland and Marble Bar as outlined in (SKM, 2003). The survey included questions on:

- Boat ownership;
- The type of engine (inboard or outboard, horsepower, 2 or 4 stroke or diesel);
- Boat use; and
- Amount of fuel used.

Table 5-15 presents the average annual fuel consumption per boat by engine type.

Table 5-15 Average Annual Fuel Consumption per Boat Engine Type

Engine/Fuel	Average Fuel Consumption (L/year)
Inboard	905
Outboard	294

Recreational boat registrations by postcode and size of boat for the Pilbara area was obtained from the Department of Transport.

5.4.5.2 Emission Estimation

Emissions for criteria pollutants and Total VOCs from recreational boating were estimated using the EET Manual for Aggregated Emissions from Commercial Ships/ Boats and Recreational Boats (Environment Australia, 1999k). An additional factor was introduced to account for non-local boats in accordance with work undertaken in the 1999/2000 Pilbara emissions inventory (SKM, 2003).

The scaling factors accounting for non-local usage for each of the ramps are outlined in Table 5-16.

Table 5-16 Scaling Factors for Non-Local Usage of Ramps

Boat Ramp	Percent Local (%)	Non Local Factor (Total/Local Boats)	Boat ramp usage as a percentage of all boat ramps (%)	Airshed
Cossack	96	1.04	1	Karratha
Dampier Public Ramp	98	1.02	18.2	Karratha
HHBSC	97.2	1.03	7.3	Karratha
Johns Creek	100	1	0.5	Karratha
Karratha Back Beach	99.4	1.01	12.9	Karratha
Point Samson	94.6	1.06	1.5	Karratha
Walcott	100	1	0.4	Karratha
Whitnell Bay	100	1	1.4	Karratha
Beadon Creek	100	1	0.6	Exmouth/Onslow
Coral Bay	17.9	5.6	19.4	Exmouth/Onslow
Bundegi	26.6	3.77	7.3	Exmouth/Onslow
Marina	53.3	1.88	3.8	Exmouth/Onslow
Tantabiddi	20.4	4.91	11.1	Exmouth/Onslow
Onslow	59.7	1.68	5.3	Exmouth/Onslow
Port Hedland Public Ramp	97.4	1.03	6.4	Port Hedland
Finucane Island	91.5	1.09	1.9	Port Hedland
Port Hedland Wharf Ramp	100	1	0.1	Port Hedland
Cape Keraudren	82.4	1.21	0.7	Port Hedland

This indicates a substantial variation across the study region, with usage from boat ramps from Exmouth being dominated by non-local boats, with much fewer non-local boats from Exmouth

north. An overall factor of 1.55 was used to multiply the study area fuel usage (or emissions). This assumption is valid if the fuel usage per trip (therefore boat size) is the same as for local and non-local boat trips.

Using the percentage boat distribution and average fuel consumption figures from the Port Hedland survey, the number of registered recreational boats in the study area, and the factor of non-local boats, total fuel consumption for recreational boats in the study area was derived.

The emission factors used to estimate annual emissions from recreational boating is summarised in Table 5-17.

Table 5-17 Recreational Boat Emissions Factors

Substance	Emission Factor (g/L)		
	Inboard Diesel	Inboard Petrol	Outboard Petrol
Carbon monoxide	17	149	400
NOx	41	15.7	0.79
Sulphur dioxide	2.1	0.304	0.304
TSP	3.5	0.195	0.195
VOCs	22	9.49	120

Notes:

No values available for outboard diesel engines in the NPI so emissions were assumed to be the same as the diesel inboard.

5.4.5.3 Temporal and Spatial Allocation

Boat ownership by household in 2014 varied markedly across the study region as presented in Table 5-18.

Table 5-18 Boat Ownership by Town

Town	Fuel Type	Motor Description	Number of Registrations
Dampier	**Diesel**	Inboard	11
		Outboard	4
	Petrol	Inboard	12
		Outboard	274
Karratha	**Diesel**	Inboard	18
		Outboard	14
	Petrol	Inboard	80
		Outboard	1,648
Marble Bar	**Petrol**	Outboard	4
Newman	**Diesel**	Inboard	3
	Petrol	Inboard	4
		Outboard	79
Nullagine	**Petrol**	Outboard	2
Onslow	**Diesel**	Outboard	2
	Petrol	Inboard	3
		Outboard	118
Pannawonica	**Diesel**	Outboard	1

Town	Fuel Type	Motor Description	Number of Registrations
	Petrol	Inboard	2
		Outboard	48
Paraburdoo	**Diesel**	Inboard	1
	Petrol	Inboard	2
		Outboard	45
Point Sampson Wickham	**Diesel**	Inboard	2
		Outboard	1
	Petrol	Inboard	11
		Outboard	303
Port Hedland	**Diesel**	Inboard	5
		Outboard	4
	Petrol	Inboard	41
		Outboard	911
Roebourne	**Petrol**	Outboard	20
Thevenard Island	**Petrol**	Outboard	1
Tom Price	**Diesel**	Outboard	1
	Petrol	Inboard	4
		Outboard	108
Total			**3,787**

Source: Department of Transport, 2020

To account for variations in usage, emissions from recreational boats were apportioned to an airshed in which they were most likely to operate.

Information from the Department of Fisheries (Ryan et. Al., 2017) indicates that recreational boating activity generally occurs between the hours of 4am and 8pm and can occur any day of the week. Emissions were adjusted to reflect this.

5.4.5.4 Emission Estimates

An estimate of emissions in 2014 and in 2030 from recreational boats are presented in Table 5-19. Emissions for Scenario 3 were scaled according to expected population growth in the Pilbara region as outlined in Section 5.5.1.

Table 5-19 Emissions Estimates from Recreational Boats in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	5.1	2.7	5.3	2.9
CO	540.9	283.6	563.2	295.3
Total VOCs	158.9	83.1	165.4	86.5
SOx	0.5	0.3	0.5	0.3
$PM_{2.5}$	0.4	0.2	0.4	0.2

5.5 Domestic and Commercial Sources

5.5.1 Population Estimates

A number of the emissions estimates for domestic and commercial sources were derived using population and household estimates within the study area. In order to determine the spatial distribution of populations within the study region, mesh blocks developed by the Australian Bureau of Statistics were utilised. They are intended to be the basic unit which comprise all other administrative boundaries that are defined by the Australian Bureau of Statistics. Most mesh blocks cover an area of around 30–60 dwellings, which is proposed as the smallest size data can be gathered so that people would not be able to be identified. In this study, population and household census data associated with mesh blocks from 2016 and 2011 were interpolated to estimate population distribution for 2014.

In 2019 The Department of Planning, Lands and Heritage released estimates of population growth for local government areas in Western Australia (The Department of Planning, 2019). Based on Band C estimates of population growth from 2016 to 2031 in the Pilbara, population estimates are expected to grow by approximately 4% over this period. This growth has been applied to future estimates of emissions for Scenario 3 (2030) where emissions have been estimated based on population. Figure 5-5 presents population density in 2014 across the study area.

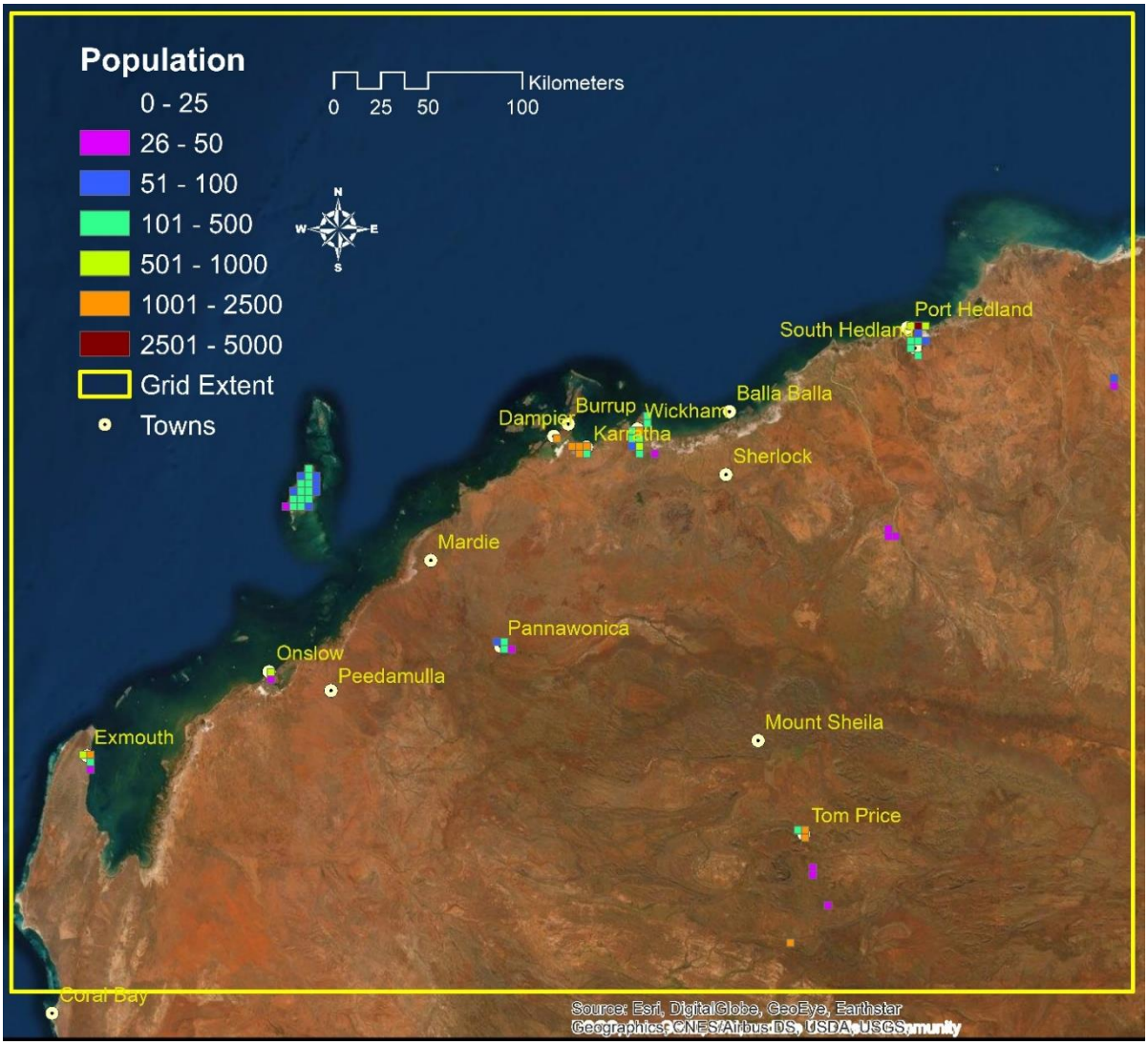


Figure 5-5: Population Density in the Study Area

5.5.2 Domestic/Commercial Solvent and Aerosol Use

This category refers to products containing solvents that are used in a wide variety of domestic and commercial applications including:

- Personal care products;
- Household cleaning products;
- Motor vehicle aftermarket products;
- Adhesive and sealant products;
- Pesticide and herbicide products;
- Coatings and related products; and
- Miscellaneous products.

Volatile organic compounds (VOCs) are emitted from these products during use. The recommended techniques for estimating emissions from domestic and commercial solvent and aerosol use rely on per capita usage for the various products.

5.5.2.1 Emission Estimation

Total VOCs emissions were calculated using the technique described in the EET Manual for Aggregated Emissions from Domestic/Commercial Solvent and Aerosol Use (Environment Australia, 1999b). Total emissions from domestic/commercial solvent and aerosol use are presented in Table 5-20.

Table 5-20 Emissions Estimates from Domestic/Commercial Solvent and Aerosol use in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
Total VOCs	291.4	110.2	303.4	114.7

5.5.2.2 Temporal and Spatial Allocation

Information on temporal spacing of emissions from domestic and commercial solvents was not obtained and so emissions were assumed to occur equally across the year. Emissions from domestic/commercial solvent and aerosol use were spatially allocated proportionally to the population distribution for each domain.

5.5.3 Cutback Bitumen

Bituminous materials used in road construction and maintenance emit volatile organic compounds (VOCs). Cutback bitumen primer and primer binder are commonly used in spray sealing operations. The bitumen is 'cut back' by blending with solvents (the 'cutter') to enable the bitumen to be used for spray sealing. Cutback bitumen is the major source of VOCs resulting from the evaporation of the cutter oil used to reduce the viscosity of the bitumen. The largest source of emissions is from the road surface. Methods of road surfacing and associated VOC emissions can vary significantly between regions due primarily to variations in temperature.

5.5.3.1 Data Collection and Information Sources

An attempt to obtain approximate usage of bitumen, cutter oil (kerosene) and flux oil (diesel) for 2014 was made by contacting contracting companies responsible for the maintenance of the roads in the region. Data was not provided by any of the contractors for the region and so emissions estimates for 2014 were derived from total cutting oil usage as outlined in (SKM, 2003) and then scaled based on the ratio between estimated VKT from (SKM, 2003) and 2014 as outlined in Section 5.4.1.

5.5.3.2 Emission Estimation

Total VOC emissions from cutback bitumen were estimated using prescribed methods outlined in the EET Manual for Aggregated Emissions from Cutback Bitumen (Environment Australia, 1999a). The total estimated volume of cutter oil used in the Pilbara in Scenarios 1, 2 and 3 is summarised in Table 5-21.

Table 5-21 Estimated Cutter Oil Consumption in Study Region

Activity	Cutter Oil Consumption (L/yr)	
	2014	2030
Resealing	26,442	28,420
Construction	88,140	94,734

Material safety data sheets (MSDSs) for cutter oil indicate a specific gravity of between 0.808 and 0.825. Default properties of fraction evaporated (65%) and density (0.813) were used.

Total VOCs emissions from cutback bitumen was calculated using:

$$E_{voc} = T_c\ (d_c * 10^{-2})\ \rho_c$$

Where:

E_{voc} = Total VOCs emissions from use of cutter oils (kg/yr)
T_c = Total cutter oil consumption in the study area (L/yr)
d_c = Fraction of cutter oil evaporated = 65%
ρ_c = Density of cutter oil = 0.813 kg/L

Table 5-22 summarises Total VOCs emissions.

Table 5-22 Total Emissions from Cutback Bitumen Operations in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
Total VOCs	111.0	26.1	119.3	28.1

5.5.3.3 Temporal and Spatial Allocation

There would be some variation in emissions both temporally and spatially with higher emissions expected upon application and decreasing with time as well as the amount of cutback bitumen required varying depending on the size and usage on each road. Data was unable to be obtained on the timing and locations of the application of cutback bitumen and so emissions were assumed to occur equally across the year. Gridded VKT data for paved roads was used for the spatial allocation of emissions within the study region. This assumes that roads with more traffic require proportionally more maintenance.

5.5.4 Service Stations

Evaporative fuel losses from service stations and fuel distribution activities are associated with the following:

- Transfer of fuel from delivery tankers to underground storage tanks at service stations;
- Refuelling of motor vehicles; and
- Breathing of the underground fuel storage tanks with changes in temperature and pressure.

5.5.4.1 Data Collection and Information Sources

As outlined in Section 5.4.1, requests for information on fuel consumption in the Pilbara region in 2014 were made to major fuel distributors operating in the region. Data on fuel consumption was not provided and so a surrogate method to estimate fuel throughput at service stations was utilised. All known service stations in the study were identified as shown in Figure 5-6.

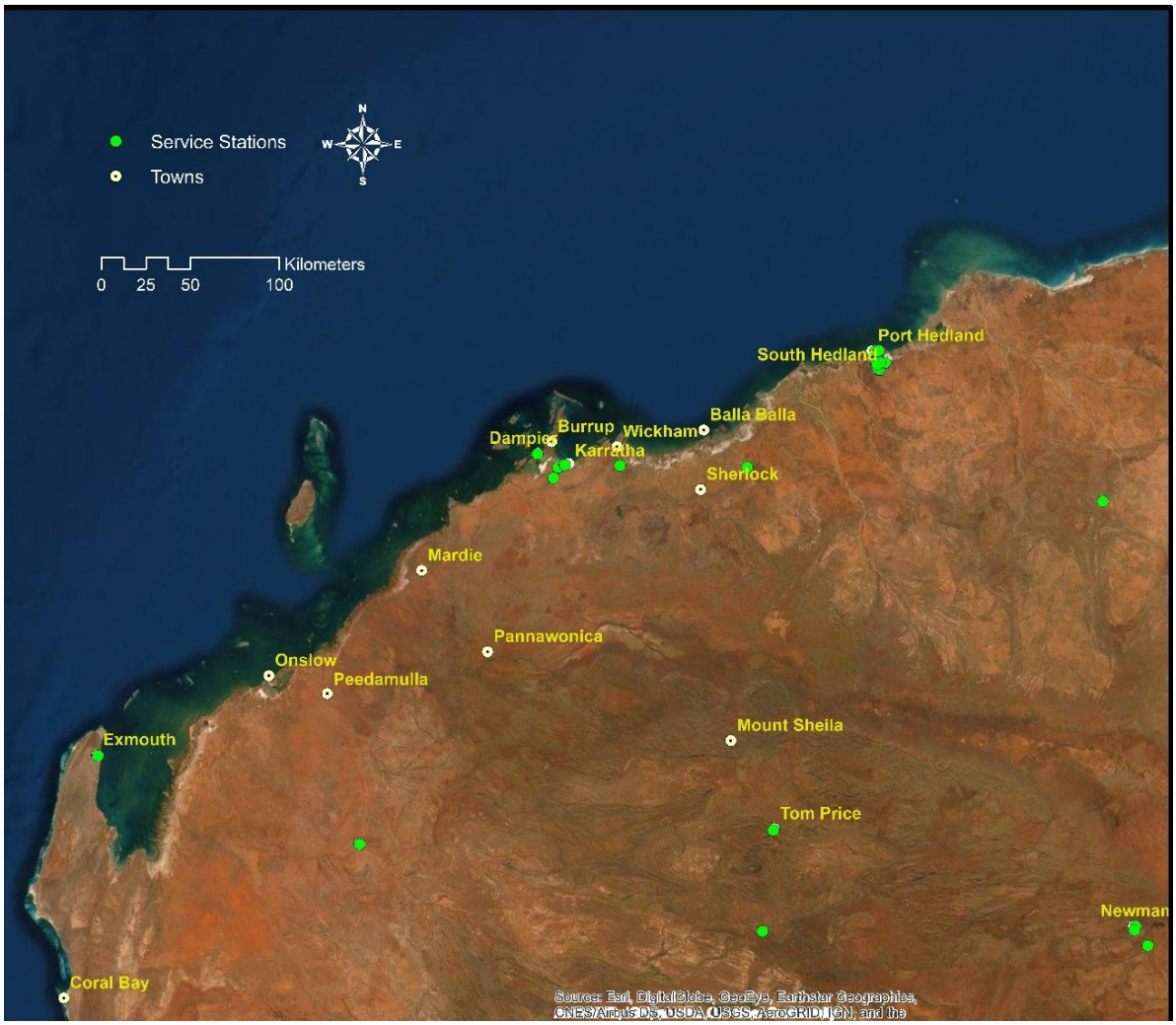


Figure 5-6: Service Stations in the Study Area

5.5.4.2 Emission Estimation

A Total VOCs emissions per capita value from service stations in the Pilbara region was calculated in SKM (2002). Estimated population data for 2014 and 2030 was used in accordance with this per capita value to estimate emissions of total VOCs in the study region.

5.5.4.3 Temporal and Spatial Allocation

Emissions from service stations were spatially allocated on a per capita basis according to the number and location of service stations in each grid cell. It was assumed that the general population would utilise the service station closest to their home location. Emissions were assumed to occur equally across the year.

5.5.5 Architectural Surface Coatings

Architectural surface coatings are applied to surfaces to enhance the aesthetic value of structures and to protect surfaces from corrosion, decay, water damage, abrasion and ultra-violet light damage. The three main components of surface coatings are resins, pigments and solvents. The predominant emissions come from VOCs contained in the coatings, and in the solvents used for cleaning up and thinning. Architectural surface coatings are generally classified as solvent-based or water-based.

5.5.5.1 Data Collection and Information Sources

Accurate sales and distribution data of architectural surface coatings are not available for the Pilbara region such that the best practice EET Manual could not be used. As such, the default method based on factors for household usage multiplied by the number of households was used.

5.5.5.2 Emission Estimation

Architectural surface coating Total VOCs emissions were calculated using the default method outlined in the EET Manual for Aggregated Emissions from Architectural Surface Coatings (Environment Australia, 2003). The total estimated emissions from architectural surface coatings in the Pilbara for all scenarios are summarised in Table 5-23.

Table 5-23 Total Emissions from Architectural Surface Coatings Operations in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
Total VOCs	237.3	95.0	247.1	98.1

5.5.5.3 Temporal and Spatial Allocation

Emissions from architectural surface coatings were spatially allocated according to the distribution of dwellings in the study area. In lieu of more detailed information outlining where and when surface coatings were applied, emissions were assumed to occur continuously across the year.

5.5.6 Domestic Fuel Burning

Domestic gaseous fuel burning (LPG) is undertaken for cooking, heating and hot water heating. Emissions are dependent on the amount and type of fuel burnt. Wood is the main solid fuel in use in the region. Coal and briquettes are also used in smaller amounts. Emissions from solid fuel burning are dependent on the type of wood burnt, the type of heater used and operating practices.

5.5.6.1 Data Collection and Information Sources

Emissions of criteria pollutants and total VOCs from domestic fuel burning were calculated using the prescribed methods in the EET Manual for Aggregated Emissions from Domestic Gaseous Fuel Burning (Environment Australia, 1999c) and the EET Manual for Aggregated Emissions from Domestic Solid Fuel Burning (Environment Australia, 1999e). Total domestic fuel burning estimates were derived from surveys undertaken as part of (SKM, 2003). The surveys differentiated between townships in the region and Aboriginal communities where typical LPG and Coal usage was lower but wood burning was higher as shown in Table 5-24.

Table 5-24 Per Capita Fuel Usage

Fuel Type	Units	Other Settlements	Aboriginal Community
LPG	L/person/year	58.2	31.2
Wood	kg/person/year	8.4	1,480
Coal	kg/person/year	1.7	0

5.5.6.2 Emission Estimation

The total estimated emissions from domestic fuel burning in the Pilbara in for all scenarios are summarised in Table 5-25.

Table 5-25 Total Emissions from Domestic Fuel Burning in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	7.4	2.3	7.7	2.3
CO	215.9	26.5	224.8	27.6
Total VOCs	200.0	21.4	208.2	22.3
SOx	0.7	0.2	0.7	0.2
PMcoarse	28.0	3.0	29.2	3.2

5.5.6.3 Temporal and Spatial Allocation

Emissions were spatially allocated in the study region according to population and settlement type. Emissions were assumed to occur continuously across the year.

5.5.7 Lawn Mowing

Atmospheric emissions from residential lawn mowing activities are generated from the use of 2-stroke and 4-stroke engine mowers. Generally, 4-stroke mowers have lower emissions of VOCs, CO and PM_{10} but higher NOx emissions. Public open space lawn mowing includes mowing activities carried out by local councils, schools and golf courses.

5.5.7.1 Data Collection and Information Sources

Emissions estimates were derived from using a per household estimate as outlined in (SKM, 2003) and estimates of households in the region. Emission factors for domestic lawnmowing were calculated using the prescribed method in the EET Manual for Aggregated Emissions from Domestic Lawn Mowing (Environment Australia, 1999d). Emissions factors from commercial lawn mowing were derived from surveys of local councils, schools and golf courses. Emission factors utilised in deriving emissions estimates are outlined in Table 5-26. Emissions estimates are outlined in Table 5-27.

Table 5-26 Emissions Factors from Lawn Mowing

Compound	Emissions Commercial Lawn Mowing (kg/Person/yr)	Emissions Household Lawn Mowing(kg/person/yr)
CO	0.66	0.00329
NOx	0.0916	0.0000172
PM_{10}	0.01234	0.0000221
SO_2	0.0057	0.00000234
Total VOCs	0.0542	0.000921

Table 5-27 Total Emissions from Lawn Mowing in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	4.9	1.9	5.1	1.9
CO	35.6	13.5	37.0	14.0
Total VOCs	3.5	1.3	3.7	1.4
SOx	0.3	0.1	0.3	0.1
PMcoarse	0.7	0.3	0.7	0.3

5.5.7.2 Temporal and Spatial Allocation

Emissions were spatially allocated in the airshed in proportion to the distribution of households. The City of Karratha indicated that public lawn mowing occurred during the hours of 7am and 4pm during weekdays. Domestic lawn mowing was assumed to occur on all days.

5.5.8 Motor Vehicle Refinishing

Emissions from motor vehicle refinishing includes emissions from spray painters, smash repairers and panel beaters. Motor vehicle refinishing consists of applying primer, a topcoat and hardener to motor vehicle surfaces to protect the surface from corrosion, abrasion, decay and damage from sunlight and water. VOCs are emitted during the application of coatings, the drying phase and from cleaning equipment such as spray guns.

5.5.8.1 Data Collection and Information Sources

Emissions were calculated using three techniques outlined in the EET Manual for Aggregated Emissions from Motor Vehicle Refinishing (Environment Australia, 1999g). Emission estimates utilised in this study are outlined in Table 5-28.

5.5.8.2 Emission Estimation

Emissions estimates were derived from using a per capita estimate as outlined in (SKM, 2003) and estimates of population in the region.

Table 5-28 Total Emissions from Motor Vehicle Refinishing in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
Total VOCs	<0.1	<0.1	<0.1	<0.1

5.5.8.3 Temporal and Spatial Allocation

Emissions from motor vehicle refinishing were spatially allocated in proportion to the number of premises in each grid cell. Emissions were assumed to occur between 7am and 5pm on weekdays.

5.5.9 Fuel Combustion (Sub Threshold)

Emissions from sub threshold facilities can be significant, particularly if the number of these facilities is a significant fraction of the total number of facilities to report. Sub threshold facilities are defined in the EET Manual for Aggregated Emissions from Fuel Combustion (Sub-Threshold) (Environment Australia, 1999h) as "industrial and commercial sites that do not burn 400 or more tonnes of fuel or waste oil in a year". This also includes facilities that do trigger the threshold but

fail to submit their reports. For the Pilbara, this definition therefore does not include the many generators used at homesteads and Aboriginal communities that are not on the interconnected grid as they are not industrial or commercial facilities.

5.5.9.1 Data Collection and Information Sources

Data required for the estimation of emissions in the EET Manual for Aggregated Emissions from Fuel Combustion (Sub-Threshold) (Environment Australia, 1999f) are fuel consumption by fuel type and by commercial/industrial facilities. The preferred source of data for fuel usage is from fuel suppliers. For this study the suppliers were contacted but none were willing to provide data in the categories that could be of assistance. The alternative to this suggested in the EET Manual is to calculate fuel consumption based on population. Fuel consumption figures for the Pilbara region were utilised from (SKM, 2003) and then scaled according to population estimates in 2014 and 2030.

5.5.9.2 Emission Estimation

The estimated emissions from sub threshold fuel combustion are presented in Table 5-29.

Table 5-29 Total Emissions from Sub-Threshold Combustion in the Study Area

Pollutant	Emissions Estimates (Tonnes/Year)			
	Scenarios 1 and 2 (2014)		Scenario 3 (2030)	
	CAMx-4 km Grid	CAMx-1.33 km Grid	CAMx-4 km Grid	CAMx-1.33 km Grid
NOx	446.2	168.8	464.6	175.7
CO	135.1	51.1	140.7	53.2
Total VOCs	44.3	16.8	46.2	17.5
SOx	53.8	20.4	56.1	21.2
PMcoarse	44.3	16.8	46.1	17.4

5.5.9.3 Temporal and Spatial Allocation

Emissions from sub threshold combustion were allocated by population across the study region. This is not strictly valid as sub-threshold facilities could be argued to be primarily concentrated in light industrial parks such as the Karratha light industrial park, and at the facilities that are likely not to report. However, given that the estimate includes emissions from power generation, as a first estimate the emissions have been allocated by population. Emissions were assumed to occur continuously across the year.

5.6 Natural Sources

In this section, information about the following natural emissions sources are presented:

1. Biogenic VOC (BVOC) emissions
2. Windblown dust
3. Bush Fires
4. Lightning NOx
5. Sea Salt

The emissions from these natural sources are summarised in Table 5-30 and Table 5-31. Natural emissions of mercury (Hg) are not included.

Table 5-30 Total emissions from natural sources in the 4 km domain.

Sectors	Total annual emissions (Tonnes/Year) in the 4 km Domain						
	CO	NO_X	PM_{10}	$PM_{2.5}$	VOCs	NH_3	SO_2
Fire	21,303	1,168	3,558	2,900	1,186	411	212
Lightning		376					
Biogenic	13,368	33,211			548,090		
Sea Salt			41,996	41,996			
Windblown dust			**26,127**	**5,402**			

Table 5-31 Total emissions from natural sources in the 1.33 km domain.

Sectors	Total annual emissions (Tonnes/Year) in the 1.33 km Domain					
	CO	NO_X	PM_{10}	$PM_{2.5}$	VOCs	SO_2
Biogenic	113	144			4,452	
Sea Salt				1,115		
Windblown dust			855	161		

5.6.1 Biogenic

Biogenic VOC (BVOC) emissions were developed using the latest version (3.1) of Model of Emissions of Gases and Aerosols from Nature (MEGAN)[8] with the following updates specific to Western Australia:

1. Incorporated published BVOC emission factors for Australian vegetation;
2. Incorporated recently developed Australian plant species composition data from the National Tree Inventory;
3. Incorporated recently developed Australian vegetation growth form from the Australian National Dynamic Land Cover Dataset, and;
4. Incorporated recently developed Australian vegetation ecotypes from the Interim Biogeographic Regionalisation for Australia and the National Vegetation Information System.

The updates have been further documented in Appendix 1.

5.6.2 Windblown Dust

Windblown dust emissions were developed using the "WBDUST" emission model, which is an adaptation of the dust scheme and global soil properties compiled by Klingmueller et al. (2017). In the WBDUST model, erodible lands can be prescribed from one of two sources:

1. A global barren land mask (resolution 0.05 or ~5 km, annual 2001-2012) from the European Centre Hamburg Model/ Modular Earth Submodel System (ECHAM/MESSy) Atmospheric Chemistry (EMAC) group
2. WRF/CAMx landuse file that classifies shrubs/crops/desert landuse to erodible lands

[8] https://www2.acom.ucar.edu/modeling/model-emissions-gases-and-aerosols-nature-megan

Figure 5-7 shows the barren land cover from the global land mask (option 1 above) as red grid cells on the CAMx 4 km domain map. There are only 3 grid cells in the entire 4 km domain classified as barren (potential dust emissive areas) and they all lie outside of the CAMx 1.33 km domain (not shown). Using the global barren land mask would result in unrealistically low dust emissions.

Figure 5-8 shows maps of the dominant landuse types in the WRF/CAMx landuse file (option 2 above) for the 1 km (left) and 4 km domains. These landuse types are mapped from the MODIS 20-class datasets provided with the standard WRF distribution described in Section 3.5. Because the WBDUST model classifies shrubs and desert landuse types as erodible areas, nearly all grid cells over land would be prescribed as dust emissions sources. This would lead to unrealistically high dust emissions.

Unsealed roads are a dust source due to vehicular traffic and wind (windblown dust). Unsealed roads are present throughout both CAMx model domains and their locations were used to develop an alternate estimate of erodible area. Using unsealed road location and assuming a road width of 8 metres, the area fraction of unsealed roads in each model grid cell was calculated and this fraction was assigned to the desert (barren) landuse category for input to the WBDUST model. Figure 5-9 shows grid cells with non-zero unsealed road area fraction for the 1 km (left) and 4 km (right) CAMx domains. The updated landuse file was then used to provide erodible area input to the WBDUST emissions model.

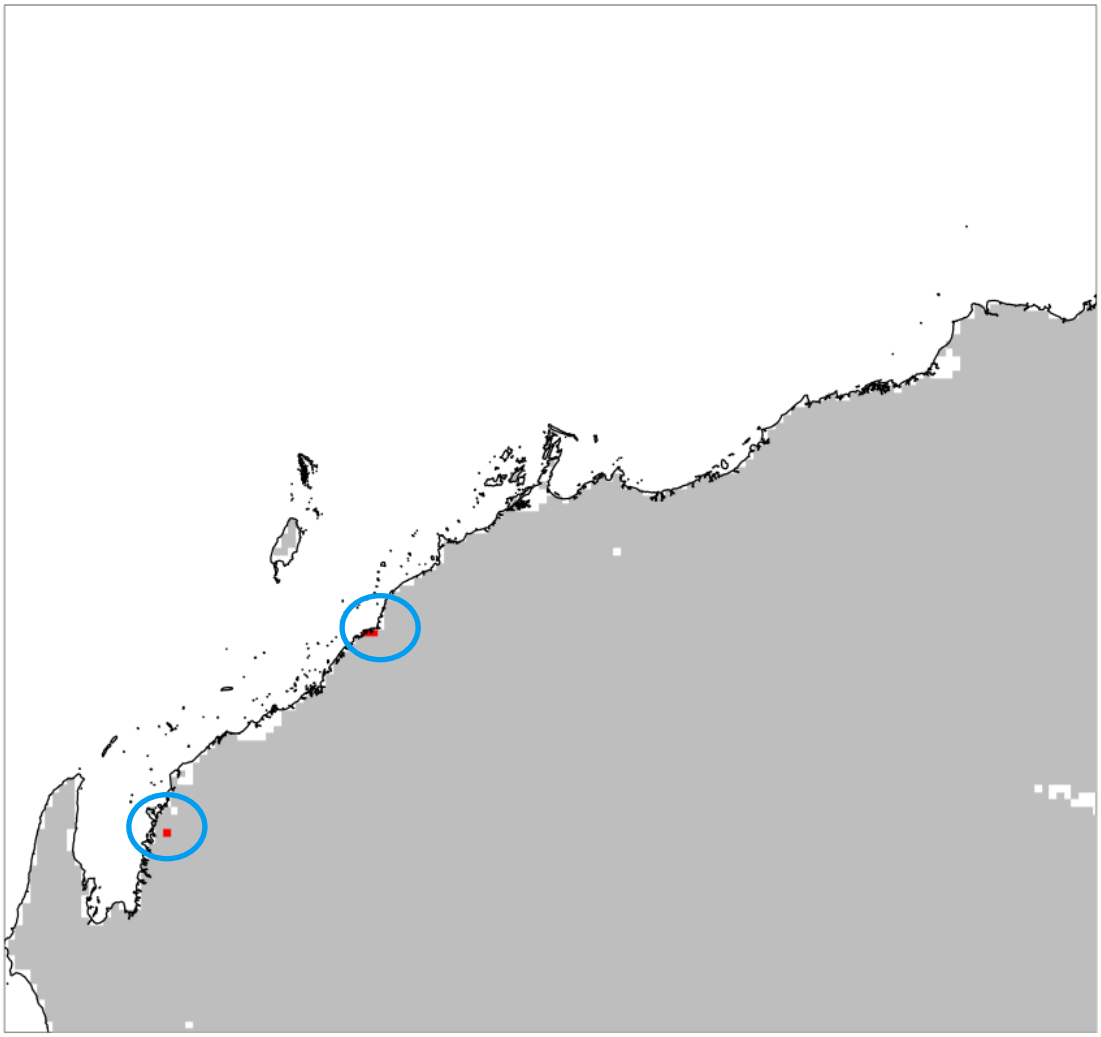


Figure 5-7: Emissive areas for windblown dust (red grid cells circled in blue) on the 4 km CAMx domain from the EMAC global barren land cover database.

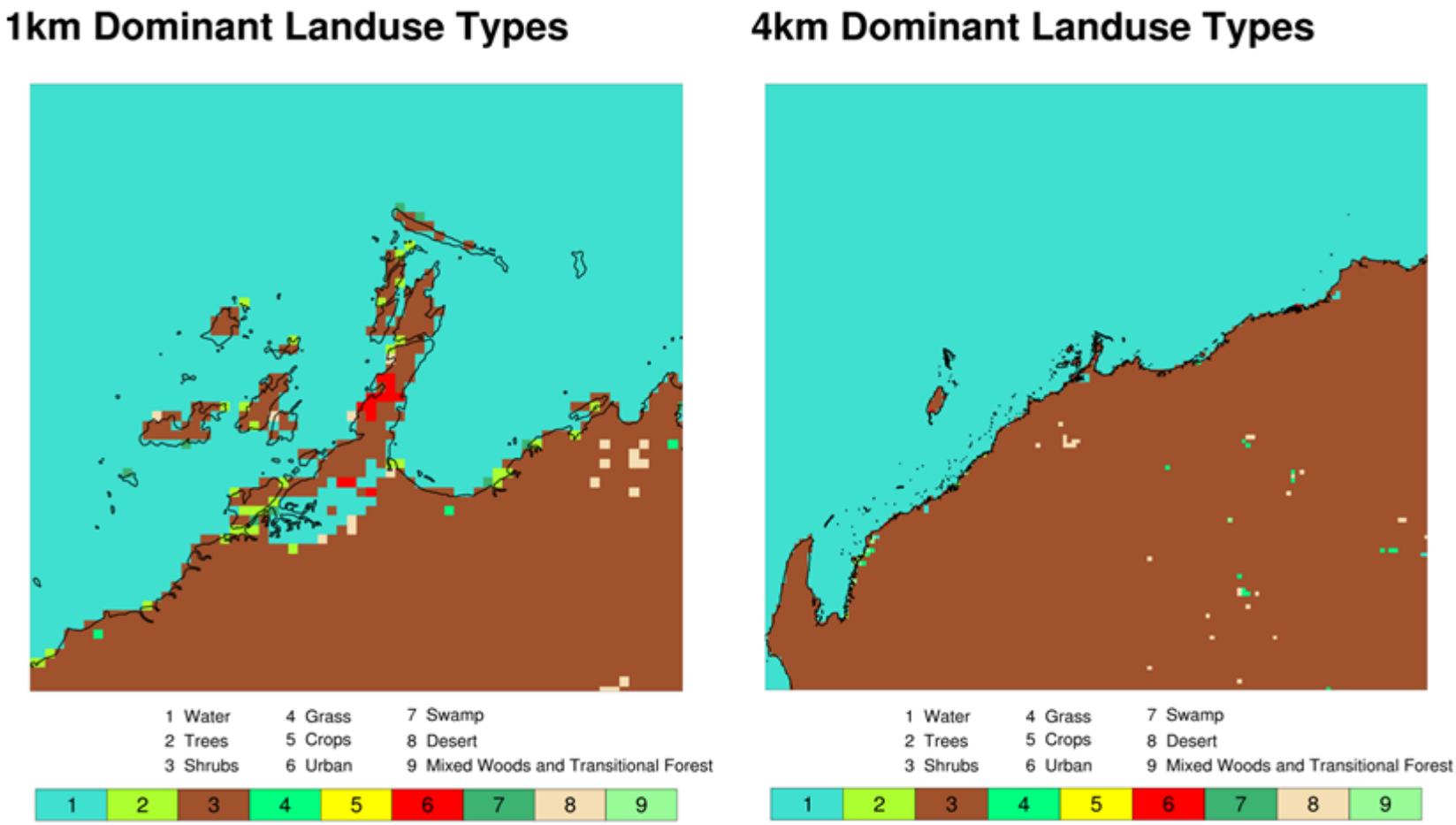


Figure 5-8: Dominant Landuse types for the CAMx 1 km (left) and 4 km (right) domains.

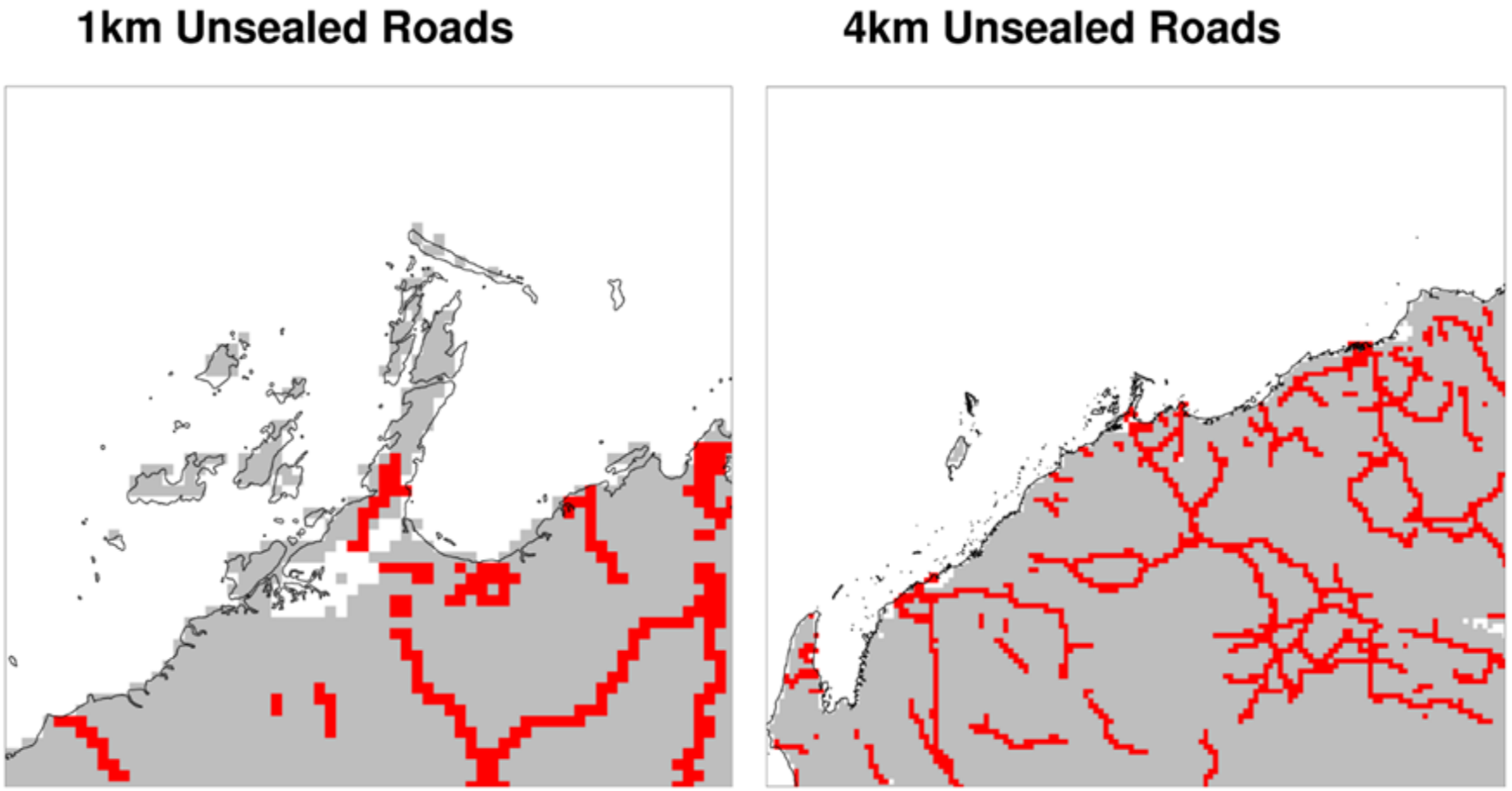


Figure 5-9: Grid cells with non-zero emissive area for windblown dust estimation (red grid cells) in the CAMx 1 km (left) and 4 km (right) domains based on unsealed road locations.

5.6.3 Bush Fires

The Fire Inventory from NCAR (FINN version 1.5) (McDonald-Buller et al., 2015; Wiedinmyer et al., 2011) was used, following a screening out of locations with flares that can produce false detections of bush fires. FINN relies on MODIS and VIIRS satellite data, which combine for several overpasses over a given location each day. Ramboll utilises the Western Regional Air Partnership (WRAP) methodology to temporally allocate the FINN fire emissions.[9] Fire emissions are allocated across several vertical layers (including the surface layer) depending upon fire size and hour of day. The virtual area[10] is used to classify each fire into one of five fire size bins, which determines the values used to calculate the fraction of emissions allocated to the first vertical layer in CAMx and the heights of the plume bottom and top for each hour of the day. Since the FINN fire inventories consist of fires that are always less than or equal to 1 km^2 in size because of the pixel size of the MODIS instrument, fire points that are within 5 km of one another are assumed to be part of the same fire; the virtual areas of each of these points are added together so they have characteristics of a larger fire.

5.6.4 Other Natural Sources

Two CAMx natural emissions processors were run using the 2014 WRF meteorological data to generate CAMx-ready emissions as follows:

- Lightning NOx (LNOx) emissions processor; and
- OCEANIC emissions processor was used to generate sea salt and dimethyl sulphide (DMS) emissions.

The LNOx processor uses Convective Available Potential Energy (CAPE) and cloud top heights diagnosed by the WRFCAMx pre-processor. CAMx v7.00 includes explicit DMS chemistry that accounts for oxidation of DMS to form SO_2 and sulphate.

5.7 Formatting Emissions for CAMx

Preparing emission inventory data for input to CAMx requires three main steps:

- Gridding emissions to the CAMx modelling grid which are in a Lambert Conformal projection to match WRF. Point source emissions are emitted at their geo-location. Some aggregated sources, e.g., shipping, aircraft and bush fire emissions, are received spatially allocated using a lat-lon grid and must be re-gridded to the CAMx grid. Other aggregated sources, e.g., road transport or residential sources, will be allocated to CAMx grid cells using a spatial surrogate, e.g., road network or population density.
- Temporally allocating emissions to each hour of the modelling year. Many anthropogenic emission estimates are annual totals which are converted to hourly emissions using representative temporal profiles (month of year, day of week, hour of day). Biogenic and bush fire emissions were created by models that have fine time resolution (hourly).
- Chemically speciating inventory pollutants to CAMx model compounds, namely:
  - NO_x to NO and NO_2;
  - VOCs to the compounds of the Carbon Bond 6 (CB6) mechanism including benzene, toluenes, xylenes and many other organics;
  - SO_x to SO_2 and condensable primary sulphate;

[9] http://www.wrapair.org/forums/fejf/documents/WRAP_2002_PhII_EI_Report_20050722.pdf

[10] Virtual area is a measure of fire size, fire type (prescribed burn or wildfire) and fuel loading

- $PM_{2.5}$ to fine nitrate, sulphate, ammonium, black carbon, organic carbon, sea salt, crustal and other;
- Coarse PM (i.e., PM_{10} - $PM_{2.5}$) to crustal and other; and
- Mercury to the elemental, oxidised and particulate forms of mercury modelled in CAMx.

CAMx can calculate plume rise for point sources if detailed stack parameters (height, diameter, temperature, flow rate) are provided. For point sources without detailed stack parameters emissions were assumed to be released in a height range that was representative for the source type, in accordance with the methodology outlined in the EMEP/CORINAIR Atmospheric Emission Inventory Guidebook for almost all point sources. Stack parameters from industrial sources for the inner grid were obtained where available. For shipping emissions, a height profile as defined in Table 5-32 was used, which reflects our analysis of aerial imagery showing anchored vessels to be of Panamax class with an air draft of 58 m[11].

Table 5-32: Vertical allocation of marine shipping emissions to CAMx model layers.

CAMx Layer	Top (m)	Thickness (m)	Allocation (%)
1	20	20	10
2	40	20	20
3	65	24	40
4	88	23	30

[11] https://www.thoughtco.com/cargo-vessel-size-classifications-2293289

6. MODELLING OF AIR EMISSIONS FROM EXISTING AND FUTURE INDUSTRY

This section includes information on the CAM_X air quality and deposition modelling that was undertaken, including model configuration, input data preparation, and the model results obtained for each scenario.

6.1 CAMx Air Quality Modelling Description

This section describes the horizontal modelling domains, vertical layer structure, model inputs and configuration applied for all CAMx model simulation conducted for this study.

6.1.1 Horizontal Modelling Domains

The CAMx 4 km and 1.33 km resolution modelling domains are shown in Figure 6-1. The 4 km domain is centred over the Burrup Peninsula and includes Barrow Island and Port Hedland. The 1.33 km domain also is centred over the Burrup Peninsula. These domains are defined on a LCC projection centred at 25°S, 130°E with true latitudes at 18°S and 36°S assuming a spherical earth model with a radius of 6370 km to be consistent with WRF. Figure 6-2 shows the CAMx 1.33 km domain in greater detail. Table 6-1 defines the CAMx grid for both domains.

Table 6-1: Domain grid definitions for the CAMx 4 km and 1.33 km domains

	Origin[1] coordinates (x, y) (km)	**Grid dimension (column x row)**
4 km grid	(-1660, 110)	(149 x 140)
1.33 km grid[2]	(-1413.333, 372.667)	(68 x 65)

[1]Southwest corner of the domain grids

[2]Definition includes outer row/column of buffer cells required by CAMx for nested domain

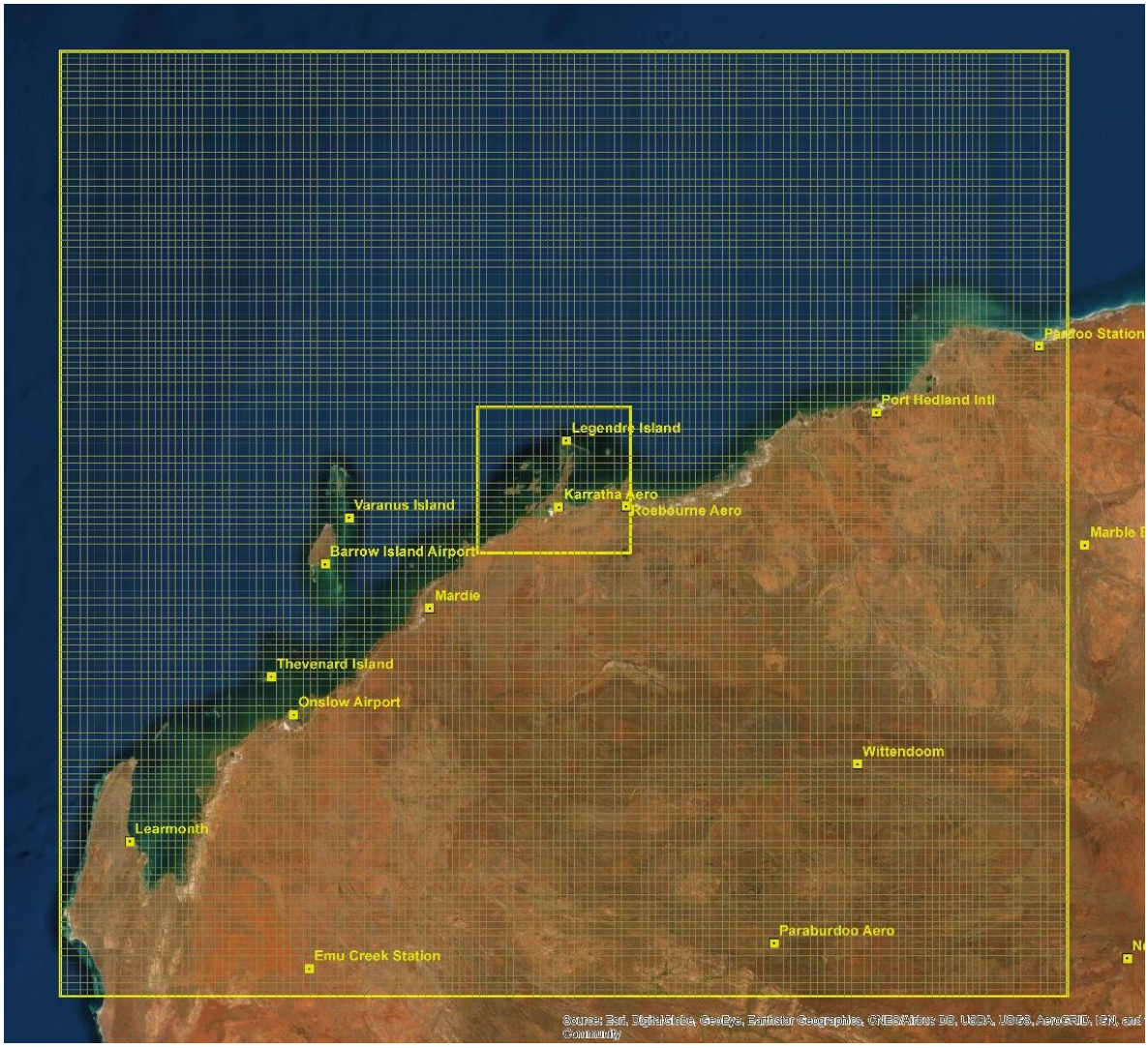


Figure 6-1: Horizontal extents of the CAMx 4 km and 1.33 km domains

6.1.2 Vertical Layer Structure

CAMx can have fewer vertical layers than WRF and successfully meet the project objectives of simulating air pollution at ground level, e.g., CAMx can omit the stratosphere and have thicker layers than WRF through most of the troposphere. The vertical layer structure for WRF and mapping to CAMx layers is presented in Table 6-2. The CAMx layers up to 90 m above ground level are identical to WRF, including a 20 m surface layer.

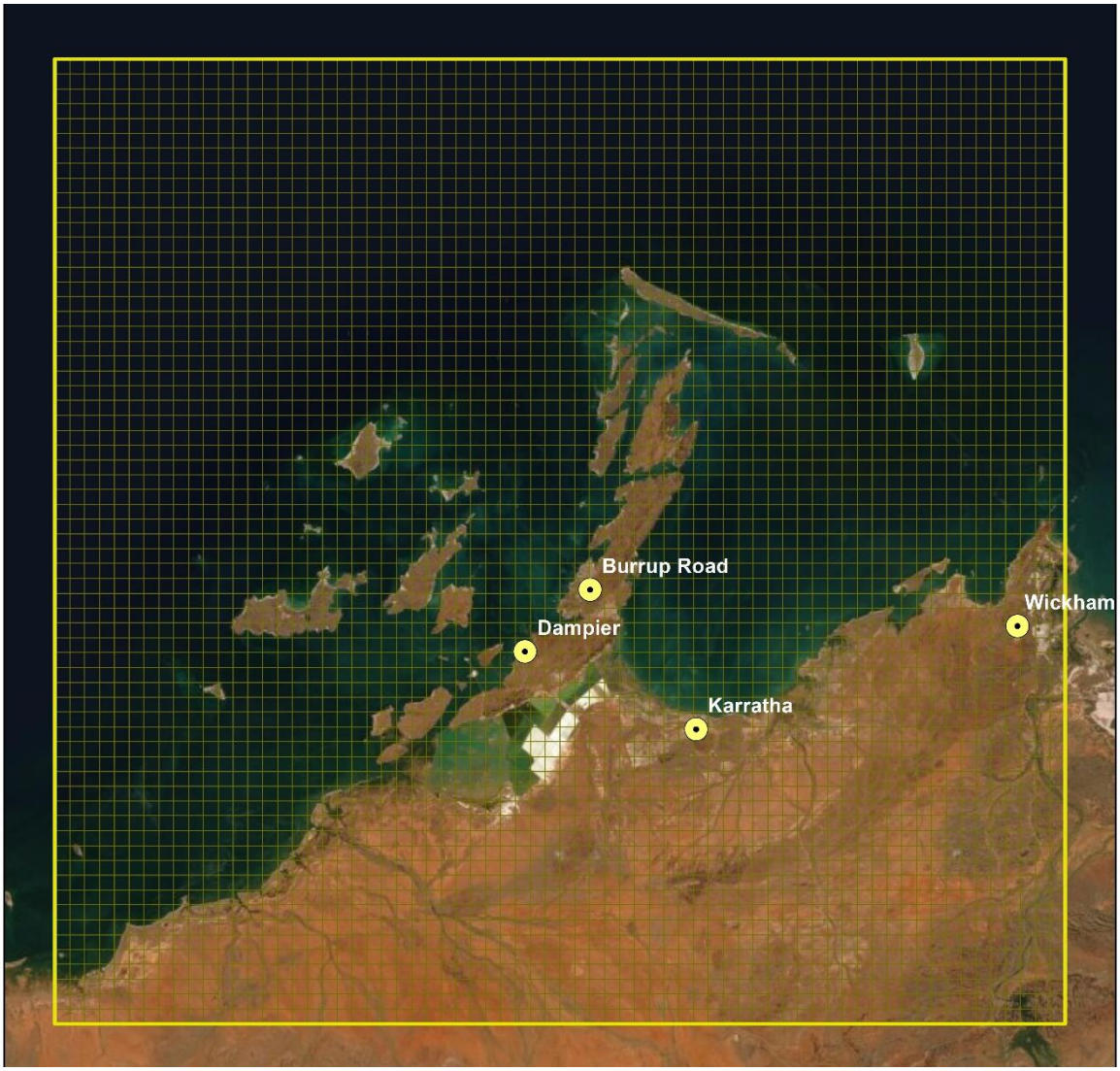


Figure 6-2: Horizontal extent of the CAMx 1.33 km domain (map from Google Earth)

Table 6-2: Mapping of WRF layers to CAMx layers

WRF			CAMx		
Layer	Pressure (mb)	Height (m)	Layer	Height (m)	Thickness (m)
38	50.00	20576			
37	76.01	17920			
36	107.80	15703			
35	146.33	13767			
34	194.49	11961			
33	242.65	10554			
32	290.81	9372			
31	338.98	8337			
30	387.14	7416			
29	435.30	6583	18	6583	1463
28	483.46	5821			
27	531.63	5120	17	5120	1024
26	570.16	4593			
25	608.69	4096	16	4096	922
24	647.22	3624			
23	685.75	3174	15	3174	843
22	724.28	2743			
21	762.81	2331	14	2331	395
20	801.34	1936	13	1936	381
19	839.87	1555	12	1555	276
18	868.76	1278	11	1278	348
17	892.84	1055			
16	906.33	931	10	931	234
15	919.81	809			
14	932.34	697	9	697	205
13	943.90	594			
12	955.46	492	8	492	175
11	966.05	400			
10	975.68	317	7	317	123
9	984.35	243			
8	990.13	195	6	195	58
7	993.99	161			
6	996.87	137	5	137	49
5	999.76	113			
4	1002.65	88	4	88	23
3	1005.54	65	3	65	24
2	1008.43	40	2	40	20
1	1010.84	20	1	20	20
surface	1013.25	0	0	0	

6.1.3 CAMx Model Options

The CAMx model options used in this project are presented in Table 6-3. The WRFCAMx pre-processor was used to convert raw WRF output files into model-ready input files formatted for CAMx. WRFCAMx is used to calculate vertical turbulent exchange coefficients (Kv) which are derived from meteorological data supplied by the WRF meteorological model. The CAMx pre-processor KvPATCH is then used to adjust Kv to improve turbulent coupling between the surface and lower boundary layer and ensure vertical mixing is present below convective clouds by raising the PBL depth through capping cloud tops.

Table 6-3: CAMx v7.00 input data and options

Input Data/Option	Data Source/Model Option	Comment
Version	CAMx Version 7.00	Released June 2020
Meteorology and Land Cover	WRF	Via WRFCAMx with KvPATCH
Dry Deposition	Zhang deposition scheme	Linked to land cover input data
Wet deposition	CAMx scheme	Linked to WRF clouds and rain
Emissions	Described in Section 3	
Boundary Concentration	The Community Atmosphere Model with Chemistry (CAM-chem)	Community Earth System Model (CESM)2.1/CAM-chem (Bucjholz et al., 2019 and Emmons et al., 2020)
Chemistry	CB6r4 gas-phase and CF aerosol scheme Including the following species: • SO_x, NO_x, NH_3, CO • VOCs including BTEX and other anthropogenic and biogenic VOCs • Primary and secondary inorganic and organic $PM_{2.5}$ • Sea salt • Coarse PM (i.e., $PM_{10} - PM_{2.5}$) to obtain PM_{10} • Hg with three chemical forms (elemental gaseous, oxidised gaseous and particulate) • Urea dust $PM_{2.5}$ and PM_{10} without chemistry	Use the CB6r4 and CF chemistry schemes in CAMx, as used by US EPA. Urea dust was added to CAMx for this study.

6.1.4 Mercury (Hg) Chemistry

CAMx can model atmospheric mercury (Hg) emission, transport, chemical conversion and deposition (Ramboll, 2020). CAMx includes three forms of Hg, namely elemental gaseous (Hg^0), oxidised gaseous (Hg^2) and particulate (HGP), with photochemical interconversion of these chemical forms (Ramboll, 2020). The chemistry scheme includes gas-phase oxidation of Hg^0 to Hg^2 by O_3, hydrogen peroxide (H_2O_2), Br-atoms and hypobromite radical (BrO). Aqueous-phase chemistry includes reduction of Hg^2 to Hg^0 by hydroperoxy radical (HO_2) and oxidation of Hg^0 to Hg^2 by dissolved O_3, hydroxyl radical (OH) and chlorine (Cl_2). Adsorption of Hg species to PM considers adsorbed Hg^0 (HGP) and Hg^2 adsorbed to carbonaceous PM (HG2PC) and other PM (HG2P).

6.1.5 Update for Urea Dust

Urea is not usually considered as a separate chemical species in air quality simulations with CAMx or similar models. Therefore, a modified CAMx configuration was used for this study by adding two model species for fine (< 2.5 µm) and coarse (2.5 to 10 µm) diameter urea particles. With this modification, the CAMx simulations account for emission, transport, and deposition of urea dust using the existing model algorithms for fine and coarse particles, such as dust. Urea dust is chemically unreactive in the atmosphere and so CAMx did not model any chemical interactions between the urea dust and other chemicals. Model results that are presented for PM_{10} and $PM_{2.5}$ include the mass of urea and the N-deposition results include the contribution from urea. Urea emissions were only provided for Scenario 3. Therefore, only the Scenario 3 model results include the contribution from urea.

6.1.6 Boundary and Initial Conditions

The CAMx concentrations for longer lived species (e.g., ozone and CO) in the 4 km domain are influenced by the concentrations at the domain boundary (BCs). The NCAR Community Atmosphere Model with Chemistry (CAM-chem) provides boundary and initial concentrations for the CAMx regional model.

CAM-Chem operational forecasts do not include atmospheric Hg. Seasonally varying but spatially constant IC/BCs for elemental Hg from measurements at the Australian Tropical Atmospheric Research Station (ATARS) in northern Australia was estimated as part of the Global Mercury Observation System (GMOS) reported by Howard et al. (2017). Climatological monthly average temperature and pressure at Darwin to convert from ng m^{-3} to ppm (CAMx uses units of ppm for gas species such as elemental mercury) was used. Figure 6-3 shows monthly averaged elemental mercury measured at ATARS (blue; left axis) and the converted values in ppt (orange; right axis). The IC/BCs for reactive gaseous and particulate Hg are set to zero.

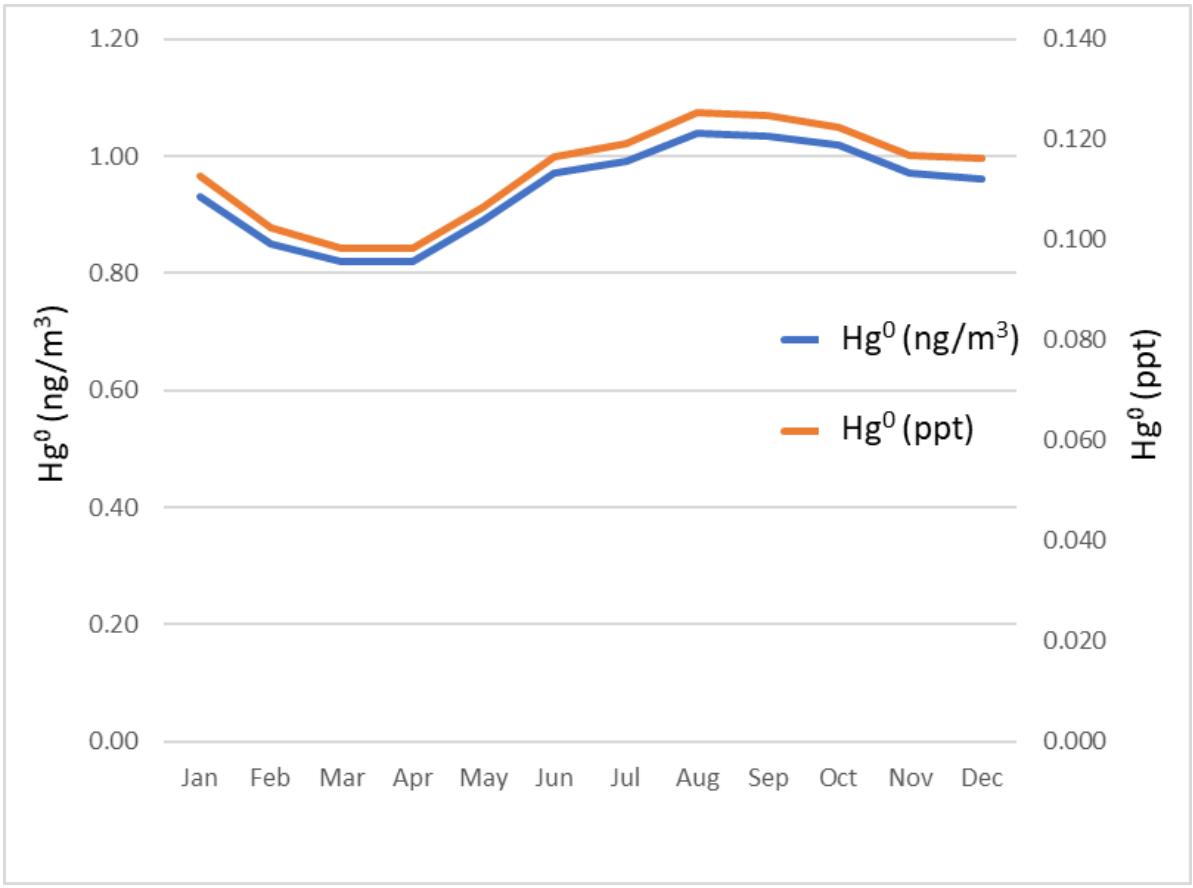


Figure 6-3: Monthly average atmospheric elemental Hg (Hg^0) measured at ATARS near Darwin (blue; left axis) and converted to ppt (orange; right axis) using climatological temperature and pressure.

CAM-Chem overstates dust concentrations in the region surrounding the CAMx modelling domain and it is necessary to adjust (decrease) the CAMx BCs for dust obtained from CAM-chem. Dust influences aerosol pH by providing alkaline material and therefore greatly over-estimating (or under-estimating) dust can bias the chemistry for anthropogenic emissions such as SO_2. CAMx simulations with dust only and compared CAMx dust concentrations to measurements at South Port Hedland was performed[12]. Port Hedland was chosen to avoid using measurements from our focus area to adjust the BCs, although it is noted that Port Hedland has dust sources. It was estimated that the CAMx BCs should produce annual average PM_{10} dust of ~15 µg m^{-3} and annual maximum of ~100 µg m^{-3} near the middle of our domains. Dust BCs from CAM-chem was divided by 5 and applied a cap of 100 µg m^{-3} to bring CAMx dust concentrations into the desired concentration range. The CAMx simulation of dust (BCs and emissions) could be improved by additional study.

6.1.7 Emission Scenarios

Air dispersion modelling was completed for three scenarios, namely:

- **Scenario 1** - All emissions, including natural, domestic and commercial sources, but excluding the point and area sources for heavy industry including railways and shipping in the region.

[12] https://www.phic-hedland.com.au/wp-content/uploads/2019/12/annual-report-_fy2017_18-port-hedland-ambient-air-quality-monitoring-program.pdf

- **Scenario 2** - Scenario 1 plus the current point and area sources for heavy industry including railways and shipping in the region.
- **Scenario 3** - Scenario 2 plus proposed future emissions (2030) from all sources.

Table 6-4: Emissions Sources for Each Scenario

Scenario	Included emissions	Excluded emissions
1	• Biogenic • Bushfire • Domestic • Commercial • On road • Global and regional background	• Existing heavy industry (point and area) sources • Industry related on and non-road emissions, i.e. heavy vehicle, railways and shipping
2	Scenario 1 plus: • Existing heavy industry (point and area) sources • Industry related on and non-road emissions, i.e. heavy vehicle, railways and shipping • Aggregate area sources	
3	Scenario 2 plus: • Proposed future sources including industry, expanded transport and other aggregated emissions	

Scenario 2 is considered the CAMx base case because it includes all existing air pollutant emission sources within the Murujuga airshed including biogenic and bush fire emissions which can substantially influence air quality. The base case simulation that was compared to observations should contain all existing sources, both natural and anthropogenic.

The CAMx base case performance was evaluated in Section 6.2 by comparing model results to available local observations provided by DWER. The base case provides a frame of reference for evaluating the effects of the other emissions scenarios by comparing modelled concentrations from those scenarios to the base case concentrations.

In addition to the base case, CAMx simulations were undertaken for the two emissions scenarios. The only difference between each of the CAMx scenarios and the base case is the emission inventory used. CAMx was run for each of the emissions scenarios and present concentration differences from the base case in Section 6.3.

6.2 Base Case Model Performance Evaluation

The CAMx base case (Scenario 2) model performance was evaluated by comparing model results to available local observations provided by DWER and industrial operators in the region. Measurement data were discussed in Section 4.1.

Figure 6-4 shows a zoomed in view of monitoring sites and industry emissions sources located in the CAMx 1.33 km domain. There are three main locations with observational data in the region: Karratha, Burrup Road, and Dampier. Burrup Road is located near several industry emissions sources. Dampier is located near the coast and is influenced by industry and shipping emissions. Dampier contains five monitoring sites operated by industry measuring $PM_{2.5}$ (Karratha and Dampier East) and PM_{10} (Karratha, Dampier East, Dampier Centre, Dampier North and Dampier West) as shown in Figure 4-1. Karratha is located south of the other two sites and is influenced by residential, commercial, vehicle and light industrial operations.

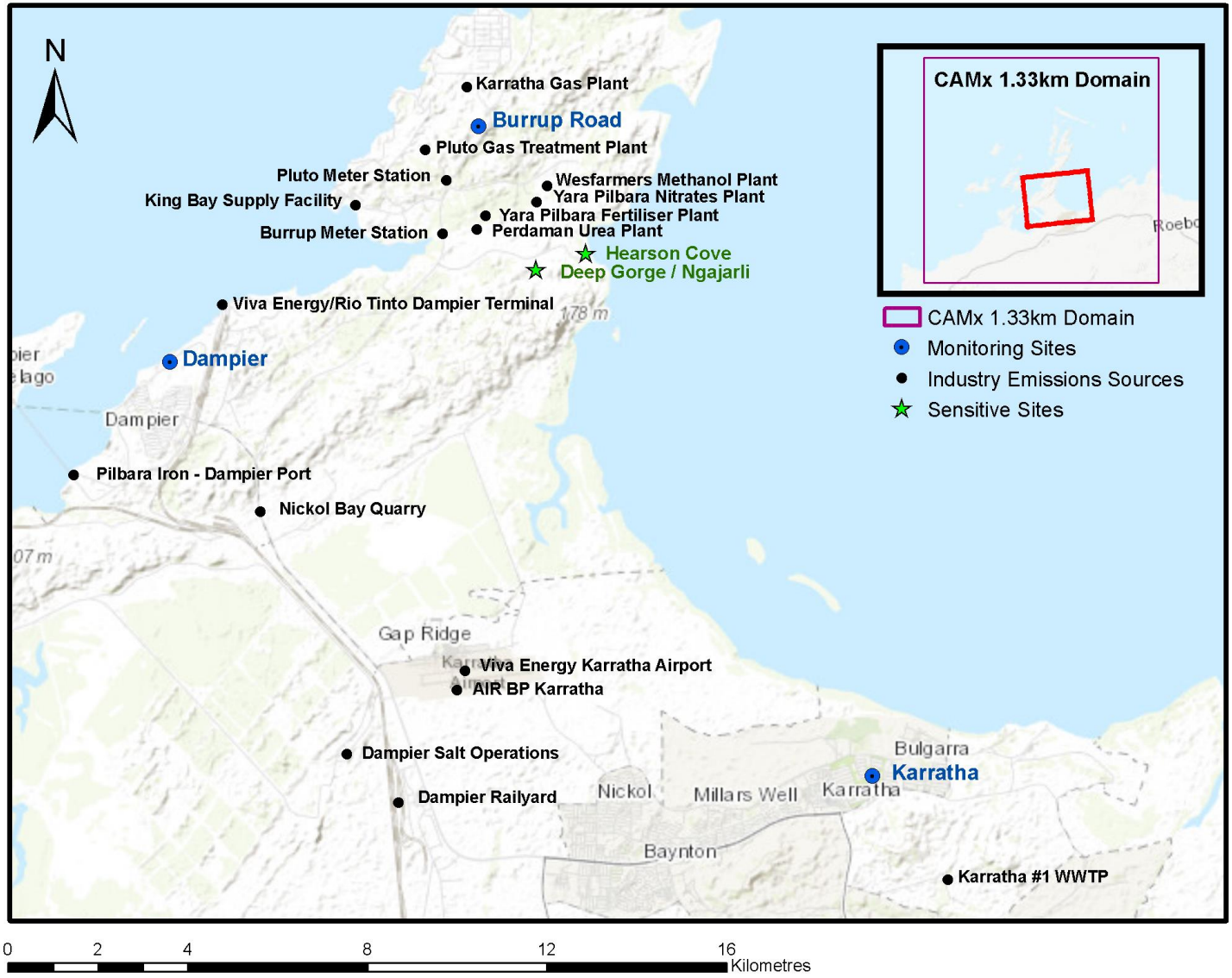


Figure 6-4: Map showing monitoring sites, nearby industry sources, and sensitive sites.

6.2.1 Model Performance for NO_2

Modelled and observed NO_2 concentrations are in similar ranges at Karratha, but the model is biased high at Burrup Road and Dampier (Figure 6-5, Figure 6-6). The high bias for NO_2 at Burrup Road may result from its proximity to major industry emissions sources which the 1.33 km grid resolution of the model is insufficiently fine to resolve the actual source-receptor relationships. The high bias at Dampier may indicate that shipping emissions are overestimated or located too close to the monitor in the modelling. Emissions from railway operations near Dampier and other nearby industrial sources may also be overestimated, which would contribute to the high bias.

6.2.2 Model Performance for O_3

Modelled maximum daily 4-hour average (MDA4) O_3 values correlate well with observations at Dampier and Karratha, the two sites with O_3 observational data in 2014 (Figure 6-7, Figure 6-8). Normalised mean bias is 7.5% and 12.5% at Dampier and Karratha respectively, and normalised mean error is 15.6% and 16.1%. From the quantile-quantile plots in Figure 6-7, it can be seen that there is a slight high bias at lower MDA4 O_3 values and a low bias at the highest observed MDA4 O_3 concentrations, but overall, the model and observations are in good agreement for O_3.

6.2.3 Model Performance for $PM_{2.5}$ and PM_{10}

Modelled PM_{10} and $PM_{2.5}$ concentrations was evaluated against observed concentrations at the monitors described in Section 4. Modelled versus observed 24-hour average $PM_{2.5}$ performance at Dampier East and Karratha shows a low normalized mean bias (NMB) compared to normalized mean error (NME), indicating that overpredictions of $PM_{2.5}$ 24-hour averages on some days are offset by underpredictions on other days (Figure 6-9). The Q-Q plots show that the model performs well in replicating the overall range and distribution of observed $PM_{2.5}$ concentrations (Figure 6-10).

Modelled PM_{10} 24-hour averages agree fairly well with observations, though not as well as $PM_{2.5}$, with higher maximum concentrations in the model compared to observations (Figure 6-11 through Figure 6-14) as shown most clearly by Q-Q plots that trend above a 1:1 line at higher concentrations. Greater model bias for PM_{10} than $PM_{2.5}$ could be caused by uncertainty in fraction of particulate matter emissions from nearby sources that are in the coarse size range (from 2.5 to 10 µm) and/or uncertainty in the modelled deposition velocity of PM_{10} which can be sensitive to details of the coarse particle size distribution.

The Dampier East and Dampier North monitors are located in the same model grid cell and the remaining two Dampier monitors are located in neighbouring model grid cells. Similar to our discussion of NO_2 model performance at Burrup Road, the 1.33 km grid resolution of the model is insufficiently fine to resolve differences in source-receptor relationships for monitors that are located nearby each other and sources. Caution is recommended in interpreting differences in PM model performance between these monitors.

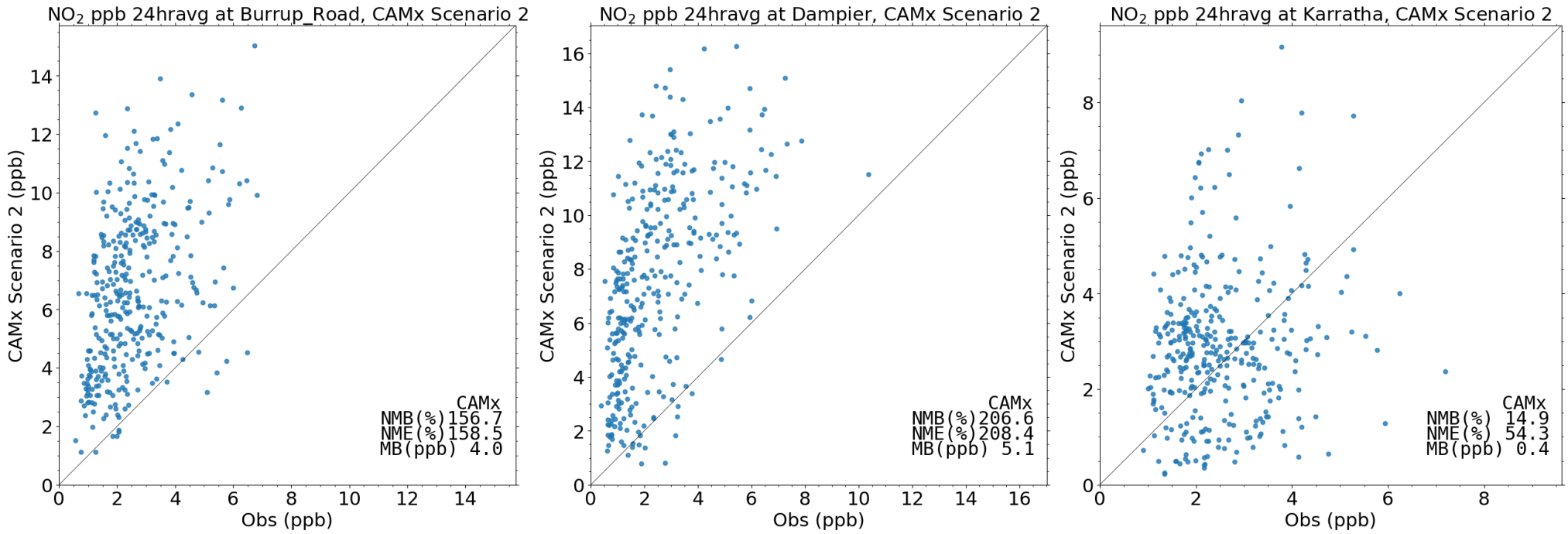


Figure 6-5: Scatter plots of 24-hr average NO_2 at monitoring sites

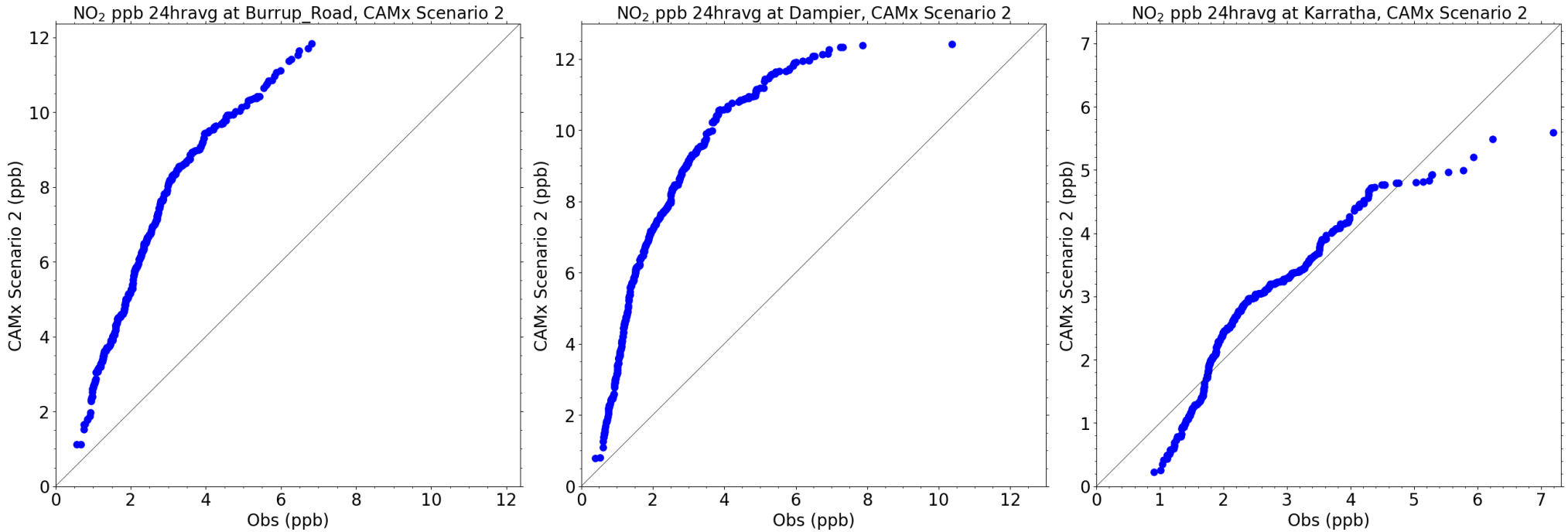


Figure 6-6: Quantile-quantile (Q-Q) plots of 24-hr average NO_2 at monitoring sites

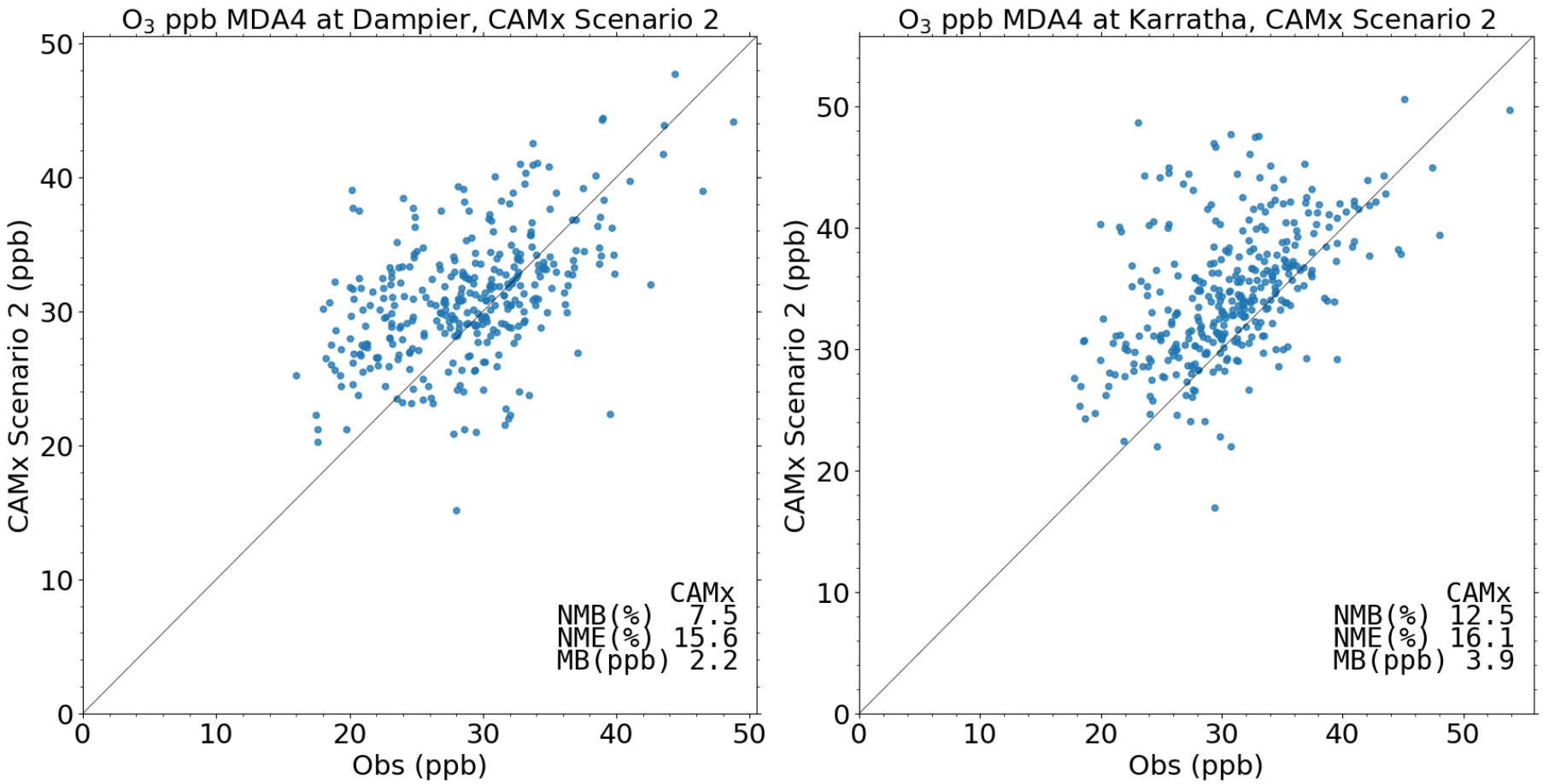


Figure 6-7: Scatter plots of MDA4 O_3 at monitoring sites

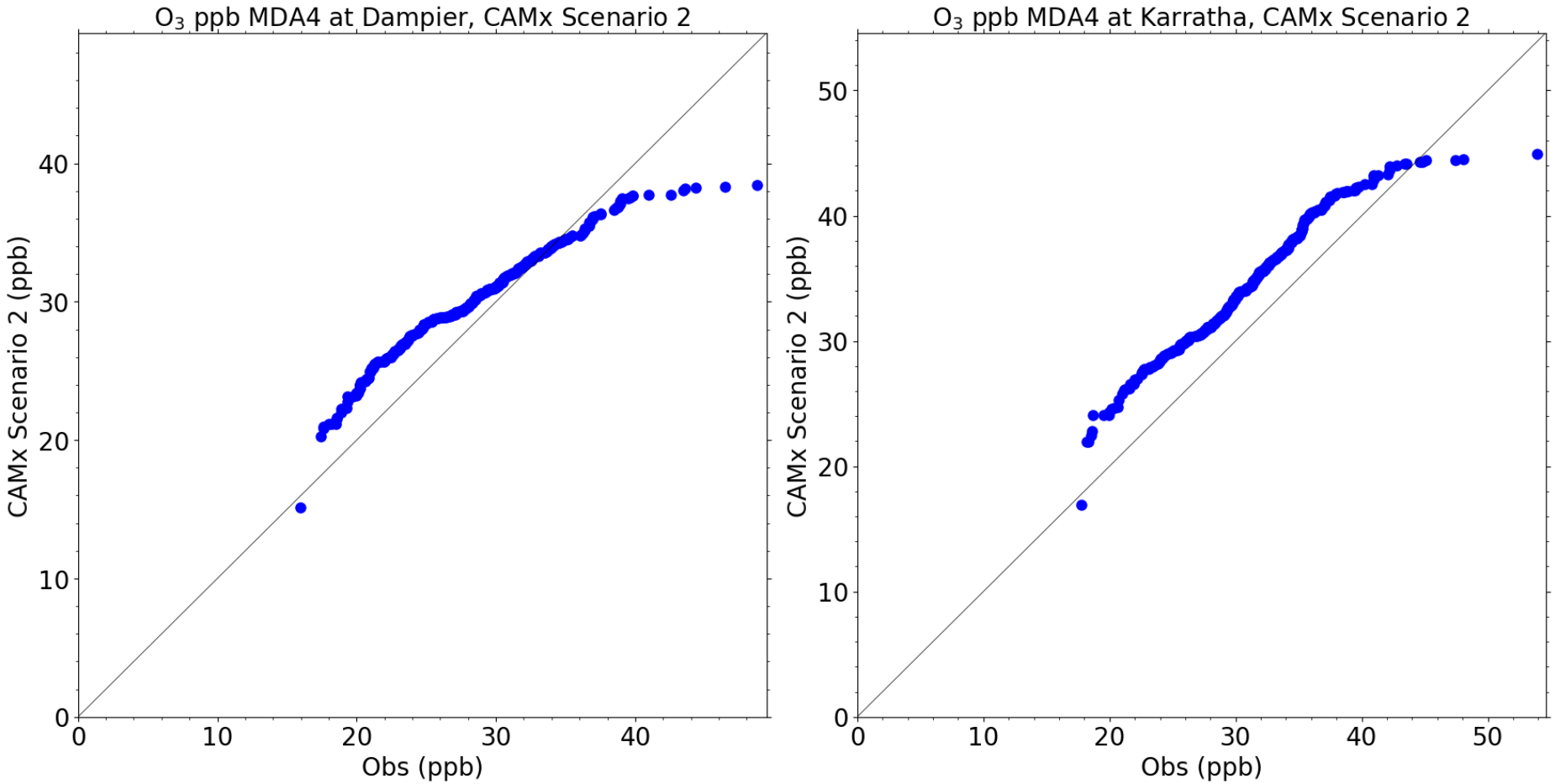


Figure 6-8: Quantile-quantile (Q-Q) plots of MDA4 O_3 at monitoring sites

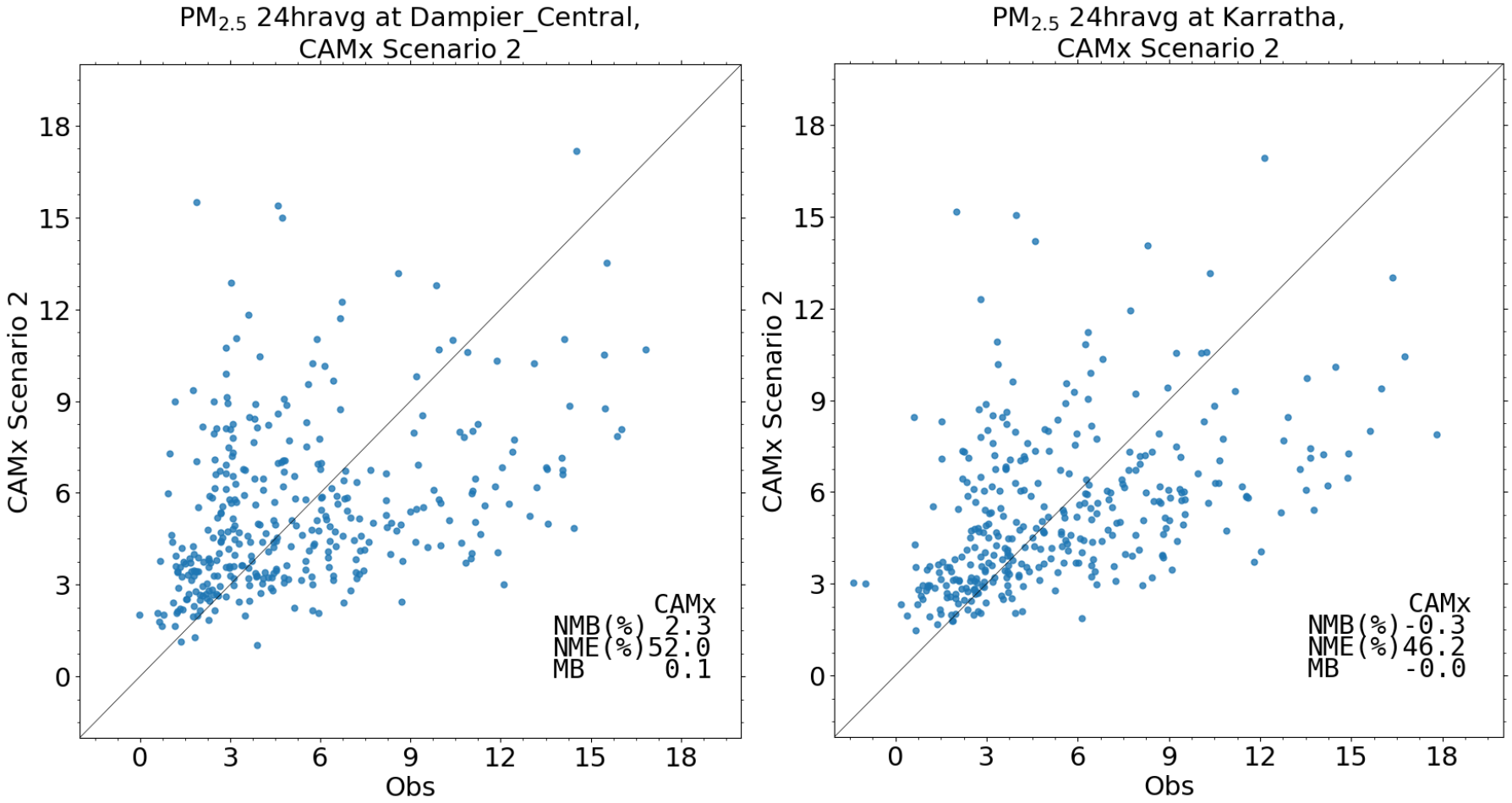


Figure 6-9: Scatter plots of average 24-hour $PM_{2.5}$ ($\mu g/m^3$) at Dampier Centre and Karratha monitoring sites

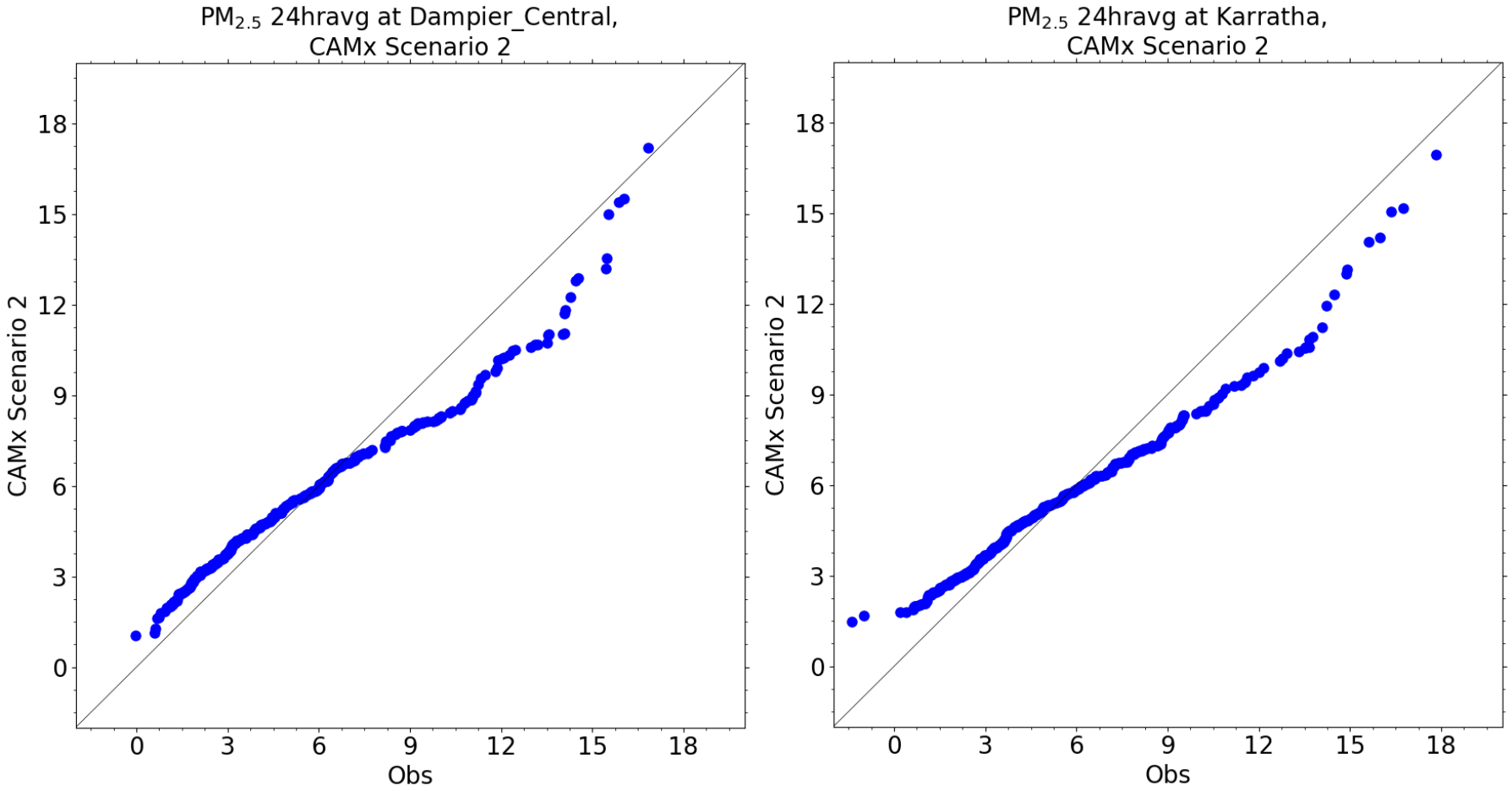


Figure 6-10: Quantile-quantile (Q-Q) plots of average 24-hour $PM_{2.5}$ (µg/m³) at Dampier Centre and Karratha monitoring sites

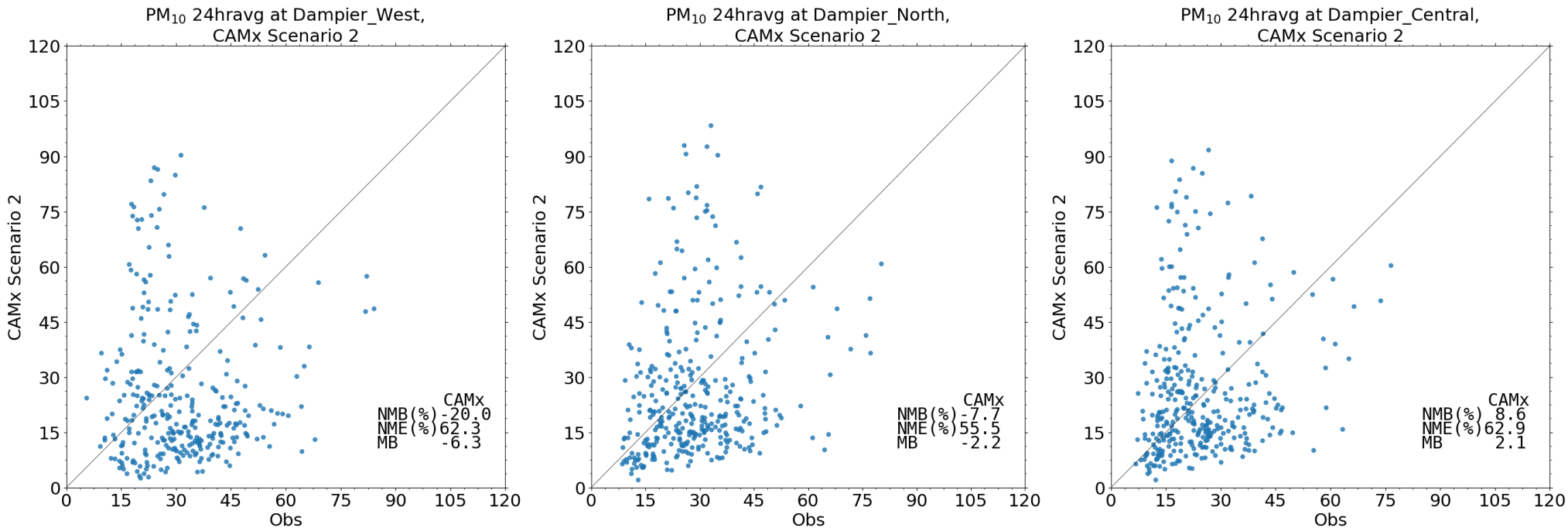


Figure 6-11: Scatter plots of average 24-hour PM_{10} (µg/m^3) at the Dampier West, Dampier North and Dampier Centre monitoring sites

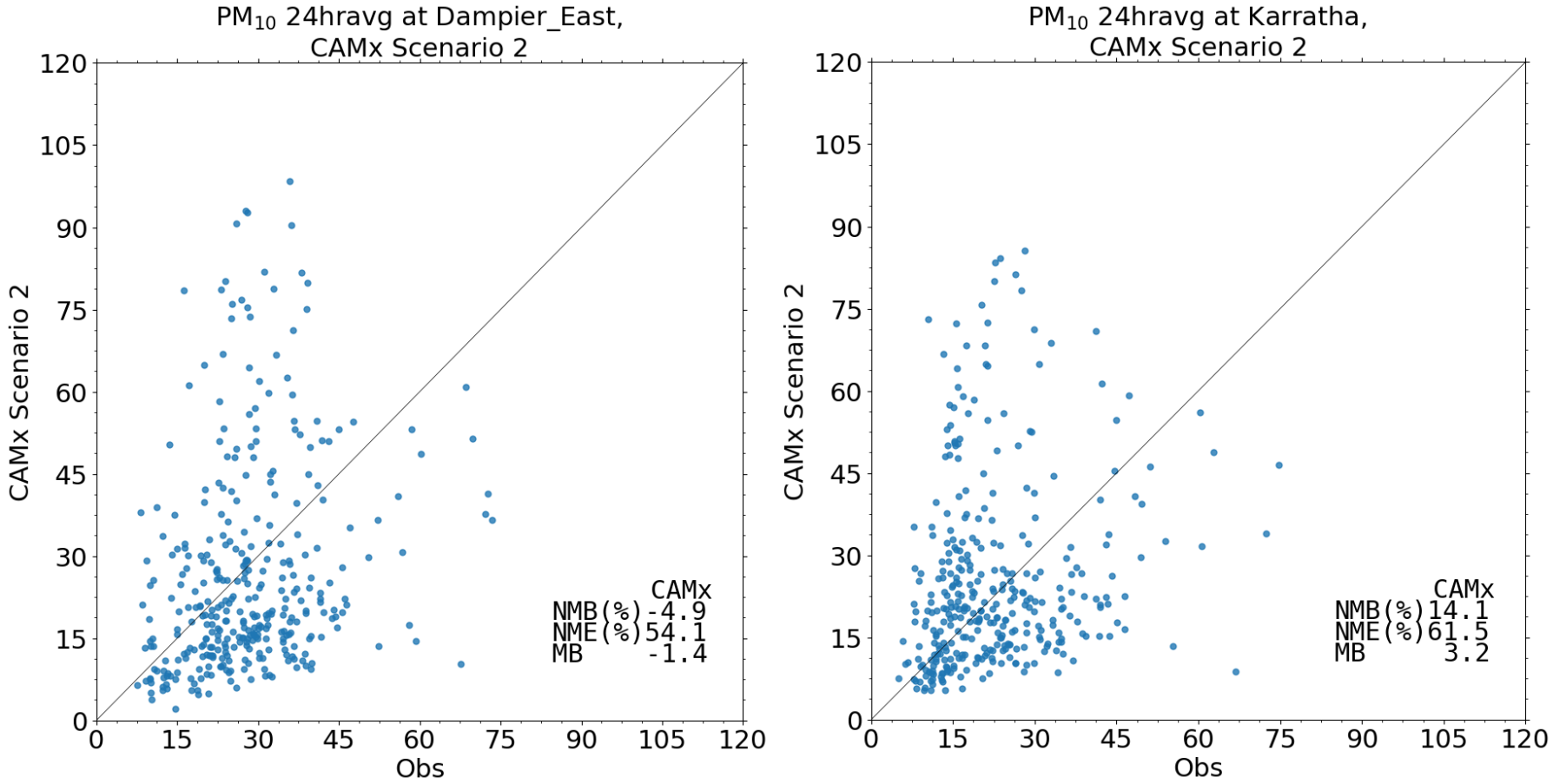


Figure 6-12: Scatter plots of average 24-hour PM_{10} (µg/m³) at the Dampier East and Karratha monitoring sites

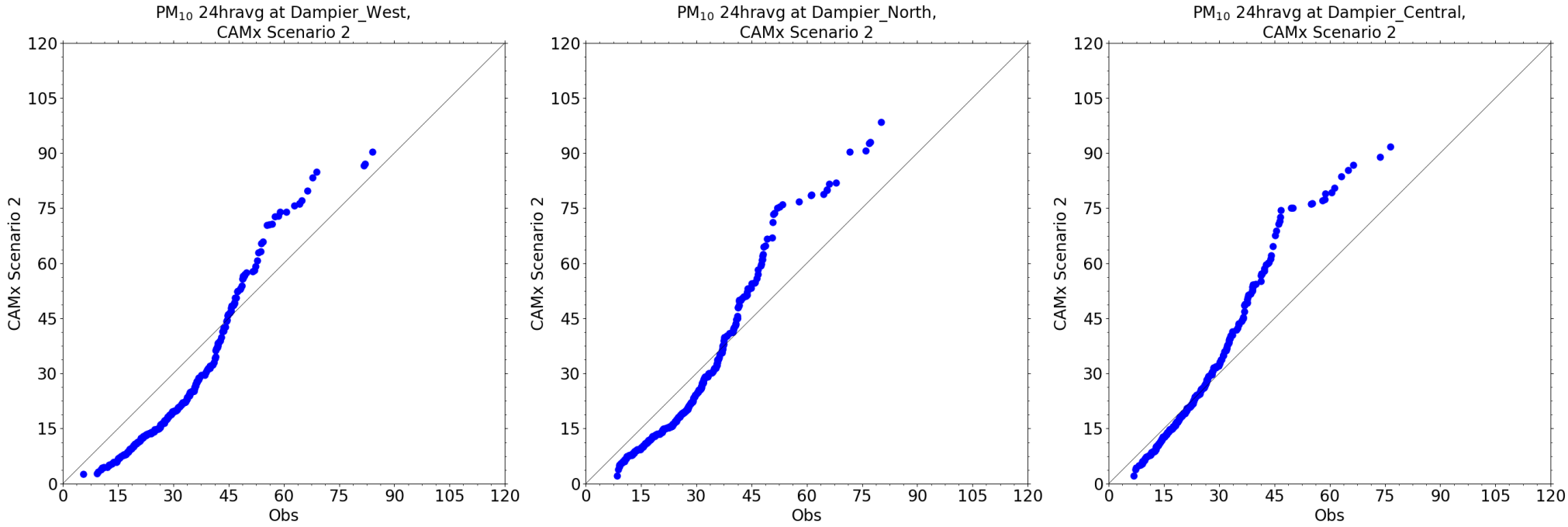


Figure 6-13: Quantile-quantile (Q-Q) plots of average 24-hour PM_{10} (µg/m³) at the Dampier West, Dampier North and Dampier Centre monitoring sites

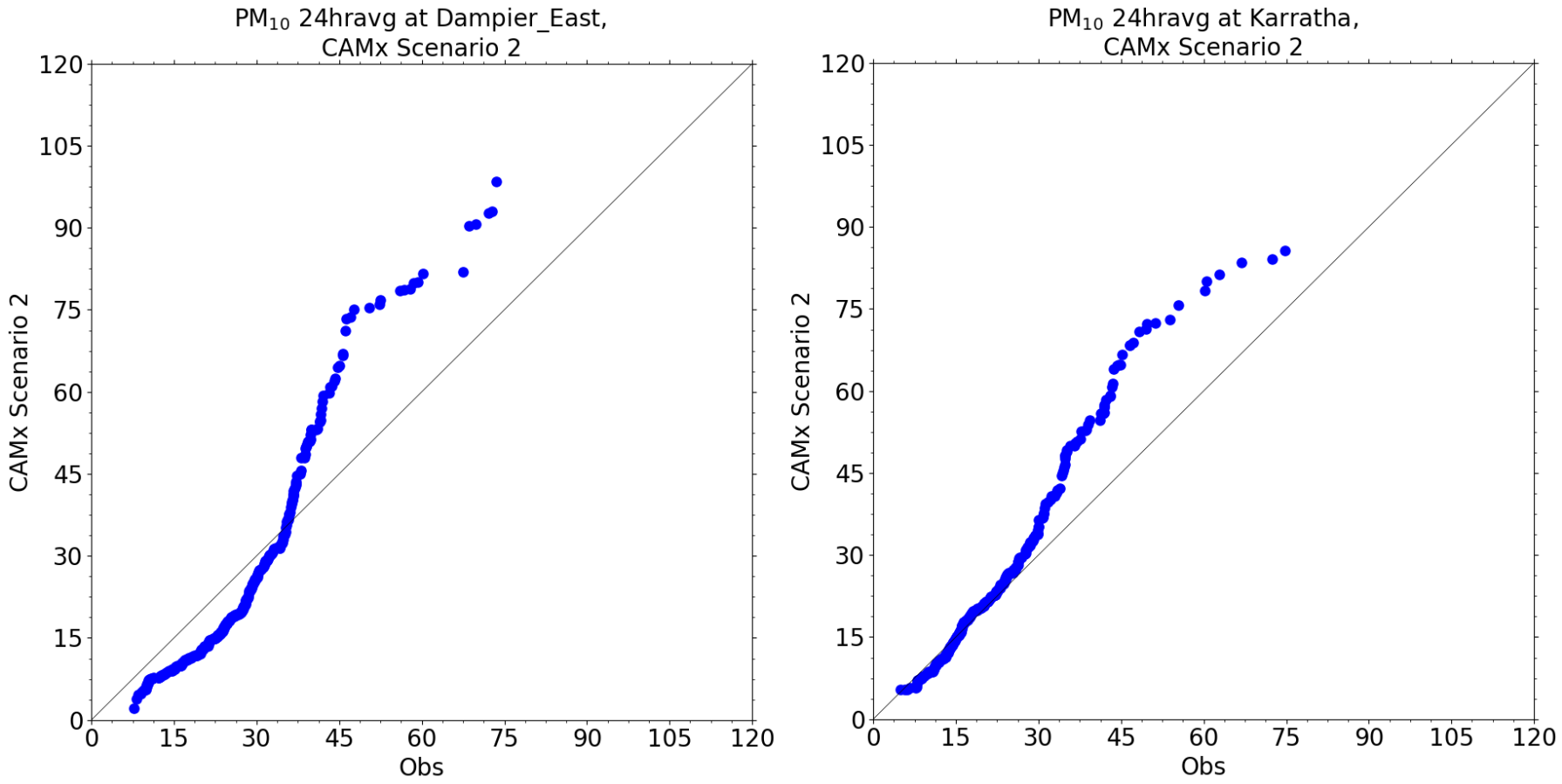


Figure 6-14: Quantile-quantile (Q-Q) plots of average 24-hour PM_{10} (µg/m³) at the Dampier East and Karratha monitoring sites

6.2.4 Model Performance for BTEX

Benzene, toluene, and xylene were monitored at the Burrup Road site in 2014 which is located near several major emissions sources. There were two co-located monitors, labelled as Ben1 and Ben2 in the data provided. In 2014, these two monitors measured benzene, toluene, and xylene at 15-minute intervals using the Syntech Spectras GC955 analyser, a gas chromatograph with a built-in pre-concentration system (Jacobs, 2019b).

