Application of a regional-scale model over the central part of Chile

1. Introduction

The severe air pollution that characterizes the Santiago Metropolitan Area is mainly a consequence of large emissions within the city itself, in combination with a very low ventilation due to low wind speeds and strong inversions, particularly in fall and winter. In spring and summer, in spite of the better ventilation and vertical mixing high concentrations of photochemical pollutants are observed. Incoming air to the Santiago basin has relatively low concentration levels for most primary pollutants. However, the presence of three large copper smelters – Caletones some 150 km to the south, Ventanas and Chagres some 100 km to the northwest of Santiago in the Aconcagua valley– implies the possibility of a regional transport of oxidized sulfur into the Santiago basin. In addition, the regional dispersion of oxidized sulfur is an issue of concern of its own due to its impact on agriculture and air quality in other urban areas of this part of the country (E.g. Rancagua, Valparaíso, etc.).The application of the HIRLAM-MATCH model system of Central Chile constitutes the first attempt to assess the regional influence of the copper smelter emissions.

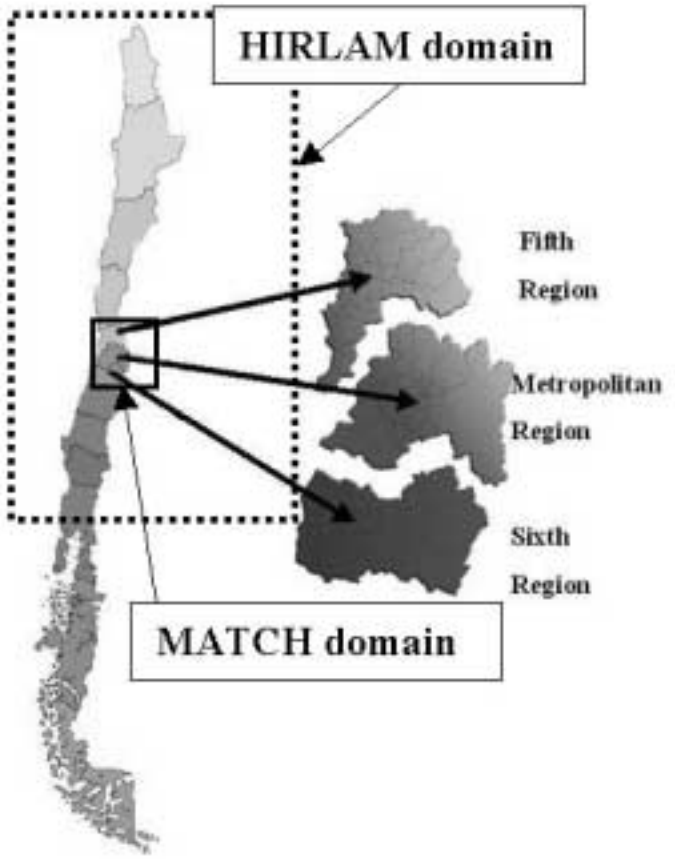


Fig.1 Geographical extension of the HIRLAM and MATCH models. Horizontal resolution is 0,1 degree (approx. 11 km) for HIRLAM and 5 km for MATCH.

The regional dispersion of pollutants in Central Chile is a complex topic that requires of a variety of concurrent efforts such as the development of emission inventories, air quality and meteorological monitoring, meteorological and dispersion modeling. When designing the project, in view of the available resources, it was decided to emphasize modeling aspects on the regional scale, i.e., dispersion processes driven by and at time scales of synoptic and subsynoptic weather patterns such as frontal passages and coastal lows. Fig.1 shows the application areas chosen for the meteorological (HIRLAM) and dispersion (MATCH) models. The project organization is presented in Table 1.

Table 1. Project organization for work area 2

	Chile	**Sweden**
Co-ordination	Laura Gallardo (Expert Advisor)	Lars Gidhagen
Experts	Gustavo Olivares (Modelling Specialist) Ariel Aguayo (Computer Science Specialist)	Magnuz Engardt (MATCH specialist) Joakim Langner (HIRLAM-MATCH specialist) Bodil Aarhus (HIRLAM specialist) Lennart Robertsson (HIRLAM-MATCH specialist) Lars Tellgren/Fredrik Andrén (Computer specialists)

Administration	Elizabeth Avila Carlos Parr/Patricio Graziano	Monika Johansson/Ingela Alderin

2. Project objectives

The main objective of this project was stated as:

> *To implement and take into operation a regional dispersion model with the purpose to determine the influences of different sources on the air quality of the central part of Chile (Metropolitan Region, Regions V and VI).*

Int the project plan, the specific objectives of this work area were formulated as:

- *To determine the meteorological fields (winds, temperature, precipitation, etc.) that affect the dispersion of pollutants in central Chile, starting from a forecast model of high resolution.*
- *To determine the temporal and spatial distribution of the pollutant deposition flows and concentrations in central Chile, including its physical and chemical transformation*
- *To validate the simulations through a systematic comparison of the results with available observations.*
- *To evaluate the contribution of different anthropogenic sources to the air pollution levels.*
- *To evaluate the efficiency of the measures contained in the attainment plans applied in central Chile (Metropolitan Region, Caletones and Ventanas copper smelters).*

3. Project activities

The project plan listed a number of specific work tasks that can be summarized as follows:

- Model implementation
- Validation of model results
- Analysis and synthesis of the regional dispersion model results
- Publications and seminars

All activities and goals defined in the project plan have been fulfilled, see result summary below.

