Assessing the air quality, toxic and health impacts of the Puchuncavi-Quintero and Huasco coal-fired power plant sites in Chile

Lauri Myllyvirta, lead analyst, Greenpeace Global Air Pollution Unit
Aidan Farrow, air pollution scientist, Greenpeace Science Unit

Summary

This case study provides a detailed analysis of the air quality, toxic and health impacts of the existing coal power plants in Huasco and Puchuncavi-Quintero, combining detailed atmospheric modeling with existing epidemiological data and literature.

The emissions from the studied coal power plants elevate the levels of toxic particles and NO_2 in the air over a large area, 100 km north-south and 150 km east-west from Puchuncavi-Quintero, reaching several other cities , including Maitencillo, Zapallar and La Ligua. Emissions from the Huasco coal power plants similarly spread across cities, villages and protected áreas, including Carrizal, Freirina, and Llanos de Challe National Park.

This pollution increases the risk of diseases such as stroke, lung cancer, heart and respiratory diseases in adults, as well as respiratory infections in children. This leads to premature deaths from these causes. SO_2, NOx and dust emissions contribute to toxic particle exposure. Emissions from the coal plants cause acid rain, which can affect crops and soils, as well as fallout of toxic heavy metals such as arsenic, nickel, chrome, lead and mercury.

These impacts are greatly exacerbated by the weak emission limits set for the plants by regulators in Chile, far exceeding emissions standards in regions such as China and the EU.

The emissions from the studied power plants expose an estimated 55,000 people to SO_2 concentrations exceeding the WHO 24-hour guideline (WHO, 2006), before considering any other pollutant emission sources in either of the regions surrounding the Huasco and Puchuncavi-Quintero plants. This exposure carries a significant risk of acute respiratory symptoms, especially for vulnerable groups such as children, elderly people and people with pre-existing respiratory ailments.

The model results predict that exceedances of ambient air quality standards for Mercury may occur in Valparaiso, Petorca and Huasco and for SO_2 in Valparaíso, Petorca, Quillota and Huasco.

The emissions from two studied coal-fired plant sites are likely to result in approximately 80 premature deaths per year due to exposure to $PM_{2.5}$ and NO_2.

Introduction

This air quality, toxic and health impacts of the existing coal fired power plants in Huasco and Puchuncavi-Quintero, Chile, have been assessed.

The Huasco and Puchuncavi-Quintero power plants are located on Chile's pacific coast (Figure 1). Huasco is a city and commune, in the Huasco Province, Atacama Region. It is home to the Electrica Guacolda Power Plant that comprises five units named Guacolda U1 to U5. Each unit is a coal-fired unit with a capacity of 152 MWe.

Puchuncaví is a town and commune in the Valparaíso Province, it is home to the Ventanas 1 and 2, Nueva Ventanas and Campiche coal-fired power plant units. The units have a capacity of 102, 218, 267 and 270 MWe respectively.

The assessment has been completed using an approach that combines atmospheric modeling using the CALPUFF dispersion modeling system with existing epidemiological data and literature.

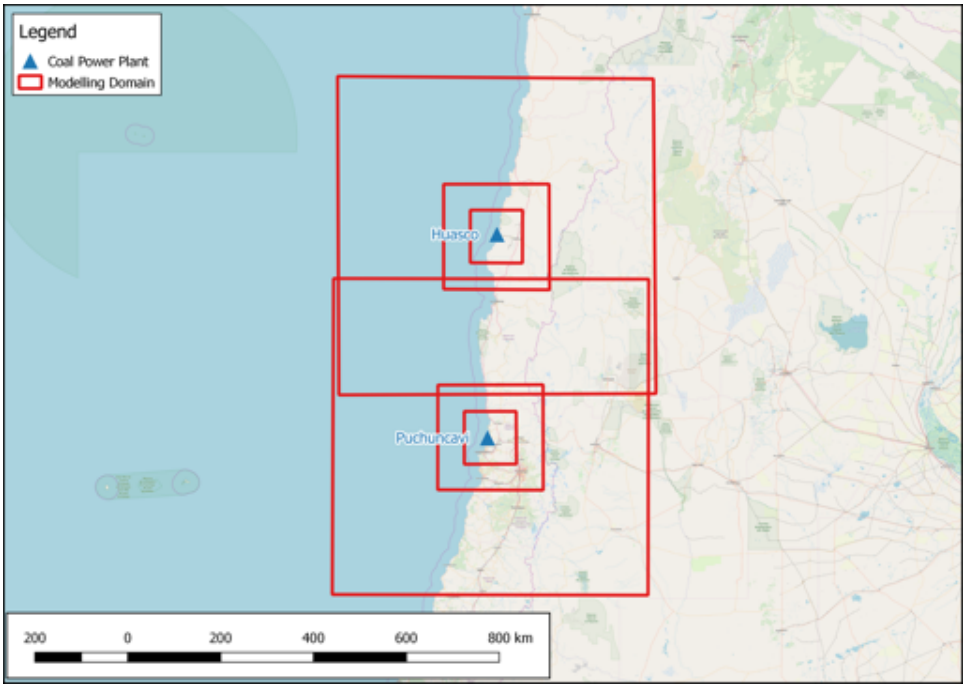

Figure 1 Calpuff modeling domains (red) and location of the studied power plants (blue triangles).

Air pollutant emissions

The power plant unit location, capacity and emission parameters used in this study are provided in the tables below. Data on SO_2, NOx and particulate matter emissions was obtained directly from official sources; as data on mercury was not reported, mercury emissions estimates were calculated based on the methodology and data in UNEP mercury toolkit (2017).

Unit	Location	Latitude	Longitude	Stack Heigh, m	Diameter, m
Guacolda U1	Huasco	-28.465	-71.257	89.0	6.00
Guacolda U2	Huasco	-28.465	-71.257	89.0	6.00
Guacolda U3	Huasco	-28.465	-71.257	89.0*	3.70
Guacolda U4	Huasco	-28.465	-71.257	89.0	3.70
Guacolda U5	Huasco	-28.465	-71.257	89.0	6.00
Ventanas 1	Puchuncavi	-32.751	-71.483	61.0	5.50
Ventanas 2	Puchuncavi	-32.751	-71.483	62.0	4.20
Nueva Ventanas	Puchuncavi	-32.751	-71.483	95.00	4.70
Campiche	Puchuncavi	-32.751	-71.483	95.0	4.70

*The stack height at Guacolda U3 is only 80m, a simplified modelling approach was adopted and the effect of modelling with a height of 89 m is minimal.

Reference: Ministerio de Energía, 2018.

Unit	Capacity, MWe	Generation, 2017 (MWh)	Utilization
Guacolda U1	152	665758	50.00%
Guacolda U2	152	543222	40.80%
Guacolda U3	152	708800	53.23%
Guacolda U4	152	821189	61.67%
Guacolda U5	152	838958	63.01%
Ventanas 1	120	614839	58.49%
Ventanas 2	218	1059302	55.47%
Nueva Ventanas	267	1927212	82.40%
Campiche	270	1822943	77.07%

Reference: Comisión Nacional de Energia, 2018a; Ministerio de Energía, 2018.

Emission data for the studied power plants under full plant operation

Unit	SO_2, mg/Nm^3	NOx, mg/Nm^3	dust*, mg/Nm^3	SO_2, kg/h	NOx, kg/h	dust, kg/h	Hg, g/h
Guacolda U1	400	500	50	99.4	142.0	7.4	3.00
Guacolda U2	400	500	50	81.09	115.9	6.07	2.94
Guacolda U3	400	500	50	30.93	87.7	3.24	3.57
Guacolda U4	400	500	50	81.63	19.5	13.64	3.73
Guacolda U5	200	200	30	21.6	18.0	2.71	3.65
Ventanas 1	400	500	50	75.12	136.0	22.74	3.25
Ventanas 2	400	500	50	125.9	180.32	16.97	5.77

Nueva Ventanas	400	500	50	232.34	224.36	12.42	6.43
Campiche	400	500	50	185.77	212.58	6.81	6.75

*Total Particulate Matter. This was further separated into particles smaller than 2.5 microns, particles between 2.5 and 10 microns, and larger than 10 microns, based on the default particle size distribution for electrostatic precipitators in U.S. EPA AP-42 (1998): 30% of emitted fly ash was assumed to be $PM_{2.5}$, and 37.5% PM_{10}. Particles larger than 10 microns were modeled with a mean aerodynamic diameter of 15 microns.

Reference: Coordinador Eléctrico Nacional, 2018; Sistema Nacional de Información y Fiscalización Ambiental, 2018; Comisión Nacional de Energía, 2018b.

The power plant and emission data shown in Tables 1, 2 and 3 were used as the basis of modeling the plants' air quality impacts using the CALMET-CALPUFF modeling system. The modeling domains used are shown in Figure 1 above.

To establish short-term maximum air quality impacts, these full-operation emission rates were modeled for a whole calendar year. Annual air quality impacts and health impacts are assessed based on average plant operating load in 2017.