Data completeness at the monitors are 72%-75%, including values reported as zero. However, Ben1 reported 13%-25% of its values as zero while Ben2 reported 64%-70% of its values as zero. This is apparent in Figure 6-9 where Ben2 shows concentrations of 0 ppb below the 64th percentile. Values reported as zero suggest that the concentrations were below the detection limit, but not zero. Ben2 appears to have a higher detection limit than Ben1. Due to the large proportion of BTEX data below detection limits, scatter plots and associated bias/error statistical metrics (as shown for O_3 and NO_2) would not be informative of BTEX model performance and so the following approach was used.

The modelled and measured BTEX concentrations are compared as percentile distributions of hourly averages in Figure 6-9 to Figure 6-11. Modelled benzene, toluene, and xylene for Scenario 2 show good agreement with observations. CAMx results showing hourly averages for benzene closely match the results for benzene at Burrup Road. CAMx species TOL is the sum of toluene, ethyl benzene, and other mono-substituted aromatics whereas XYL is a sum of xylene isomers and other multi-substituted aromatics (e.g., trimethylbenzene isomers). Consequently, TOL and XYL have an inherently high bias relative to measured toluene and xylene, although toluene is usually the dominant contributor to TOL and xylene isomers are usually the dominant contributor to XYL. CAMx results for TOL and XYL agree well with the monitored values, especially near the top of the distributions at around the 90th percentile.

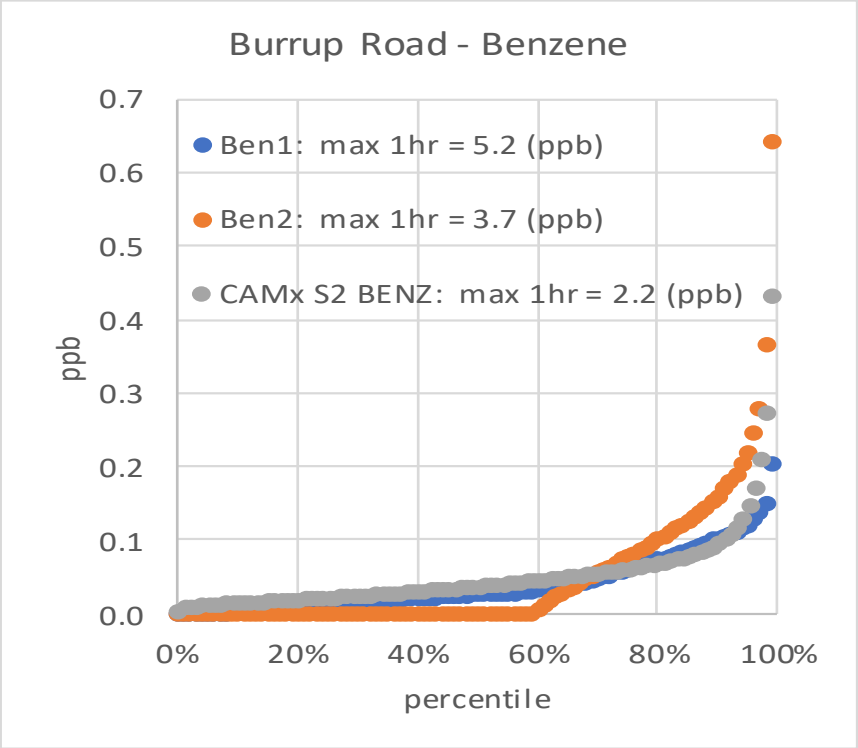


Figure 6-15: Percentile plot comparing two benzene measurements (Ben1: blue; Ben2: orange) against CAMx Scenario 2 Benzene (grey) at Burrup Road monitor.

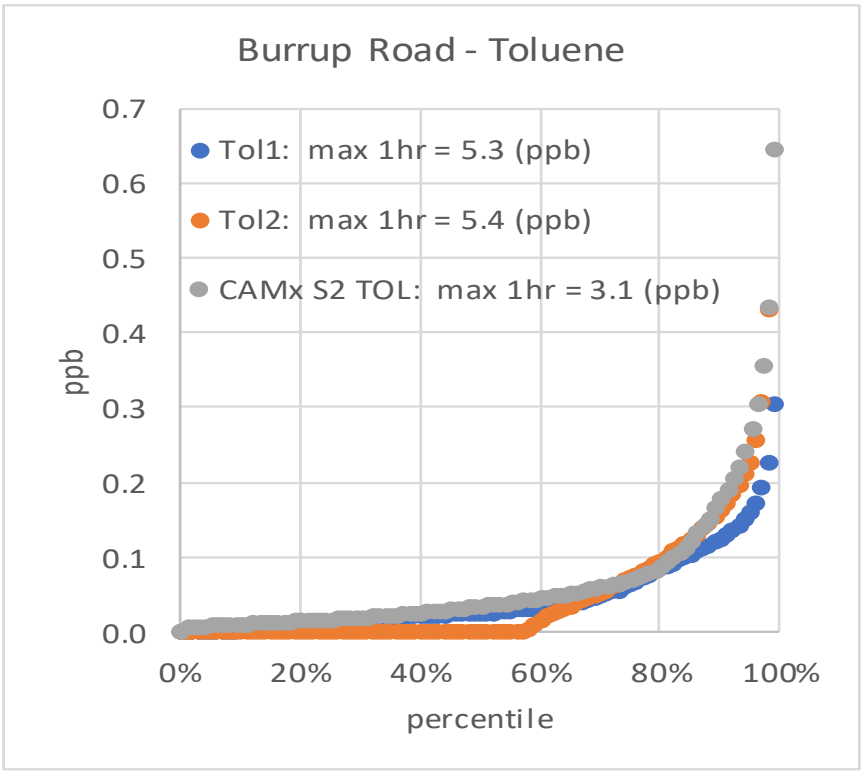


Figure 6-16: Percentile plot comparing two toluene measurements (Tol1: blue; Tol2: orange) against CAMx Scenario 2 TOL (grey) at Burrup Road monitor.

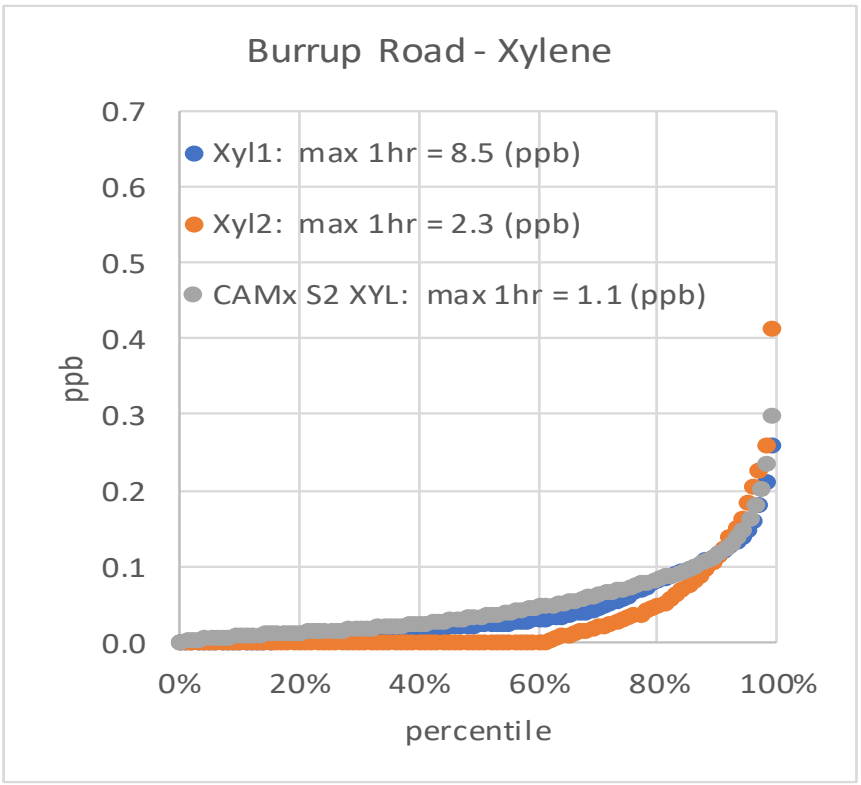


Figure 6-17: Percentile plot comparing two xylene measurements (Xyl1: blue; Xyl2: orange) against CAMx Scenario 2 XYL (grey) at Burrup Road monitor.

6.2.5 Model Performance Summary

CAMx model results for Scenario 2 show good agreement with measurements at Burrup Road, Dampier, and Karratha:

- Modelled and observed NO_2 concentrations are in similar ranges at Karratha, but the model is biased high at Burrup Road and Dampier (Figure 6-5, Figure 6-6). The high bias for NO_2 at Burrup Road may result from its proximity to major industry emissions sources which the 1.33 km grid resolution of the model is insufficiently fine to resolve the actual source-receptor relationships. However, the high bias for NO_2 concentrations when taken together with a high bias for total N deposition (discussed below) suggests that NOx emissions from shipping and/or industry near Dampier may be overestimated.
- Modelled maximum daily 4-hour average (MDA4) O_3 values correlate well with observations at Dampier and Karratha.
- Modelled 24-hour average $PM_{2.5}$ and PM_{10} concentrations agree fairly well with observations in Dampier although the 1.33 km model resolution is insufficiently fine to resolve details of the source-receptor relationships.
- Modelled benzene, toluene, and xylene for Scenario 2 show good agreement with observations.
- CAMx results for TOL and XYL agree well with the monitored values, especially near the top of the distributions at around the 90th percentile.

6.3 Predicted Ground Level Concentrations from Existing and Future Industry

Table 2-1 and Table 2-2 list the current/2025 standards for NO_2, SO_2, CO, benzene, toluene, xylene, O_3, $PM_{2.5}$, PM_{10}, inorganic Hg, and NH_3. Concentration maps are shown for all criteria pollutants in Table 2-1 except for organic Hg (CAMx simulates inorganic mercury only) and ethylbenzene (the CB6 chemical mechanism used in this CAMx run includes ethylbenzene as part of TOL).

A series of figures below show model results for the three scenarios. Figure 6-18 to Figure 6-38 show concentrations from Scenario 2. Figure 6-39 to Figure 6-84 show future industry emissions (Scenario 2 minus Scenario 1). Figure 6-60 to Figure 6-93 show future emissions (Scenario 3 minus Scenario 2). The figures show a subregion of the 1.33 km CAMx domain centred on the Burrup Peninsula. Similar figures showing the full domain extent are available in Appendix 2.

6.3.1 Scenario 2 Maximum Predicted Air Concentrations

TOL (Figure 6-20, Figure 6-21, Figure 6-22), and XYL (Figure 6-23, Figure 6-24, Figure 6-25) concentrations all fell well below the air quality standard for every metric. The highest predicted ground level concentrations centred near the Dampier site due to emission sources in that region. Exceedances of benzene (Figure 6-18, Figure 6-19) were predicted, however the exceedances were predicted at or near to industrial facilities and no exceedances were predicted at sensitive receptor locations, including Dampier and Karratha (indicated by the green stars in Figure 6-4).

Annual average Hg concentrations are orders of magnitude below the air quality standard of 0.2 $\mu g/m^3$, with a maximum concentration of 8E-6 $\mu g/m^3$ (Figure 6-33) and the higher concentrations occurring near Dampier and Karratha. Annual maximum 1-hour (MDA1) Hg concentrations are similarly low with a maximum of 4E-4 $\mu g/m^3$ (Figure 6-34). Hg ground level concentrations due to industry sources are orders of magnitude smaller than air quality standards in both Scenario 2 (Figure 6-54, Figure 6-55) and Scenario 3 (Figure 6-75, Figure 6-76).

Annual maximum 24-hour and annual maximum 1-hour (MDA1) SO_2 concentrations (Figure 6-26 and Figure 6-27 respectively) were mostly below the current and 2025 standards (20 ppb for annual max 24-hour and 100/75 ppb for MDA1 respectively). Peak concentrations were predicted off the coast near Dampier which exceeded the current and future standards by a few ppb for annual maximum 24-hour SO_2, reaching as high as 113 ppb for MDA1 SO_2.

Predicted annual average and maximum daily 1-hour average (MDA1) NO_2 concentrations were high near Dampier and Wickham (refer to Figures 6-28 and 6-29 and Figures A2-11 and A2-12, respectively). This was most likely due to rail operations associated with nearby industrial facilities. Annual average NO_2 concentrations exceeded current air quality standards at these locations with a maximum of 18.2 ppb, which exceeds the standard of 15 ppb at the industrial facility locations. MDA1 NO_2 concentrations were generally well below the current standard of 80 ppb; however, the maximum in the 1.33 km domain reached 75 ppb. The NO_2 MDA1 maxima in Scenario 2 occur near offshore shipping emissions and Dampier Port operations (Figure 6-29).

Annual maximum daily 8-hour average (MDA8) CO concentrations (Figure 6-30) did not exceed the air quality standard of 9,000 ppb and ranged from 150 ppb offshore to a high of 1,567 ppb near Burrup Road. Other highs include areas around Wickham. Both areas of high MDA8 CO concentrations are located close to emissions sources.

Annual maximum daily 1-hour average (MDA1) NH_3 concentrations (Figures 6-31 and A2-14) were below the air quality standard of 460 ppb with a maximum of 343 ppb. Peak concentrations occurred near industrial sources around Dampier Road and near Wickham (although the concentrations near Wickham were associated with a regional bushfire event). The peak concentrations near Dampier were likely associated with venting of ammonia gas during intermittent shutdown operations at the Yara Ammonia Plant.

Annual maximum daily 8-hour average (MDA8) O_3 concentrations (Figure 6-32) were relatively consistent throughout the 1.33 km domain, ranging from 37 ppb to 51 ppb, below the current standard of 65 ppb, with highs located offshore, north of Burrup Road.

Annual average PM_{10} concentrations exceeded the standard of 25 $\mu g/m^3$ at industrial facilities located at Dampier Port (Figure 6-35). Annual maximum 24-hour PM_{10} concentrations exceeded the standard of 50 $\mu g/m^3$ everywhere in the 1.33 km domain (Figure 6-36). Annual maximum 24-hour PM_{10} for much of the region exceeded 100 $\mu g/m^3$ although analysis of Scenario 1 shows that the maximums were likely associated with natural sources. Although this study used fine grid resolution in the context of photochemical modelling studies, the dust emissions from large export facilities might be responsible for more localised concentration impacts (DoE, 2004) that were not resolved by the modelling. Annual average $PM_{2.5}$ concentrations mostly met the current and 2025 standards of 8/7 $\mu g/m^3$ respectively (Figure 6-37). Annual maximum 24-hour $PM_{2.5}$ concentrations mostly fell within the current standard of 25 $\mu g/m^3$ and 20 $\mu g/m^3$ for 2025 (Figure 6-38).

Figure 6-18. Benzene (ppb) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

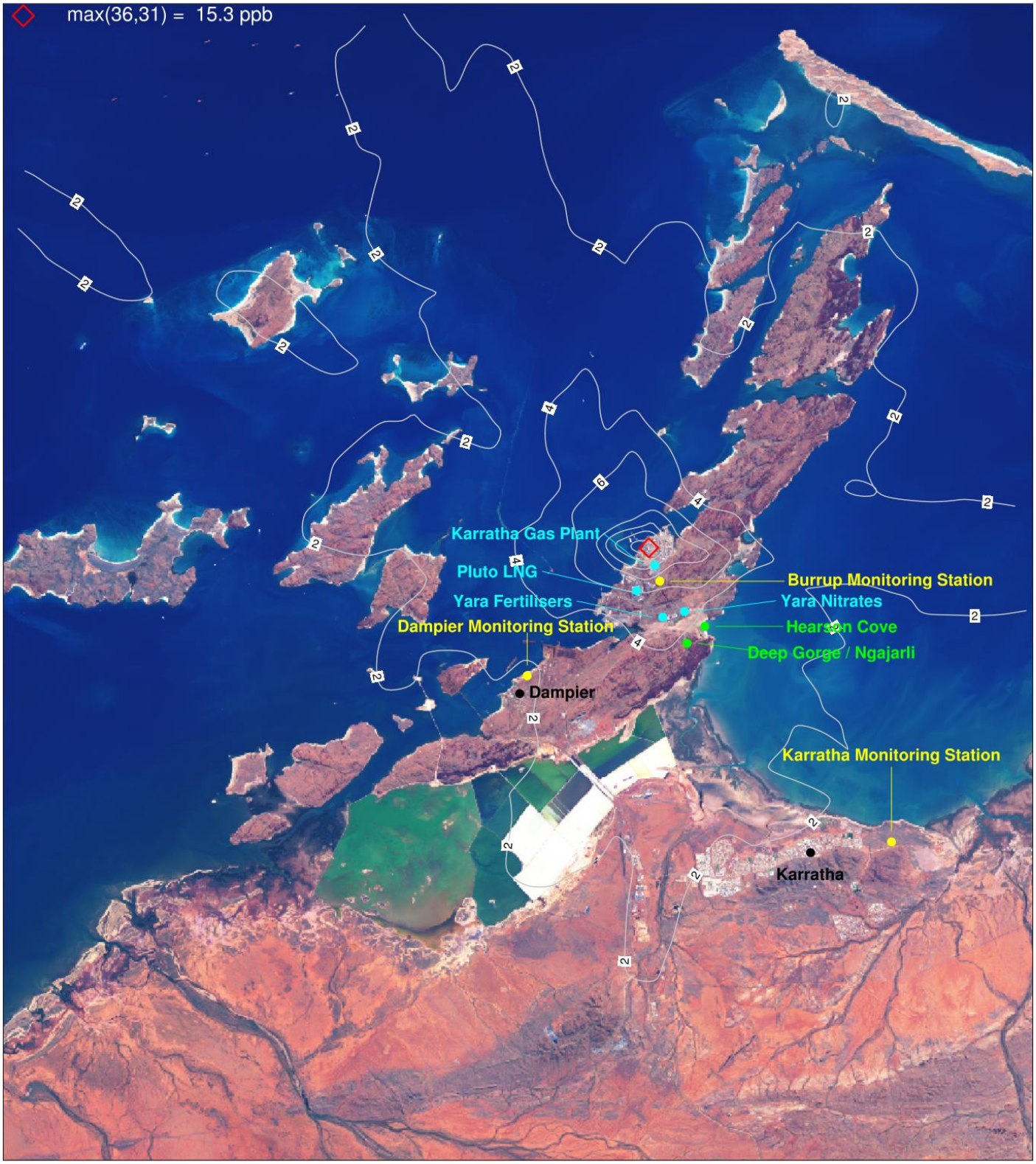


Figure 6-19. Benzene (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-20. TOL (ppb) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-21. TOL (ppb) annual max 24-hour concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-22. TOL (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-23. XYL (ppb) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-24. XYL (ppb) annual max 24-hour concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

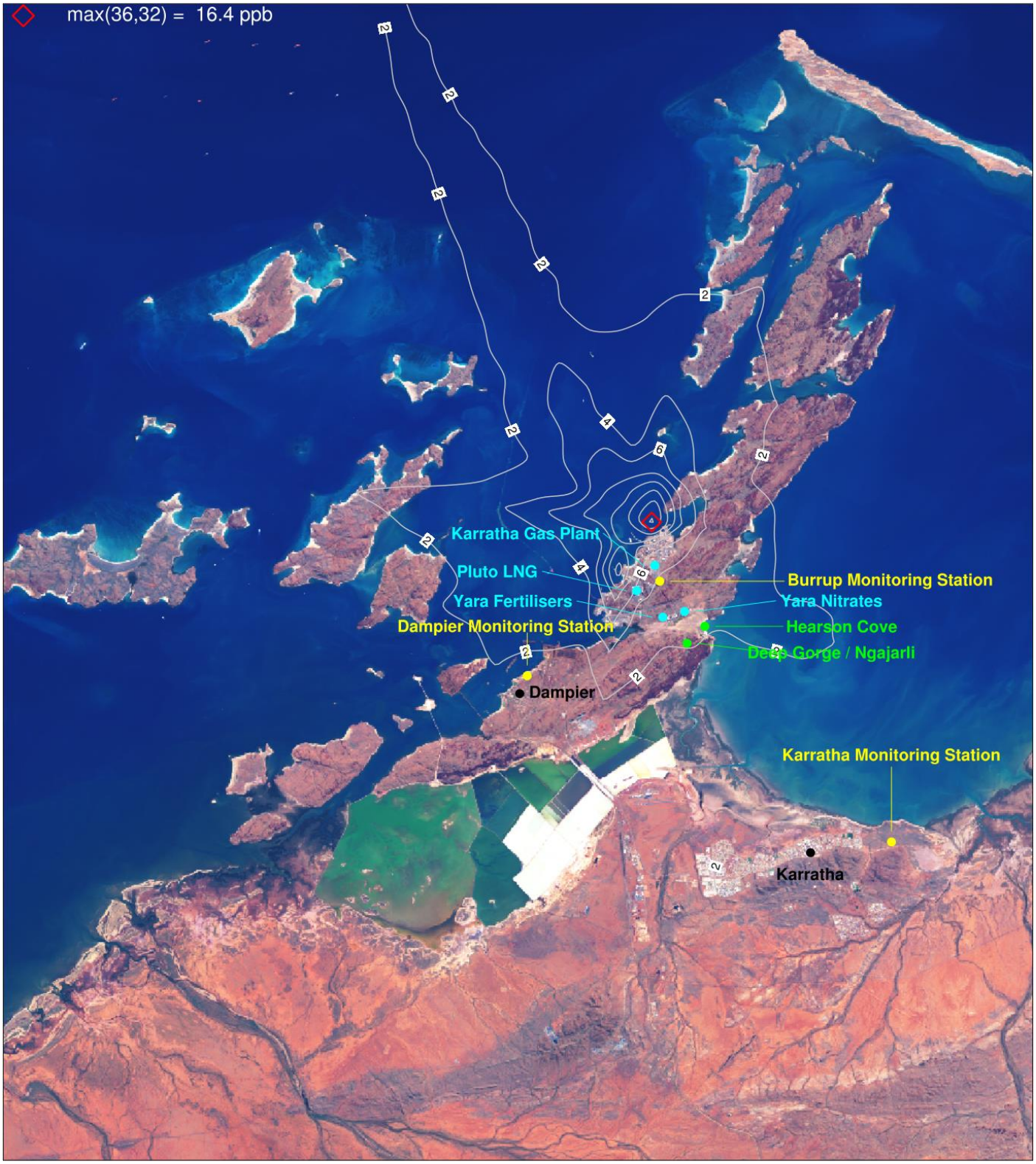


Figure 6-25. XYL (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

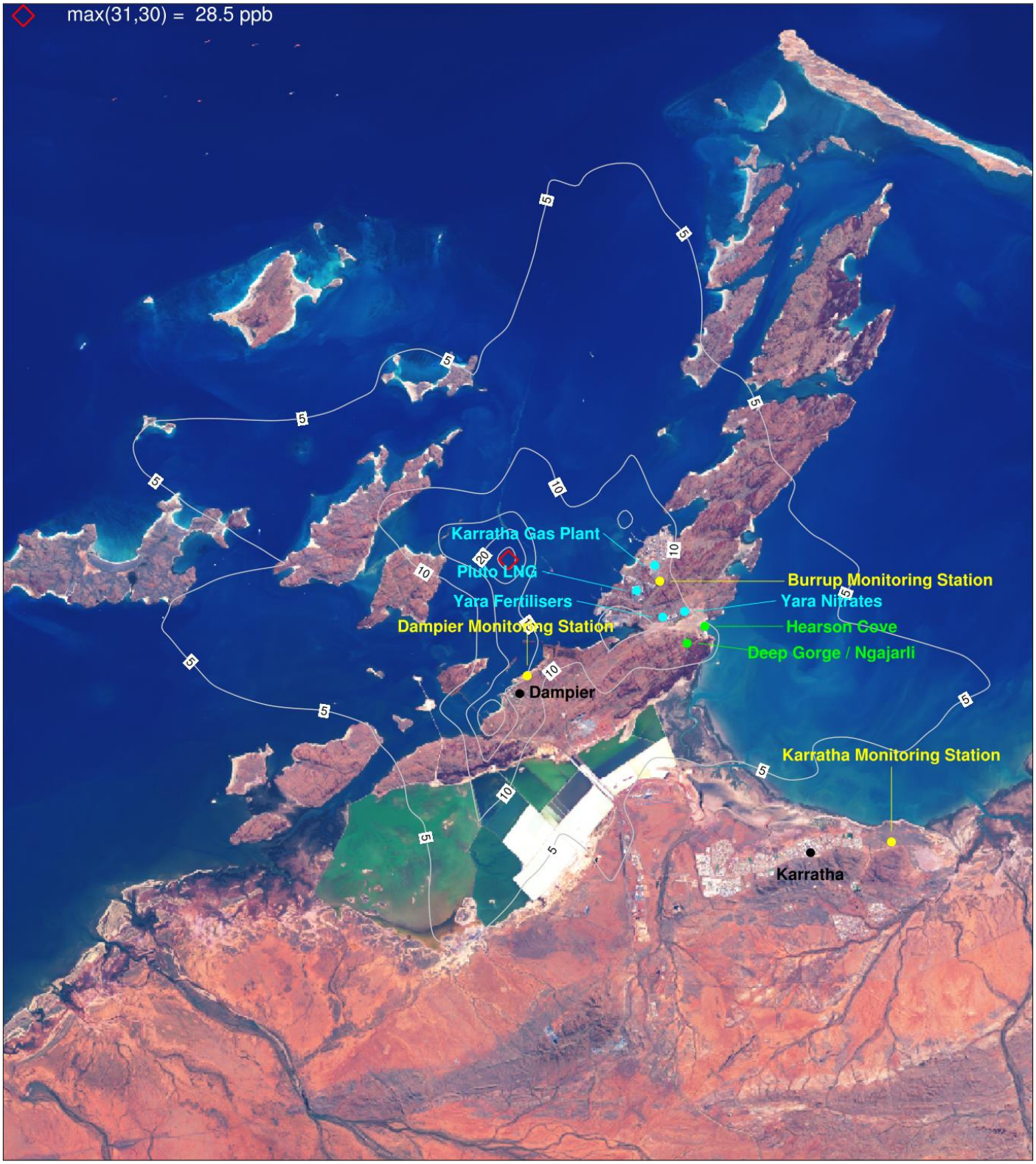


Figure 6-26. SO_2 (ppb) annual max 24-hour concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

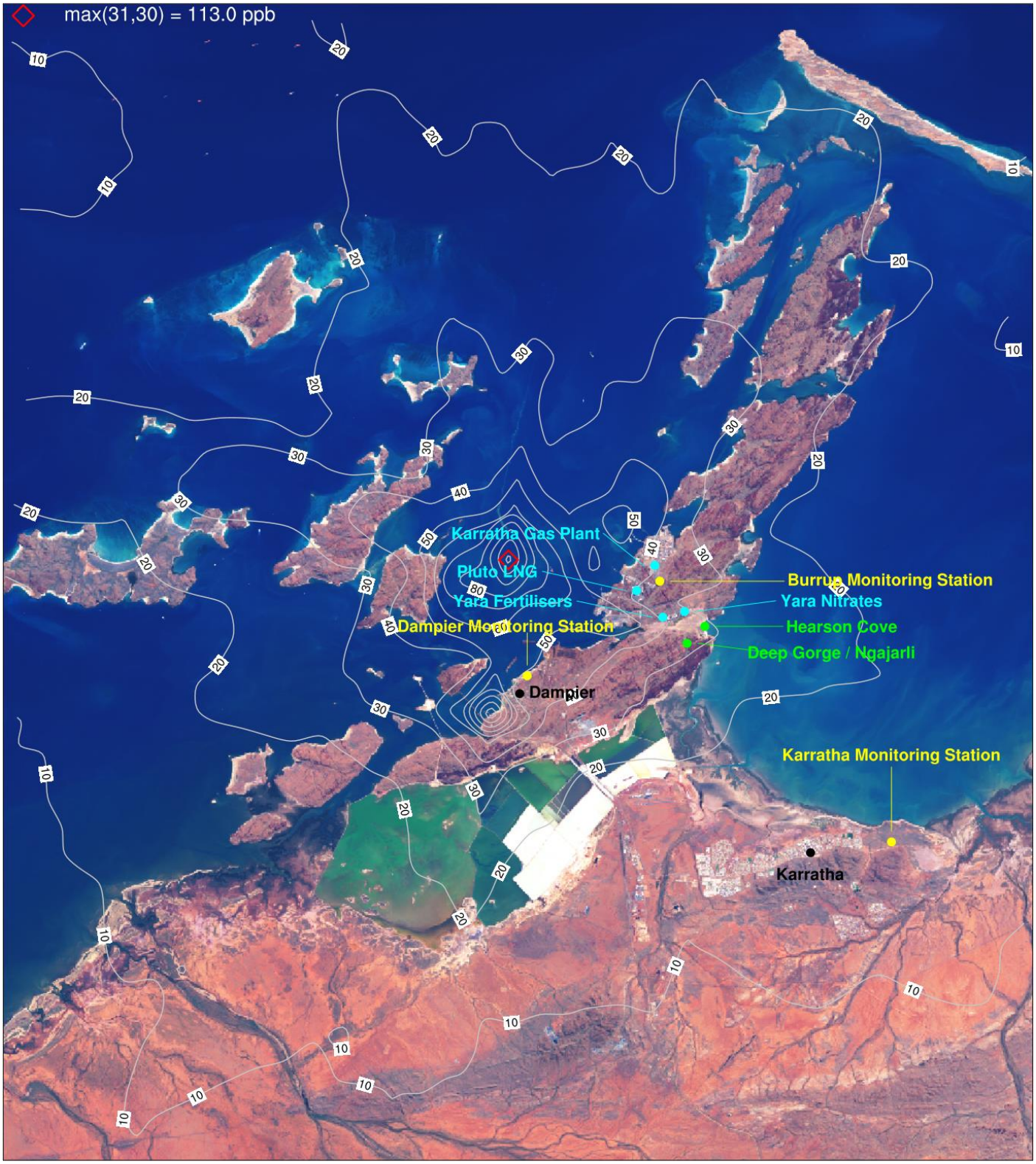


Figure 6-27. SO_2 (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

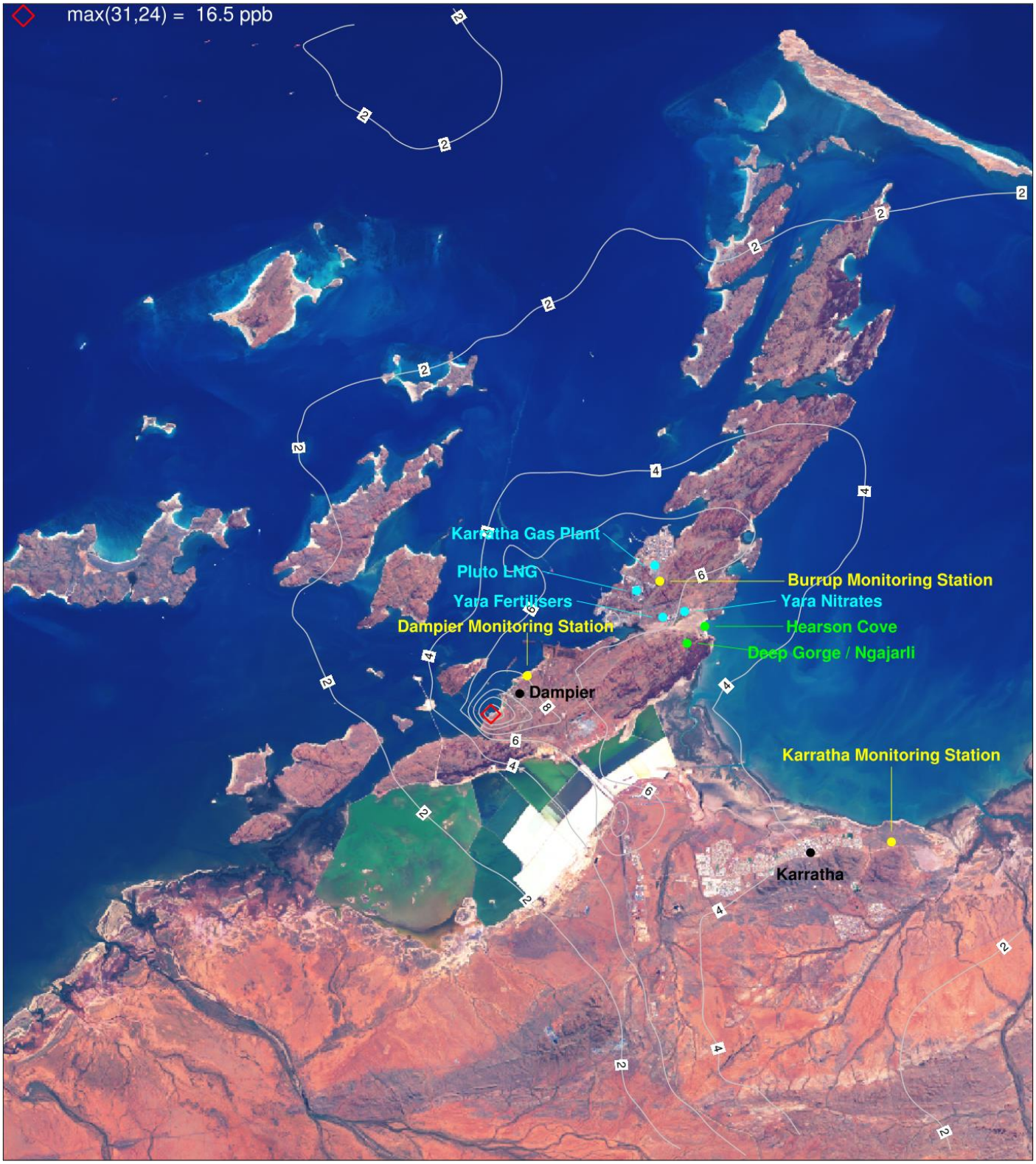


Figure 6-28. NO_2 (ppb) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-29. NO_2 (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-30. CO (ppb) annual max 8-hour (MDA8) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

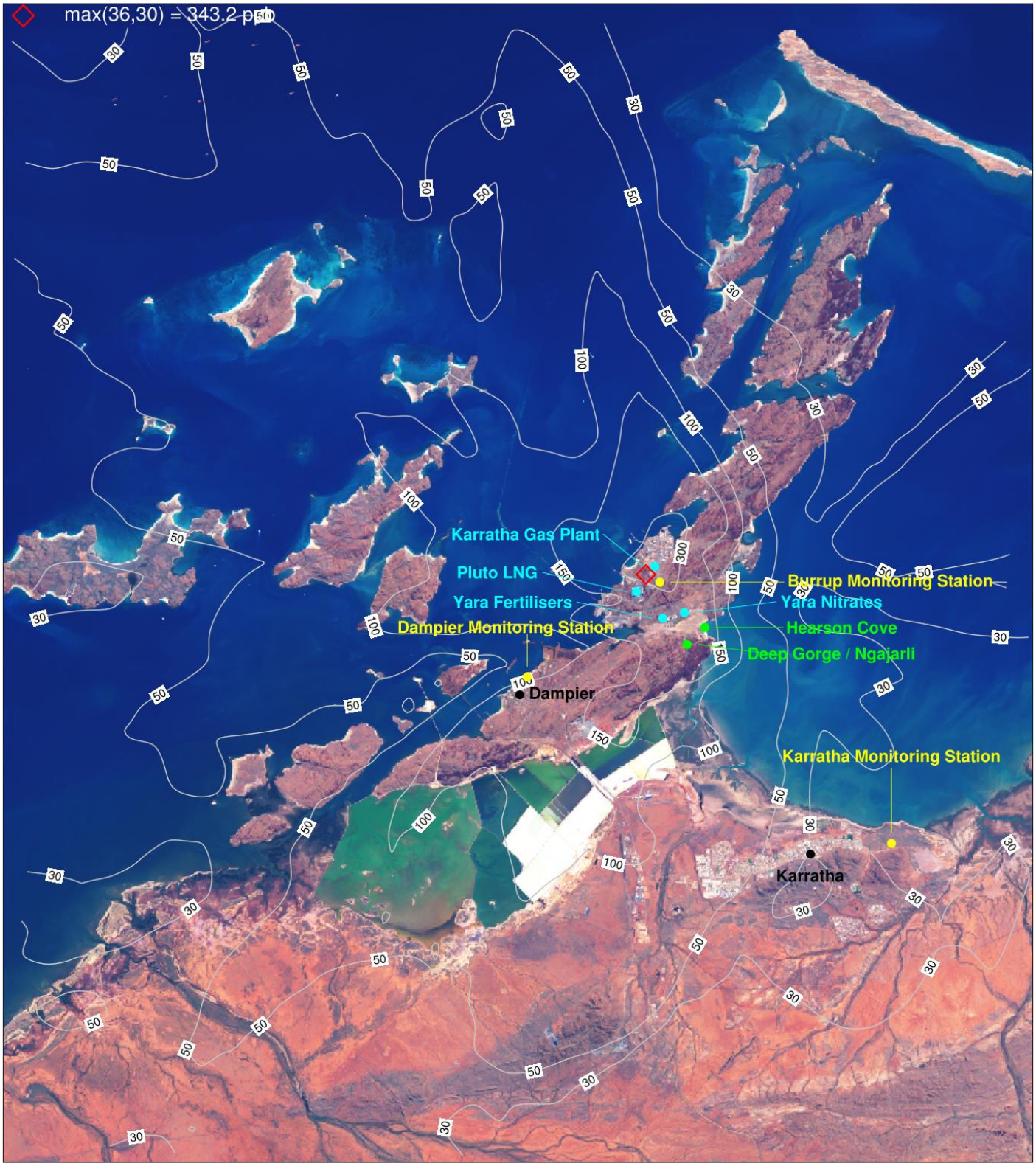


Figure 6-31. NH_3 (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

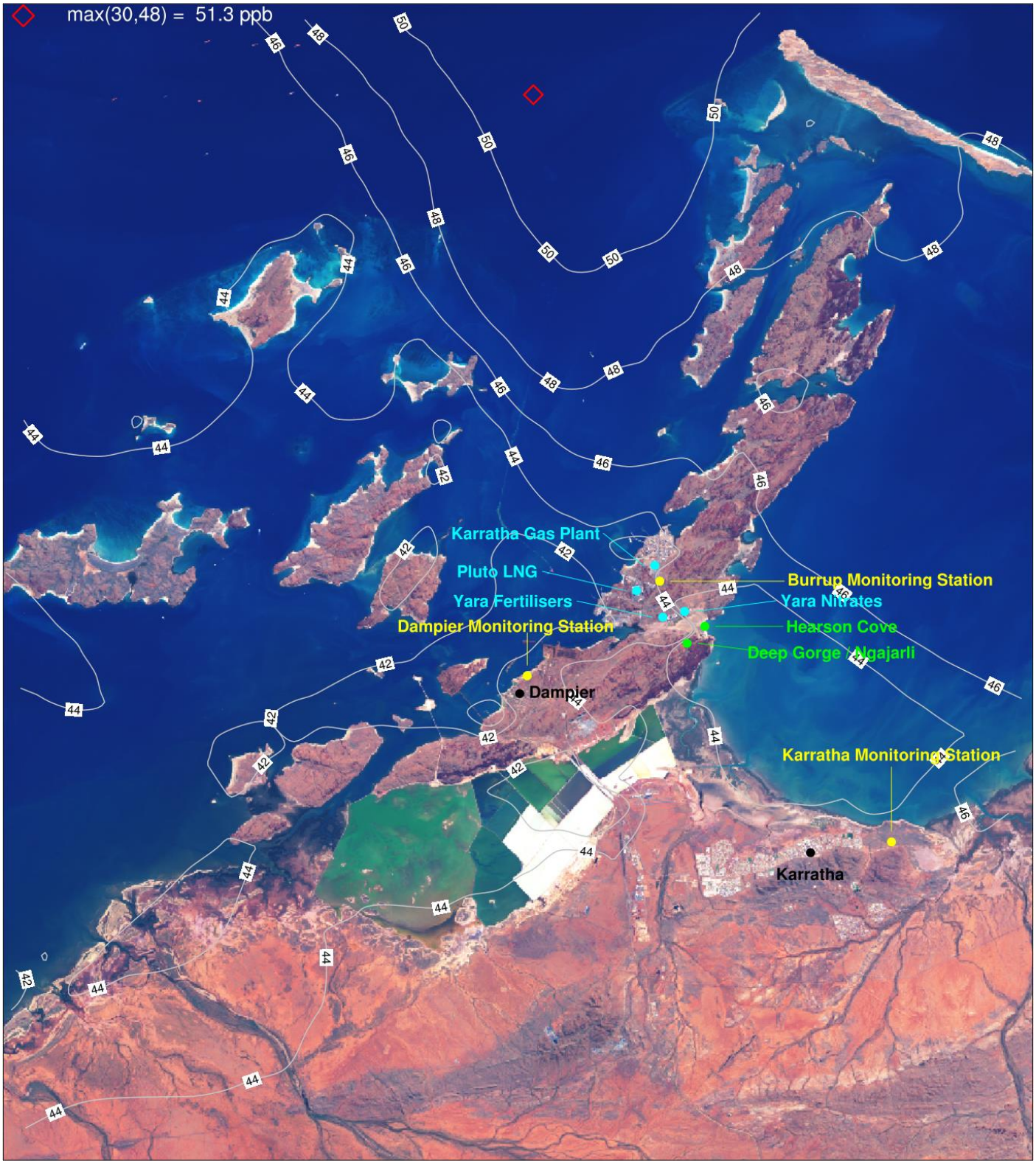


Figure 6-32. Ozone (ppb) annual max 8-hour (MDA8) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-33. Hg (µg/m³) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-34. Hg (µg/m^3) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-35. PM_{10} (µg/m³) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

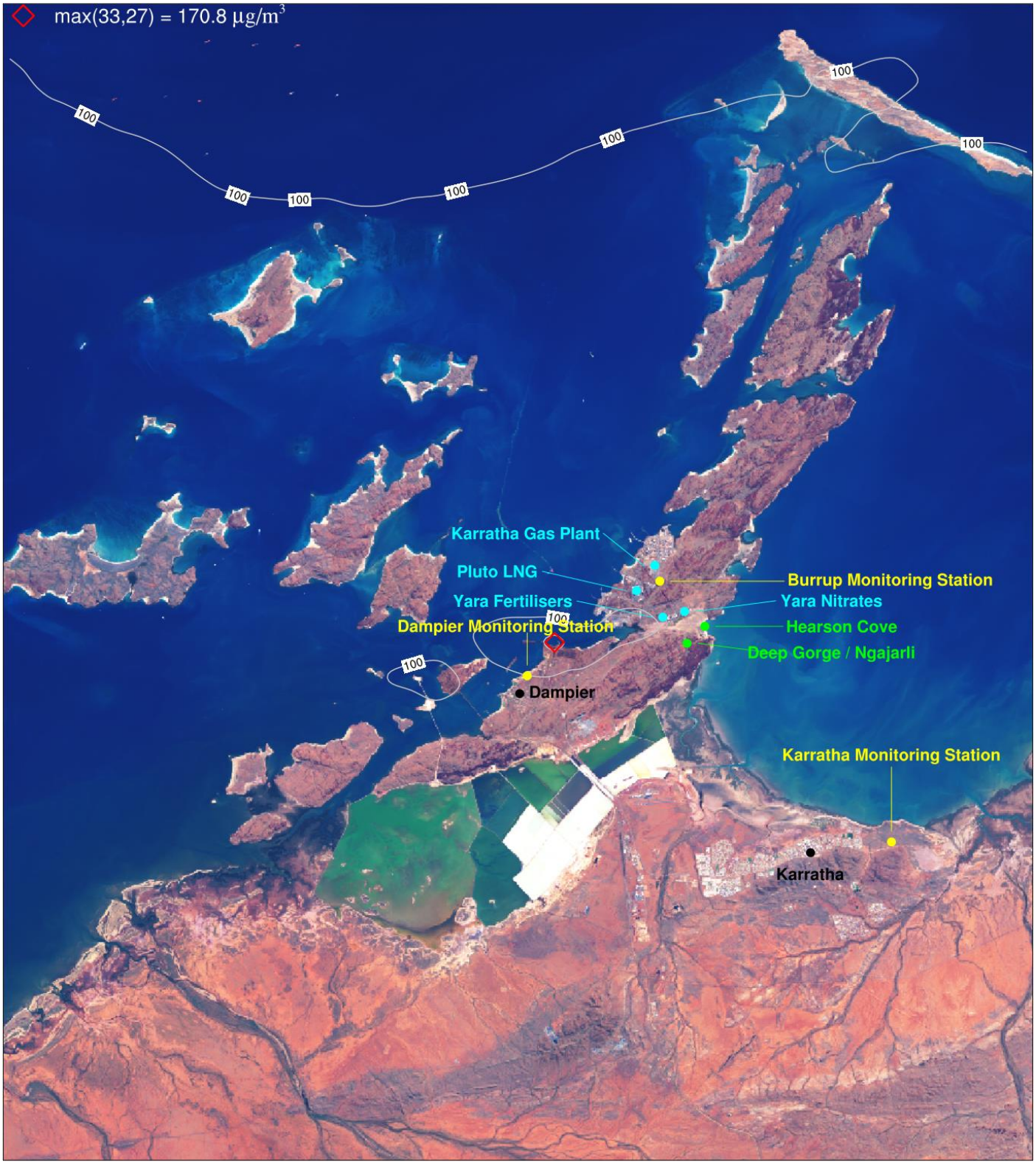


Figure 6-36. PM_{10} (µg/m³) annual max 24-hour concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

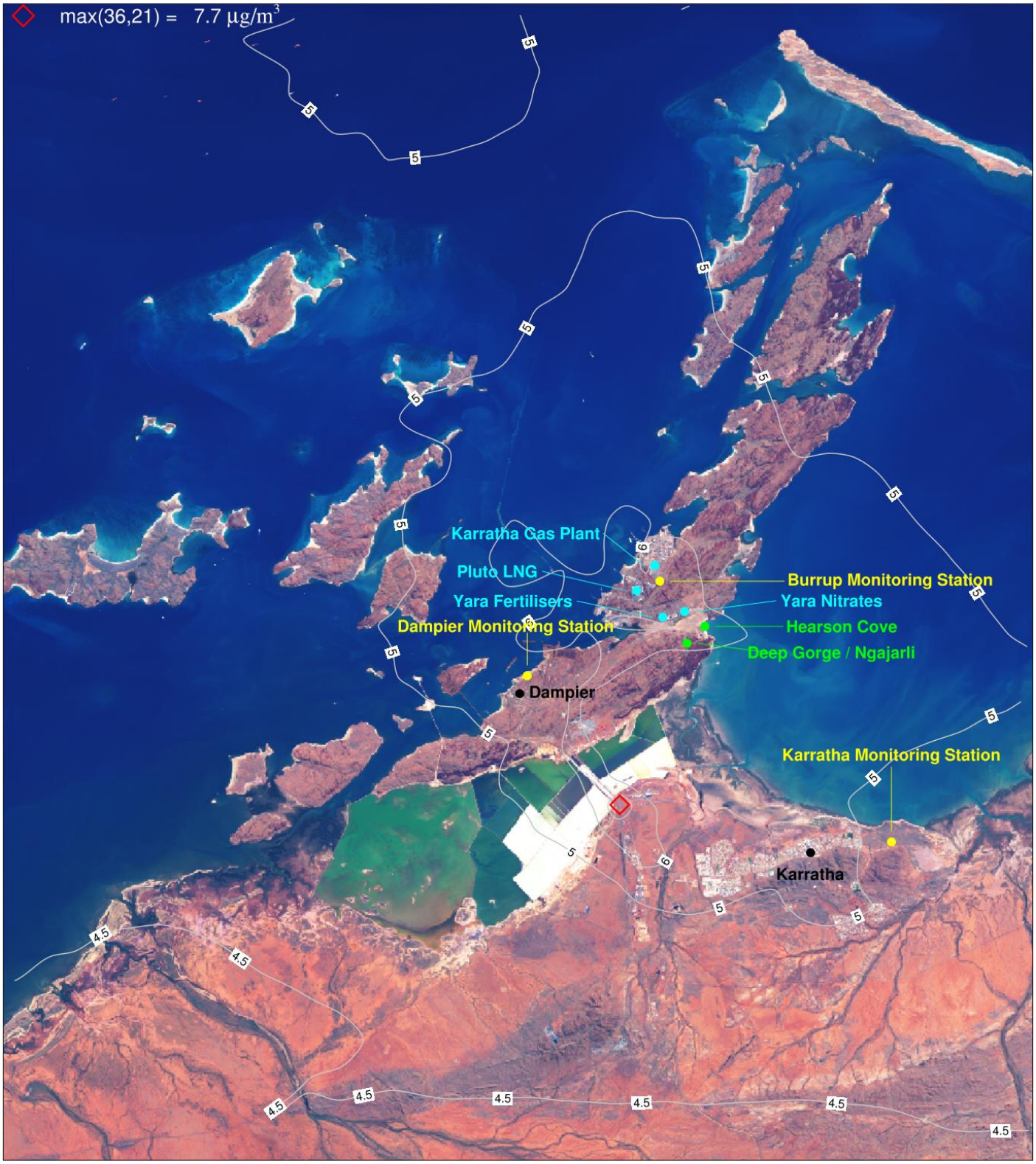


Figure 6-37. $PM_{2.5}$ (µg/m³) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-38. $PM_{2.5}$ (µg/m³) annual max 24-hour concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

6.3.2 Predicted Ground Level Concentrations from Existing Industry

Predicted ground level concentrations due to emissions from existing industry are shown in Figure 6-39 to Figure 6-59. The majority of benzene, TOL, and XYL emissions came from the industry near or on the Burrup Peninsula (Figure 6-41 to Figure 6-46). SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and NH_3 emissions are also centred near industry near or on the Burrup Peninsula, showing that industrial sources and shipping contribute to emissions in the area. For $PM_{2.5}$ in particular (Figure 6-58), the location of the regional maximum offshore off the Burrup Peninsula points to both primary (e.g. black carbon from exhaust) and secondary (SO_2 and NOx) $PM_{2.5}$ contributions from shipping emissions. However, total cumulative ground level concentrations (Scenario 2, discussed above) remain below current air quality standards except for benzene and PM_{10} and $PM_{2.5}$.

For several short-term air quality metrics (i.e., MDA1) industry emissions are a large contributor showing that the highest short-term ground level concentrations tend to occur when industrial emissions are high. SO_2 and NO_2 show significant influences from shipping emissions offshore, especially for MDA1 values. Predicted SO_2 and NO_2 ground level concentrations are also relatively high in the areas around Wickham and Burrup Road. However, they are lower than the predicted ground level concentrations near Dampier. Relatively high NO_2 ground level concentrations also occur inland near rail transportation corridors. NO_X emissions from industry result in the suppression of O_3 near Dampier. Ammonia emissions from industrial sources have the potential to increase $PM_{2.5}$ concentrations near the source by forming ammonium sulphate and/or ammonium nitrate (Figure 6-49). Hg annual average concentrations (see Figure 6-54) are low around Dampier (maximum of 8E-5 µg/m^3) and Karratha (around 4E-6 µg/m^3).

Figure 6-39. Benzene (ppb) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

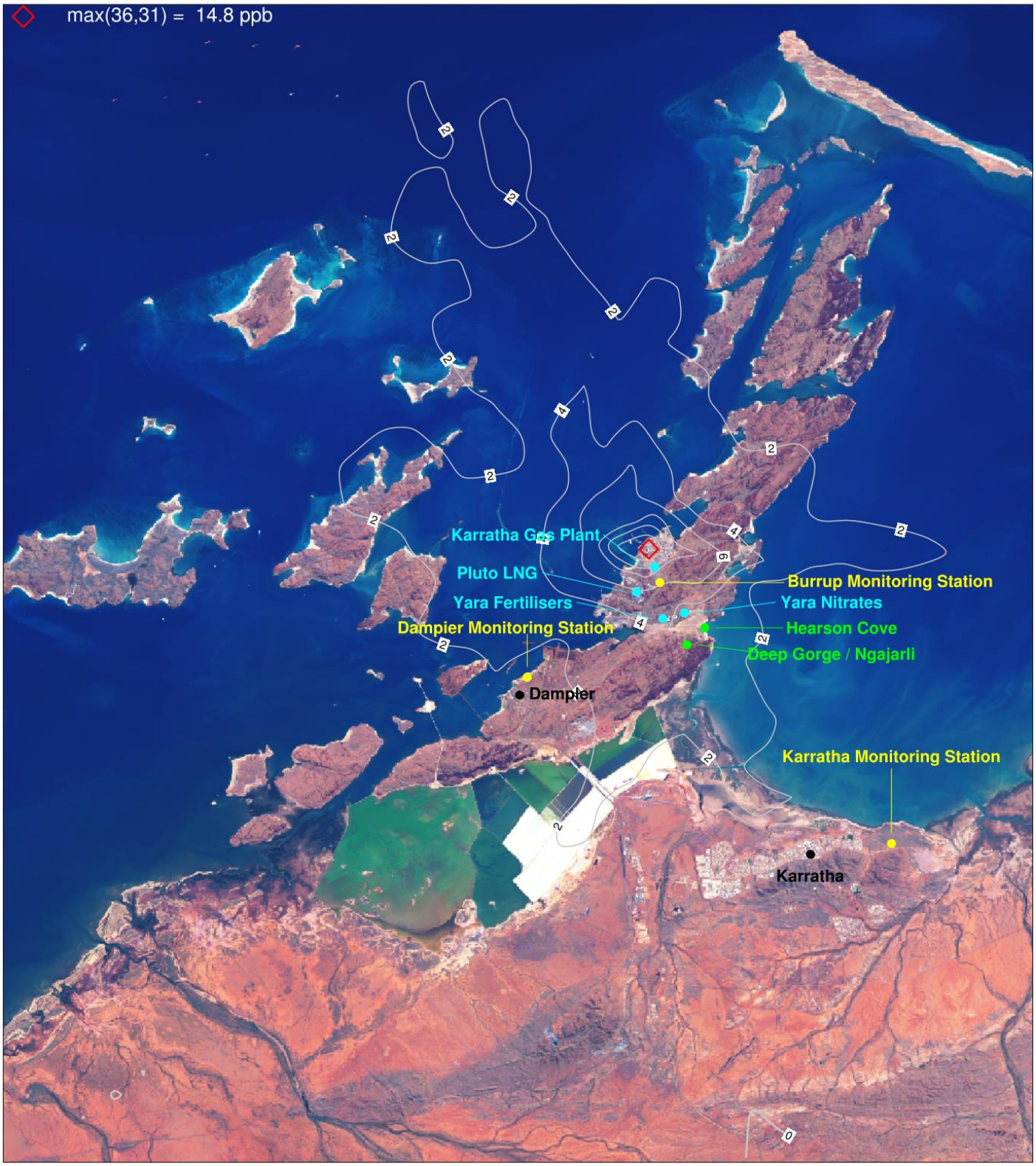


Figure 6-40. Benzene (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

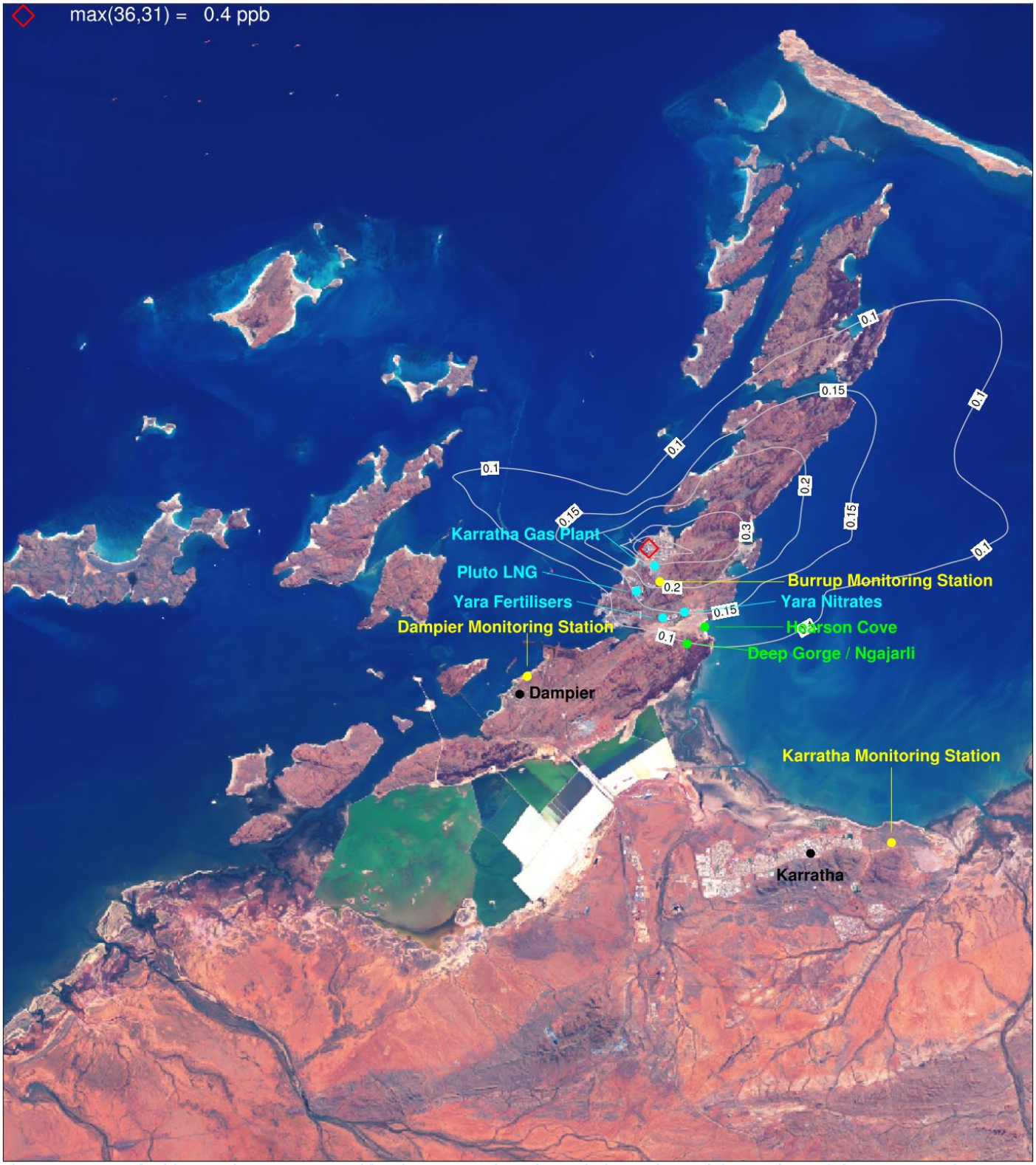


Figure 6-41. TOL (ppb) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-42. TOL (ppb) annual max 24-hour ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

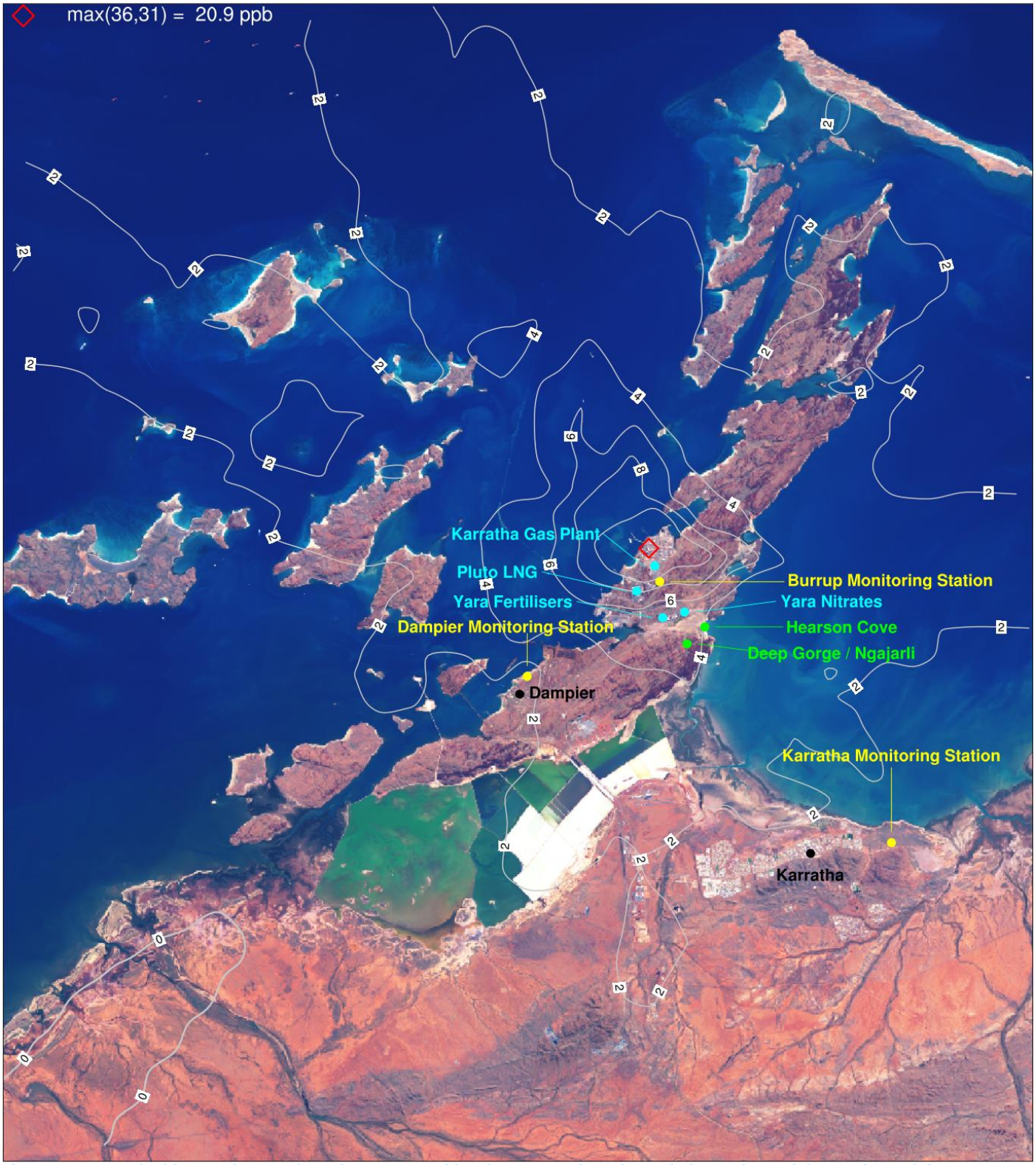


Figure 6-43. TOL (ppb) annual max 1-hour (MDA1 ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-44. XYL (ppb) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-45. XYL (ppb) annual max 24-hour ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

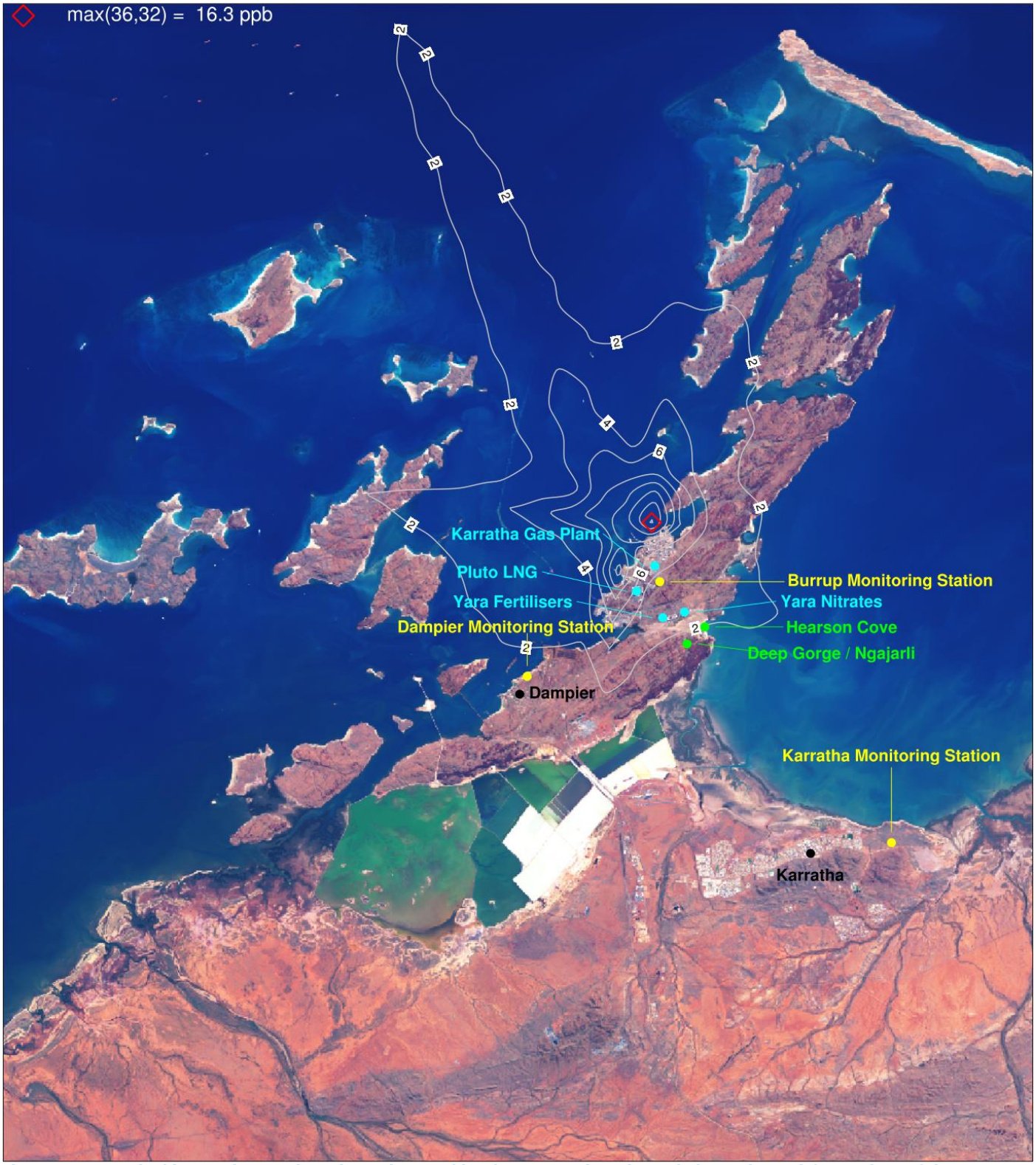


Figure 6-46. XYL (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

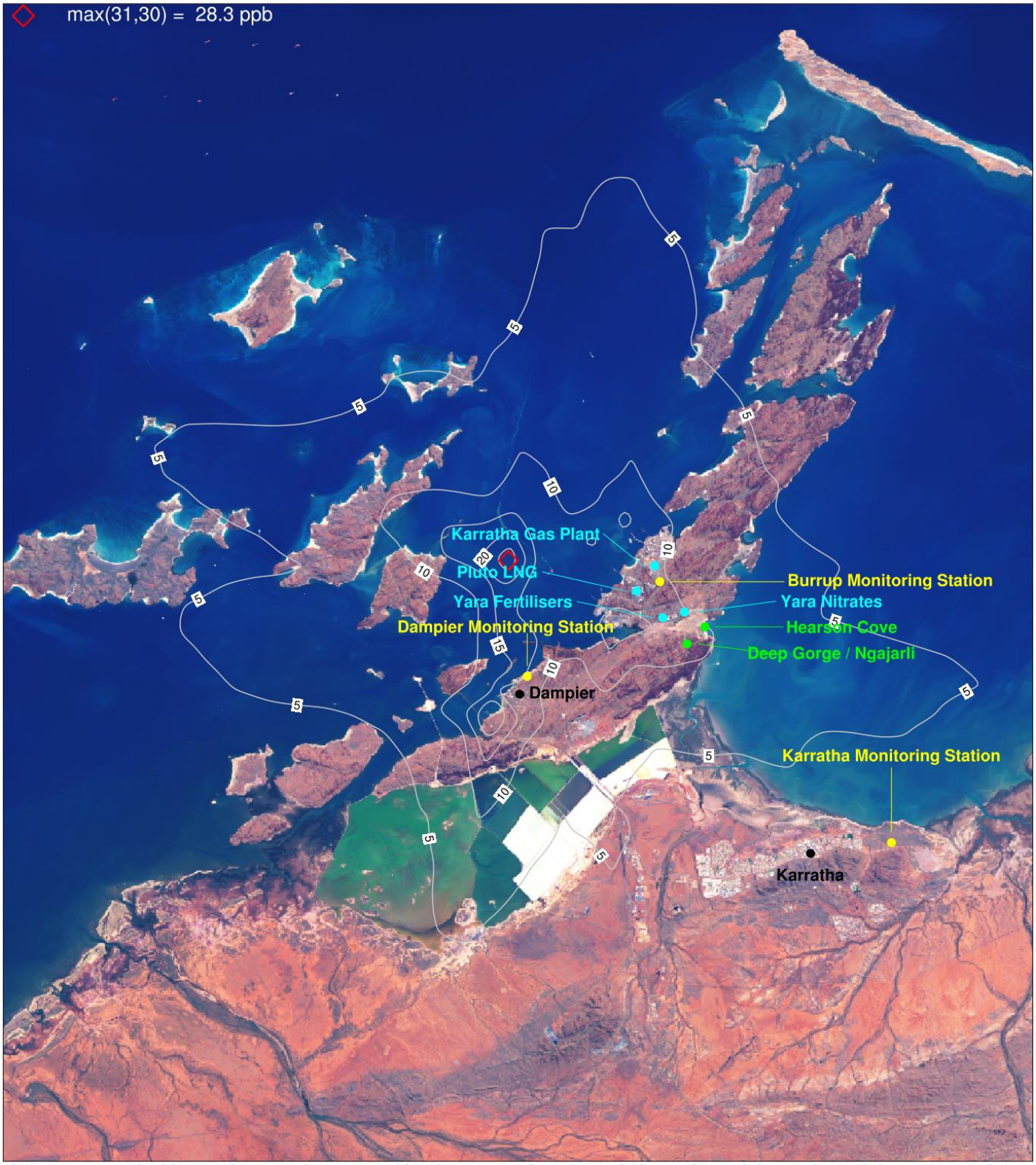


Figure 6-47. SO_2 (ppb) annual max 24-hour ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

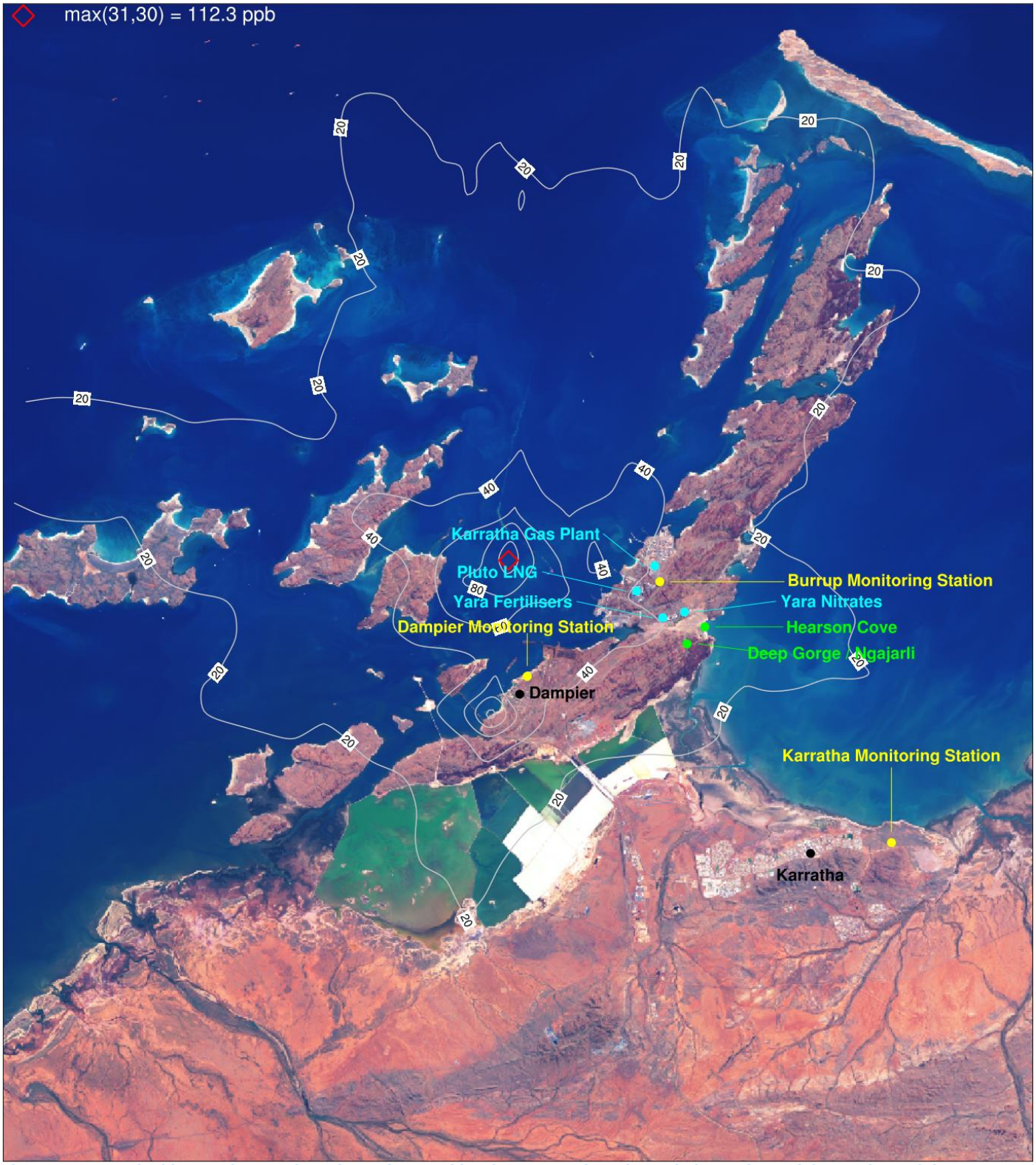


Figure 6-48. SO_2 (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

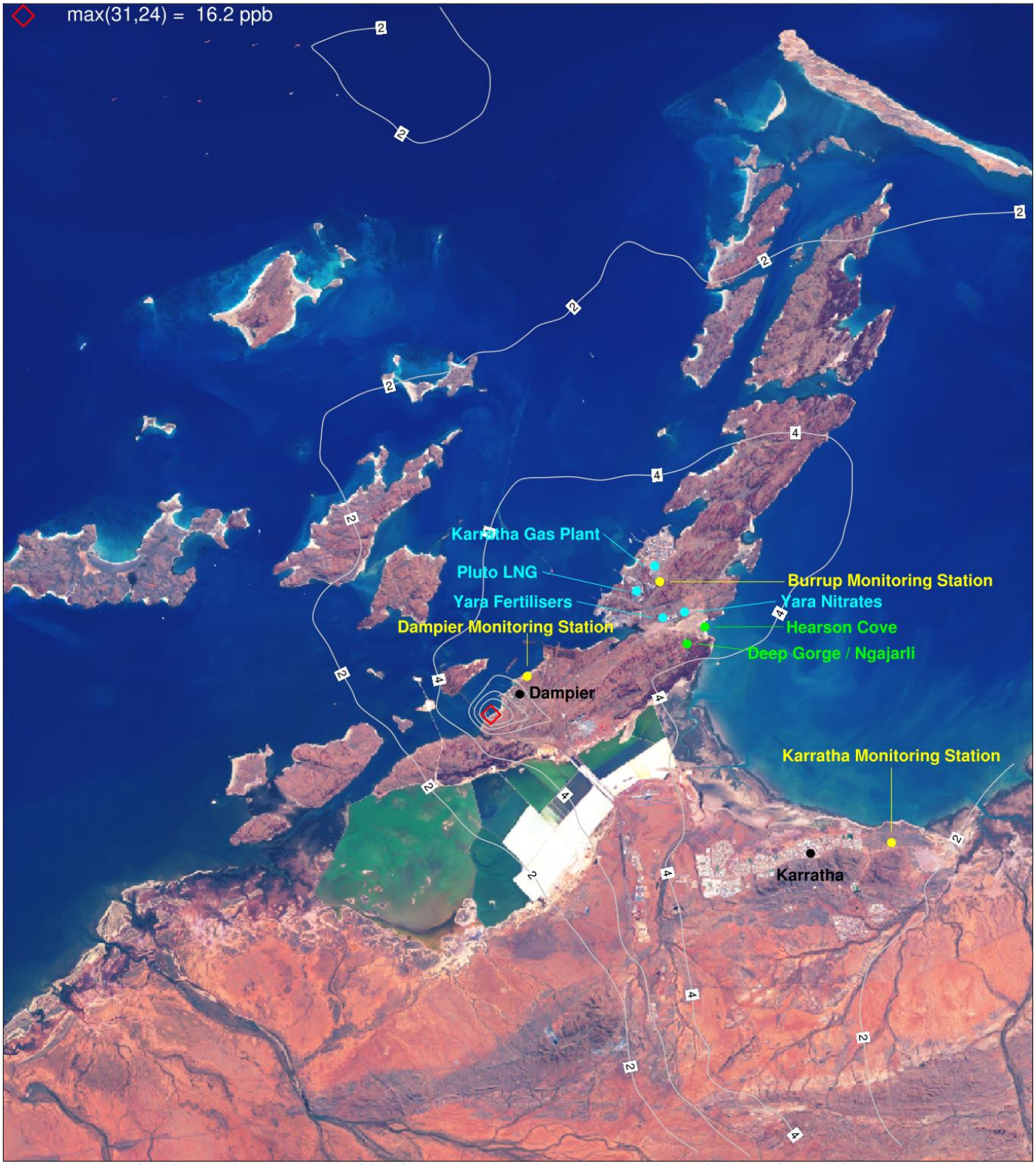


Figure 6-49. NO_2 (ppb) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

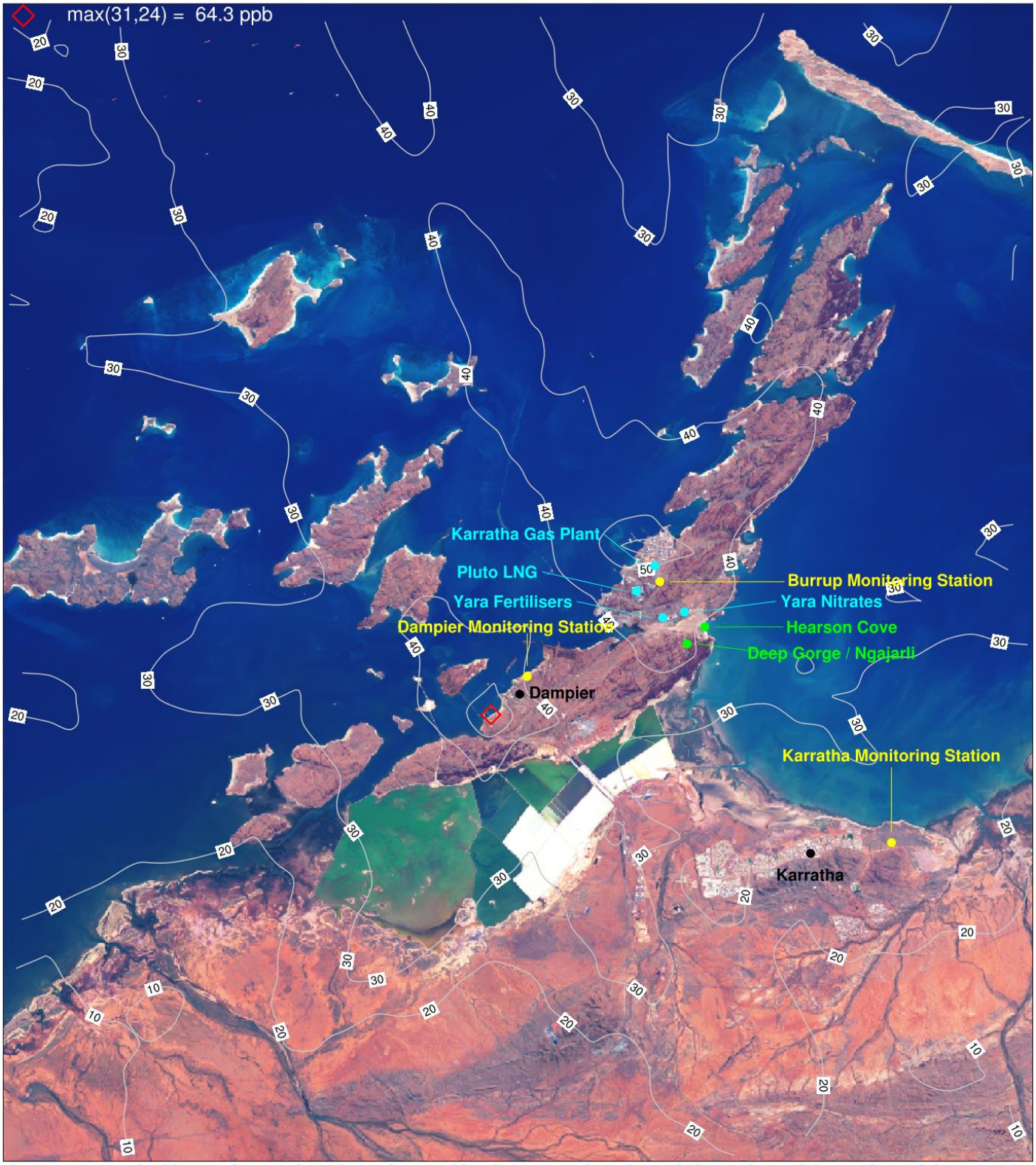


Figure 6-50. NO_2 (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-51. CO (ppb) annual max 8-hour (MDA8) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

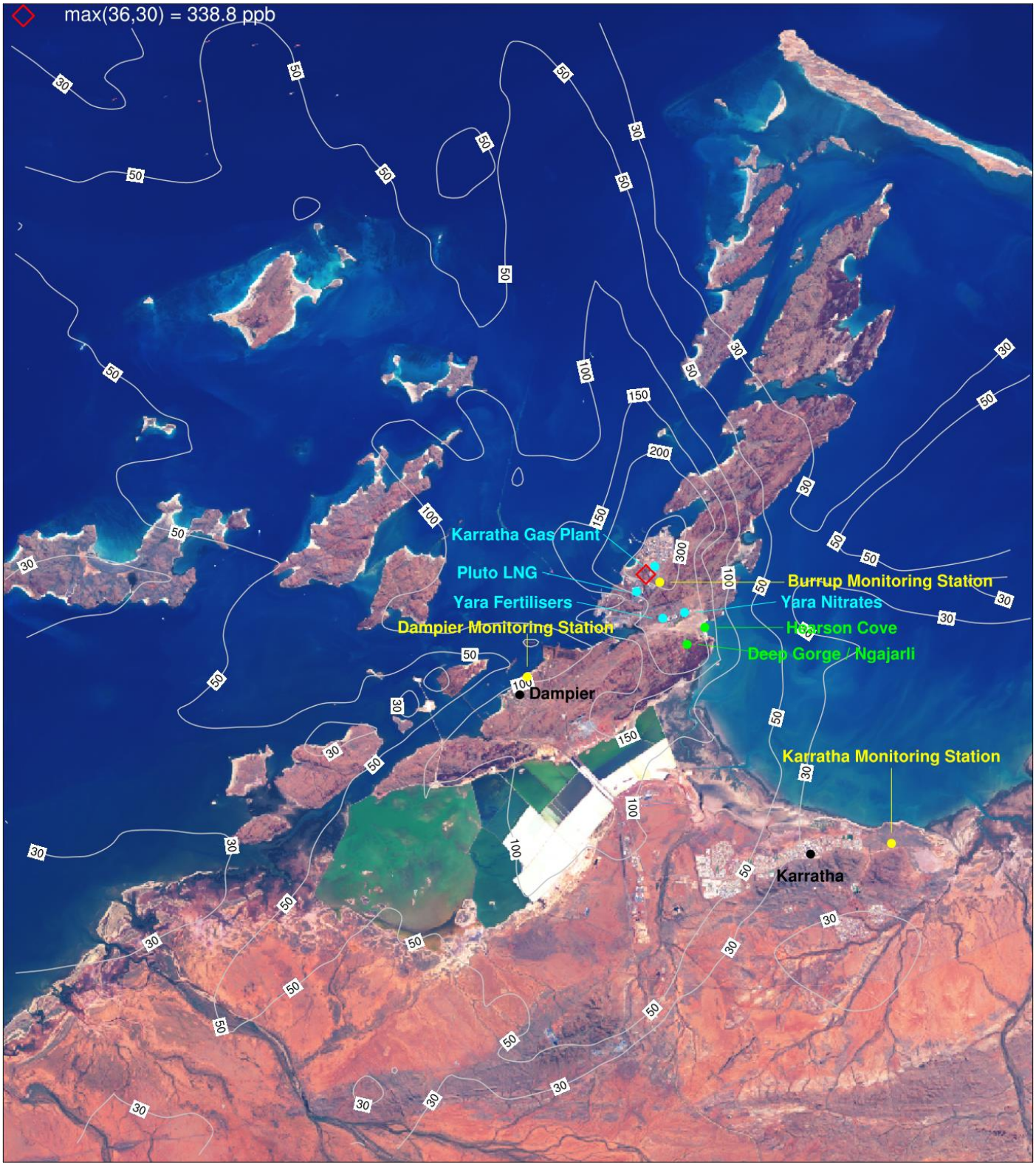


Figure 6-52. NH_3 (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

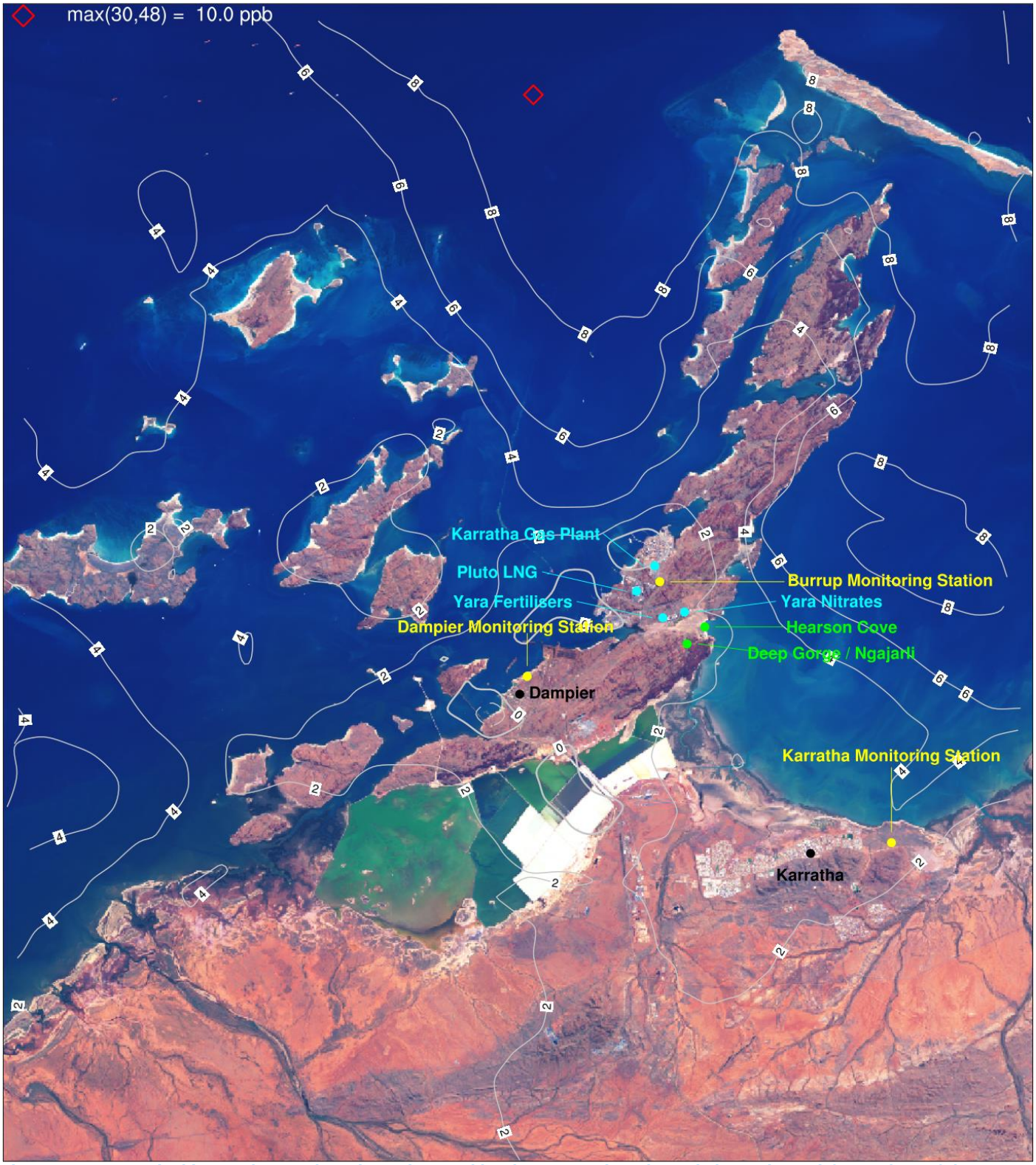


Figure 6-53. Ozone (ppb) annual max 8-hour (MDA8) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-54. Hg (µg/m³) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-55. Hg (µg/m³) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-56. PM_{10} (µg/m³) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-57. PM_{10} (µg/m³) annual max 24-hour ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-58. $PM_{2.5}$ (µg/m³) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-59. $PM_{2.5}$ (µg/m³) annual max 24-hour ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

6.3.3 Predicted Ground Level Concentrations from Future Industry

The predicted change in ground level concentrations from Scenario 2 (2014) due to future (2030) industry are shown in Figure 6-59 to Figure 6-84. Annual average Hg concentrations remain mostly constant with a small decrease near Dampier (Figure 6-75). Predicted Hg ground level concentrations from both existing and future industrial sources are small and can be negative due to indirect effects of changes in oxidant concentrations on mercury concentration. Annual maximum daily 1-hour average (MDA1) NO_2 decreases by 13.6 ppb near Dampier which likely results from Woodside's proposed replacement of existing gas turbines with more efficient-low NO_x devices at Karratha Gas Plant (Figure 6-71). An increase in MDA1 NO_2 over water occurs in an area where O_3 concentrations also increase and may result from complex changes to the NO_2/NO_x ratio. $PM_{2.5}$ and PM_{10} also show decreases in the area near Dampier in 2030, likely connected to decreases in PM precursors (Figure 6-77 to Figure 6-80). MDA1 SO_2 concentrations decrease offshore by up to 86 ppb due to the introduction of International Maritime Organisation (IMO) regulations that limit the fuel-sulphur content for marine vessels (Figure 6-69).