4. Summary of achieved results

4.1 Model implementation

The regional dispersion model implemented for Central Chile uses as input meteorological wind fields calculated in Sweden and emissions from the Santiago Metropolitan area derived from the AIRVIRO database administrated by CONAMA Región Metropolitana (see Fig. 2). Preliminary emission inventories for other urban areas in the Central Chile were also included in and administrated through AIRVIRO.

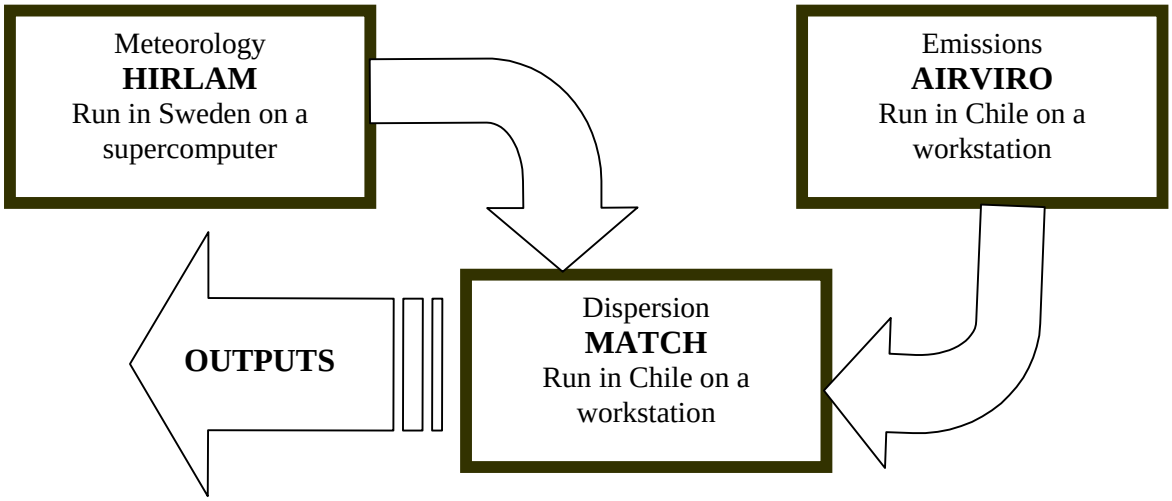


Fig. 2 Scheme over the implementation of the modeling system.

SMHI has, as part of the project, provided CONAMA with a suite of meteorological scenarios covering various typical meteorological conditions that affect Central Chile, including extreme conditions under El Niño and La Niña years. HIRLAM was executed for six month-long periods: May-June 1997, January and May 1998, June-July, October and November-December 1999. By re-combining those six monthly periods, CONAMA is able to generate wind fields also for dispersion simulations of coming years and future emission scenarios.

The MATCH implemented in Santiago can be used with different chemical complexity (Table 2). All validations and results within this project area have been performed with the M3 model version, i.e. solving for SO_2 and sulfate.

Table 2. MATCH model versions implemented in Santiago

MATCH model 1 (M1)	Inert tracer	Arbitrary inert tracer without deposition to the surface.
MATCH model 2 (M2)	Inert tracer with deposition.	As M1 but with species dependent dry and wet deposition.
MATCH model 3 (M3)	Sulphur chemistry	Linear sulphur chemistry based on the concept of EMEP. Including deposition.
MATCH model 4 (M4)	10-component chemistry	Chemical scheme including sulphur and reduced and oxidised nitrogen. Including deposition.
MATCH model 5 (M5)	Photochemistry	A complete photochemical scheme that includes ca. 130 reactions among 58 chemical compounds, including aromatics, ketones, peroxyacetyl nitrate, etc..

4.2 Validation of model results

The windfields simulated by HIRLAM have been compared both to Chilean synoptic surface stations, as well as with existing vertical sounding data from Quintero/Santo Domingo and La Platina. Comparisons with the network installed in the Santiago basin were also performed. Fig. 3 shows how HIRLAM is able to simulate the meteorological conditions during wintertime episodes of the so called A-type (coastal lows along the coast).