Local mercury deposition depends strongly on the speciation of mercury – how much of the mercury is emitted in divalent form (Hg2+), elemental gaseous form and bound to particles. The divalent form is most easily deposited locally. Average distribution of the different species with flue gas desulfurization reported by Lee et al. (2006) were used.

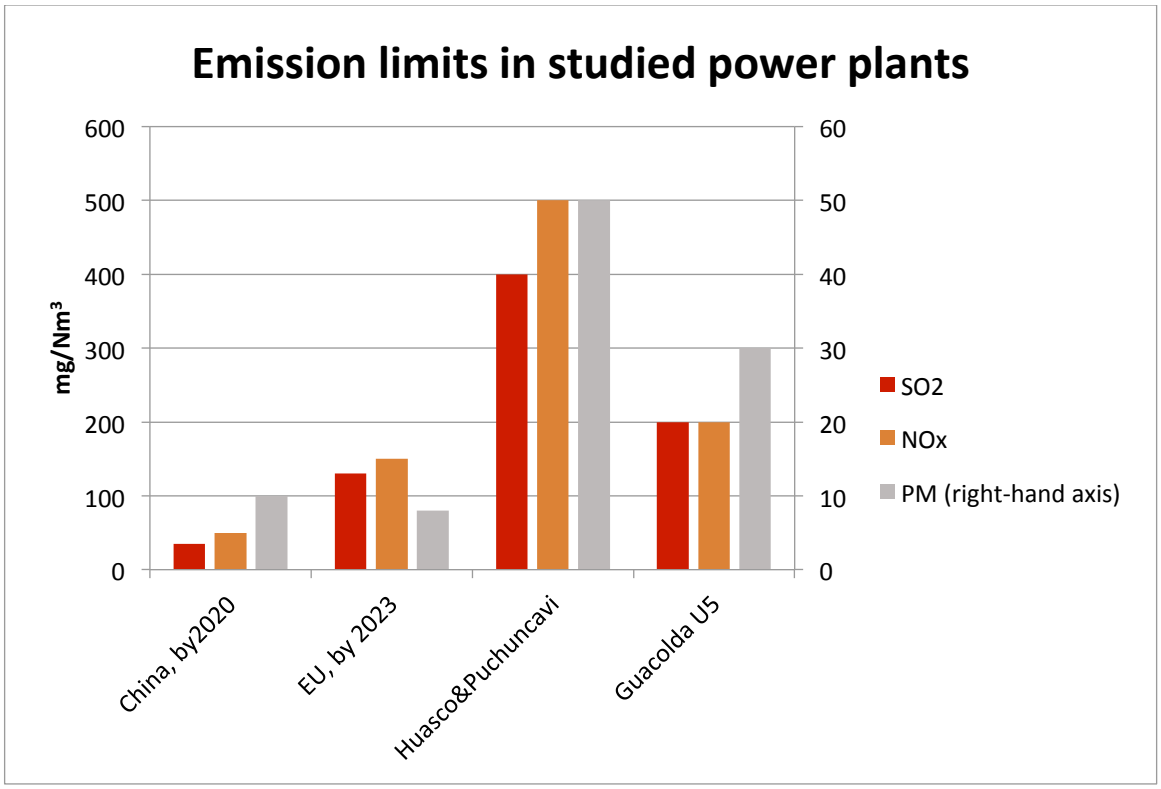

Figure 2 Emission levels of the studied power plants compared with legal limits in China and the European Union.

Impacts on air quality

Methods

Atmospheric dispersion modeling for the case studies was carried out using version 7 (June 2015) of the CALPUFF modeling system. CALPUFF is an advanced non-steady-state meteorological and air quality modeling system widely used in the assessment of long-range air quality impacts. The model uses detailed atmospheric data for every hour of the year to predict the dispersion, deposition and chemical transformation of pollutants, to assess how much the emissions from the studied emissions sources increase ambient pollutant levels and deposition of pollutants, at different locations, during every hour of the year.

3-dimensional meteorological data for the simulations was generated using the TAPM modeling system, developed by Australia's national science agency CSIRO, and cross-validated against the observational data. TAPM uses as its inputs global weather data from the GASP model of the Australian Bureau of Meteorology, combined with higher-resolution terrain data. TAPM outputs were converted into formats accepted by CALPUFF's meteorological preprocessor, CALMET, using the CALTAPM utility, and the meteorological data were then prepared for CALPUFF execution using CALMET. CALMET generates a set of time-varying micrometeorological parameters (hourly 3-dimensional temperature fields, and hourly

gridded stability class, surface friction velocity, mixing height, Monin-Obukhov length, convective velocity scale, air density, short-wave solar radiation, surface relative humidity and temperature, precipitation code, and precipitation rate) for input to CALPUFF.

Terrain height and land-use data were also prepared using the TAPM system and global datasets made available by CSIRO. A set of nested grids with a 50x50 grid size and 15km, 5km and 2.5km horizontal resolutions and 12 vertical levels was used, centered on each power plant.

Chemical transformation of sulphur and nitrogen species was modeled using the ISORROPIA II chemistry module within CALPUFF, and required data on ambient ozone levels was processed from measurements reported by Chilean authorities (Coordinador Eléctrico Nacional, 2018; Sistema Nacional de Información y Fiscalización Ambiental, 2018; Comisión Nacional de Energía, 2018b). Monthly average ammonia levels were obtained from background measurements in a study of ammonia levels in Santiago (Toro et al 2014). Data on ambient H2O2 levels was not available, so the U.S. EPA default value of 1ppb (Exponent 2011) was used for all months. The CALPUFF results were reprocessed using the POSTUTIL utility to repartition different nitrogen species (NO, NO_2, NO_3 and HNO_3) based on background ammonia concentrations.

Results

Emissions from the power plants affect air quality over a large area spanning approximately 150 kilometers north-south and 100 kilometers east-west. In the most affected locations, within 10-20km of the coal power plants, the maximum predicted 24-hour mean ground level SO_2 contribution from the plants exceed the WHO guideline values (WHO, 2006), and near to the Ventanas power plants, it is exceeded by a factor of two.

The emissions from the studied power plants expose an estimated 55,000 people to SO_2 concentrations exceeding the WHO 24-hour guideline, before considering any other emission sources in the region. This exposure carries a significant risk of acute respiratory symptoms, especially for vulnerable groups such as children, elderly people and people with pre-existing respiratory ailments.

The modeled contribution to ambient $PM_{2.5}$ concentrations from the plants at Huasco and Puchuncavi are shown in figures 3 (annual mean) and 4 (maximum 24-hour mean). Each plant contributes close to 1 $\mu g/m^3$ to the annual mean $PM_{2.5}$ concentration within the area local to the plant, while a smaller contribution is made over an area extending hundreds of kilometers to the north, south and east of the source.