Benzene, toluene, and xylene ground level concentrations increase in the future due to additional industrial emissions (Figure 6-60 to Figure 6-67). Industry contributions to O_3 concentrations also increase for maximum daily 8-hour average (MDA8) O_3 most likely because VOC emission increase combined with NO_x emission decreases for some sources (i.e., higher VOC/NO_x ratio) accelerate O_3 formation downwind of industry sources in Scenario 3 compared to Scenario 2 (Figure 6-74) although additional sensitivity modelling would be needed to demonstrate the O_3 sensitivity to NOx and VOC emission changes. Industry contributions to MDA8 CO increase by 359 ppb near the Yara Ammonium Nitrate Plant that were not included in Scenario 2 as the Plant did not exist in 2014 (Figure 6-72).

Although there was an increase in the total mass of ammonia emissions to air due to the inclusion of the Perdaman Urea Project, the short-term maximum 1-hour concentrations of NH_3 were predicted to significantly decrease in the region. This is due to the reduction of ammonia due to proposed mitigation of vented ammonia emissions during shutdown events at the Yara Ammonia plant.

6.3.3.1 Ammonium Nitrate

Ammonium nitrate PM is emitted into the Murujuga airshed. Ammonium nitrate PM is semi-volatile and, in the atmosphere, tends to convert to gaseous nitric acid and ammonia at a rate that depends on temperature, humidity, and the presence of other PM (Seinfeld and Pandis, 2016). Gaseous nitric acid and ammonia can interact with particles and return to the particulate phase, e.g., nitric acid can interact with sea salt spray and form sodium nitrate PM; ammonia can interact with sulphuric acid and form ammonium sulphate PM. The CAMx photochemistry schemes include reactions that form and remove ammonium nitrate PM in the atmosphere. Close to sources of ammonium nitrate PM emission it is reasonable to expect that the sum of ammonium PM and nitrate PM (ammonium plus nitrate) is indicative of the ammonium nitrate source contribution. 2014 industry ground level concentrations of ammonium plus nitrate (Figure 6-82) show a maximum of 0.1 $\mu g/m^3$, which increases to 0.5 $\mu g/m^3$ in the future industry scenario (Figure 6-83).

Figure 6-60. Benzene (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

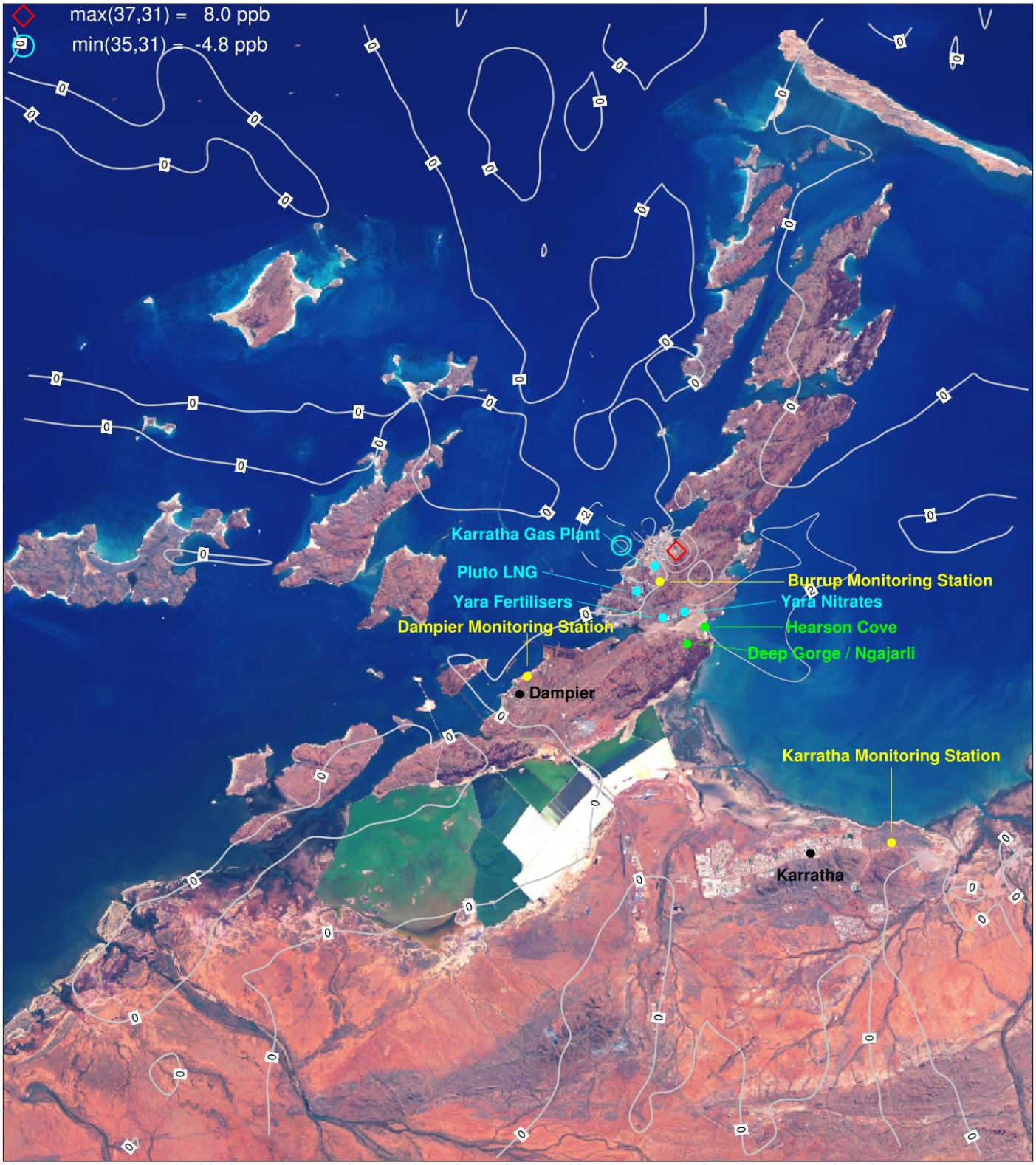


Figure 6-61. Benzene (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-62. TOL (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

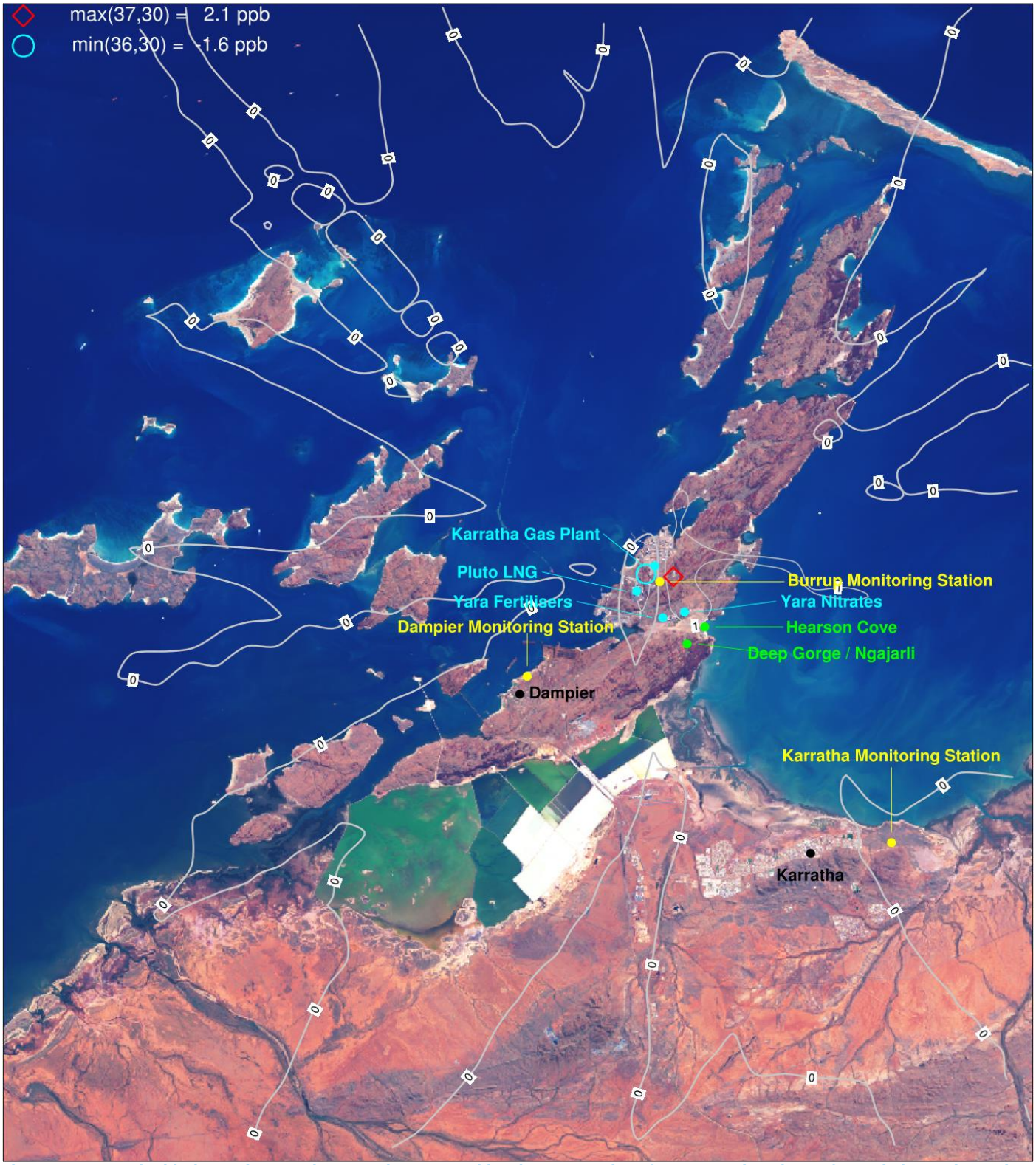


Figure 6-63. TOL (ppb) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

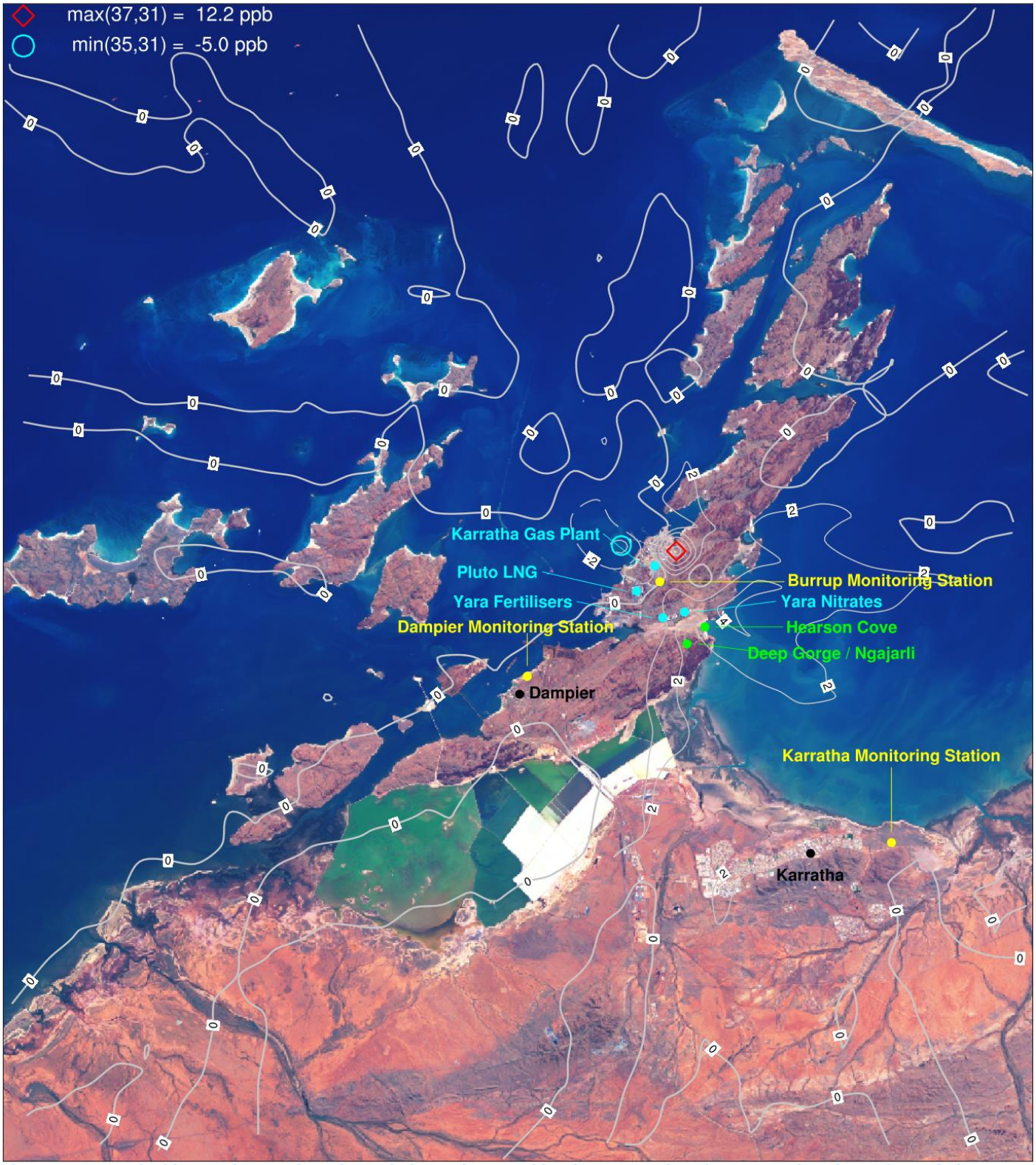


Figure 6-64. TOL (ppb) annual max 1-hour (MDA1) change in ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

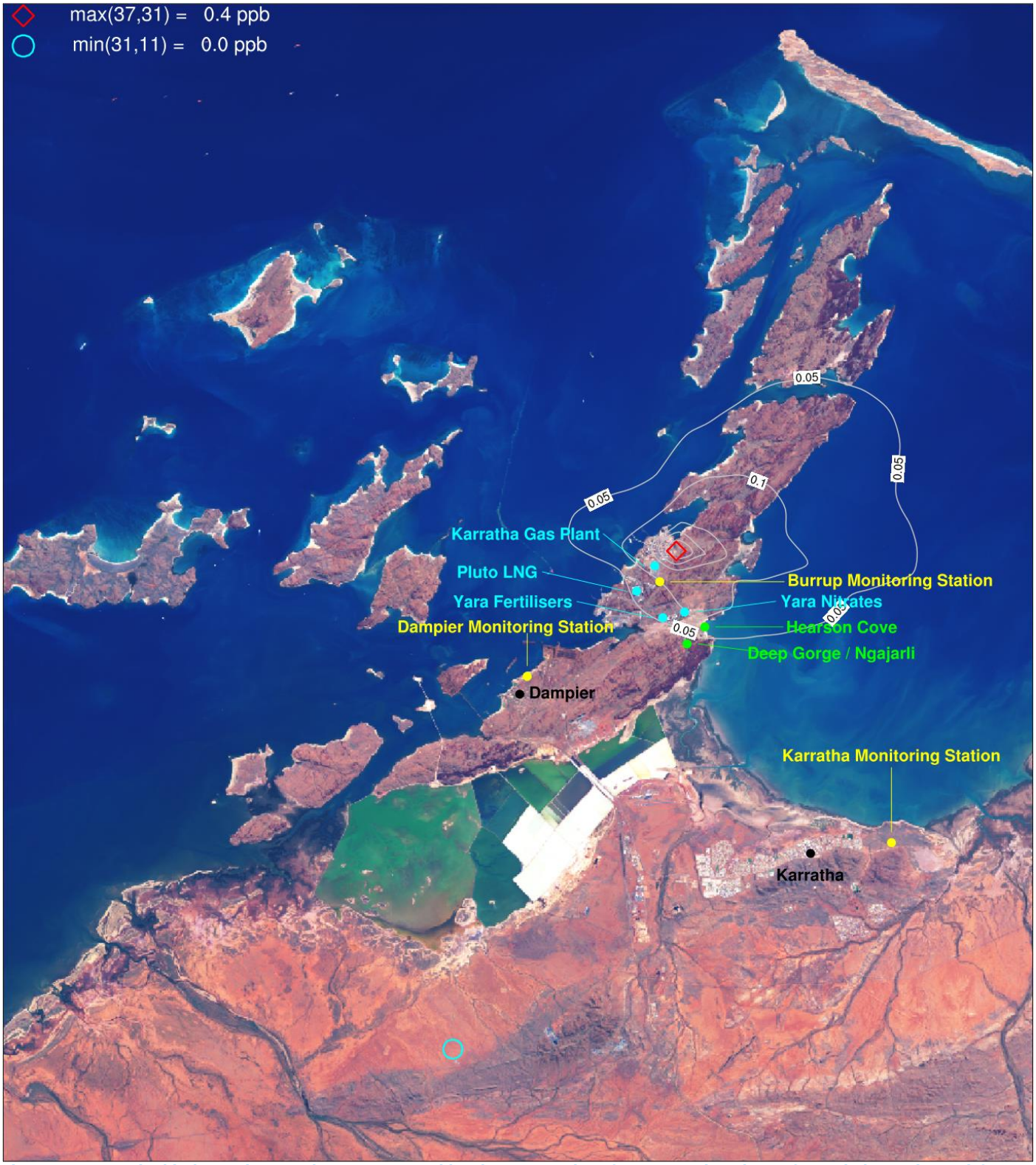


Figure 6-65. XYL (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

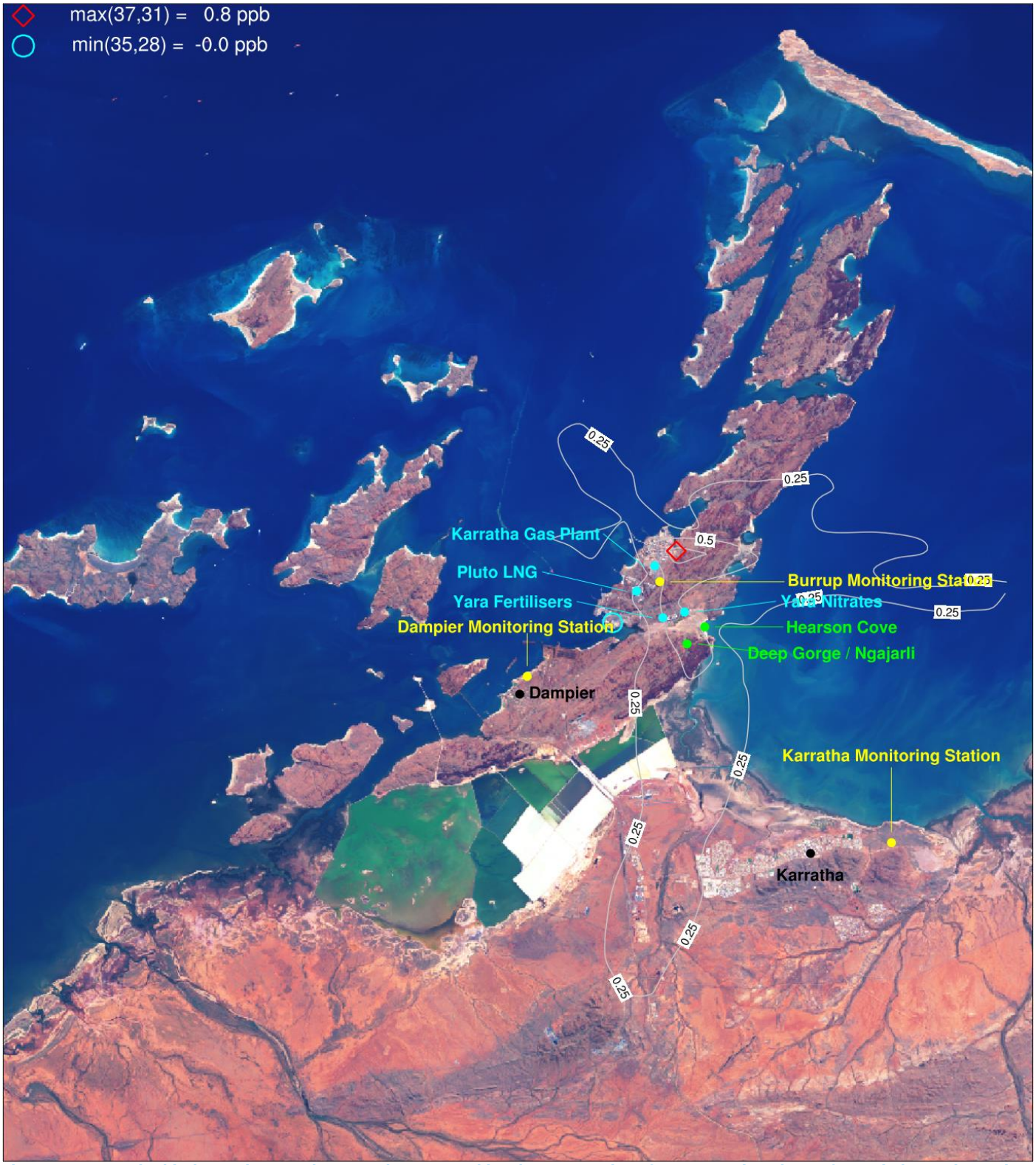


Figure 6-66. XYL (ppb) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

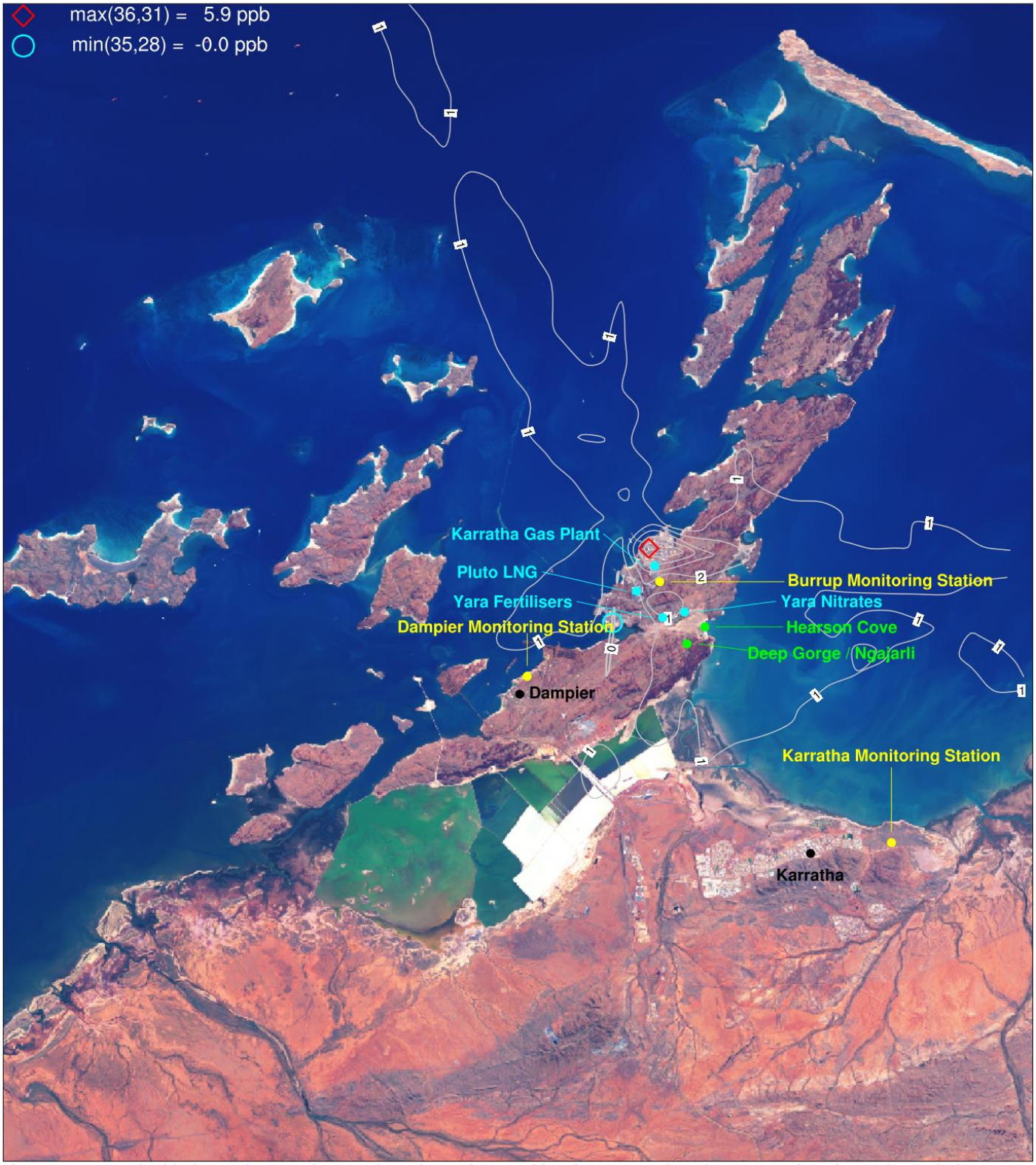


Figure 6-67. XYL (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-68. SO_2 (ppb) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-69. SO_2 (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-70. NO_2 (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

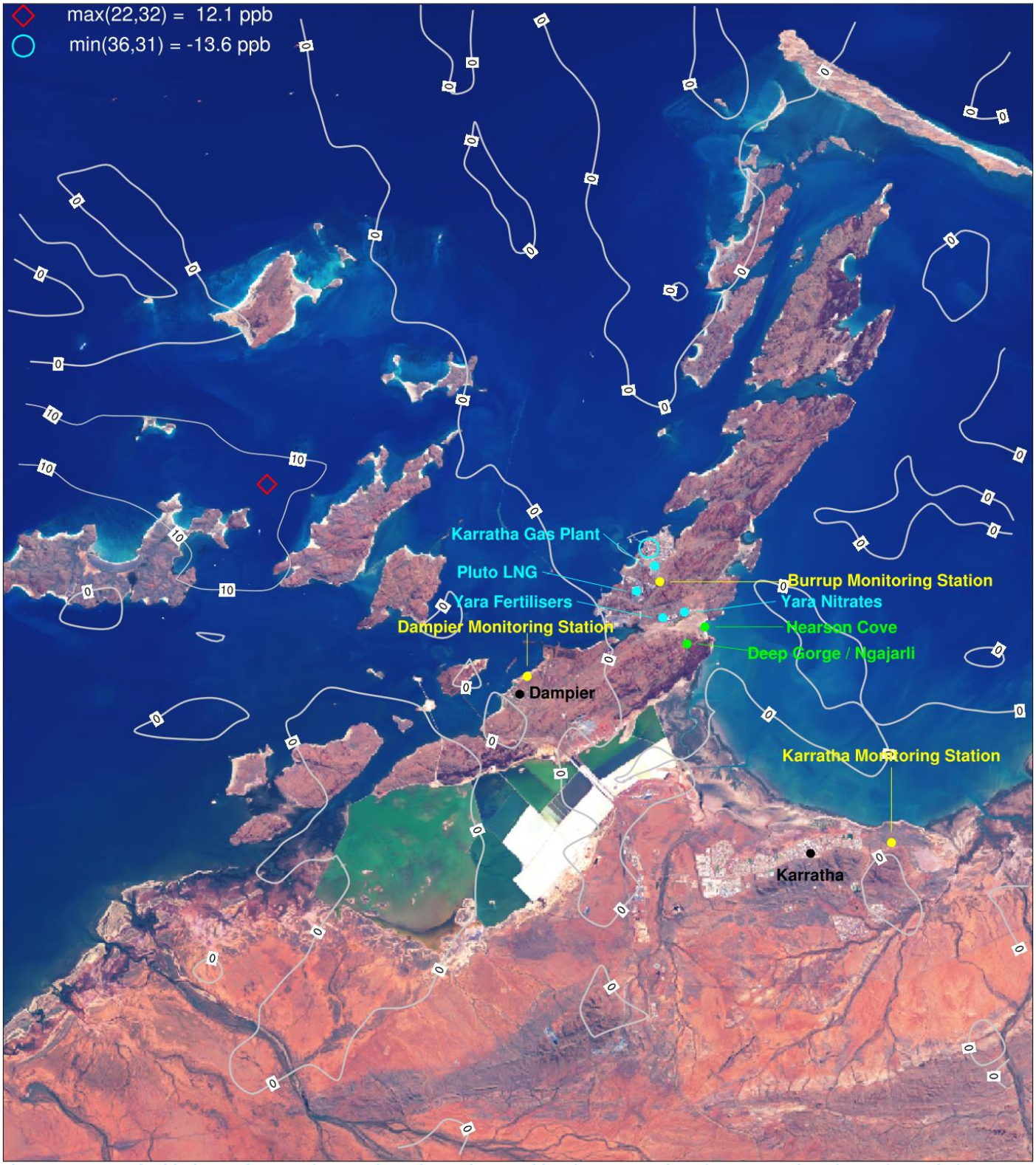


Figure 6-71. NO_2 (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-72. CO (ppb) change in annual max 8-hour (MDA8) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-73. NH_3 (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

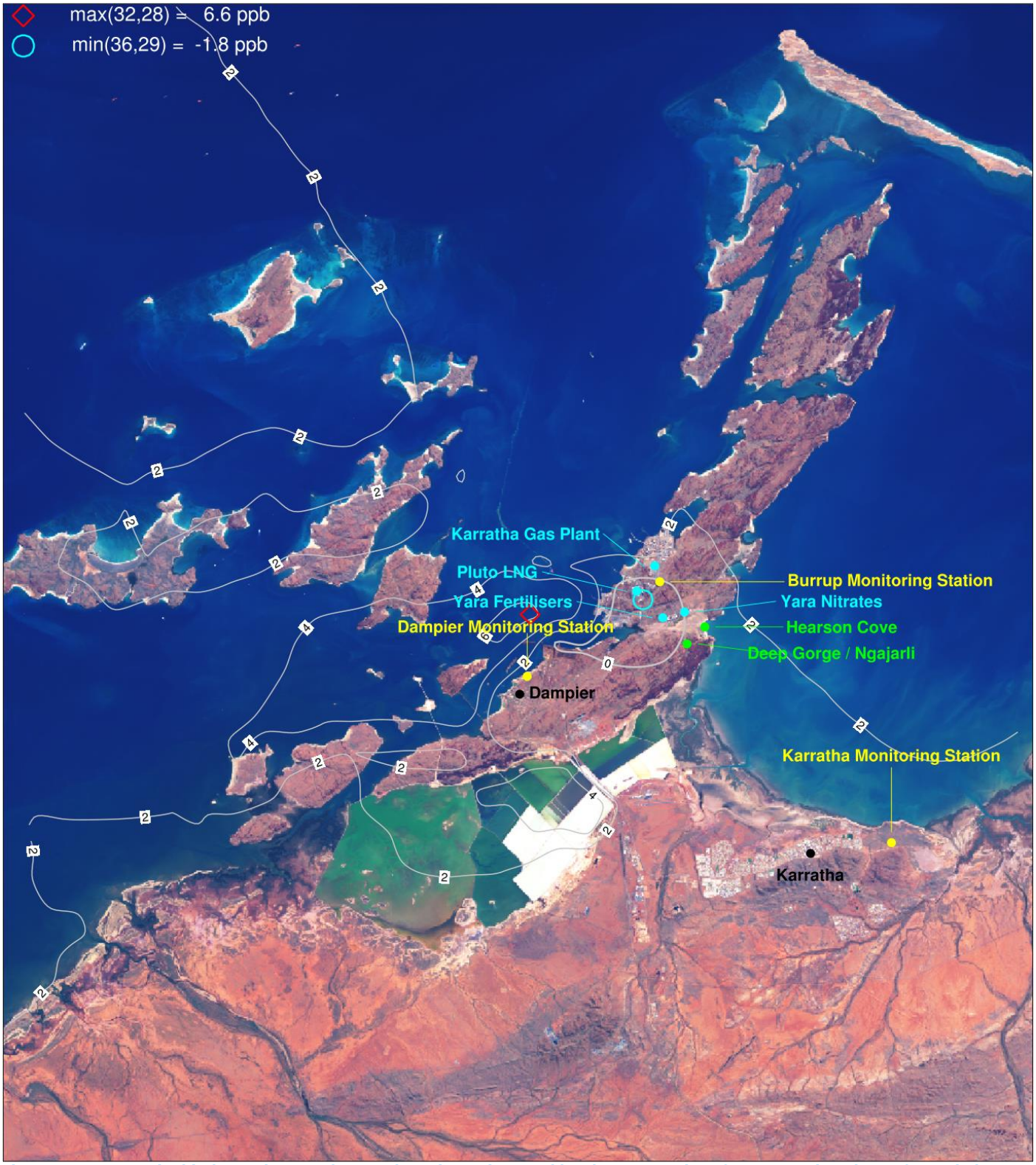


Figure 6-74. Ozone (ppb) change in annual max 8-hour (MDA8) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

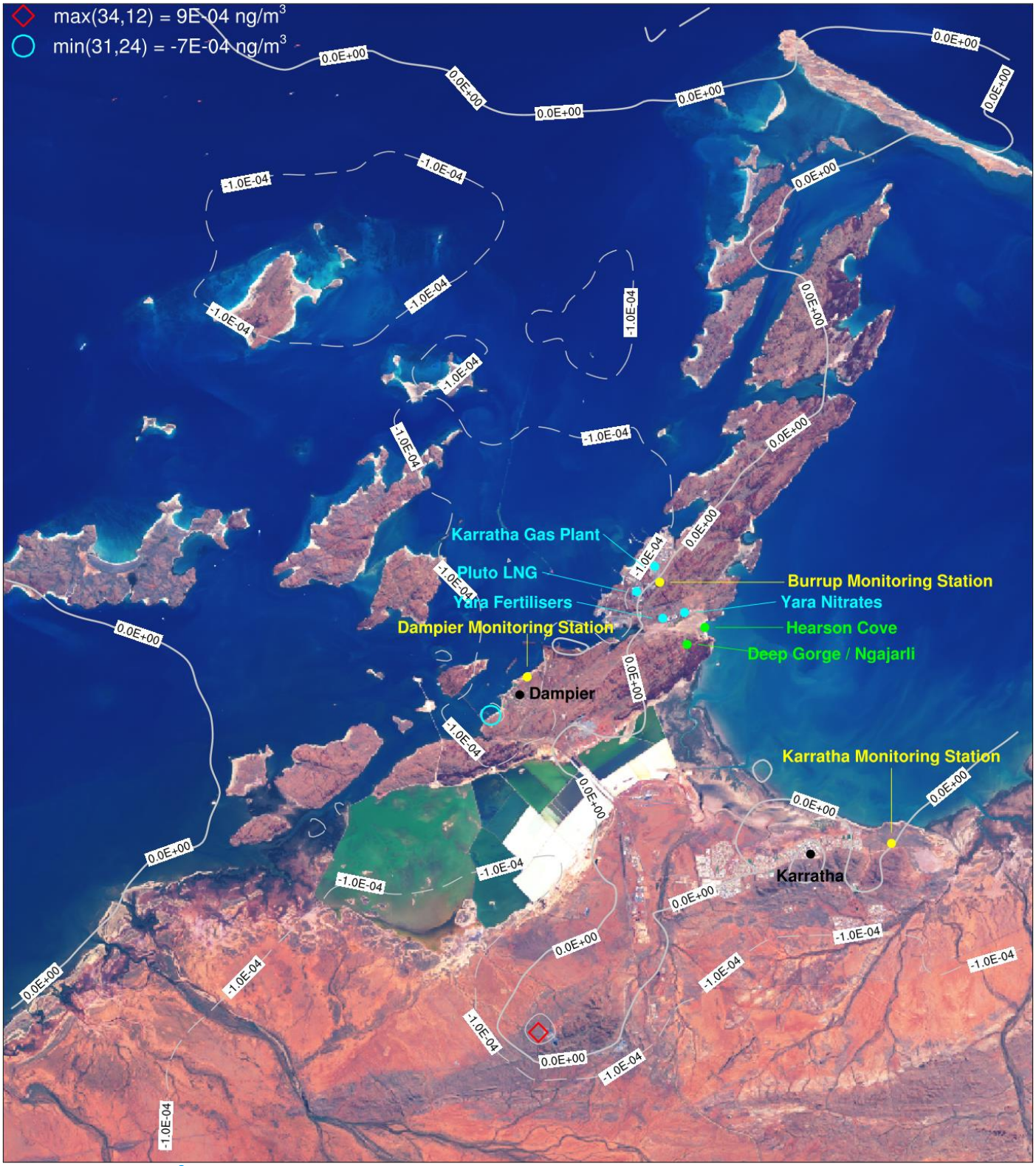


Figure 6-75. Hg (ng/m^3) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

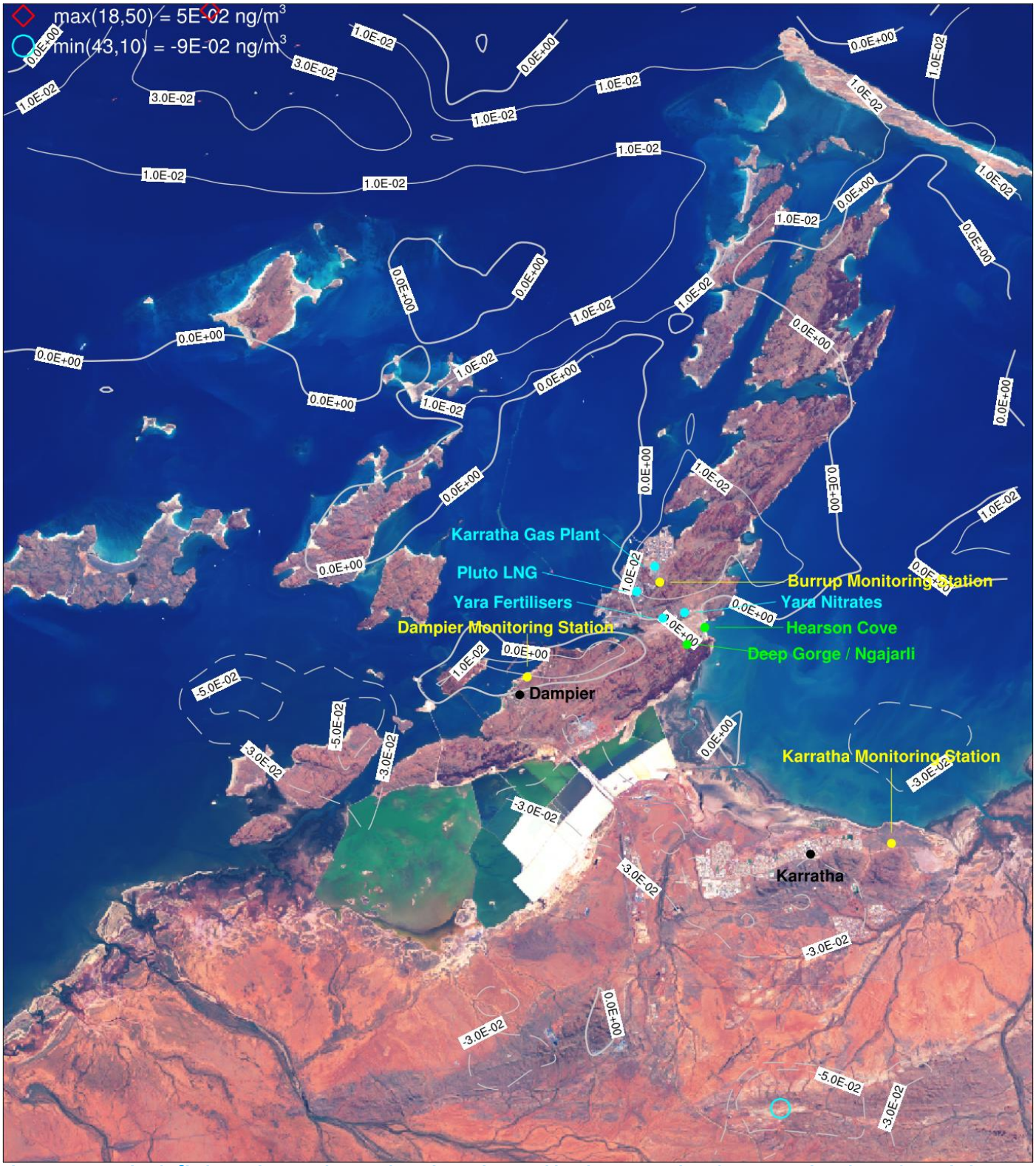


Figure 6-76. Hg (ng/m^3) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-77. PM_{10} (µg/m^3) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-78. PM_{10} (µg/m^3) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-79. $PM_{2.5}$ (µg/m³) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

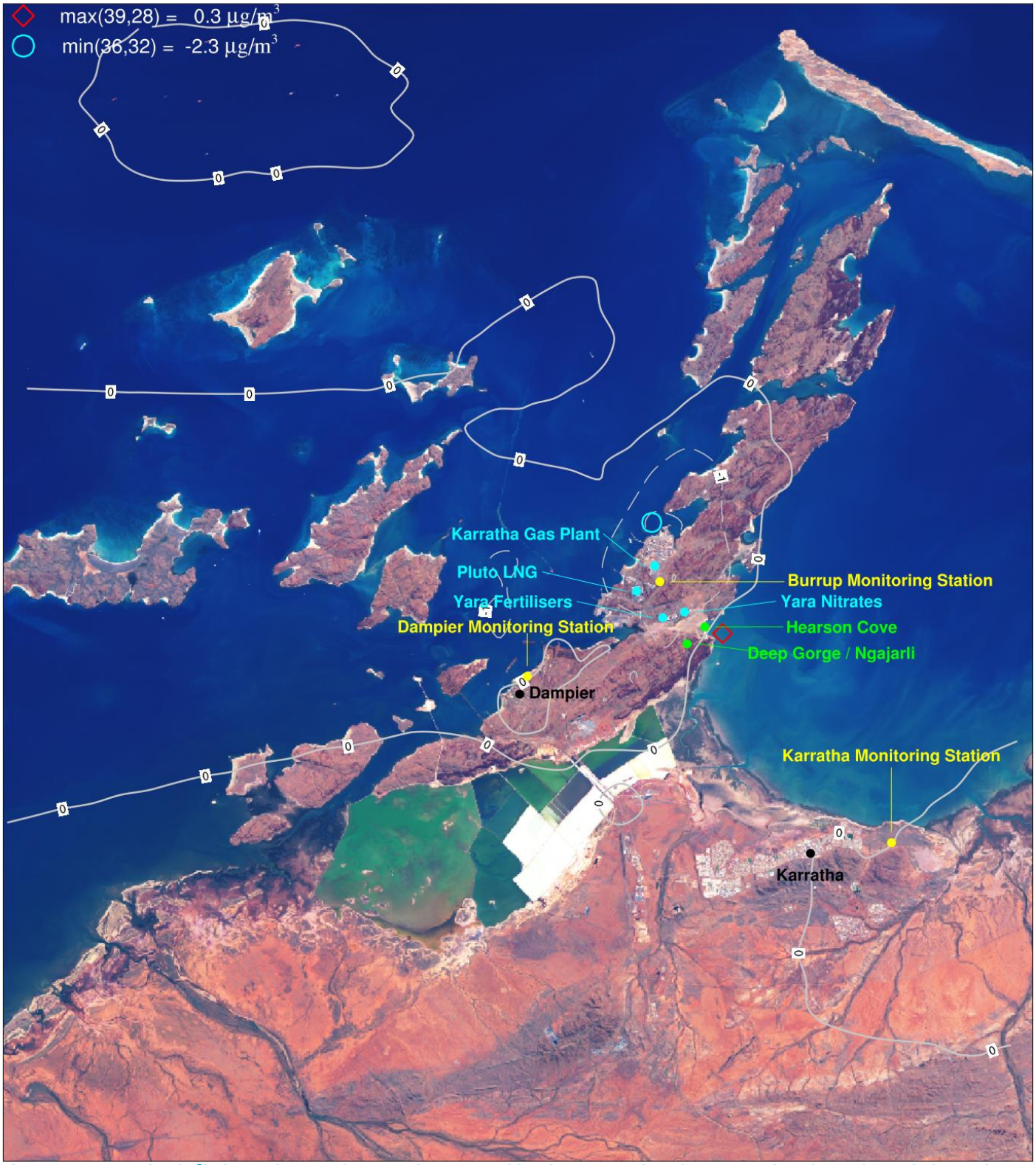


Figure 6-80. $PM_{2.5}$ (µg/m³) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-81. Ammonium plus nitrate (µg/m³) annual average concentrations for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

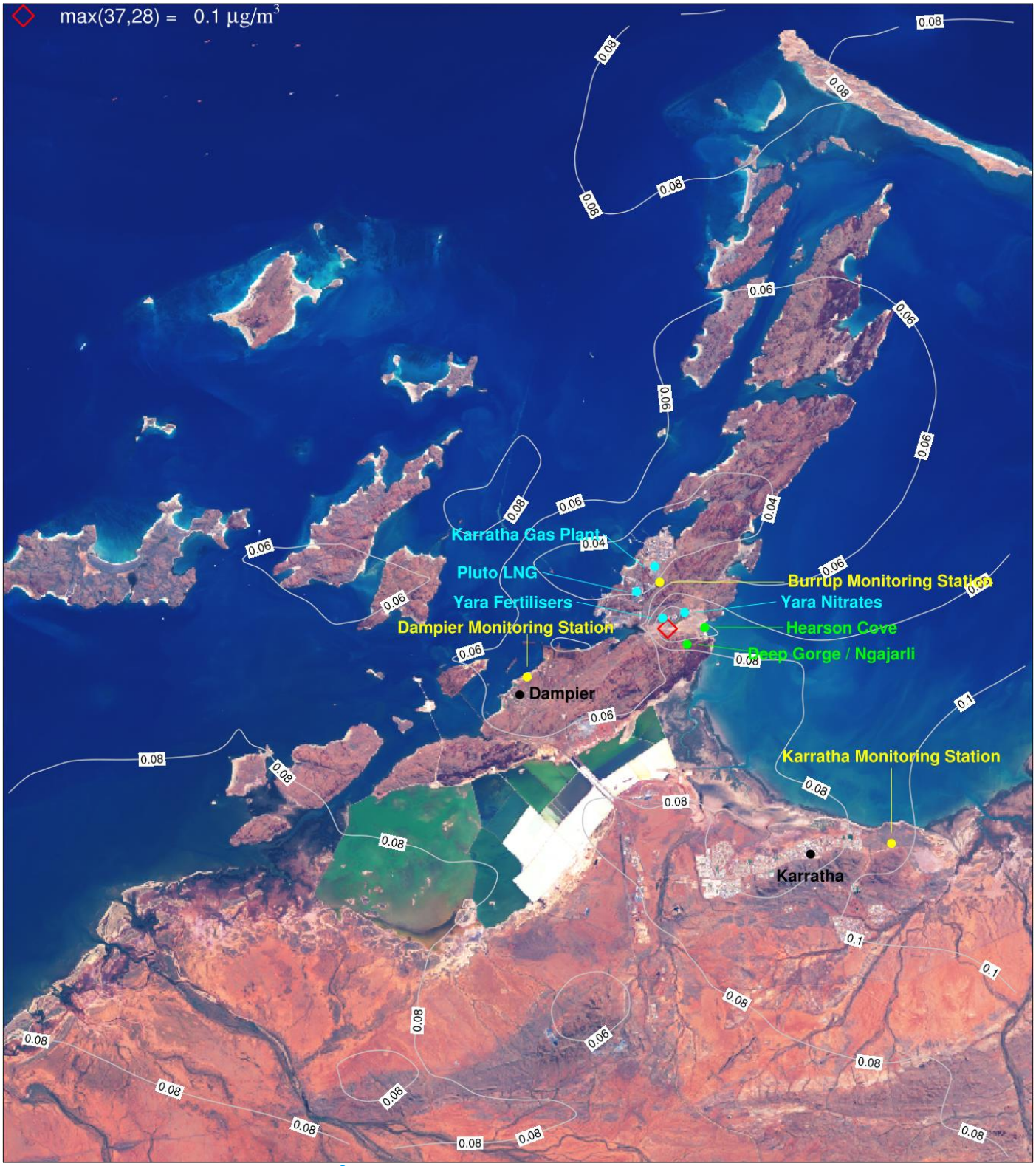


Figure 6-82. Ammonium plus nitrate (µg/m³) annual average ground level concentrations due to industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-83. Ammonium plus nitrate (µg/m³) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-84. Urea fine dust (µg/m³) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

6.3.4 Concentrations at Sensitive Receptors

Ambient concentrations for NO_2, O_3, PM_{10}, $PM_{2.5}$, SO_2, and benzene were reported at locations of monitoring sites and sensitive sites for Scenario 2 and Scenario 3 in Table 6-5, Table 6-6, and Table 6-8. It should be noted that these concentrations are for the grid cell containing each location (i.e., representative of a 1.33 by 1.33 km area) because CAMx is a grid model and is not able to provide concentrations at discrete receptor locations.

NO_2 annual maximum daily 1-hour (MDA1) and annual average concentrations were predicted to be below the MDA1 standard of 80 ppb and 15 ppb for annual average (Table 6-5). The majority of the contribution to predicted ground level concentrations of NO_2 is from industry. Future industry either increased or decreased NO_2 depending on location and concentration metric. The largest NO_2 increase in Table 6-5 is 3.00 ppb in annual maximum MDA1 NO_2 at Karratha whereas the largest decrease is 4.85 ppb in annual maximum MDA1 NO_2 at Burrup Road. The NO_2 decrease at Burrup Road is attributable to planned NOx emission reductions at Woodside. The NO_2 increase at Karratha is for a location where O_3 concentrations also increase and may result from complex changes to the NO_2/NOx ratio.

O_3 was predicted to be below the 8-hr standard of 65 ppb at all locations for both Scenarios 2 and 3 (Table 6-5). Future industry increased O_3 at all locations. In general, these O_3 increases are attributable to VOC emission increases combined with NO_X emission decreases for some sources (i.e., higher VOC/NO_X ratio) that accelerate O_3 formation downwind of industry sources in Scenario 3 compared to Scenario 2.

Table 6-6 shows that PM_{10} exceeds the annual average standard (25 µg/m^3) at all locations for both Scenarios 2 and 3, with the exception of Karratha for Scenario 2 which falls just below 25 µg/m^3 (24.59 µg/m^3). PM_{10} exceeds the 24-hr standard (50 µg/m^3) at all locations for both Scenarios 2 and 3. However, there is some uncertainty that the simulation of background PM_{10} is unbiased because of uncertainties in the boundary concentrations (from CAM-chem) and windblown dust emissions. Most of the PM_{10} emissions are not due to industrial activity. In the annual average, only 2 to 4 µg/m^3 are attributed to industry at Hearson Cove, Deep Gorge/Ngajarli, Burrup Road and Dampier and only 0.92 µg/m^3 at Karratha. Future industry is expected to increase annual average PM_{10}, but by less than 0.6 µg/m^3. Annual maximum 24-hr PM_{10} concentrations are expected to stay around the same with increases smaller than 0.45 µg/m^3 at these locations and a small decrease (0.04 µg/m^3) at Dampier.

Table 6-6 also reports the contributions from background (non-industrial) sources, from CAMx Scenario 1. These estimated background contributions include: 1) dust (crustal material) and other PM that enters the model through the boundaries of the 4 km domain; 2) windblown dust emissions from unpaved roadways; 3) sea salt PM; 4) secondary organic aerosol from biogenic VOC emissions; and 5) primary and secondary PM from anthropogenic (non-industrial) emissions sources. Estimated background PM_{10} contributes 23-29 µg/m^3 to the annual average and 85-95 µg/m^3 in maximum 24-hr concentrations (although the maximum 24-hr PM_{10} could have occurred on different dates for Scenario 1 and Scenario 2). Background PM_{10} makes up 85-96% of the annual average PM_{10} (see Table 6-7) and represents 92-99% of the maximum 24-hr total PM_{10} concentrations. Dust sources alone (i.e., crustal material from categories 1 and 2 above) contribute approximately 66-73% of the annual average PM_{10} and 79-86% of the maximum 24-hr PM_{10} concentrations. Background $PM_{2.5}$ contributes 4.6-5.8 µg/m^3 to the annual average and around 16-17 µg/m^3 in maximum 24-hr concentrations. Background $PM_{2.5}$ makes up 82-94% of the annual average total $PM_{2.5}$ (see Table 6-7) and represents 87-99% of the maximum 24-hr total $PM_{2.5}$ concentrations. Dust sources alone (i.e., crustal material from categories 1 and 2

above) contribute approximately 31-44% of the annual average $PM_{2.5}$ and 66-74% of the maximum 24-hr $PM_{2.5}$ concentrations.

$PM_{2.5}$ was predicted to be below the annual average standard (current/future of 8/7 µg/m^3) at all locations for both Scenarios 2 and 3, and the 24-hr standard (current/future of 25/20 µg/m^3). However, there is some uncertainty that the simulation of background $PM_{2.5}$ is unbiased because of uncertainties in the boundary concentrations (from CAM-chem) and windblown dust emissions. The predicted annual average $PM_{2.5}$ concentrations are similar to the $PM_{2.5}$ observed at each of the monitoring stations (Table 4-4). $PM_{2.5}$ concentrations are similar at the locations in Table 6-6, consistent with most of the $PM_{2.5}$ being regional and a minority of the $PM_{2.5}$ coming from industry. $PM_{2.5}$ concentrations are expected to stay relatively constant with slight decreases in the future, with the exception of Burrup Road, which is expected to see a decrease of 0.54 µg/m^3 in annual maximum 24-hr $PM_{2.5}$, and Deep Gorge, which is expected to remain relatively constant with a slight increase of 0.03 µg/m^3.

Table 6-7 shows the percent contribution to annual average PM_{10} and $PM_{2.5}$ (µg/m^3) ground level concentrations (GLCs) from industry GLCs and future industry GLCs. Industry GLCs contribute around 8% to 9% of annual average PM_{10} in Scenario 2 at Hearson Cove, Deep Gorge, and Burrup Road with larger contribution at Dampier (15.5%) and lower contribution at Karratha (3.8%). For $PM_{2.5}$, industry GLCs contribute around 13% to 17% of annual average $PM_{2.5}$ in Scenario 2 at Hearson Cove, Deep Gorge, and Burrup Road with larger contribution at Dampier (18.4%) and lower contribution at Karratha (6.2%).

Future industry GLCs contribute only around 1% to 2% to annual average PM_{10} in Scenario 3 with the contribution at Karratha being the highest (2.3%) and the lowest contribution at Burrup Road (0.9%). Future industry GLCs contributions to annual average $PM_{2.5}$ in Scenario 3 are negative at all sites except Karratha (0% change from Scenario 2) likely due to decreases in secondary $PM_{2.5}$ precursor emissions associated with a drop in shipping emissions in the region.

SO_2 concentrations at monitoring sites and sensitive sites stay well below the 1-hr standard (current/future of 100/75 ppb) at all locations for both Scenarios 2 and 3, and the 24-hr standard (20 ppb) (Table 6-8). The majority of the contribution to predicted ground level concentrations of SO_2 is from industry. Future concentrations are expected to drop substantially, by 33.04 ppb for MDA1 SO_2 at Dampier Monitoring Station. These decreases are attributable to the introduction of International Maritime Organisation (IMO) regulations that limit the fuel-sulphur content for marine vessels.

Benzene was below the 1-hr standard (9 ppb) and the annual average standard (3 ppb) at all monitor locations and sensitive locations for both Scenarios 2 and 3 (Table 6-8). However, benzene concentrations exceed the 1-hr standard for Scenario 2 in the vicinity of Karratha Gas Plant (15.3 ppb). Future benzene concentrations are expected to increase by up to 1.41 ppb in annual maximum MDA1 benzene at Hearson Cove and 1.28 ppb at Deep Gorge/Ngajarli. The modelled future benzene increases are associated with potential fugitive Total VOCs from the proposed methanol plant which were provided without detailed speciation. The higher benzene in the future year, while still well below the guidelines, is uncertain because it was obtained while assuming default VOC speciation (specifically, default benzene fraction of fugitive VOC) for fugitive leaks.

Table 6-9 shows the annual max 1-hour (MDA1), annual average, and annual max TOL and XYL air concentrations in the CAMx grid cells that contain Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha. Concentrations remain well below the standard

(MDA1/annual average/annual max of 89/200/1000 ppb for TOL and 41/200/250 for XYL). Predicted ground level concentrations due to industry are highest in the grid cell containing Burrup Road, reaching 8.81 ppb for TOL and 3.37 ppb for XYL for MDA1. Future industry ground level concentrations reach 1.88 ppb in MDA1 for TOL at Hearson Cove and 1.53 ppb for XYL at Burrup Road.

Table 6-10 shows the annual max 1-hour (MDA1) and annual average mercury and annual max 8-hour (MDA8) CO air concentrations in the CAMx grid cells containing Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha. Mercury concentrations are well below the standard of 2 $\mu g/m^3$ for MDA1. Predicted Hg ground level concentration changes due to both existing and future industrial sources are extremely small at all the sites, and in many cases, they are negative due to indirect effects of changes in oxidant concentrations on mercury concentration. CO MDA8 concentrations also remain well below the standard of 2000 ppb with concentrations staying below 450 ppb in all grid cells except Hearson Cove, which reached a concentration of 975.2 ppb.

Table 6-11 shows the annual average total VOCs (in ppb), ammonium plus nitrate (in $\mu g/m^3$), and urea fine dust (in $\mu g/m^3$) air concentrations in the CAMx grid cells containing Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha. Annual average VOCs range from around 7 ppb to 15 ppb in each of the grid cells. Industry ground level concentrations are highest in the grid cell containing Burrup Road (9.52 ppb versus less than 2.5 ppb in the other grid cells). Future industry ground level concentrations are highest in the grid cells containing Burrup Road (8.82 ppb) and Hearson Cove (10.12 ppb). Ammonium plus nitrate concentrations range from 0.48 to 0.504 $\mu g/m^3$ with industry ground level concentrations contributing between 0.05 $\mu g/m^3$ and 0.11 $\mu g/m^3$. Future industry ground level concentrations are expected to increase between 0.08 $\mu g/m^3$ and 0.15 $\mu g/m^3$. Predicted urea dust ground level concentrations due to industrial emissions are expected to increase by up to 0.75 $\mu g/m^3$ in the future industry scenario.

Table 6-12 shows the annual max 1-hour (MDA1) NH_3 air concentrations in the CAMx grid cells containing Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha. MDA1 NH_3 concentrations are highest at Burrup Road (326 ppb), followed by Deep Gorge/Ngajarli (268 ppb) and Hearson Cove (236 ppb). Future industry ground level concentrations are expected to decrease substantially at these three receptors (with predicted reductions of 206 ppb at Hearson Cove and 309 ppb at Burrup Road) due to proposed mitigation of vented ammonia emissions from the Yara Ammonia Plant, such that the future year industrial scenario shows MDA1 NH_3 concentrations of 30 ppb or less across all receptors.

Table 6-5. Annual max 1-hour (MDA1) and annual NO_2, and annual max 8-hour (MDA8) O_3 (ppb) ground level concentrations (GLCs) in the CAMx grid cells that contain Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha.

		NO_2 (ppb)		O_3 (ppb)
		MDA1	Annual Avg	MDA8
CAMx Scenario 2	Hearson Cove	44.46	5.21	44.05
	Deep Gorge/Ngajarli	45.45	4.28	43.25
	Burrup Road	48.07	6.22	44.32
	Dampier	45.24	7.55	42.71
	Karratha	32.86	3.39	45.67
Industry GLCs (S2-S1)	Hearson Cove	40.01	4.99	1.62
	Deep Gorge/Ngajarli	40.27	4.04	1.45
	Burrup Road	44.26	6.04	1.22
	Dampier	40.05	7.17	0.77
	Karratha	22.36	2.24	2.72
Future Industry GLCs (S3-S2)	Hearson Cove	-1.00	0.56	0.36
	Deep Gorge/Ngajarli	-1.88	0.52	0.43
	Burrup Road	-4.85	0.67	0.38
	Dampier	1.17	0.63	1.71
	Karratha	3.00	0.14	0.70
CAMx Scenario 3	Hearson Cove	43.46	5.76	44.40
	Deep Gorge/Ngajarli	43.56	4.80	43.68
	Burrup Road	43.23	6.89	44.69
	Dampier	46.41	8.19	44.43
	Karratha	35.86	3.53	46.37

Table 6-6. Annual average and annual max PM_{10} and $PM_{2.5}$ ($\mu g/m^3$) ground level concentrations (GLCs) in the CAMx grid cells that contain Hearson Cove, Deep Gorge, Burrup Road, Dampier Monitoring Station, and Karratha.

		PM_{10} ($\mu g/m^3$)		$PM_{2.5}$ ($\mu g/m^3$)	
		Annual Avg	Annual Max 24hr	Annual Avg	Annual Max 24hr
Background dust (S1)	Hearson Cove	28.56	93.74	5.79	16.77
	Deep Gorge/Ngajarli	24.74	90.61	5.04	16.12
	Burrup Road	27.38	95.36	5.41	16.96
	Dampier	22.54	93.67	4.57	16.73
	Karratha	23.66	85.30	4.78	15.82
CAMx Scenario 2	Hearson Cove	31.11	97.66	6.80	18.07
	Deep Gorge/Ngajarli	27.17	91.48	5.79	16.27
	Burrup Road	29.93	96.31	6.54	19.42
	Dampier	26.68	102.26	5.60	17.47
	Karratha	24.59	86.67	5.10	16.31
	Hearson Cove	2.54	3.93	1.01	1.31

		PM_{10} (µg/m^3)		$PM_{2.5}$ (µg/m^3)	
		Annual Avg	**Annual Max 24hr**	**Annual Avg**	**Annual Max 24hr**
Industry GLCs (S2-S1)	**Deep Gorge/Ngajarli**	2.43	0.87	0.75	0.15
	Burrup Road	2.55	0.95	1.13	2.46
	Dampier	4.13	8.59	1.03	0.74
	Karratha	0.92	1.37	0.32	0.48
Future Industry GLCs (S3-S2)	**Hearson Cove**	0.44	0.45	-0.11	-0.22
	Deep Gorge/Ngajarli	0.46	0.27	-0.10	0.03
	Burrup Road	0.29	0.26	-0.20	-0.54
	Dampier	0.33	-0.04	-0.26	-0.05
	Karratha	0.57	0.42	0.01	-0.16
CAMx Scenario 3	**Hearson Cove**	31.54	98.12	6.69	17.85
	Deep Gorge/Ngajarli	27.63	91.75	5.69	16.30
	Burrup Road	30.22	96.58	6.34	18.87
	Dampier	27.01	102.22	5.34	17.42
	Karratha	25.16	87.09	5.11	16.15

Table 6-7. Percent contribution to annual average PM_{10} and $PM_{2.5}$ ($\mu g/m^3$) ground level concentrations (GLCs) from industry GLCs, future industry GLCs and background dust in the CAMx grid cells that contain Hearson Cove, Deep Gorge, Burrup Road, Dampier Monitoring Station, and Karratha.

		Contribution (%) to Annual Avg PM_{10}	Contribution (%) to Annual Avg $PM_{2.5}$
Industry GLCs (S2-S1)/S2	**Hearson Cove**	8.2%	14.9%
	Deep Gorge/Ngajarli	8.9%	12.9%
	Burrup Road	8.5%	17.2%
	Dampier	15.5%	18.4%
	Karratha	3.8%	6.2%
Future Industry GLCs (S3-S2)/S3	**Hearson Cove**	1.4%	-1.6%
	Deep Gorge/Ngajarli	1.7%	-1.8%
	Burrup Road	0.9%	-3.1%
	Dampier	1.2%	-5.0%
	Karratha	2.3%	0.2%
Background Dust (S1/S2)	**Hearson Cove**	91.8%	85.1%
	Deep Gorge/Ngajarli	91.1%	87.0%
	Burrup Road	91.5%	82.7%
	Dampier	84.5%	81.6%
	Karratha	96.2%	93.9%

Table 6-8. Annual max 1-hour (MDA1) and annual max 24-hour SO_2, and MDA1 and annual average Benzene (ppb) ground level concentrations (GLCs) in the CAMx grid cells that contain Hearson Cove, Deep Gorge, Burrup Road, Dampier Monitoring Station, and Karratha.

		SO2 (ppb)		Benzene (ppb)	
		MDA1	Annual Max 24hr	MDA1	Annual Avg
CAMx Scenario 2	Hearson Cove	34.33	11.10	3.78	0.10
	Deep Gorge/Ngajarli	29.18	10.61	3.62	0.08
	Burrup Road	35.98	9.93	6.90	0.18
	Dampier	53.25	16.31	1.69	0.06
	Karratha	13.99	3.78	1.46	0.06
Industry GLCs (S2-S1)	Hearson Cove	33.32	10.84	3.17	0.08
	Deep Gorge/Ngajarli	28.22	10.36	3.04	0.06
	Burrup Road	35.02	9.66	6.35	0.16
	Dampier	52.48	16.05	1.12	0.04
	Karratha	13.04	3.37	0.91	0.02
Future Industry GLCs (S3-S2)	Hearson Cove	-25.85	-8.18	1.41	0.05
	Deep Gorge/Ngajarli	-21.75	-7.80	1.28	0.02
	Burrup Road	-26.37	-7.10	0.89	0.20
	Dampier	-33.04	-11.84	0.87	0.01
	Karratha	-9.76	-2.48	0.46	0.00
CAMx Scenario 3	Hearson Cove	8.48	2.92	5.19	0.15
	Deep Gorge/Ngajarli	7.43	2.81	4.90	0.10
	Burrup Road	9.61	2.83	7.79	0.37
	Dampier	20.21	4.47	2.57	0.07
	Karratha	4.23	1.31	1.92	0.06

Table 6-9. Annual max 1-hour (MDA1), annual average, and annual maximum TOL (ppb) and XYL (ppb) ground level concentrations (GLCs) in the CAMx grid cells that contain Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha.

		TOL (ppb)			XYL (ppb)		
		MDA1	Annual Avg	Annual Max 24hr	MDA1	Annual Avg	Annual Max 24hr
CAMx Scenario 2	Hearson Cove	5.31	0.14	1.58	2.11	0.07	0.54
	Deep Gorge/Ngajarli	5.11	0.11	1.70	1.95	0.05	0.49
	Burrup Road	9.65	0.24	2.14	3.51	0.10	0.98
	Dampier	2.30	0.08	0.39	1.41	0.05	0.26
	Karratha	1.94	0.15	0.47	0.98	0.09	0.28
Industry GLCs (S2-S1)	Hearson Cove	4.36	0.12	1.37	1.93	0.06	0.51
	Deep Gorge/Ngajarli	4.20	0.08	1.48	1.75	0.04	0.45
	Burrup Road	8.81	0.22	1.93	3.37	0.10	0.95
	Dampier	1.53	0.05	0.16	1.20	0.03	0.21
	Karratha	0.94	0.03	0.11	0.33	0.02	0.05
Future Industry GLCs (S3-S2)	Hearson Cove	1.88	0.07	0.87	1.30	0.05	0.61
	Deep Gorge/Ngajarli	1.74	0.03	0.63	1.10	0.03	0.60
	Burrup Road	1.30	0.29	2.05	1.53	0.14	0.65
	Dampier	1.28	0.02	0.33	0.59	0.01	0.09
	Karratha	1.32	0.01	0.17	0.54	0.01	0.07
CAMx Scenario 3	Hearson Cove	7.19	0.21	2.46	3.41	0.12	1.15
	Deep Gorge/Ngajarli	6.85	0.14	2.33	3.04	0.08	1.09
	Burrup Road	10.95	0.53	4.20	5.05	0.24	1.63
	Dampier	3.58	0.10	0.72	2.00	0.07	0.35
	Karratha	3.27	0.15	0.64	1.52	0.10	0.34

Table 6-10. Annual max 1-hour (MDA1) and annual average mercury (µg/m^3), and annual maximum 8-hour (MDA8) CO (ppb) ground level concentrations (GLCs) in the CAMx grid cells that contain Hearson Cove, Deep Gorge, Burrup Road, Dampier Monitoring Station, and Karratha.

		Mercury (µg/m^3)		CO (ppb)
		MDA1	Annual Avg	MDA8
CAMx Scenario 2	Hearson Cove	9.59E-05	5.77E-06	975.20
	Deep Gorge/Ngajarli	1.10E-04	5.59E-06	450.31
	Burrup Road	8.49E-05	5.67E-06	402.16
	Dampier	9.25E-05	6.24E-06	247.36
	Karratha	2.08E-04	5.85E-06	246.27
Industry GLCs (S2-S1)	Hearson Cove	-6.97E-05	-1.87E-07	766.50
	Deep Gorge/Ngajarli	-5.19E-05	-3.40E-07	264.13
	Burrup Road	-4.11E-05	-2.12E-07	172.56
	Dampier	-4.75E-05	6.92E-08	16.16
	Karratha	-1.03E-05	-4.93E-07	-0.05
Future Industry GLCs (S3-S2)	Hearson Cove	4.25E-06	1.34E-07	214.33
	Deep Gorge/Ngajarli	-2.24E-06	9.29E-08	99.50
	Burrup Road	2.35E-05	4.97E-08	78.33
	Dampier	1.48E-05	-1.80E-07	4.92
	Karratha	-2.00E-05	-5.91E-09	0.14
CAMx Scenario 3	Hearson Cove	1.00E-04	5.91E-06	1189.53
	Deep Gorge/Ngajarli	1.08E-04	5.69E-06	549.81
	Burrup Road	1.08E-04	5.72E-06	480.49
	Dampier	1.07E-04	6.06E-06	252.28
	Karratha	1.88E-04	5.85E-06	246.41

Table 6-11. Annual average total VOCs (ppb), ammonium plus nitrate (µg/m^3) and urea fine dust (µg/m^3) ground level concentrations (GLCs) in the CAMx grid cells that contain Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha.

		Total VOCs (ppb)	Ammonium plus Nitrate	Urea fine dust
		Annual Avg	Annual Avg	Annual Avg
CAMx Scenario 2	Hearson Cove	8.91	0.54	-
	Deep Gorge/Ngajarli	8.04	0.49	-
	Burrup Road	14.89	0.48	-
	Dampier	7.75	0.48	-
	Karratha	10.03	0.48	-
Industry GLCs (S2-S1)	Hearson Cove	3.41	0.11	-
	Deep Gorge/Ngajarli	2.44	0.07	-
	Burrup Road	9.52	0.05	-
	Dampier	1.79	0.05	-
	Karratha	0.93	0.08	-
Future Industry GLCs (S3-S2)	Hearson Cove	10.12	0.15	0.75
	Deep Gorge/Ngajarli	3.61	0.12	0.41
	Burrup Road	8.82	0.15	0.34
	Dampier	1.00	0.10	0.12
	Karratha	0.63	0.08	0.06
CAMx Scenario 3	Hearson Cove	19.04	0.69	-
	Deep Gorge/Ngajarli	11.65	0.61	-
	Burrup Road	23.71	0.63	-
	Dampier	8.75	0.58	-
	Karratha	10.66	0.57	-

Table 6-12. Annual max 1-hour (MDA1) NH_3 (ppb) ground level concentrations (GLCs) in the CAMx grid cells that contain Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha.

		NH_3 (ppb)
		MDA1
CAMx Scenario 2	Hearson Cove	236.34
	Deep Gorge/Ngajarli	268.33
	Burrup Road	326.10
	Dampier	68.24
	Karratha	31.87
Industry GLCs (S2-S1)	Hearson Cove	231.34
	Deep Gorge/Ngajarli	263.53
	Burrup Road	321.53
	Dampier	64.73
	Karratha	27.33
Future Industry GLCs (S3-S2)	Hearson Cove	-206.06
	Deep Gorge/Ngajarli	-246.71
	Burrup Road	-309.04
	Dampier	-57.51
	Karratha	-24.66
CAMx Scenario 3	Hearson Cove	30.28
	Deep Gorge/Ngajarli	21.61
	Burrup Road	17.06
	Dampier	10.73
	Karratha	7.21

6.3.5 Summary of Predicted Ground Level Concentrations from Existing and Future Industry

A summary of the predicted ground level concentrations for Scenario 2 and Scenario 3 includes the following:

- Analysis of source contributions to the predicted ground level concentrations of benzene, toluene and xylene emissions in the Murujuga airshed indicate that the majority contribution is from industry near or on the Burrup Peninsula.
- Exceedances of the benzene standard were predicted for Scenario 2; however, these exceedances were predicted to occur at industrial facility locations and no exceedances were predicted at sensitive receptor locations, including Dampier and Karratha.
- Future industry emissions increase benzene but concentrations remain well below the guideline at sensitive receptor locations, including Dampier and Karratha.
- SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and NH_3 peak ground level concentrations are centred at industrial facilities near or on the Burrup Peninsula, showing that industrial sources and shipping contribute to emissions in the area, but with total air concentrations for these compounds remaining below current air quality standards except for PM_{10} and $PM_{2.5}$ outside of industrial facilities.

- Industry GLCs contribute from 3.8% to 15.5% of annual average PM_{10} and 6.2% to 18.4% of annual average $PM_{2.5}$ in Scenario 2. Future industry GLCs contribute only around 1% to 2% to annual average PM_{10} in Scenario 3. Contributions to annual average $PM_{2.5}$ in Scenario 3 are negative or zero. This is likely due to decreases in secondary $PM_{2.5}$ resulting from a drop in shipping precursor emissions in the region.
- Estimated background PM_{10} dust concentrations contribute 17-23 µg/m^3 (65-73%) to the annual average and 74-83 µg/m^3 (78-86%) in maximum 24-hr concentrations (although the maximum 24-hr dust and maximum 24-hr total PM_{10} could have occurred on different dates).
- Background $PM_{2.5}$ dust concentrations contribute 1-3 µg/m^3 (30-44%) to the annual average and around 11-13 µg/m^3 (66-74%) in maximum 24-hr concentrations.
- For several short-term air quality metrics (i.e., MDA1) industry is a large contributor indicating the highest short-term predicted concentrations are a result of industrial emissions.
- Offshore SO_2 and NO_2 show strong influences from shipping emissions.
- Future annual maximum daily 1-hour average (MDA1) NO_2 decreased by 4.85 ppb near Burrup Road which likely results from Woodside's proposed replacement of existing gas turbines with more efficient-low NO_x devices at the Karratha Gas Plant (Woodside, 2019).
- Future MDA1 SO_2 concentrations decrease offshore by up to 86 ppb due to the introduction of International Maritime Organisation (IMO) regulations that limit the fuel-sulphur content for marine vessels.
- Industrial contributions to O_3 are negative near Dampier where strong NO_x emissions locally suppress O_3.
- Future industry emissions tend to increase O_3 but O_3 concentrations in all scenarios are below air quality standards.
- Future industry emissions increase MDA8 CO by 359 ppb near the Yara Ammonium Nitrate Plant.
- TOL and XYL concentrations remain well below the standard in the grid cells containing Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha. Industry ground level concentrations are highest in the grid cell containing Burrup Road. Future industry ground level concentrations reach 1.88 ppb in MDA1 for TOL at Hearson Cove and 1.53 ppb for XYL at Burrup Road.
- CO annual max 8-hour (MDA8) and Hg MDA1 and annual average air concentrations in the CAMx grid cells containing Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha remain well below the standard in all grid cells.
- Annual average ground level concentrations for VOCs range from around 7 ppb to 15 ppb in each of the grid cells containing Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha. Industry ground level concentrations are highest in the grid cell containing Burrup Road. Future industry ground level concentrations are highest in the grid cells containing Burrup Road (8.82 ppb) and Hearson Cove (10.12 ppb).
- Ammonium plus nitrate ground level concentrations range from 0.48 to 0.54 µg/m^3. Future industry ground level concentrations are expected to increase between 0.08 µg/m^3 and 0.15 µg/m^3.
- Urea fine dust ground level concentrations from industry are expected to increase by up to 0.75 µg/m^3 in the future industry scenario.
- NH_3 MDA1 air concentrations in the CAMx grid cells containing Hearson Cove, Deep Gorge/Ngajarli, Burrup Road, Dampier Monitoring Station, and Karratha are all below the standard and decrease to 30 ppb or less in the future industry scenario.

6.4 Deposition of Air Emissions from Existing and Future Industry

6.4.1 Scenario 2 Deposition

Annual deposition maps for NO_2, HNO_3, PNO_3, SO_2, PSO_4, total oxidised nitrogen, and total oxidised sulphur in units of meq/m^2/year, and total dust (FCRS + CCRS) and total mercury (Hg = HGP + HG2P + HG2PC) in grams/m^2/year are shown in Figure 6-85 to Figure 6-114. The figures show deposition for the 1.33 km CAMx domain. Figure 6-85 to Figure 6-94 show deposition for Scenario 2. The figures show a subregion of the 1.33 km CAMx domain centred near or on the Burrup Peninsula. Similar figures showing the full domain extent are available in Appendix 3.

Dust deposition occurs throughout the 1.33 km domain and ranges from 1.2 to nearly 10 g/m^2/yr. However, there is some uncertainty that the simulation of total dust deposition is unbiased because of uncertainties in the dust boundary concentrations (from CAM-chem) and windblown dust emissions. Industrial deposition of up to 2E-3 g/m^2/yr was predicted to occur at Hearson Cove and Deep Gorge/Ngajarli. An area of higher industry-related dust deposition extends eastward from the maximum near Dampier with a secondary high in the area around Wickham. Future industrial emissions are only expected to increase dust deposition marginally (up to 7.2E-4 g/m^2/yr) compared to current emissions.

Hg deposition values are low across the domain. Contributions from both existing and future industrial sources to Hg ground level concentrations are found to be small and therefore the spatial patterns seen in Hg deposition result from spatial variation in the deposition of background Hg. There is little change expected in the future.

HNO_3, NO_2, and total N deposition values are higher over land than over water because HNO_3 and NO_2 deposit more rapidly (i.e. have higher deposition velocity) to vegetation and the ground than to water. In general, deposition to water surfaces tends to be slow because the atmosphere tends to be stable over water which inhibits atmospheric mixing and slows deposition. Particulate nitrate (PNO_3) is a small contributor to total N deposition because it deposits more slowly than HNO_3 and NO_2. Higher N deposition amounts occur in the area between Dampier and Burrup Road with some additional deposition along the coast near Karratha in the 1.33 km domain. Almost all N deposition comes from the industrial emissions sources in the region. Future deposition values are not expected to change substantially for HNO_3 and NO_2. N deposition is expected to increase up to 10.3 meq/m^2/yr in the area around emissions sources. Particulate nitrate (PNO_3) deposition is low across the domain with the highest deposition values occurring offshore. Predicted deposition rates due to future industry are expected to increase marginally across the domain with the highest increases (around 0.2 meq/m^2/yr) occurring offshore and in the area around Burrup Road. As discussed in the next section, there is evidence for deposition of total N being biased high, possibly because NO_x emissions from shipping and/or industry near Dampier are over-estimated.

Particulate sulphate (PSO_4), SO_2, and total S deposition occur mostly offshore near Dampier and over land near Dampier, showing that most of the S deposition is coming from shipping and industrial emissions in that area. Total S deposition is elevated near Hearson Cove and Deep Gorge/Ngajarli. Future S deposition is expected to decrease in response to the introduction of IMO regulations that limit fuel-sulphur content for marine vessels.

Future year deposition of fine urea dust is shown in Figure 6-114 in grams/m^2/year. The deposition maximum is centred around Hearson Cove and Deep Gorge/Ngajarli with a value of

0.09 g/m^2/yr. Urea dust deposition is zero for Scenarios 1 and 2 because all emissions were associated with future proposals.

Figure 6-94, Figure 6-103, and Figure 6-113 show the CAMx model results for ammonium plus nitrate for Scenario 2, industry deposition rates, and future industry deposition rates respectively. Ammonium plus nitrate concentrations are around 0.5 meq/m^2/yr across most areas with a maximum of 0.8 meq/m^2/yr around Karratha. Future industry deposition rates are expected to increase by around 0.04 meq/m^2/yr. 2014 industry deposition rates are around 0.15 meq/m^2/yr with the increase centred around Yara Fertilisers.

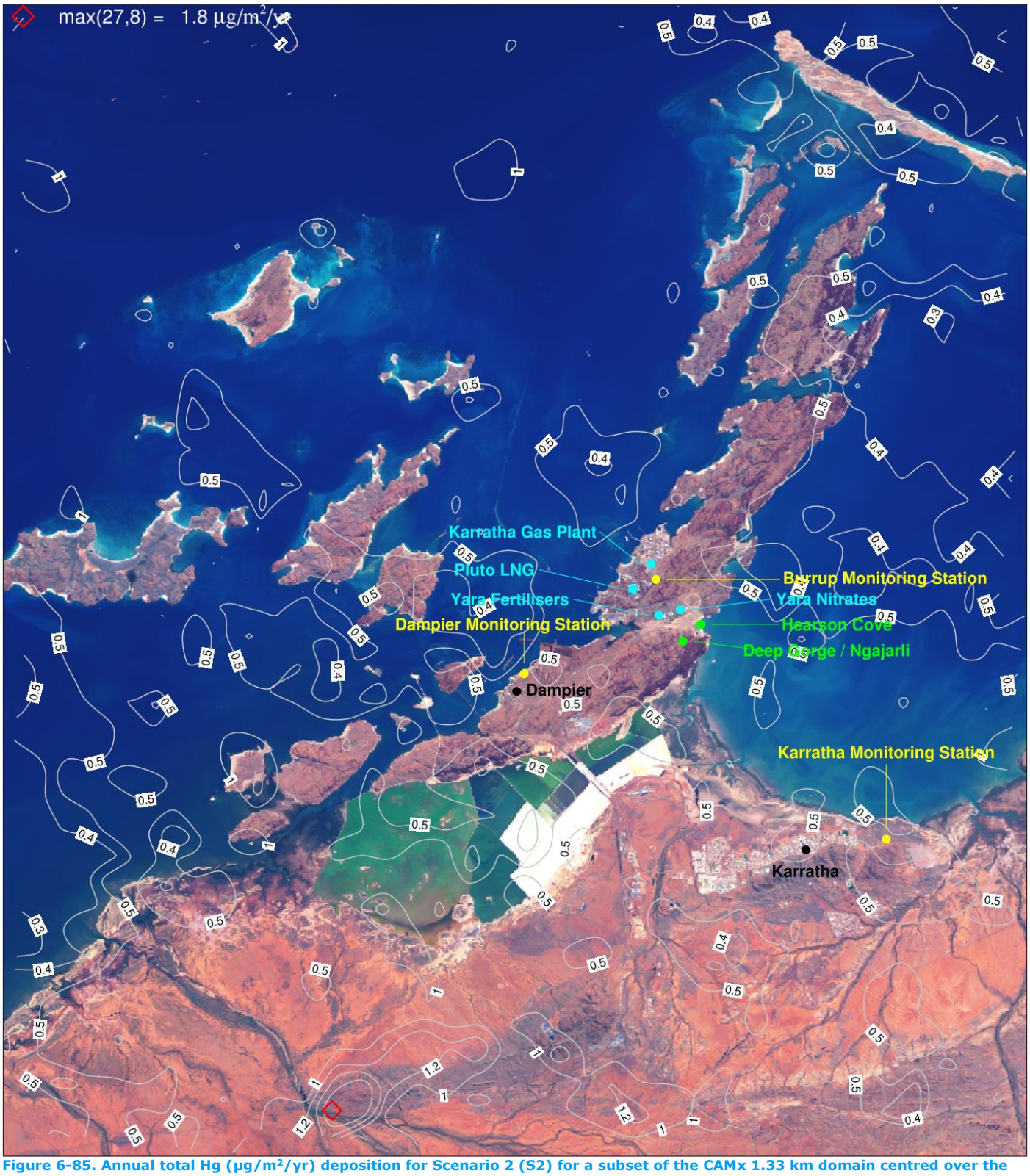


Figure 6-85. Annual total Hg (µg/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

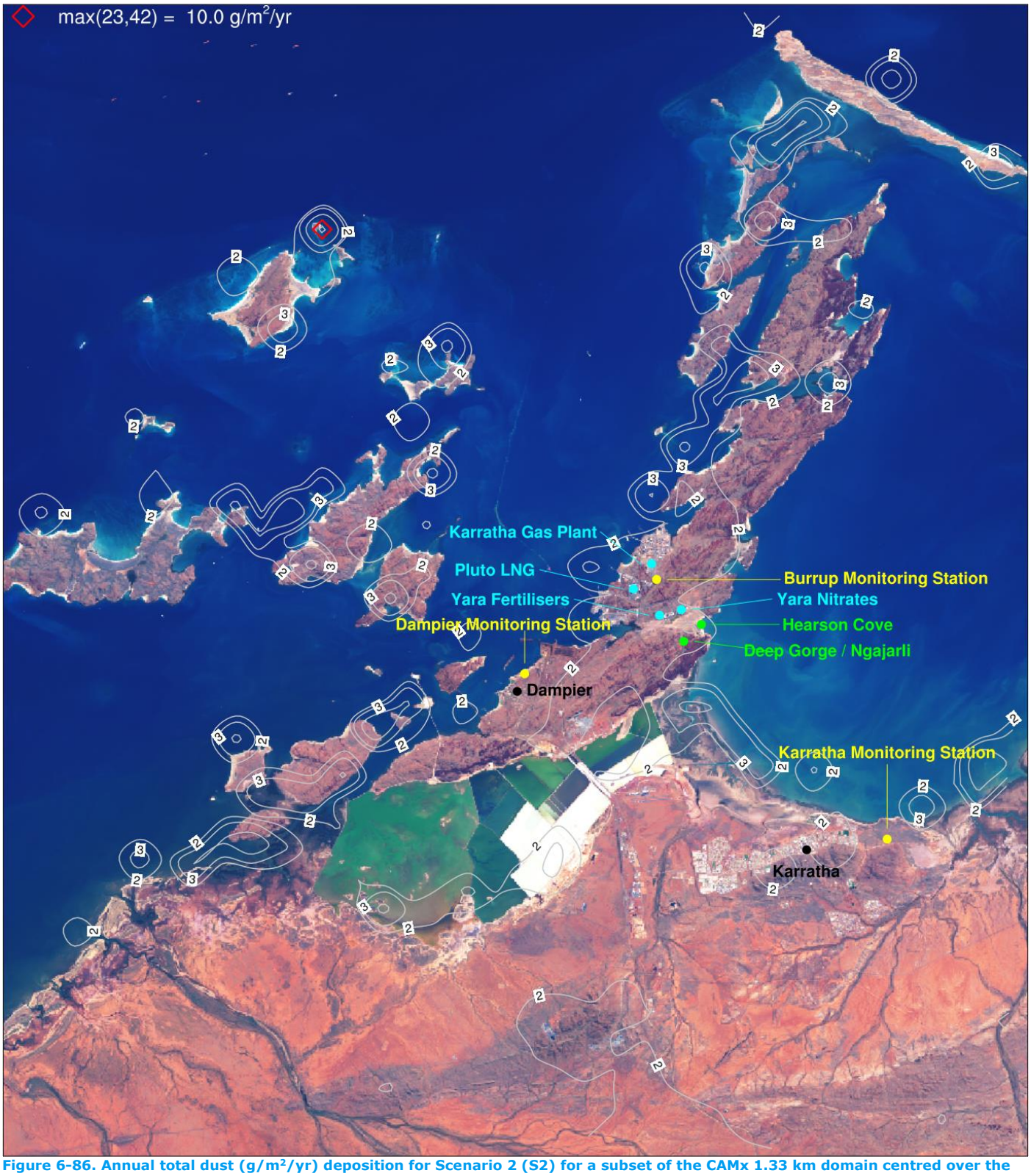


Figure 6-86. Annual total dust (g/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

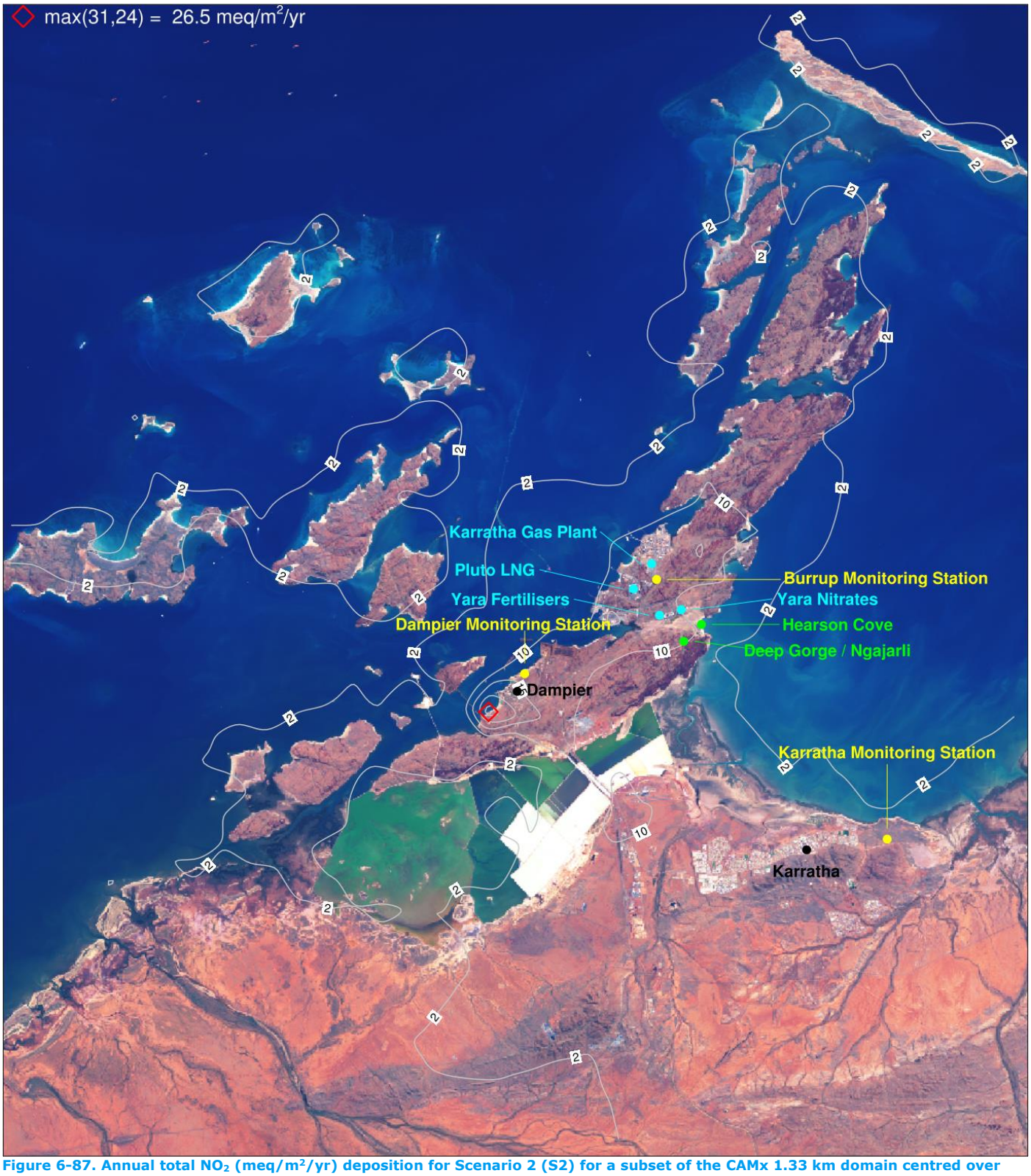


Figure 6-87. Annual total NO_2 (meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

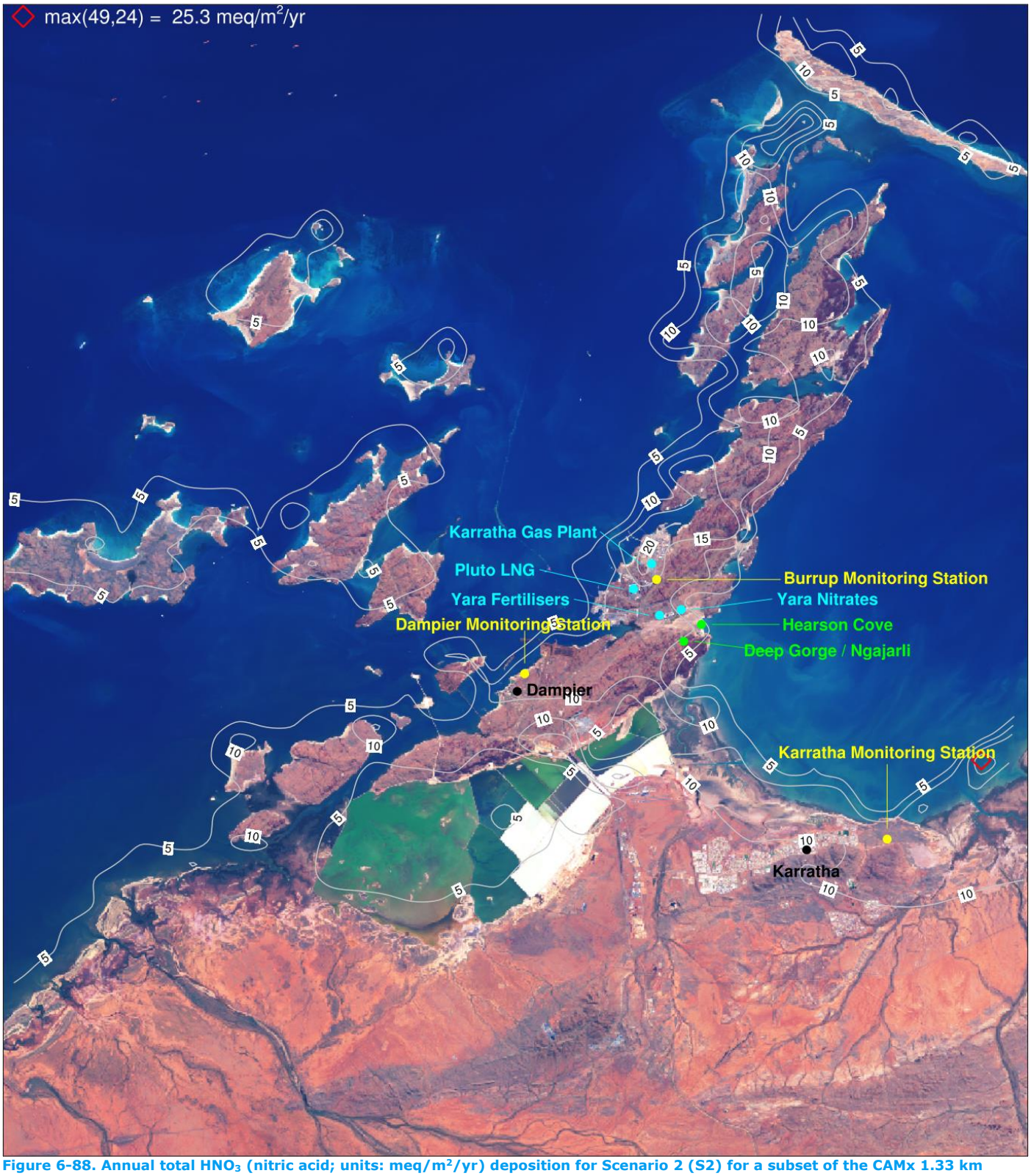


Figure 6-88. Annual total HNO_3 (nitric acid; units: meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

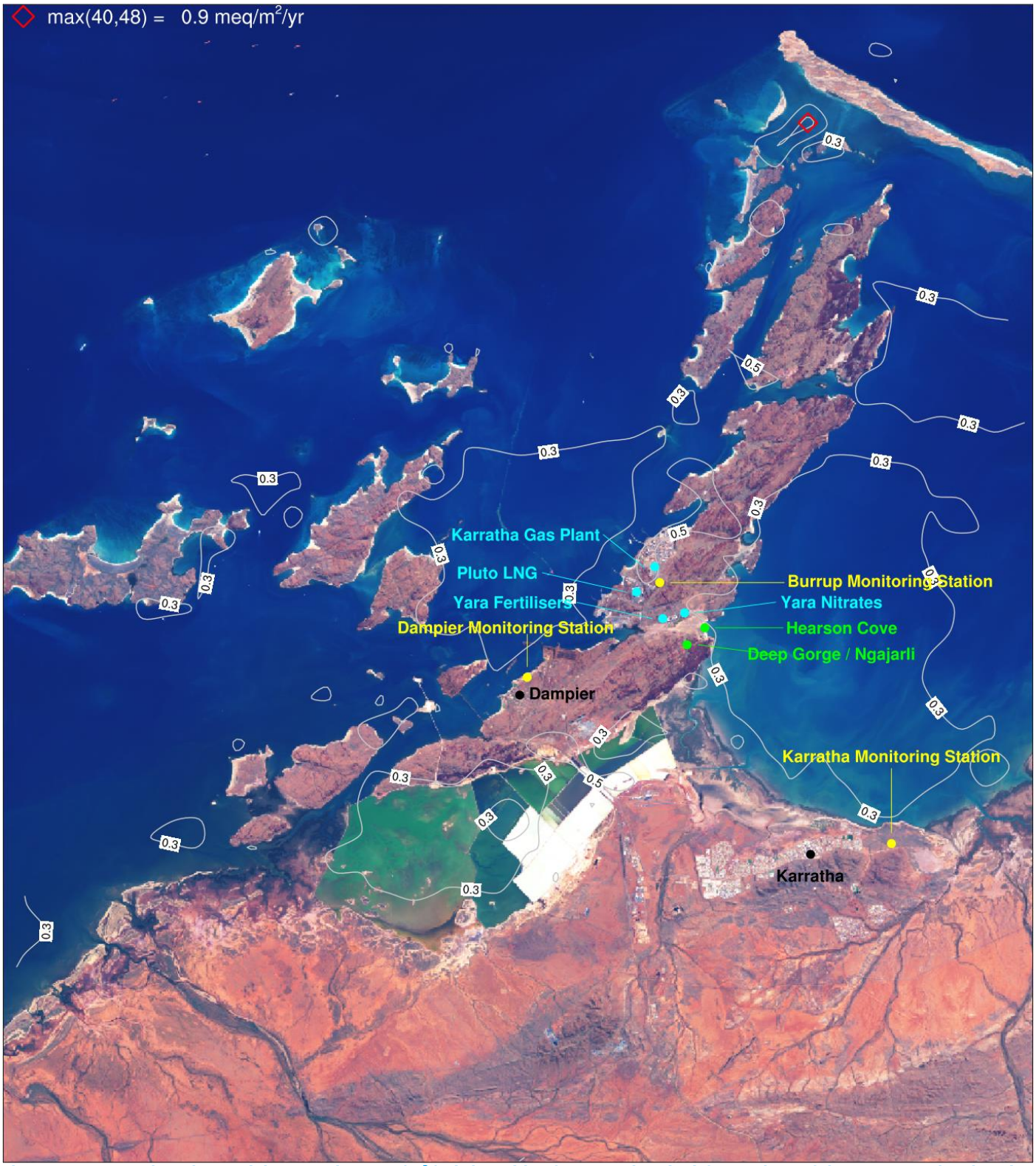


Figure 6-89. Annual total PNO_3 (nitrate; units: meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

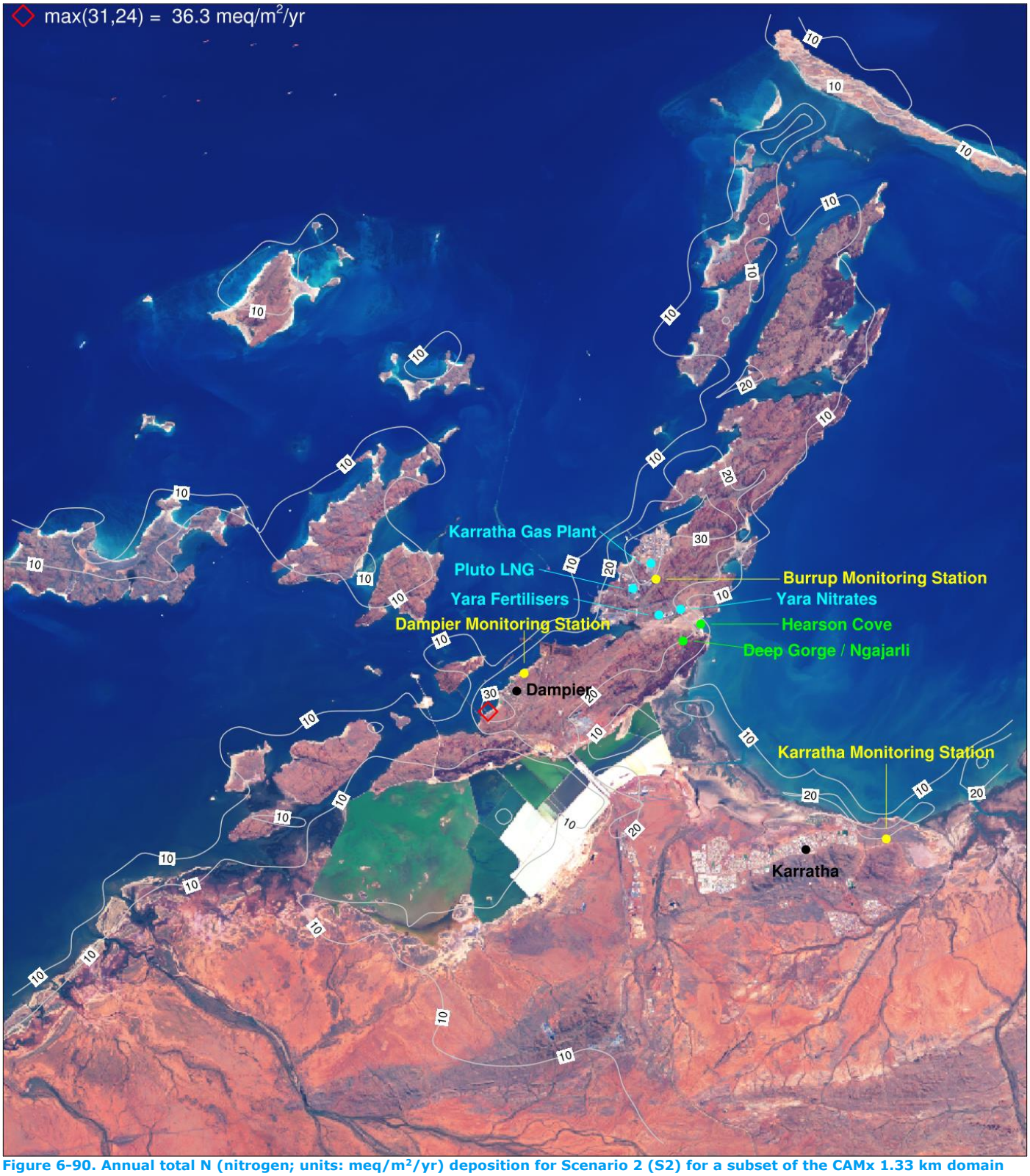


Figure 6-90. Annual total N (nitrogen; units: meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

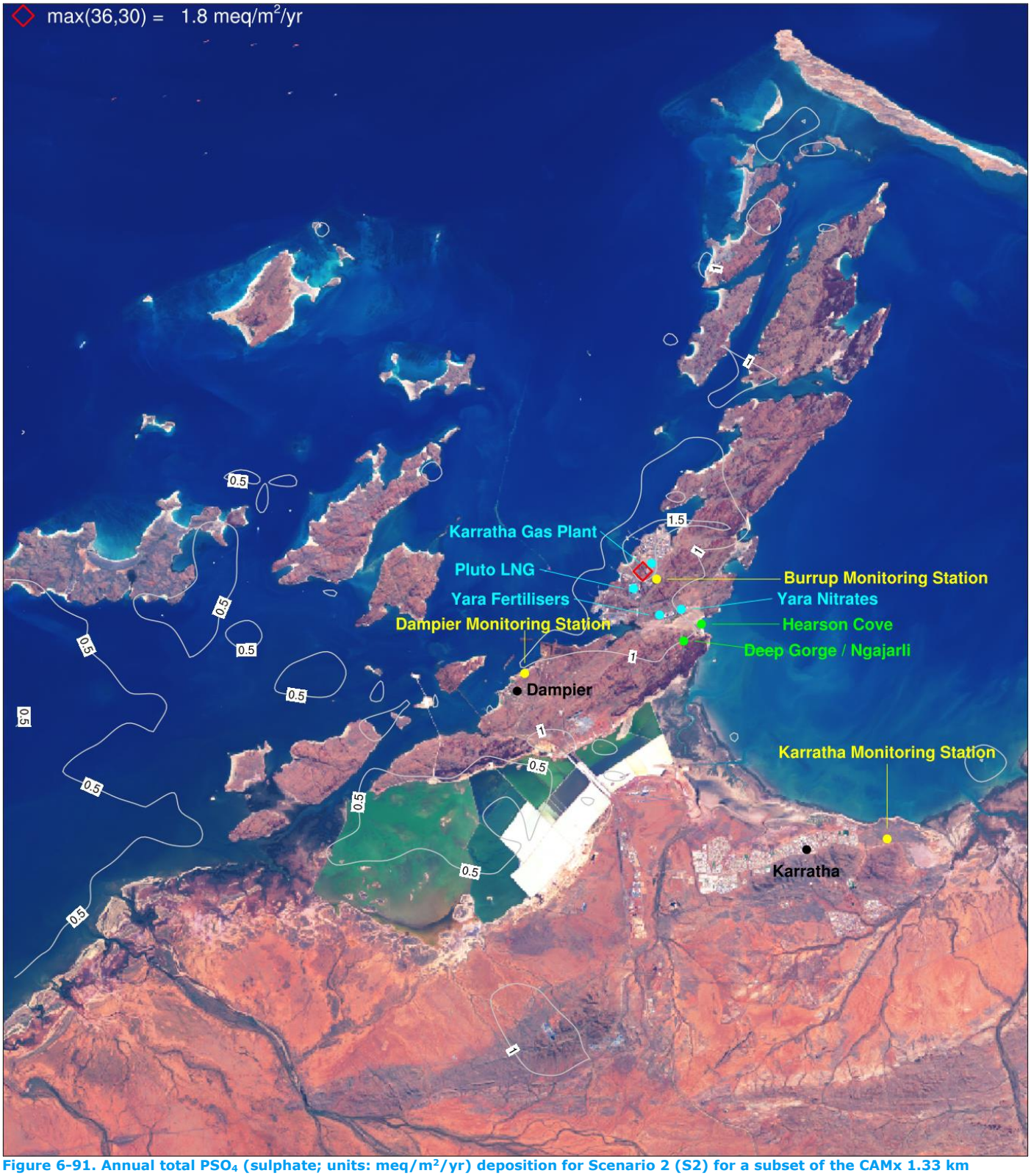


Figure 6-91. Annual total PSO_4 (sulphate; units: meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

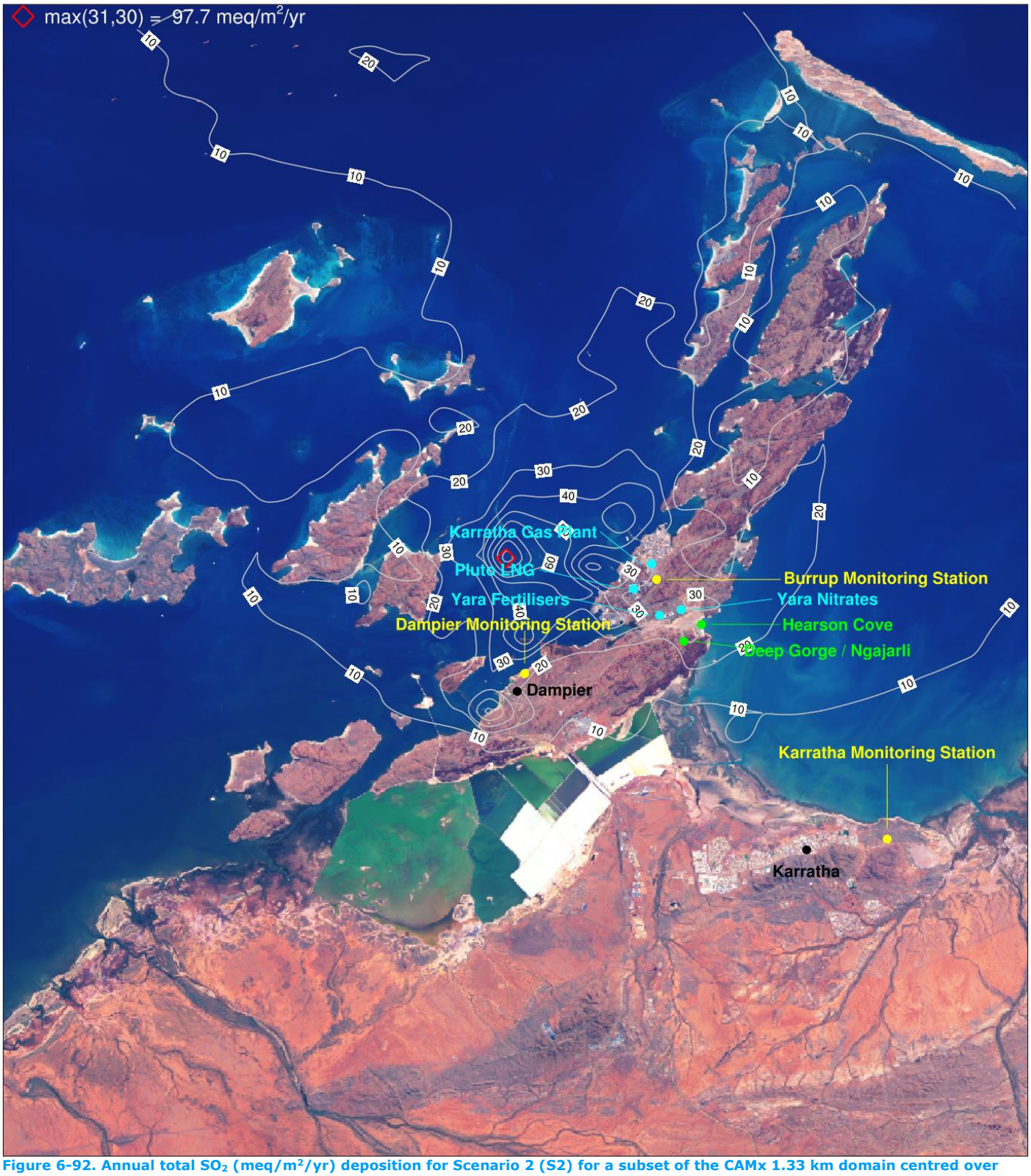


Figure 6-92. Annual total SO_2 (meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

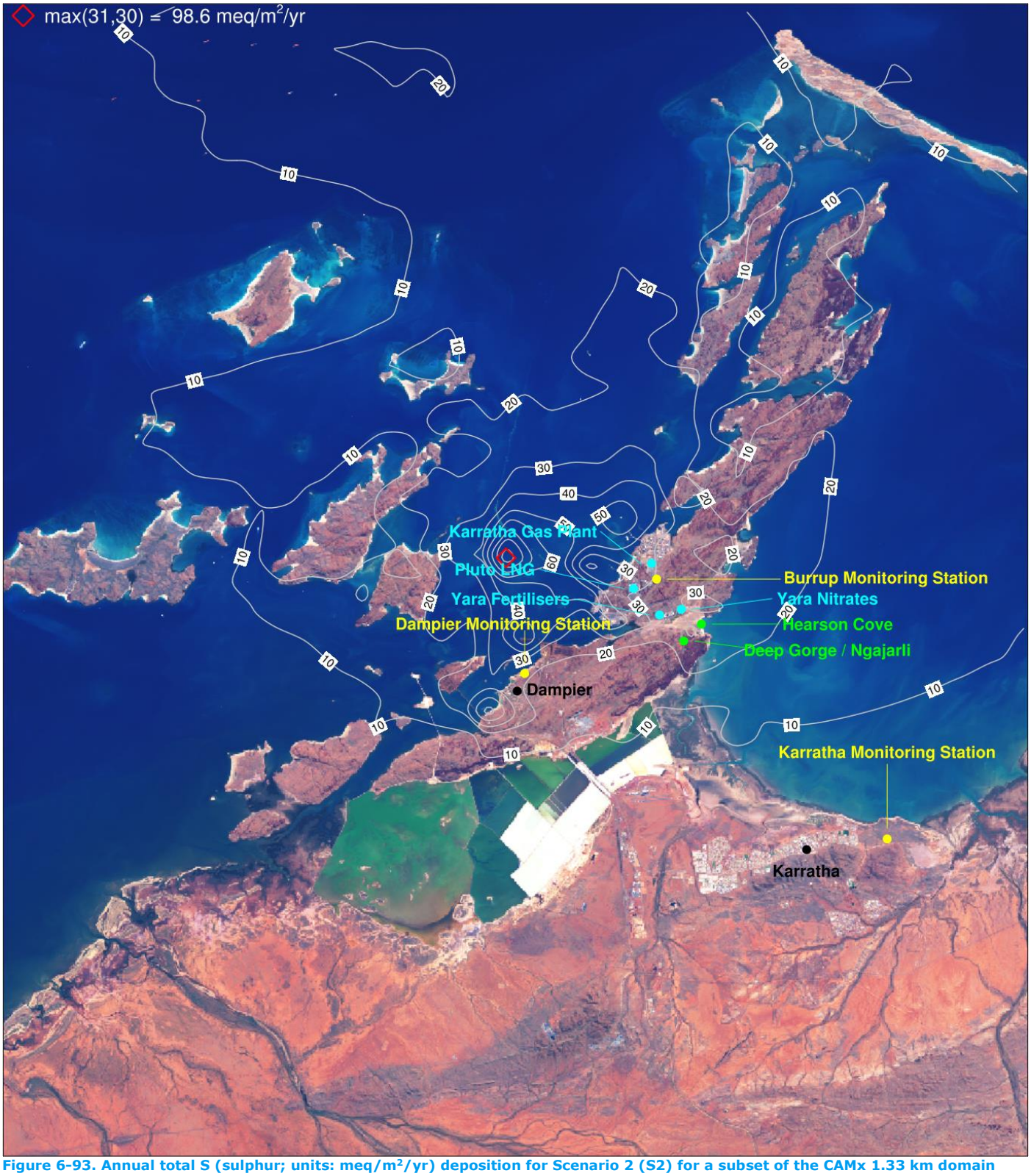


Figure 6-93. Annual total S (sulphur; units: meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

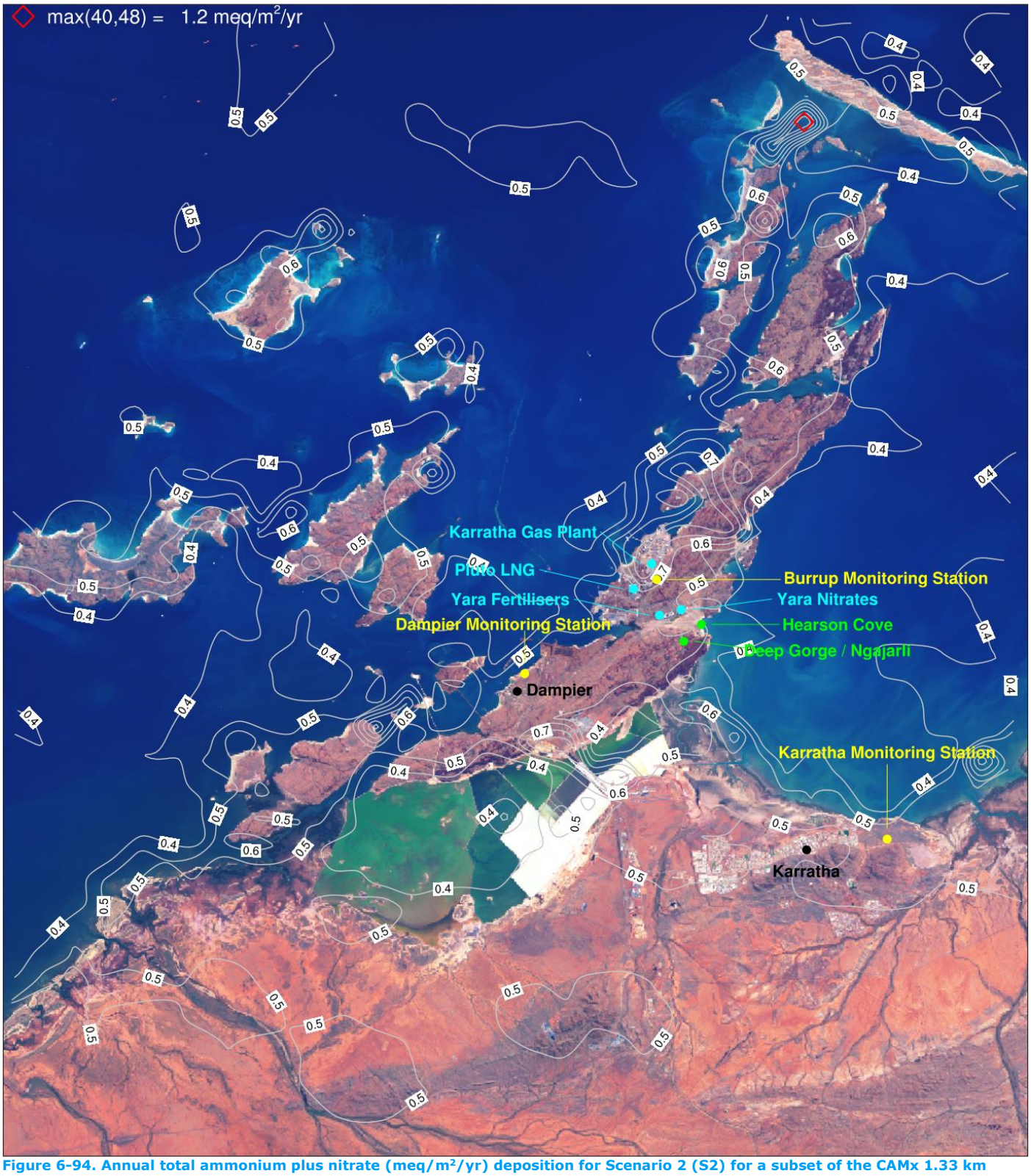


Figure 6-94. Annual total ammonium plus nitrate (meq/m²/yr) deposition for Scenario 2 (S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

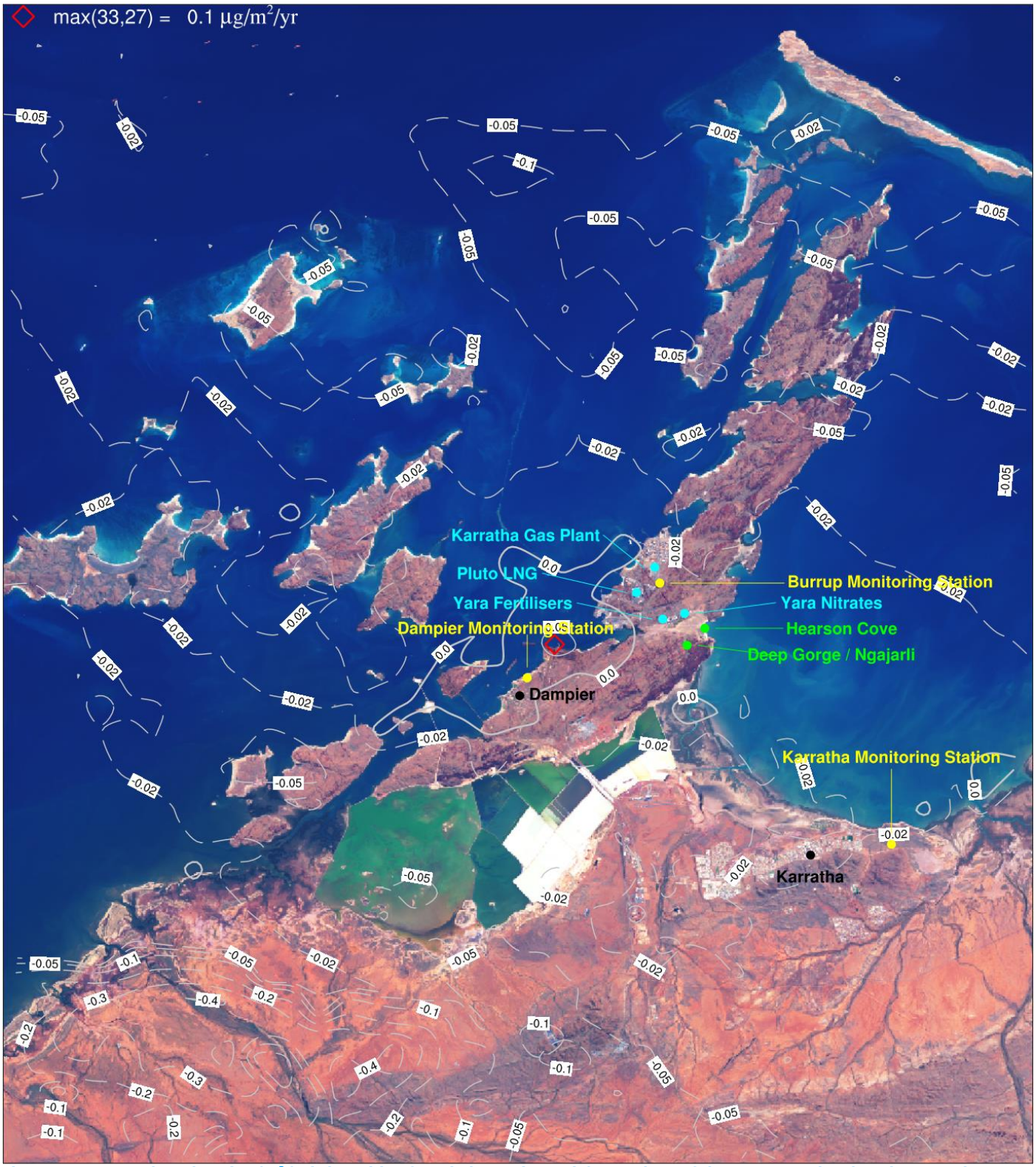


Figure 6-95. Annual total Hg (µg/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-96. Annual total dust (g/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-97. Annual total NO_2 (meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

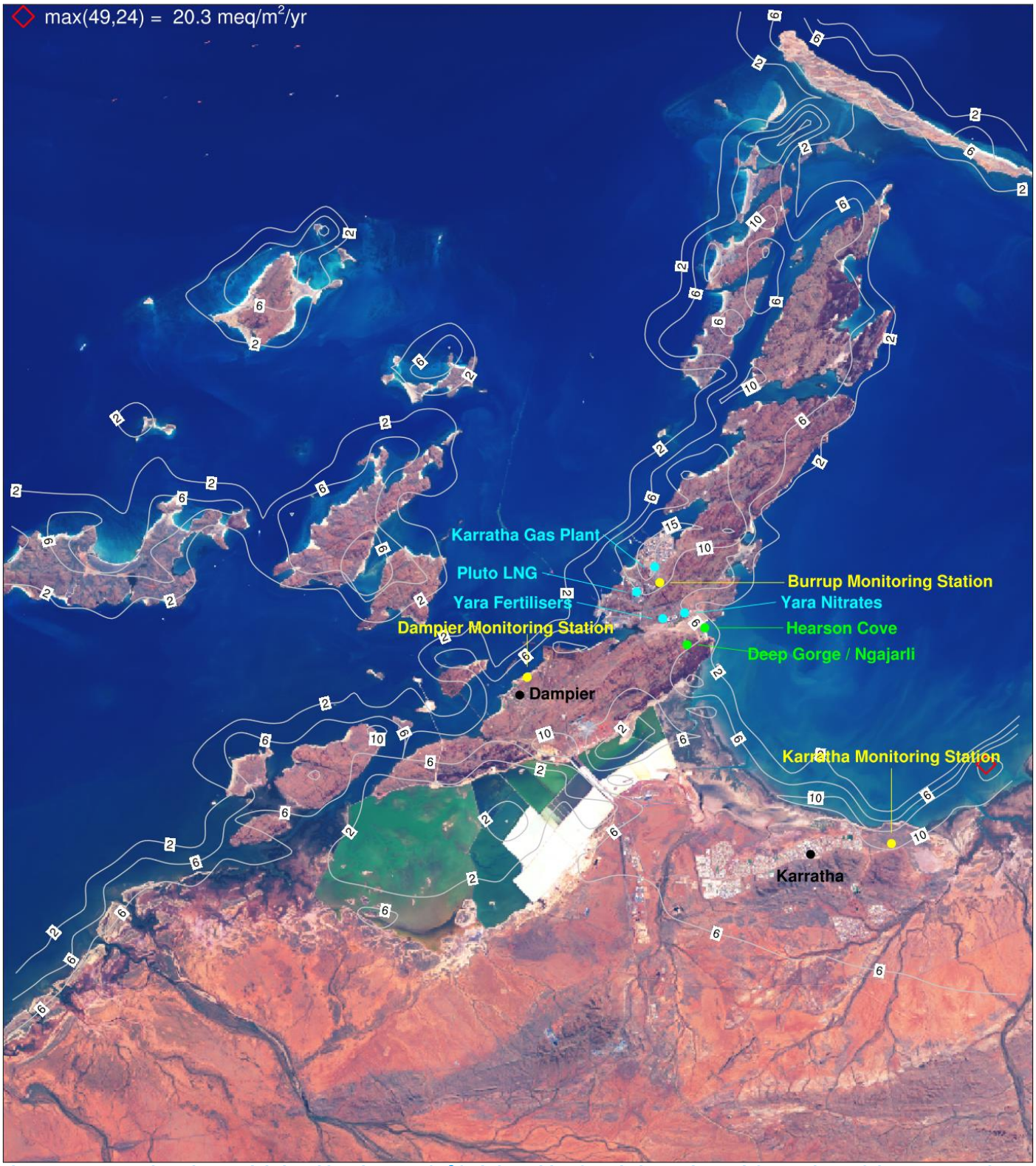


Figure 6-98. Annual total HNO_3 (nitric acid; units: meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

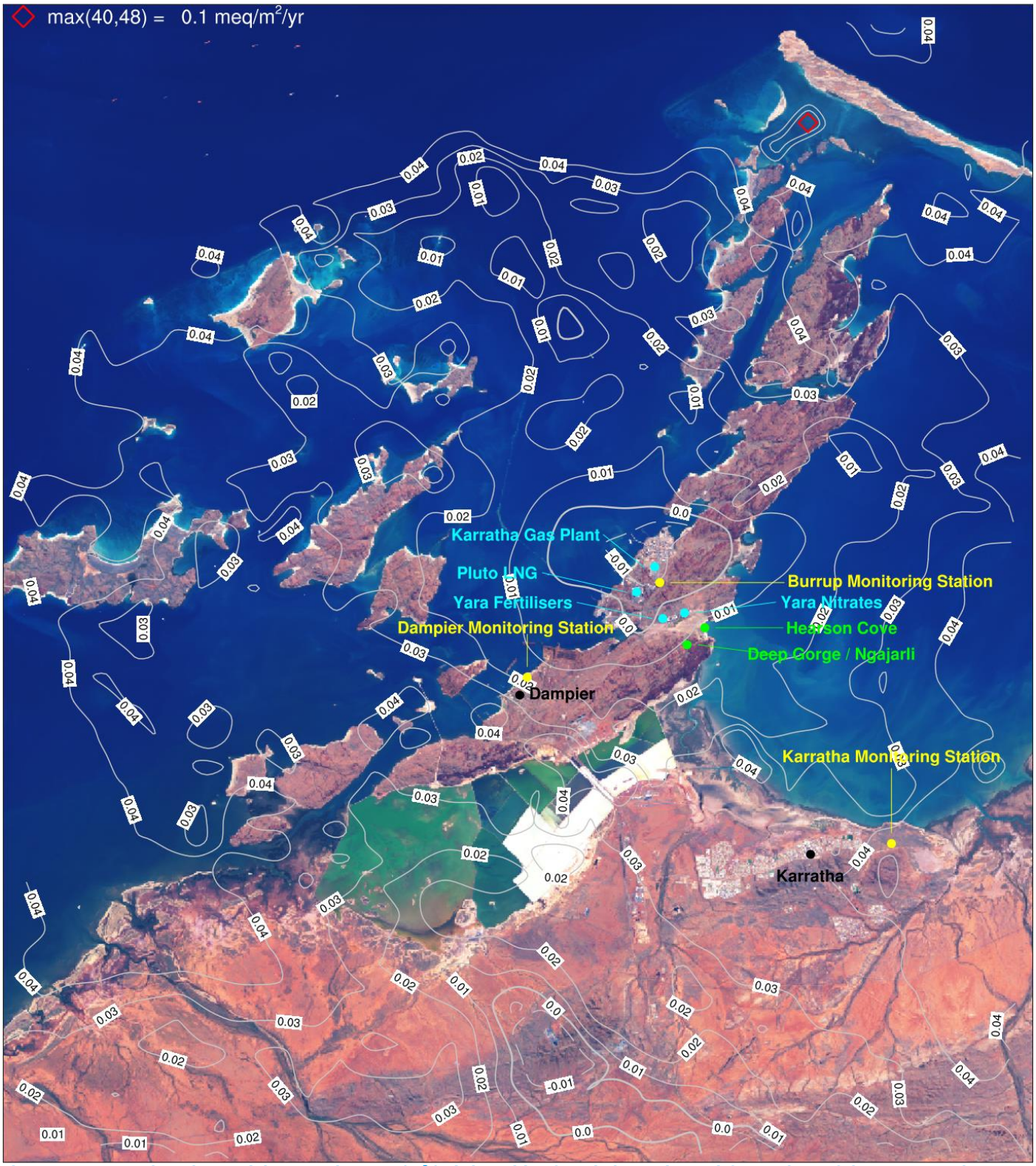


Figure 6-99. Annual total PNO_3 (nitrate; units: meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

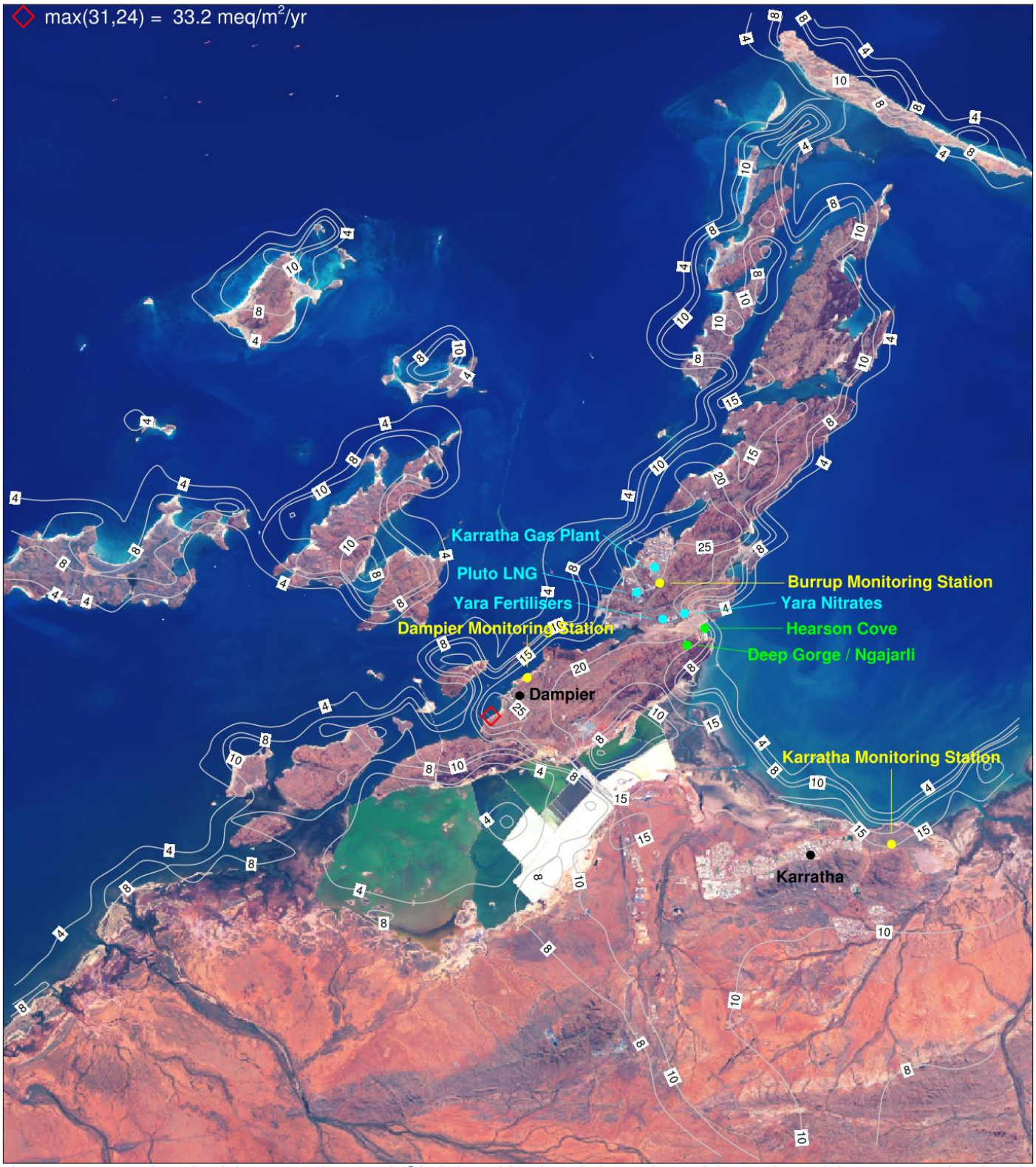


Figure 6-99. Annual total N (nitrogen; units: meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-100. Annual total PSO_4 (sulphate; units: meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

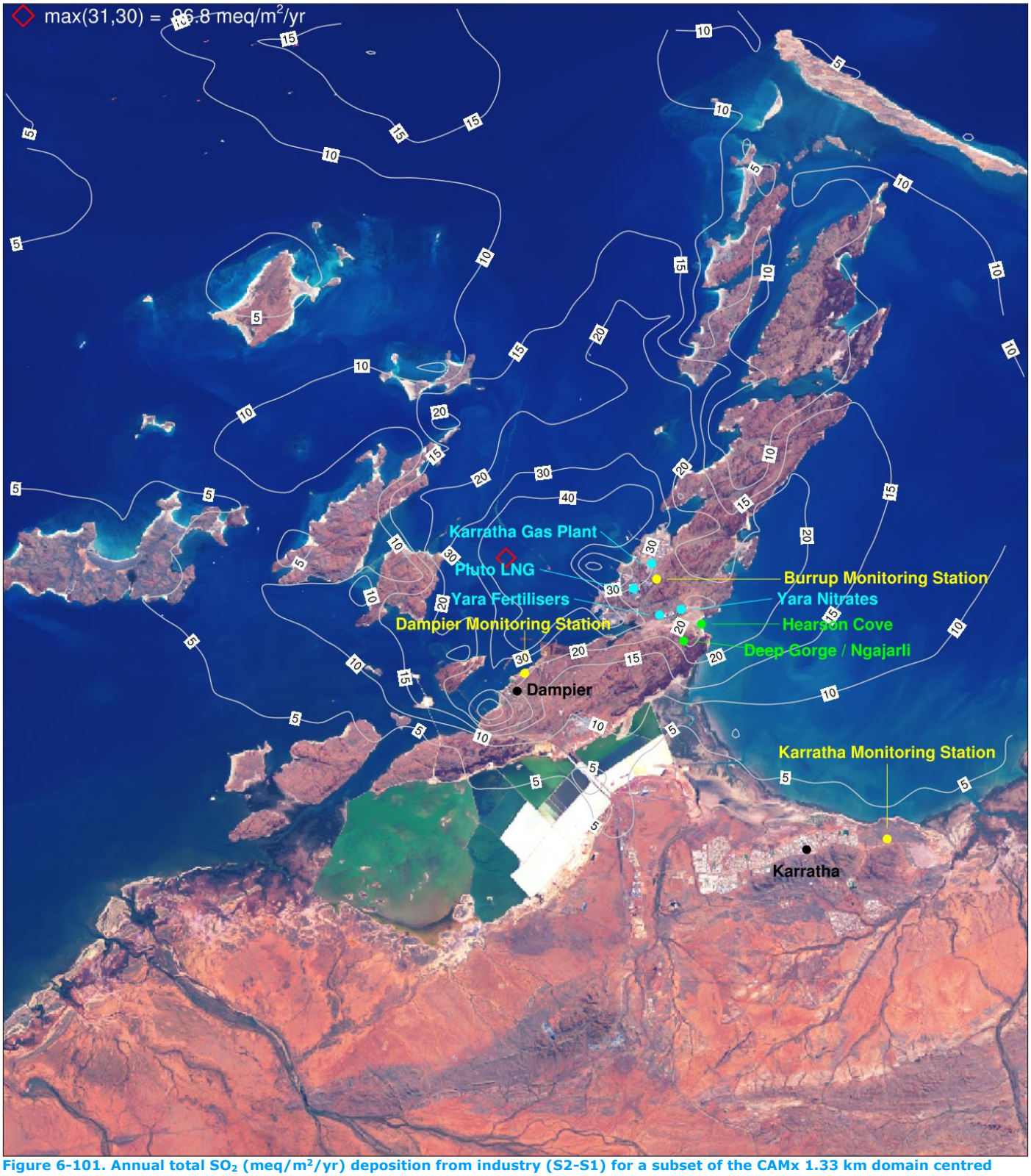


Figure 6-101. Annual total SO_2 (meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

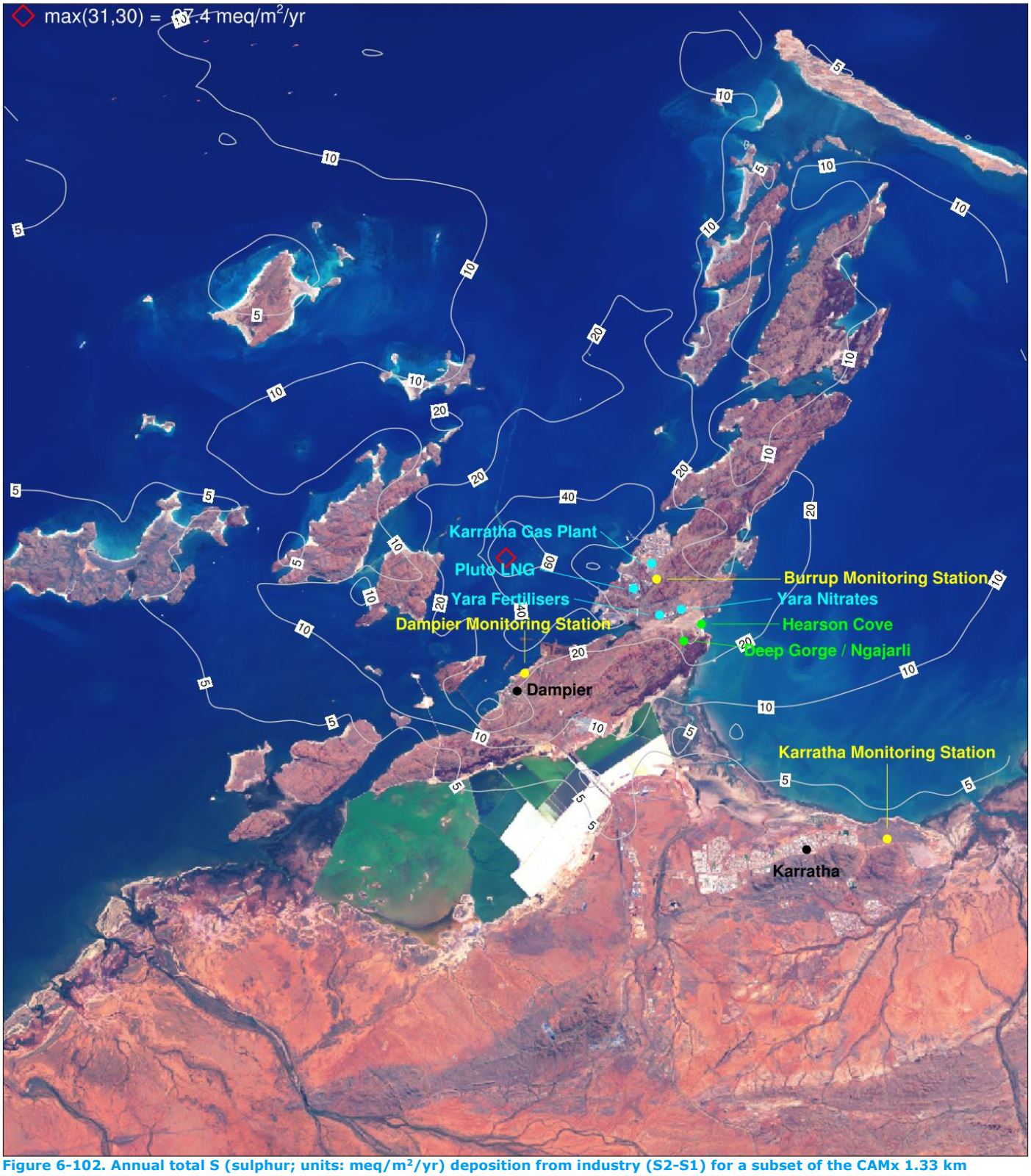


Figure 6-102. Annual total S (sulphur; units: meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

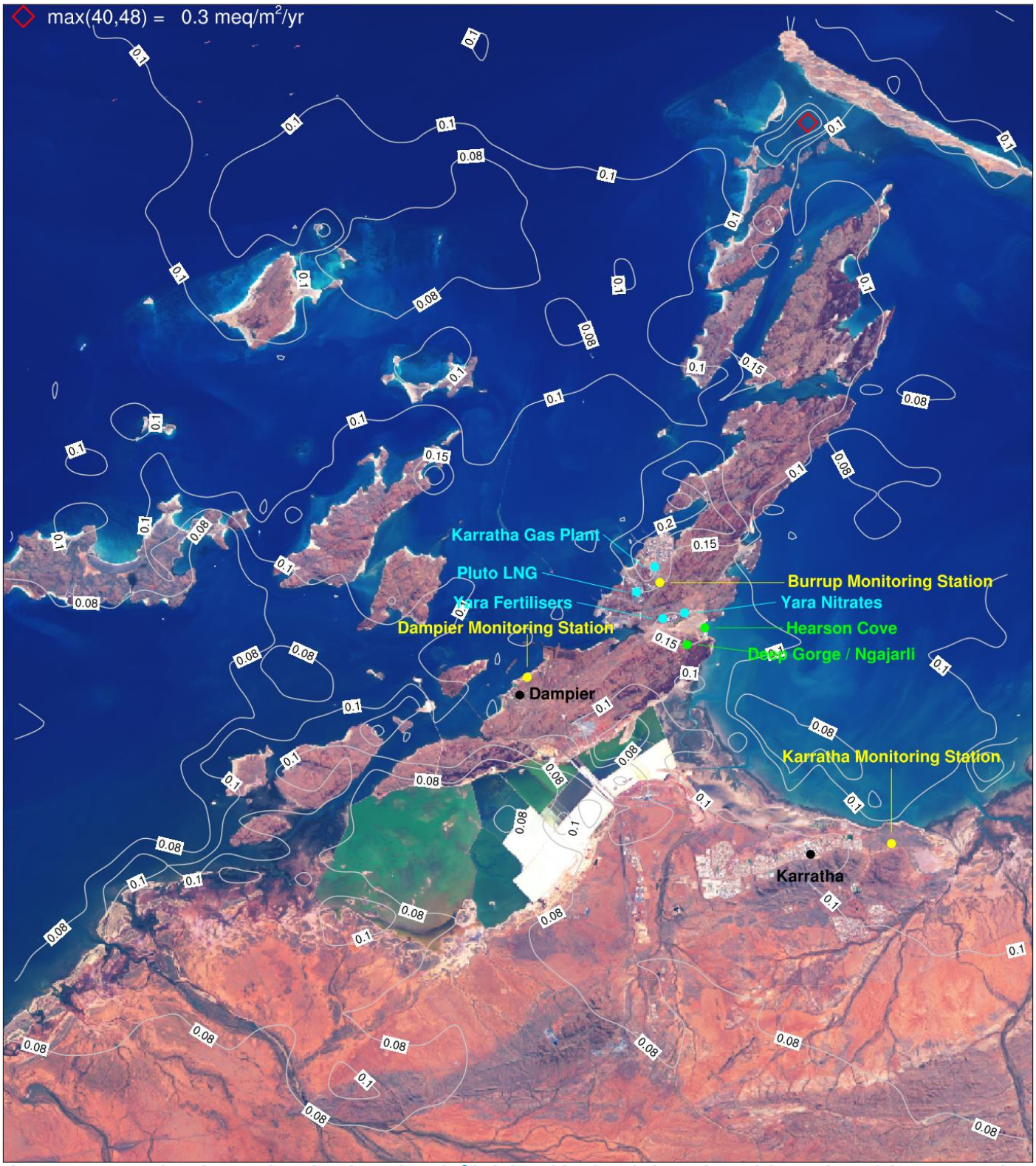


Figure 6-103. Annual total ammonium plus nitrate (meq/m²/yr) deposition from industry (S2-S1) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

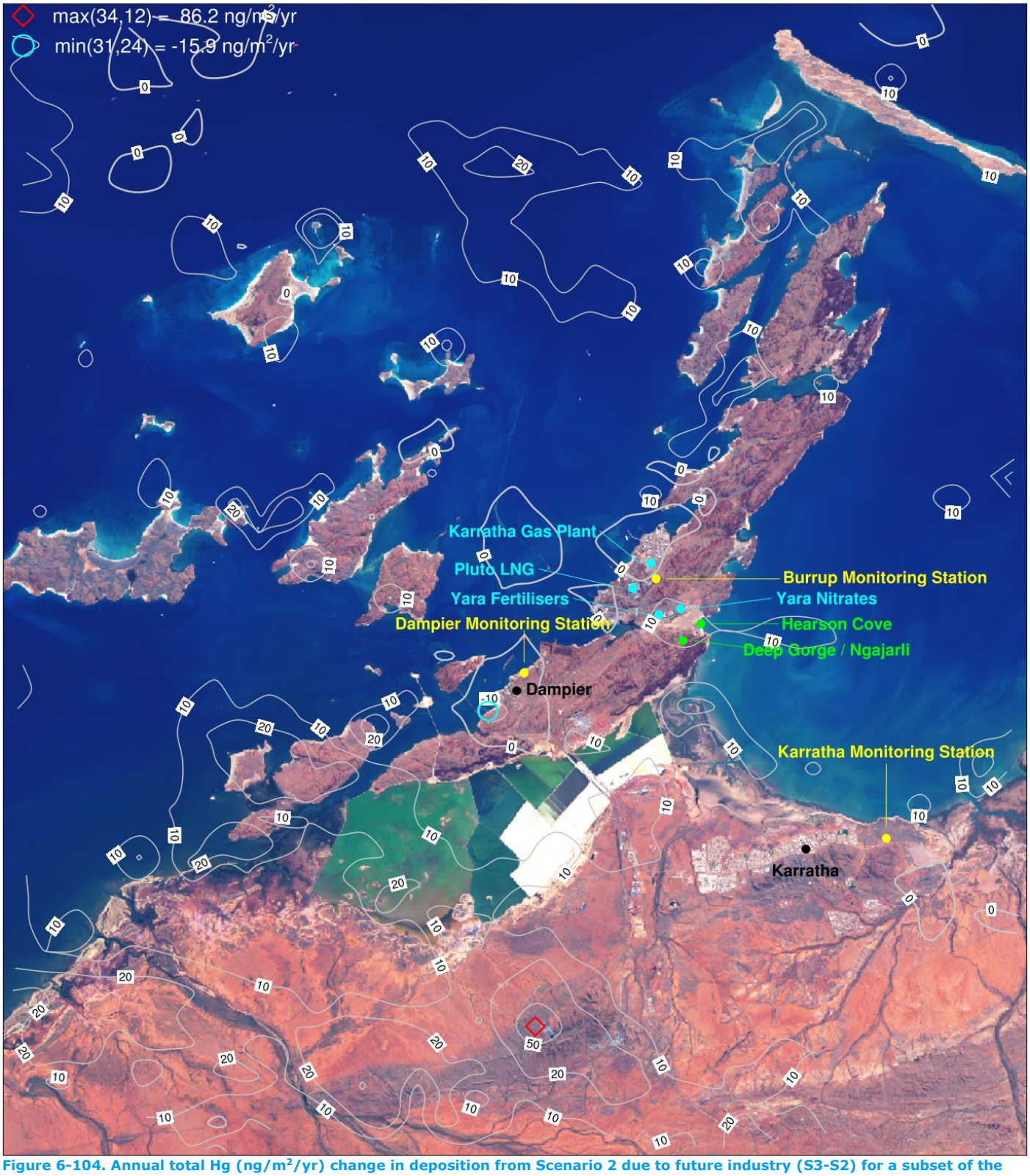


Figure 6-104. Annual total Hg (ng/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

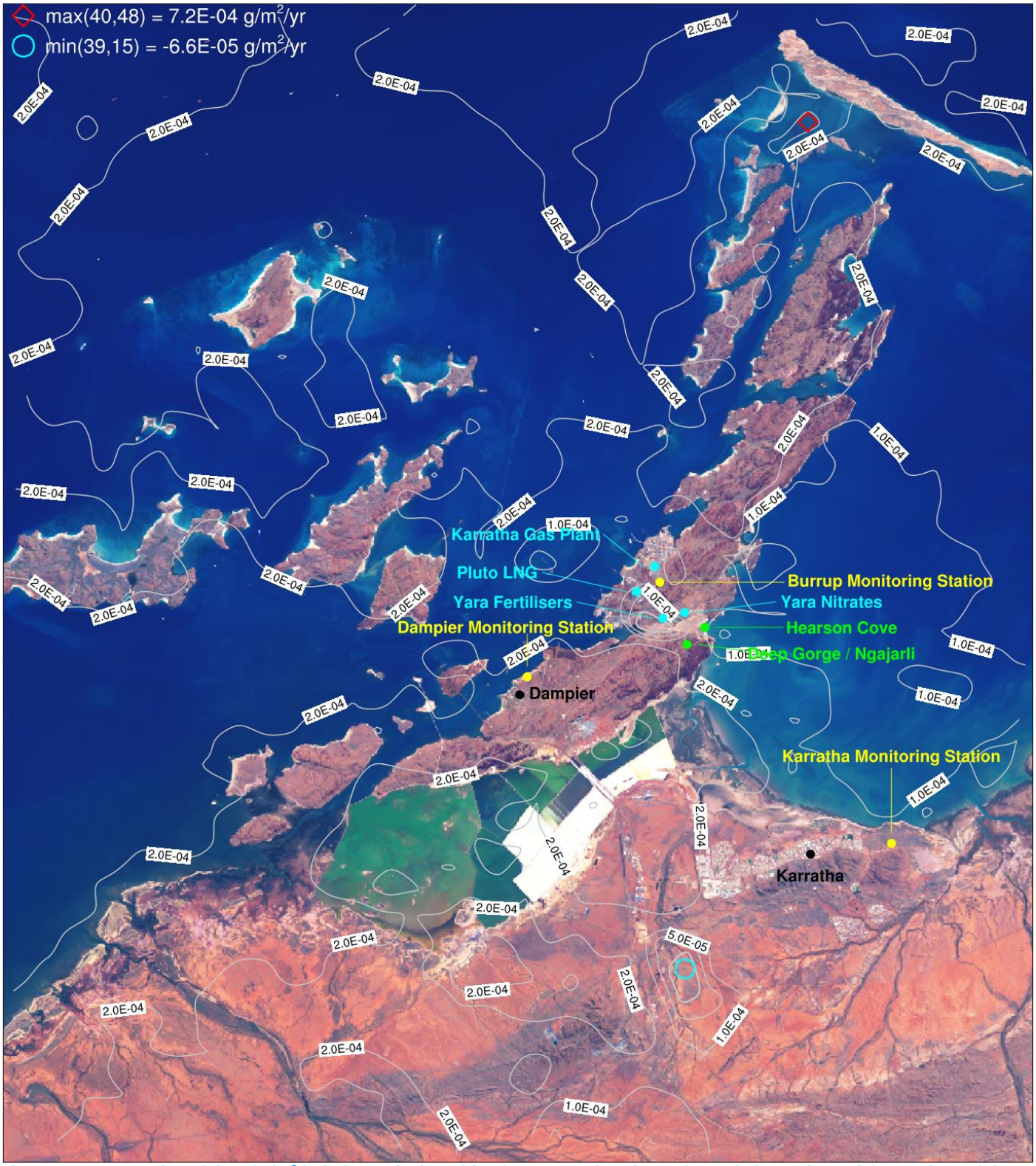


Figure 6-105. Annual total dust (g/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

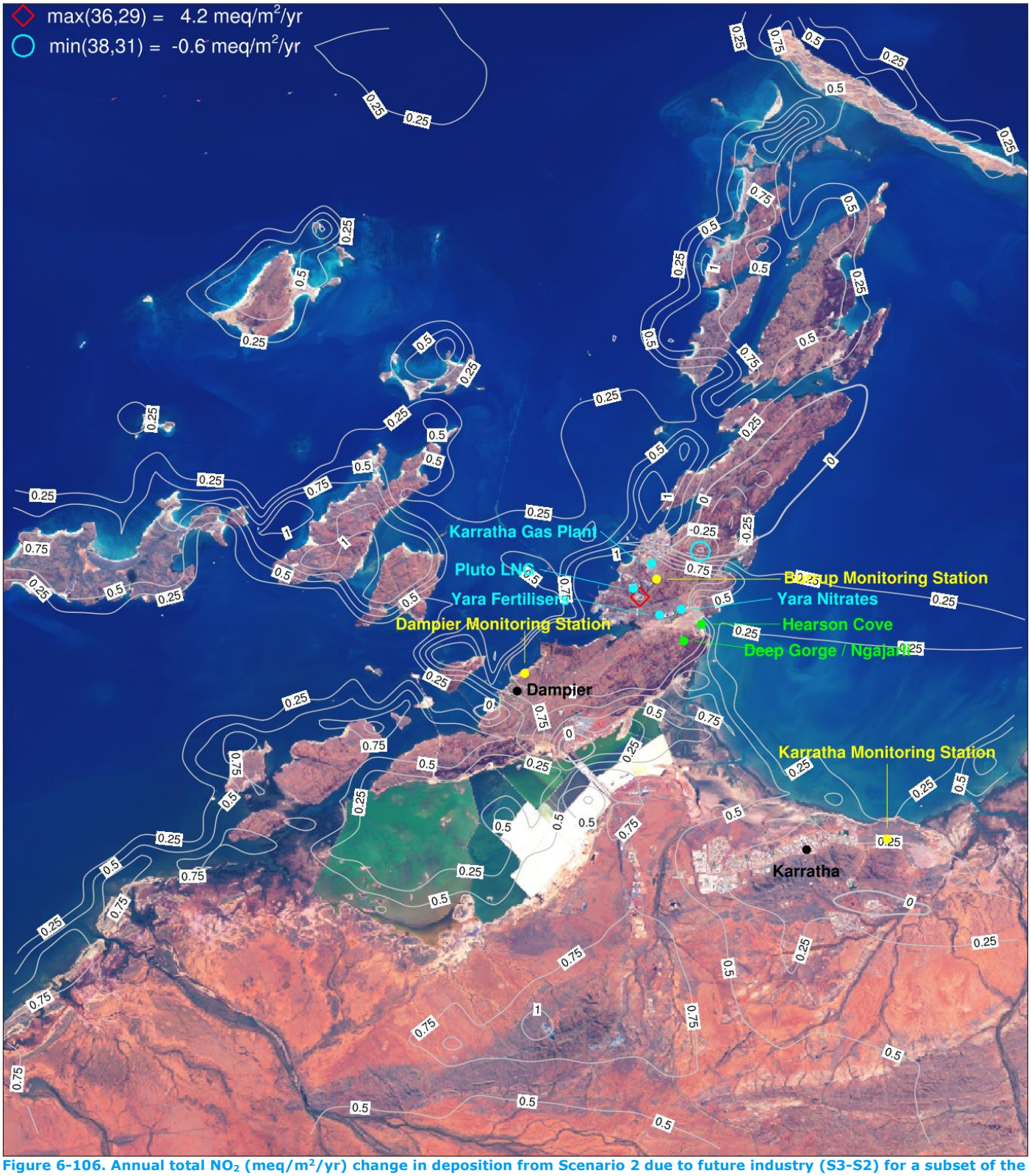


Figure 6-106. Annual total NO_2 (meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-107. Annual total HNO_3 (nitric acid; units: meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

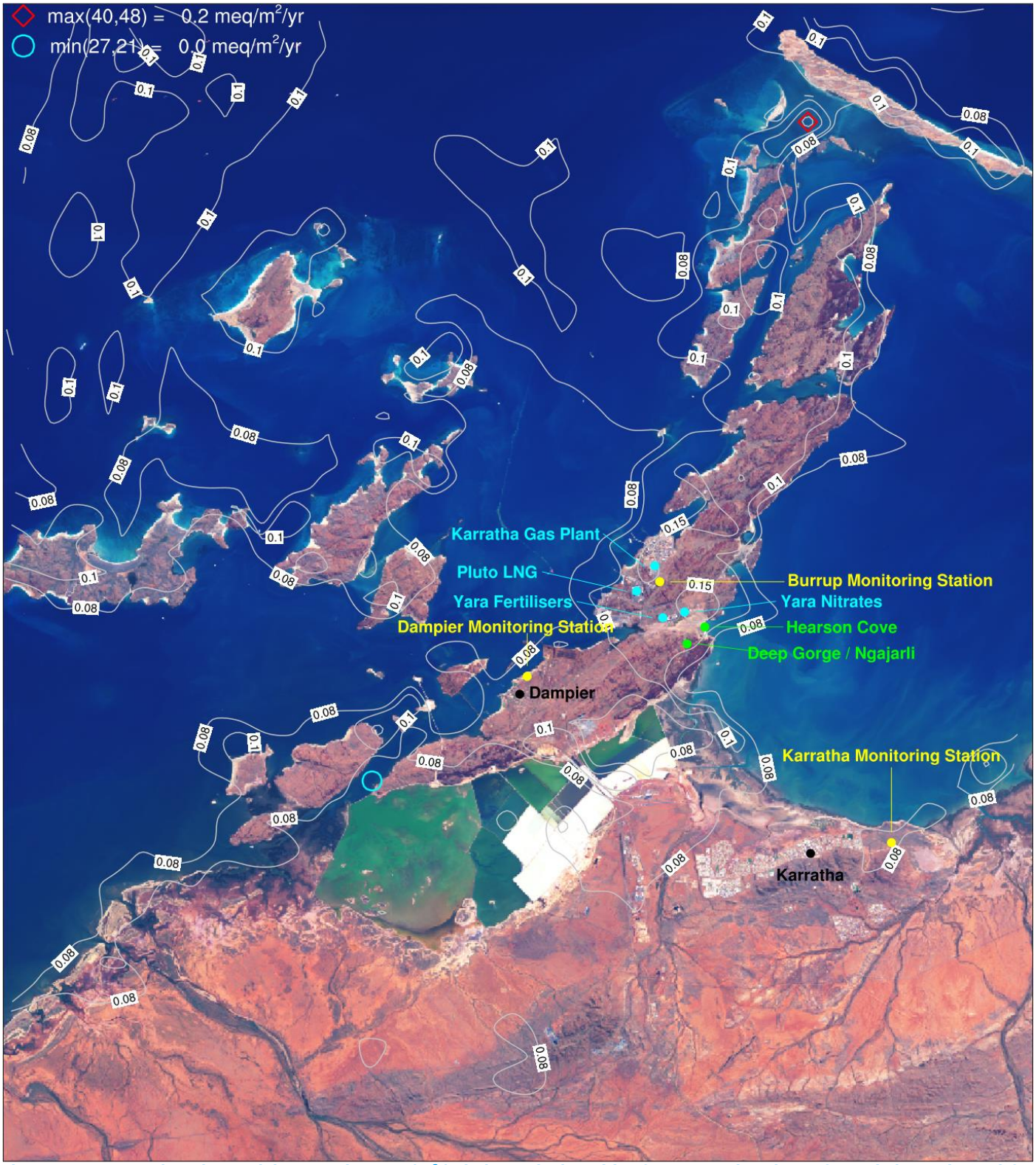


Figure 6-108. Annual total PNO_3 (nitrate; units: meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

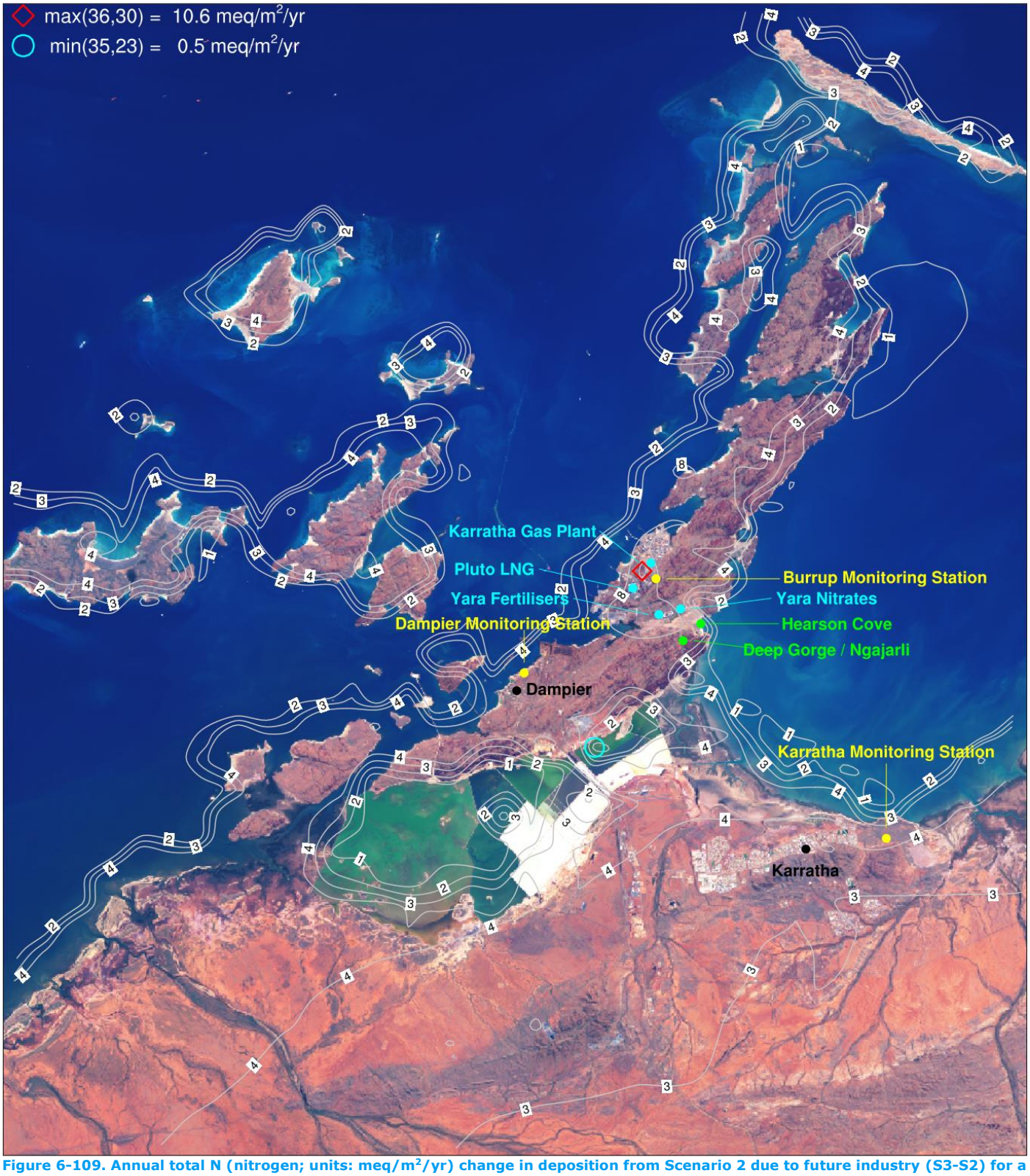


Figure 6-109. Annual total N (nitrogen; units: meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

Figure 6-110. Annual total PSO_4 (sulphate; units: meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

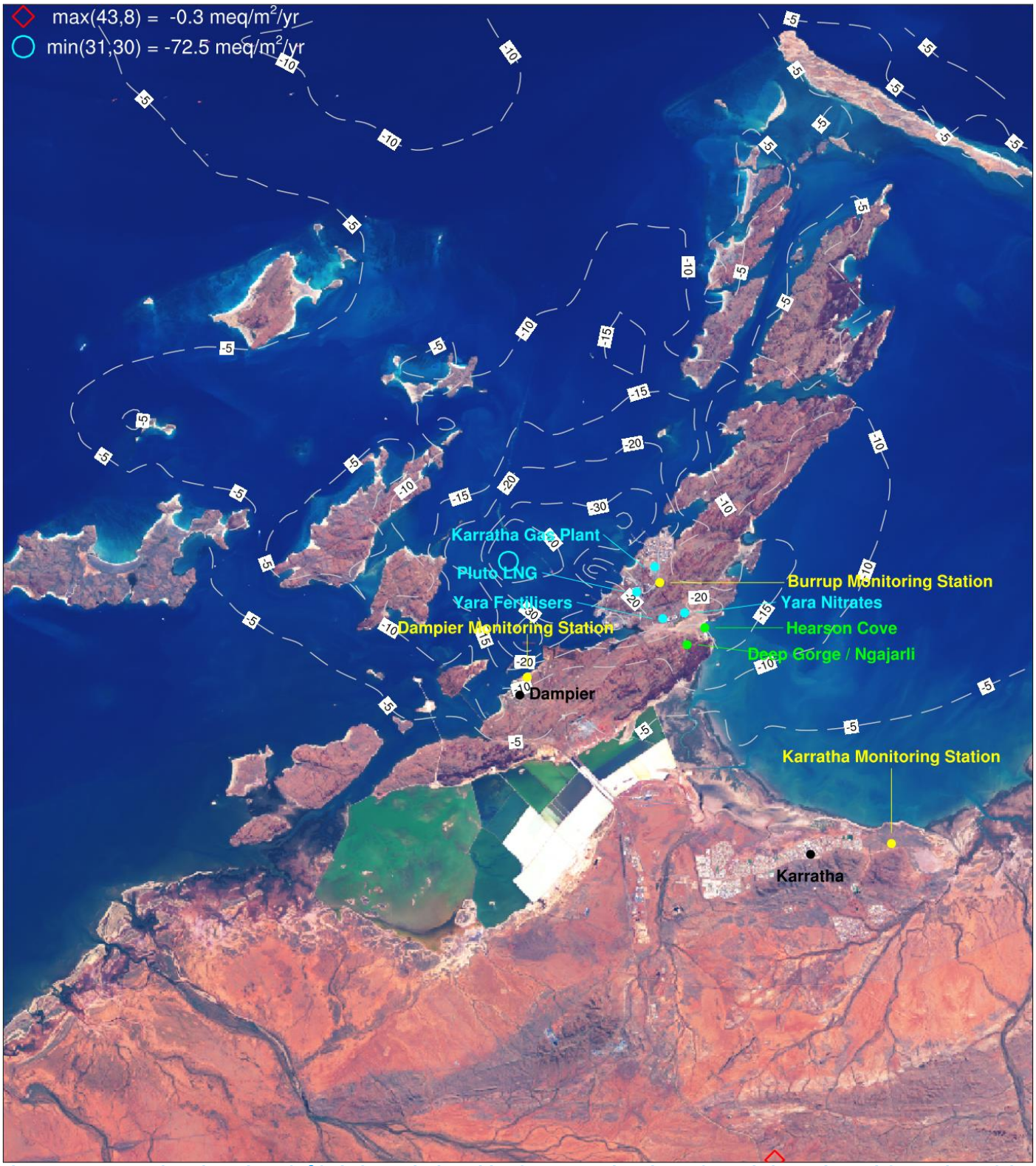


Figure 6-111. Annual total SO_2 (meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

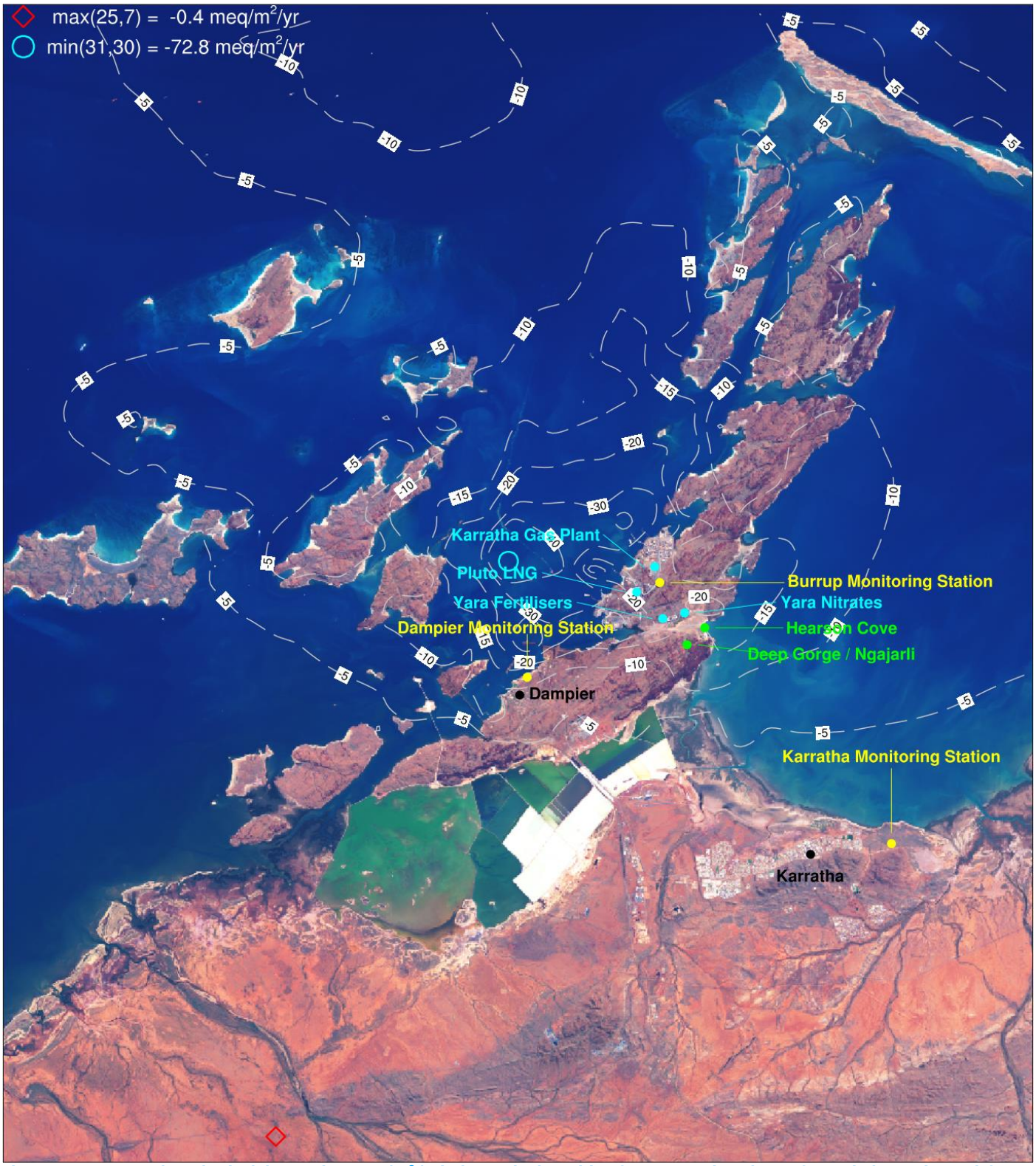


Figure 6-112. Annual total S (sulphur; units: meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

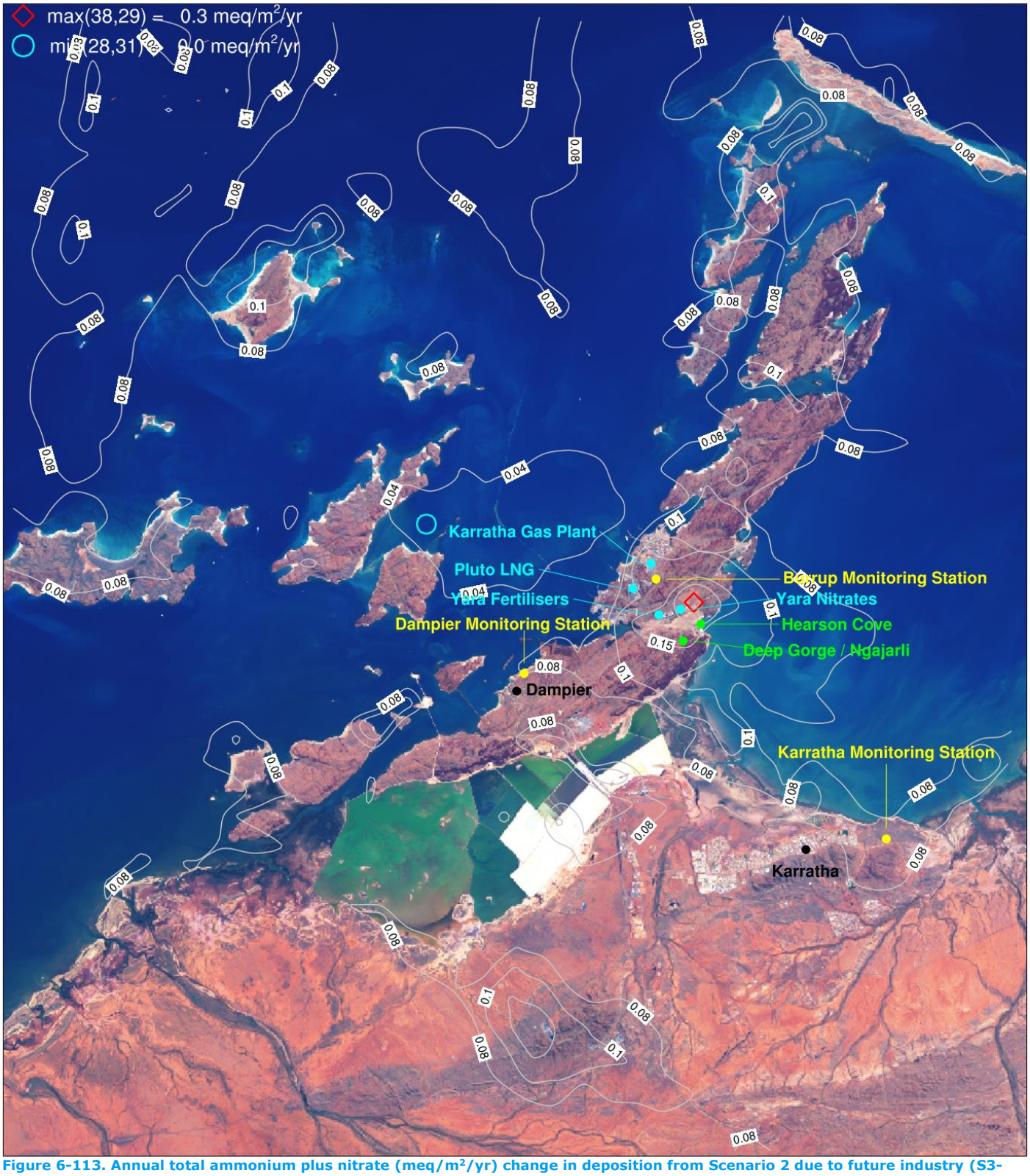


Figure 6-113. Annual total ammonium plus nitrate (meq/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

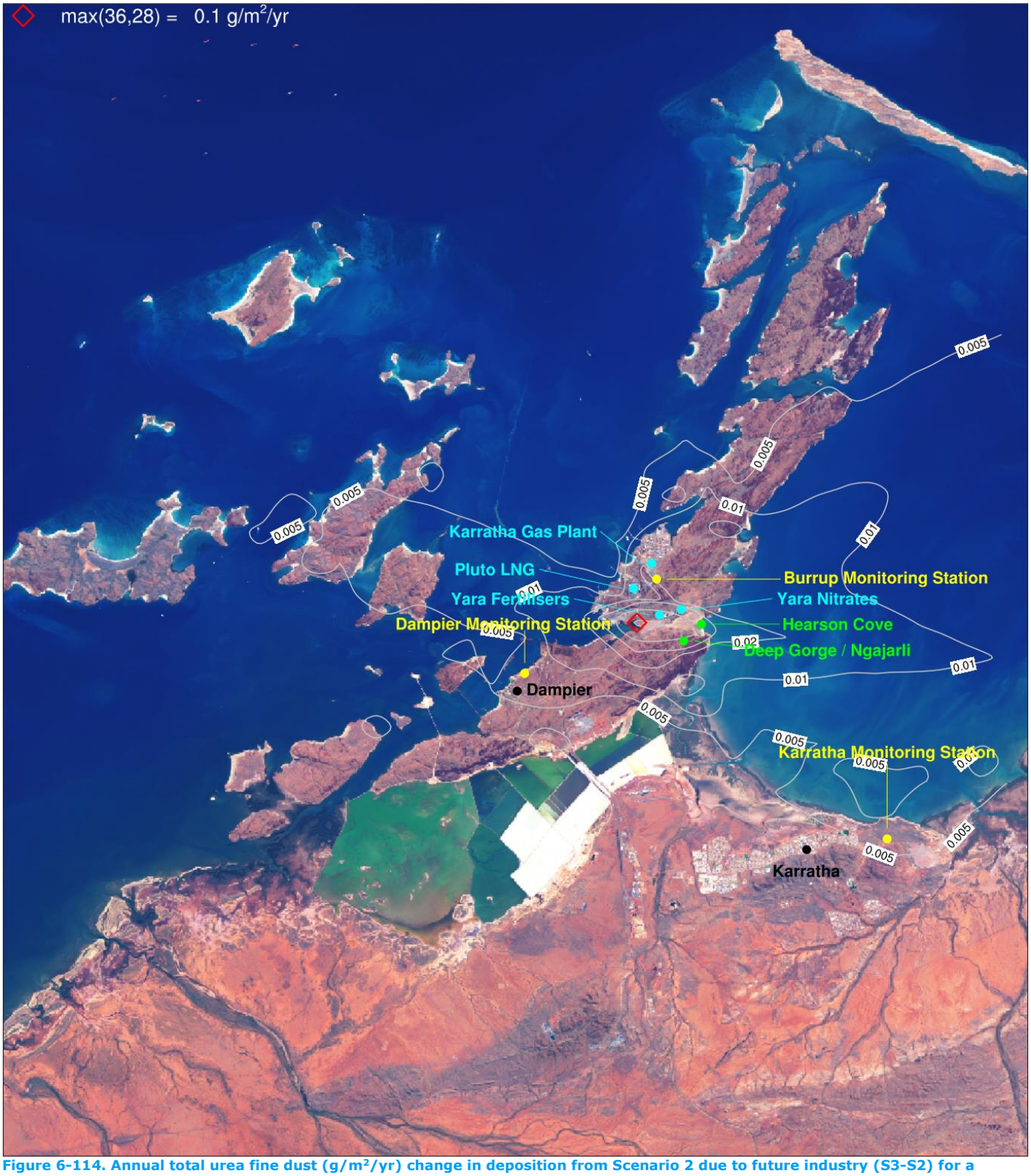


Figure 6-114. Annual total urea fine dust (g/m²/yr) change in deposition from Scenario 2 due to future industry (S3-S2) for a subset of the CAMx 1.33 km domain centred over the Burrup Peninsula.

6.4.2 Deposition at Selected Locations

Table 6-13 reports the annual deposition for total nitrogen (N) and sulphur (S) in meq/m^2/yr for monitoring sites and sensitive sites. The deposition amounts are for the grid cell containing each location (i.e., representative for the average land cover over a 1.33 by 1.33 km area) because CAMx is a grid model.

Scenario 2 deposition amounts at Burrup Road for total N of 24.57 meq/m^2/yr is within the range of measurements recorded from 2012–2014 (17.1 – 28.8 meq/m^2/yr). Total S deposition of 22.95 meq/m^2/yr for Scenario 2 also falls within the measured range of 19.8 – 31.6 meq/m^2/yr measured between 2004 and 2008. Most of the S and N deposition in Scenario 2 is attributable to industry emissions.

Industry contributions to N deposition are expected to increase in the future at locations within the Burrup peninsula with the largest predicted increase being 7.59 meq/m^2/yr at the Hearson Cove monitor. Industry contributions to S deposition, on the other hand, are expected to decrease as a result of the introduction of IMO regulations that limit fuel-sulphur content for marine vessels. Industry contributions to S deposition at Burrup Road monitoring station, for example, is expected to decrease by up to 15.29 meq/m^2/yr. Future reductions in S deposition due to reduced marine vessel fuel S content occur throughout the Burrup Peninsula whereas future increases in N deposition due to new NOx emission sources tend to be larger near the new sources.

Annual deposition totals for ammonium plus nitrate (in meq/m^2/yr) in the CAMx grid cells that contain Dampier Monitoring Station, Burrup Road, Hearson Cove, and Deep Gorge/Ngajarli are shown in Table 6-14. Deposition concentrations range from 0.44 meq/m^2/yr in the grid cell containing Karratha to 0.60 meq/m^2/yr at Hearson Cove. Industry contributions make up 0.09 meq/m^2/yr at Karratha and 0.17 meq/m^2/yr at Hearson Cove. Future industry contributions are expected to increase from 0.07 to 0.20 meq/m^2/yr.

Table 6-13. Annual sum deposition values for total nitrogen (N) and total S (sulphur) in the CAMx grid cells that contain the Dampier Monitoring Station, Burrup Road, Hearson Cove, and Deep Gorge.

		N (meq/m^2/yr)	S (meq/m^2/yr)
		Annual Sum	Annual Sum
CAMx Scenario 2	Hearson Cove	22.94	18.58
	Deep Gorge/Ngajarli	12.91	22.76
	Burrup Road	24.57	22.95
	Dampier	26.30	25.27
	Karratha	15.11	3.78
Industry Deposition (S2-S1)	Hearson Cove	19.82	17.56
	Deep Gorge/Ngajarli	10.94	21.50
	Burrup Road	21.22	21.86
	Dampier	22.98	24.16
	Karratha	10.72	2.47
Change in Industry Deposition (S3-S2)	Hearson Cove	7.59	-12.13
	Deep Gorge/Ngajarli	3.80	-14.36
	Burrup Road	6.02	-15.29

		N (meq/m²/yr)	S (meq/m²/yr)
		Annual Sum	Annual Sum
	Dampier	6.33	-15.22
	Karratha	2.92	-1.34
CAMx Scenario 3	Hearson Cove	30.53	6.45
	Deep Gorge/Ngajarli	16.71	8.40
	Burrup Road	30.60	7.66
	Dampier	32.63	10.05
	Karratha	18.03	2.44

Table 6-14. Annual sum deposition for ammonium plus nitrate in the CAMx grid cells that contain the Dampier Monitoring Station, Burrup Road, Hearson Cove, and Deep Gorge.

		Ammonium plus Nitrate (meq/m²/yr)
		Annual Sum
CAMx Scenario 2	Hearson Cove	0.60
	Deep Gorge/Ngajarli	0.52
	Burrup Road	0.59
	Dampier	0.54
	Karratha	0.44
Industry Deposition (S2-S1)	Hearson Cove	0.17
	Deep Gorge/Ngajarli	0.13
	Burrup Road	0.13
	Dampier	0.12
	Karratha	0.09
Change in Industry Deposition (S3-S2)	Hearson Cove	0.20
	Deep Gorge/Ngajarli	0.13
	Burrup Road	0.11
	Dampier	0.08
	Karratha	0.07
CAMx Scenario 3	Hearson Cove	0.80
	Deep Gorge/Ngajarli	0.65
	Burrup Road	0.70
	Dampier	0.63
	Karratha	0.51

6.4.3 Summary of Deposition of Air Emissions from Existing and Future Industry

A summary of the deposition of air emissions from Scenario 2 and Scenario 3 includes the following:

- HNO_3, NO_2, and total N deposition amounts are higher over land than over water because HNO_3 and NO_2 dissolves into water.
- Particulate nitrate (PNO_3) is a small contributor to total N deposition because it deposits more slowly than HNO_3 and NO_2.
- PSO_4, SO_2, and S deposition occur mostly offshore near Dampier and over land near Dampier, showing that most of the deposition is coming from shipping and industrial plants in the area.
- Almost all N and S deposition comes from the industrial emissions sources in the region.
- Scenario 2 deposition of total N at Burrup Road is higher than measurements recorded from 2012–2014 suggesting that NO_X emissions from industry and/or shipping may be over-estimated in Scenario 2.
- Industry contributions to N deposition are expected to increase in the future with the largest increase occurring near Burrup Road.
- Industry contributions to S deposition are expected to decrease in the future as a result of the introduction of IMO regulations that limit fuel-sulphur content for marine vessels.
- Hg deposition values are low and there is little change expected in the future.
- Annual deposition totals for ammonium plus nitrate range from 0.44 meq/m^2/yr in the grid cell containing Karratha to 0.60 meq/m^2/yr at Hearson Cove. Industry contributions make up 0.09 meq/m^2/yr at Karratha and 0.17 meq/m^2/yr at Hearson Cove. Future industry contributions to deposition are expected to increase from 0.07 to 0.20 meq/m^2/yr.

7. SUMMARY AND RECOMMENDATIONS

7.1 Summary

Murujuga (the Dampier Archipelago, including the Burrup Peninsula) contains unique ecological and archaeological areas of national and international heritage value including areas of significant cultural and spiritual significance to Aboriginal people.

Murujuga is also home to industry that contributes to the local and state economy and provides employment in the area. In response to concerns that industrial emissions may be affecting the areas of cultural significance, several scientific studies assessing potential impacts have been conducted for the region.

The Western Australian Department of Water and Environmental Regulation (DWER) commissioned Ramboll Australia Pty Ltd (Ramboll) to undertake a study on the cumulative impacts of air emissions within the Murujuga airshed including air emissions from existing and proposed future industries, shipping, and aggregated sources in the Pilbara region.

Ramboll used the CAMx air quality model, which includes photochemistry of the atmosphere, to evaluate air concentrations and deposition for these pollutants:

- Nitrogen dioxide (NO_2);
- Ozone (O_3);
- Sulphur dioxide (SO_2);
- Carbon monoxide (CO);
- Ammonia (NH_3);
- Volatile organic compounds (VOCs), including benzene, toluene, ethylbenzene, and xylene (BTEX);
- Particulate matter as PM_{10} and $PM_{2.5}$;
- Chemical constituents of PM including urea dust, ammonium nitrate, and ammonium sulphate; and
- Inorganic Mercury (Hg).

A complete emission inventory of all sources was necessary to conduct photochemical modelling. The following emissions sources were included:

- Industrial emissions sources;
- Mobile sources including:
    - Commercial shipping and recreational boating;
    - On-road and off-road mobile vehicles;
    - Airports; and
    - Railways.
- Domestic and commercial sources including:
    - Recreational boats
    - Aerosols and solvents;
    - Cutback bitumen
    - Gaseous fuel combustion;
    - Liquid fuel combustion (domestic);

    - Portable fuel containers (domestic and public open space);
    - Gaseous and solid fuel combustion (domestic); and
    - Surface coatings (domestic, commercial and industrial).
    - Industrial solvents;
    - Automotive fuel retailing; and
    - Motor vehicle refinishing.
- Natural sources including:
    - Vegetation;
    - Wind blown dust;
    - Bushfires; and
    - Oceanic Sources (Sea salt and dimethyl sulphide).

The CAMx modelling considered three scenarios in order to quantify current industry ground level concentrations (Scenario 2 – Scenario 1) and anticipated changes to ground level concentrations due to future industry expansion (Scenario 3 – Scenario 2), namely:

- **Scenario 1** - All emissions, including natural, domestic and commercial sources, but excluding the point and area sources for heavy industry including railways and shipping in the region.
- **Scenario 2** - Scenario 1 plus the point and area sources for heavy industry including railways and shipping in the region.
- **Scenario 3** - Scenario 2 plus proposed future emissions (2030) from all sources.

A base year of 2014 was identified as having meteorology that is typical of recent years, rather than being an extreme year and was utilised in the modelling. The CAMx modelling uses meteorology from a weather model (WRF) and background air quality from a global air quality model (CAM-chem). CAMx is a grid model, meaning that it represents the atmosphere as a system of inter-connected grid boxes, also called grid cells. The grid cell size is what determines how finely the model can resolve space. The CAMx model has 1.33 km grid cells (meaning 1.33 km by 1.33 km squares) over Murujuga and the adjacent area. The model also has a 4 km resolution grid covering a wide portion of the Pilbara.

CAMx model results for Scenario 2 were compared with available air monitoring data for 2014. The comparison indicated reasonable agreement with the measurements at Burrup Road, Dampier, and Karratha noting the following:

- There is a high NO_2 model bias at Burrup Road and Dampier. The bias at Burrup Road is likely due to the model not having a fine enough resolution to resolve the source-receptor relationships at this location. The bias at Dampier is likely due to influence from shipping and industry emissions in the region.
- Ozone concentrations at Dampier and Karratha correlate closely with observed concentrations and have little bias.
- There was good agreement between modelled and measured distributions of benzene, toluene, and xylene concentrations, especially for higher concentrations (around the 90^{th} percentile).
- Modelled 24-hour average $PM_{2.5}$ and PM_{10} concentrations agree fairly well with observations in Dampier although the 1.33 km model resolution is insufficiently fine to resolve details of the source-receptor relationships.

A summary of the predicted ground level concentrations for Scenario 2 and Scenario 3 includes the following:

- Analysis of source contributions to the predicted ground level concentrations of benzene, toluene and xylene emissions in the Murujuga airshed indicate that the majority contribution is from industry near or on the Burrup Peninsula
- Exceedances of the benzene standard were predicted for Scenario 2, however these exceedances were predicted to occur at or near industrial facilities and no exceedances were predicted at sensitive receptor locations, including Dampier and Karratha.
- Future industry benzene emissions increased but concentrations remained well below the guideline at sensitive receptor locations, including Dampier and Karratha.
- SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and NH_3 peak ground level concentrations are centred at industrial facilities near or on the Burrup Peninsula, showing that industrial sources and shipping contribute to emissions in the area, but with total air concentrations for these compounds remaining below current air quality standards except for PM_{10} and $PM_{2.5}$ at sensitive receptor locations, including Dampier and Karratha.
- Industry GLCs contribute from 3.8% to 15.5% of annual average PM_{10} and 6.2% to 18.4% of annual average $PM_{2.5}$ in Scenario 2. Future industry GLCs contribute only around 1% to 2% to annual average PM_{10} in Scenario 3. Contributions to annual average $PM_{2.5}$ in Scenario 3 are negative or zero likely due to decreases in secondary $PM_{2.5}$ precursor emissions.
- Estimated background (Non-industrial) PM_{10} dust concentrations contribute 23-29 $\mu g/m^3$ (85-96%) to the annual average and 85-95 $\mu g/m^3$ (92-99%) in maximum 24-hr concentrations (although the maximum 24-hr dust and maximum 24-hr total PM_{10} could have occurred on different dates). Dust sources alone (i.e., crustal material from categories 1 and 2 above) contribute approximately 66-73% of the annual average PM_{10} and 79-86% of the maximum 24-hr PM_{10} concentrations.
- Background (Non-industrial) $PM_{2.5}$ dust concentrations contribute 4.6-5.8 $\mu g/m^3$ (82-94%) to the annual average and around 16-17 $\mu g/m^3$ (82-94%) in maximum 24-hr concentrations. Dust sources alone (i.e., crustal material from categories 1 and 2 above) contribute approximately 31-44% of the annual average $PM_{2.5}$ and 66-74% of the maximum 24-hr $PM_{2.5}$ concentrations.
- For several short-term air quality metrics (i.e., MDA1) industrial emissions are a large contributor to the highest predicted ground level concentrations.
- Offshore SO_2 and NO_2 show strong influences from shipping emissions.
- Future annual maximum daily 1-hour average (MDA1) NO_2 were predicted to decrease by 13.6 ppb near Dampier which likely results from Woodside's proposed replacement of existing gas turbines with more efficient-low NOx devices at the Karratha Gas Plant.
- Future MDA1 SO_2 concentrations decrease offshore by 86 ppb due to the introduction of International Maritime Organisation (IMO) regulations that limit the fuel-sulphur content for marine vessels.
- Industrial emissions result in suppression of O_3 near Dampier due to strong NOx emissions.
- Future industry emissions tend to increase O_3 but O_3 concentrations in all scenarios are below air quality standards.
- Future industry emissions increase MDA8 CO by 359 ppb near the Yara Ammonium Nitrate Plant.
- Annual average ground level concentrations for VOCs range from around 9 ppb to 26 ppb at sensitive receptor locations, including Dampier and Karratha. Industry ground level concentrations are highest in the grid cell containing Burrup. Future industry ground level concentrations are highest in the grid cells containing Burrup Road (14.5 ppb) and Hearson Cove (29.9 ppb).
- Ammonium plus nitrate concentrations are less than 1 $\mu g/m^3$ at sensitive receptor locations, including Dampier and Karratha. Future industry ground level concentrations are expected to increase by less than 0.2 $\mu g/m^3$.

- Urea fine dust ground level concentrations from industry are expected to increase by up to 0.6 µg/m^3 in the future industry scenario.
- NH_3 MDA1 air concentrations at sensitive receptor locations are all below the standard and are expected to decrease to 30 ppb or less in the future industry scenario.
- Updated NH_3 emission estimates introduced short-term variations that substantially increased maximum NH_3 concentrations near the affected emission sources but had little impact on PM concentrations.

A summary of the predicted deposition for Scenario 2 and Scenario 3 includes the following:

- HNO_3, NO_2, and total N deposition amounts are higher over land than over water because HNO_3 and NO_2 dissolves into water.
- Particulate nitrate (PNO_3) is a small contributor to total N deposition because it deposits more slowly than HNO_3 and NO_2.
- PSO_4, SO_2, and S deposition occur mostly offshore near Dampier and over land near Dampier, showing that most of the deposition is coming from shipping and industrial plants in the area.
- Almost all N and S deposition comes from the industrial emissions sources in the region.
- Industry contributions to N deposition are expected to increase in the future with the largest increase occurring near Burrup Road.
- Industry contributions to S deposition are expected to decrease in the future as a result of the introduction of IMO regulations that limit fuel-sulphur content for marine vessels.
- Hg deposition values are low and there is little change expected in the future.
- Annual deposition totals for ammonium plus nitrate are less than 1 meq/m^2/yr for all sensitive receptor locations, including Dampier and Karratha. Industry deposition at Karratha is 0.08 meq/m^2/yr and 0.20 meq/m^2/yr at Burrup Road. Future industry deposition is expected to increase by 0.2 meq/m^2/yr or lower.
- Updated NH_3 emission estimates had little impact on deposition values.

7.2 Recommendations

7.2.1 Modelling Methodology

The implementation of the following recommendations could result in improvements for any future work undertaken using the current modelling methodology.

- The quality of the SRTM3 terrain dataset over the mainland in the south of the domain may be more reasonable, and possibly more accurate than the standard WRF datasets, but project timelines did not allow for a sensitivity test of the noisier data over the islands. As a result, Ramboll used the standard USGS datasets that are distributed with WRF. Ramboll would recommend that any future work undertake a sensitivity analysis to assess potential improvements in the prediction of meteorology.
- It is recommended that future modelling include source apportionment for priority sources to assess the contribution at locations of interest.
- CAM-Chem overstates dust concentrations in the region surrounding the CAMx modelling domain and it is necessary to adjust (decrease) the CAMx BCs for dust obtained from CAM-chem. Dust influences aerosol pH by providing alkaline material and therefore greatly over-estimating (or under-estimating) dust can bias the chemistry for anthropogenic emissions such as SO_2. The CAMx simulation of dust (BCs and emissions) could be improved by additional study.

- Plume in grid modelling should be investigated to refine the modelled NO_2 ground level concentrations near industrial emissions sources although hourly source characteristics (i.e., emission rates, plume rise) also would be advantageous for such a detailed modelling approach.

7.2.2 Emissions Estimates

Estimates of emissions from sources are a critical input into air dispersion modelling, but it is acknowledged that all estimates have a certain level of uncertainty. Emissions estimates were derived from a large number of sources and techniques. The accuracy of data included in this assessment was often limited by the availability of information from both public sources and directly from operators. As such, estimates were often derived from default emissions factors or engineering judgement where applicable or available.

When assessing uncertainty in emissions estimates, the magnitude of the emission source is an important factor in determining if the level of uncertainty present in the estimate is of significance or not. Refining emissions estimates from a source generating only small quantities of pollutants, but with high uncertainty, is likely to have a reduced influence on outcomes than refining emissions from a source that generates large quantities of pollutants with low levels of uncertainty. Emissions from industry and commercial shipping were one of the dominant sources of pollutants in the study region and given their proximity to receptors of interest, significant effort was made to obtain the most accurate information available with particular focus on sources located near or on the Burrup peninsula. Ramboll would recommend that the following recommendations aimed at improvements to the emissions estimates from these sources be given priority.

7.2.2.1 Industry and Shipping

Ramboll recommends the following to improve emissions estimates from industry and shipping.

- The outcomes from the assessment indicates a high bias for NO_2 at the Burrup Road and Dampier monitors. Whilst this may have been a function of the resolution of the modelling, analysis of the plots indicates significant contributions from other sources such as railways and shipping emissions in the region of which there was a degree of uncertainty related to emissions estimates. A more detailed characterisation in the quantity and temporal variation of emissions from these operations would likely enhance the outcomes of the assessment.
- Emissions data from some industry sources were derived from NPI estimates. There are varying levels of uncertainty in the emissions factors often used to derive emissions reported in the NPI. Emissions estimates presented in the publicly available NPI database are also presented for a whole facility which may not allow for accurate distribution and parameterisation of emissions from individual sources. More detailed characterisation of emissions from some industry sources in the Burrup peninsula would assist in reducing potential uncertainty.
- Shipping emissions could be further refined by utilising an un-anonymised private AIS dataset with additional vessel detail for all shipping movements in the region instead of the composite approach using the CEDS database and the publicly available AIS dataset from AMSA. The current assessment used AIS records which do not provide unique vessel identification information. With access to vessel identities, vessel-specific characteristics can be accessed through cross referencing with vessel characteristics databases (e.g., IHS Markit or Clarkson). These specifications can provide a much more accurate depiction of vessel emissions. The AIS data assessment can also be expanded to include transiting emissions to provide a uniform approach for estimating vessel emissions within the model domain. Additionally, further

details on specific fuel use at individual ports or terminals could be taken into consideration to more accurately refine emissions factors. Such information may be gleaned from port- or terminal-specific emission reduction or fuel use programs.

- It should be noted that it would be difficult to completely match shipping emissions of SO_2 for 2014 data as discussion with Pilbara Ports indicates that some ships fuel switch from high to low sulphur fuel at the request of some of the onshore operators but that fuel-switching was not enforceable and so was done on an ad-hoc basis. The introduction of the lower sulphur limits in fuel by the IMO will reduce some of the uncertainty in the future.
- Predicted deposition of pollutants in some grid cells located in close vicinity to each other, displayed a higher degree of variability than would be expected which was likely a function of the landuse maps utilised in the study. Development of more accurate landuse maps would likely result in improved performance related to deposition, particularly in coastal areas.

7.2.2.2 Other Sources

Whilst the magnitude of emissions from sources other than shipping and industry in the Murujuga airshed was significantly lower, the accuracy of emissions estimates from these could still be improved through the implementation of the following recommendations.

- Emissions estimates from airports could have been improved through the inclusion of more detailed aircraft movements at Karratha airport. As well as commercial airlines, there was some uncertainty regarding the movements from helicopter operators during the 2014 period. Development of a more detailed emissions dataset utilising third party tools such as the Aviation Environmental Design Tool (AEDT) (U.S FAA, 2015) would further enhance the dataset.
- There was some uncertainty with emissions from wind-blown dust. A more accurate characterisation of erodible areas in the study region would improve performance of the emissions estimates using the methodology utilised for the modelling.
- Certain default assumptions were utilised in determining emissions from vehicles in the region. There was a higher degree of uncertainty associated with estimates determined from vehicle movements on suburban or remote roads as compared with major roads as they were not monitored by Main Roads WA or local governments. Another limitation of the study was the differences in vehicle classification/ groupings between the emissions model (COPERT Australia) and various sources of information including ABS, Main Roads WA and Department of Transport (DoT). Information based on vehicle movement studies on suburban and remote roads and greater corroboration between the classifications of the datasets would improve the emissions datasets.
- Emissions from sub-threshold facilities are relatively large but have a high degree of uncertainty. Whilst efforts were made to request fuel distribution figures to sub threshold facilities from wholesalers, this information was not supplied. Emissions estimates from these sources could be further refined with the detailed distribution information.

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APPENDIX 1

MEGAN V3.1 UPDATES FOR AUSTRALIA

MEGAN V3.1 UPDATES FOR AUSTRALIA

Appendix 1 describes three tasks that were undertaken by Dr. Alex Guenther to provide improved input data sets for the Model of Emissions of Gases and Aerosols from Nature version 3.1 (MEGAN3.1) biogenic VOC emission model. This includes 1) emission factors, 2) plant species composition data, and 3) growth form and ecotype data. The MEGAN-ready (netcdf and CSV) data files are described along with the methodology used to develop the data.

The biogenic emission model name remains MEGAN3.1 because there were no changes to the model algorithms. The updated landcover data files (described below) named GF3a and EVT3b and available from the MEGAN web site (https://bai.ess.uci.edu/megan/data-and-code/growth-form-and-ecotypes).

Task 1. Review published literature for Australian vegetation BVOC emission factors and incorporate them into MEGAN3.1.