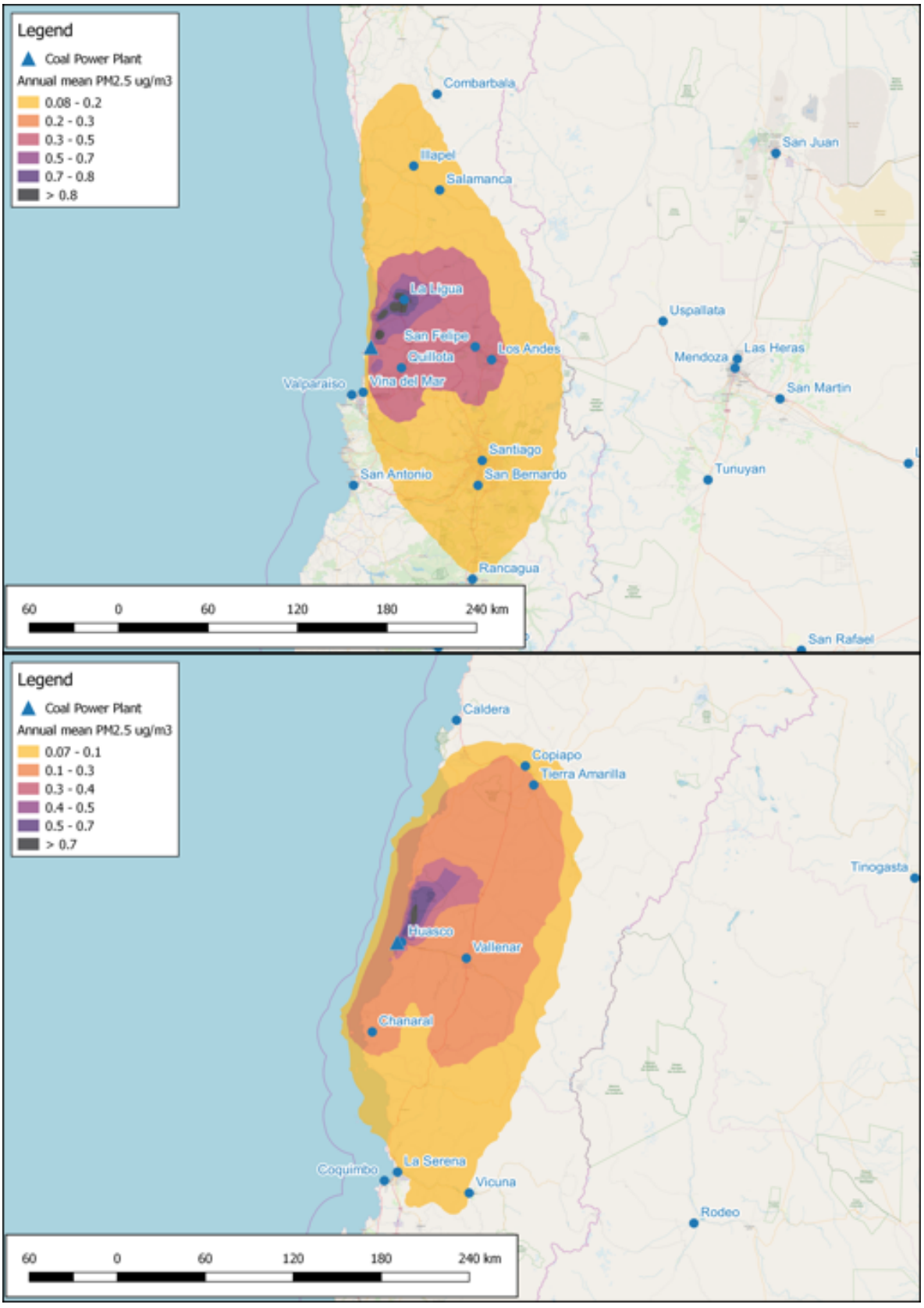

Figure 3 ***Projected annual average $PM_{2.5}$ concentration attributable to emissions from the studied power plants.***

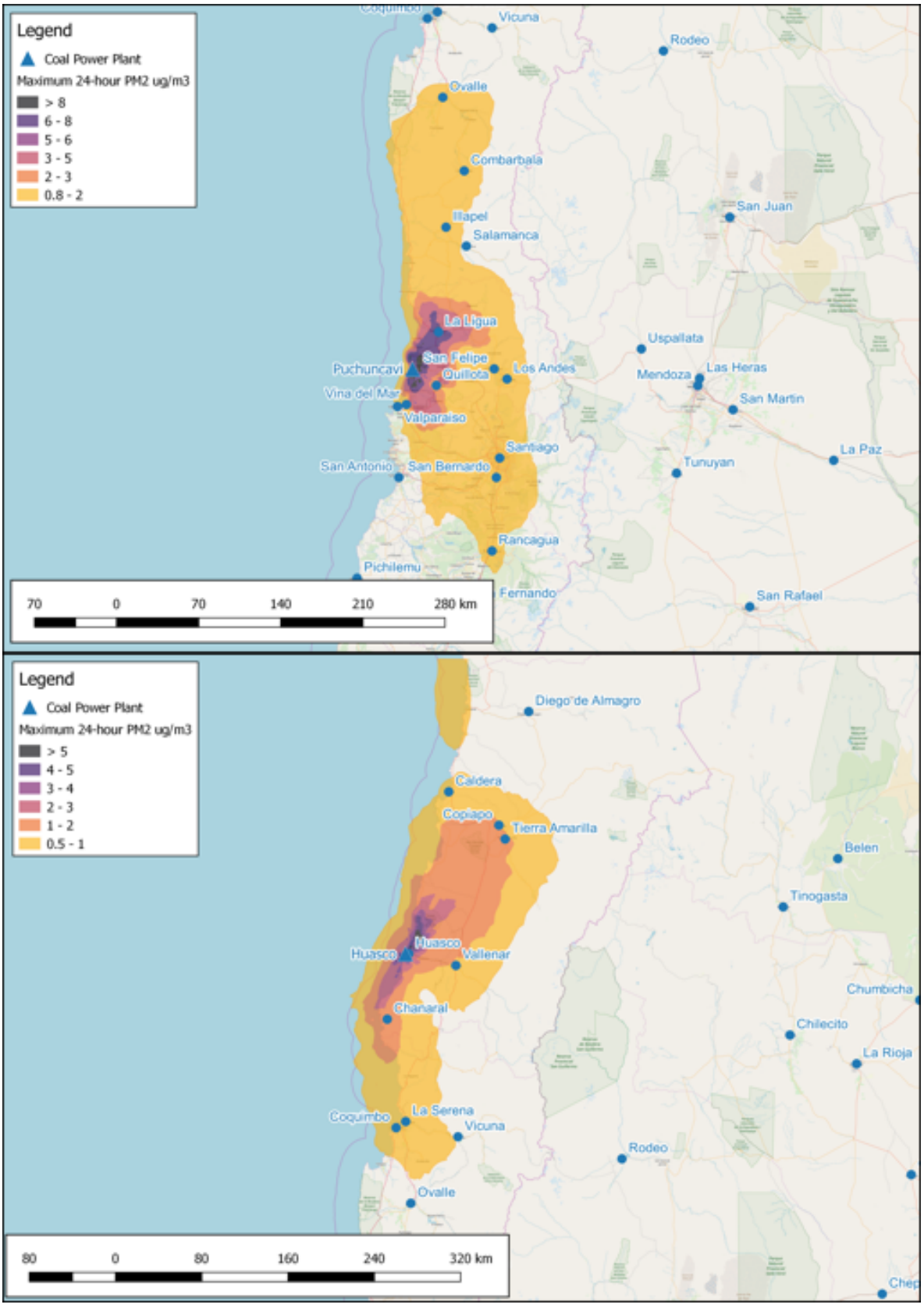

Figure 4 ***Projected maximum 24 hours $PM_{2.5}$ concentration attributable to emissions from the studied power plants.***

The modeled maximum contribution to 24-hour average $PM_{2.5}$ shows that the short-term impact of the power plants on $PM_{2.5}$ concentrations is significant (Figure 4). Unlike the annual mean concentrations shown in Figure 3, the modeled maximum 24-hour average contributions show the maximum predicted impact of plant emissions on ambient pollutant concentrations during a single 24-hour period. The modeled plant process contribution suggests that the plants can add up to 8 $\mu g/m^3$ $PM_{2.5}$ to the daily mean concentration on the worst effected days which is one third of the WHO guideline value (25 $\mu g/m^3$). This means that the plants are likely to significantly contribute to exceedances of the guideline, when other pollutant sources are considered. The maximum 24-hour average contributions are likely to occur when emissions are greatest and when weather conditions limit the dispersion of pollutants and increase secondary particle formation.