MEGAN3.1 and other biogenic VOC emission models assume that emission rates are the product of an emission factor (EF) and an emission activity factor, similar to the approach used for most anthropogenic emission estimates. While research activities tend to focus on emission activity factors, uncertainties in EF make an important contribution and may even dominate the total uncertainty in BVOC emission rate estimates. There have been relatively few BVOC EF studies conducted anywhere in Australia and there have been none in Western Australia. However, some of the important genera occurring in Western Australia have been sampled in other parts of Australia or on other continents. In addition, satellite observations with global coverage provide information that can be used to establish emission factors. The available EF data for Australia were used to generate the two required MEGAN3.1 Emission Factor Processor (EFP) comma separated values (CSV) files: DB_emissions.Aus20 and Description_Vegetation.Aus20. The DB_emissions.Aus20 CSV file contains 569 entries that provide emission factors for Australian vegetation covering the 18 MEGAN chemical categories although most entries are for isoprene which is the dominant emission in Australia. The Description_Vegetation.Aus20 includes vegetation descriptions of all of the vegetation types included in the DB_emisions.Aus20 database.

As described in the task 2 section, Australian vegetation canopy cover includes two dominant genera, Eucalyptus (~33%) and Acacia (~12%), and ten other genera that comprise another ~7% (Atriplex, Melaleuca, Maireana, Sarcocornia, Allocasuarina, Casuarina, Callitris, Avicennia, Banksia, and Leptospermium). The remaining vegetation is classified as “other shrubs” that contribute another ~33% and “other broadleaf trees” that contribute another ~16%. Most of the emission factors were based on the enclosure measurement data. The exceptions were the isoprene and monoterpene emission factors assigned to Eucalyptus and the isoprene emission factor assigned to “other shrubs”.

The ambient concentration data reported by Emmerson et al. (2016) for south eastern Australia sites and Ayers and Gillett (1988) for Northcentral Australia were used to estimate emission factors for Eucalyptus trees that were included in the DB_emissions.Aus20 database along with enclosure measurements. For the “other shrubs” category, which are the dominant cover in Western Australia, the isoprene emission factor was based on isoprene emissions estimated for Western Australia shrublands based on OMI satellite HCHO data (Stavrakou et al. 2015). The OMI isoprene emission results were compared with estimates from GOME satellite data and were found to be within 10% for Australian forests and woodlands but were about 20% higher for Pilbara shrublands in Western Australia.

The enclosure measurement data used to develop the MEGAN3.1 terpenoid EF file for Australia include observations from three studies conducted in Australia (He et al. 2000, He et al. 2000b, and Winters et al. 2009). These three studies reported isoprene and monoterpene emission factors for 12 Eucalyptus species. Emission measurements reported for an additional 17 studies conducted outside of Australia in the past 2 decades were used to assign emission factors to an additional 4 Eucalyptus species and for the Acacia, Atriplex, and Casuarina genera (Aydin et al. 2014a, Aydin et al. 2014b, Geron et al. 2006, Harley et al. 2003, Huang et al. 2011, Karlik and Winer 2001, Mutanda et al. 2016, Nunes and Pio 2001, Otter et al. 2002, Padhy and Varshney 2005, Street et al. 1997, Tambunan et al. 2006, Varshney and Singh 2003, Wang et al. 2003, Yang et al. 2001, Zhao et al. 2004). Emission factors for the Melaleuca, Callitris, Banksia and Avicennia genera were assigned on the basis of older emission measurement studies that were conducted prior to 2000 and have higher uncertainties.

Finally, emission factors for the four genera for which there were no reported emissions data were assigned based on emissions data for other genera in the same family. For example, Allocasuarina species were assigned the value established for Casuarina (both are in the Casuarinaceae family) and Leptospermum species were assigned values for Eucalyptus (both are in the Myrtacea family). Maireana and Sarcocornia species were assigned emission factors based on other species in the Chenopodiacea family.

Field studies have shown that the Acacia genus includes some species that have high isoprene emission, some have a high monoterpene emission and others have low emission of both (Harley et al. 2003). This makes it difficult to assign a representative isoprene and monoterpene emission factor to Australian Acacia woodlands where the most species have not been sampled and the landcover is only identified by genus (Acacia) without information on species.

The result would be a relatively high uncertainty associated with isoprene emission from Acacia. However, taxonomists have recently divided the traditional Acacia genus into five separate genera: Acacia, Senegalia, Vachellia, Acaciela and Mariosousa. The MEGAN database was updated to reflect this new taxonomic structure and the results demonstrate a consistent emission behavior for these new genera. The Vachellia species are high monoterpene emitters, the Senegalia species are high isoprene emitters and the remaining Acacia species (which includes almost all of the traditional Australian Acacia species) have low emissions.

Task 2. Incorporate improved Australian plant species composition data into MEGAN3.1

The National Vegetation Information System (NVIS) is a comprehensive data system that provides information on the extent and distribution of vegetation types in Australian landscapes. The NVIS version 5.1 data includes the 99 landcover types displayed in Figure A-1 and listed in Table A-1. Many of these landcover types are dominated by a single plant species or genus which makes the dataset suitable for characterising emission types for BVOC emission modelling. The landcover types in Western Australia shown in Figure A-1 illustrate the distributions which include tree covered riparian areas, closed shrublands, open shrublands and grasslands.

The 100 m spatial resolution NVIS5.1 dataset for Australia was degraded to 1/120 degree (~1 km^2) and integrated with the global MEGAN17EVT Emission Vegetation Type scheme using ARCGIS to generate the MEGAN20EVT netcdf file (EVT3a). The NVIS vegetation subgroups were mapped to MEGAN vegetation types and CSV files were generated to represent landcover vegetation speciation for trees (NVIStree) and shrubs (NVISshrub). Files for crops (NVIScrop) and herbaceous (NVIherb) were assigned a single type.

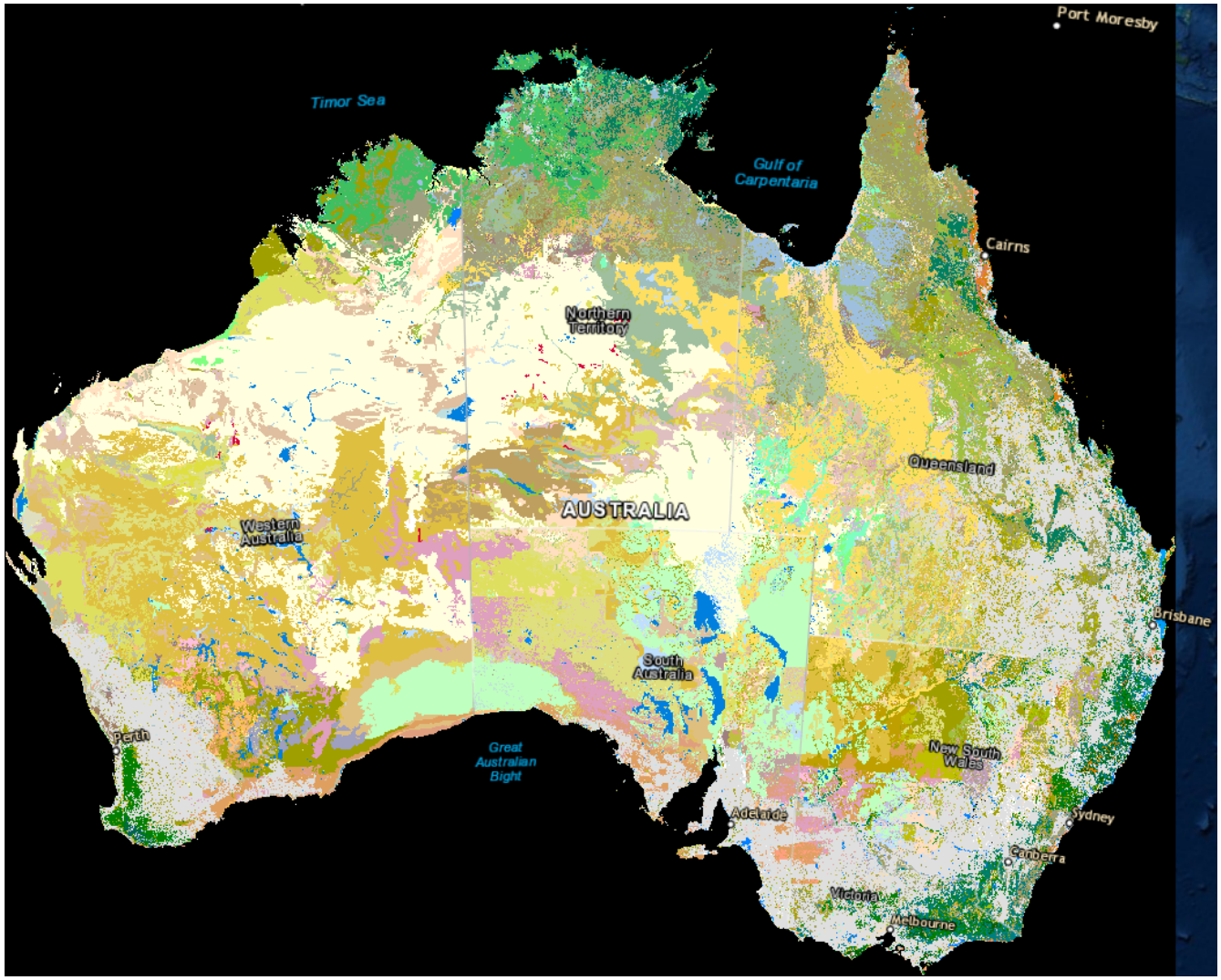

Figure A-1: NVIC landcover distribution across Australia. Color scheme key is given in Table A.1.

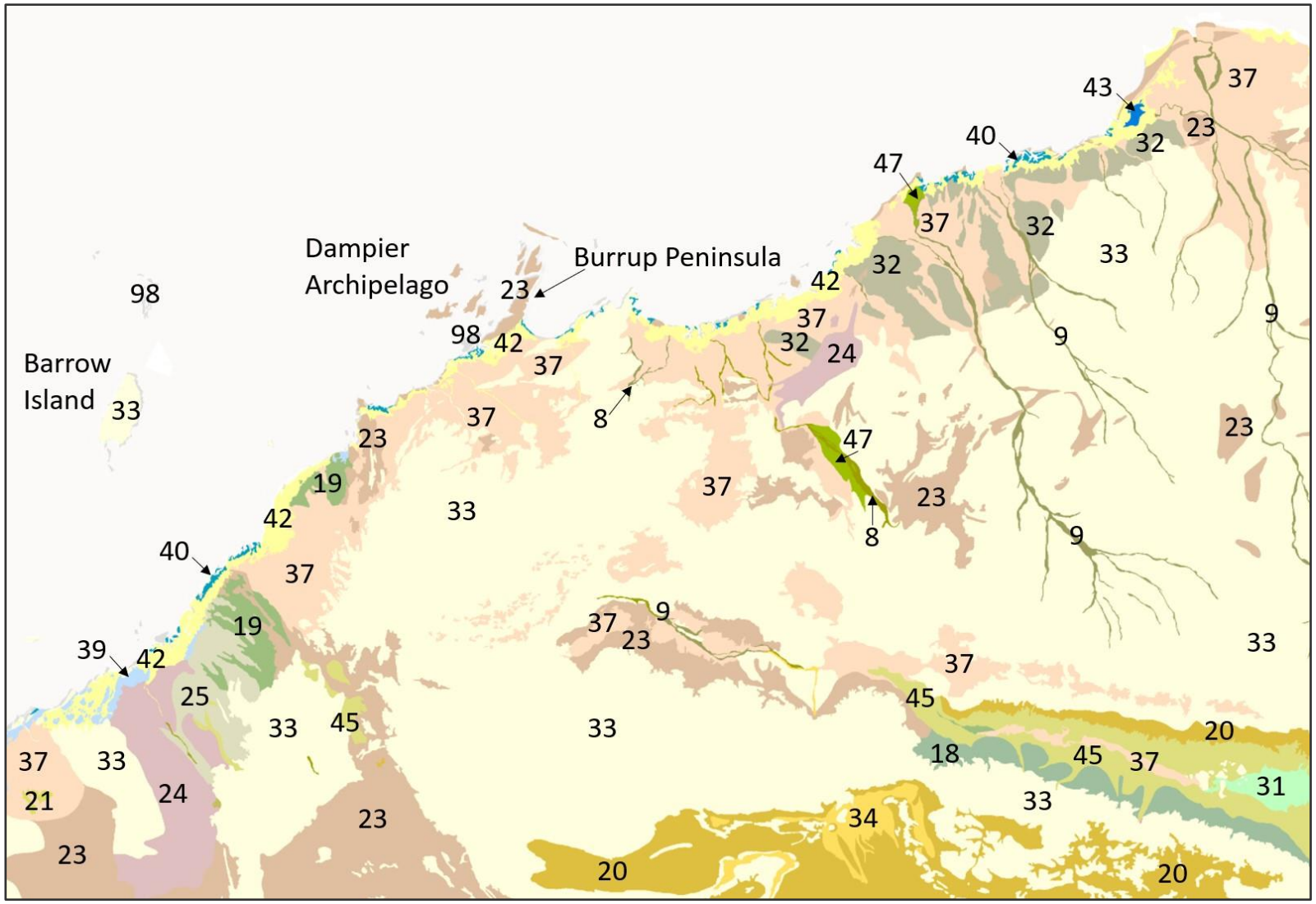

Figure A-2: NVIC landcover distribution in Western Australia. Numeric labels follow the colour scheme key given in Table A-1.

Table A-1: NVIS 5.1 colour scheme for major vegation subgroups.

NVIS 5.1 Major Vegetation Subgroups (numeric order)		
MVS Num	MVS Name	Key
1	Cool temperate rainforest	
2	Tropical or sub-tropical rainforest	
3	Eucalyptus (+/- tall) open forest with a dense broad-leaved and/or tree-fern understorey (wet sclerophyll)	
4	Eucalyptus open forests with a shrubby understorey	
5	Eucalyptus open forests with a grassy understorey	
6	Warm temperate rainforest	
7	Tropical Eucalyptus open forests and woodlands with a tall annual grassy understorey	
8	Eucalyptus woodlands with a shrubby understorey	
9	Eucalyptus woodlands with a tussock grass understorey	
10	Eucalyptus woodlands with a hummock grass understorey	
11	Tropical mixed spp forests and woodlands	
12	Callitris forests and woodlands	
13	Brigalow (Acacia harpophylla) forests and woodlands	
14	Other Acacia forests and woodlands	
15	Melaleuca open forests and woodlands	
16	Other forests and woodlands	
17	Boulders/rock with algae, lichen or scattered plants, or alpine fjaeldmarks	
18	Eucalyptus low open woodlands with hummock grass	
19	Eucalyptus low open woodlands with tussock grass	
20	Mulga (Acacia aneura) woodlands +/- tussock grass +/- forbs	
21	Other Acacia tall open shrublands and [tall] shrublands	
22	Acacia (+/- low) open woodlands and shrublands with chenopods	
23	Acacia (+/- low) open woodlands and shrublands with hummock grass	
24	Acacia (+/- low) open woodlands and shrublands +/- tussock grass	
25	Acacia (+/- low) open woodlands and sparse shrublands with a shrubby understorey	

NVIS 5.1 Major Vegetation Subgroups (numeric order)		
26	Casuarina and Allocasuarina forests and woodlands	
27	Mallee with hummock grass	
28	Low closed forest or tall closed shrublands (including Acacia, Melaleuca and Banksia)	
29	Mallee with a dense shrubby understorey	
30	Heathlands	
31	Saltbush and bluebush shrublands	
32	Other shrublands	
33	Hummock grasslands	
34	Mitchell grass (Astrebla) tussock grasslands	
35	Blue grass (Dicanthium) and tall bunch grass (Vitiveria syn: Chrysopogon) tussock grasslands	
36	Temperate tussock grasslands	
37	Other tussock grasslands	
38	Wet tussock grassland with herbs, sedges or rushes, herblands or ferns	
39	Mixed chenopod, samphire +/- forbs	
40	Mangroves	
41	Saline or brackish sedgelands or grasslands	
42	Naturally bare, sand, rock, claypan, mudflat	
43	Salt lakes and lagoons	
44	Freshwater, dams, lakes, lagoons or aquatic plants	
45	Mulga (Acacia aneura) open woodlands and sparse shrublands +/- tussock grass	
46	Sea, estuaries (includes seagrass)	
47	Eucalyptus open woodlands with shrubby understorey	
48	Eucalyptus open woodlands with a grassy understorey	
49	Melaleuca shrublands and open shrublands	
50	Banksia woodlands	
51	Mulga (Acacia aneura) woodlands and shrublands with hummock grass	
52	Mulga (Acacia aneura) open woodlands and sparse shrublands with hummock grass	
53	Eucalyptus low open woodlands with a shrubby understorey	
54	Eucalyptus tall open forest with a fine-leaved shrubby understorey	

NVIS 5.1 Major Vegetation Subgroups (numeric order)	
55	Mallee with an open shrubby understorey
56	Eucalyptus (+/- low) open woodlands with a chenopod or samphire understorey
57	Lignum shrublands and wetlands
58	Leptospermum forests and woodlands
59	Eucalyptus woodlands with ferns, herbs, sedges, rushes or wet tussock grassland
60	Eucalyptus tall open forests and open forests with ferns, herbs, sedges, rushes or wet tussock grasses
61	Mallee with a tussock grass understorey
62	Dry rainforest or vine thickets
63	Sedgelands, rushs or reeds
64	Other grasslands
65	Eucalyptus woodlands with a chenopod or samphire understorey
66	Open mallee woodlands and sparse mallee shrublands with a hummock grass understorey
67	Open mallee woodlands and sparse mallee shrublands with a tussock grass understorey
68	Open mallee woodlands and sparse mallee shrublands with an open shrubby understorey
69	Open mallee woodlands and sparse mallee shrublands with a dense shrubby understorey
70	Callitris open woodlands
71	Casuarina and Allocasuarina open woodlands with a tussock grass understorey
72	Casuarina and Allocasuarina open woodlands with a hummock grass understorey
73	Casuarina and Allocasuarina open woodlands with a chenopod shrub understorey
74	Casuarina and Allocasuarina open woodlands with a shrubby understorey
75	Melaleuca open woodlands
79	Other open Woodlands
80	Other sparse shrublands and sparse heathlands
90	Regrowth or modified forests and woodlands
91	Regrowth or modified shrublands
92	Regrowth or modified graminoids
93	Regrowth or modified chenopod shrublands, samphire or forblands
96	Unclassified forest

NVIS 5.1 Major Vegetation Subgroups (numeric order)		
97	Unclassified native vegetation	
98	Cleared, non-native vegetation, buildings	
99	Unknown/No data	

Task 3. Incorporate improved Australian vegetation growth form and ecotype data into MEGAN3.1

Growth form distributions of trees, shrubs, grass, and crops are a required input for MEGAN3.1. The MEGAN2.1 growth form distribution data were based on MODIS satellite observations of total green vegetation cover fraction and tree cover fractions developed by Hansen et al. (2003). The MEGAN2.1 total green vegetation cover was replaced with an updated MODIS maximum green vegetation fraction dataset, based on a twelve-year climatology (Broxton et a. 2014), for MEGAN3.0. Crop, shrub and grass fractions were estimated by assigning the non-tree fraction (calculated as total green vegetation cover minus tree cover) based on the land cover type.

For example, if the landcover was cropland then it was assumed that the crop area was 100% of the non-tree fraction. If the landcover was open shrubland then the non-tree fraction was assigned 0% crop, 50% shrub, 50% grass and so on for other landcover types (e.g. grassland, closed shrubland, etc). The MEGAN growth form data were updated for this project to improve distributions of shrub cover which is the dominant BVOC source for Western Australia.

Two potential global datasets were investigated: the Consensus product (Tuanmu and Jetz 2014) was developed for biodiversity and ecosystem modelling and includes tree, shrub, grass and crop fractions. The GLCShare product (Latham et al. 2014) was developed by the Food and Agricultural Organization (FAO) of the United Nations and included input from national experts around the world. All of these datasets have 1/120 degree (30 seconds which is ~1 km^2) spatial resolution.

Random point sampling using high resolution Google imagery in ArcGIS was used to assess and compare the ability of the MEGAN3.0, Consensus and GLCShare products to accurately characterise tree, shrub, grass and crop cover. The analysis indicated that MEGAN3.0 was the most accurate for tree cover, Consensus was the best for shrub and grass cover, and GLCShare was the most accurate for cropland. The three datasets were integrated to generate the updated growth form netcdf files (m20crop, m20tree, m202shrub, m202grass) based on the Broxton et al. 2014 total cover, the MEGAN3.0 MODIS (Hansen et al. 2003) tree cover, the Consensus shrub and grass cover and the GLCShare crop cover.

Figure A-3 compares the total vegetation cover distribution form the MEGAN2.1 and the updated product for landscapes in Western (mostly shrublands), Southwestern (mostly cropland), Northern (mostly savanna) and Southeastern Australia (mostly forest). On a global scale the average total cover is about the same for the two datasets but in Western Australia the updated vegetation cover tends to be 5 to 10 % lower than the MEGAN2.1 total cover estimates.

While the landcover updates tend to lower BVOC emissions, the impact is limited since MEGAN uses satellite LAI to quantify the amount of vegetation that can emit BVOC. Thus, decreasing the total vegetation cover just increases the LAI of vegetation covered surfaces and results in a decrease in light dependent compounds (such as isoprene) since there is more canopy shading. In

addition, Figure A-4 shows that the updated Consensus shrub distribution generally has lower shrub cover than MEGAN2.1, which decreases the estimated BVOC emissions in Western Australia by about 40%.

The updated grass cover is higher but the grasses are generally assigned lower emission factors. In the case of isoprene, with an emission factor based on landscape average emissions estimated by satellite data, the lower shrub cover does not have a large impact since it is used to develop the isoprene emission factor. In other words, the lower shrub cover results in a higher isoprene emission factor and so the estimated isoprene emission is about the same but there are changes in the small-scale distributions.

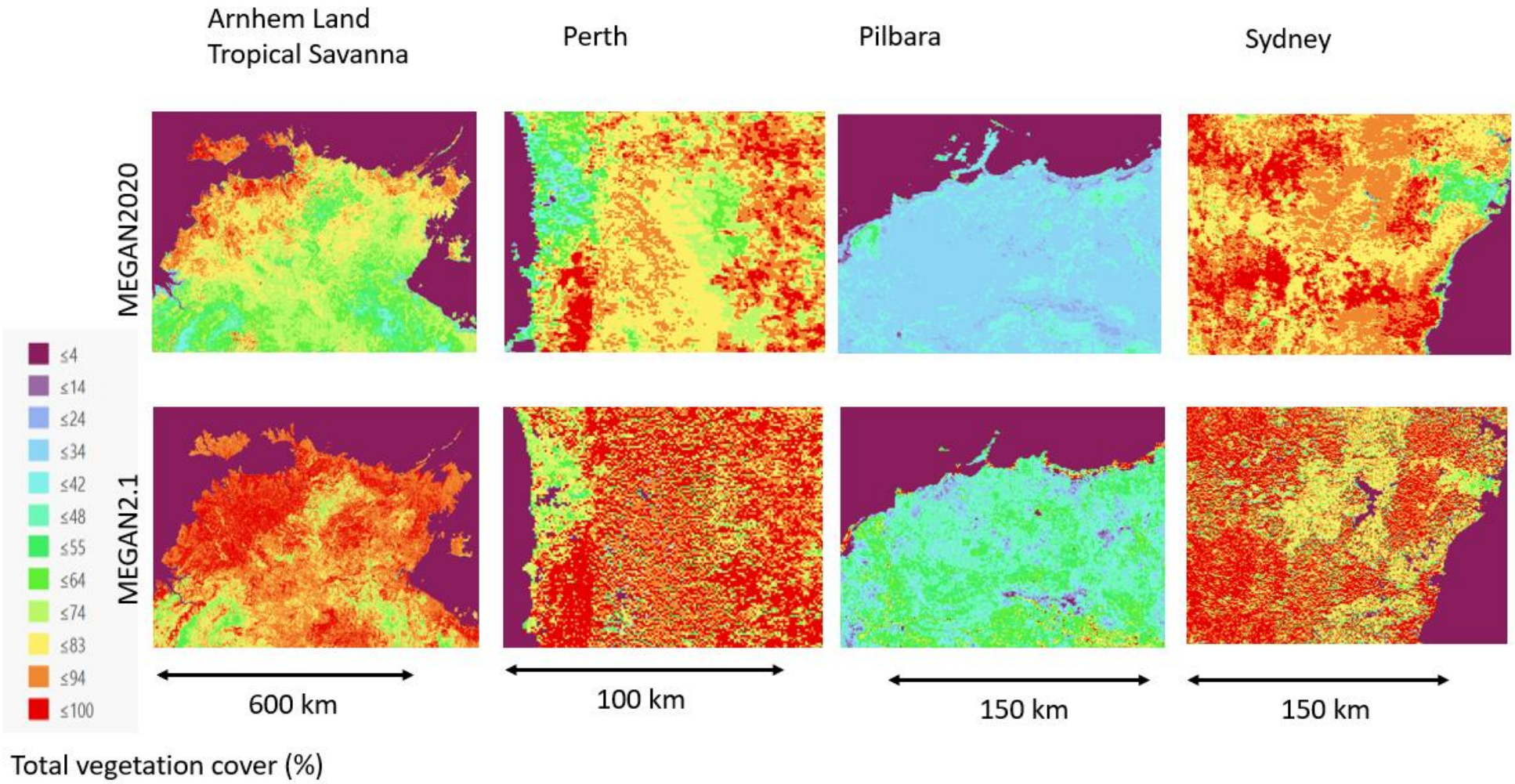

Figure A-3: Comparison of distributions of total vegetation cover (%) in the MEGAN2.1 and MEGAN3.0 datasets and with the MEGAN2020 product developed for this project for Pilbara (Western Australia), Perth (Southwestern Australia), Arnhem land (Northern Australia), and Sydney (Southeastern Australia).

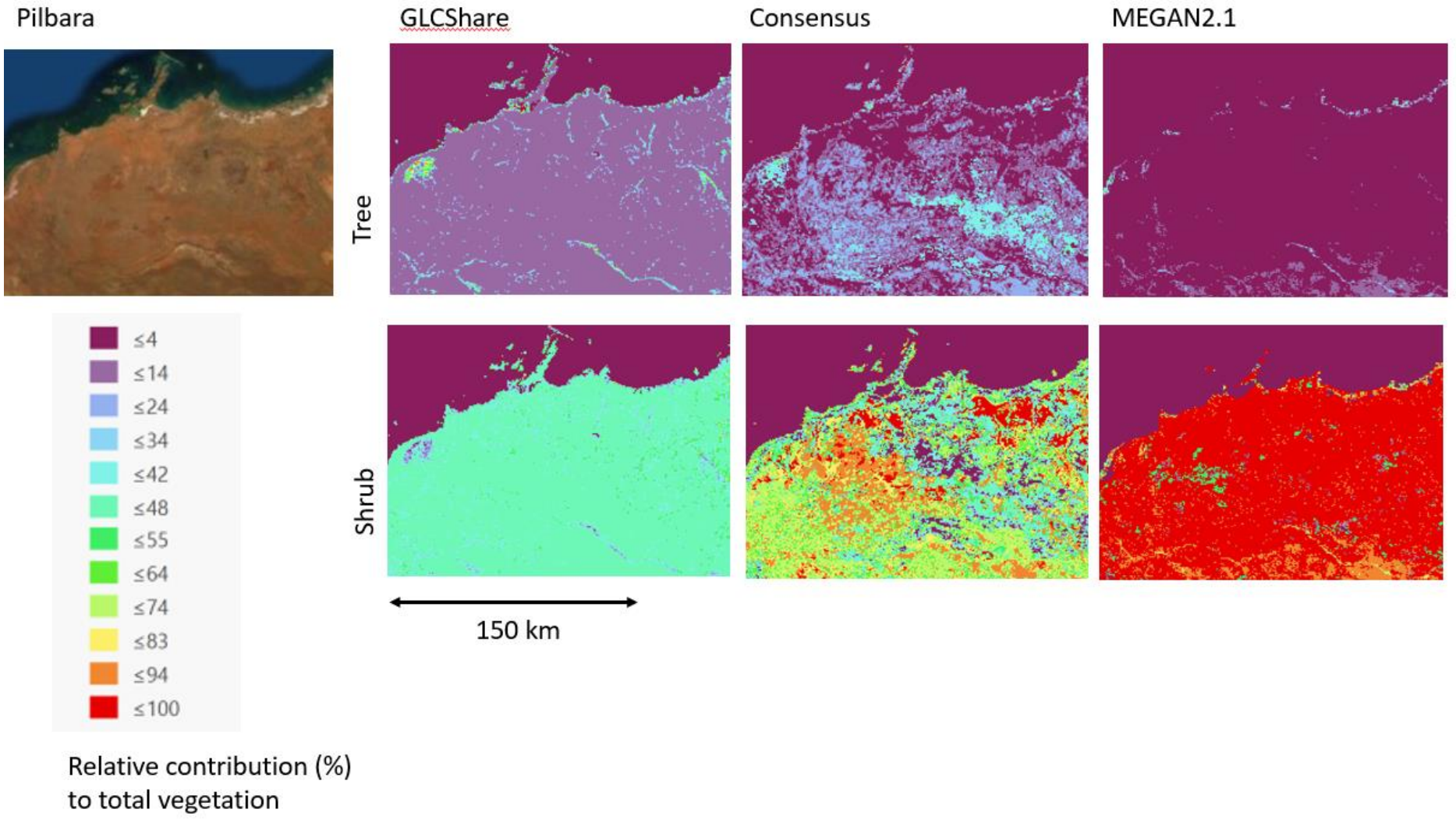

Figure A-4: Comparison of distributions of shrub and tree vegetation cover (%) in the MEGAN2.1, GLCShare and Consensus datasets for the Pilbara region in Western Australia.

APPENDIX 2

GROUND LEVEL CONCENTRATION PLOTS FOR CAM_X 1.33 KM DOMAIN

Scenario 2 Ground Level Concentrations

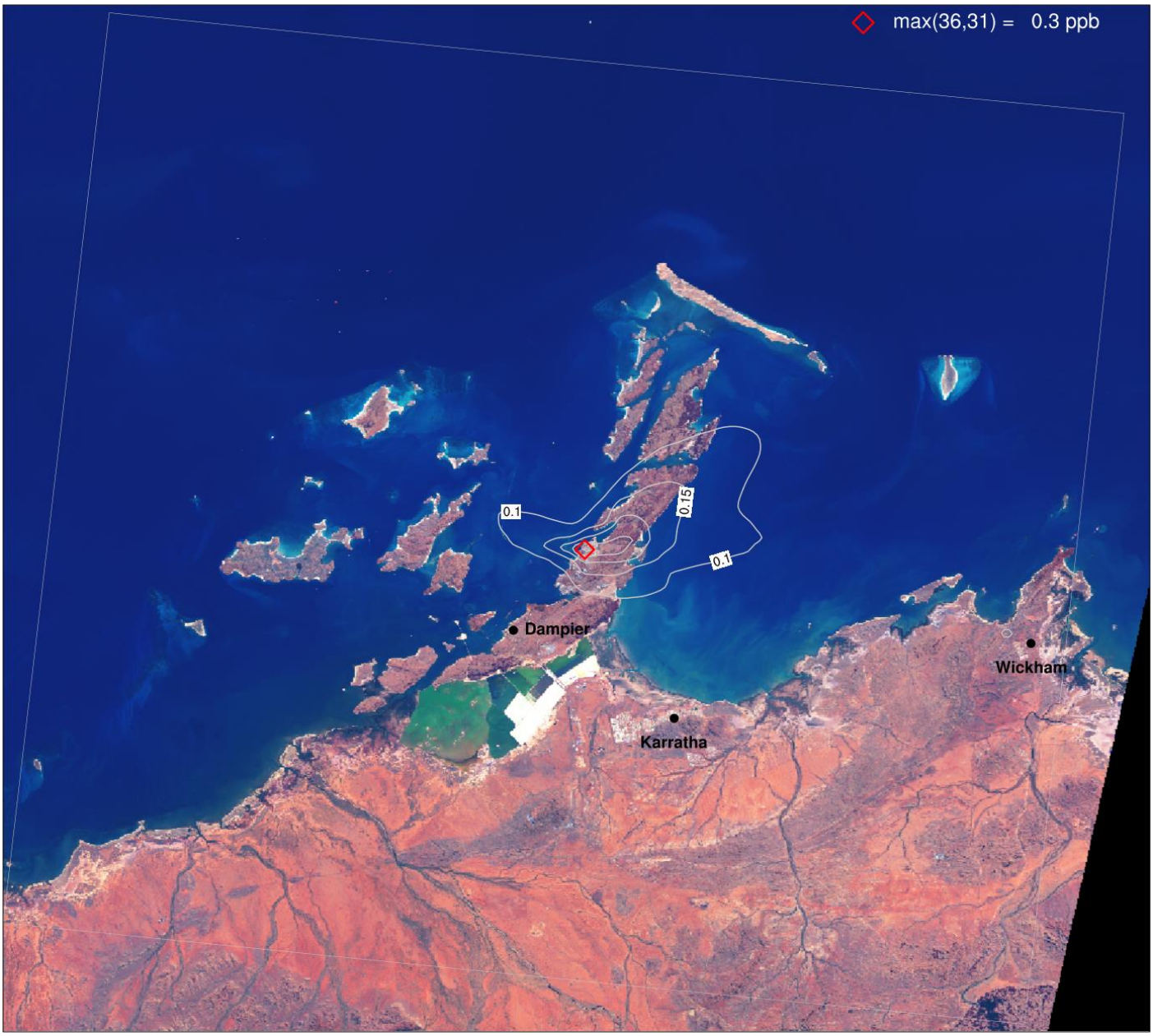

Figure A2-1. Benzene (ppb) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

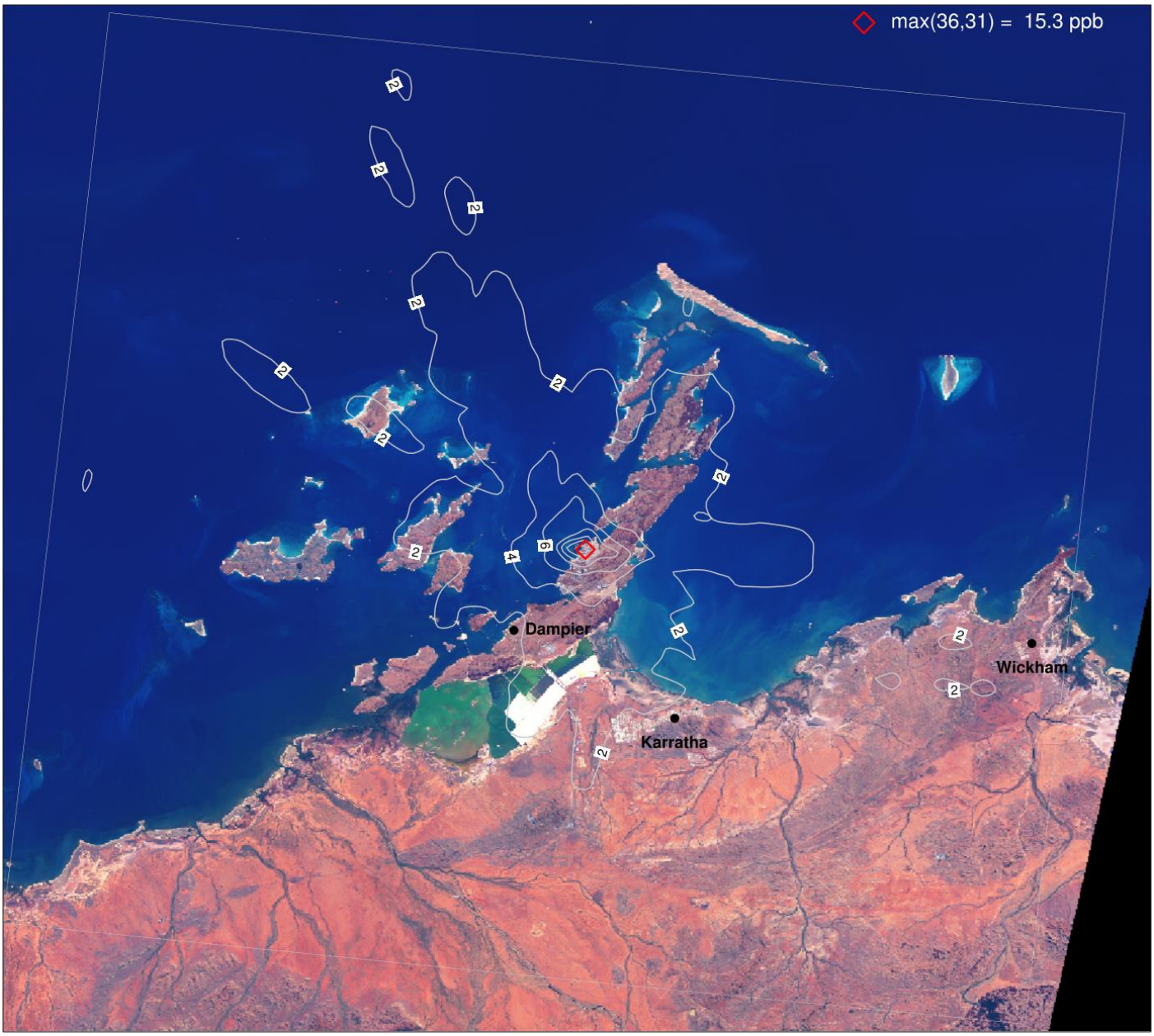

Figure A2-2. Benzene (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

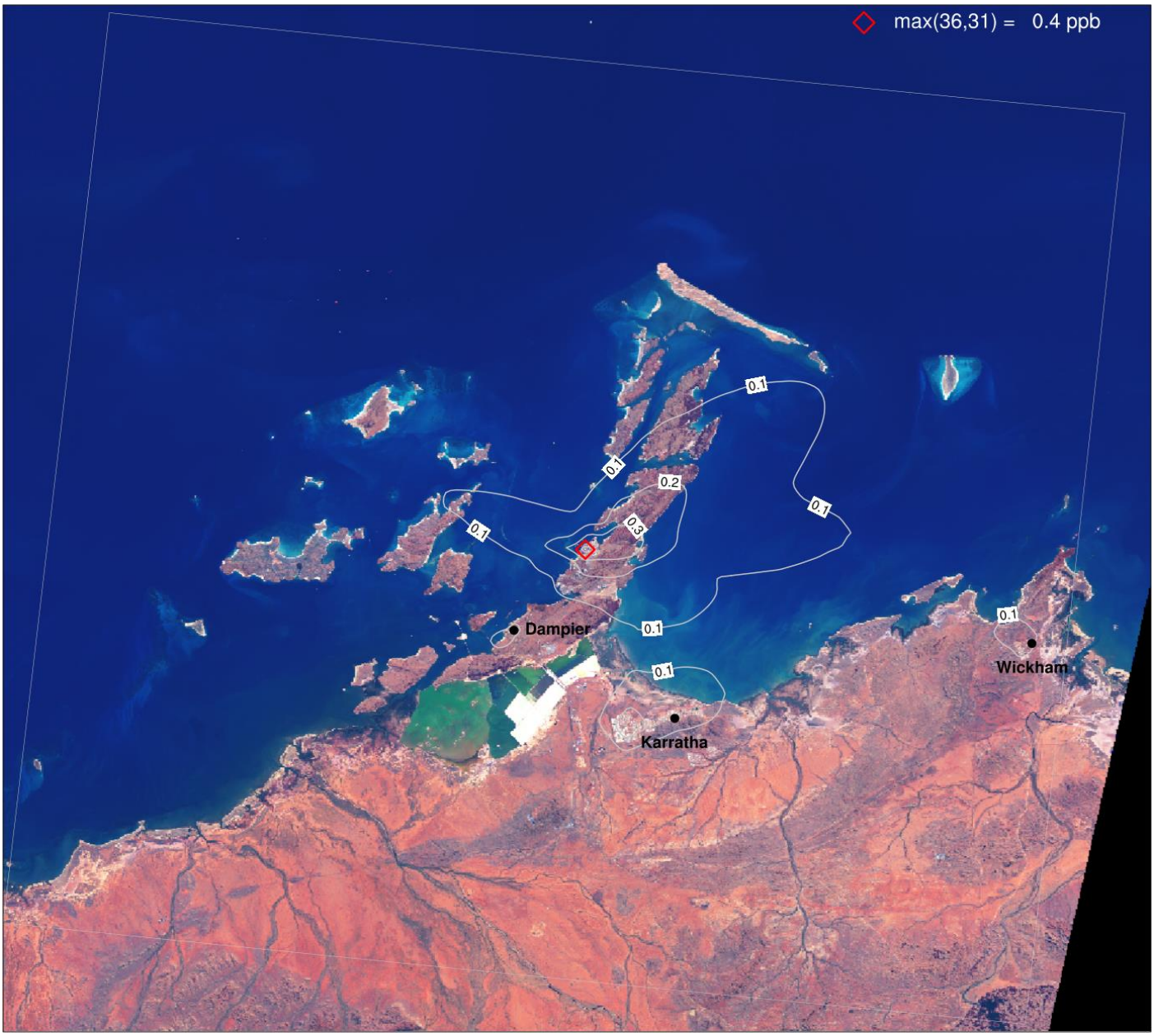

Figure A2-3. TOL (ppb) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

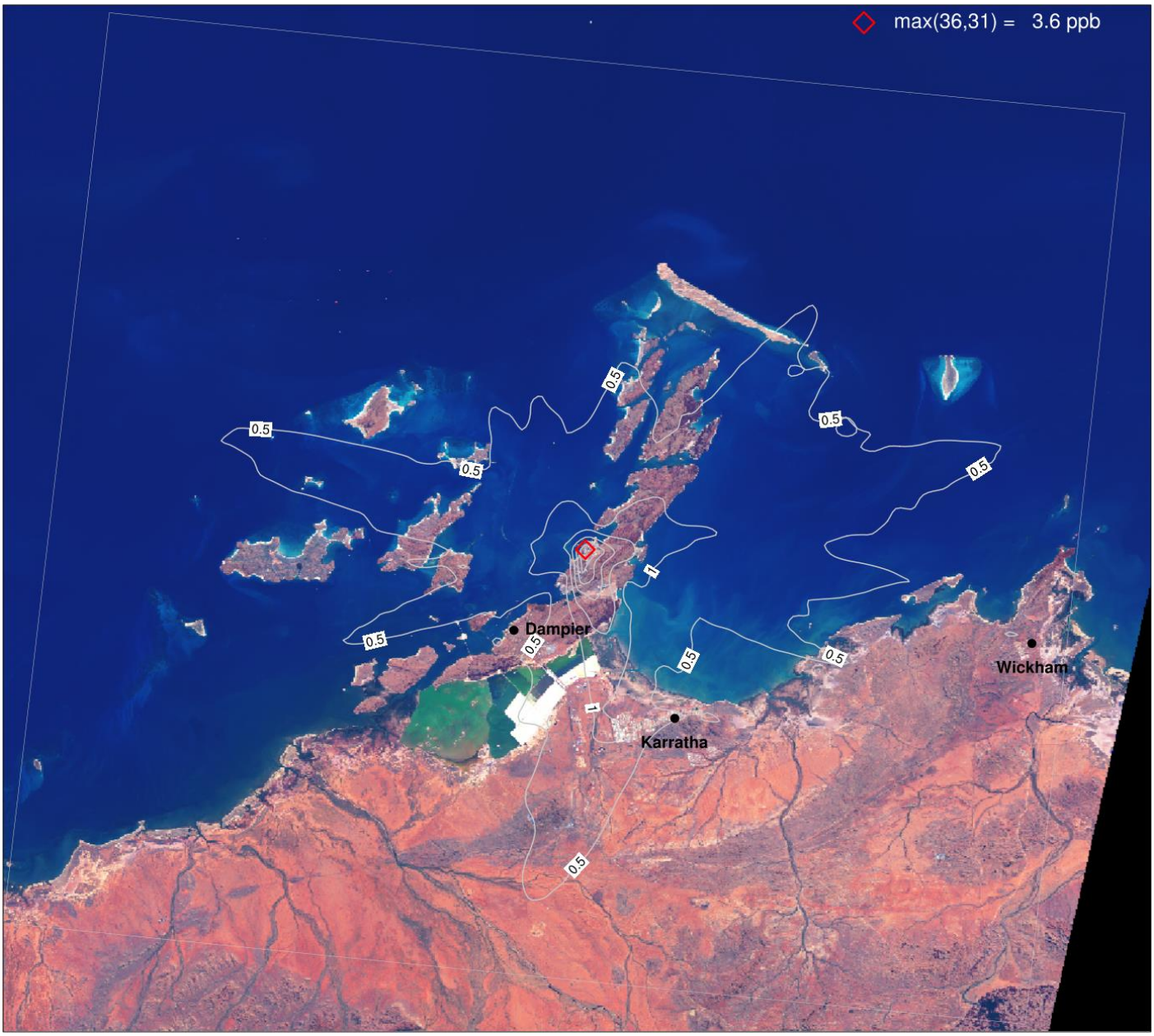

Figure A2-4. TOL (ppb) annual max 24-hour concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

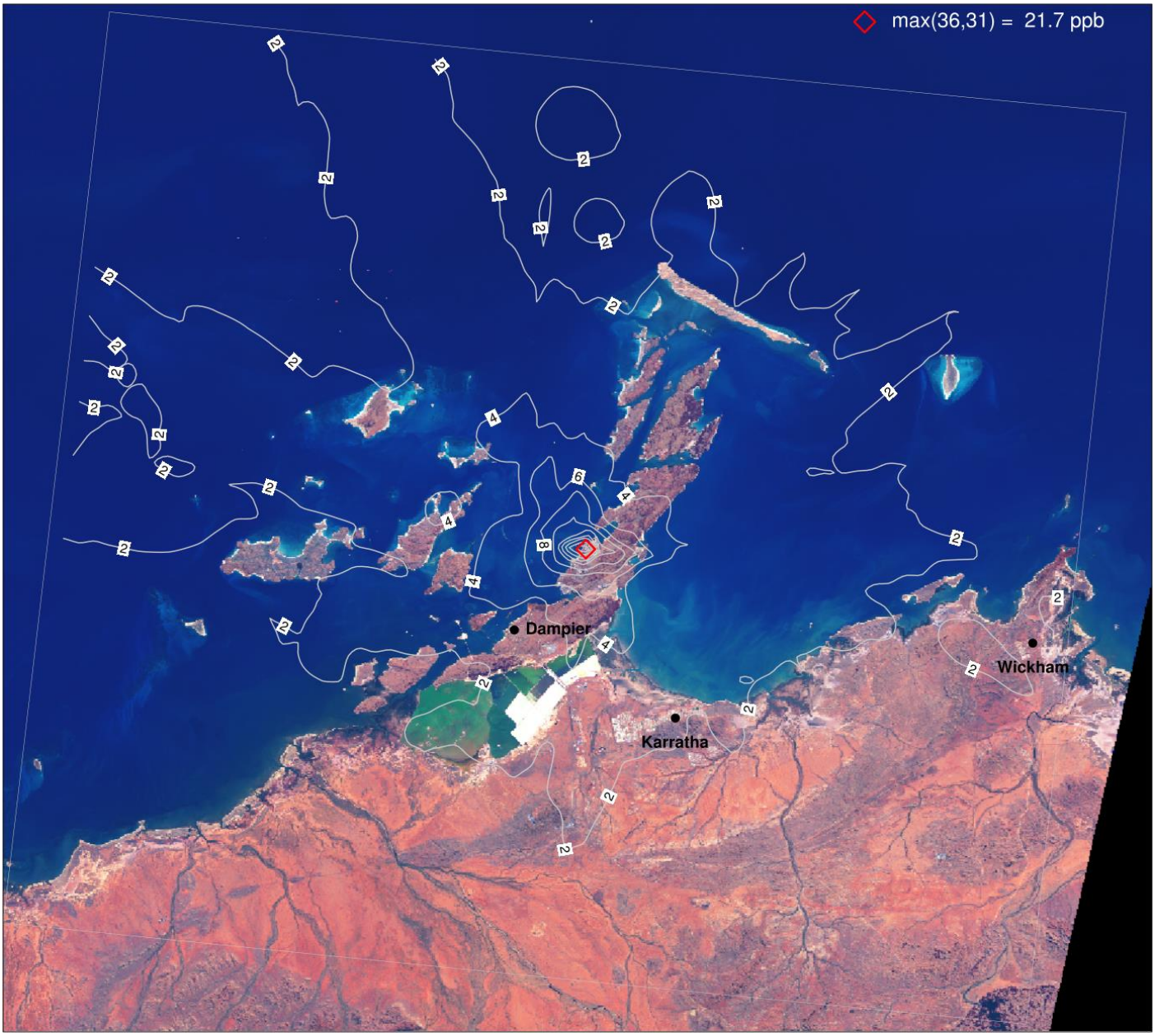

Figure A2-5. TOL (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

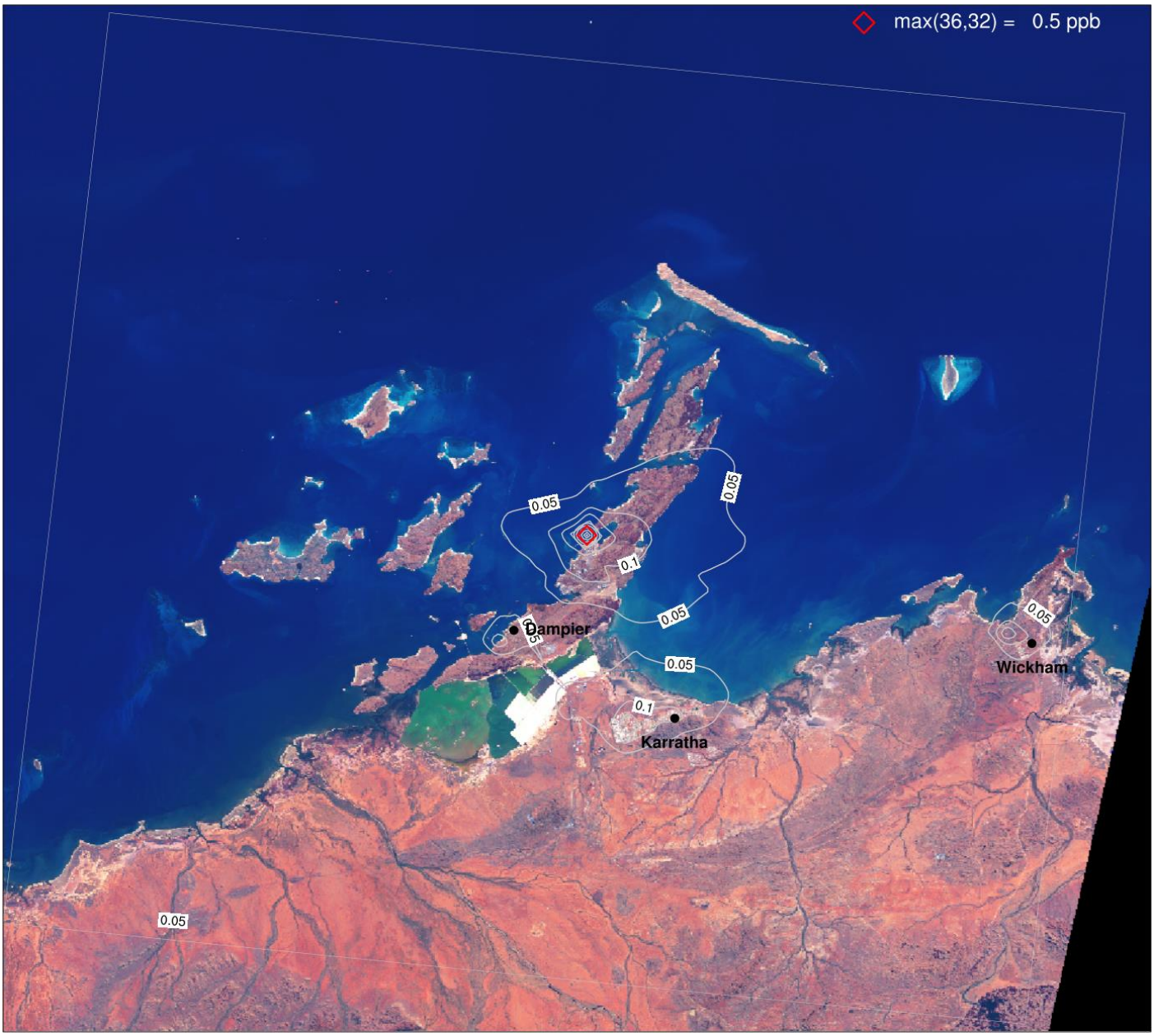

Figure A2-6. XYL (ppb) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

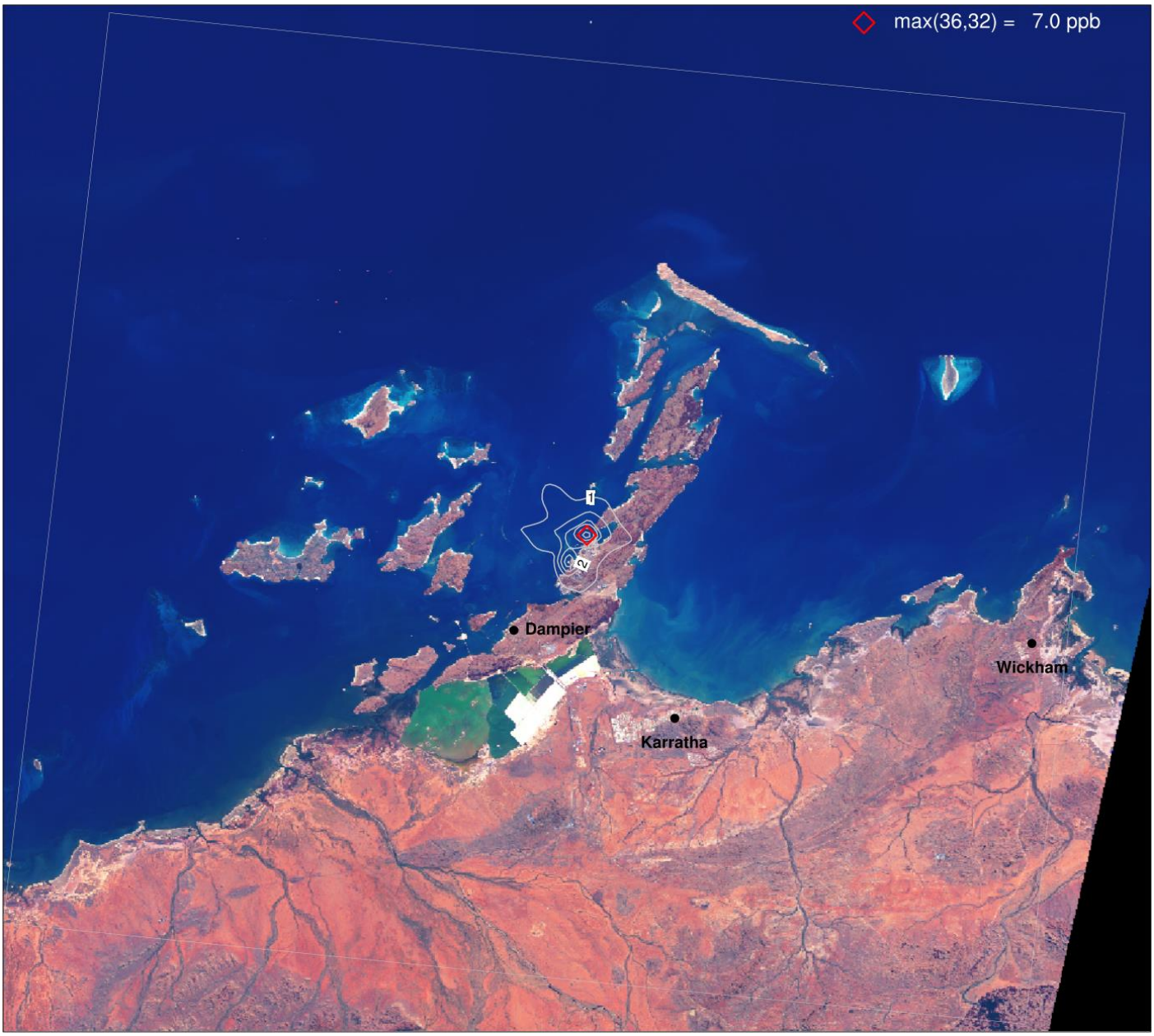

Figure A2-7. XYL (ppb) annual max 24-hour concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

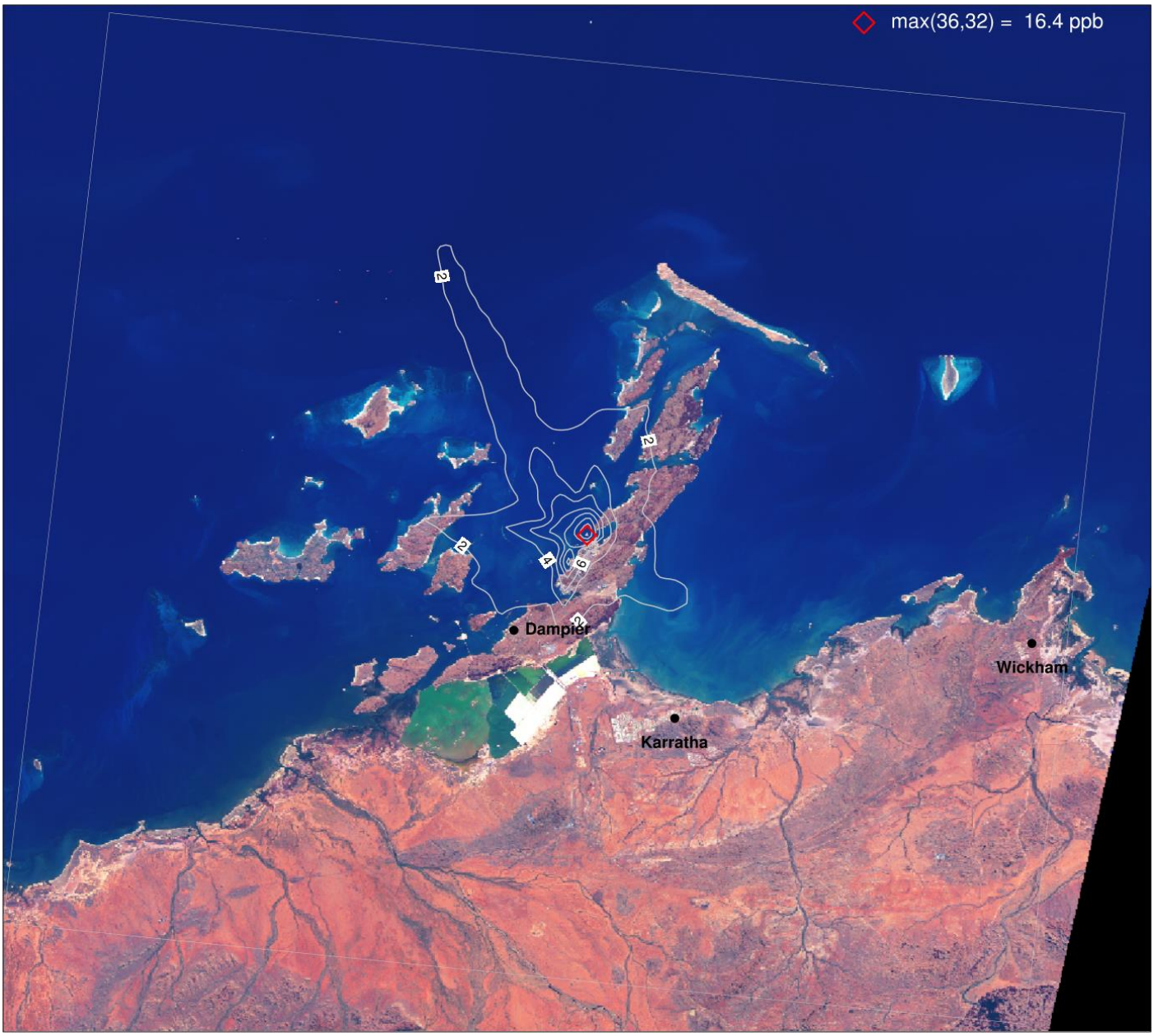

Figure A2-8. XYL (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

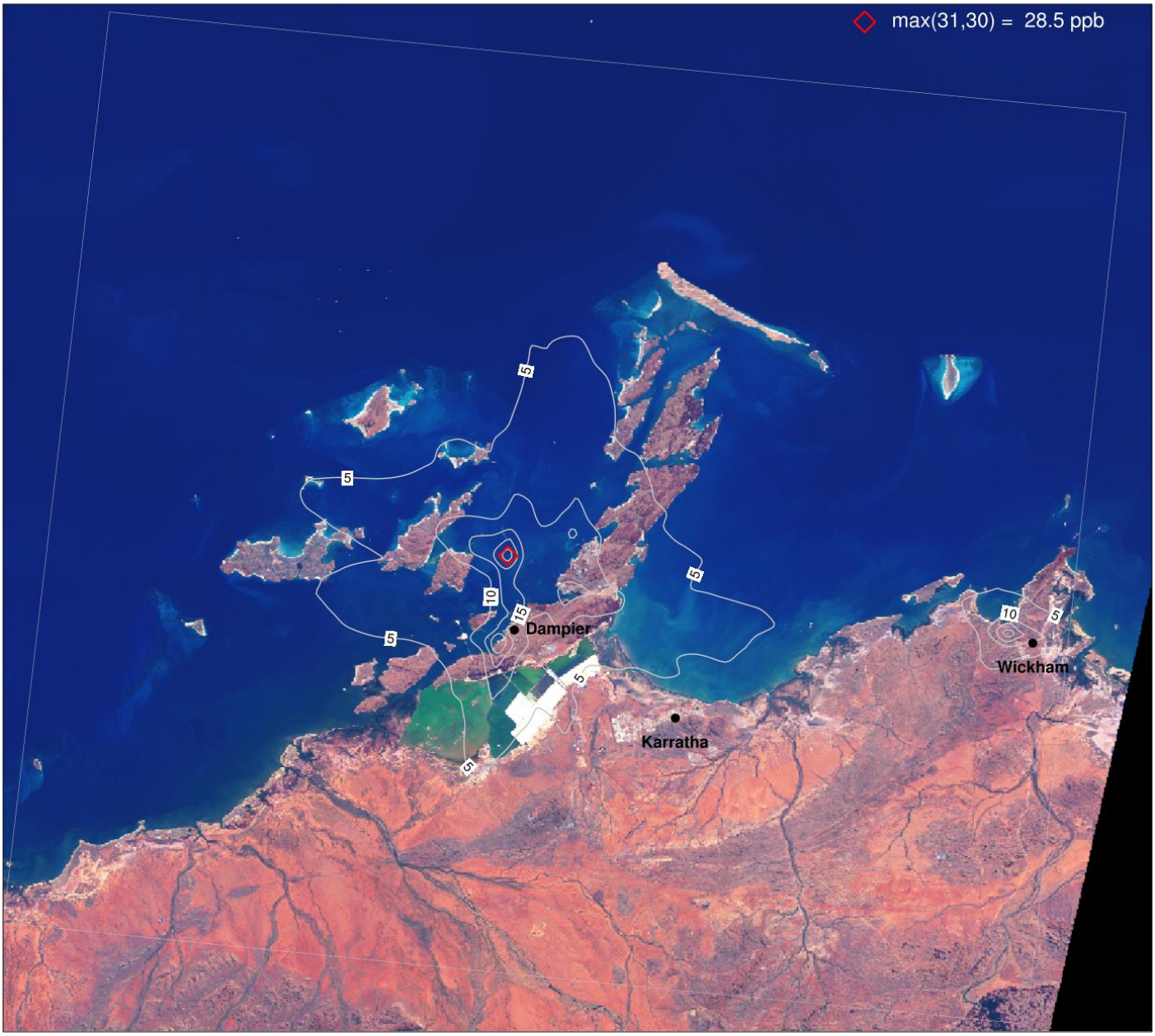

Figure A2-9. SO_2 (ppb) annual max 24-hour concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

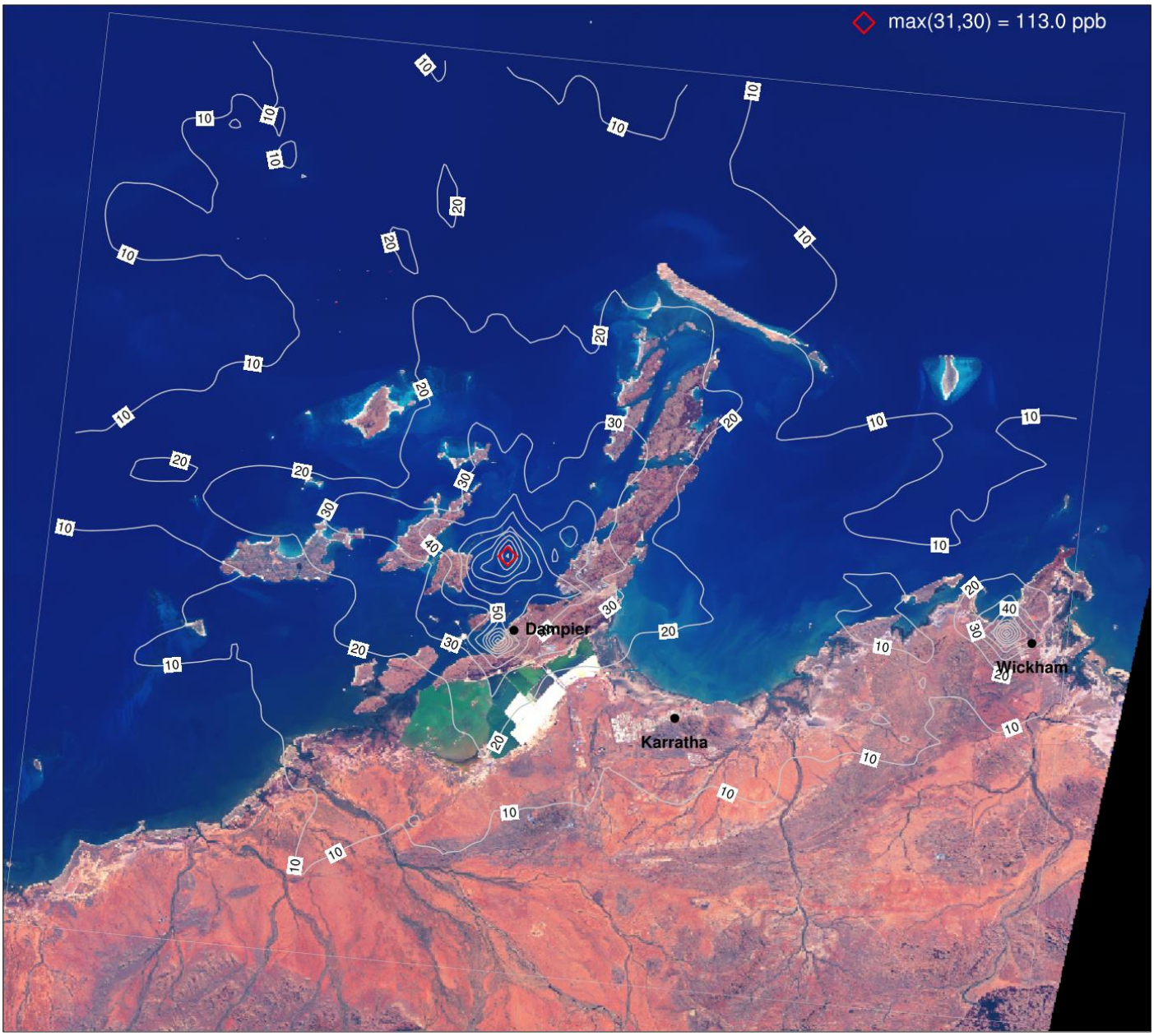

Figure A2-10. SO_2 (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

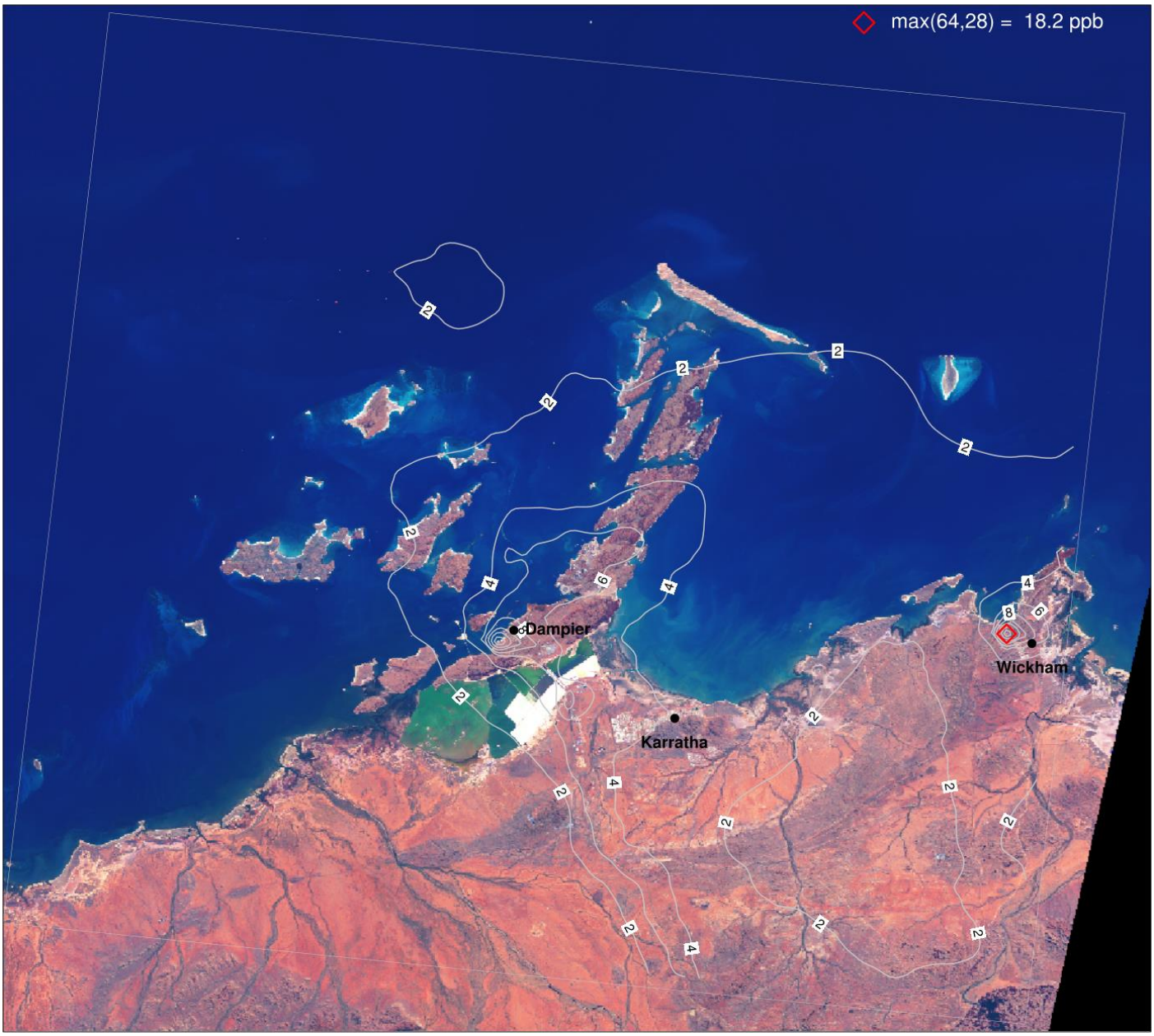

Figure A2-11. NO_2 (ppb) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

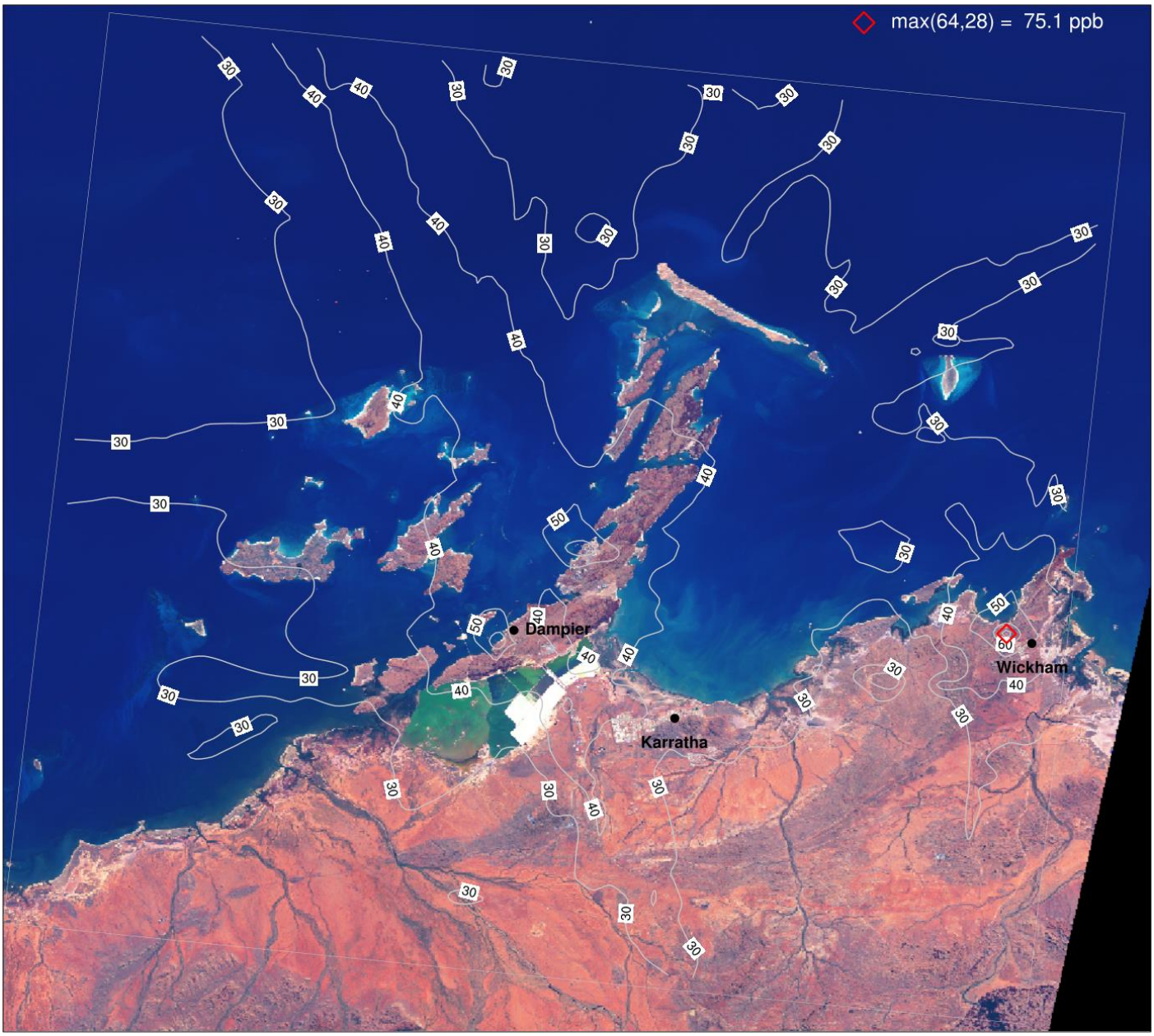

Figure A2-12. NO_2 (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

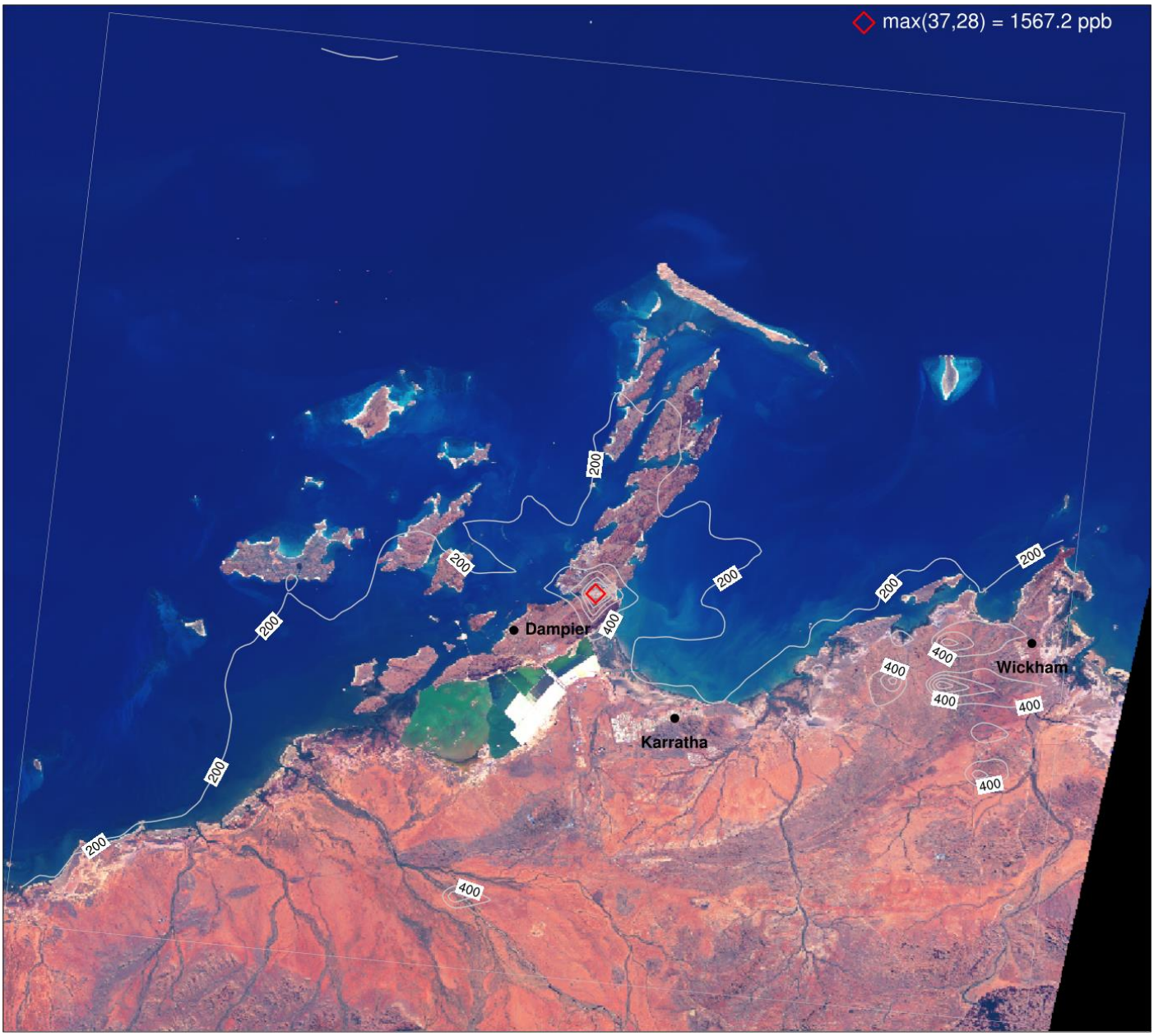

Figure A2-13. CO (ppb) annual max 8-hour (MDA8) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

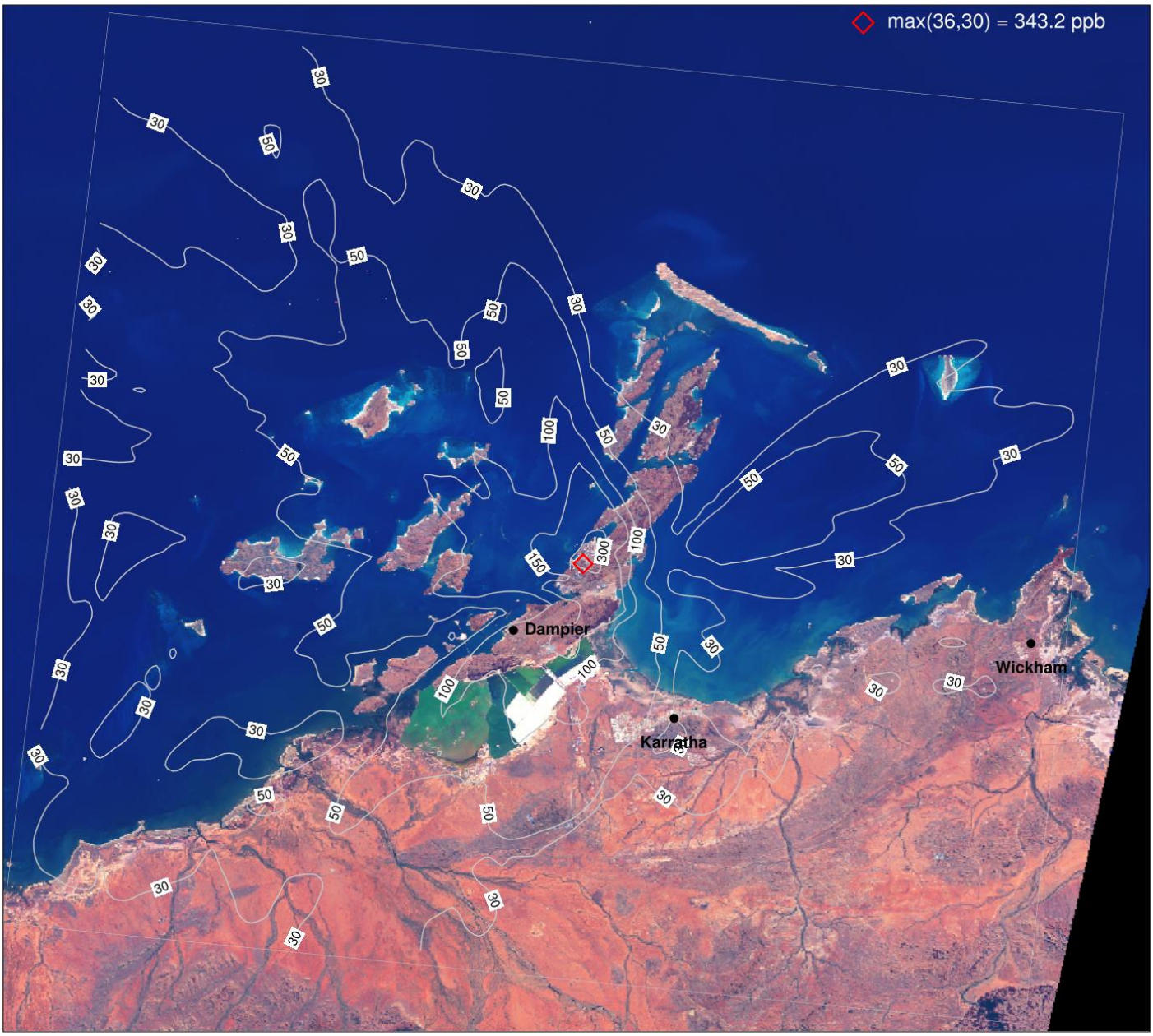

Figure A2-14. NH_3 (ppb) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

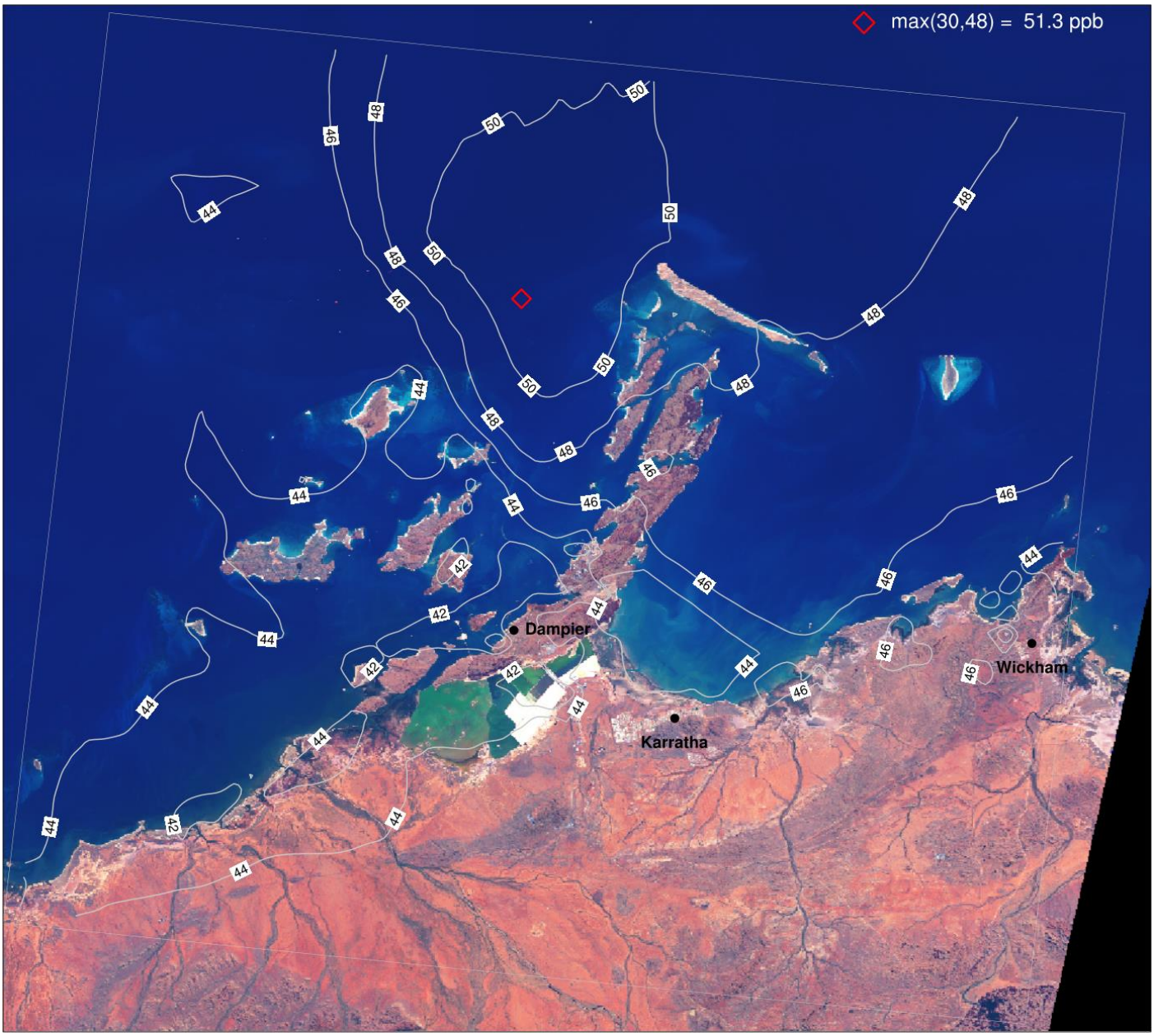

Figure A2-15. Ozone (ppb) annual max 8-hour (MDA8) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

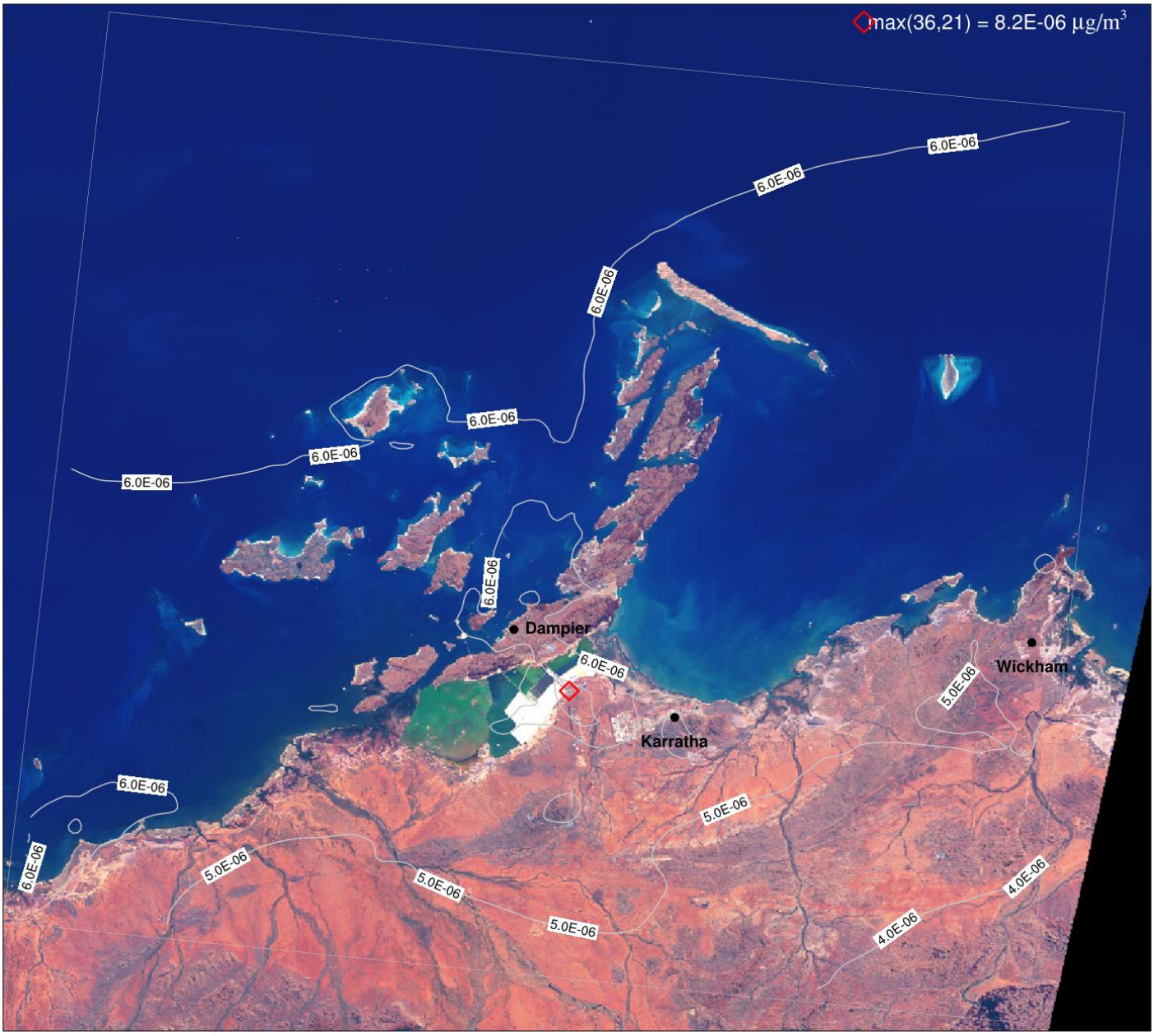

Figure A2-16. Hg (µg/m³) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

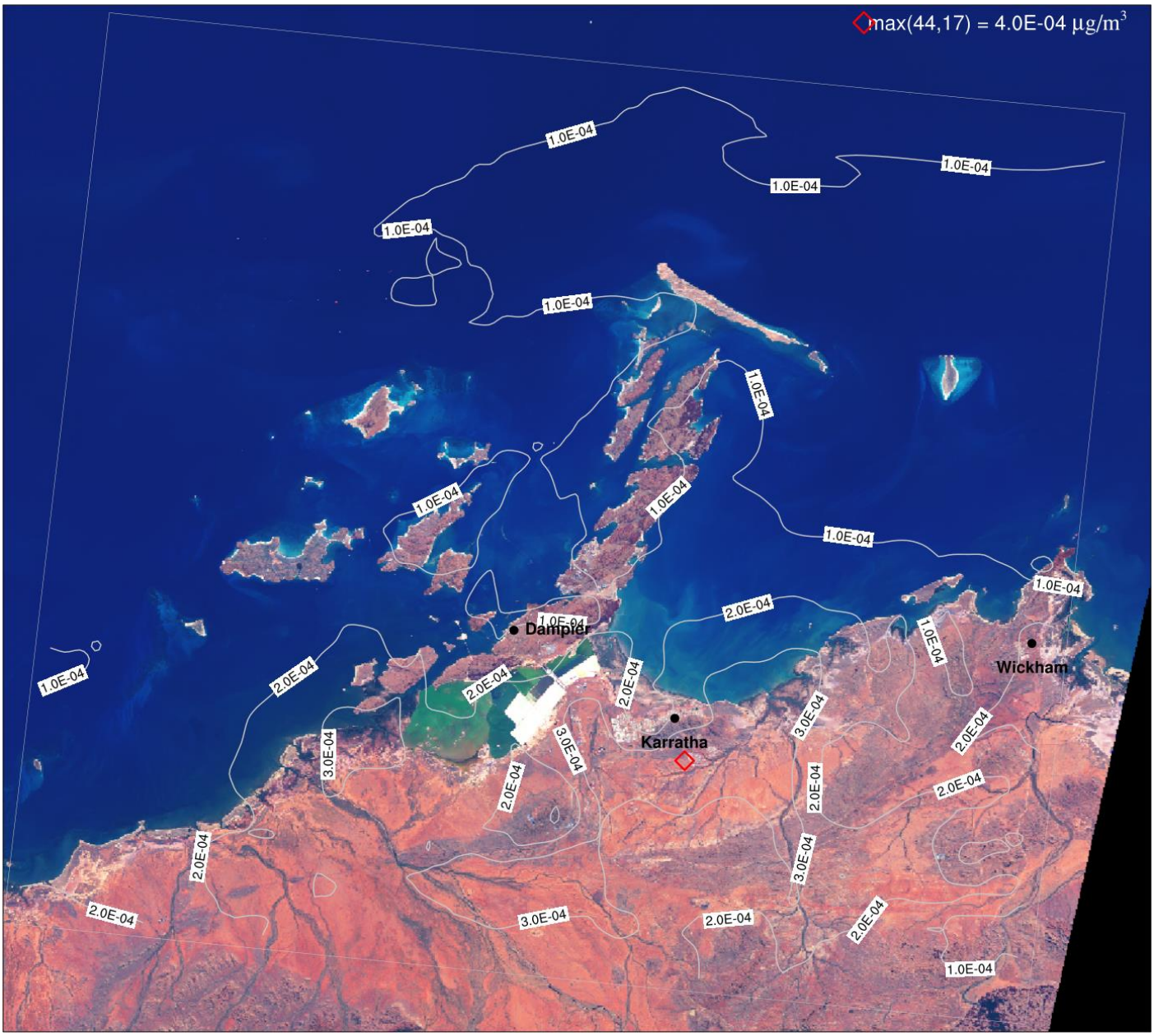

Figure A2-17. Hg (µg/m^3) annual max 1-hour (MDA1) concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

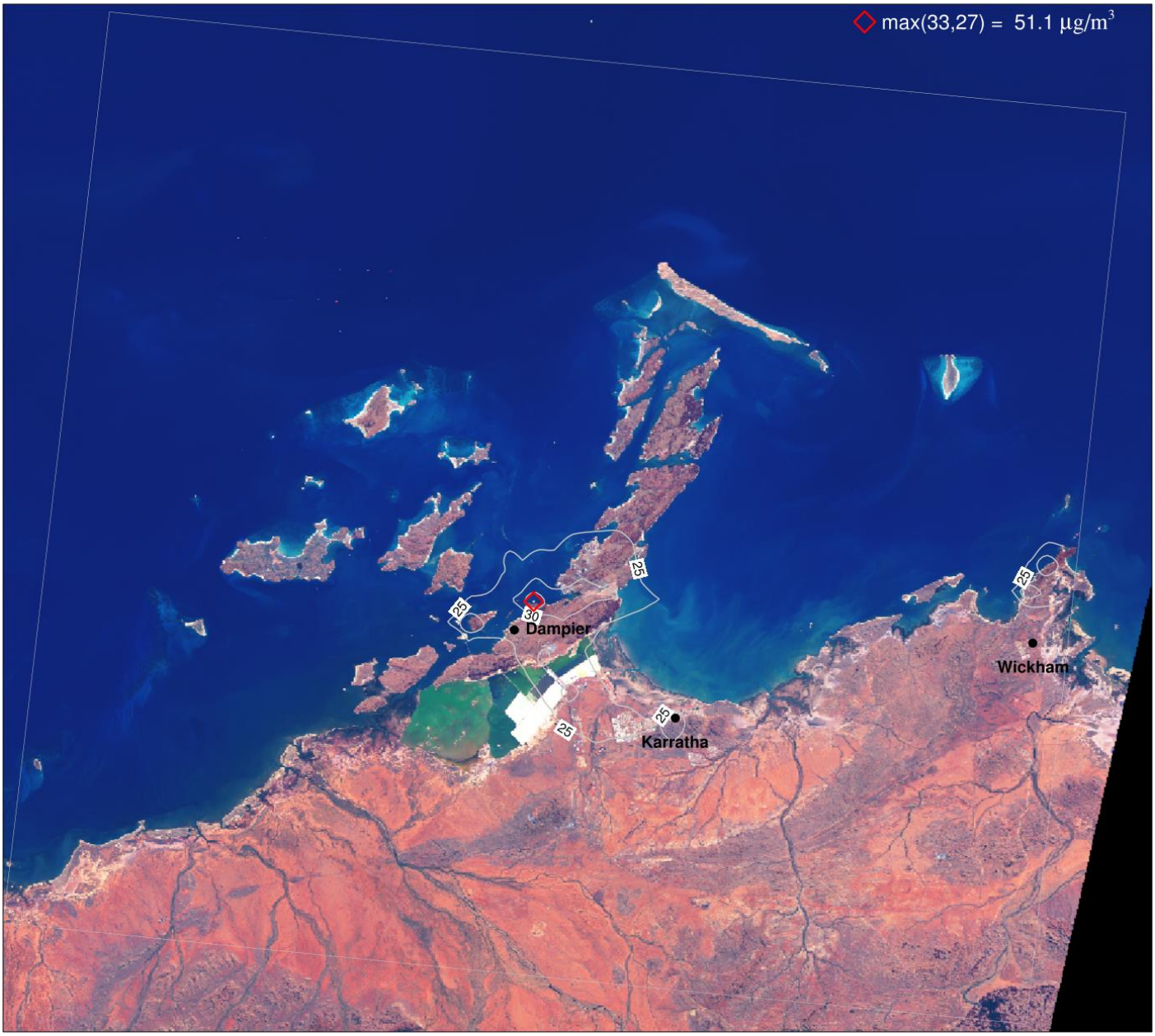

Figure A2-18. PM_{10} (µg/m^3) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

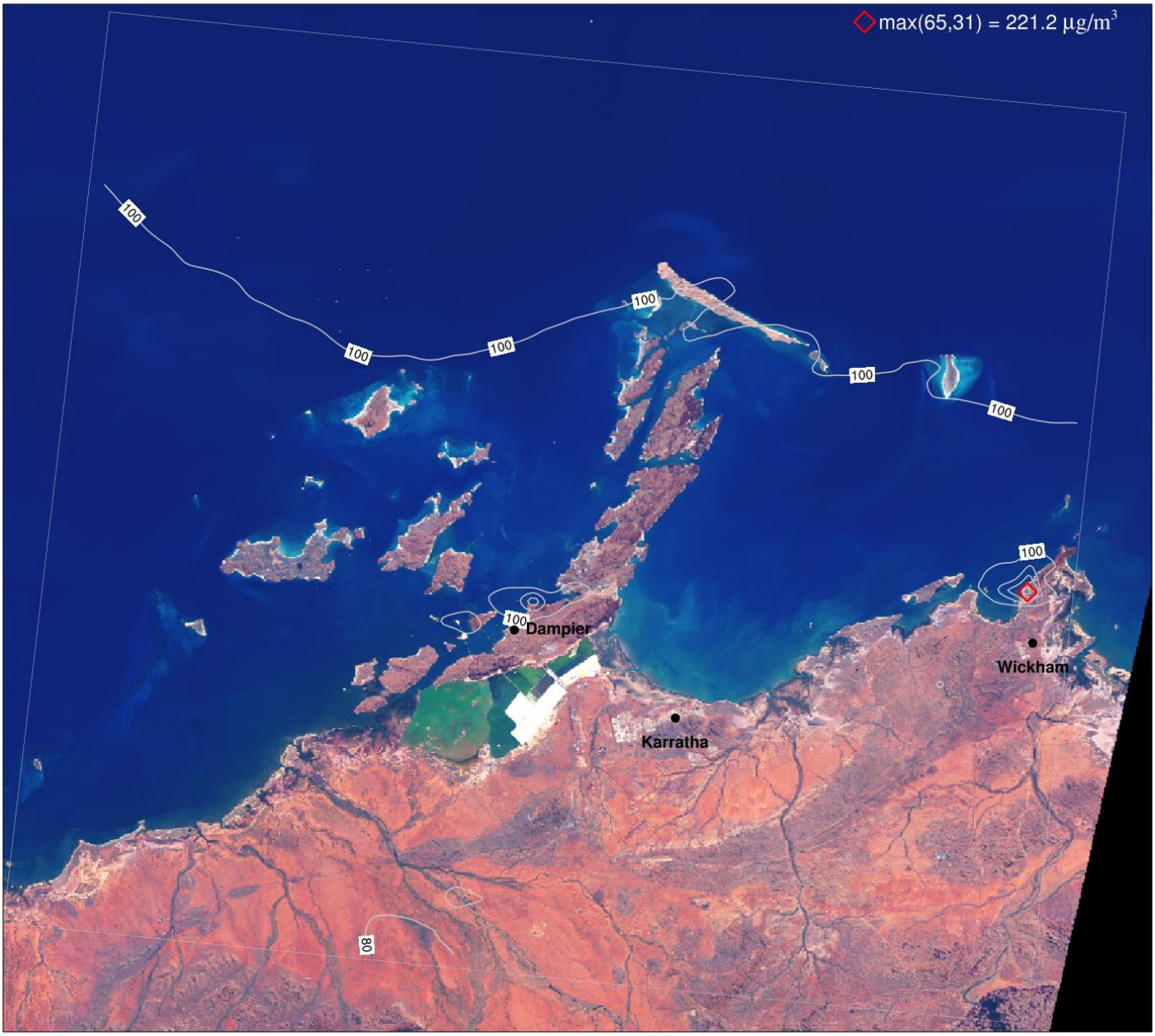

Figure A2-19. PM_{10} (µg/m^3) annual max 24-hour concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

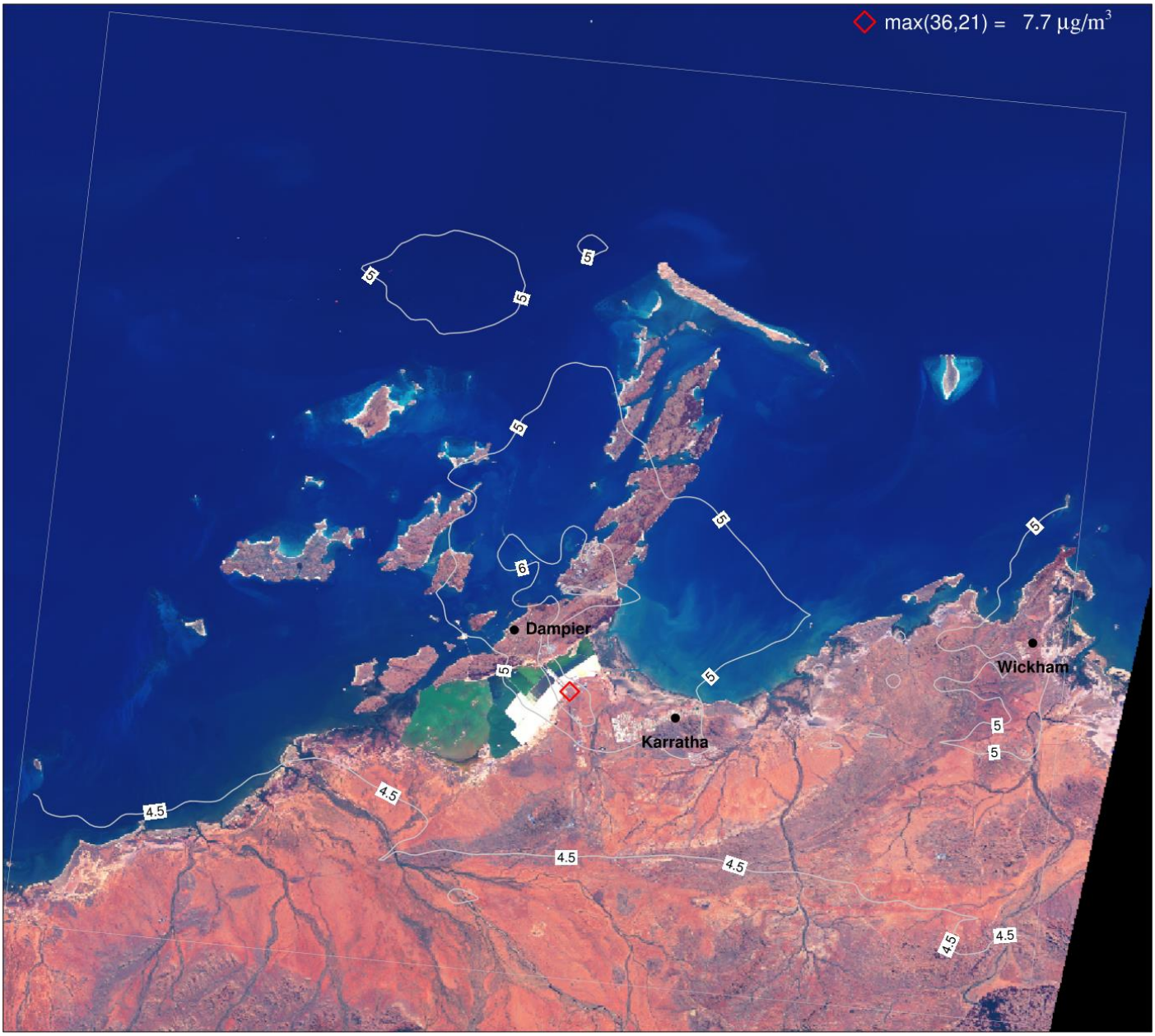

Figure A2-20. $PM_{2.5}$ (µg/m^3) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

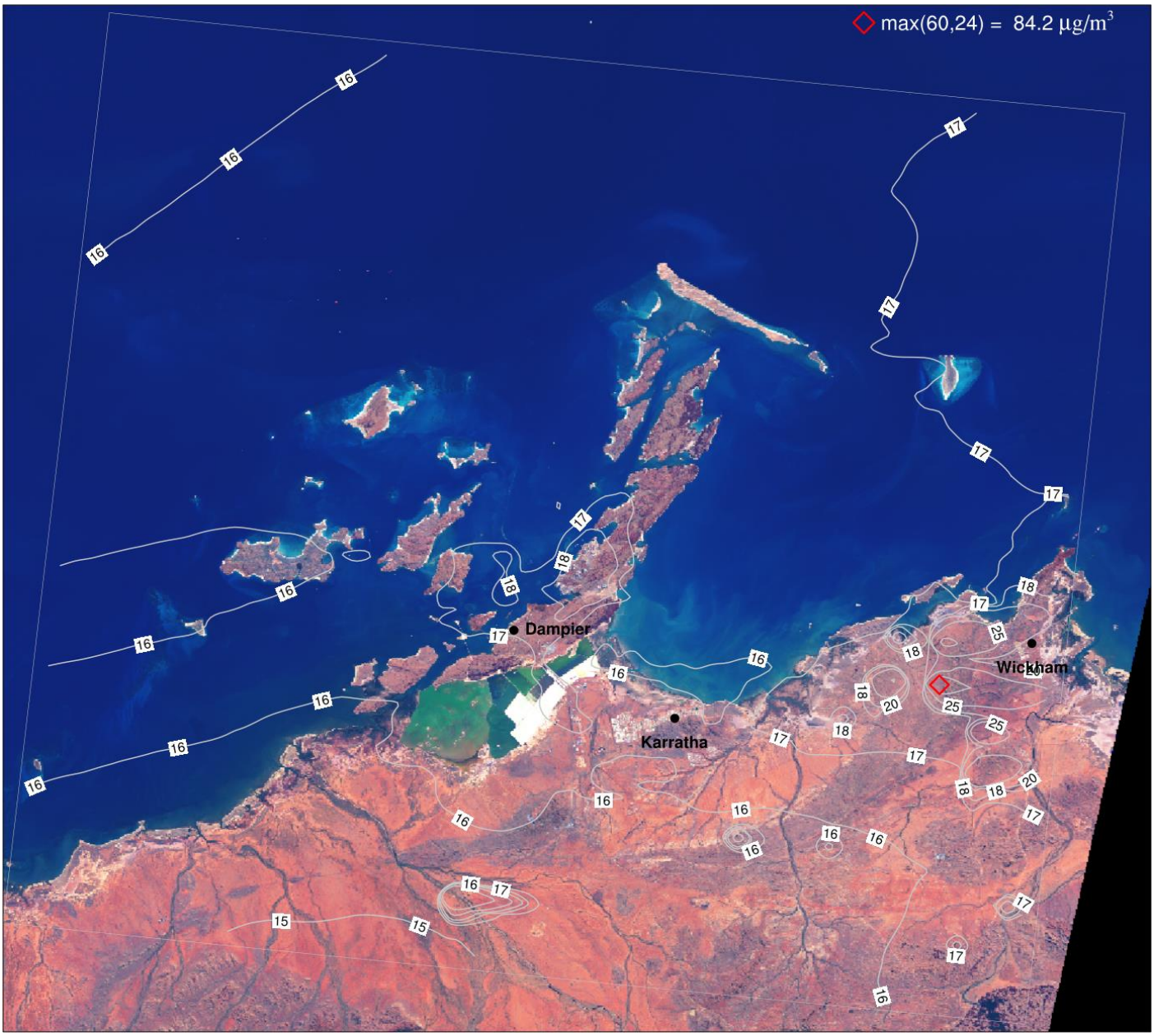

Figure A2-21. $PM_{2.5}$ (µg/m^3) annual max 24-hour concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

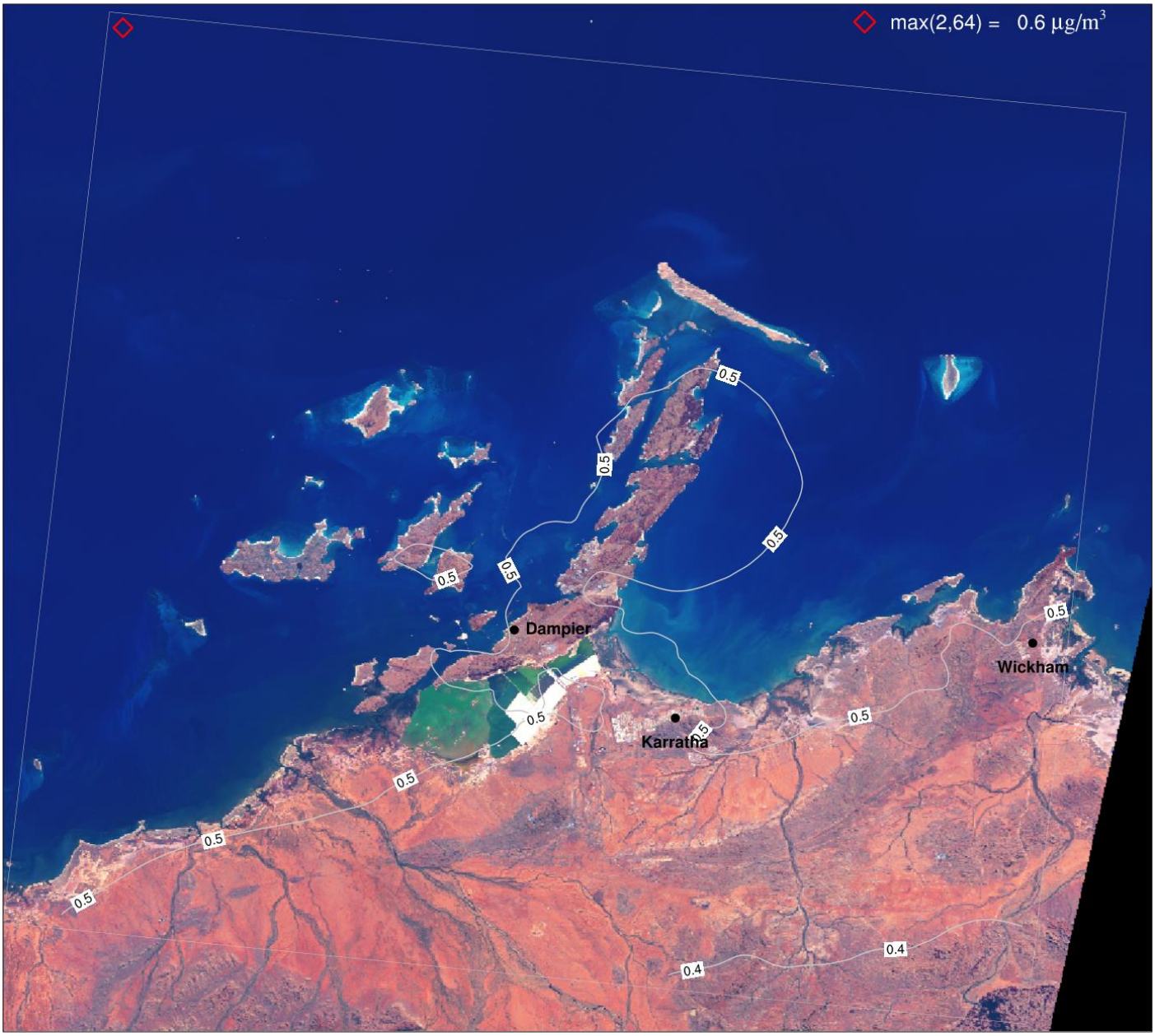

Figure A2-22. Ammonium plus nitrate (µg/m³) annual average concentrations for Scenario 2 (S2) for the CAMx 1.33 km domain.

Industry Ground Level Concentrations

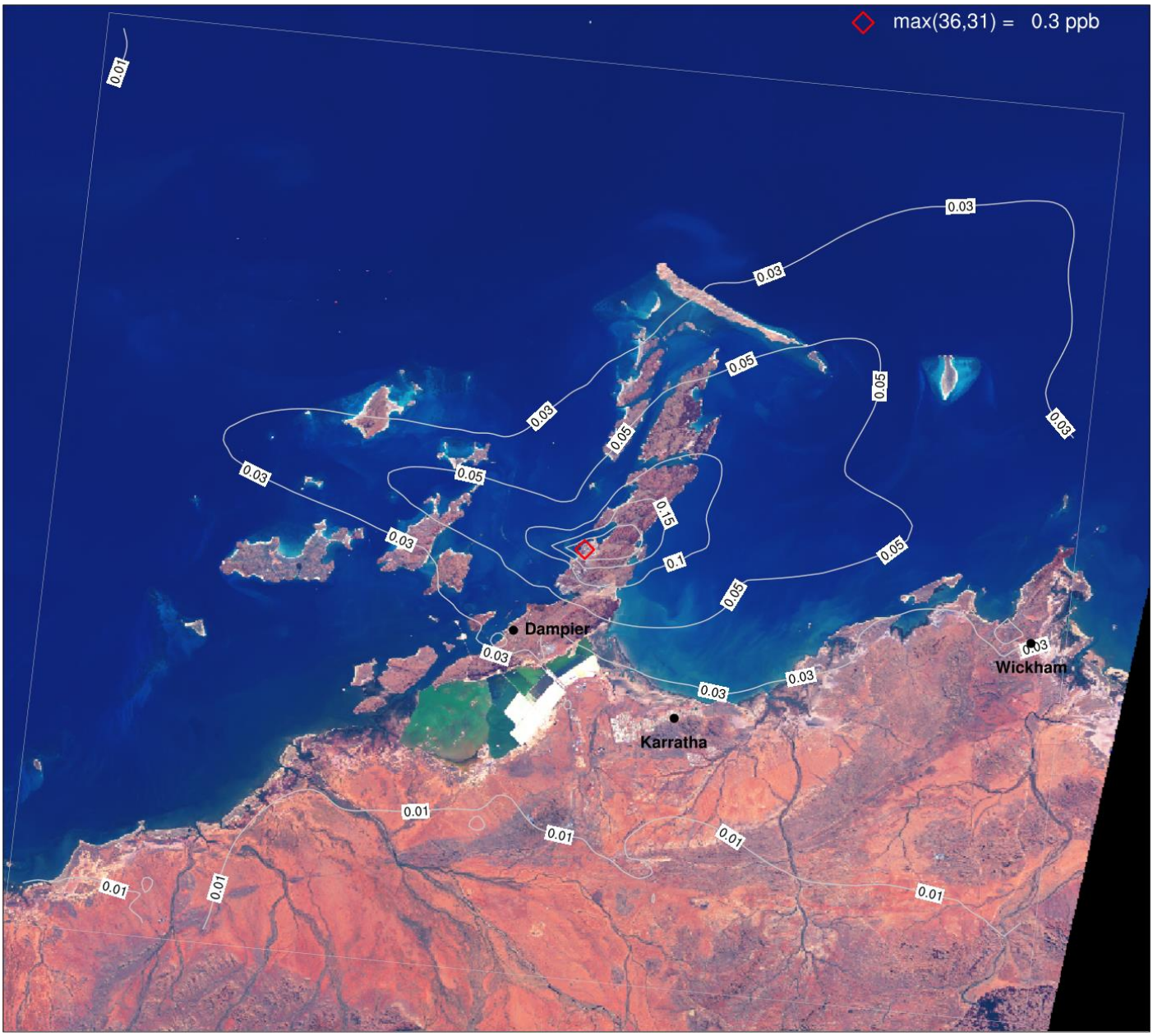

Figure A2-23. Benzene (ppb) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

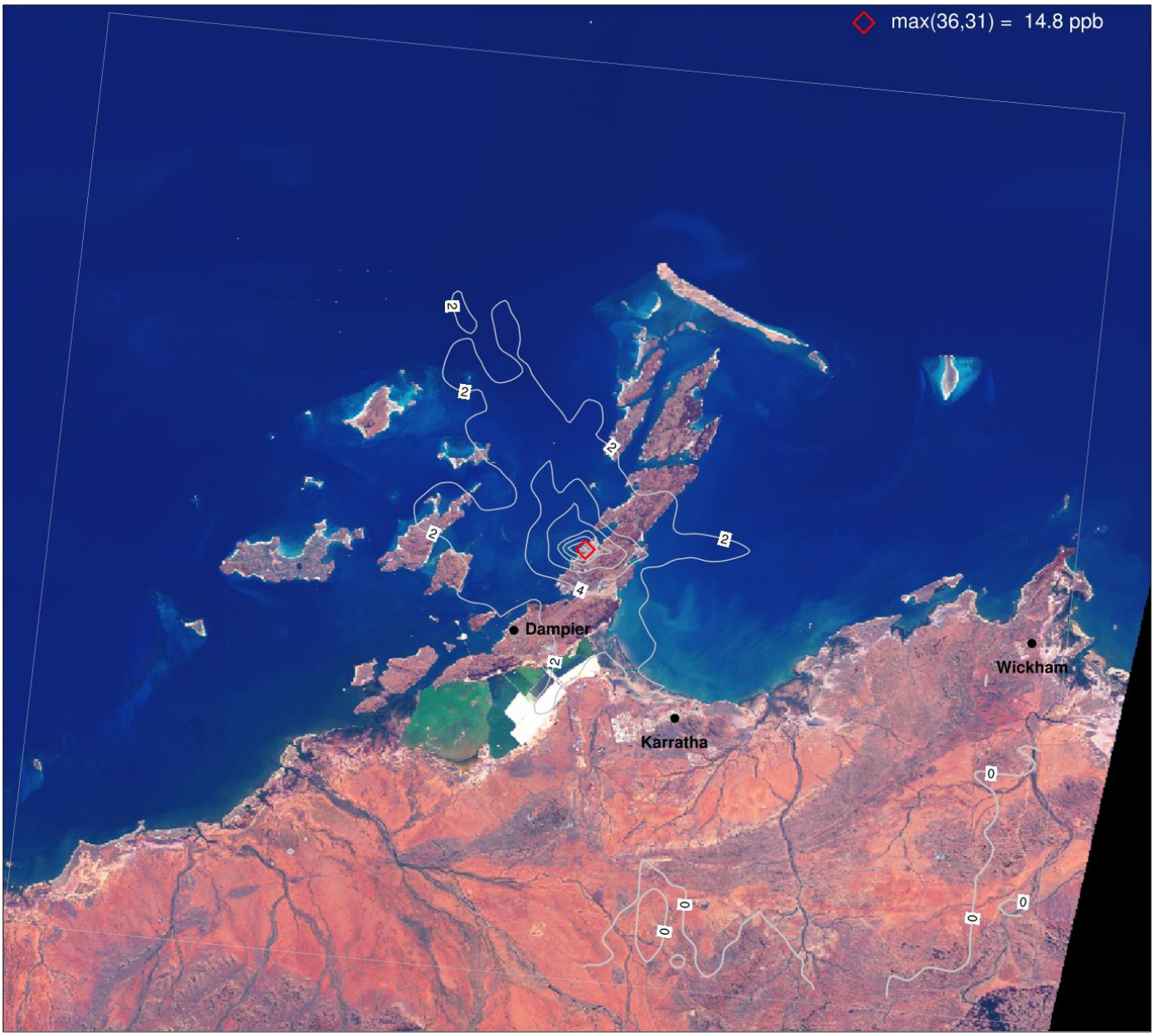

Figure A2-24. Benzene (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

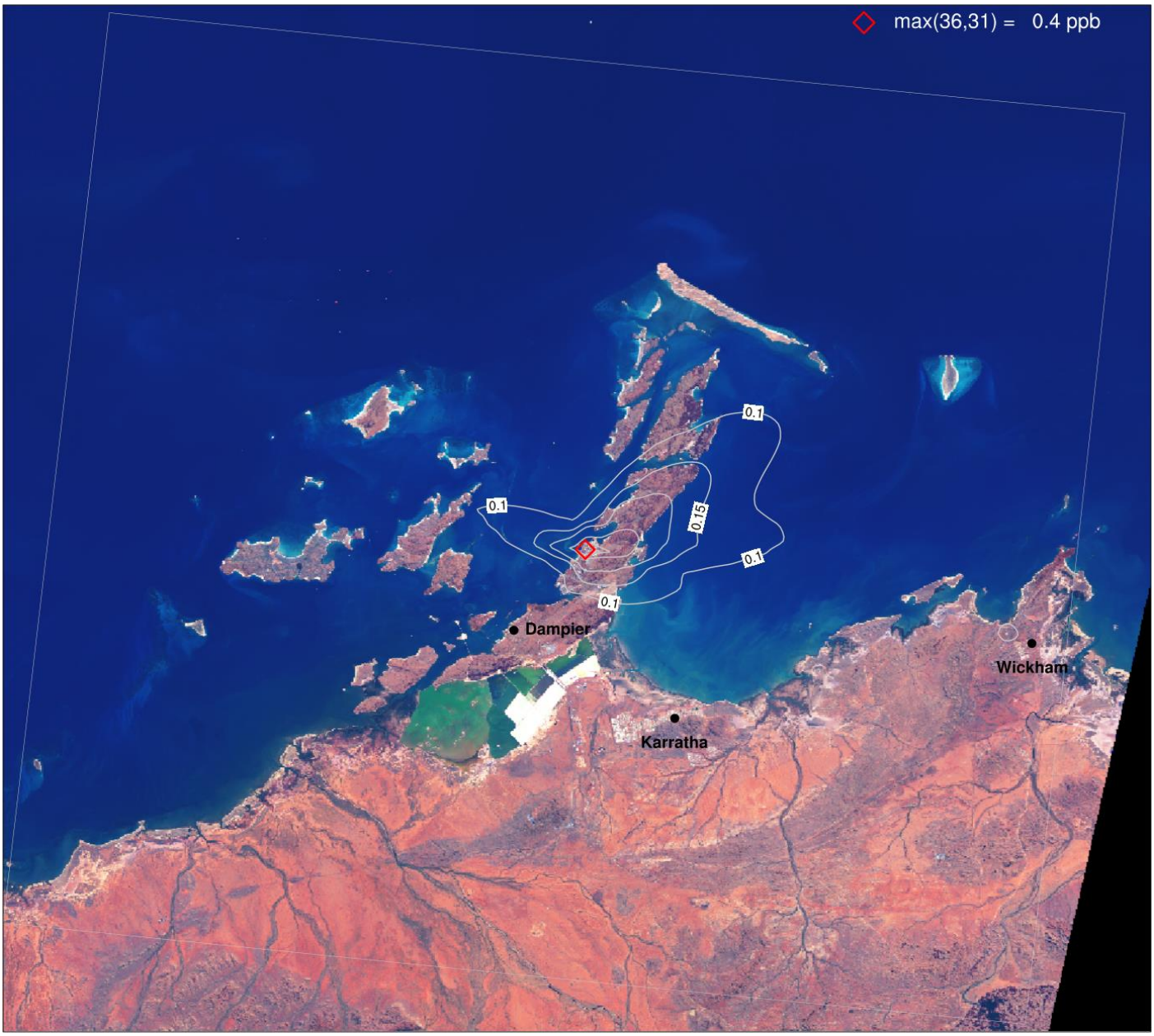

Figure A2-25. TOL (ppb) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

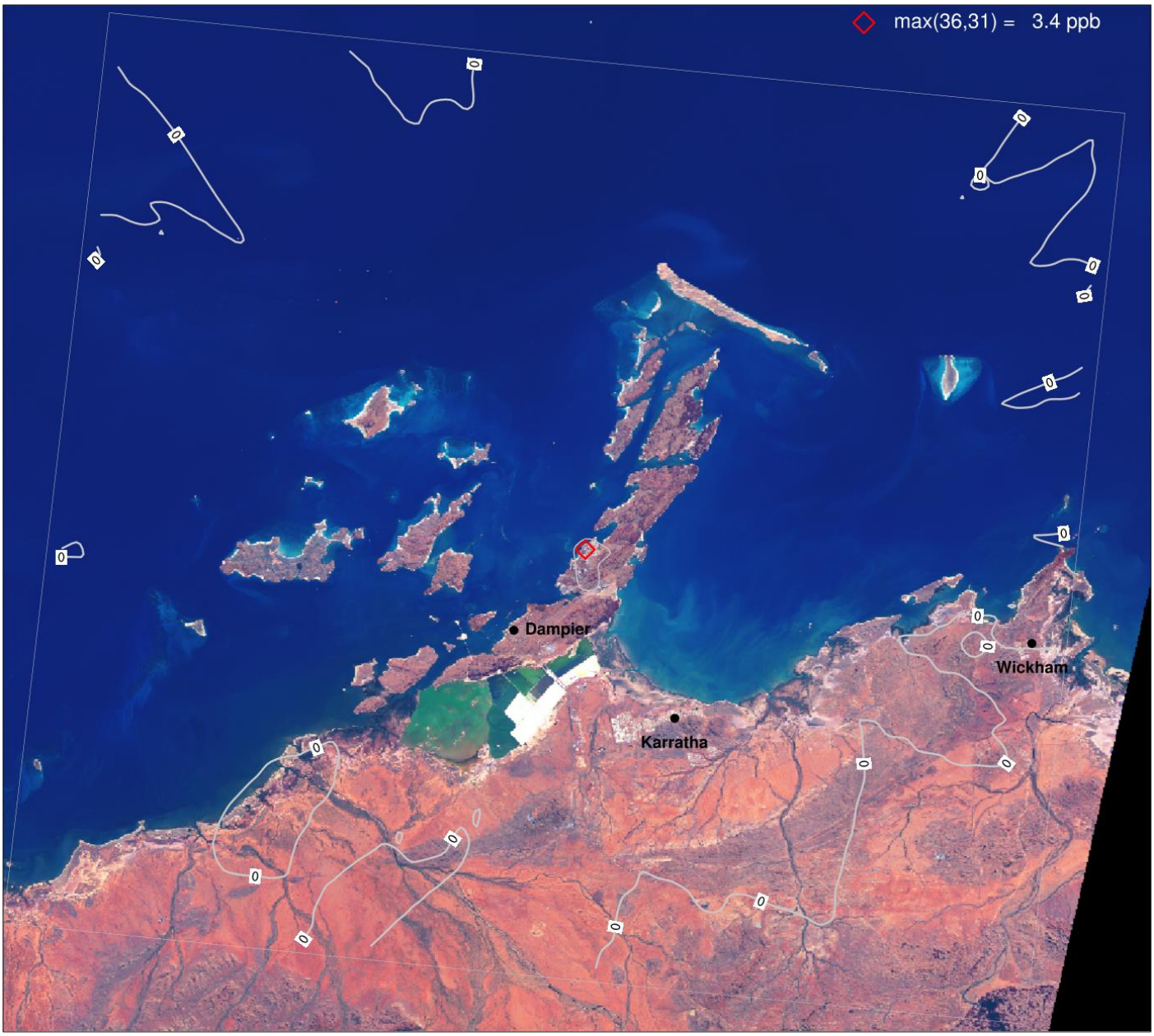

Figure A2-26. TOL (ppb) annual max 24-hour ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

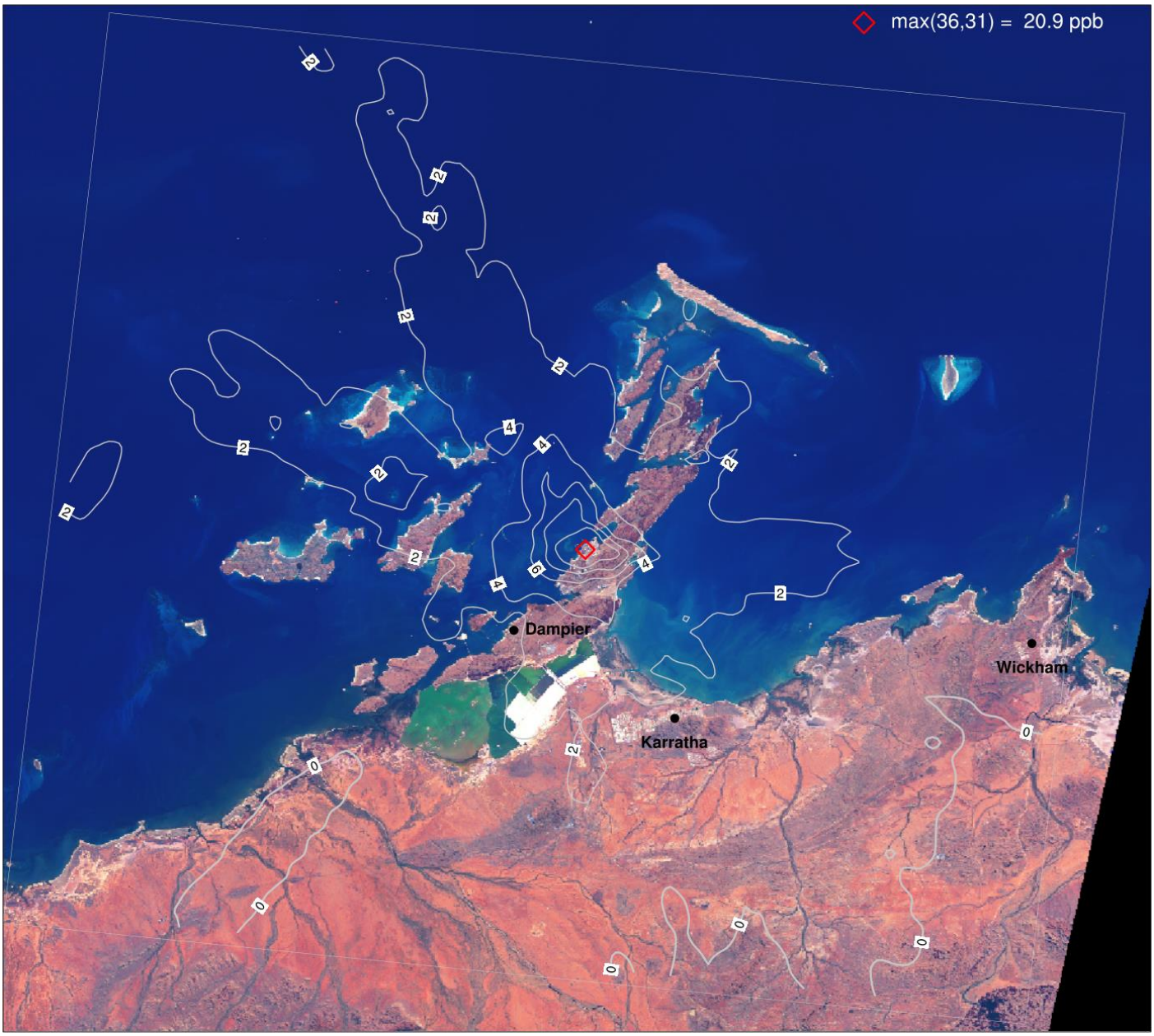

Figure A2-27. TOL (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

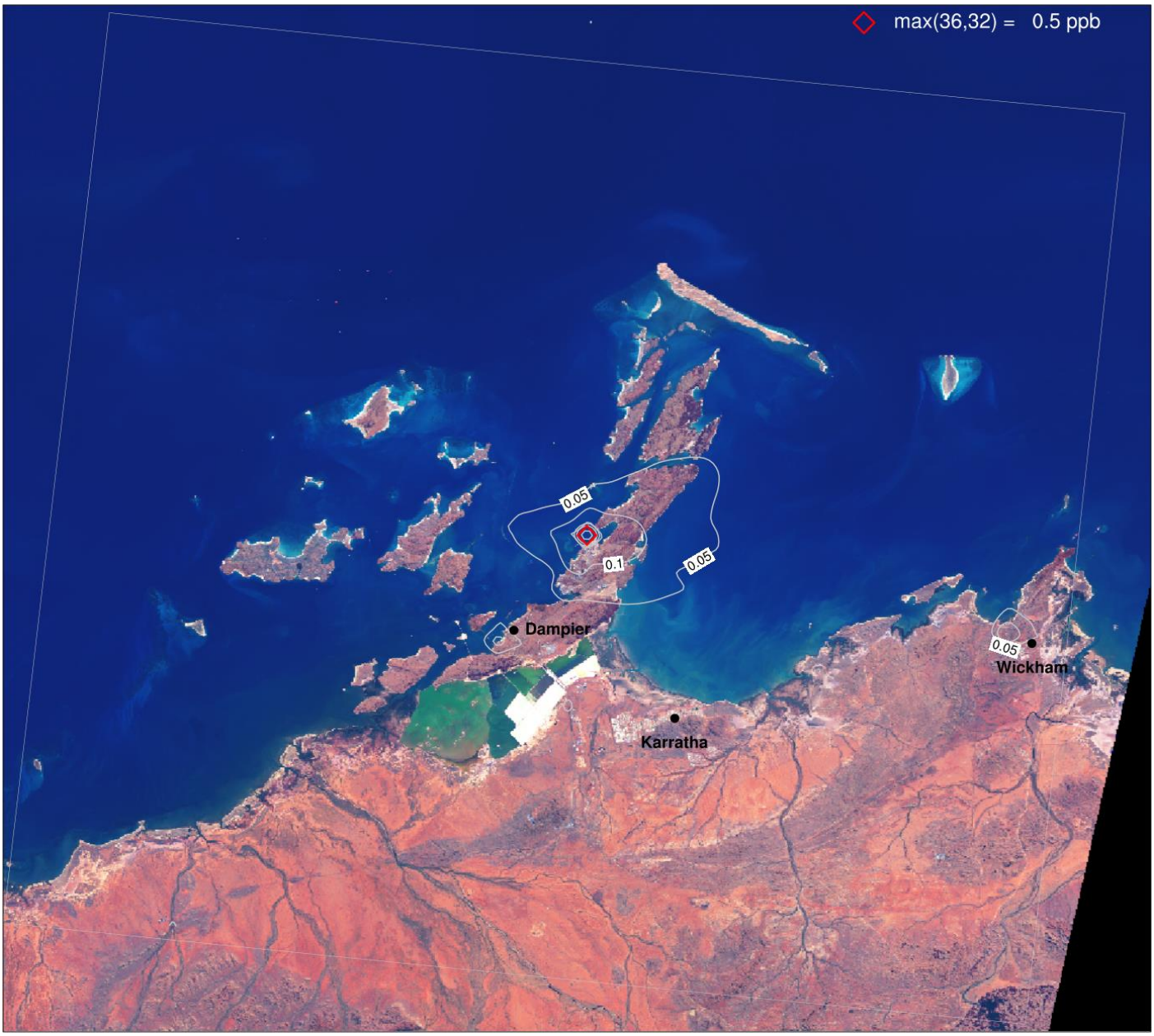

Figure A2-28. XYL (ppb) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

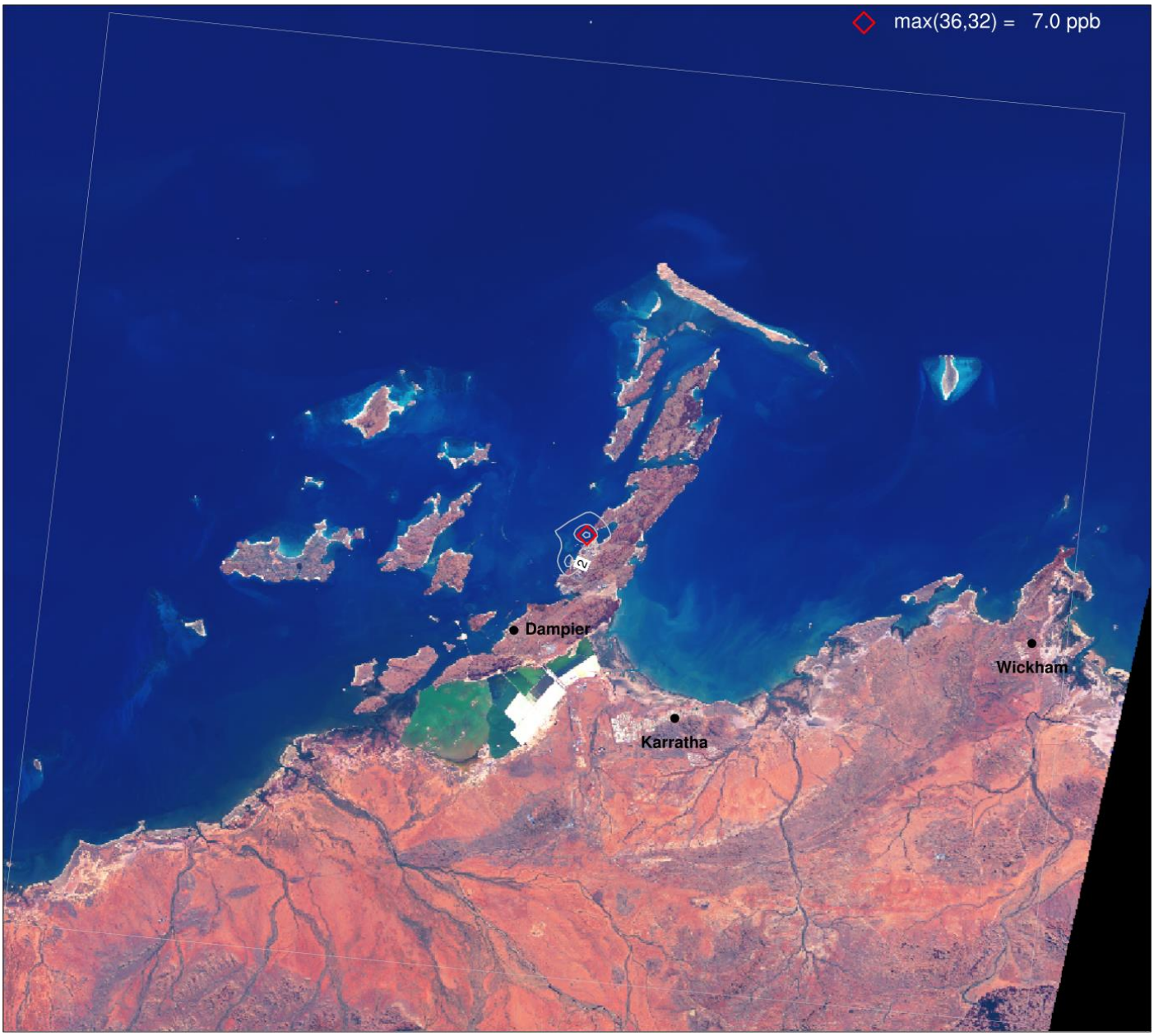

Figure A2-29. XYL (ppb) annual max 24-hour ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

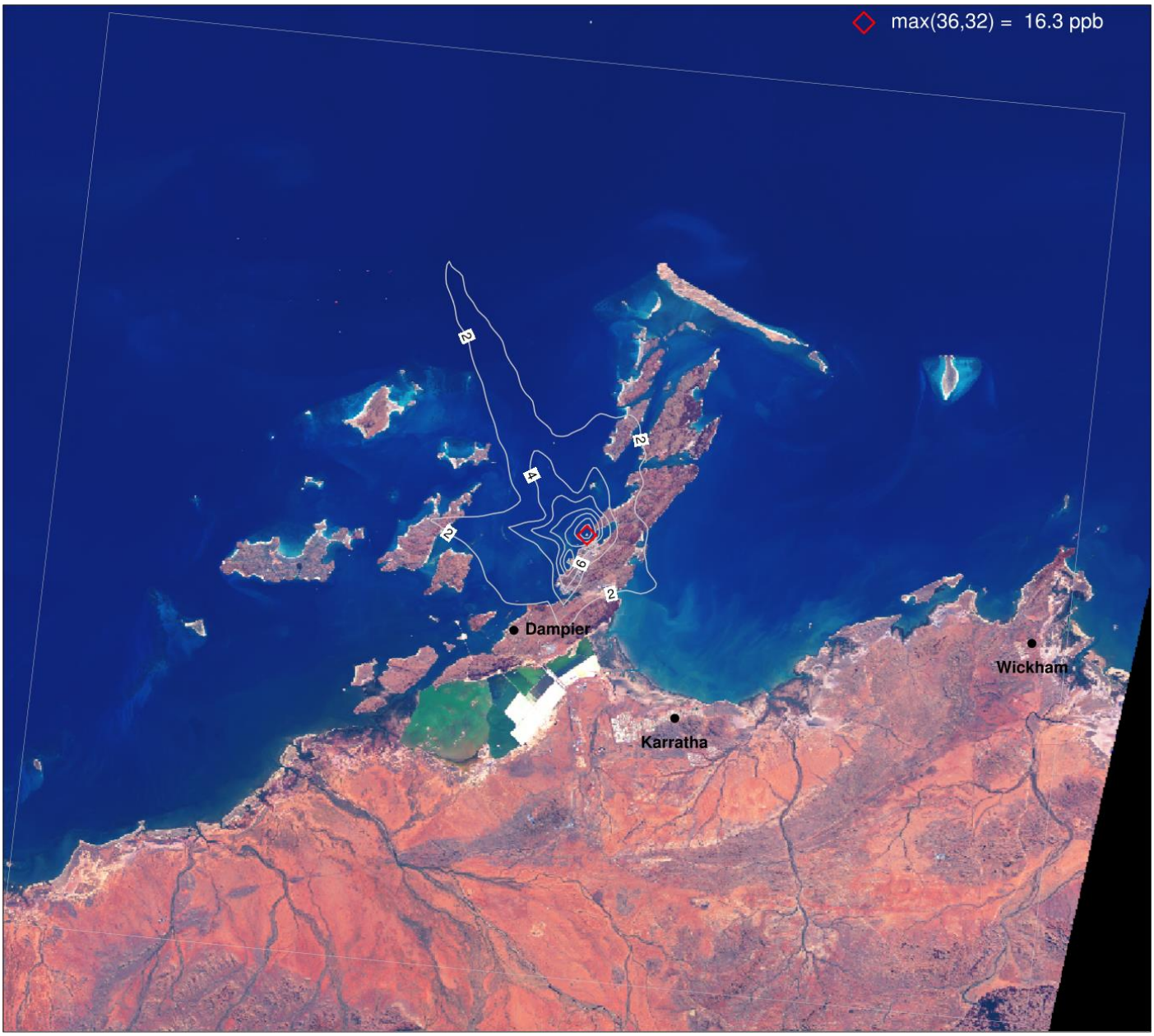

Figure A2-30. XYL (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

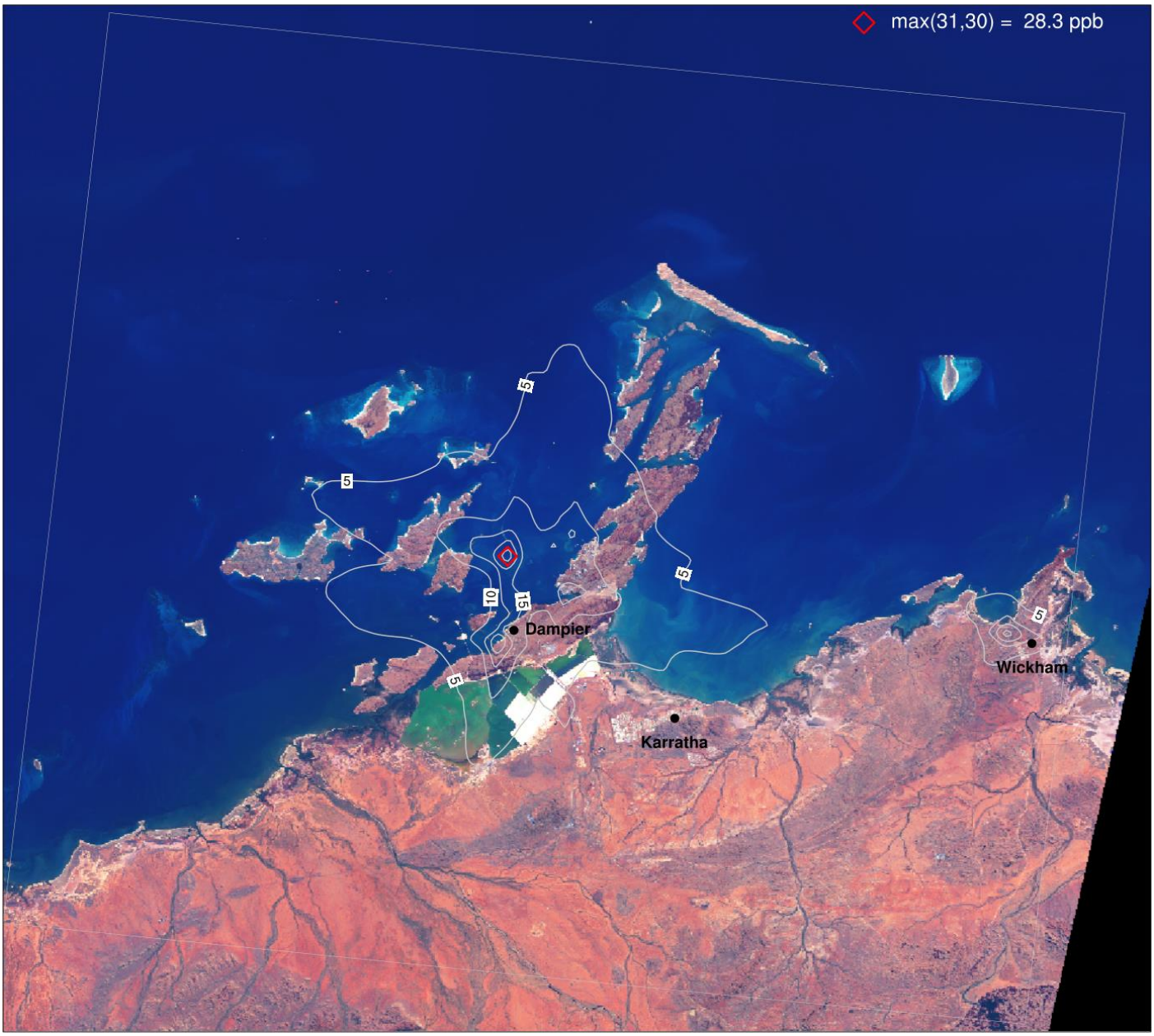

Figure A2-31. SO_2 (ppb) annual max 24-hour ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

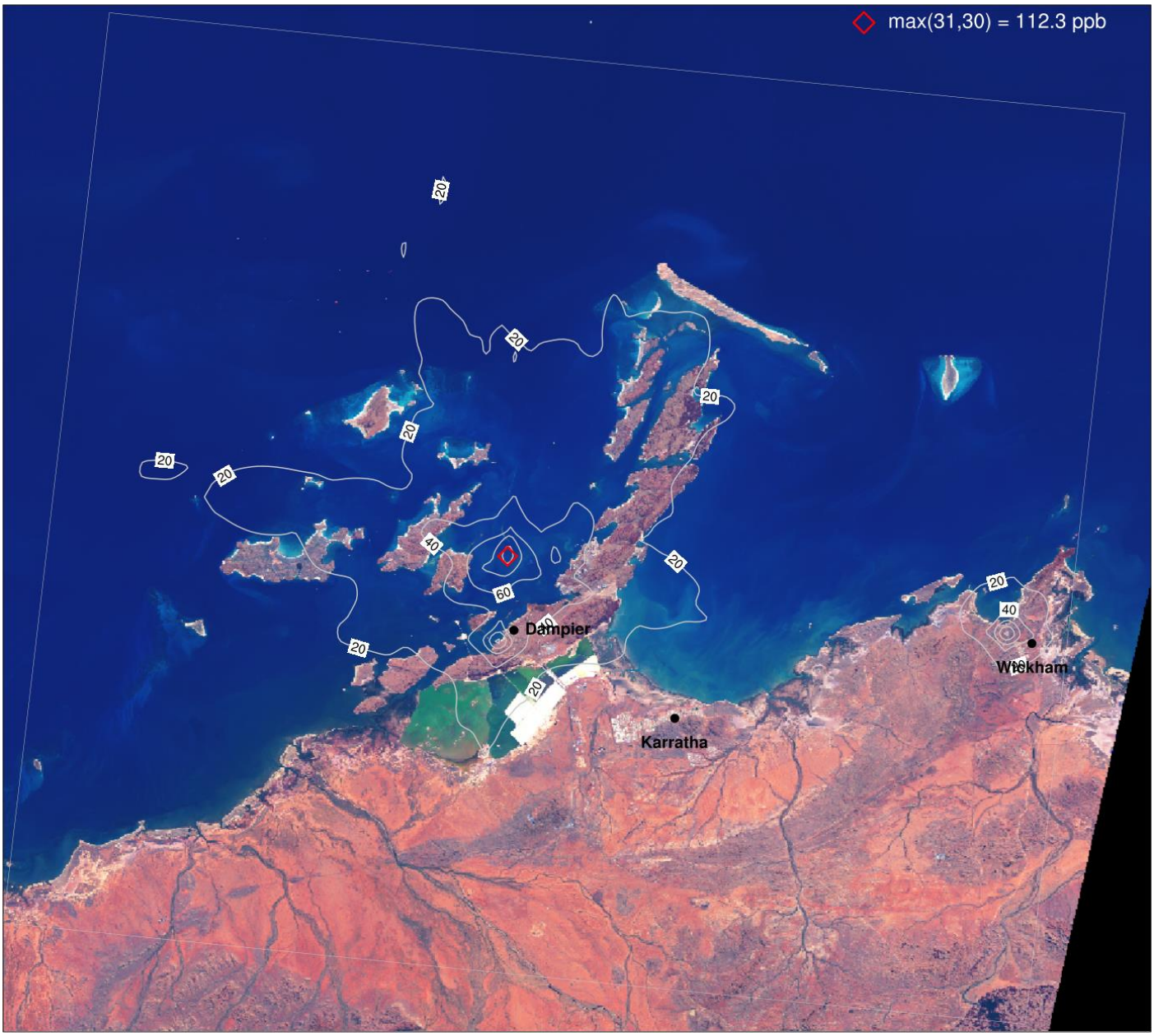

Figure A2-32. SO_2 (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

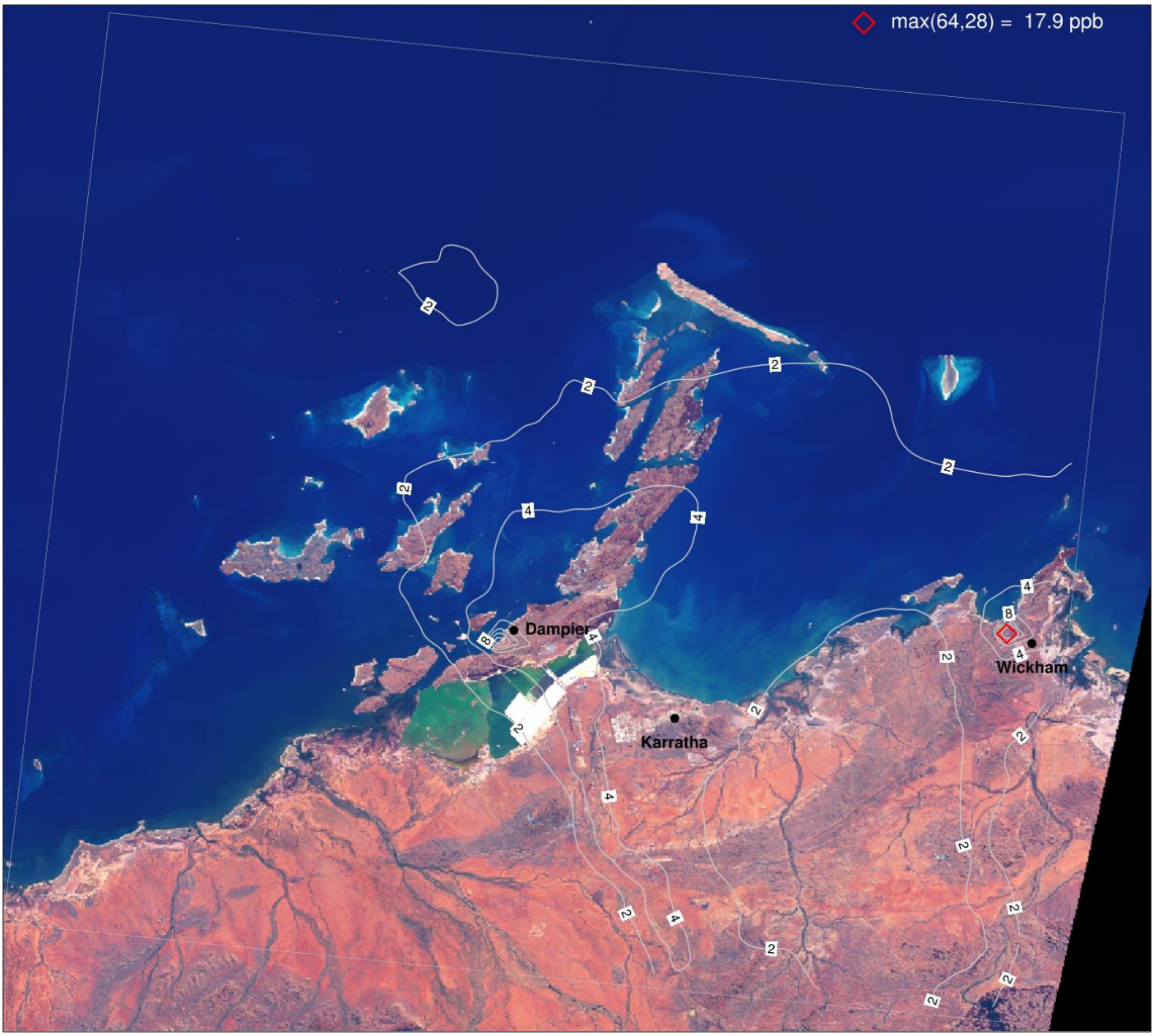

Figure A2-33. NO_2 (ppb) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

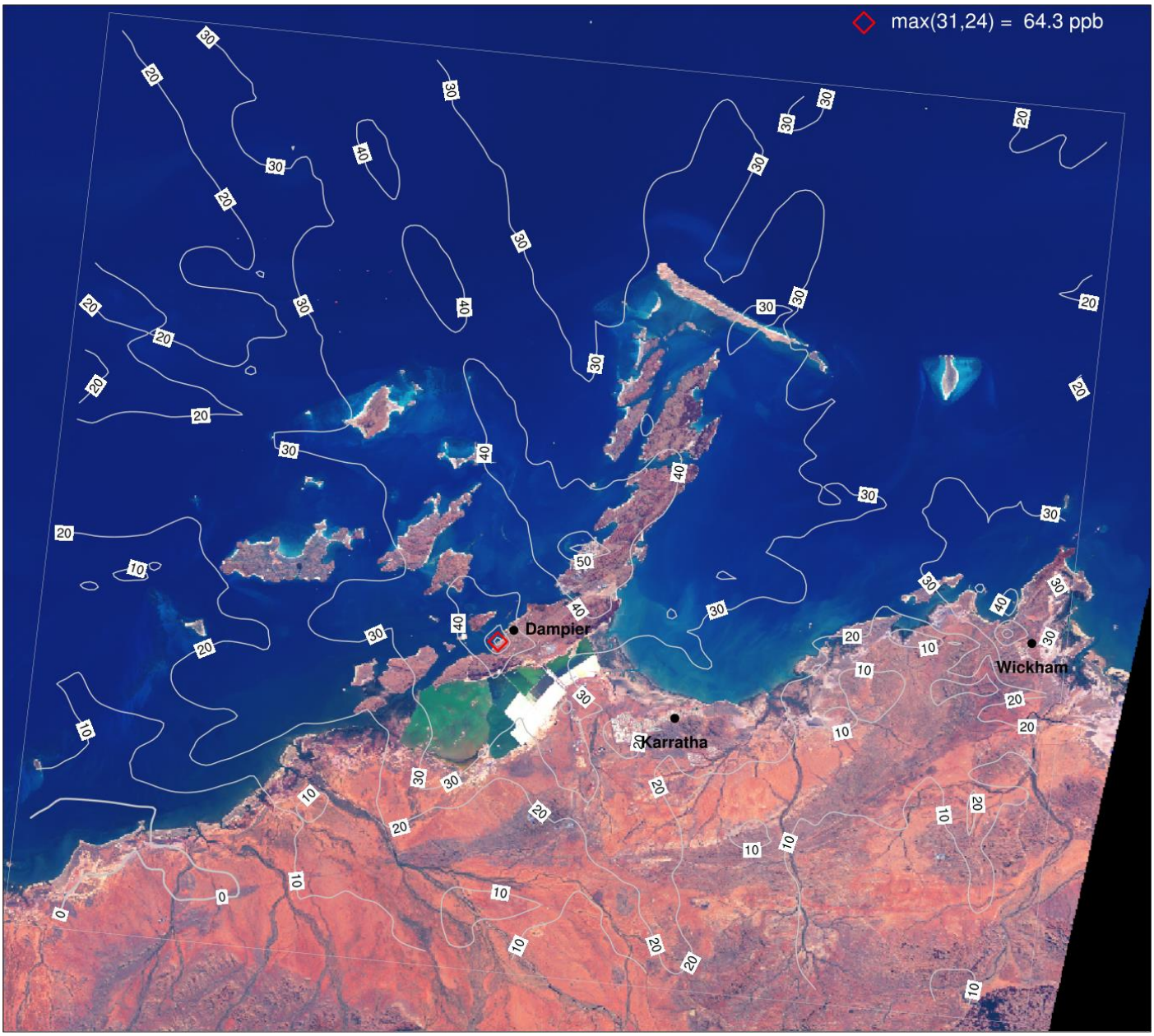

Figure A2-34. NO_2 (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

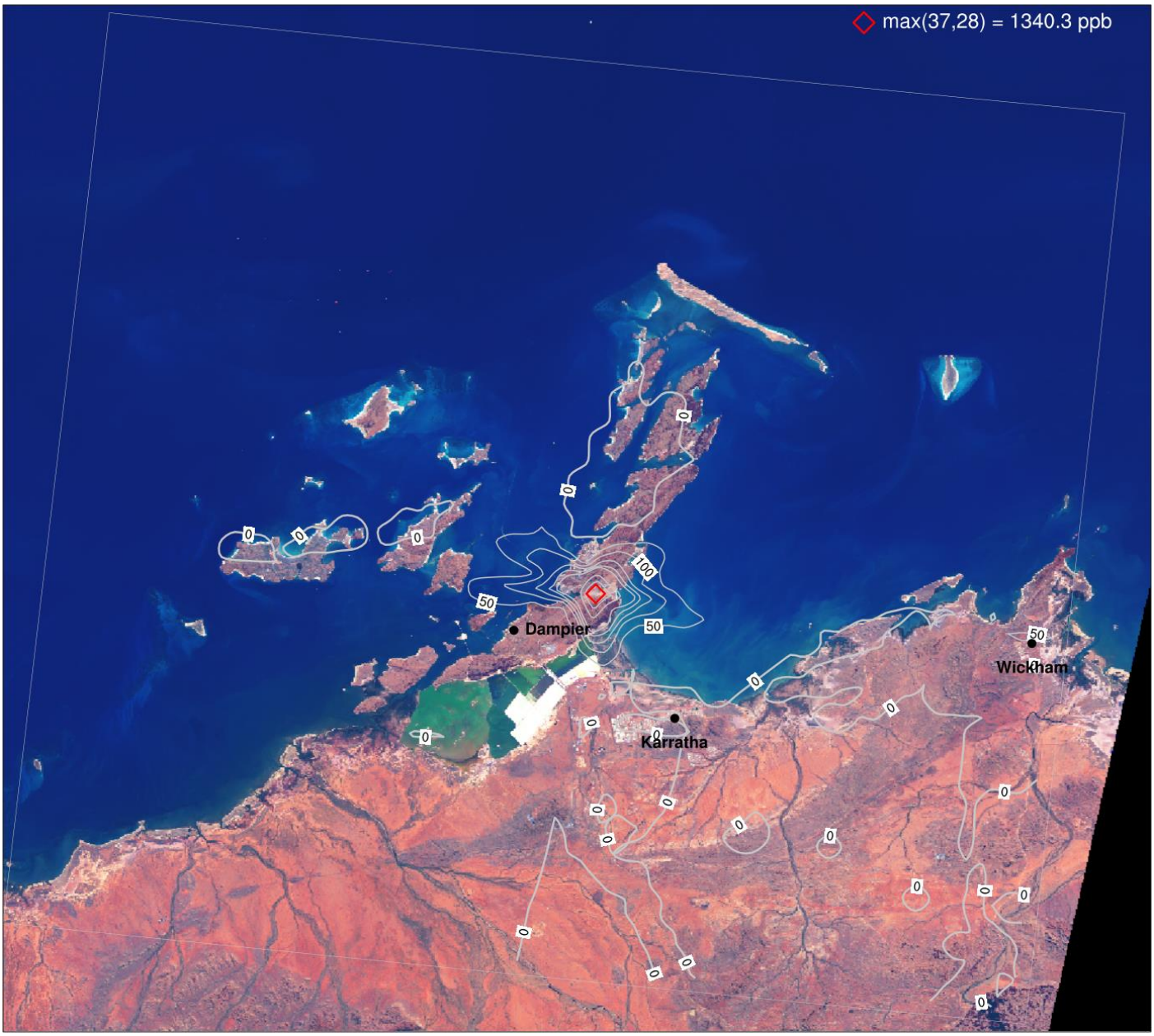

Figure A2-35. CO (ppb) annual max 8-hour (MDA8) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

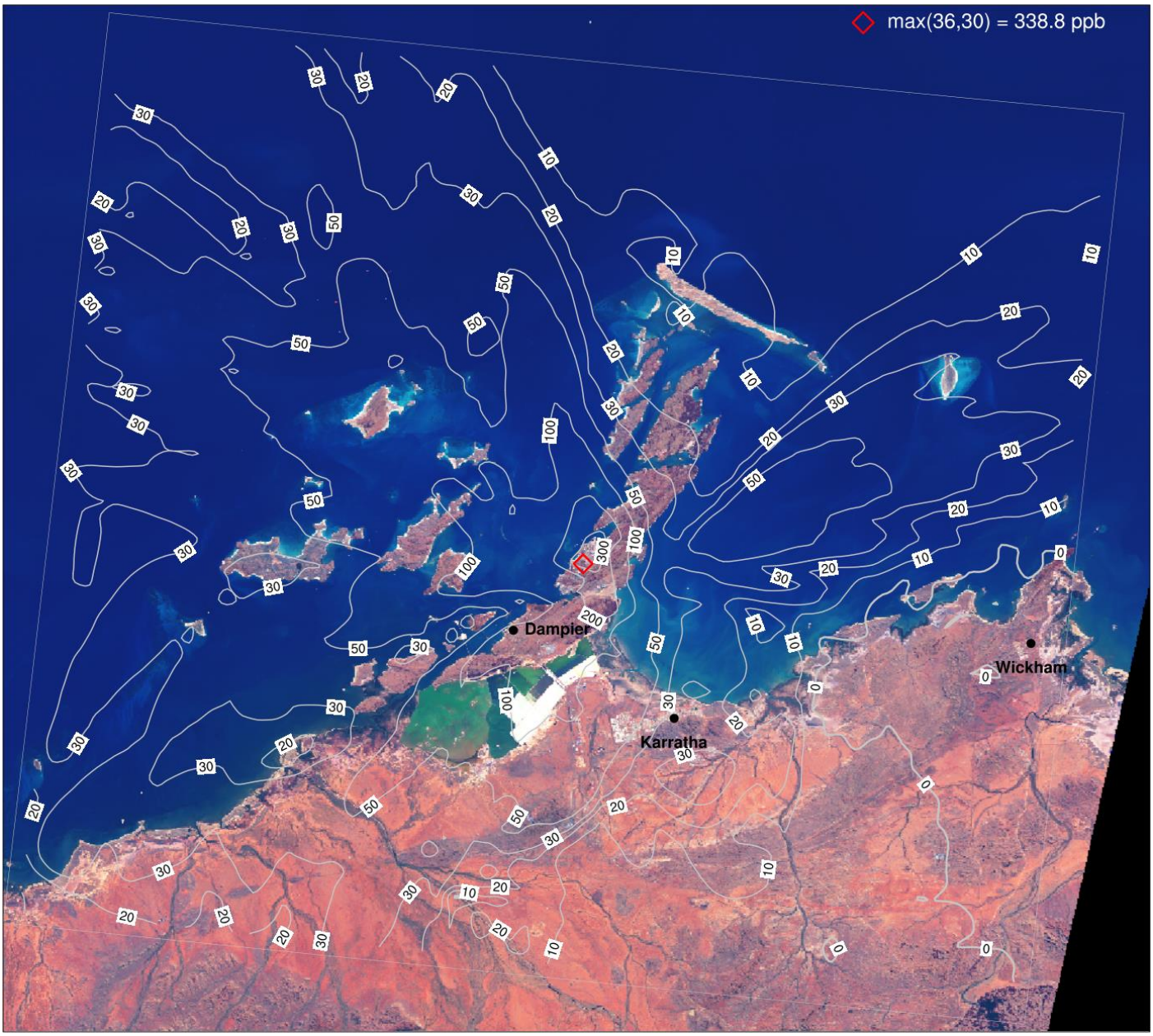

Figure A2-36. NH_3 (ppb) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

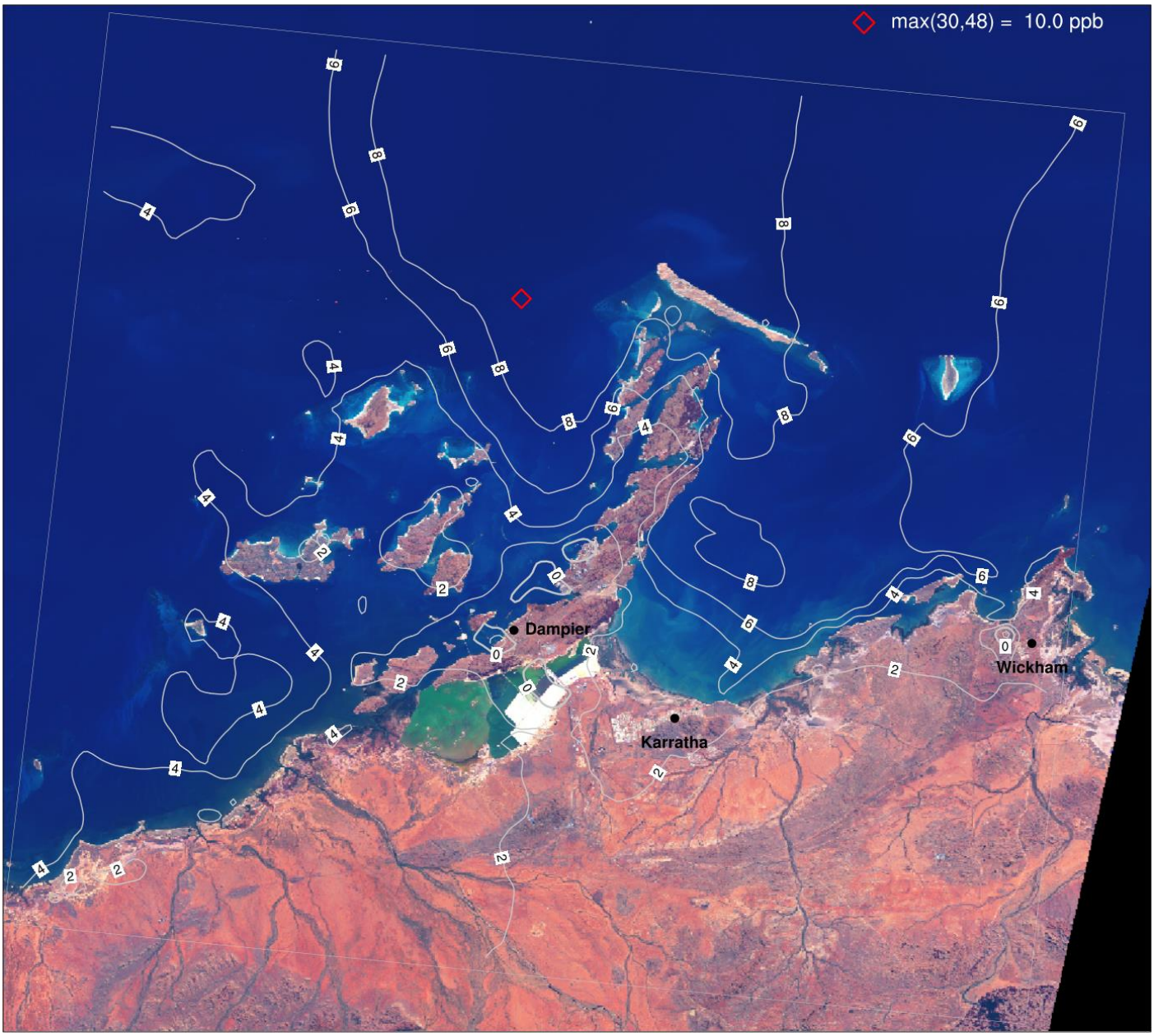

Figure A2-37. Ozone (ppb) annual max 8-hour (MDA8) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

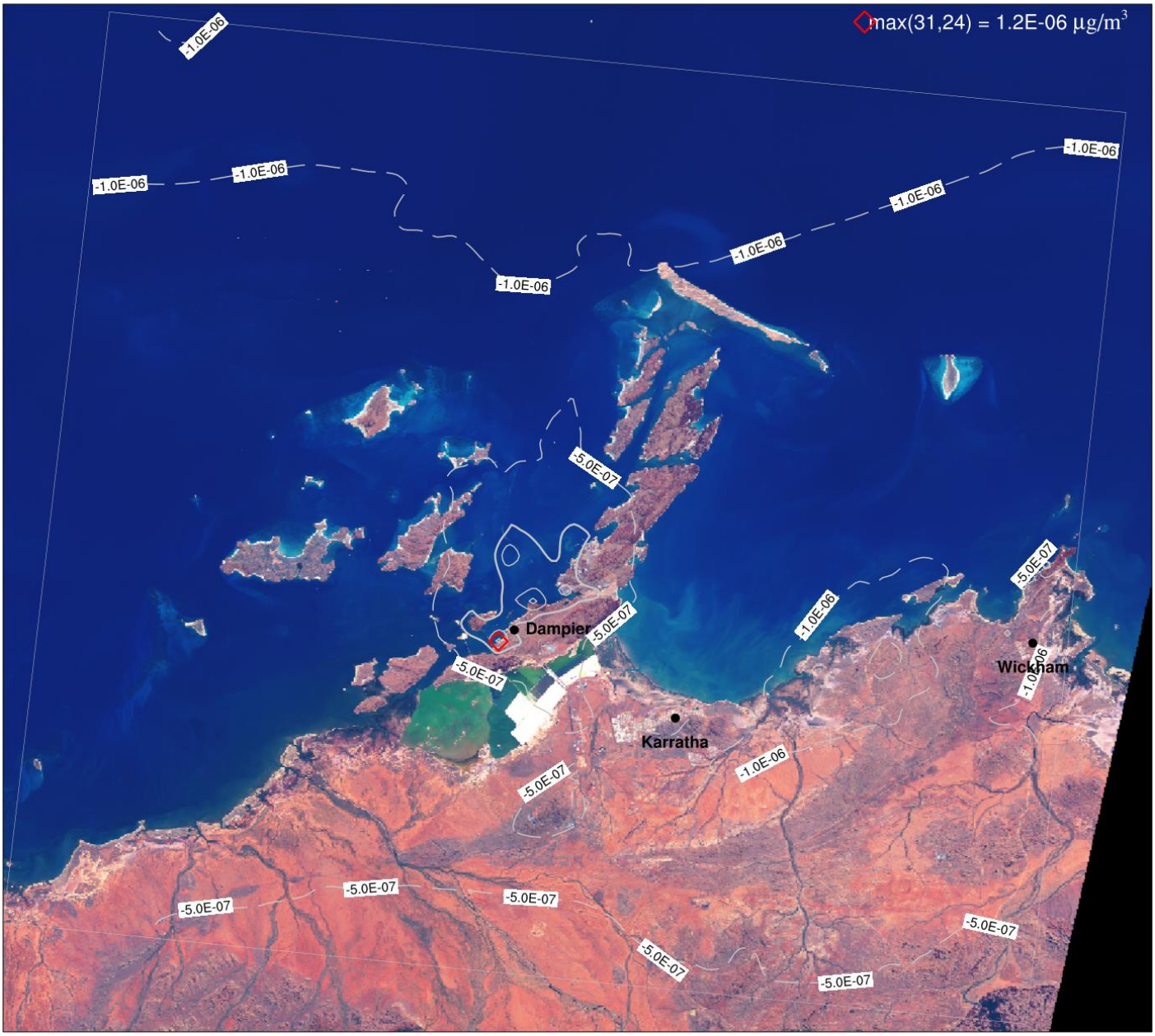

Figure A2-38. Hg (µg/m^3) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

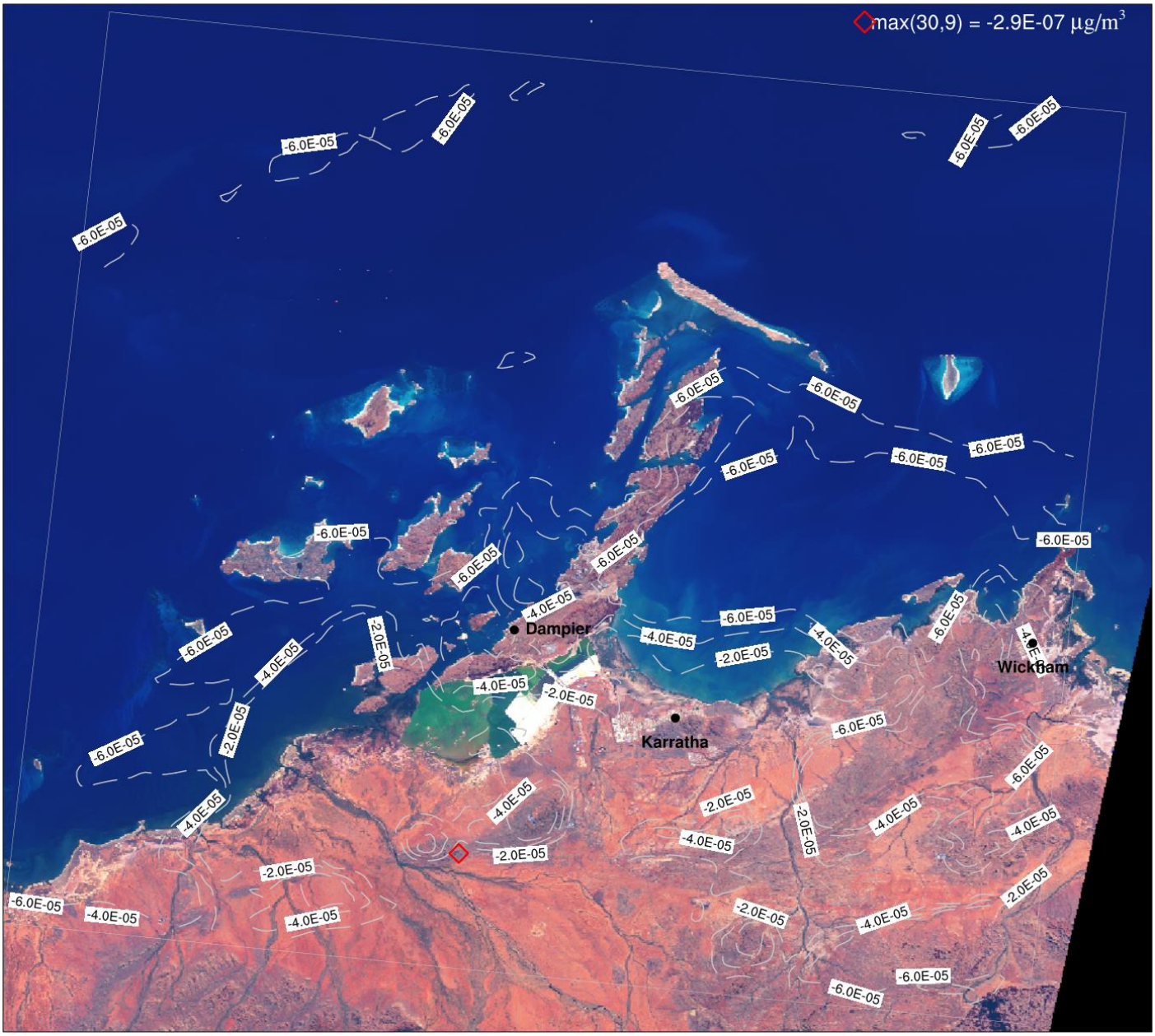

Figure A2-39. Hg (µg/m³) annual max 1-hour (MDA1) ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

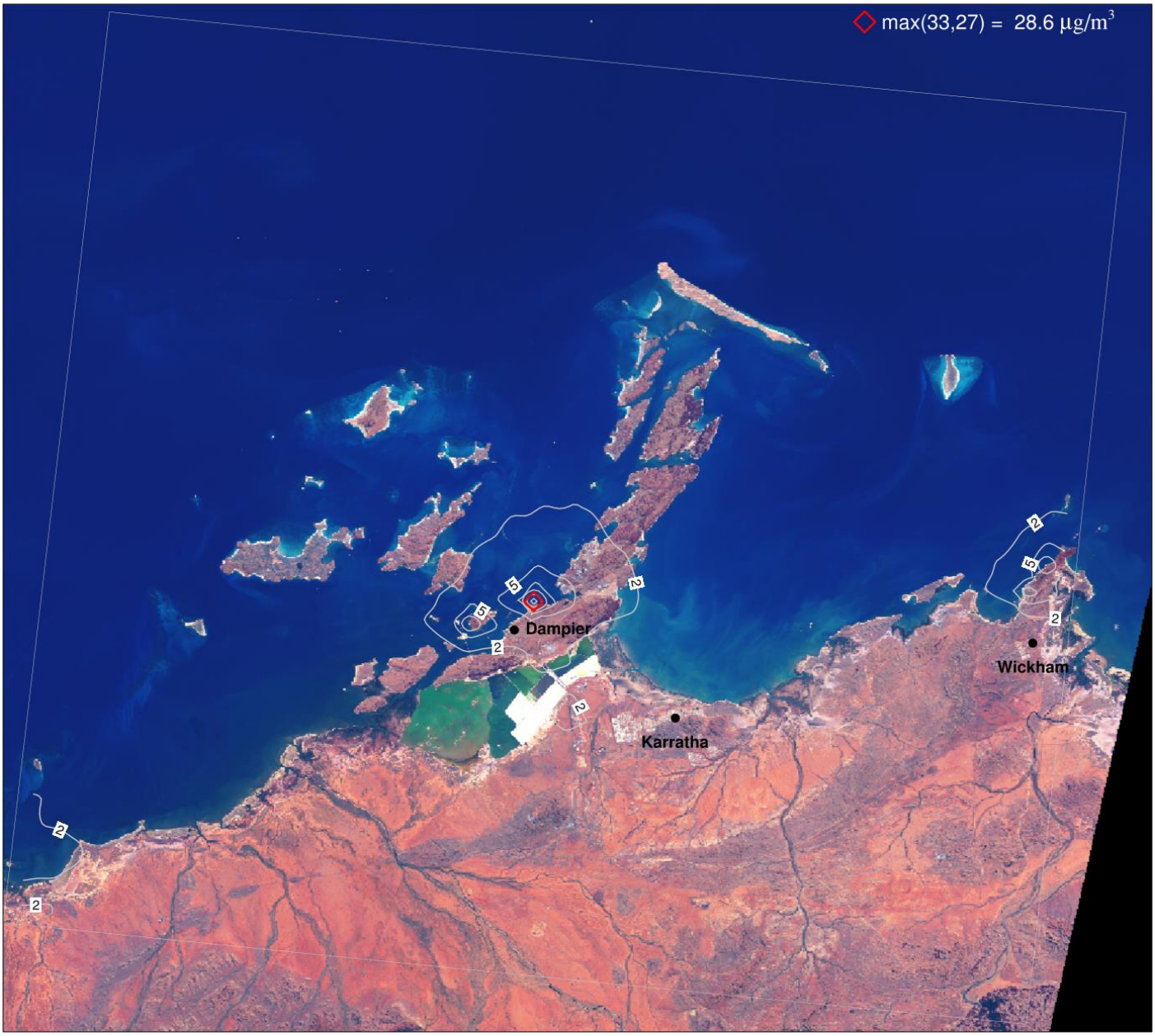

Figure A2-40. PM_{10} (µg/m^3) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

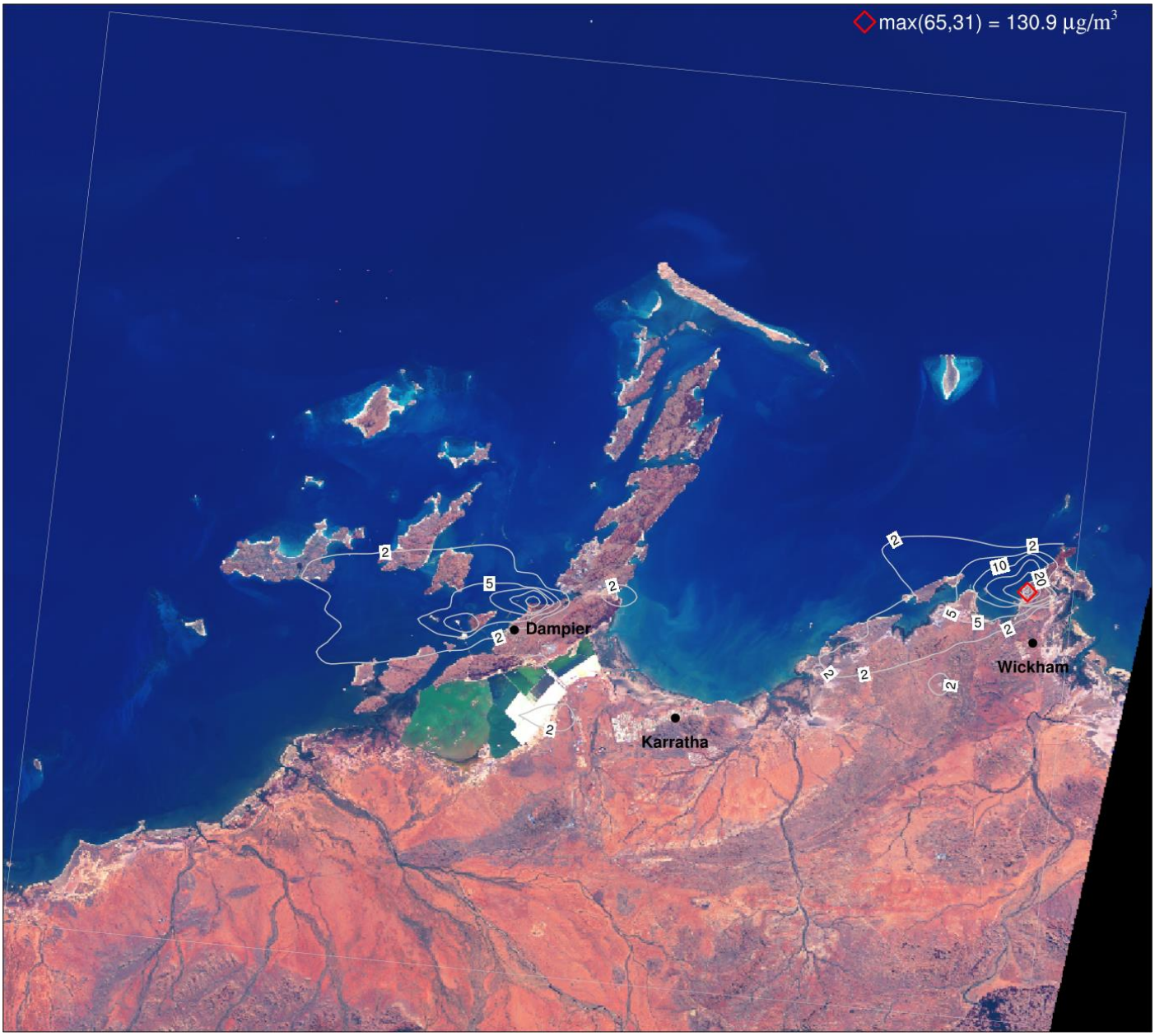

Figure A2-41. PM_{10} (µg/m^3) annual max 24-hour ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

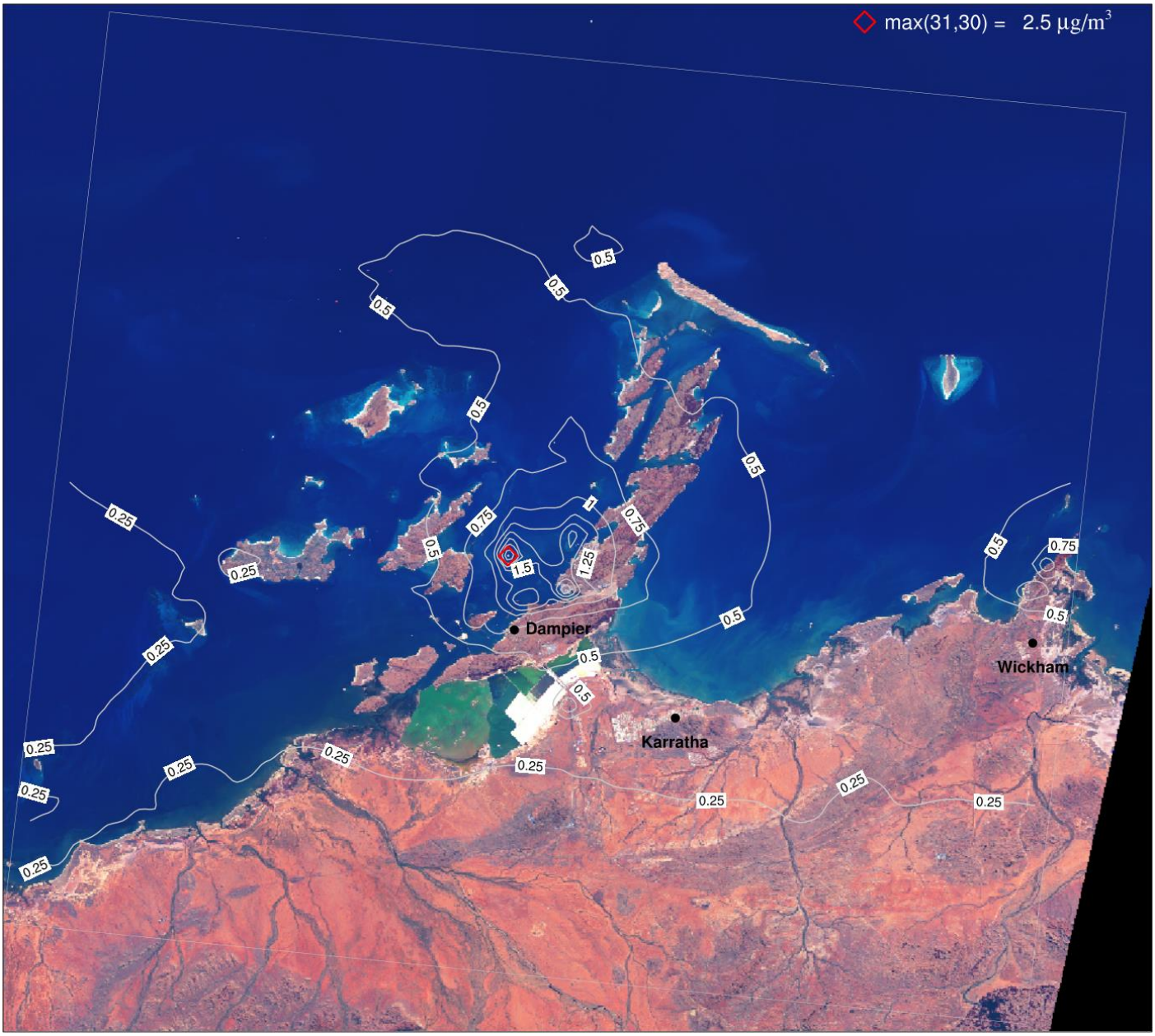

Figure A2-42. $PM_{2.5}$ (µg/m^3) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

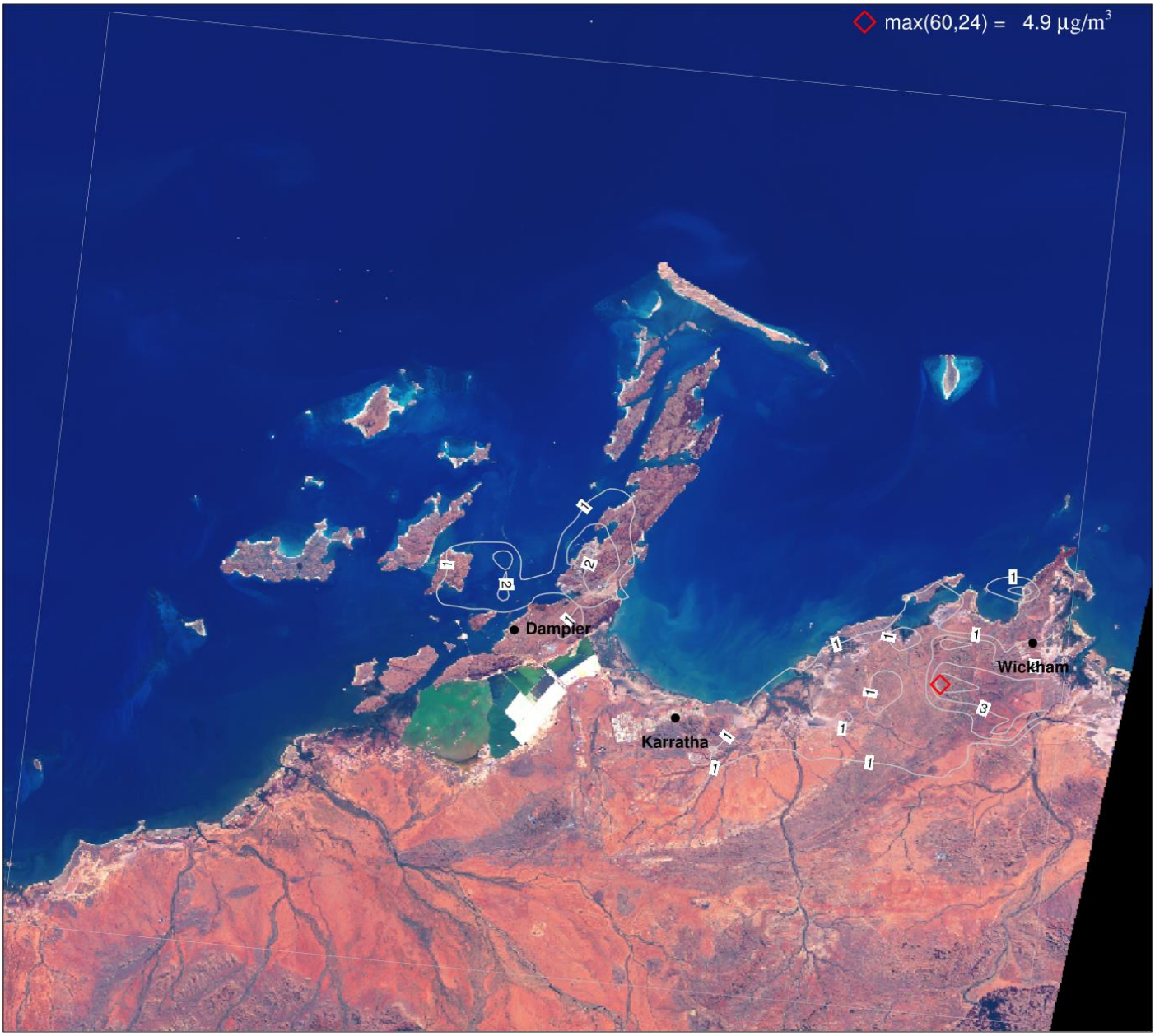

Figure A2-43. $PM_{2.5}$ (µg/m^3) annual max 24-hour ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

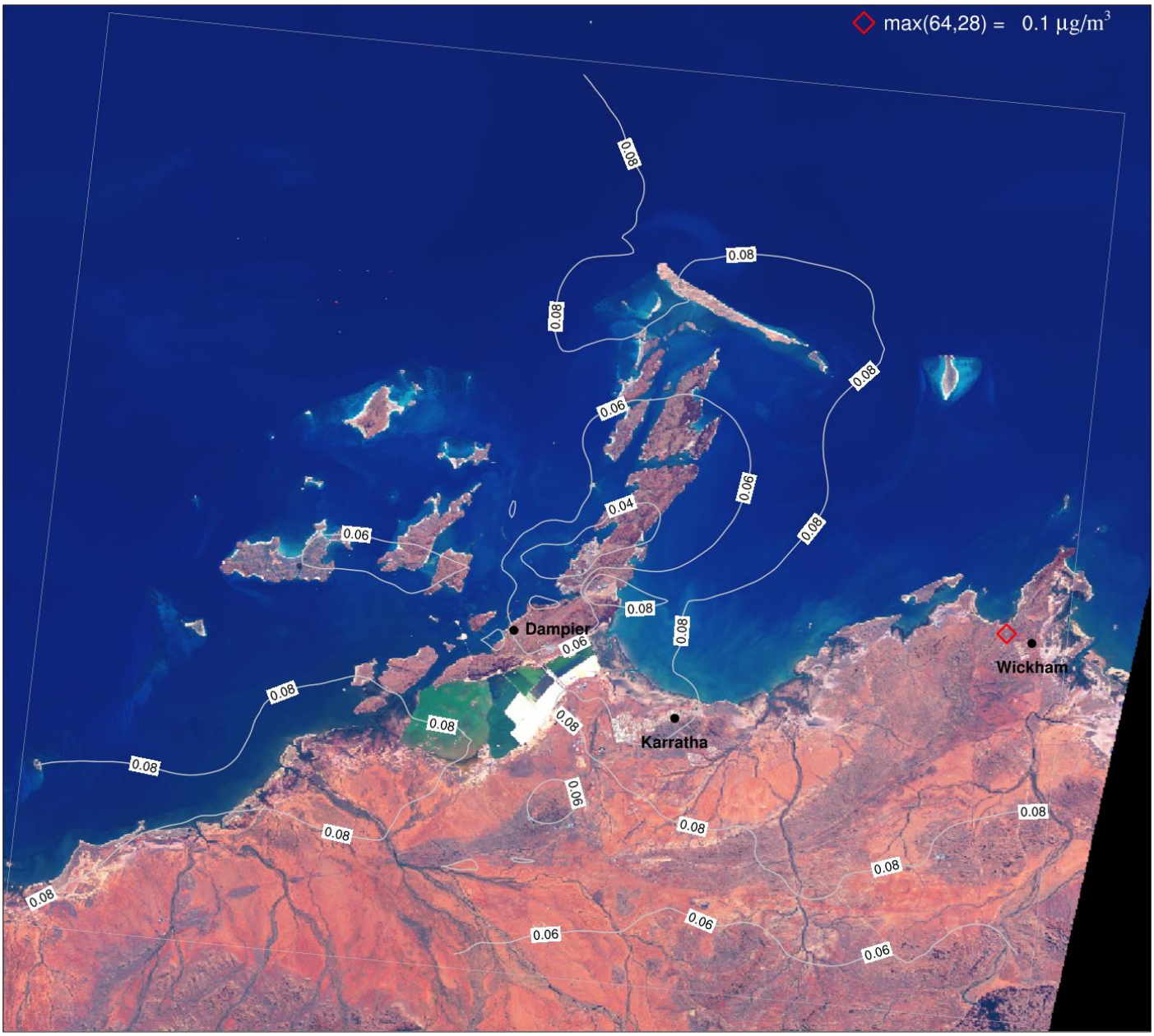

Figure A2-44. Ammonium plus nitrate (µg/m³) annual average ground level concentrations due to industry (S2-S1) for the CAMx 1.33 km domain.