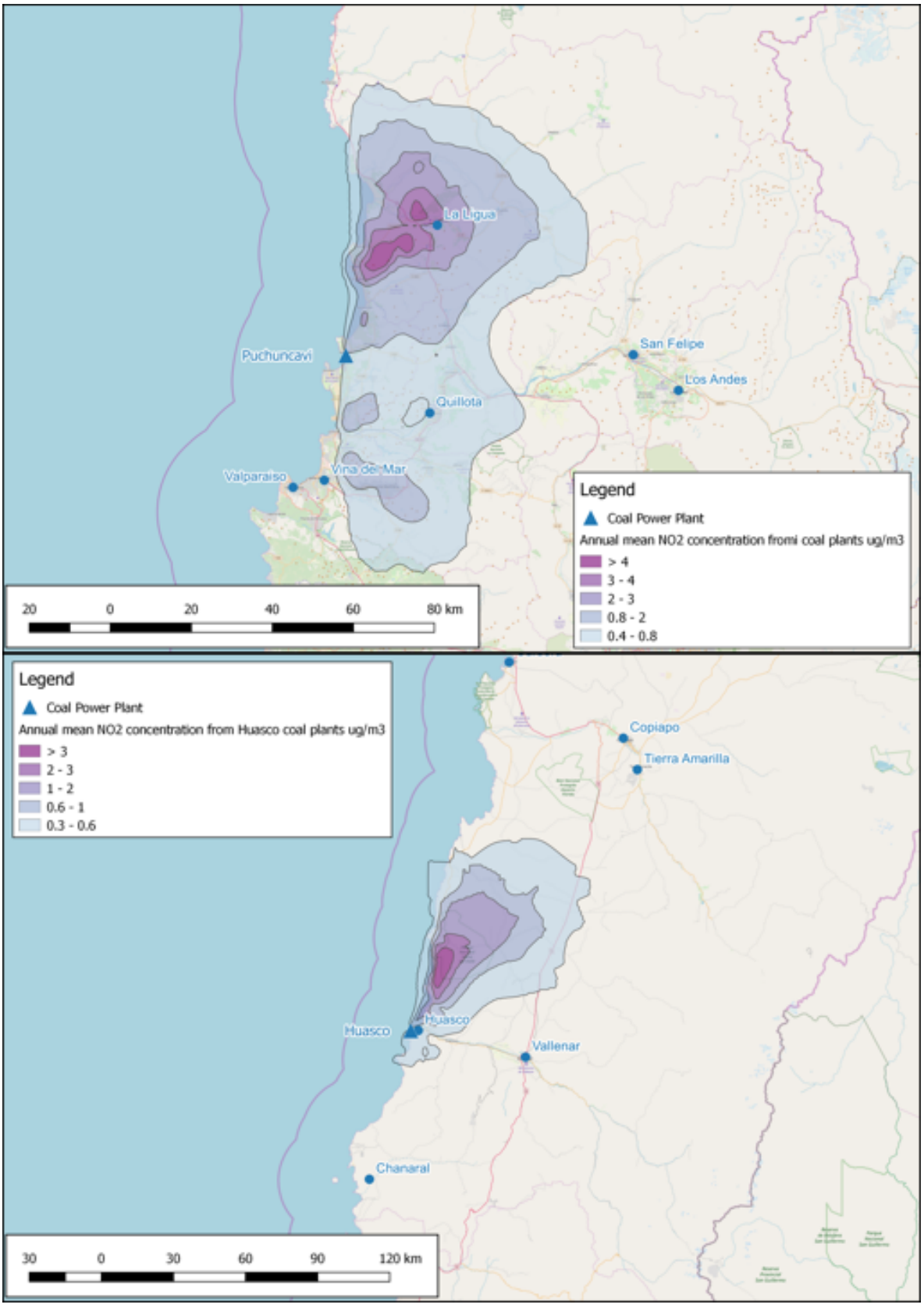

Figure 5 Projected annual average NO_2 concentrations caused by emissions from the studied power plants.

The modeled contribution to ambient NO_2 concentrations from the plants at Huasco and Puchuncavi are shown in figures 5 (annual mean) and 6 (maximum 1-hour mean). Each plant contributes over 3 $\mu g/m^3$ to the annual mean NO_2 concentration within the area local to the plant, while a smaller contribution is made over an area extending hundreds of kilometers to the north and east of the sources.

Differences in the spatial pattern of $PM_{2.5}$ and NO_2 contributions from the plants can be attributed to the relatively short atmospheric residence time of NO_2 and the relatively short time scales over which secondary NO_2 forms. By comparison the residence time of $PM_{2.5}$ and formation of secondary $PM_{2.5}$ occurs on longer timescales.

The modeled maximum contribution to 1-hour average NO_2 shows that the short-term impact of the power plants on NO_2 concentrations is significant (Figure 6). The modeled maximum 1-hour average contributions show the maximum predicted impact of plant emissions on ambient pollutant concentrations during a single 1-hour period. The modeled plant process contribution suggests that the plants can add over 70 $\mu g/m^3$ NO_2 to the 1-hour mean concentration on the worst effected days and in the worst affected areas, or one third of the WHO guideline value (200 $\mu g/m^3$). This large contribution from the power plants reduces the head-room available before NO_2 resulting from other emission sources, cause an exceedance of local air quality standards.

The modeled maximum 24-hour mean contribution to ambient SO_2 concentrations from the plants at Huasco and Puchuncavi are shown in figure 7. The modeled maximum 24-hour average contributions show the maximum predicted impact of plant emissions on ambient pollutant concentrations during a single 24-hour period. The modeling results suggest that the additional 24-hour mean SO_2 concentration from the plants can exceed 20 $\mu g/m^3$, the WHO guideline value, on the worst effected days and in the worst affected areas. Using the NASA high resolution population dataset (Jones, B., and B. C. O'Neill 2017), we estimate that the total number of people exposed to exceedances of the WHO guideline around the two power plant sites is 55,000.

The modeled concentrations show that exceedances for Mercury may occur in Valparaiso, Petorca and Huasco. Similarly, the modeling results predict SO_2 exceedances in Valparaíso, Petorca, Quillota and Huasco.

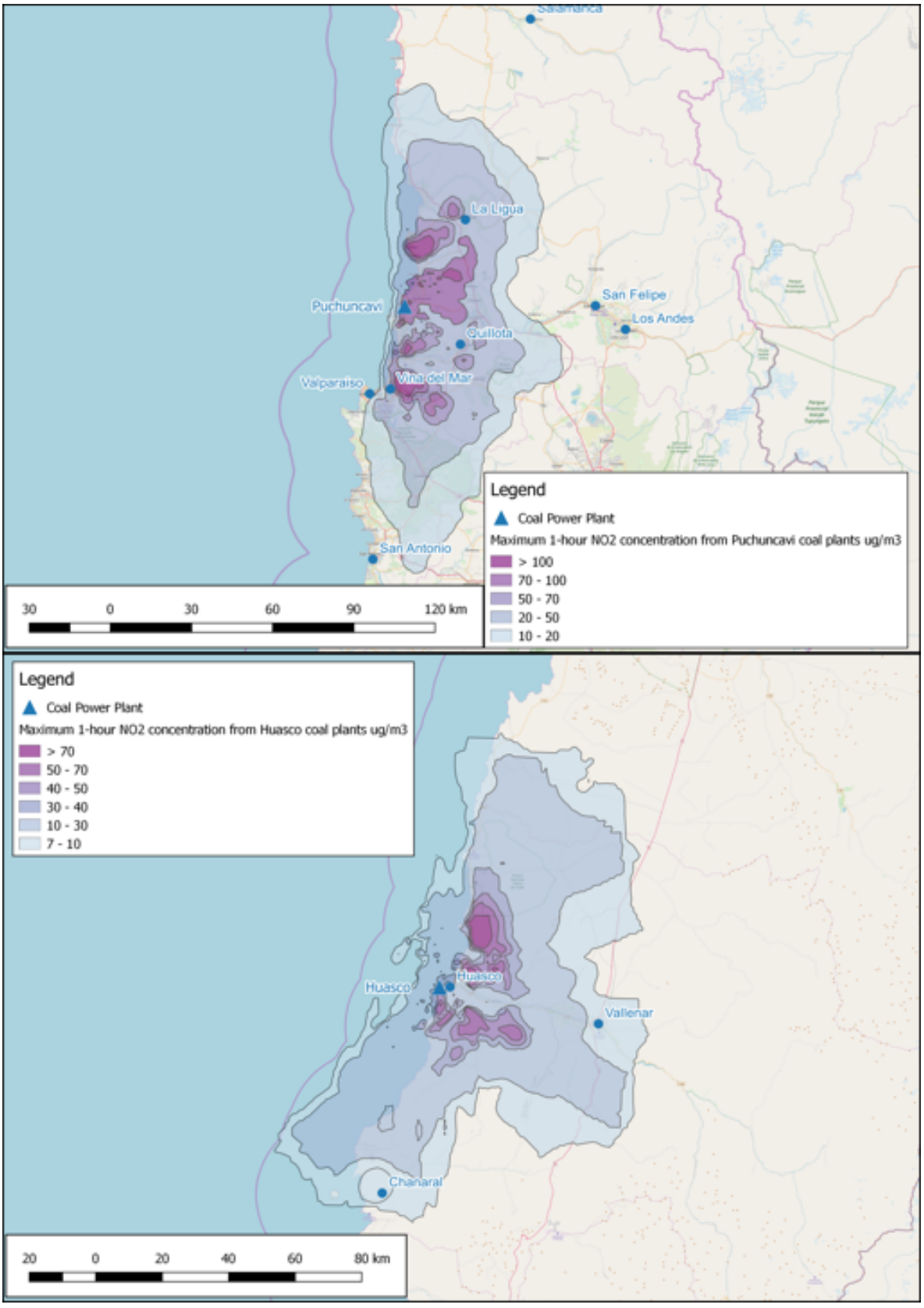

Figure 6 Projected 1-*hour maximum NO_2 concentrations caused by emissions from the studied power plants.*