Future Industry Ground Level Concentrations

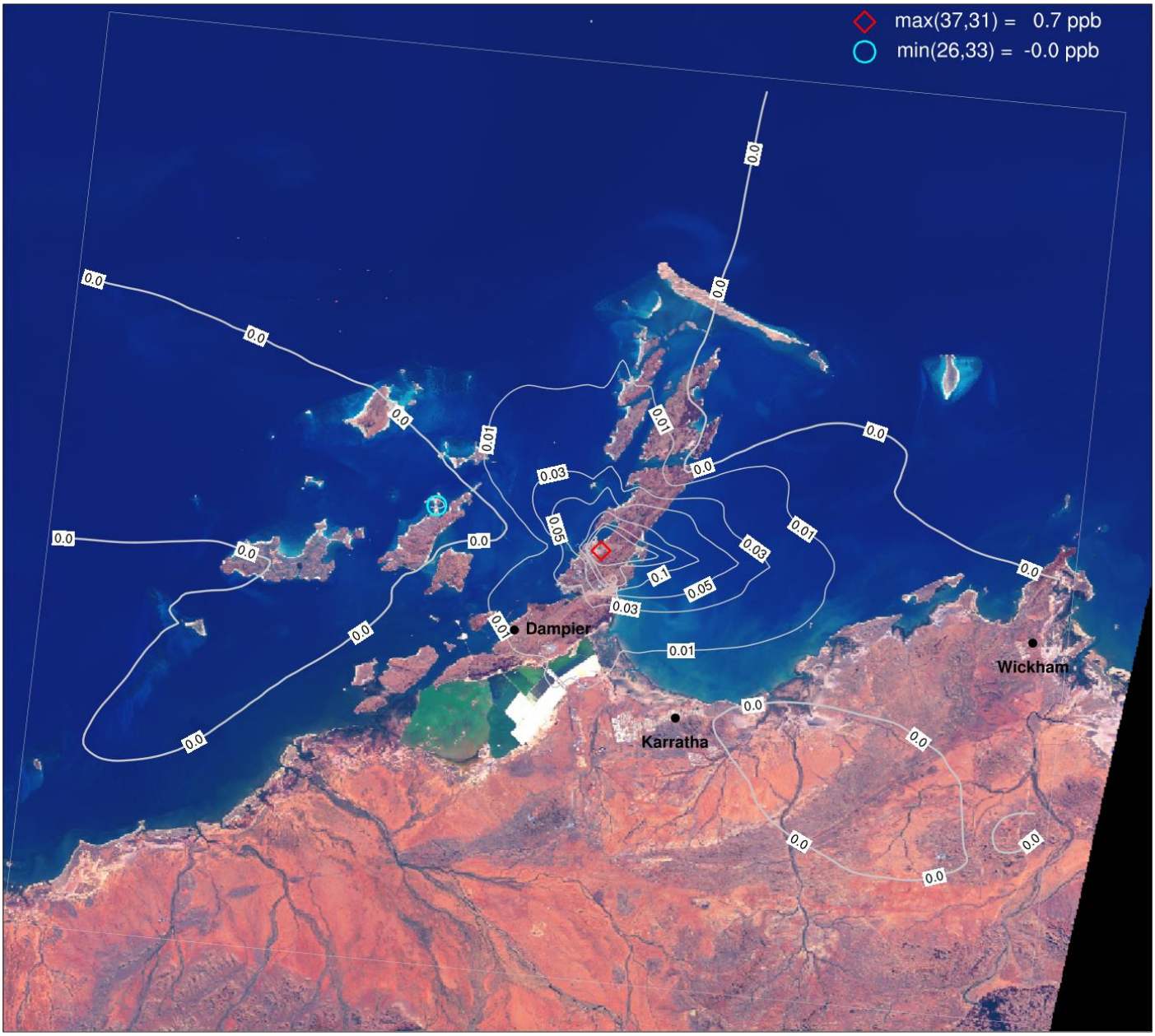

Figure A2-45. Benzene (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

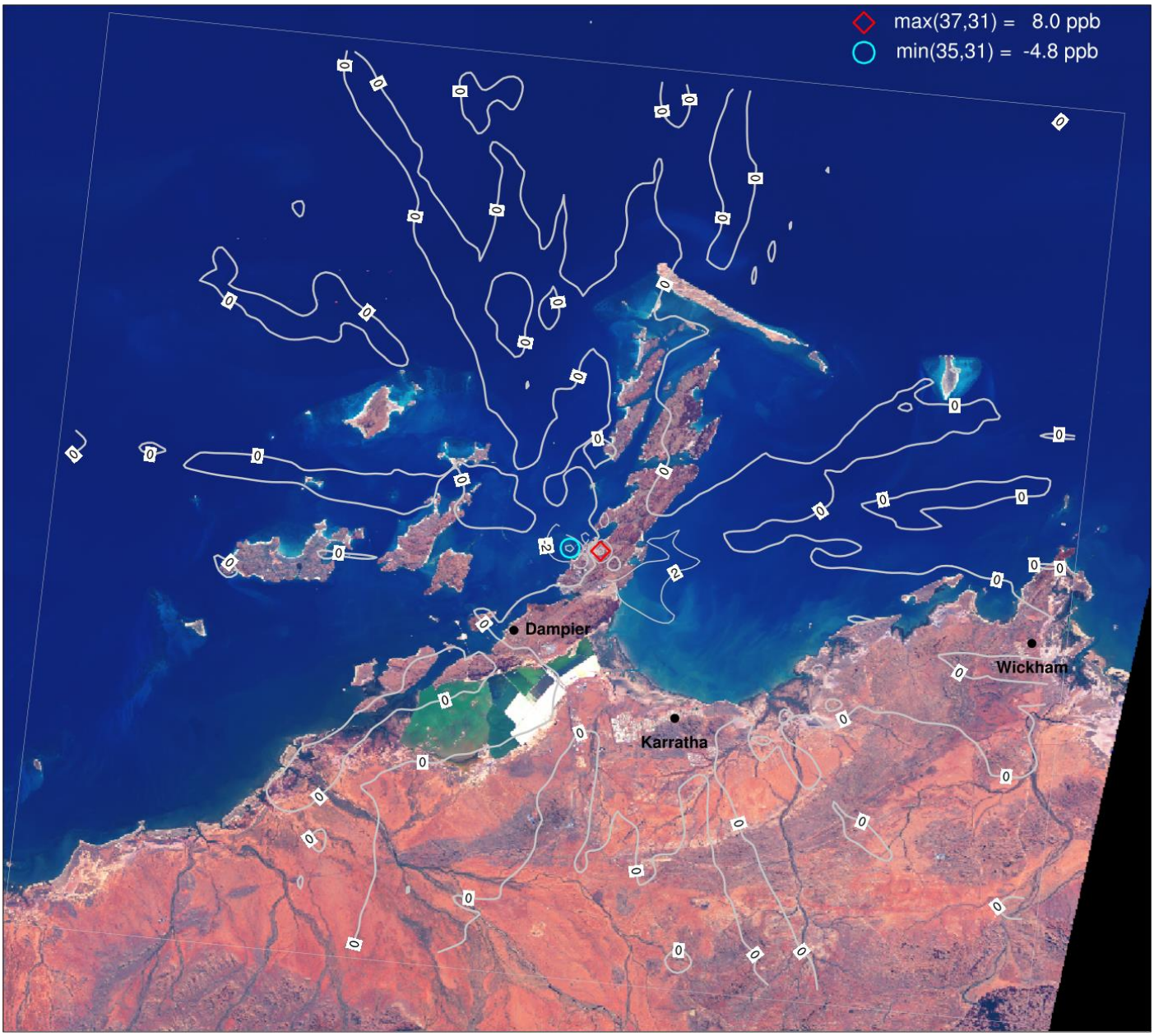

Figure A2-46. Benzene (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

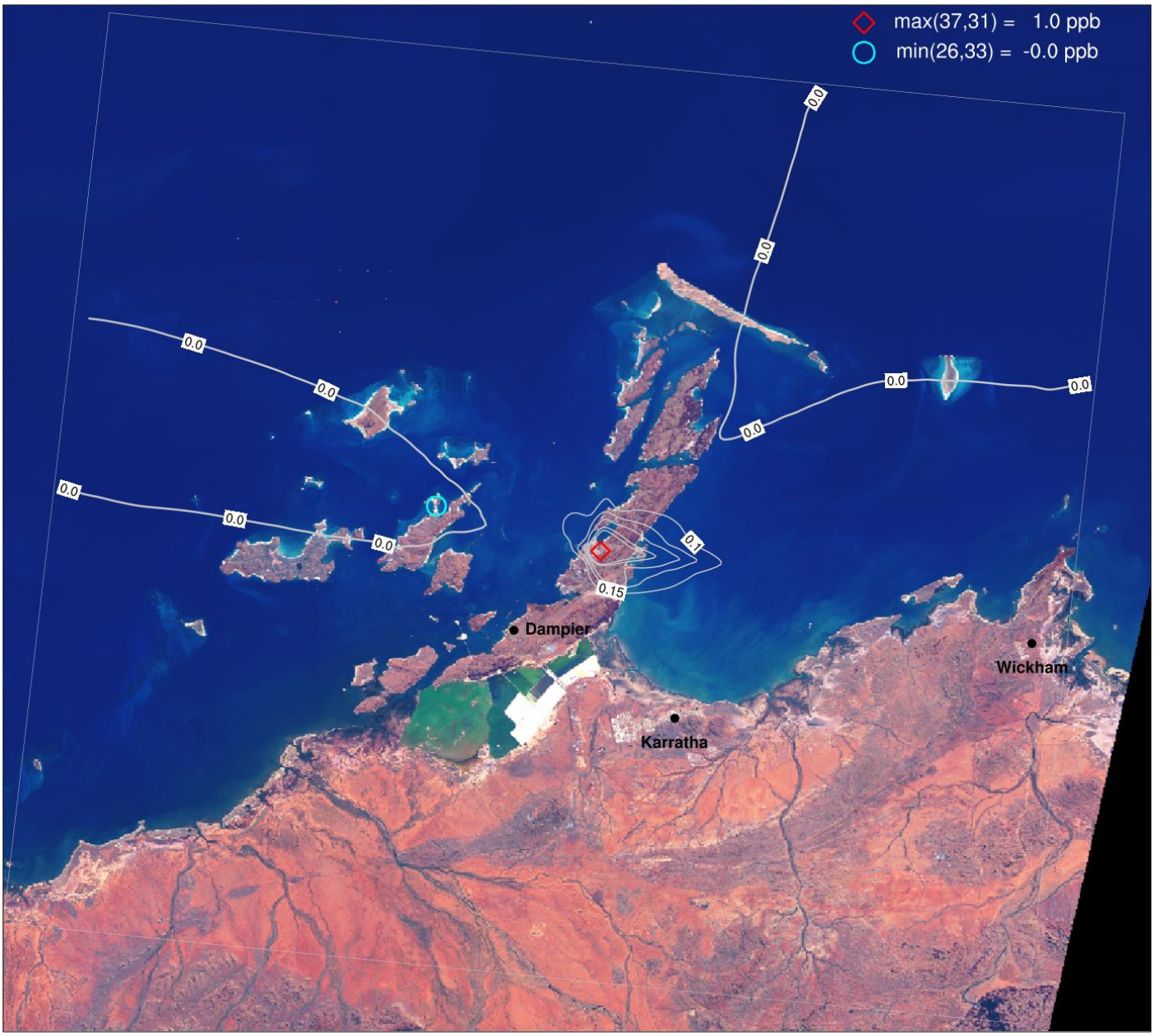

Figure A2-47. TOL (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

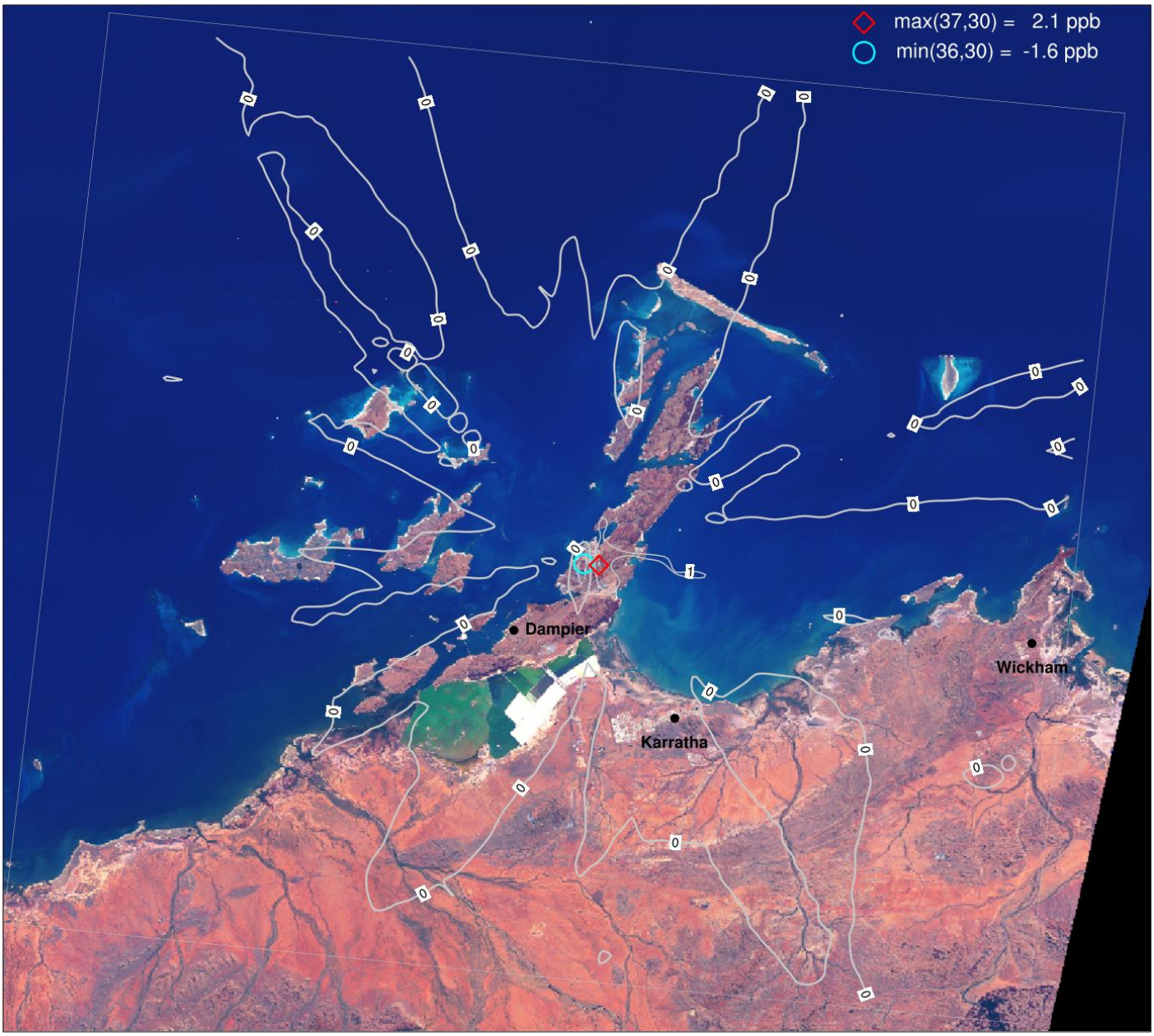

Figure A2-48. TOL (ppb) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

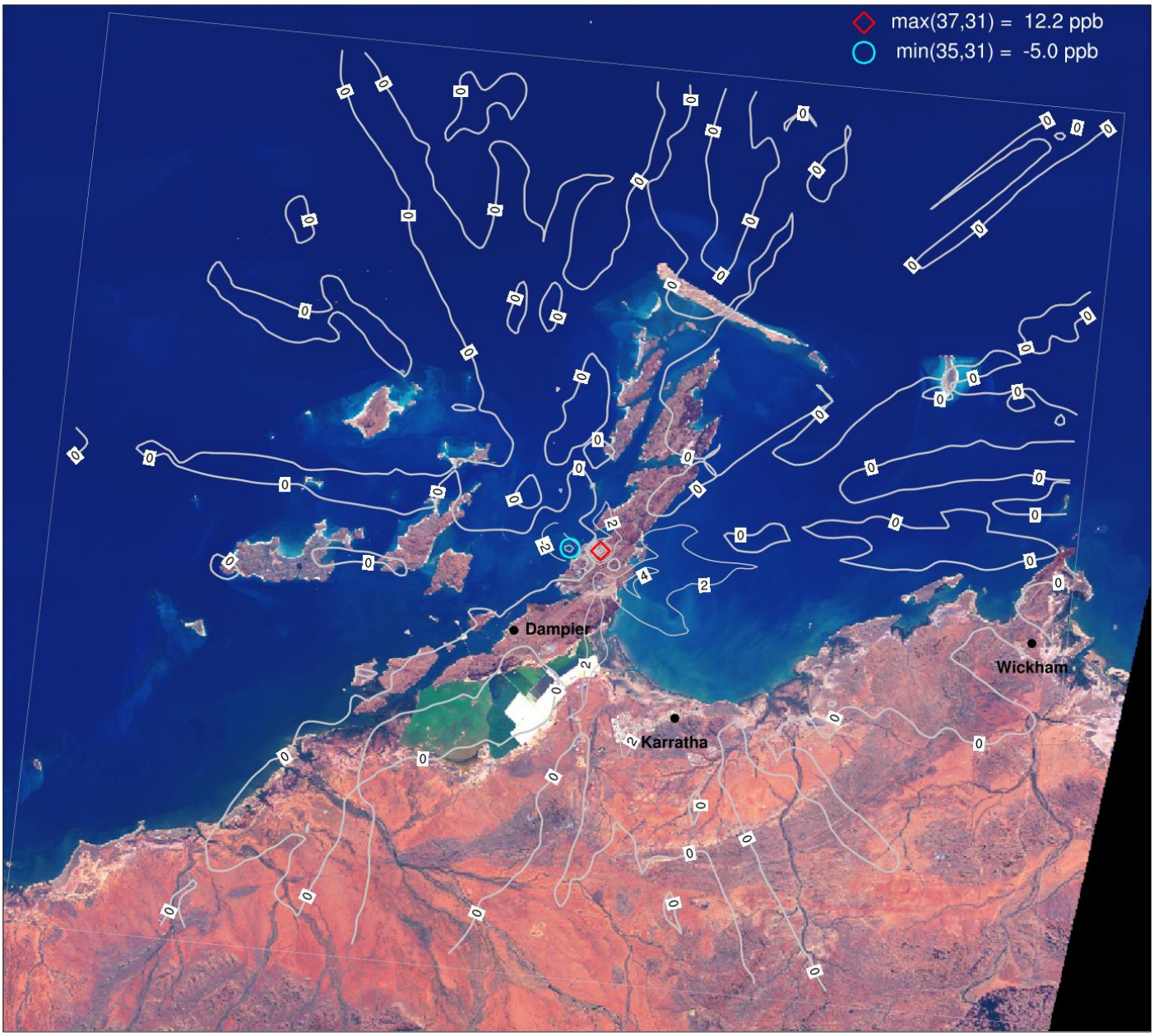

Figure A2-49. TOL (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

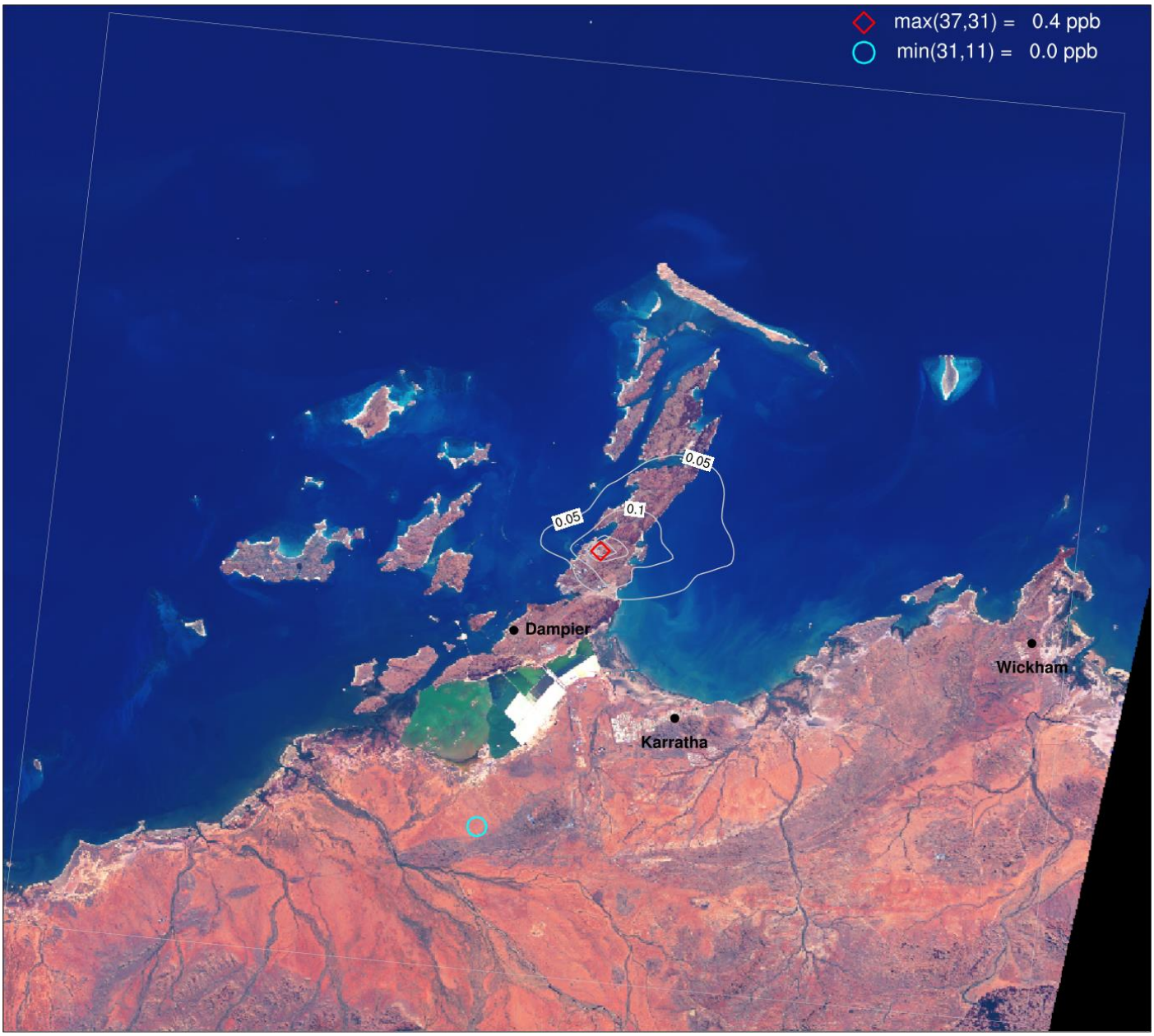

Figure A2-50. XYL (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

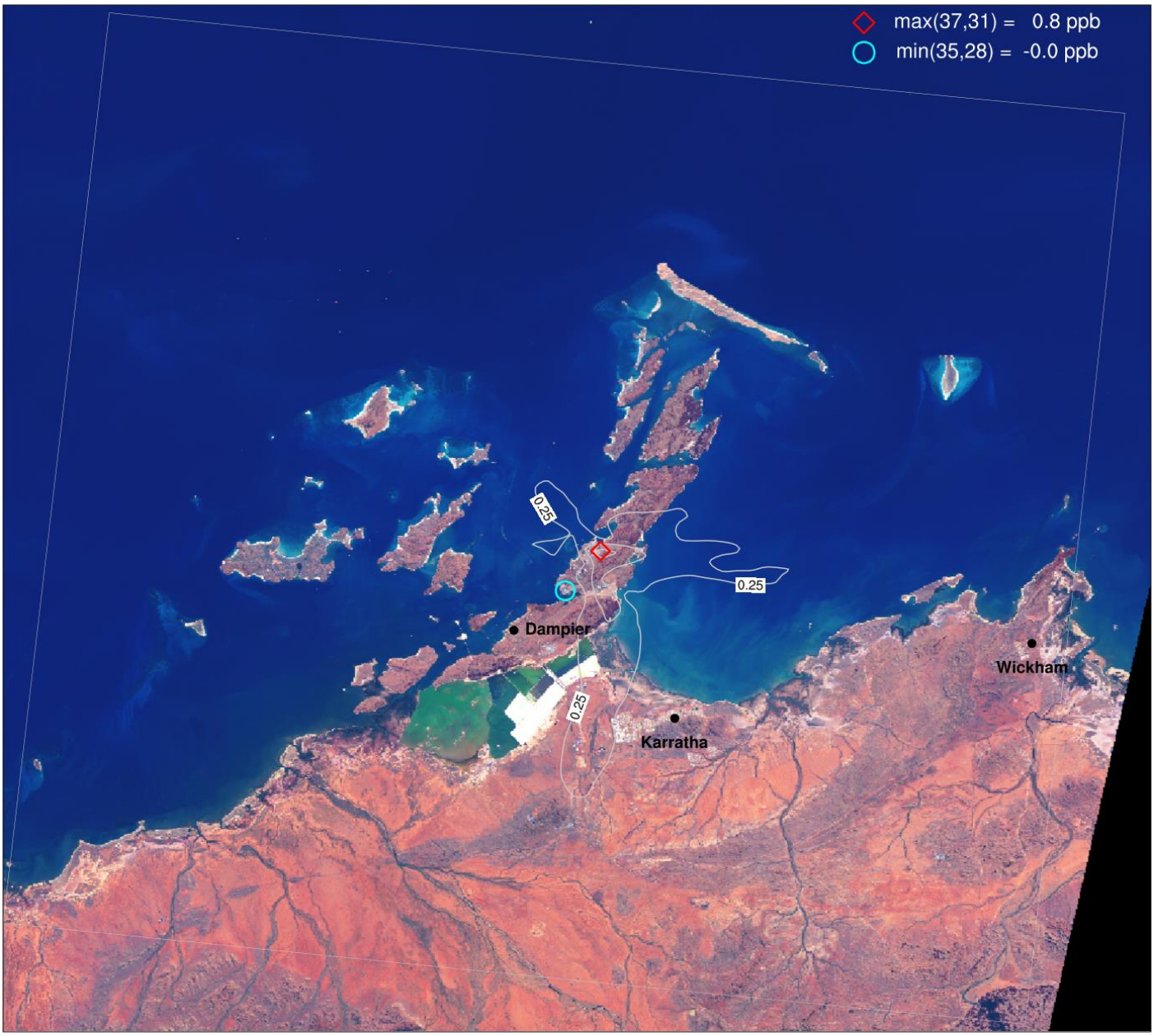

Figure A2-51. XYL (ppb) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

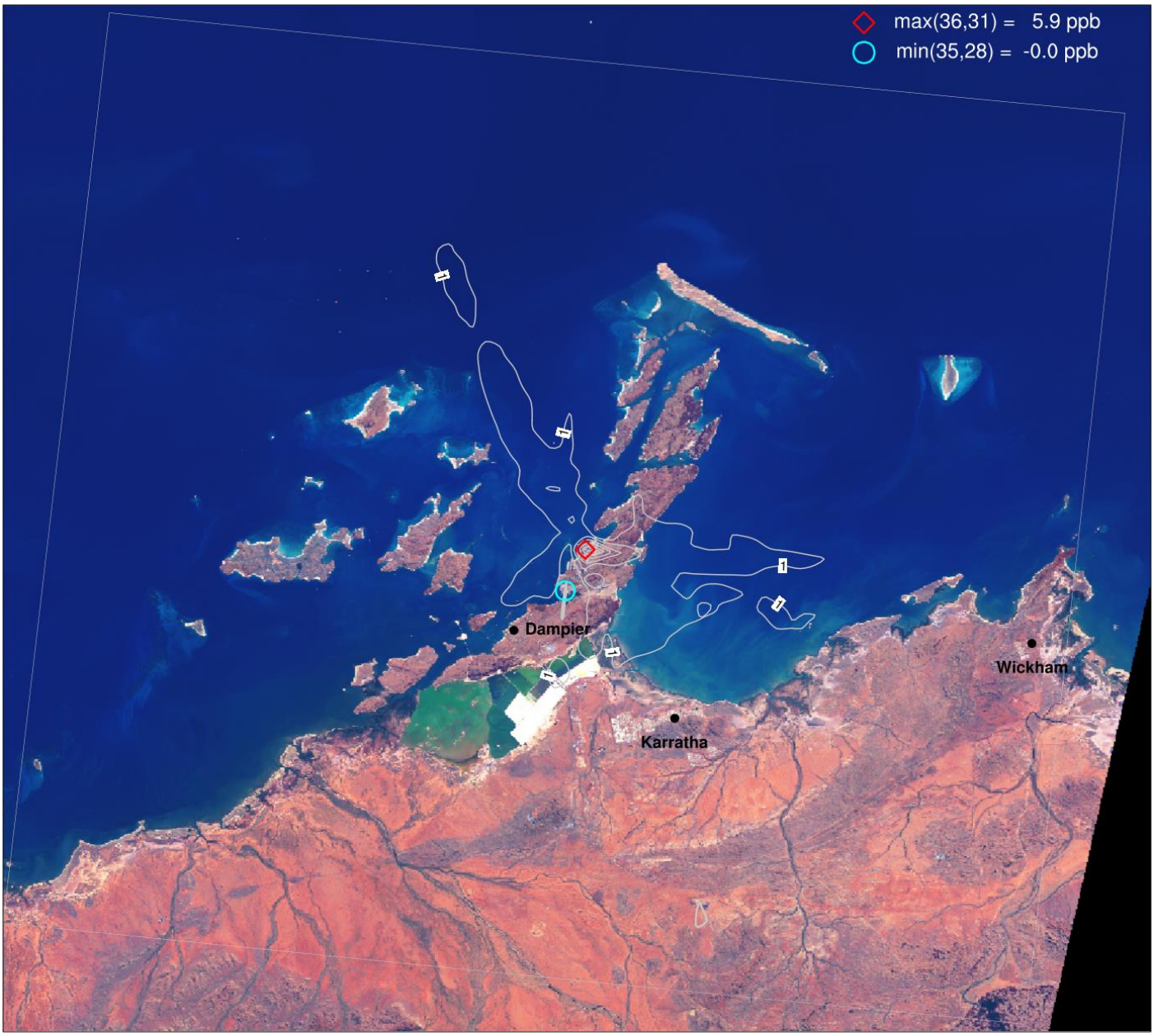

Figure A2-52. XYL (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

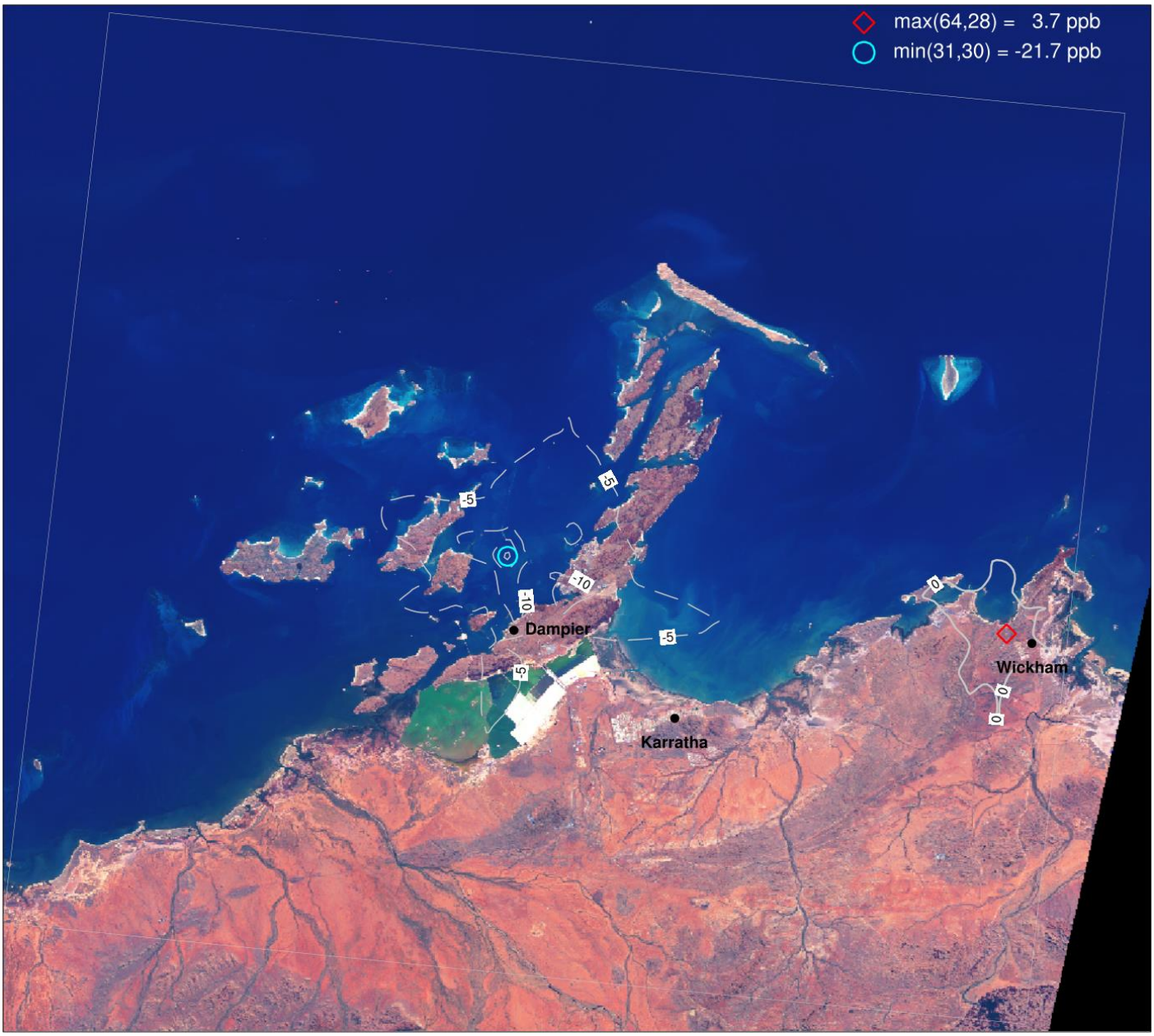

Figure A2-53. SO_2 (ppb) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

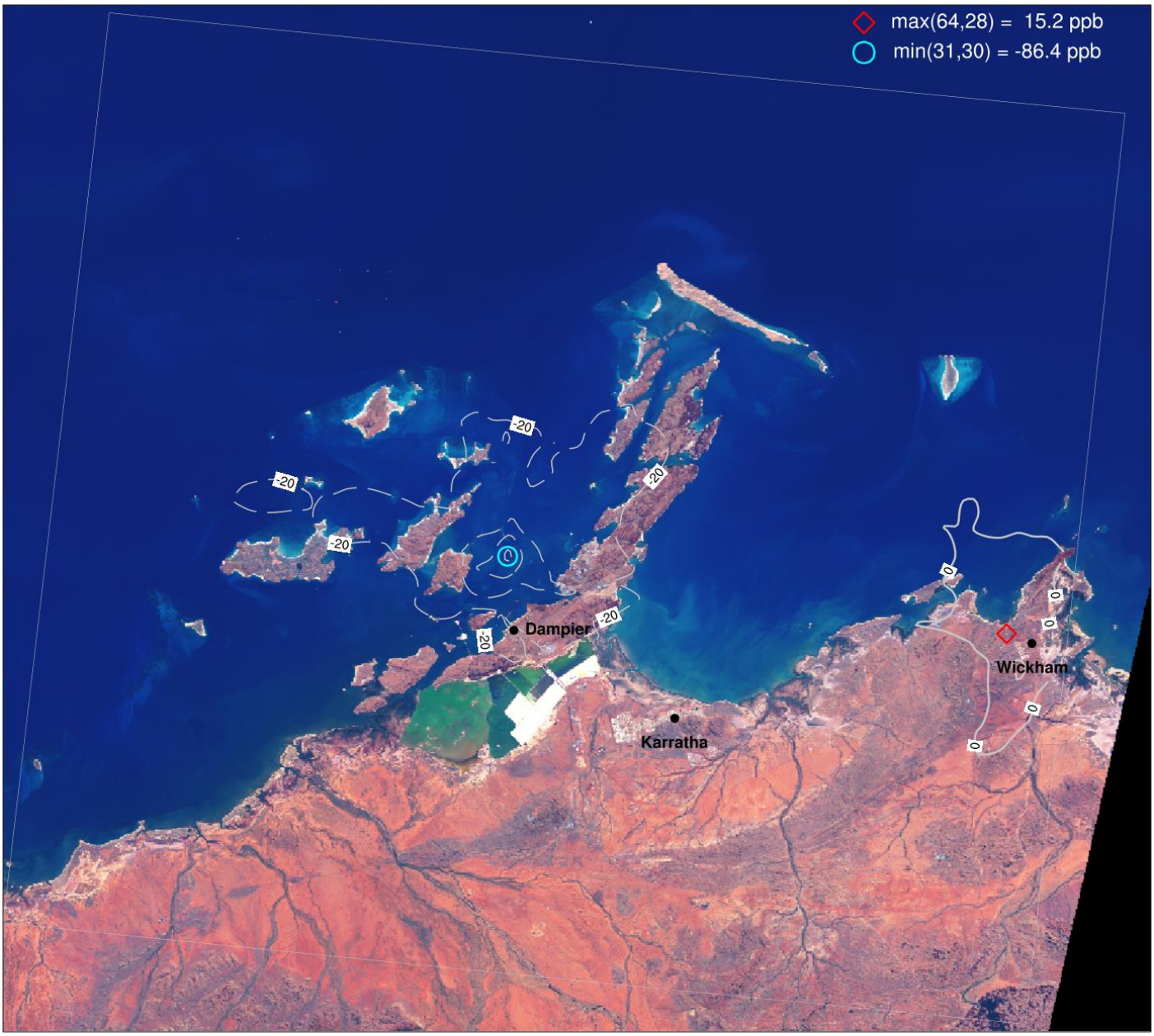

Figure A2-54. SO_2 (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

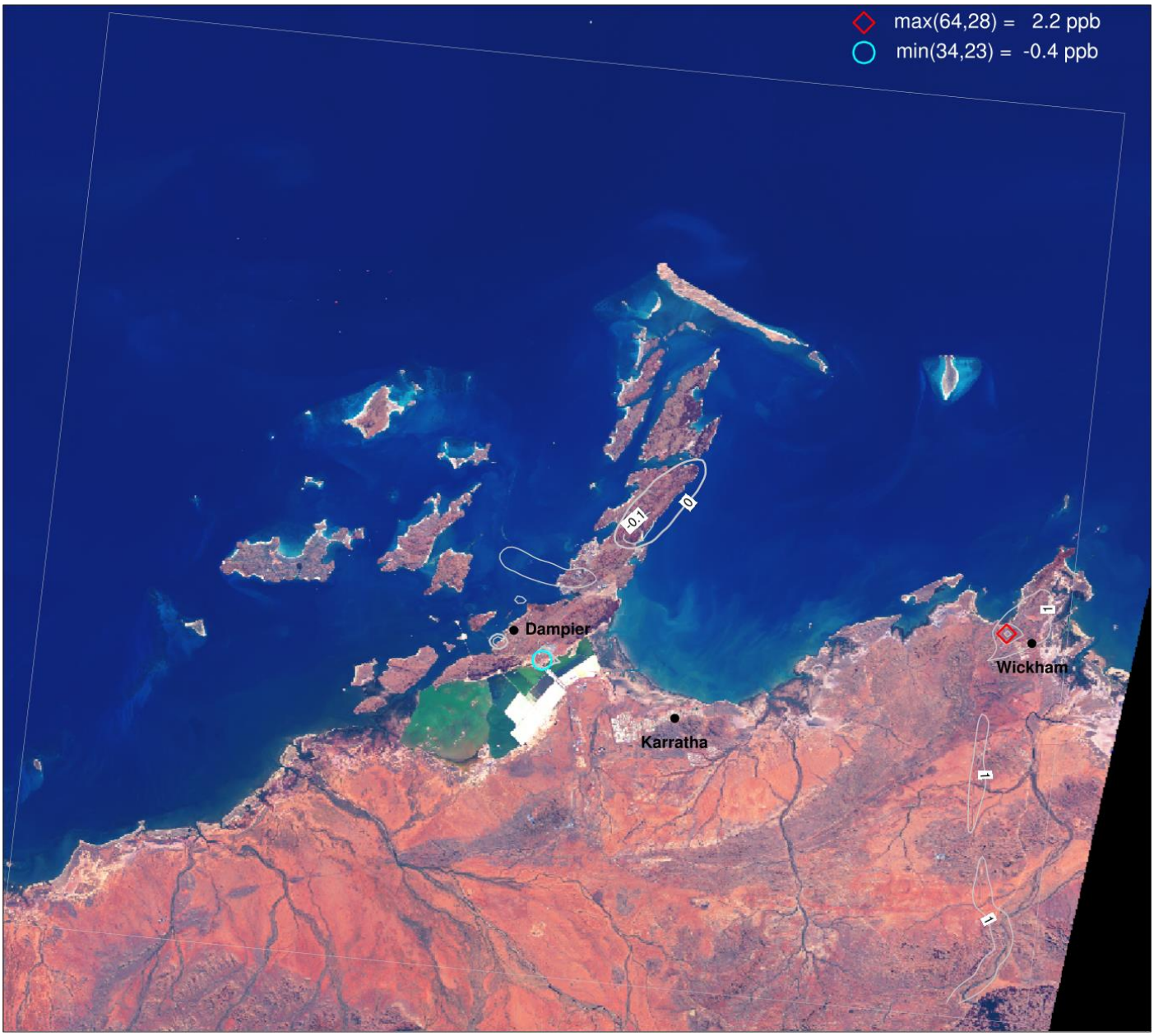

Figure A2-55. NO_2 (ppb) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

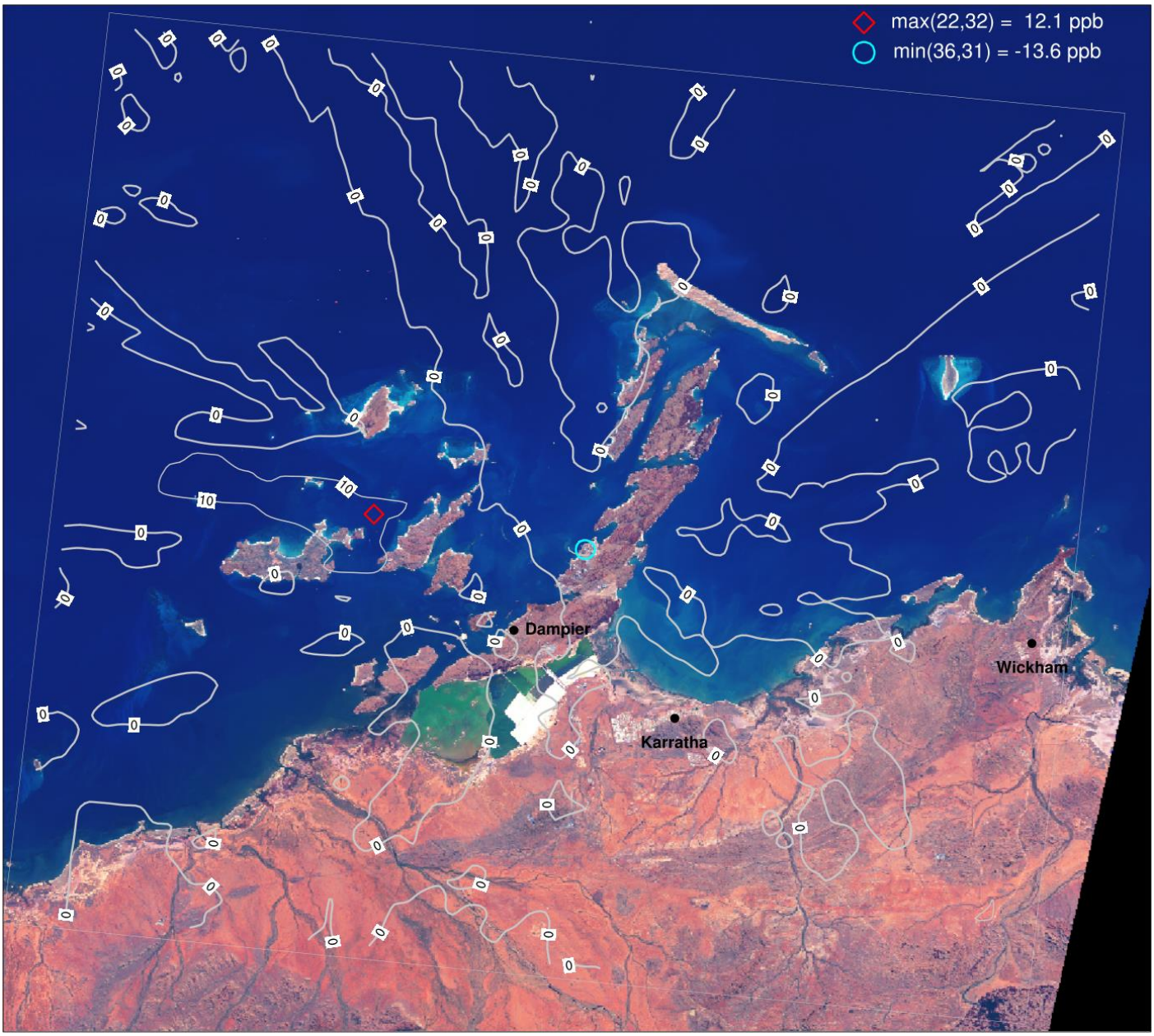

Figure A2-56. NO_2 (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

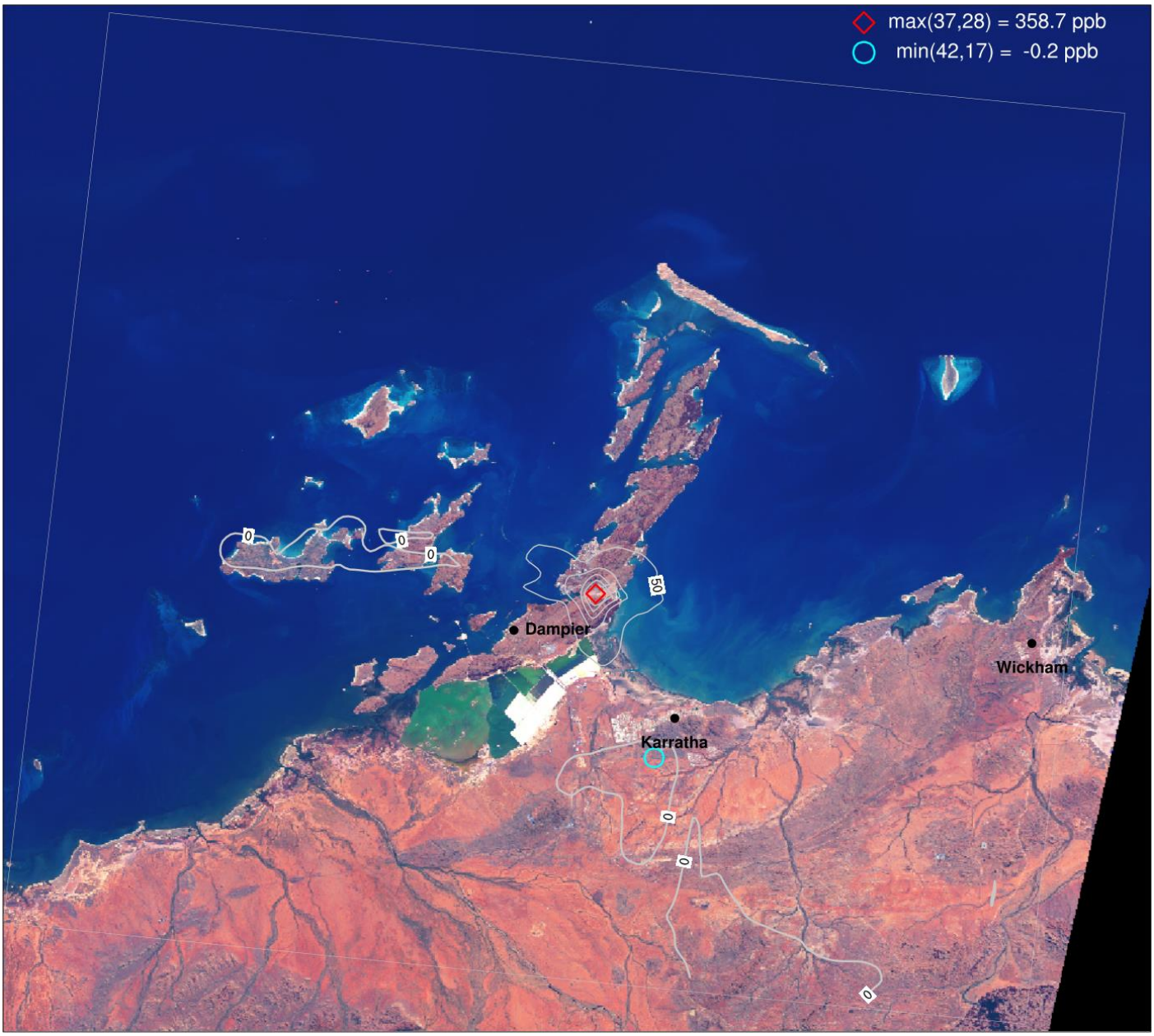

Figure A2-57. CO (ppb) change in annual max 8-hour (MDA8) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

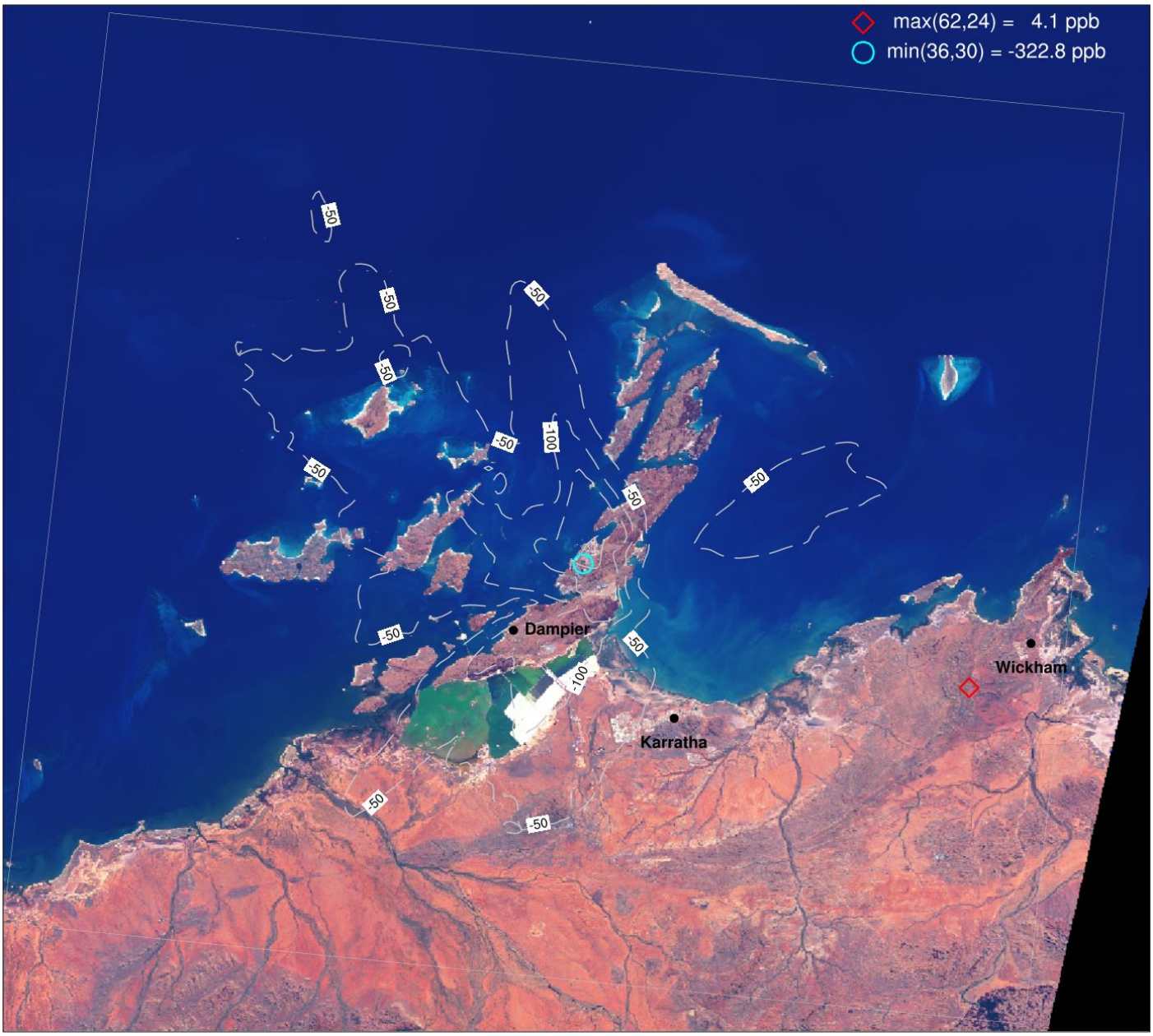

Figure A2-58. NH_3 (ppb) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

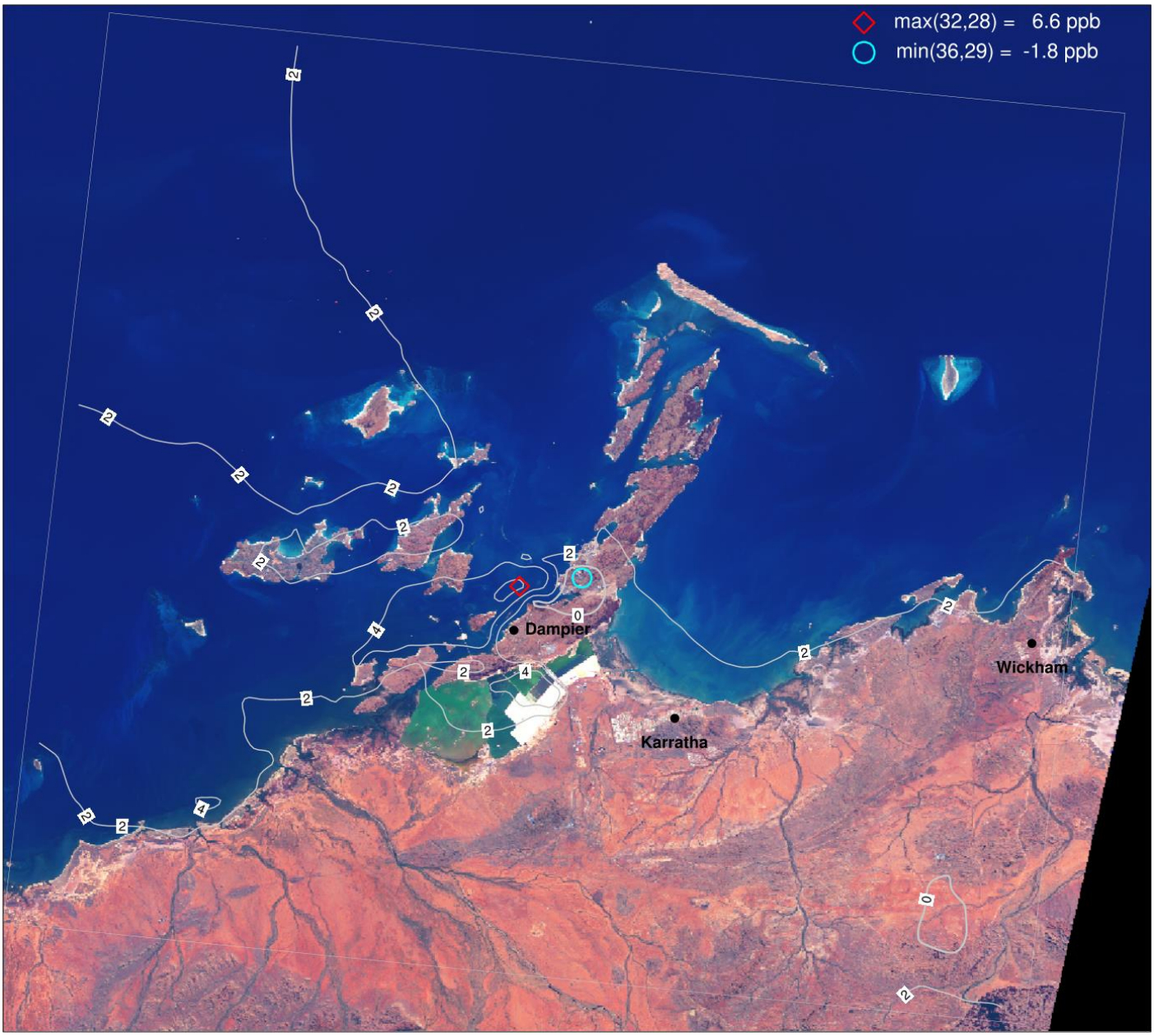

Figure A2-59. Ozone (ppb) change in annual max 8-hour (MDA8) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

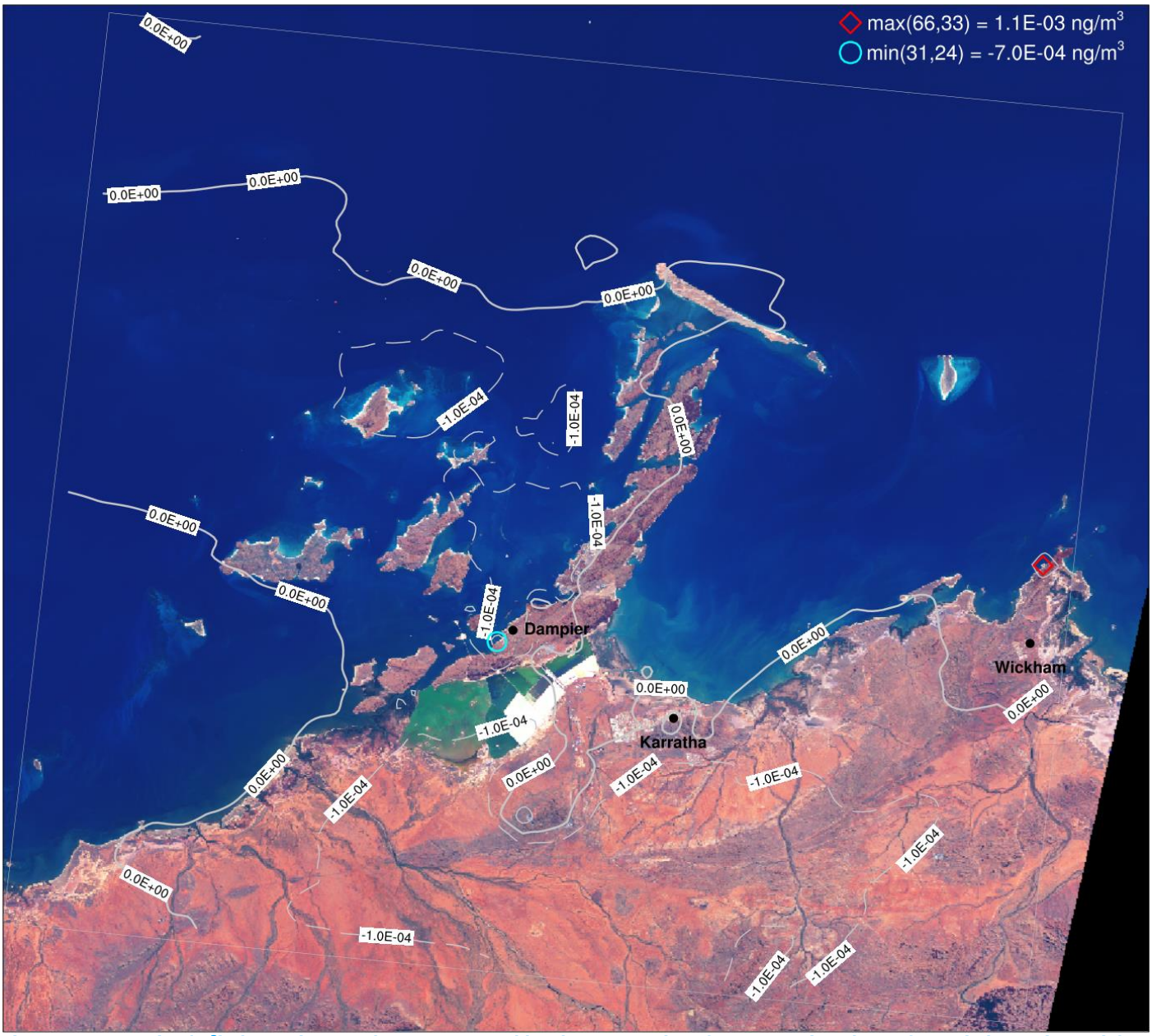

Figure A2-60. Hg (ng/m³) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

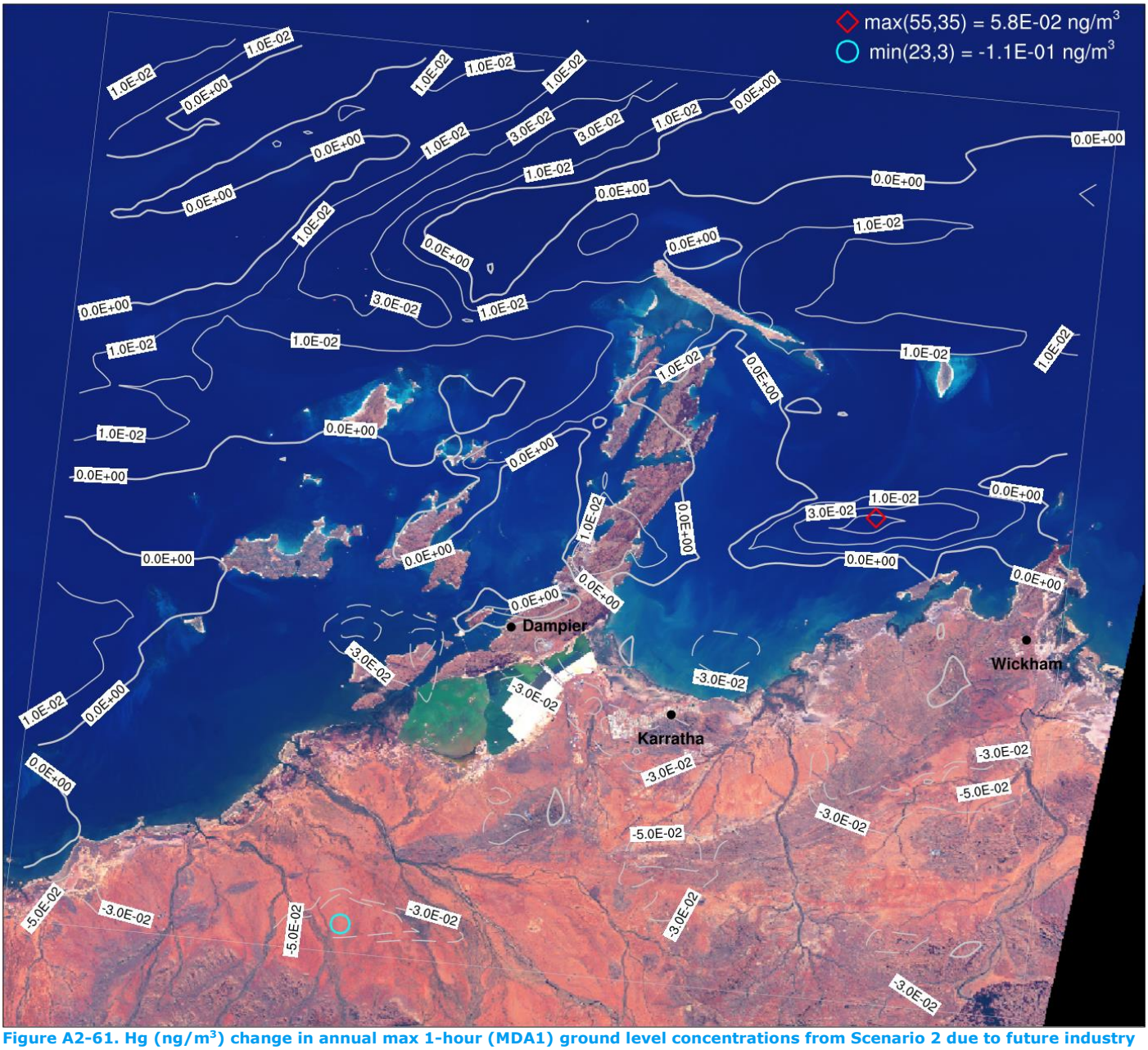

Figure A2-61. Hg (ng/m³) change in annual max 1-hour (MDA1) ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

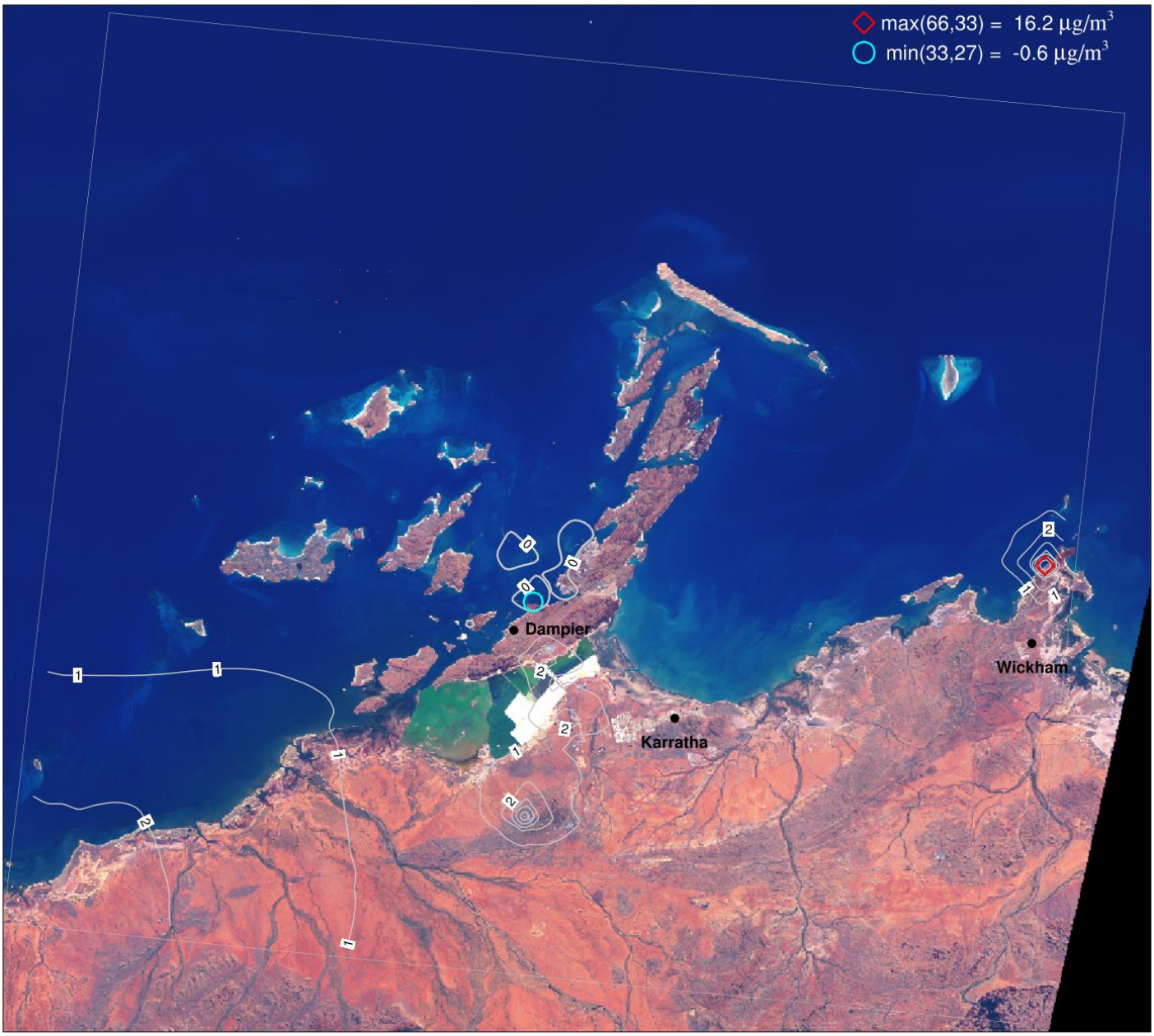

Figure A2-62. PM_{10} (µg/m³) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

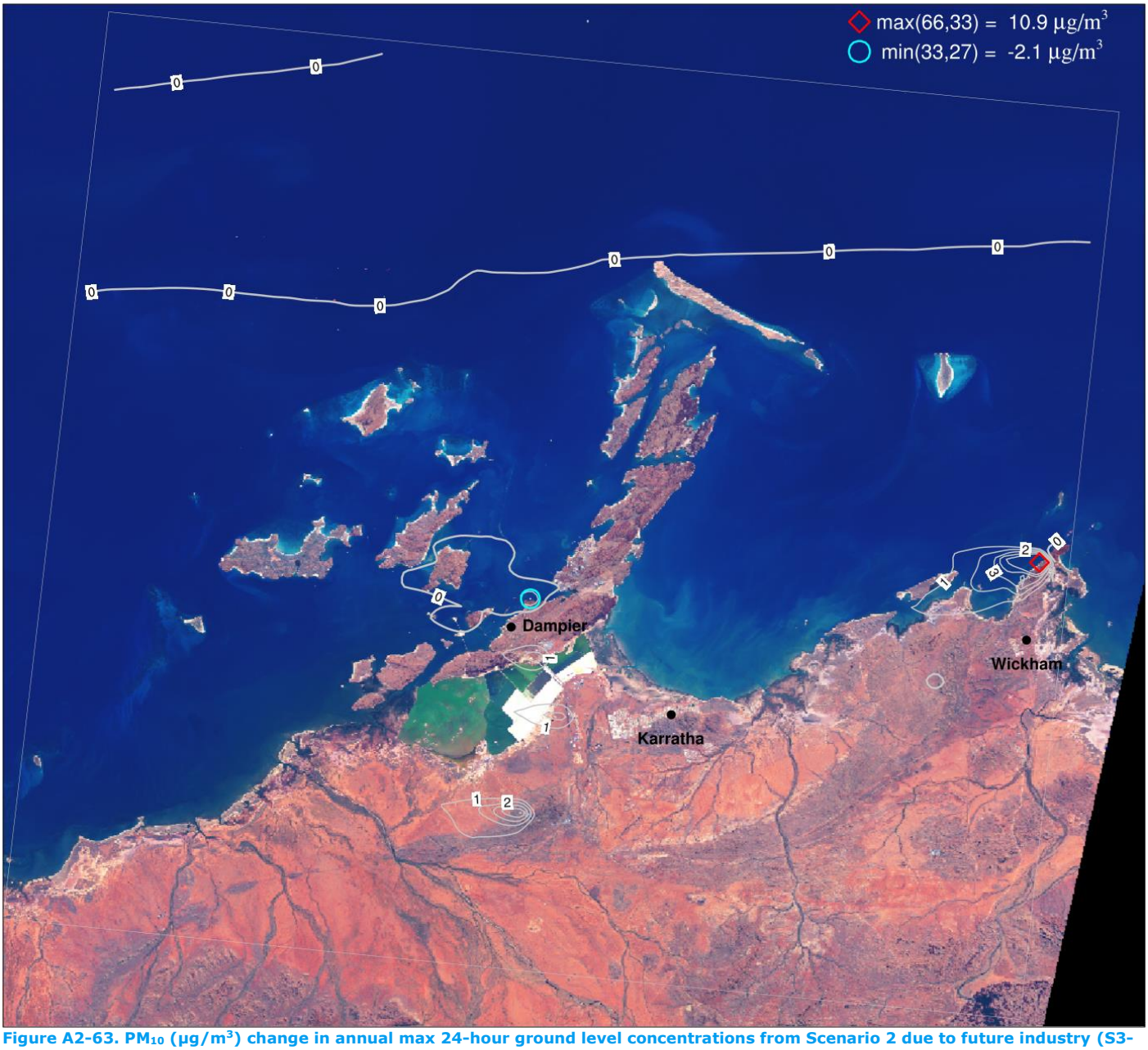

Figure A2-63. PM_{10} (µg/m³) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

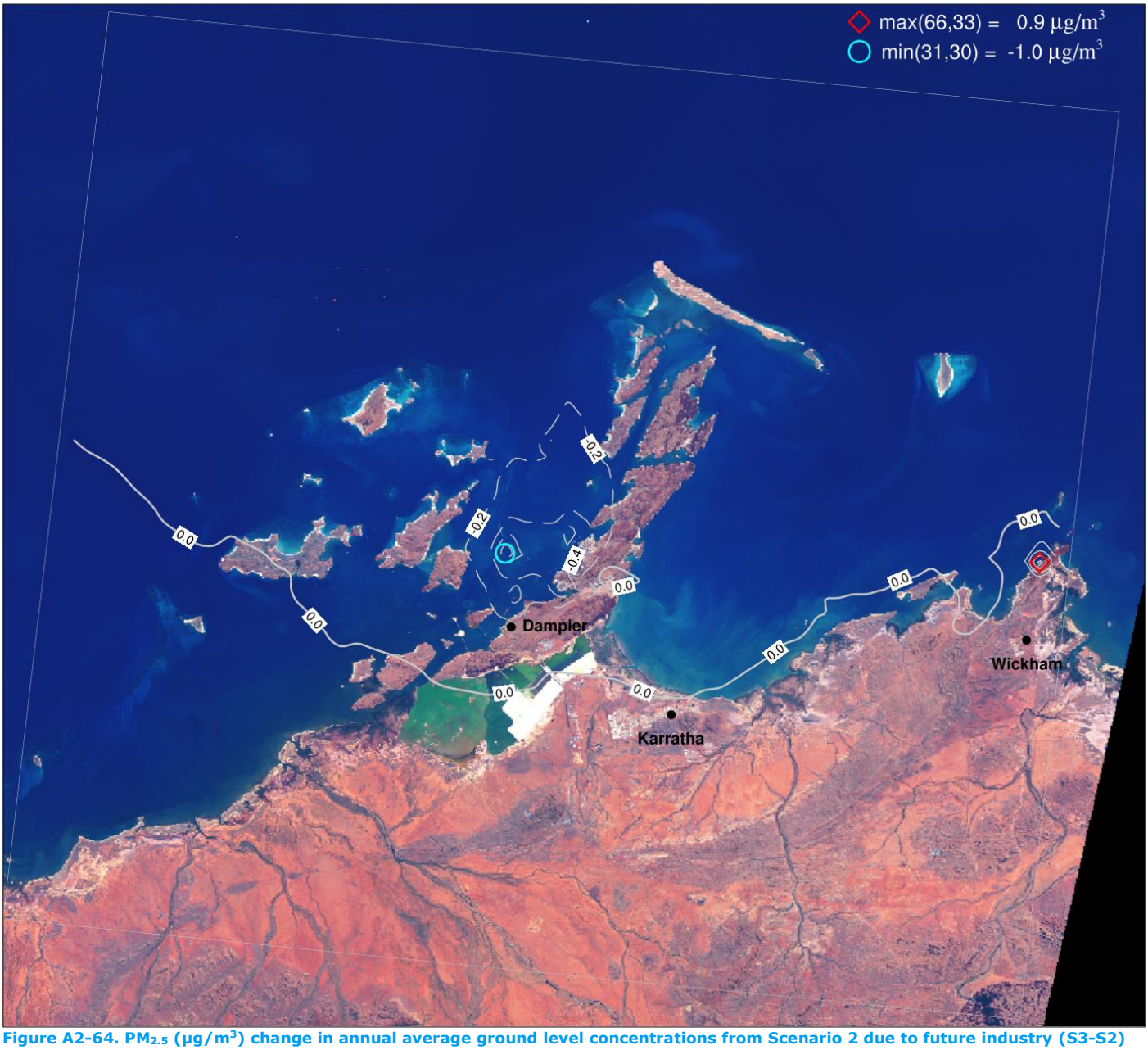

Figure A2-64. $PM_{2.5}$ (µg/m^3) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

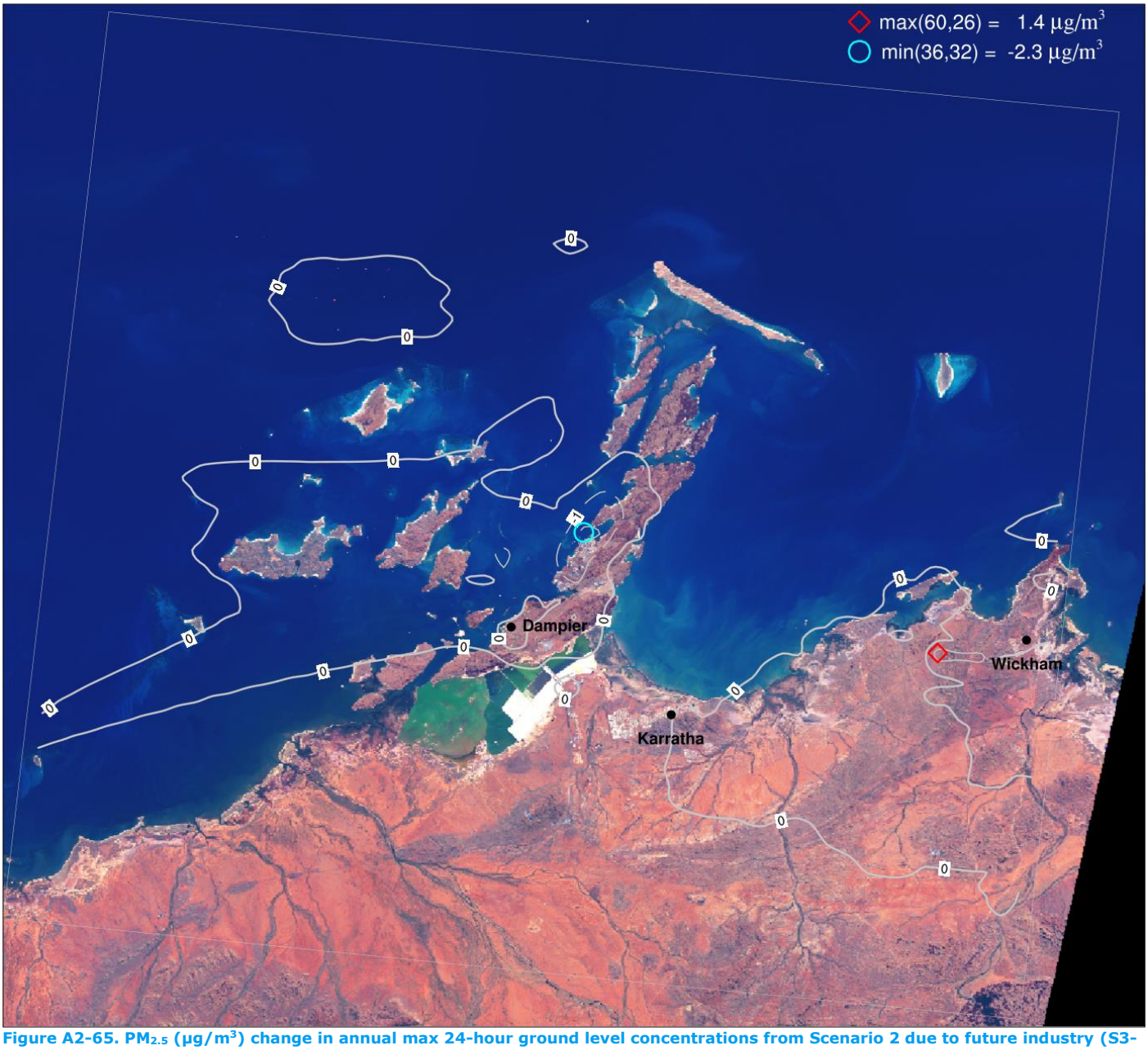

Figure A2-65. $PM_{2.5}$ (µg/m^3) change in annual max 24-hour ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

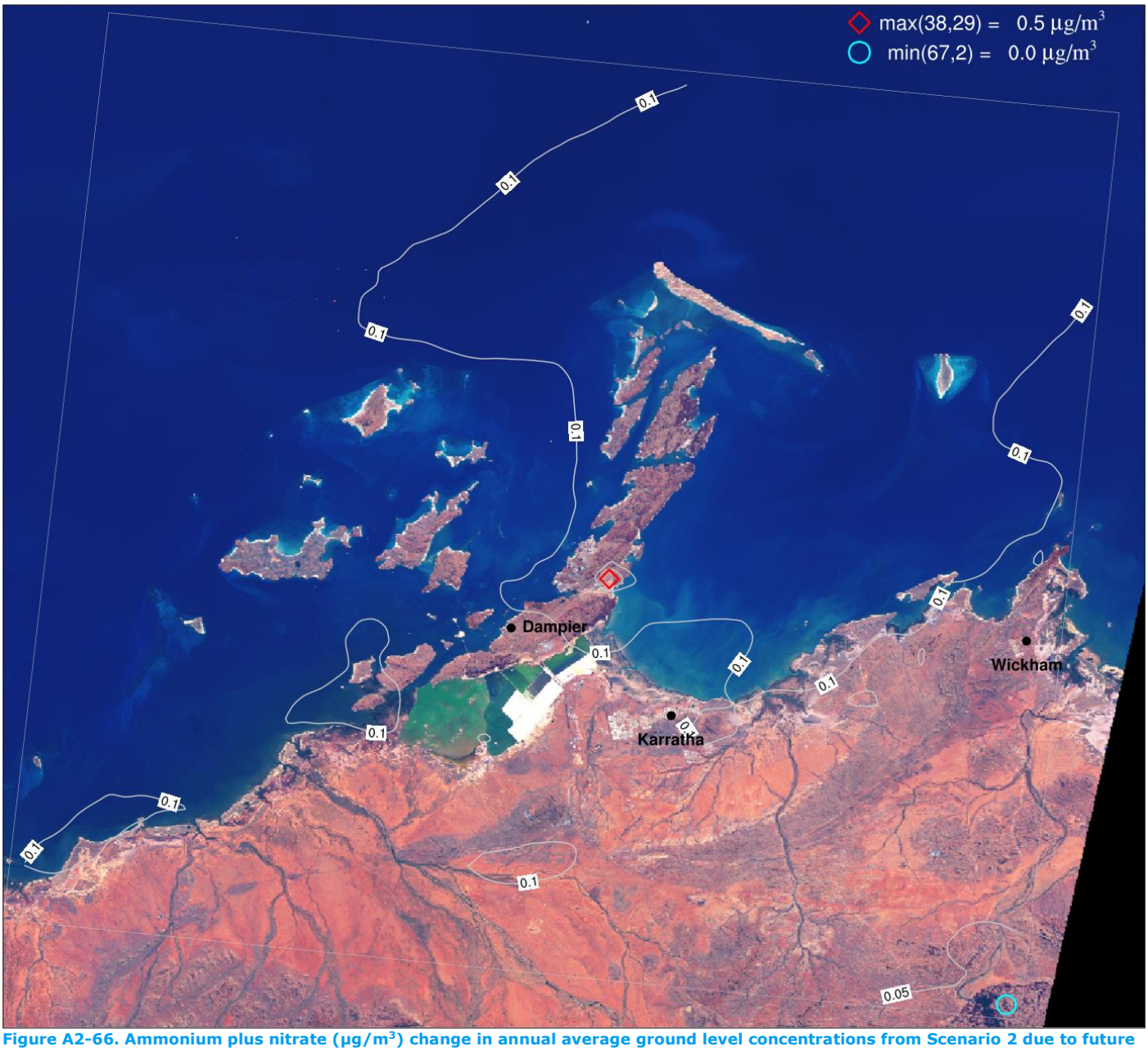

Figure A2-66. Ammonium plus nitrate (µg/m³) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

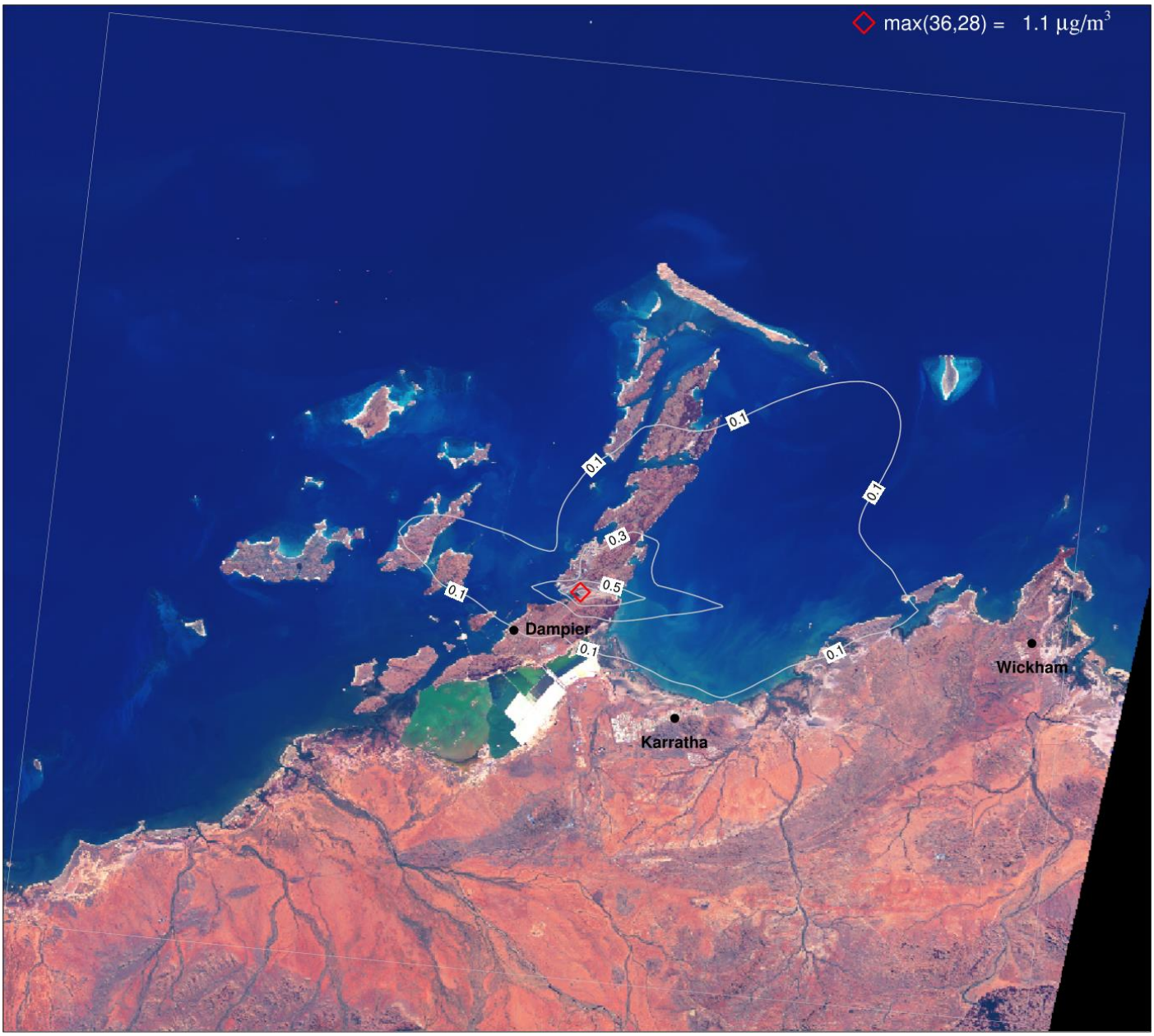

Figure A2-67. Urea fine dust (µg/m^3) change in annual average ground level concentrations from Scenario 2 due to future industry (S3-S2) for the CAMx 1.33 km domain.

APPENDIX 3

ANNUAL DEPOSITION PLOTS FOR CAMX 1.33 KM DOMAIN

Scenario 2 Deposition

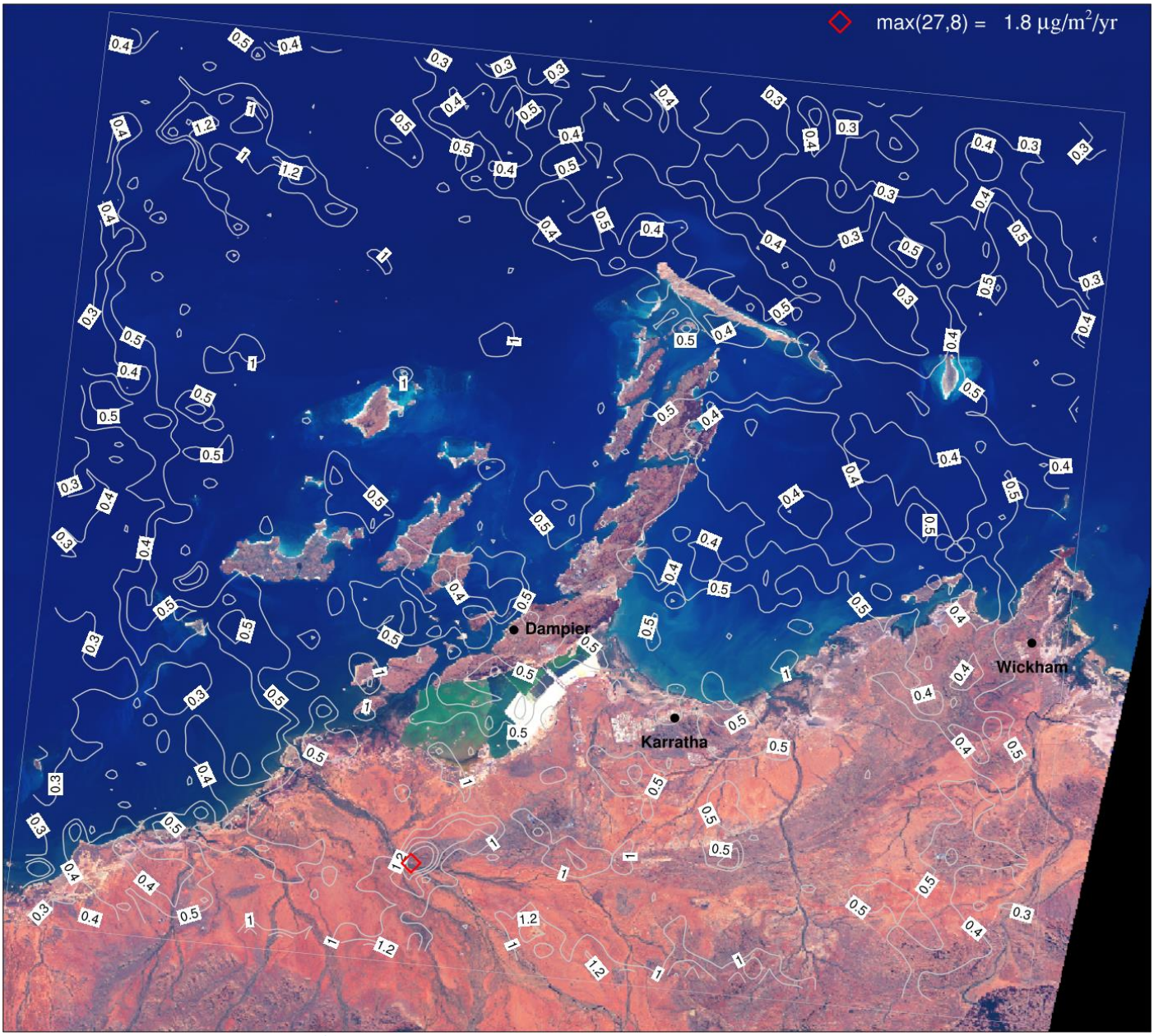

Figure A3-77. Annual total Hg (µg/m²/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

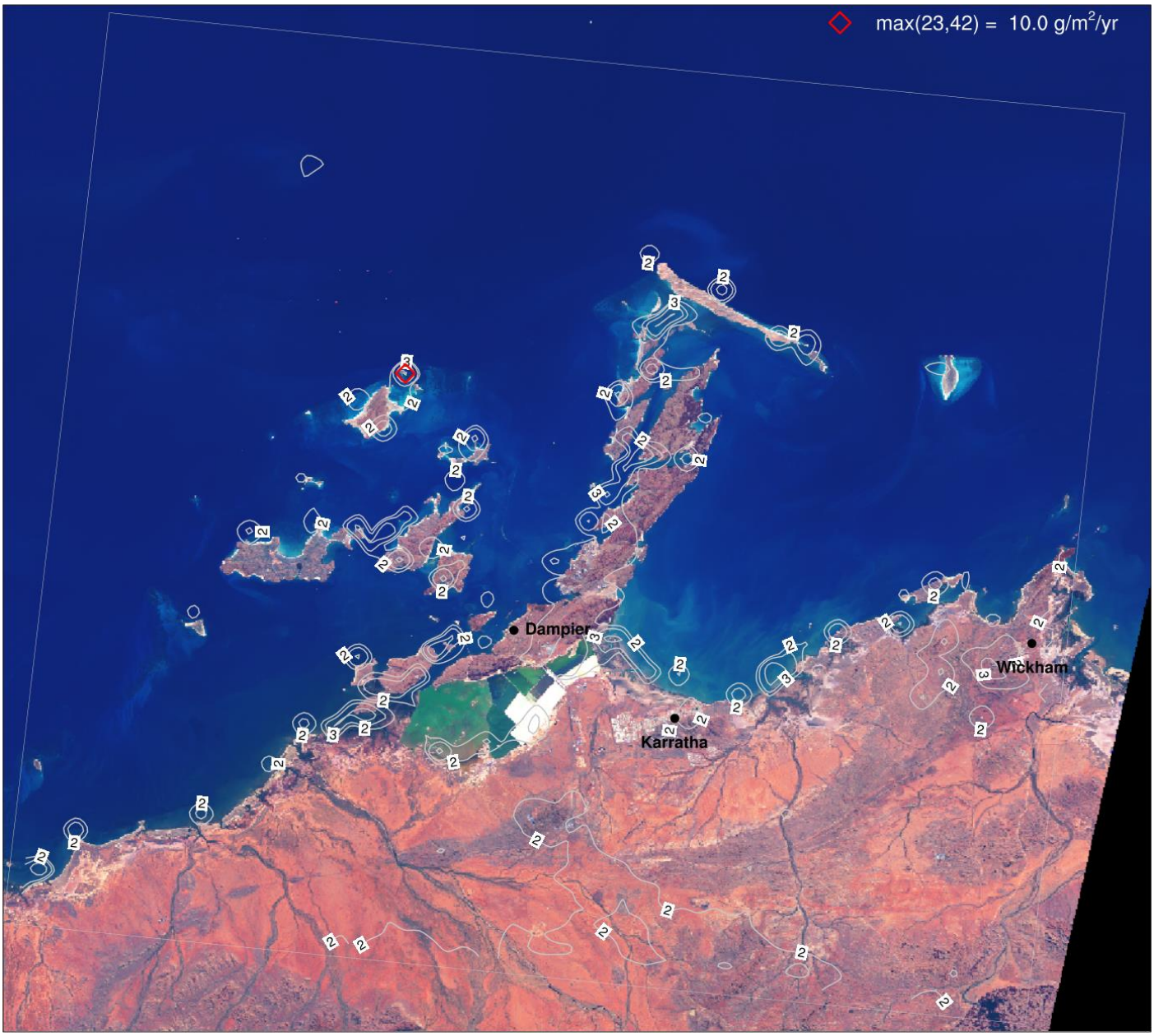

Figure A3-78. Annual total dust (g/m^2/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

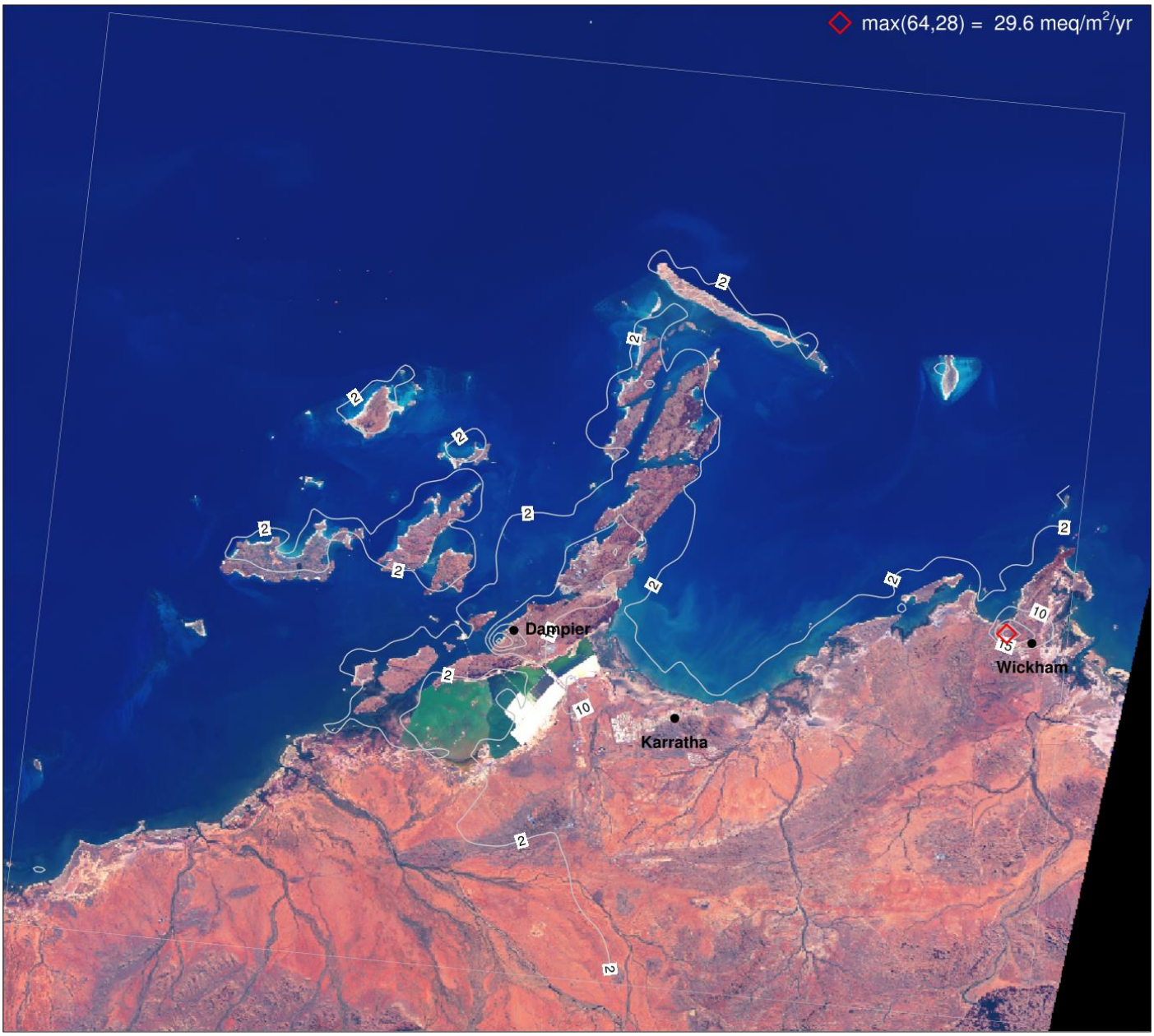

Figure A3-79. Annual total NO_2 (meq/m^2/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

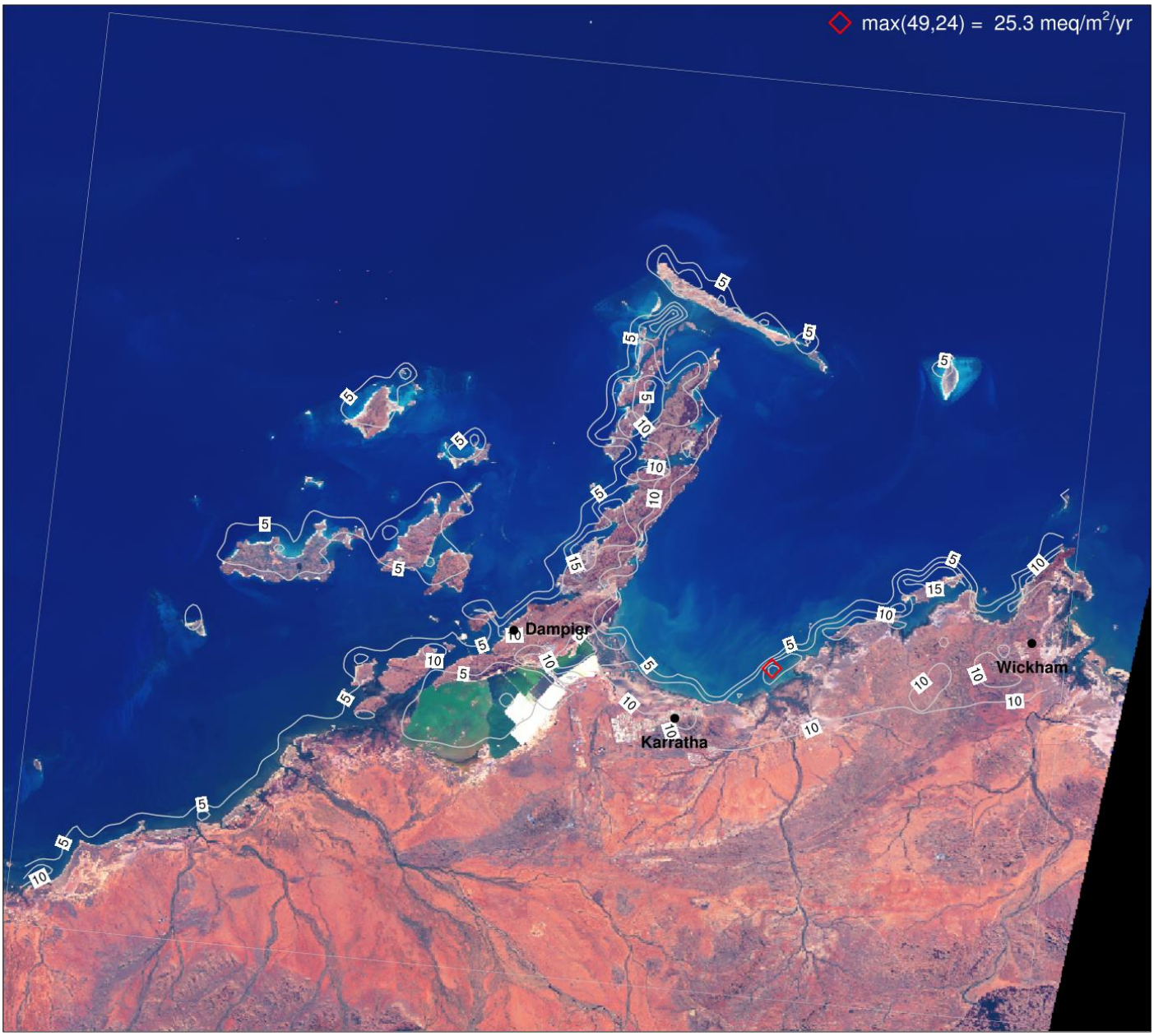

Figure A3-80. Annual total HNO_3 (nitric acid; units: meq/m^2/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

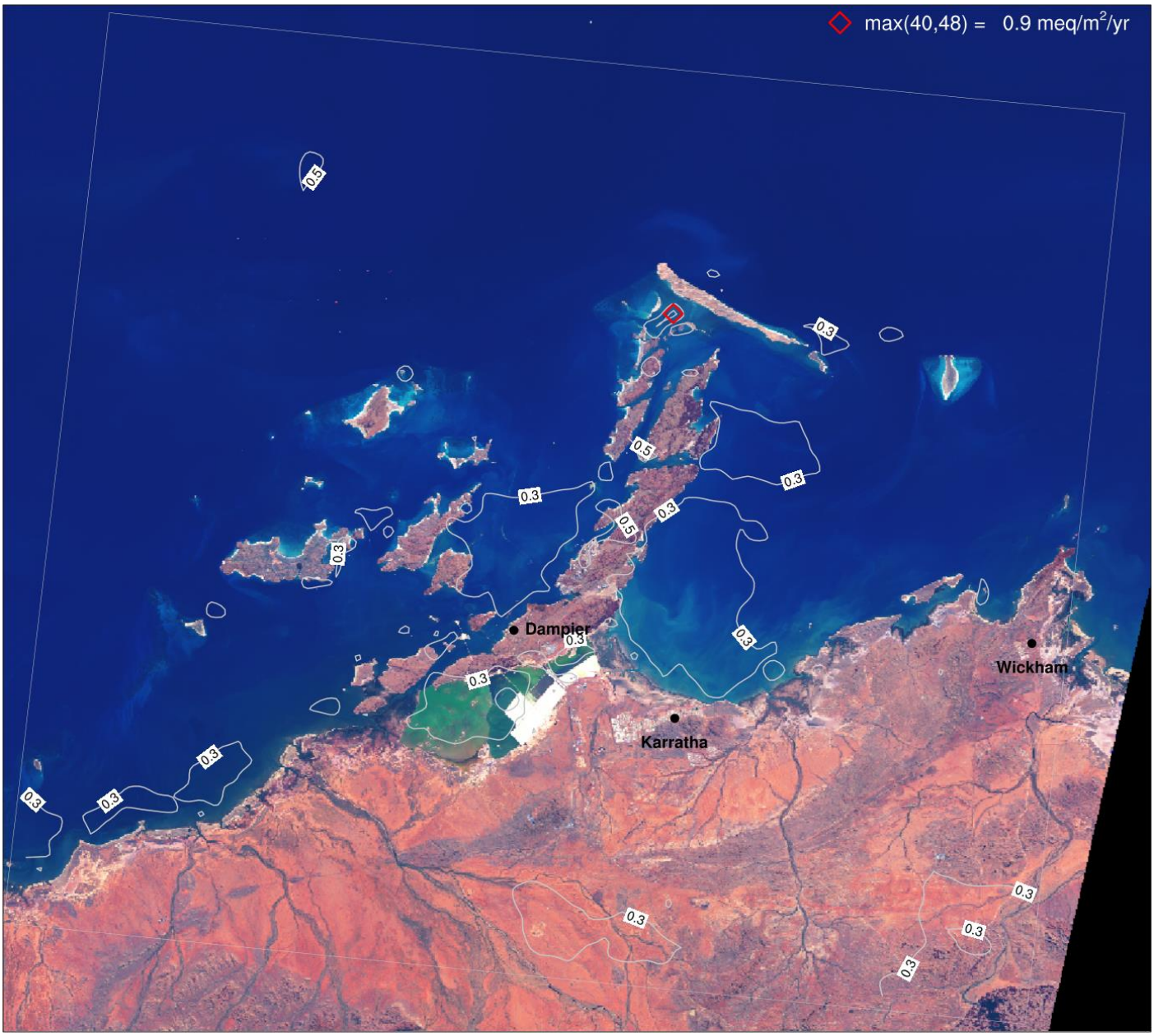

Figure A3-81. Annual total PNO_3 (nitrate; units: meq/m²/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