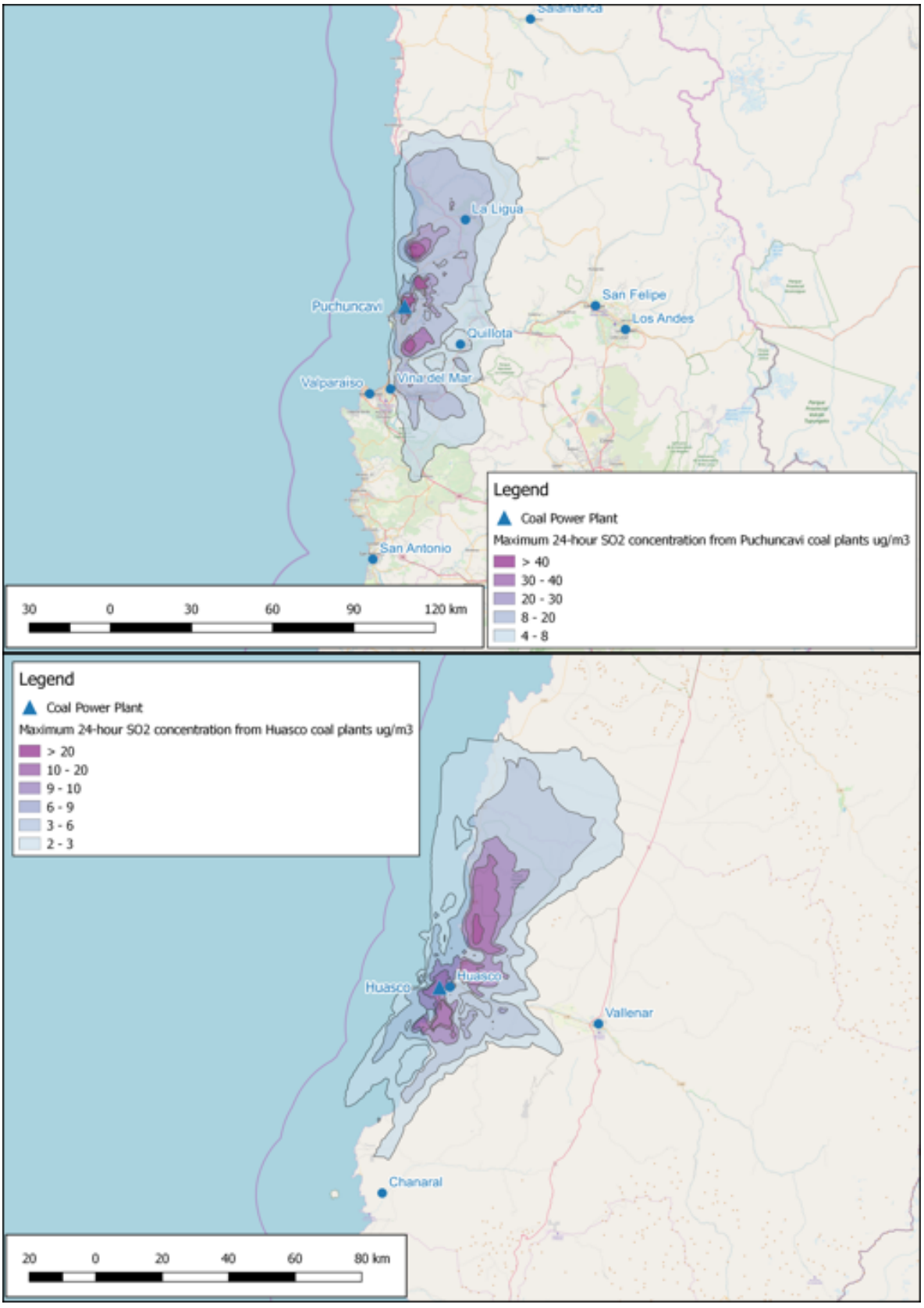

Figure 7 ***Projected 24-hour maximum SO_2 concentrations caused by emissions from the studied power plants.***

The air quality impact of emissions from the plants is seasonally variable. Figures 8 to 10 show the monthly variation in predicted contributions to surface NO2, PM2.5 and SO2.

The largest air quality impact during all months happens northeast of the plants in Huasco. The impact here is controlled by topography and prevailing winds which affect pollutant dispersion.

The coast to the south of the plants is most affected in the winter months from May to September when winds from the north are more common. Overall $PM_{2.5}$ air quality impact is largest during winter due to lower wind speeds and atmospheric conditions that are more conducive to the formation of secondary particles, including higher humidity.

In Punchuncavi, the area north-northeast of the site is affected during all months, while the impact in the areas southeast of the plant is most pronounced from April to September. The highest predicted daily concentrations for $PM_{2.5}$ and SO_2 occur in October and November. Highest average $PM_{2.5}$ concentration for the whole month occurs in October.

The highest predicted daily concentration for $PM_{2.5}$ occurs in November and the highest daily SO_2 concentration in February. Highest average $PM_{2.5}$ concentration for the whole month occurs in June.

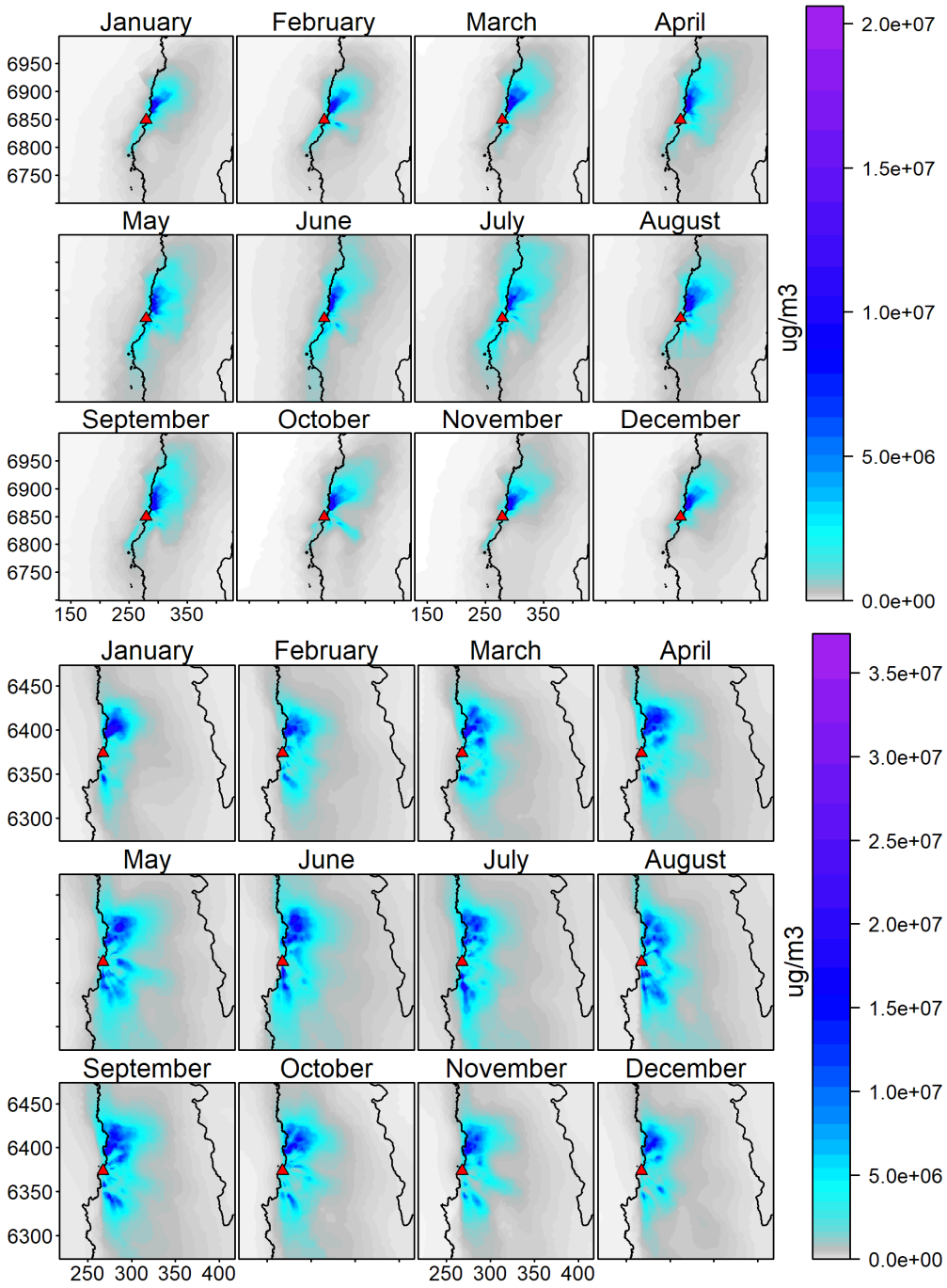

Figure 8 Projected monthly mean NO_2 contributions from the studied Huasco (Top) and Puchuncavi (Below) power plants

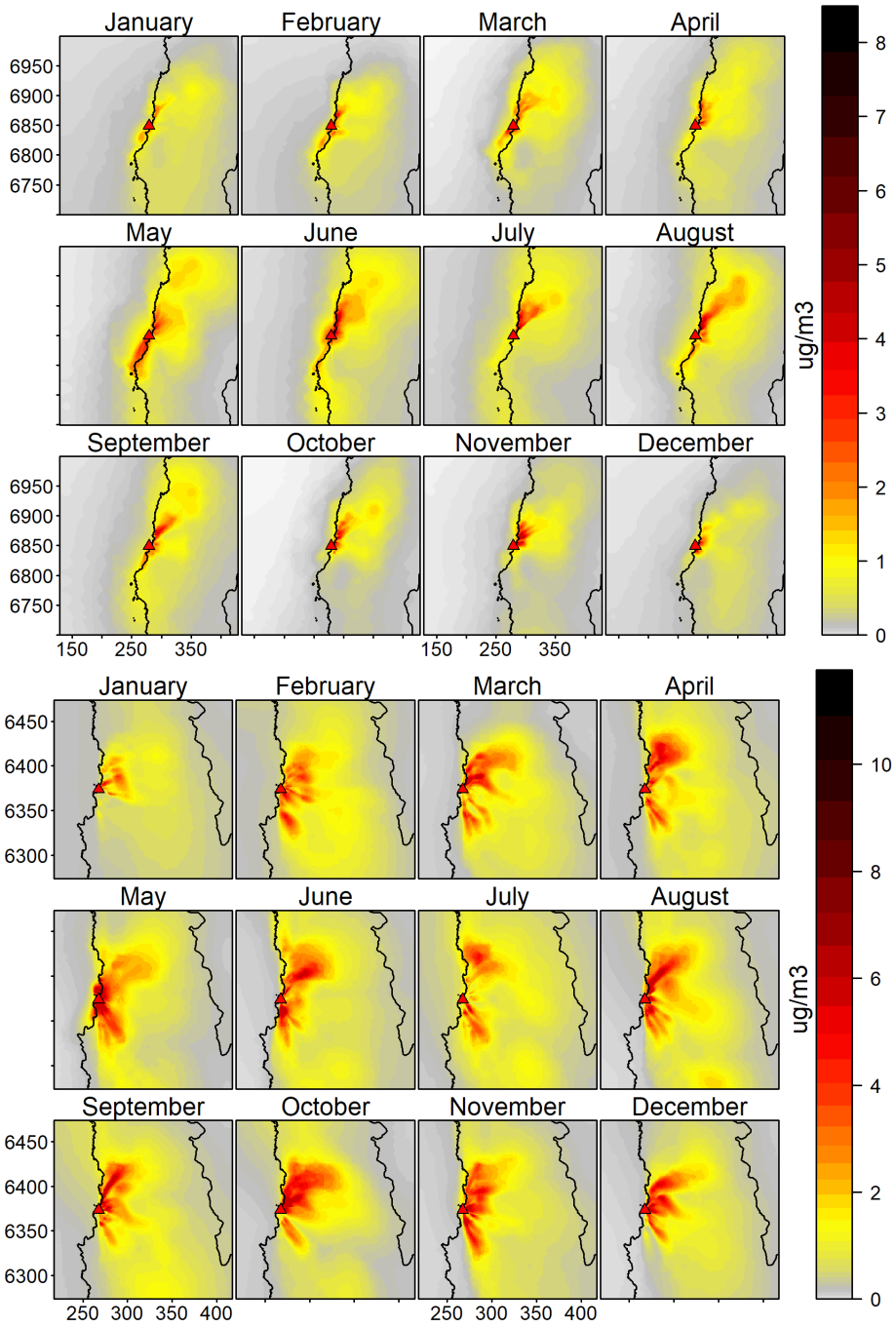

Figure 9 *Projected monthly mean $PM_{2.5}$ contributions from the studied Huasco (Top) and Puchuncavi (Below) power plants*

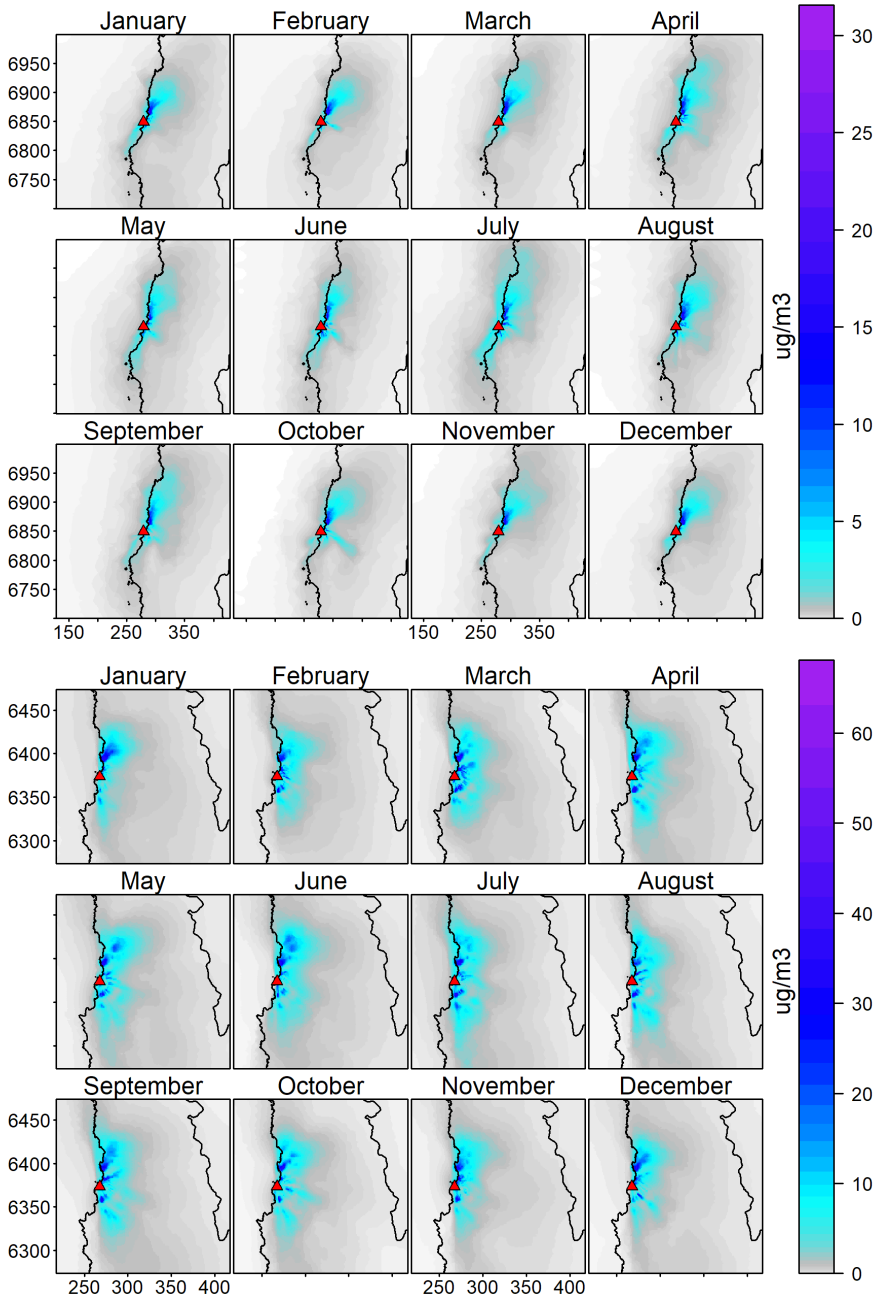

Figure 10 Projected monthly mean SO_2 contributions from the studied Huasco (Top) and Puchuncavi (Below) power plants

Health impacts

Methods

We assessed the health impacts of the ground-level pollutant concentrations attributed to the two coal power plant emissions sites, combining high-resolution population data, data on current rates of death from different causes from WHO databases, and existing scientific studies on the links between pollutant exposure and health risks. We follow the health impact assessment recommendations of U.S. EPA for $PM_{2.5}$ and WHO for NO_2, as in Koplitz et al. (2017).

These recommendations include the effects of exposure to $PM_{2.5}$ and NO_2, but not the effects of direct exposure to SO_2. This is because separating the effects of multiple pollutants is challenging when their concentrations are highly correlated, which is usually the case. The main health impact of SO_2 emissions is the exposure to sulfate particles, which are a part of $PM_{2.5}$, formed from the emitted SO_2; this effect is included in the impact estimates.

The fundamental equation used for projecting increases in health impacts, based on Anenberg et al (2010) is:

$$\Delta y_{ij} = y_{0ij}\left(1 - exp^{-\beta_i \Delta x_j}\right)p_j$$

where Δy is the change in mortality, y_0 is the baseline mortality, p is the population in the applicable age group, Δx is the change in concentration, i is the specific cause of mortality and j is the country. β is the coefficient in the regression equation of the effect estimate for the specific mortality cause:

$$RR = exp^{\beta \Delta X}$$

where RR is the risk ratio reported in the original study and ΔX is the concentration change for which the risk ratio is reported (see Table 5 for the RR values used).

Location-specific population was based on high-resolution gridded population data for 2015 from NASA SEDAC (Jones and O'Neil 2017), and then Baseline death rates in Chile from different causes were obtained from WHO Global Health Estimates (2014), birth rates and incidence of low birth weight from World Bank's DataBank service (http://databank.worldbank.org/data/home.aspx).

Table 5 Risk ratios from different studies used for health impact assessment.