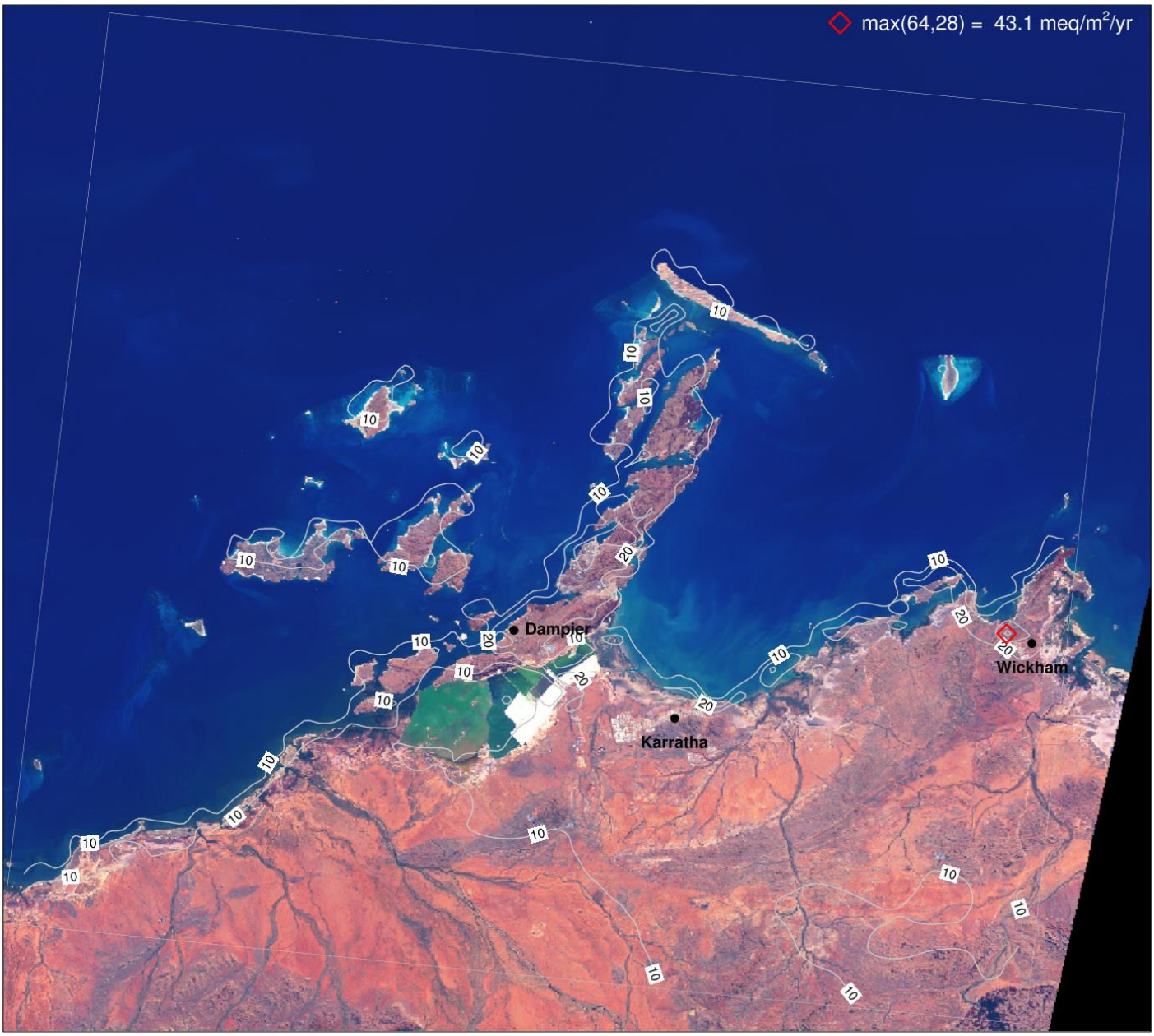

Figure A3-82. Annual total N (nitrogen; units: meq/m^2/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

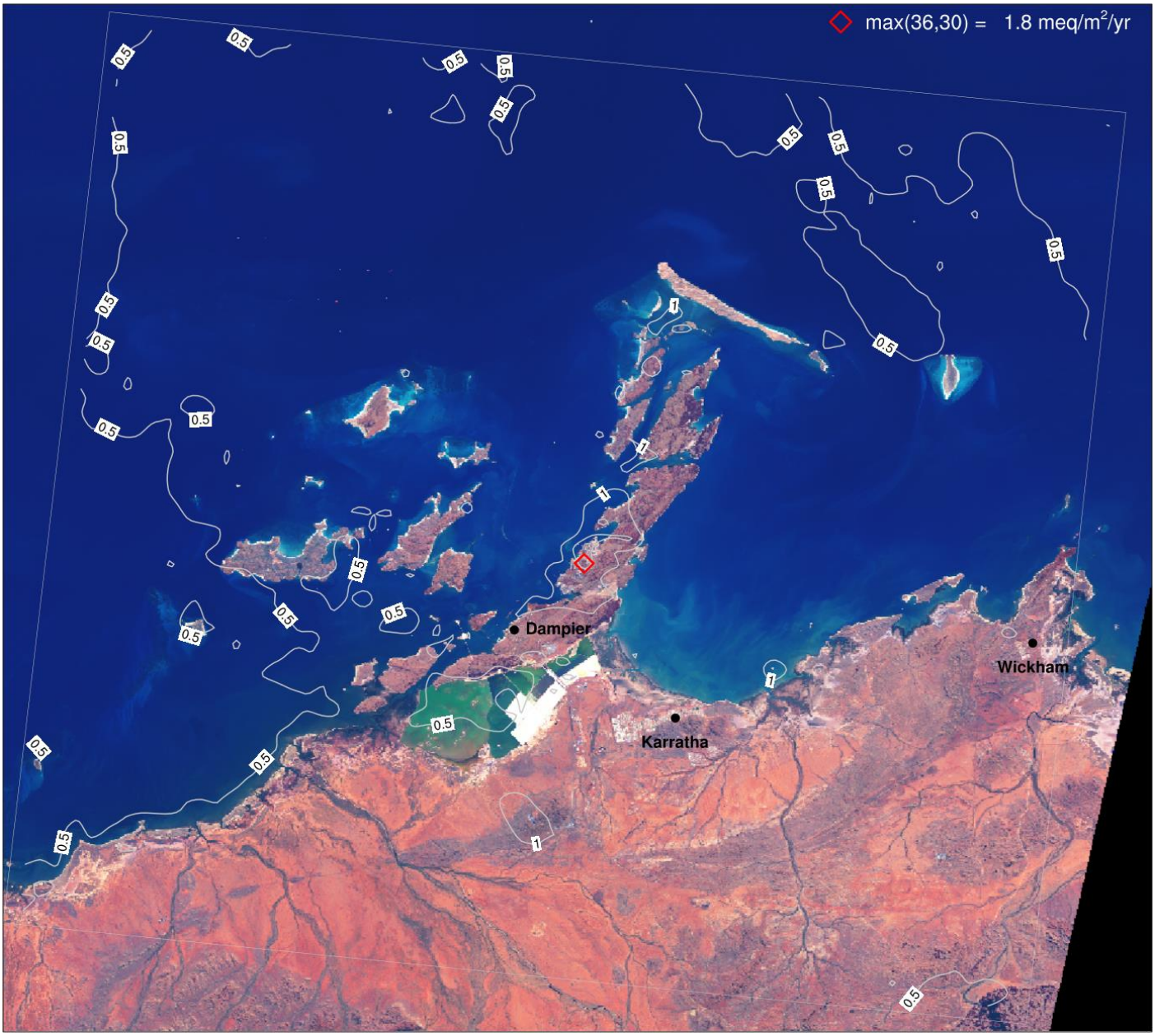

Figure A3-83. Annual total PSO_4 (sulphate; units: meq/m^2/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

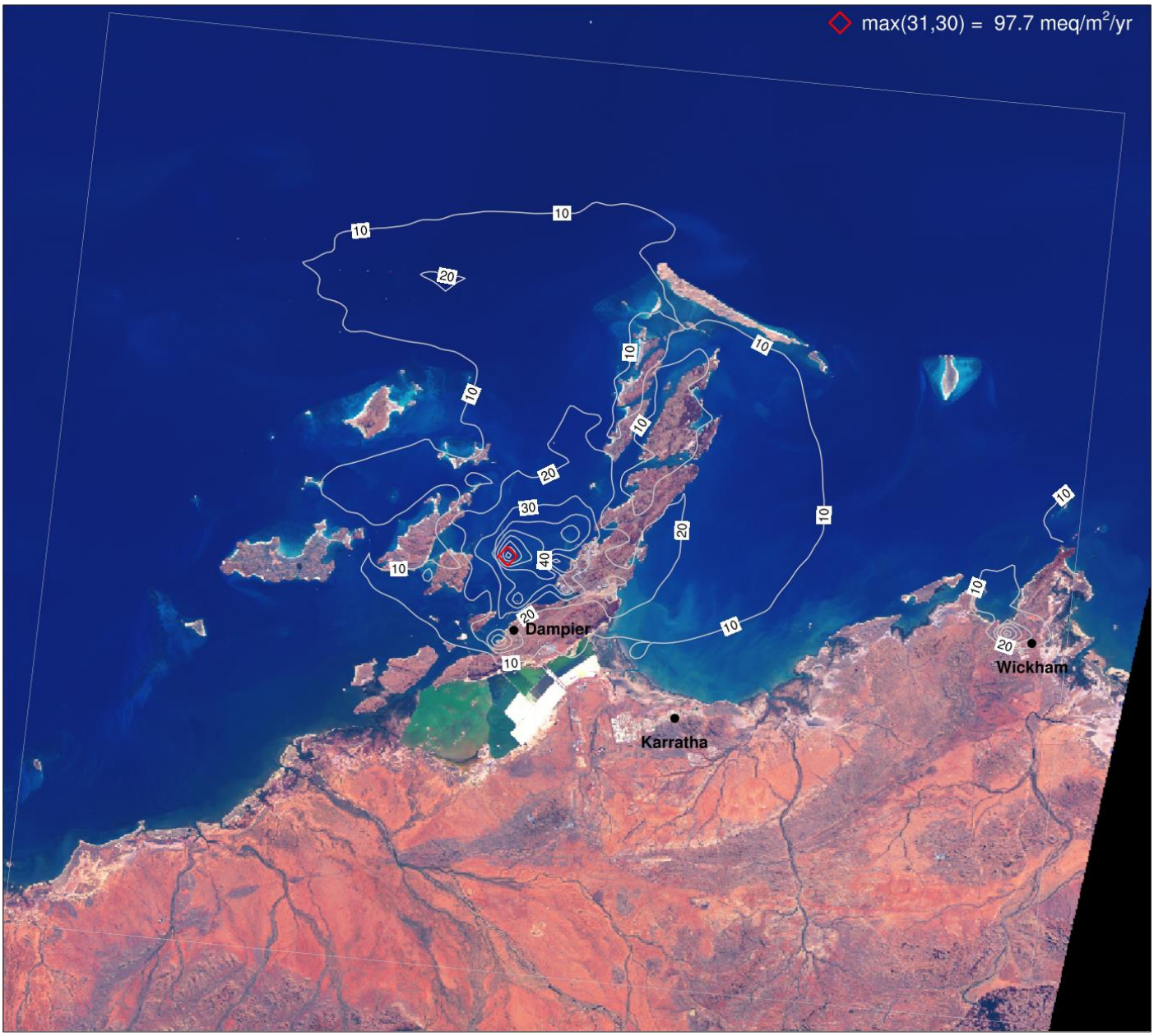

Figure A3-84. Annual total SO_2 (meq/m^2/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

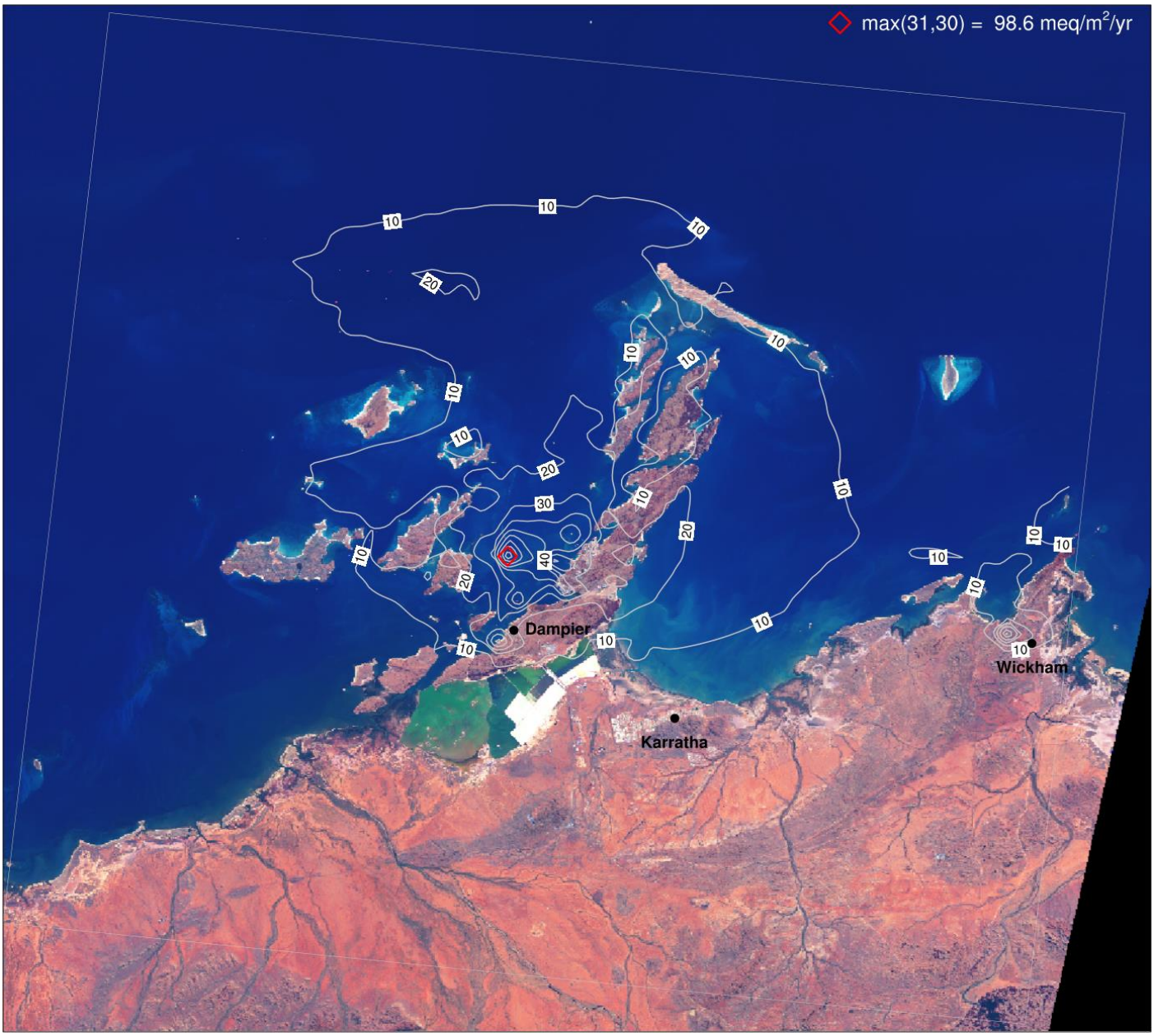

Figure A3-85. Annual total S (sulphur; units: meq/m^2/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

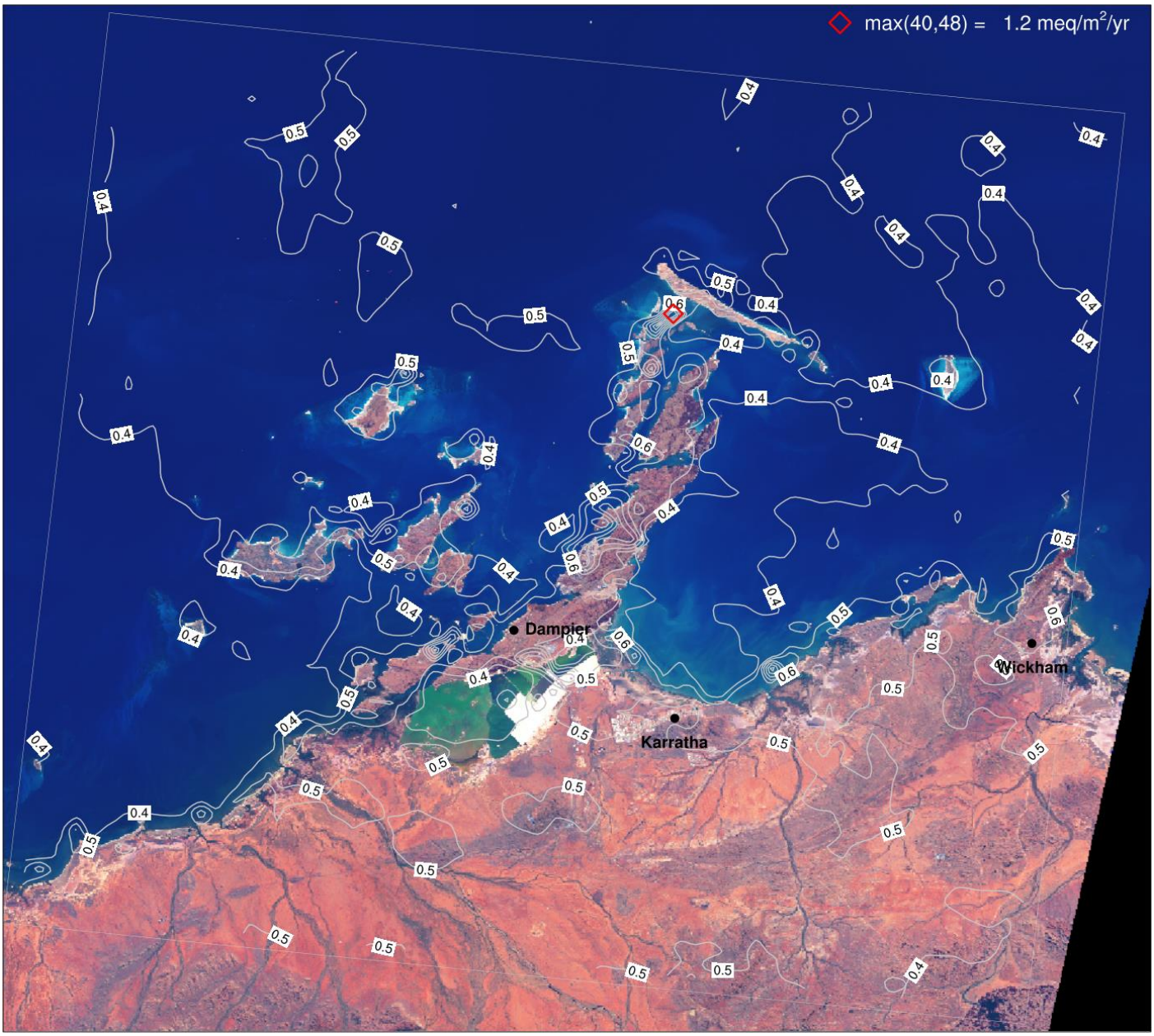

Figure A3-86. Annual total ammonium plus nitrate (meq/m²/yr) deposition for Scenario 2 (S2) for the CAMx 1.33 km domain.

Deposition from Industry

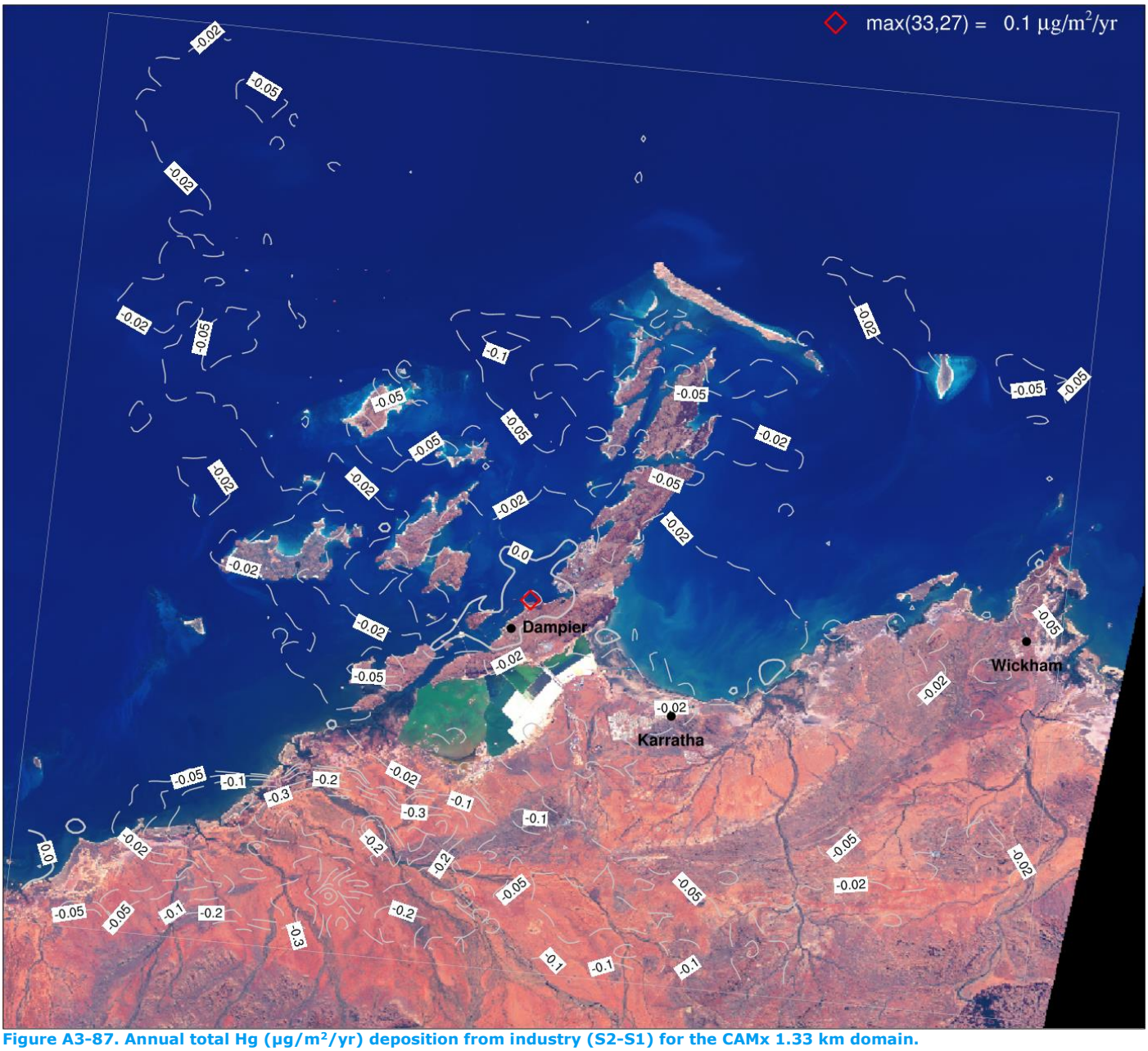

Figure A3-87. Annual total Hg (µg/m²/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

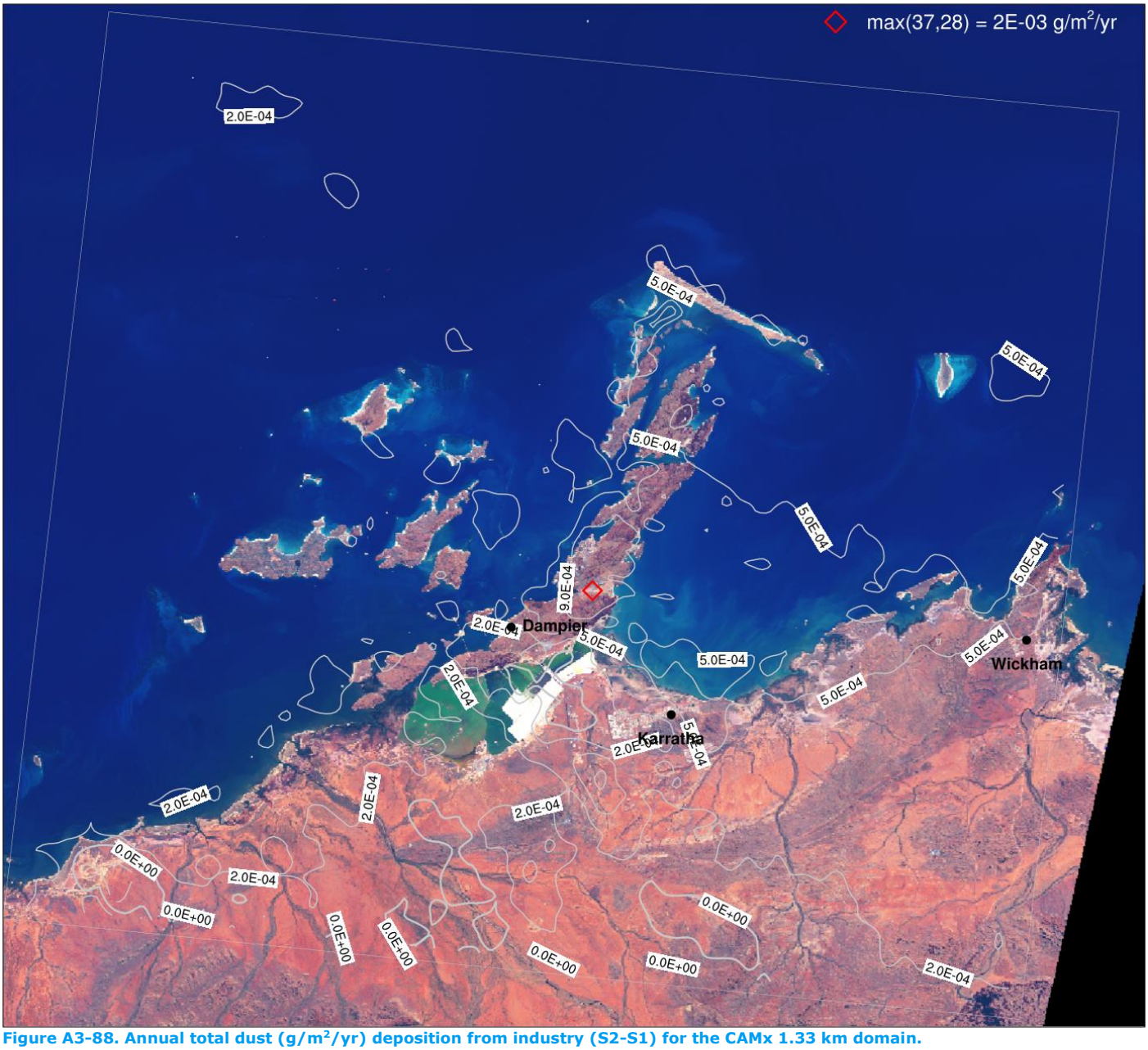

Figure A3-88. Annual total dust (g/m^2/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

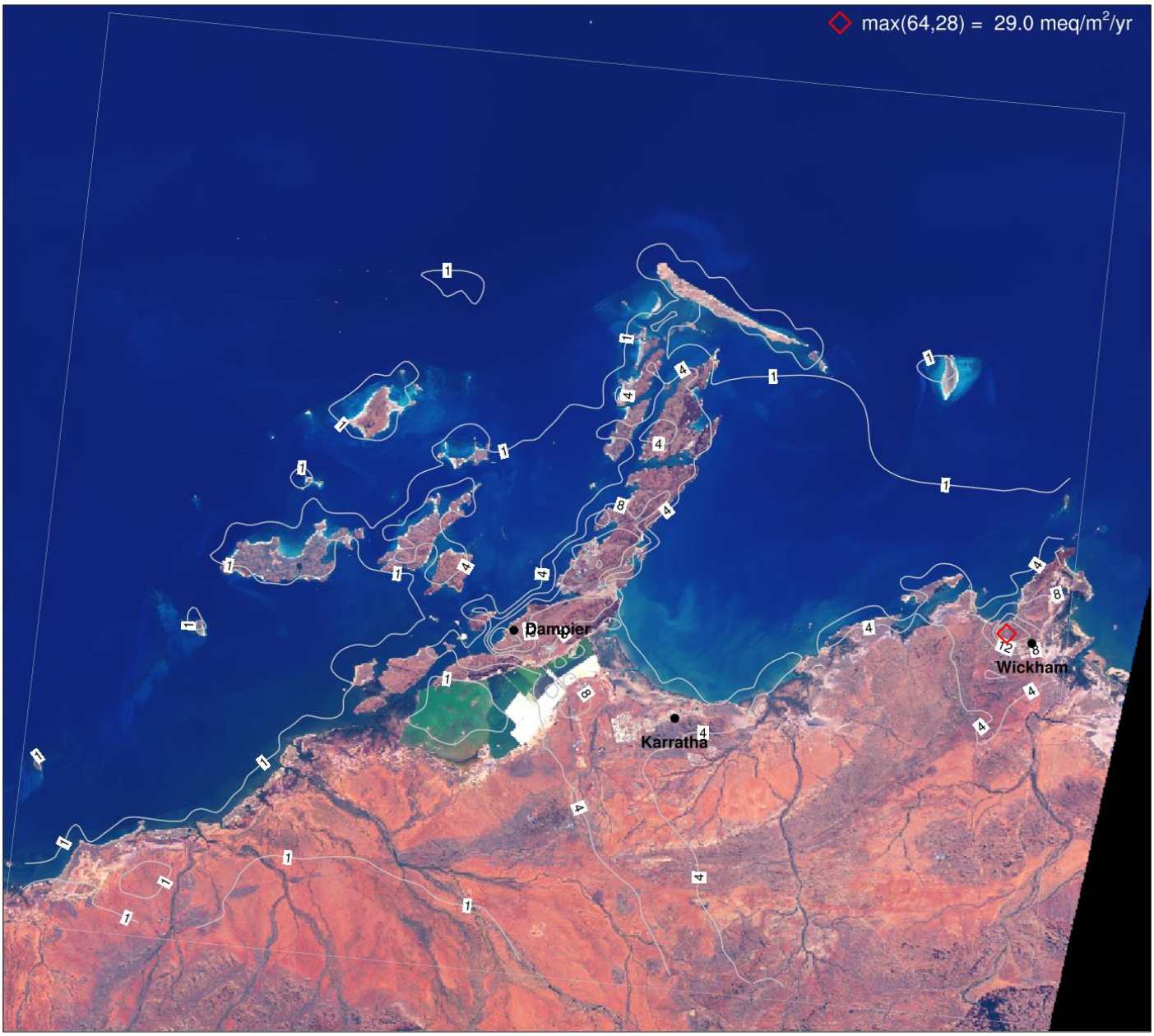

Figure A3-89. Annual total NO_2 (meq/m^2/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

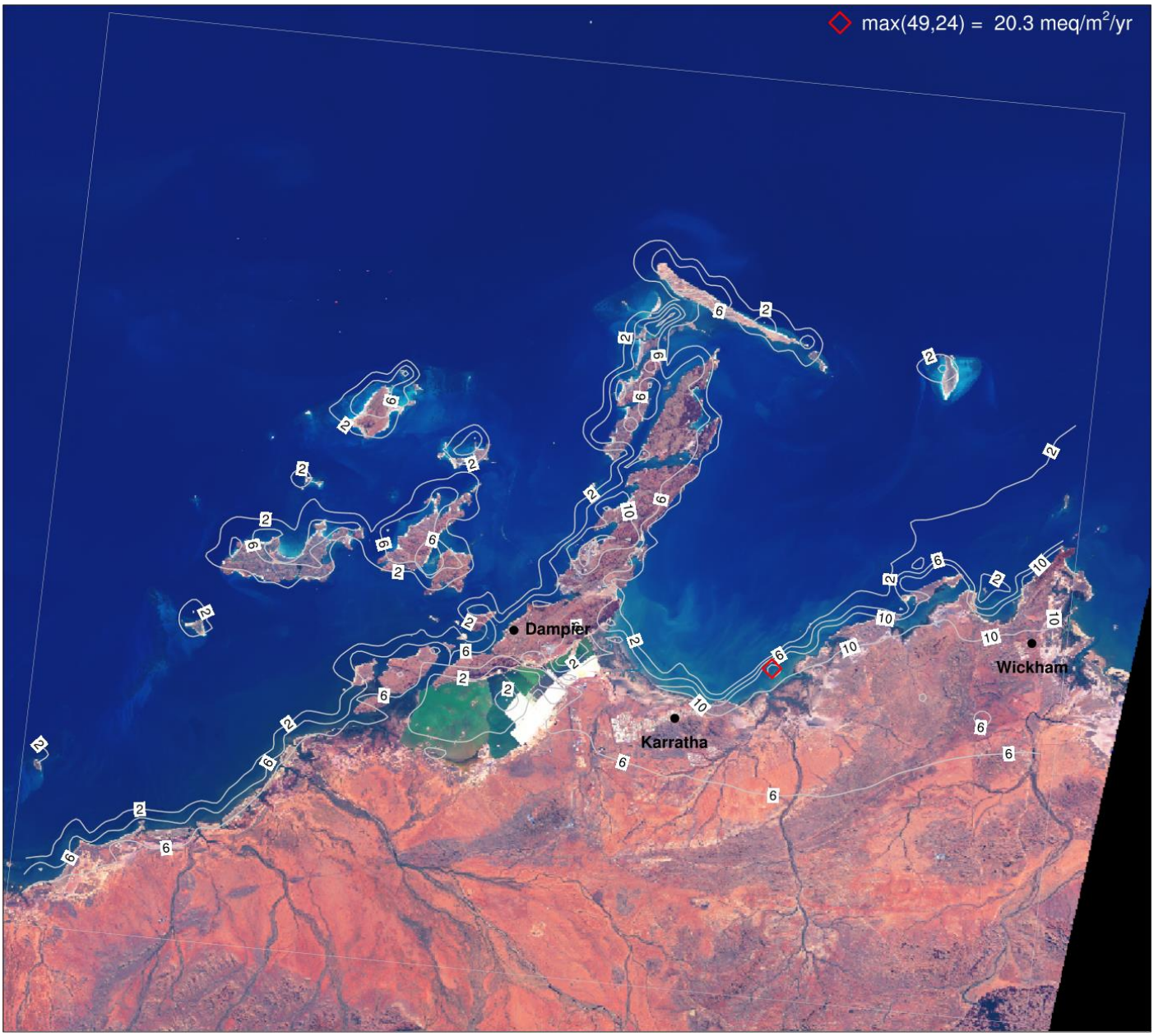

Figure A3-90. Annual total HNO_3 (nitric acid; units: meq/m^2/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

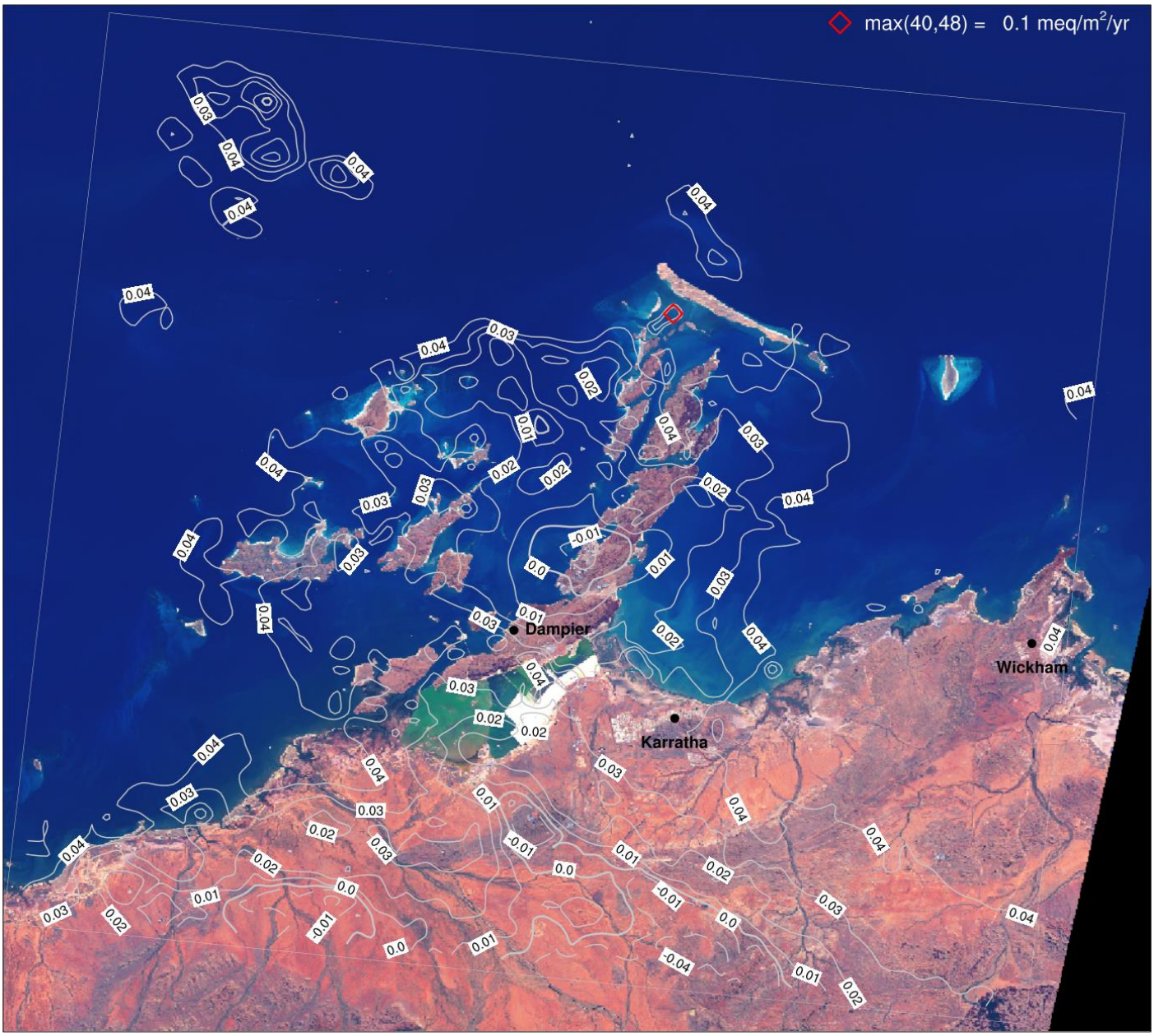

Figure A3-91. Annual total PNO_3 (nitrate; units: meq/m²/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

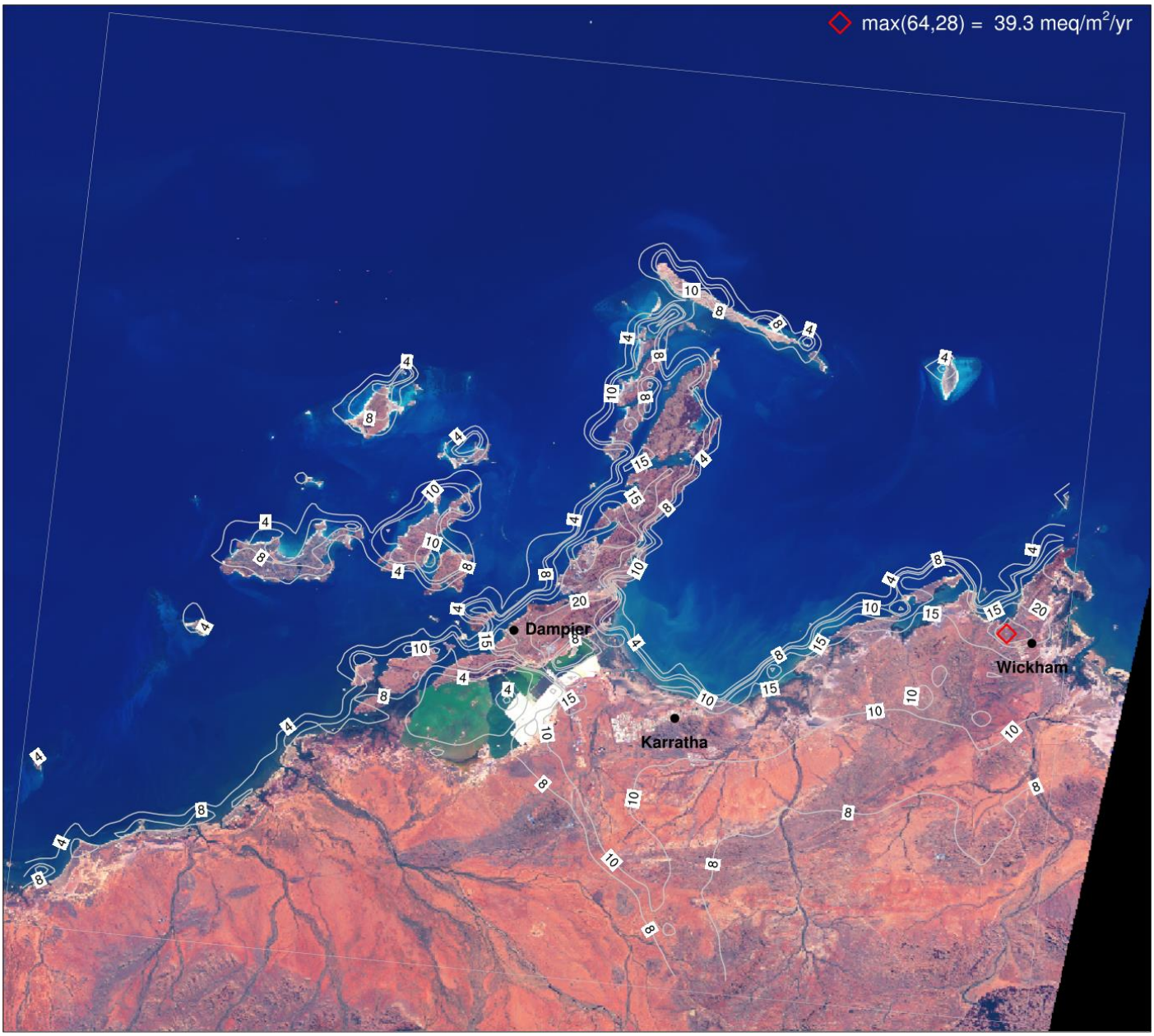

Figure A3-92. Annual total N (nitrogen; units: meq/m^2/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

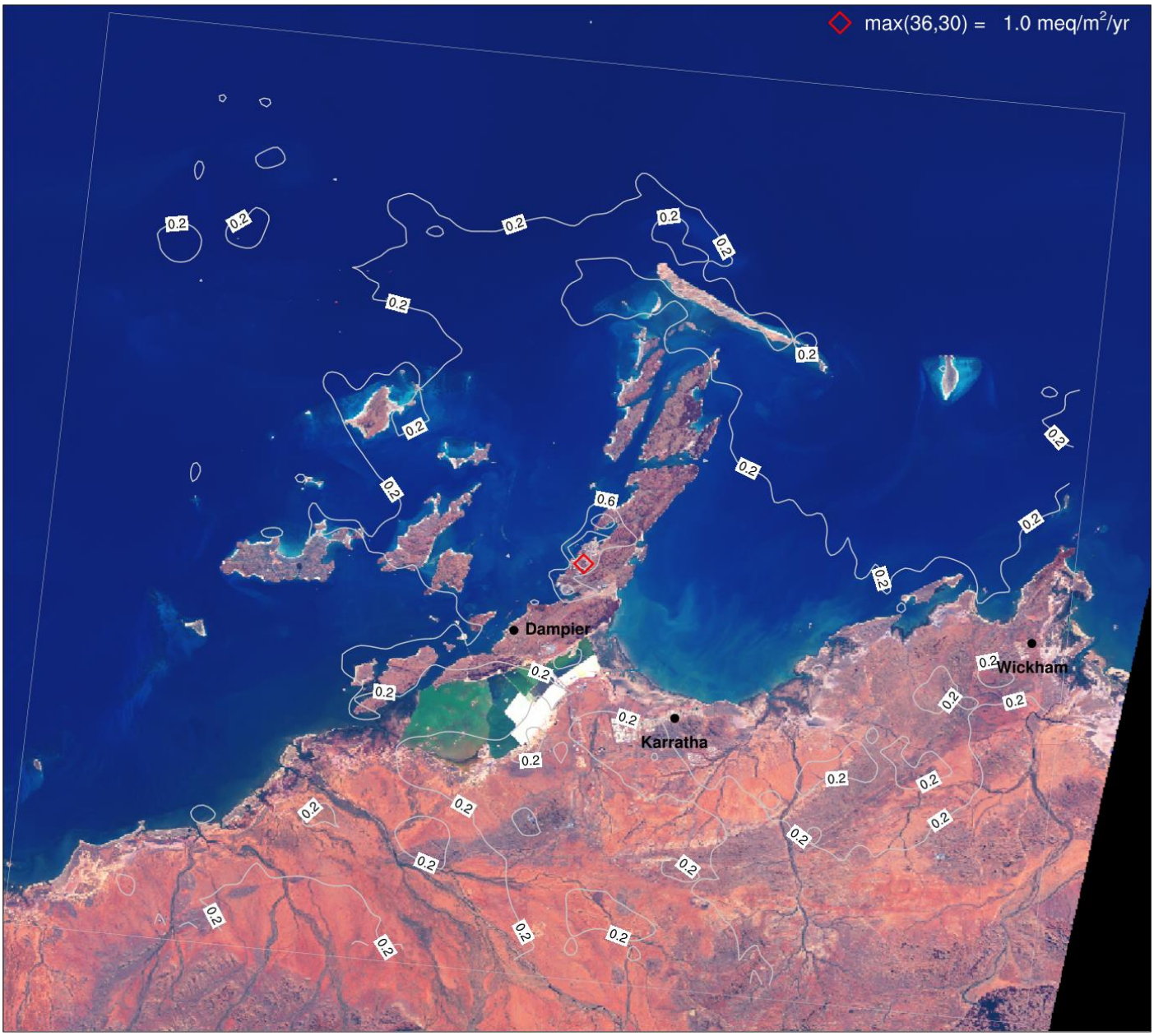

Figure A3-93. Annual total PSO_4 (sulphate; units: meq/m^2/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

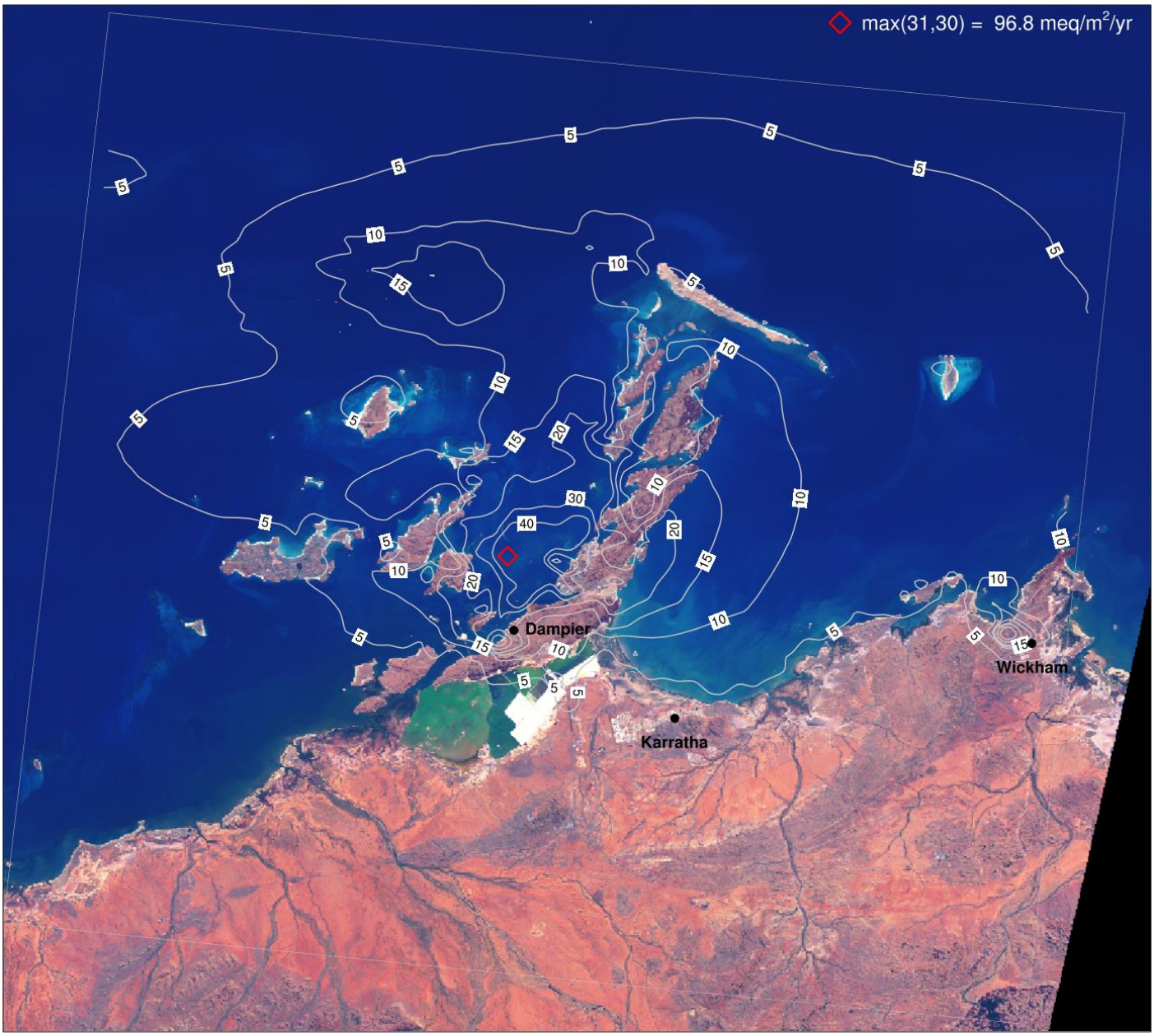

Figure A3-94. Annual total SO_2 (meq/m^2/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

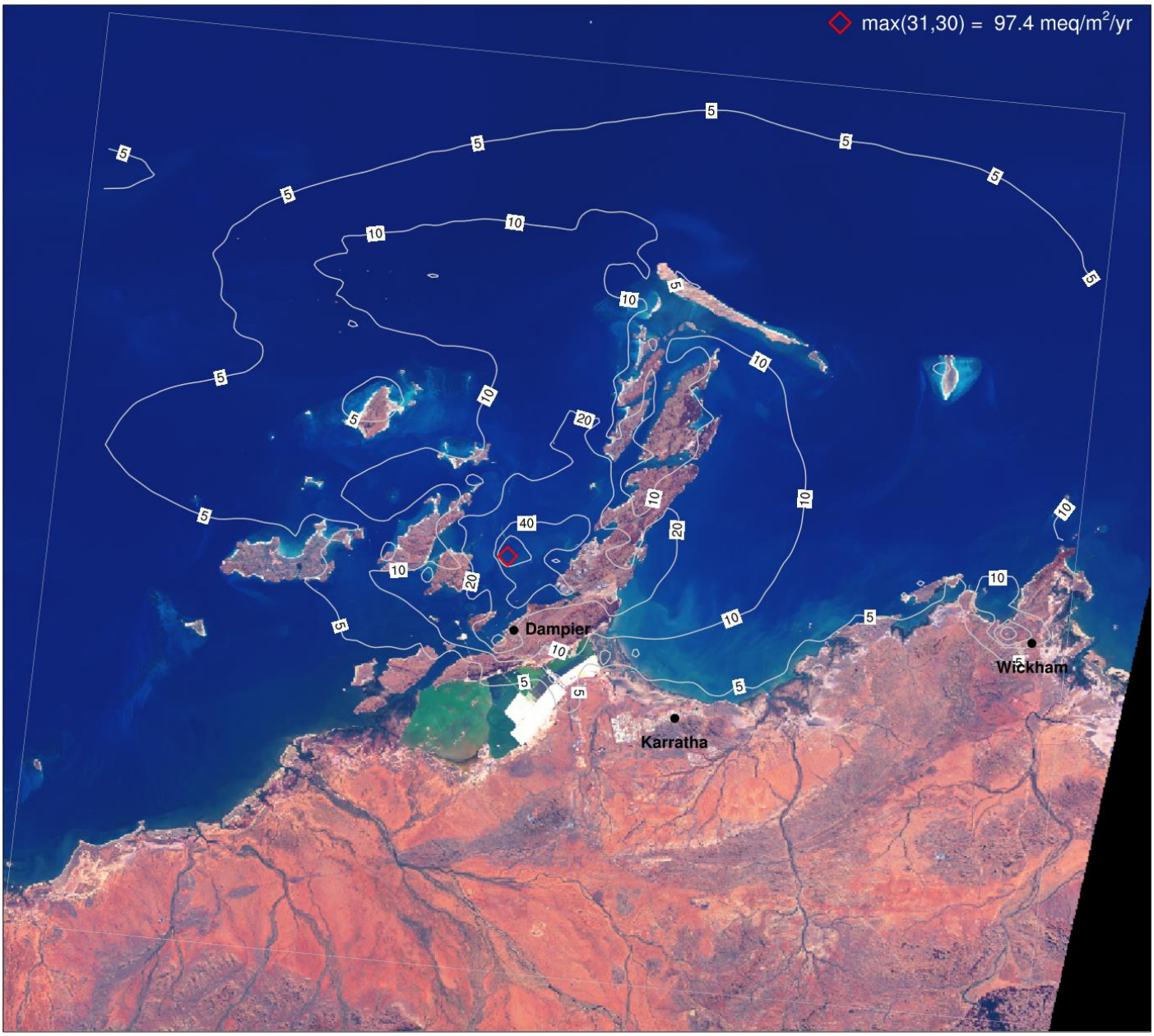

Figure A3-95. Annual total S (sulphur; units: meq/m^2/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

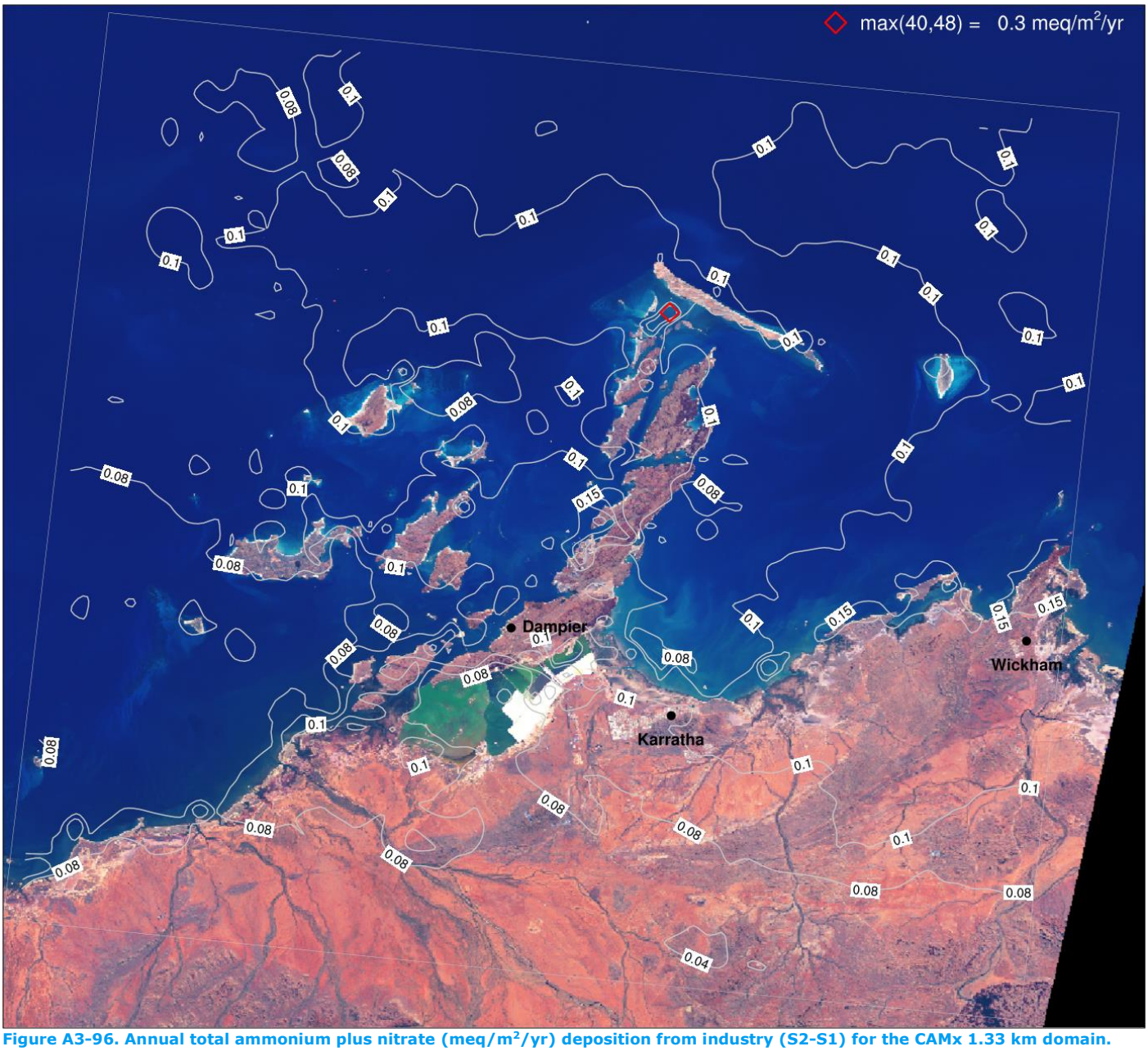

Figure A3-96. Annual total ammonium plus nitrate (meq/m²/yr) deposition from industry (S2-S1) for the CAMx 1.33 km domain.

Deposition from Future Industry

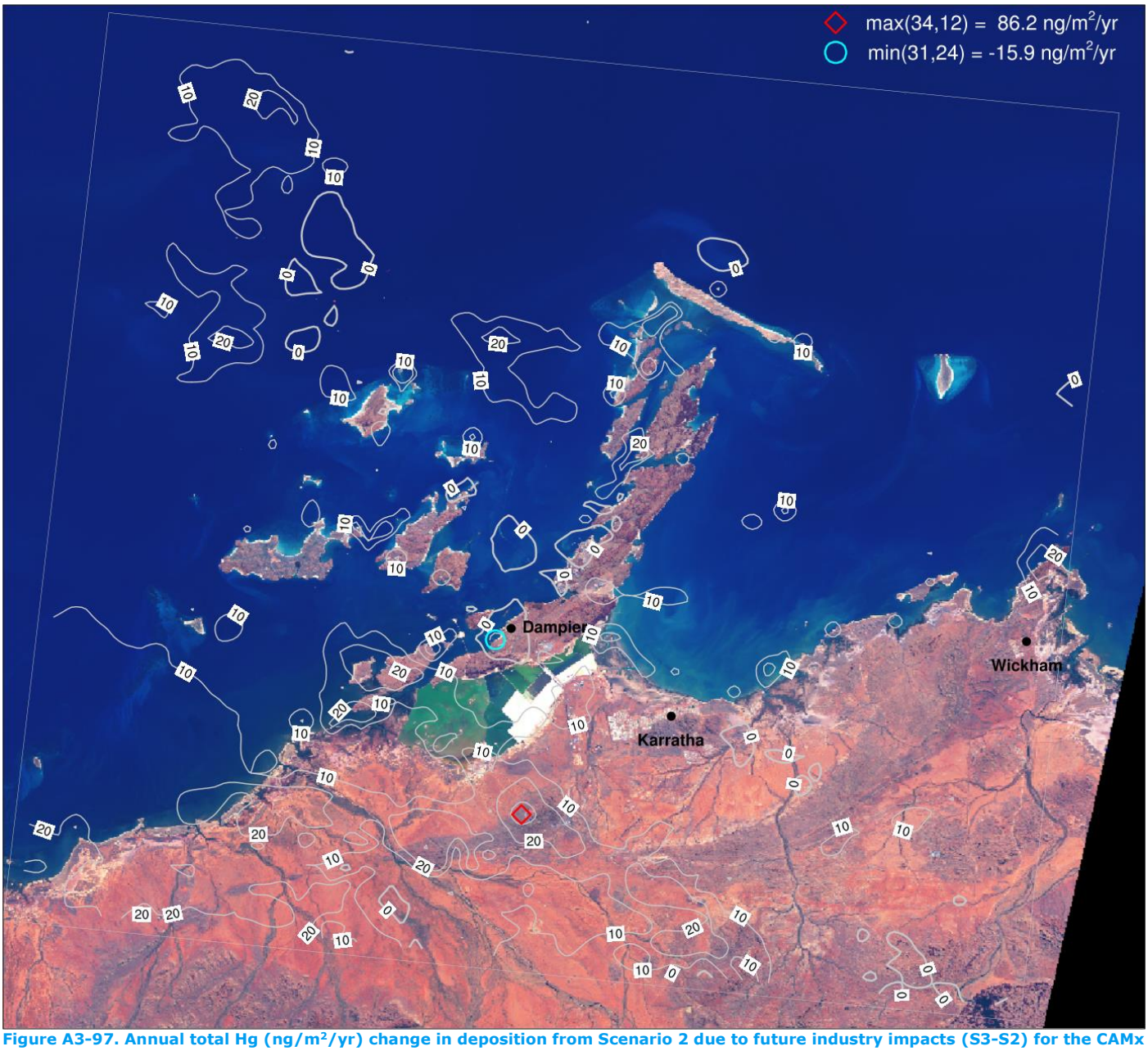

Figure A3-97. Annual total Hg (ng/m²/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

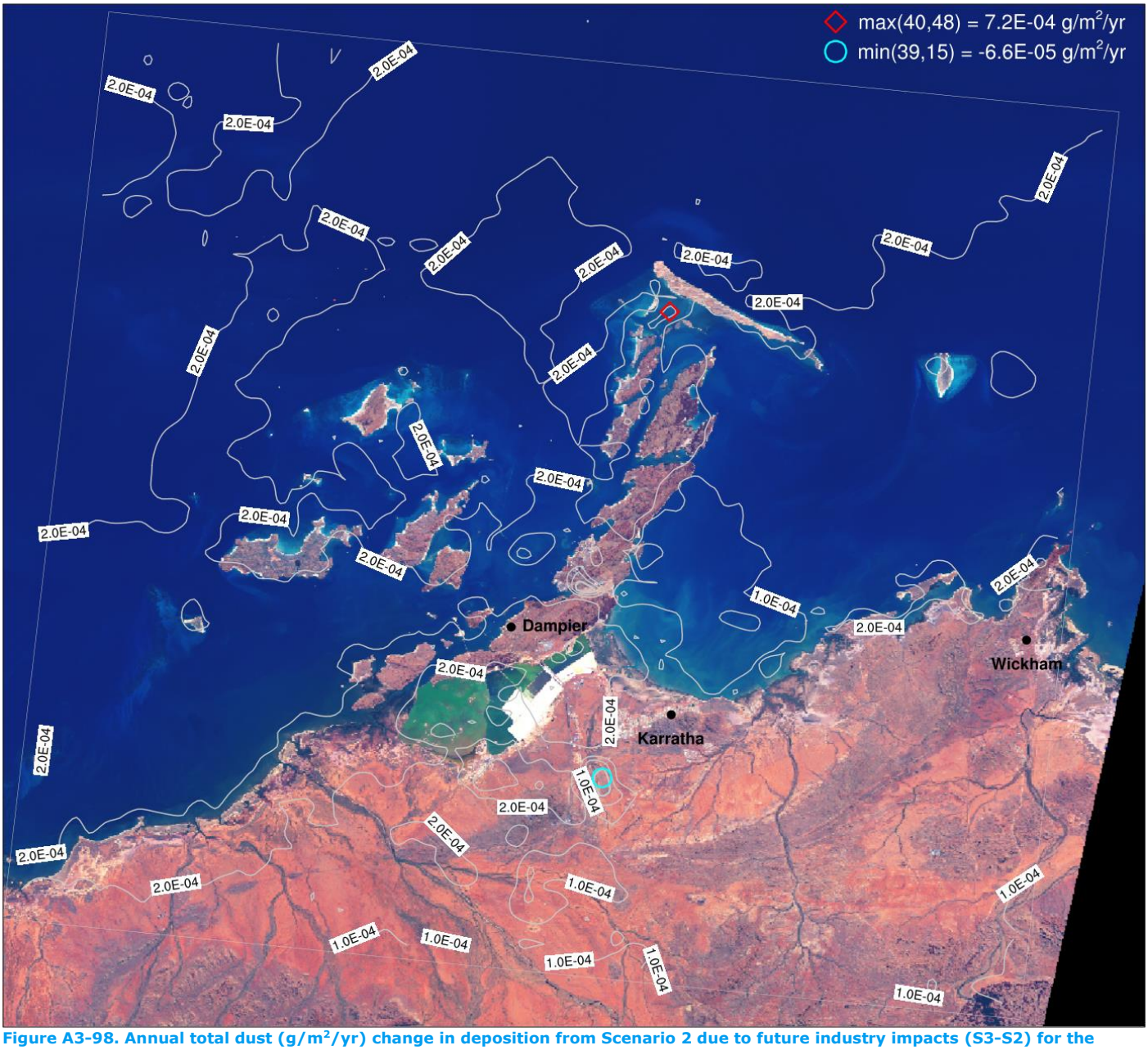

Figure A3-98. Annual total dust (g/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

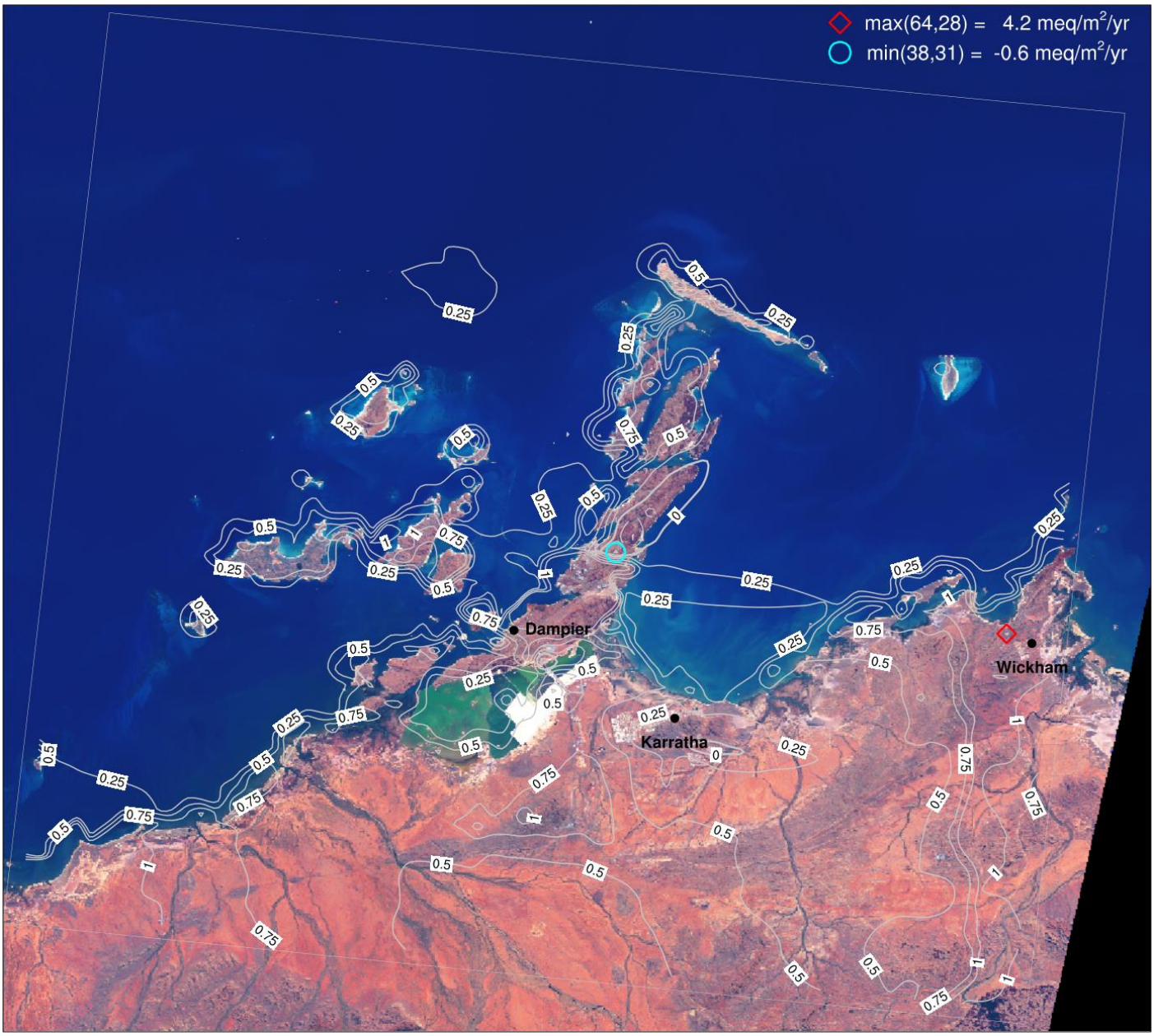

Figure A3-99. Annual total NO_2 (meq/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

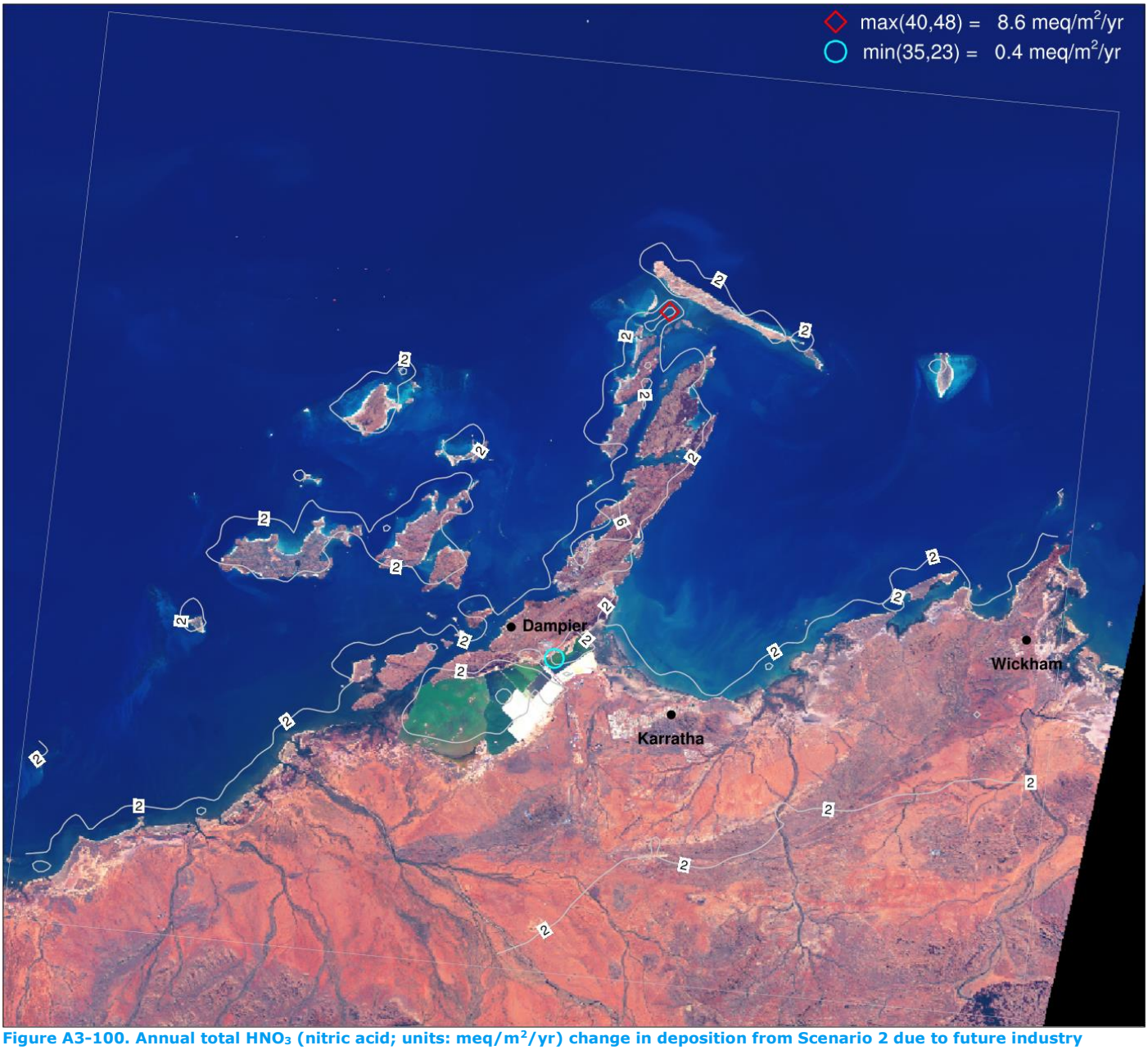

Figure A3-100. Annual total HNO_3 (nitric acid; units: meq/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

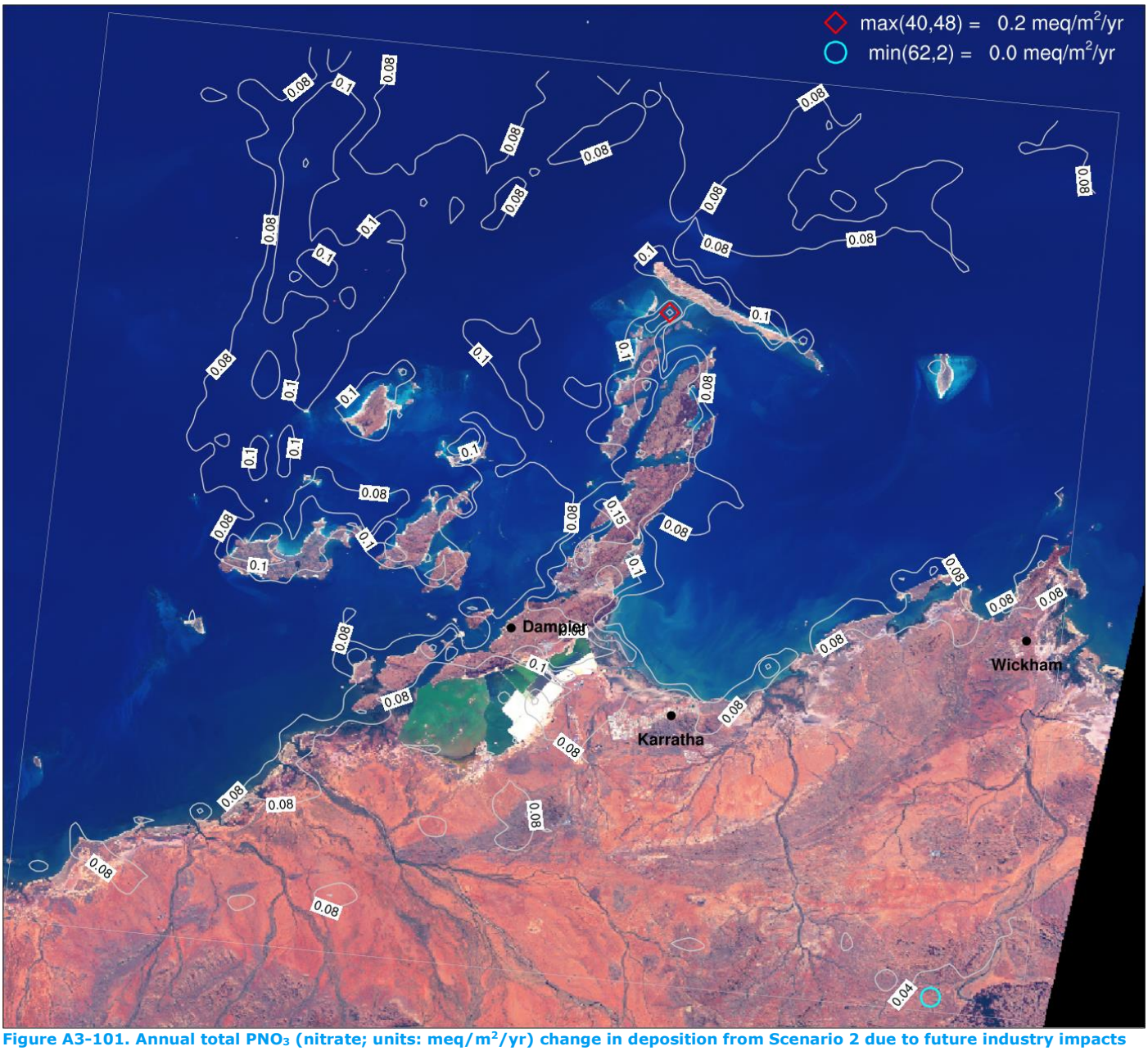

Figure A3-101. Annual total PNO_3 (nitrate; units: meq/m²/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

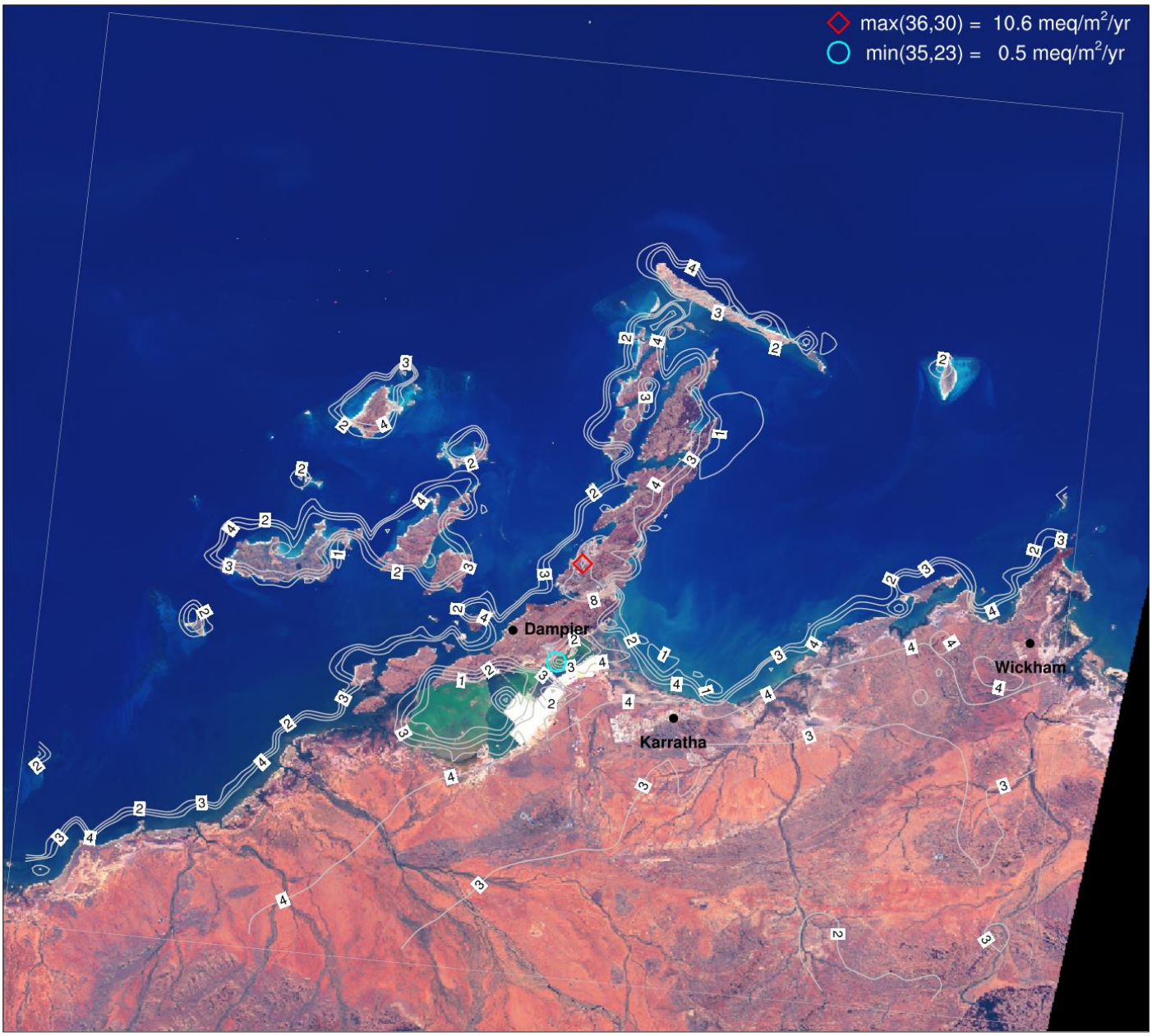

Figure A3-102. Annual total N (nitrogen; units: meq/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

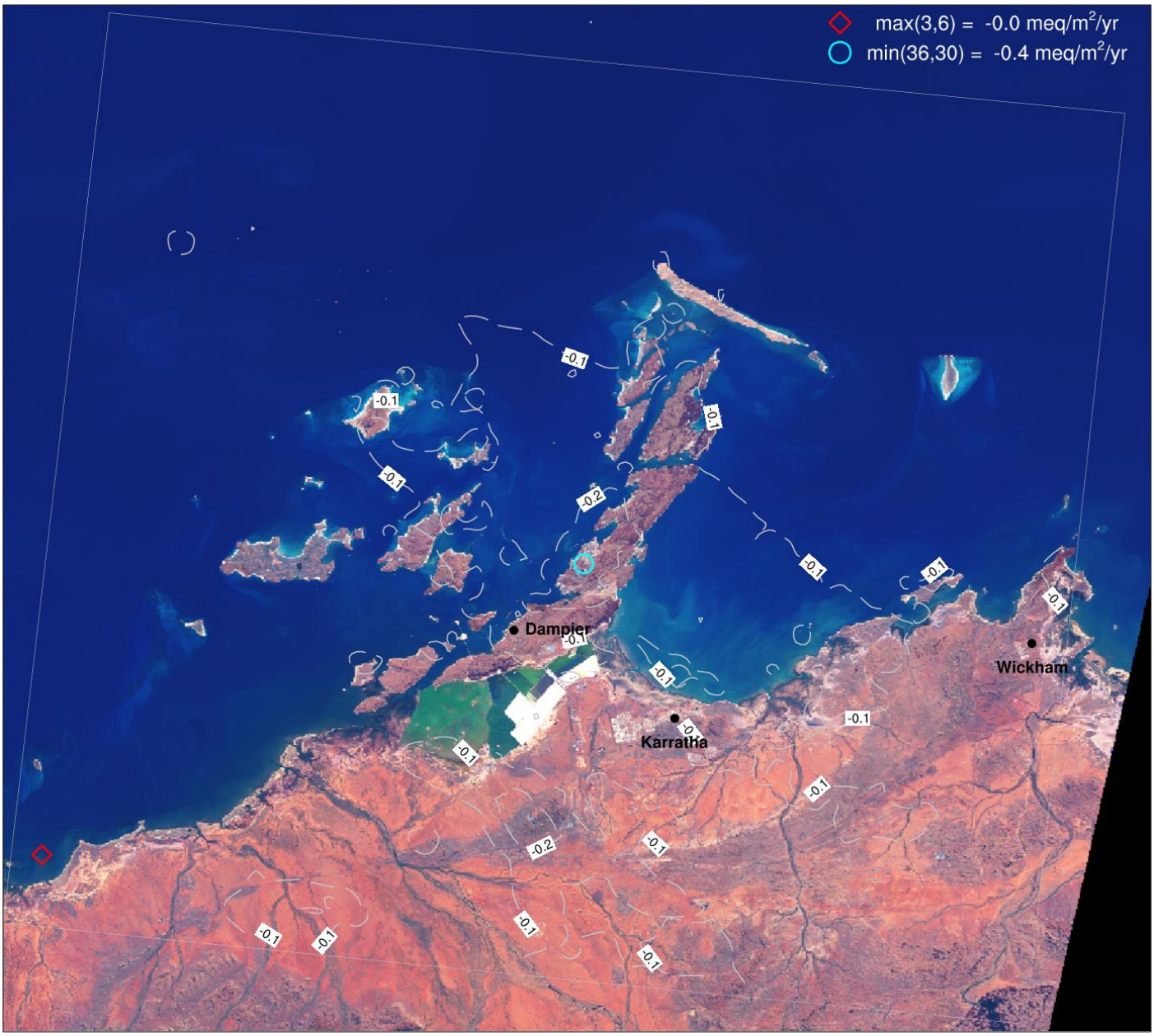

Figure A3-103. Annual total PSO_4 (sulphate; units: meq/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

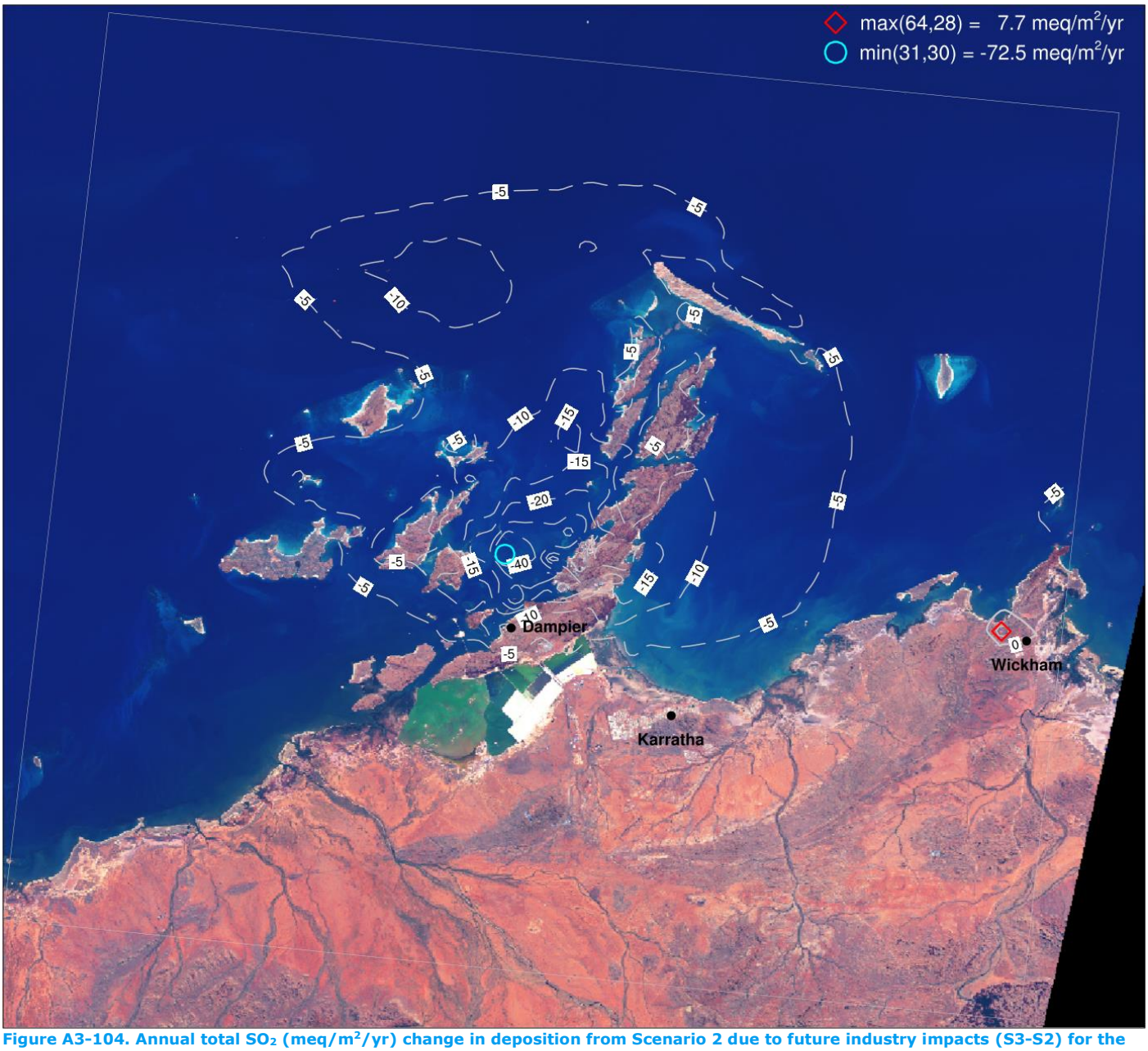

Figure A3-104. Annual total SO_2 (meq/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

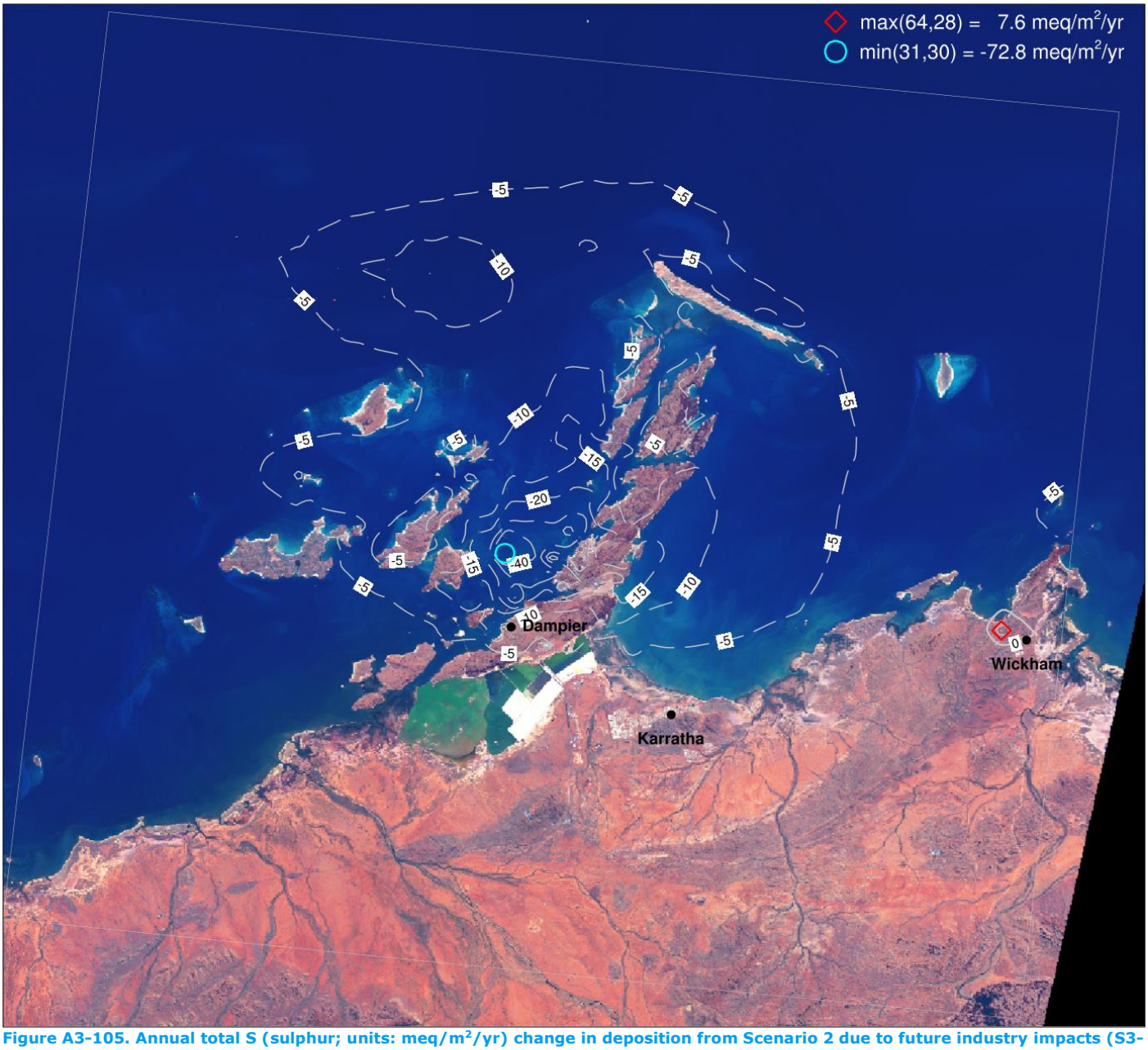

Figure A3-105. Annual total S (sulphur; units: meq/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

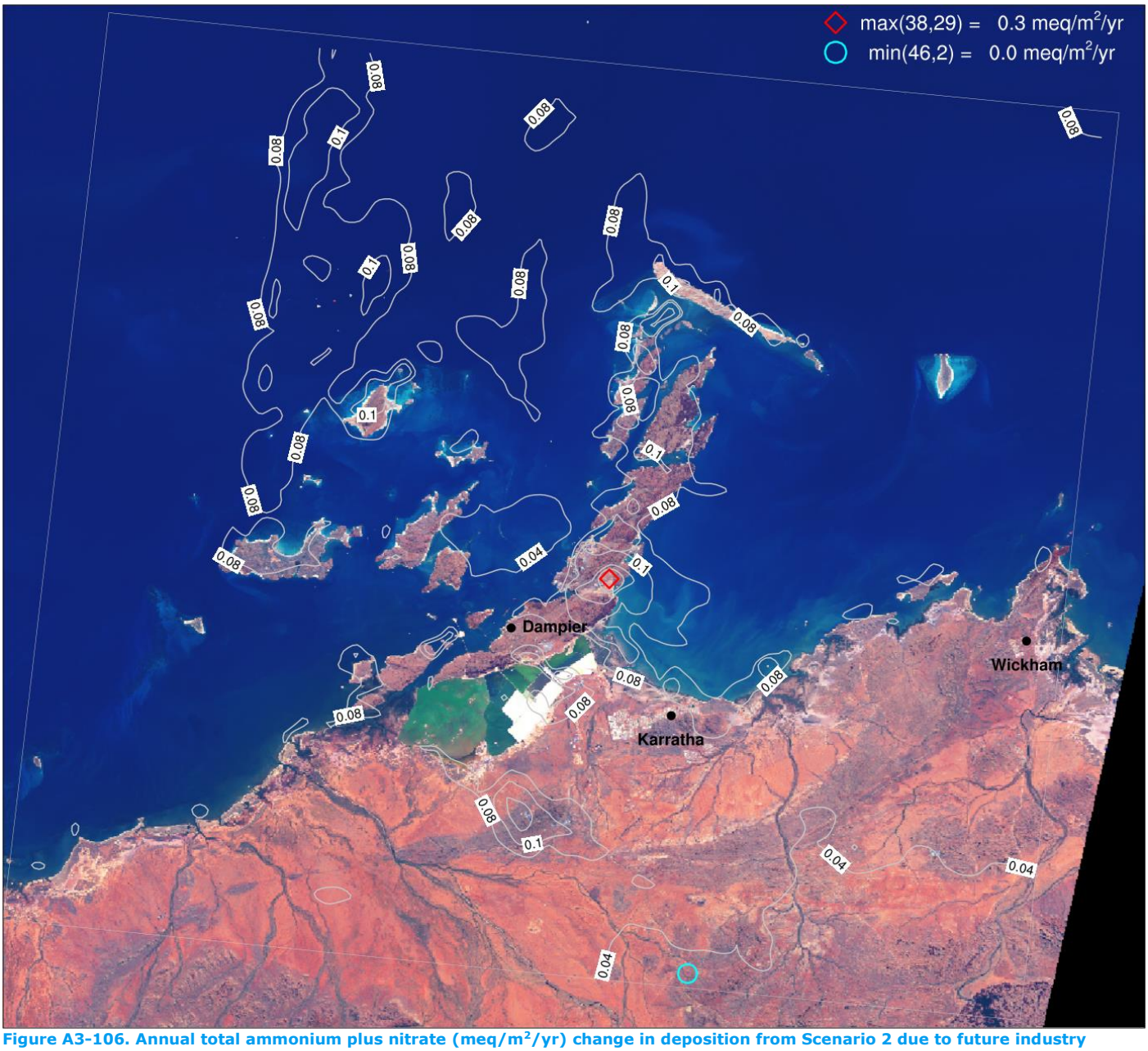

Figure A3-106. Annual total ammonium plus nitrate (meq/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.

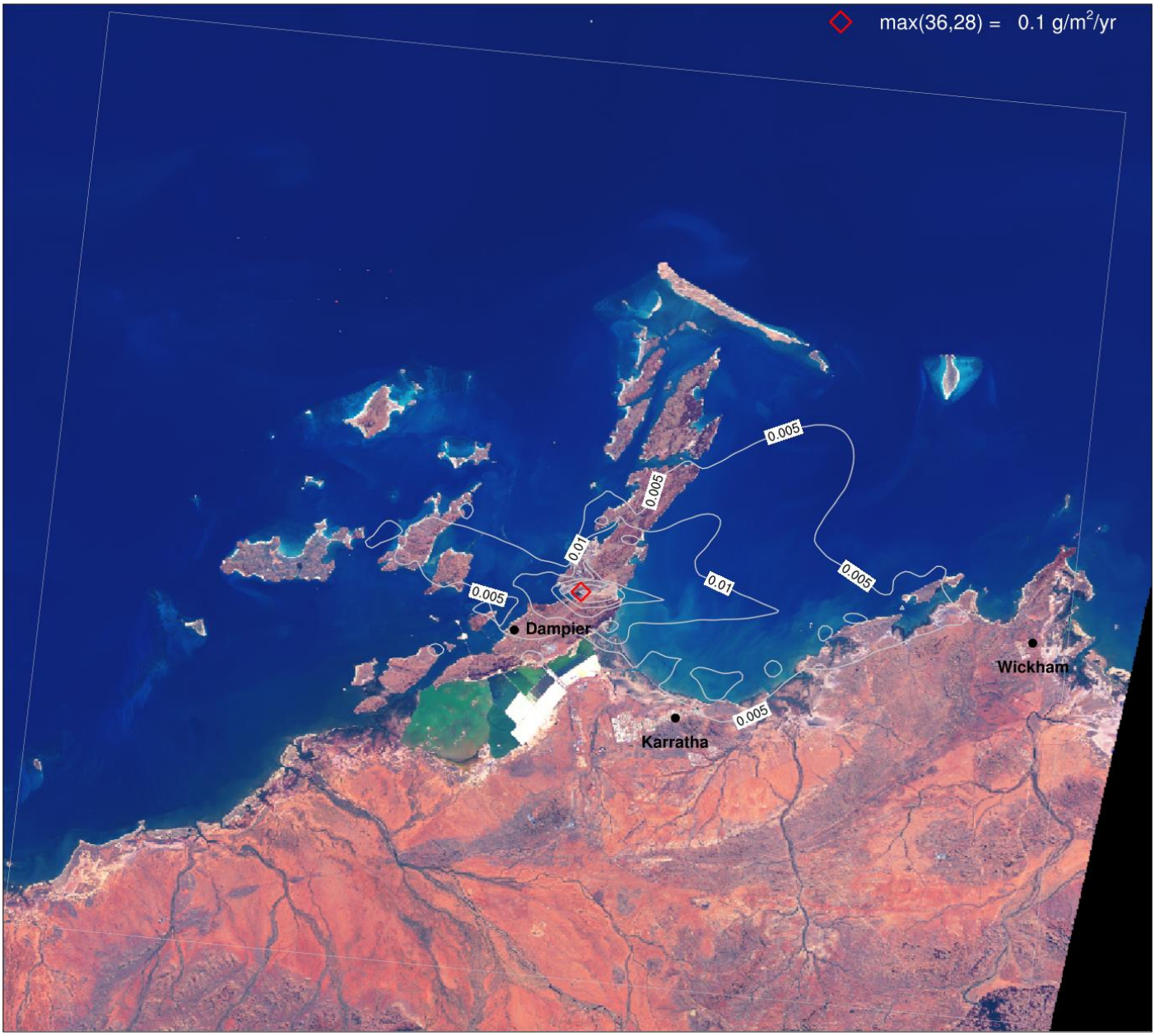

Figure A3-107. Annual total urea fine dust (g/m^2/yr) change in deposition from Scenario 2 due to future industry impacts (S3-S2) for the CAMx 1.33 km domain.