Risk ratio for 10 µg/m^3 increase in $PM_{2.5}$ exposure	**Central**	**95% CI, low**	**95% CI, high**	**Reference**
Cardiopulmonary diseases	1.128	1.077	1.182	Krewski et al 2009
Ischemic heart disease	1.287	1.177	1.407	Krewski et al 2009
Lung cancer	1.142	1.057	1.234	Krewski et al 2009
Risk ratio for 10µg/m^3 increase in NO_2 exposure				
All causes[1]	1.055	1.021	1.08	WHO 2013

[1] *When calculating total health impacts, central and low values for NO_2 are scaled down by 1/3 to remove possible overlap with $PM_{2.5}$ impacts, as indicated in WHO (2013).*

Results

The emissions from two studied coal-fired plants sites are likely to result in approximately 80 premature deaths per year due to exposure to $PM_{2.5}$ and NO_2 (Table 5).

Pollutant	Cause	Huasco	Puchuncavi	Total
$PM_{2.5}$	*Lung cancer*	1	7	8
	Other cardiovascular diseases	1	12	13
	Ischemic heart disease	2	11	12
	Stroke	1	10	12
	Other respiratory diseases	1	4	5
	Chronic obstructive pulmonary disease	0	3	4
	Total	**6**	**48**	**54**
NO_2	**All causes**	**1**	**32**	**33**
All	**Total**	**7**	**69**	**76**

Table 5 Projected premature deaths and other health impacts caused by emissions from the studied power plants, cases per year.

Toxic fallout

The CALPUFF model was also used to predict the deposition of pollutants onto land and water, due to rain and dry deposition. The pollutant emissions from coal-fired power plants lead to deposition of toxic heavy metals, fly ash, acid rain and mercury (Figure 11, Figure 12 and Figure 13). The deposition mainly occurs during rains and in this region is consequently largest to the north-northeast of the power plants. At both Huasco and Puchuncavi, the majority of toxic deposition takes place during the rains in the winter.

Of the 220kg/year of mercury estimated to be emitted by the plants, approximately 100kg or 40% is estimated to be deposited into land and freshwater ecosystems. Mercury deposition rates as low as 125mg/ha/year can lead to accumulation of unsafe levels of mercury in fish (Swain et al 1992). The plants are estimated to cause mercury deposition above 125mg/ha/yr over an area of approximately 400km^2, based on the modeling results (Figure 11). Using the high-resolution population data, we estimate that 30,000 people live in this area.

While actual mercury uptake and biomagnification depends very strongly on local chemistry, hydrology and biology, the predicted mercury deposition rates are certainly a cause for concern and for further study.

Acid deposition could affect forests and other natural ecosystems. Farmers can see affected yields or increased input costs as they have to neutralize the deposition. Acid rain also damages property and culturally important buildings. Coal fly ash contains toxic heavy metals that are associated with a range of health risks. Most intense acid and fly ash deposition takes place to the north-northeast and south-southeast of the plants, on the coast, with deposition in the most affected areas exceeding 20kg of SO_2-equivalent per hectare per year in an area of approximately 60km^2. (Figure 12). Fly ash deposition rates exceeding 5kg/ha/year are predicted in the vicinity of the plants in an area of approximately 70km^2 (Figure 13).

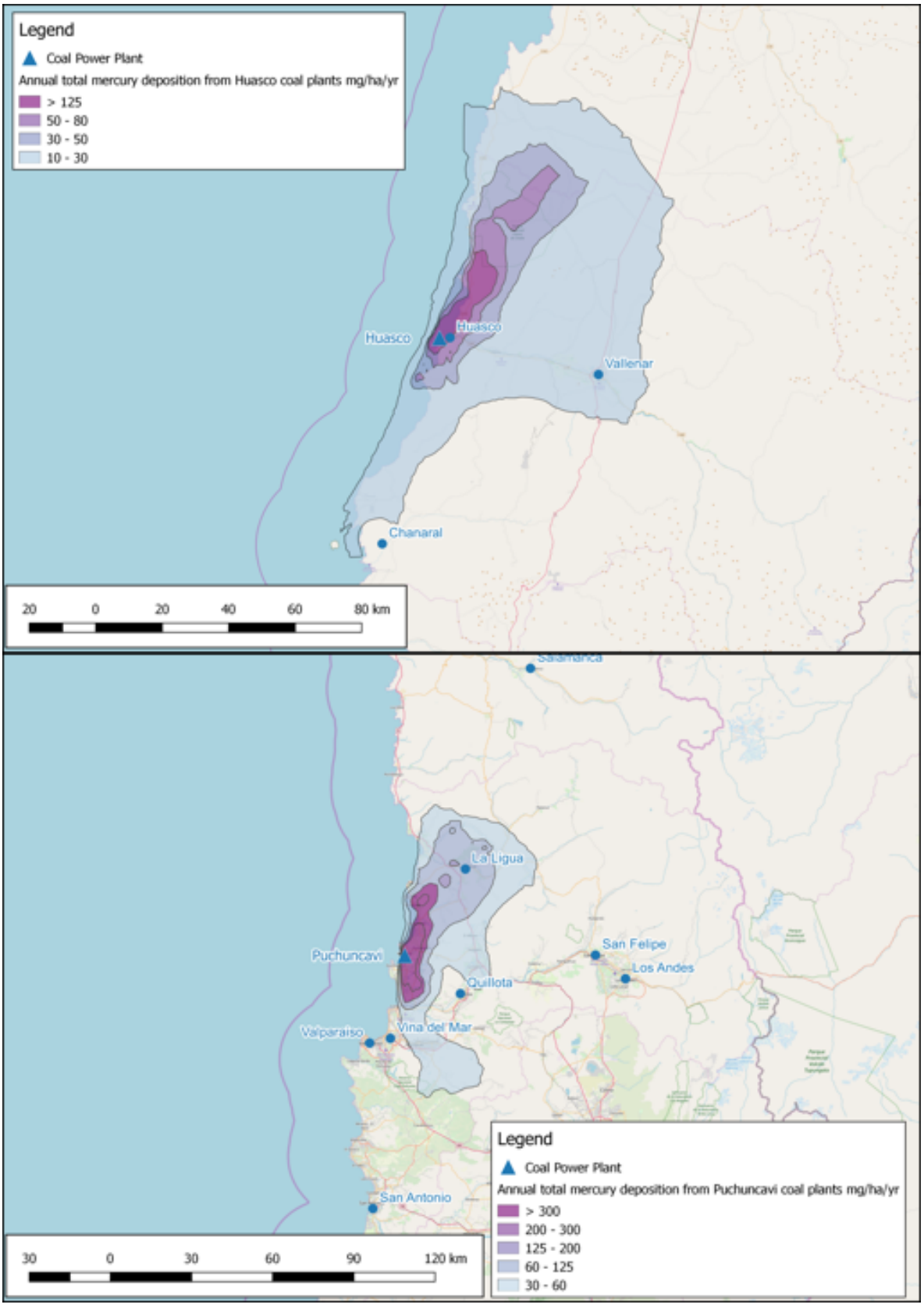

Figure 11 Projected mercury deposition from the studied power plants.

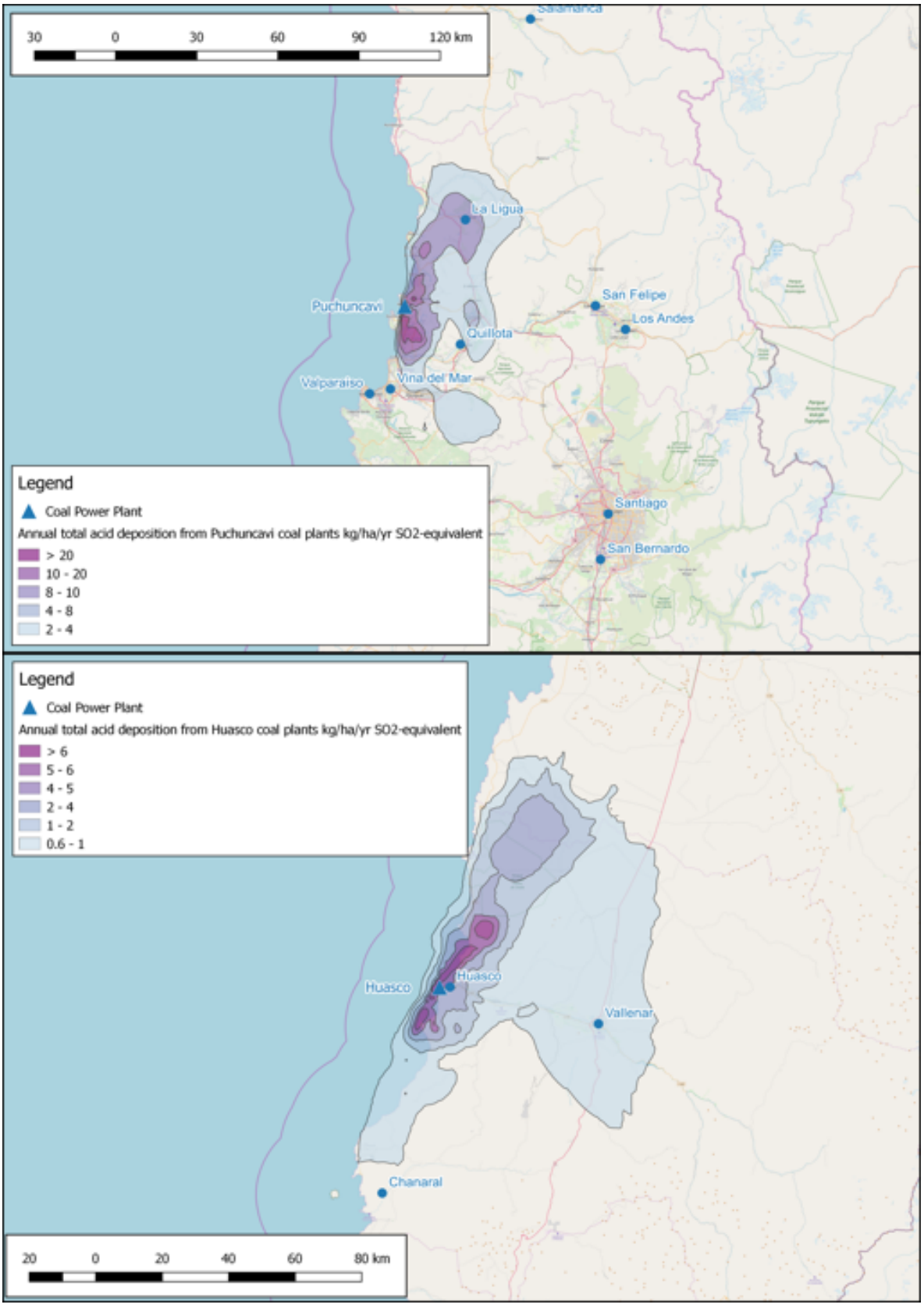

Figure 12 Projected acid deposition (SO2 equivalent) from the Celukan Bawang power plant.

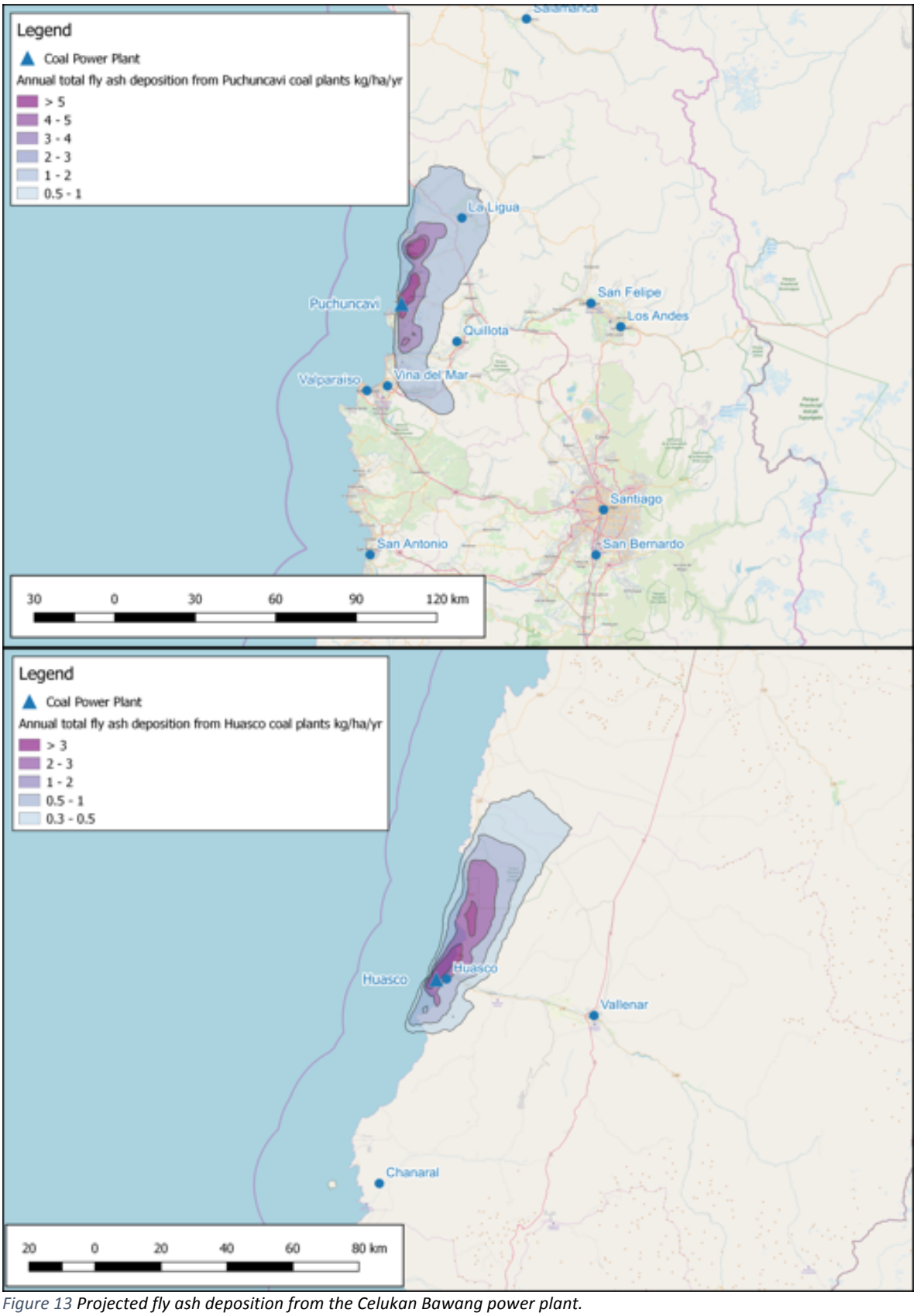

Figure 13 ***Projected fly ash deposition from the Celukan Bawang power plant.***

References

Anenberg S.C. et al, 2010. An estimate of the gobal burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. Environ Health Perspect. 118:1189–1195. doi: 10.1289/ehp.0901220

Coordinador Eléctrico Nacional, 2018. Restricciones Ambientales de centrales termoeléctricas. https://www.coordinador.cl/informe-documento/determinacion-de-parametros-operacionales-de-unidades-generadoras/restricciones-operativas/

Comisión Nacional de Energía, 2018a. Energía Abierta: factores-de-emision-anual-por-unidad-de-generacion. http://datos.energiaabierta.cl/dataviews/248821/factores-de-emision-anual-por-unidad-de-generacion/

Comisión Nacional de Energía, 2018b. Consumo de combustibles de centrales del sistema eléctrico nacional para el año 2017. http://cne.cl/wp-content/uploads/2015/05/consumo-de-combustible-SEN.xlxs

Exponent 2011: CALPUFF Modeling System Version 6. User Instructions. http://www.src.com/calpuff/download/CALPUFF_Version6_UserInstructions.pdf

Jones, B., and B. C. O'Neill. 2017. Global Population Projection Grids Based on Shared Socioeconomic Pathways (SSPs), 2010-2100. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC).

Koplitz, N. et al. 2017: Burden of Disease from Rising Coal-Fired Power Plant Emissions in Southeast Asia. Environmental Science & Technology. http://dx.doi.org/10.1021/acs.est.6b03731

Krewski, D et al. 2009. Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality (No. 140). Boston, MA: Health Effects Institute.

Lee SJ, Seo YC, Jang HN, Park KS, Baek JI, An HS, Song KS, 2006. Speciation and mass distribution of mercury in a bituminous coal-fired power plant. Atmospheric Environment 40:2215–2224.

Ministerio de Energía, 2018. Estudio de variables ambientales y sociales que deben abordarse para el cierre o reconversión programada y gradual de generación eléctrica a carbón. Consultora INODU. 192p.

Sistema Nacional de Información y Fiscalización Ambiental, 2018. Datos abiertos: Emisiones de Centrales Termoeléctricas (D.S. 13/2011) para el año 2017. http://snifa.sma.gob.cl/v2/DatosAbiertos

Toro RA, M Canales, RG Flocchini, RGE Morales, MA Leiva, 2014. Urban Atmospheric Ammonia in Santiago City, Chile. Aerosol and Air Quality Research, 14:33–44.

UNEP, 2017. Toolkit for Identification and Quantification of Mercury Releases. UN Environment Chemicals Branch, Geneva, Switzerland.

US EPA, 2005. AP 42, Fifth Edition Compilation of Air Pollutant Emissions Factors.

World Bank (WB), Databank, World Development Indicators. http://databank.worldbank.org/data/home.aspx

World Health Organisation (WHO), 2006. WHO Air Quality Guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005.

World Health Organization (WHO), 2013. Health risks of air pollution in Europe-HRAPIE project. http://www.euro.who.int/__data/assets/pdf_file/0006/238956/Health_risks_air_pollution_HRAPIE_project.pdf?ua=1

World Health Organization (WHO), 2014. Global Health Estimates. http://www.who.int/healthinfo/global_burden_disease/estimates/en/index1.html