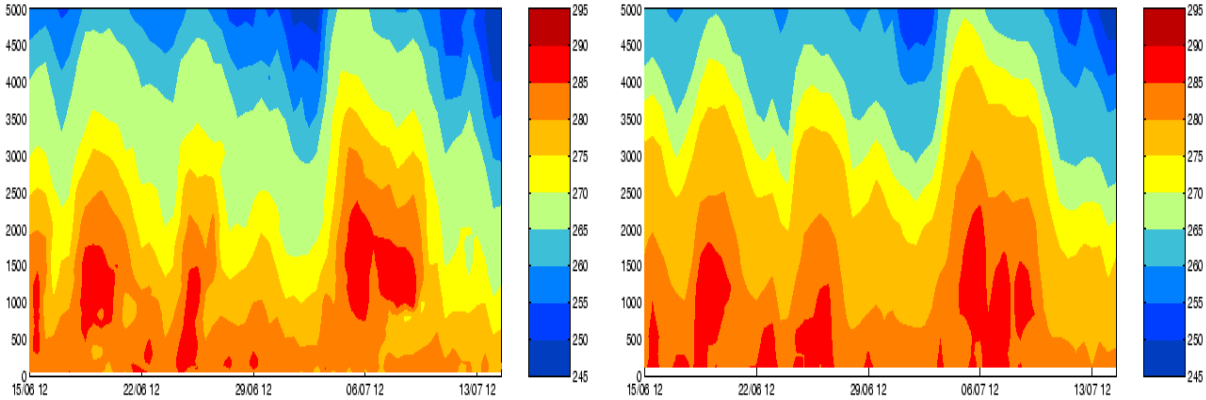
The systematic validation made between HIRLAM results and measured data has showed:

- The model is able to describe the differences in wind patterns, cloudiness and precipitation during different seasons, i.e. the shift from clear weather conditions with pronounced diurnal variations in wind speed and direction and temperature at inland locations during summer to more cloudy conditions during winter connected with synoptic disturbances.
- HIRLAM captures synoptic variations (moving low- and high-pressure systems and fronts) during major parts of the simulated months. This is evidenced through comparisons with observations of surface pressure, cloudiness and precipitation as well as soundings of wind and temperature (see Fig. 3). The main exception to this is the period May-June 1997, which is poorly simulated.
- In particular the model is able to capture the meteorological conditions during the two major winter episodes in May 1998 and July 1999. These periods were characterized by very stable conditions and low wind speeds in the central region of Chile connected to the movement of low level lows along the coast, so called A-type episodes.
- The model has a tendency to under estimate low-level cloudiness in the central Chile region during winter periods. This leads to too strong vertical mixing during daytime and too strong surface winds. However, this is not a problem during the major air pollution episodes (A-type) because then there is generally little cloudiness.

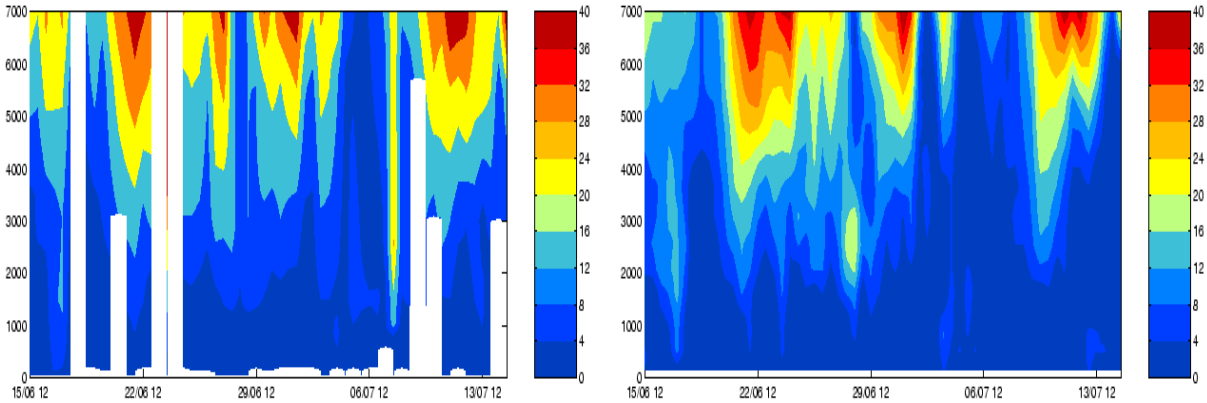
- The model is good at predicting surface wind speeds in the Santiago region. However, with a tendency towards too high values during winter and a too low during summer.
- For wind direction at the surface there are larger differences between observations and simulations. The differences between the model and the observations are however of the same magnitude as the difference between neighboring observation stations. This indicates that the model performance is as good as could be expected given the model resolution and that differences seen are governed by small-scale topographic effects.
- Comparisons of vertical profiles of horizontal wind at a La Platina located in the southern outskirts of Santiago shows that the agreement between model simulated and observed wind direction and speed is much better at one hundred meters above the surface than at the surface. The agreement improves further when comparing higher levels and at 1700 m above surface the agreement is very good. This supports the conclusion that the model simulations provide a good description of the horizontal wind patterns on a regional scale in central Chile except for the layer close to the surface.

Observation **June-July 1999** Model simulation

Temperature (K)



Wind speed (m/s)



Wind direction (deg)

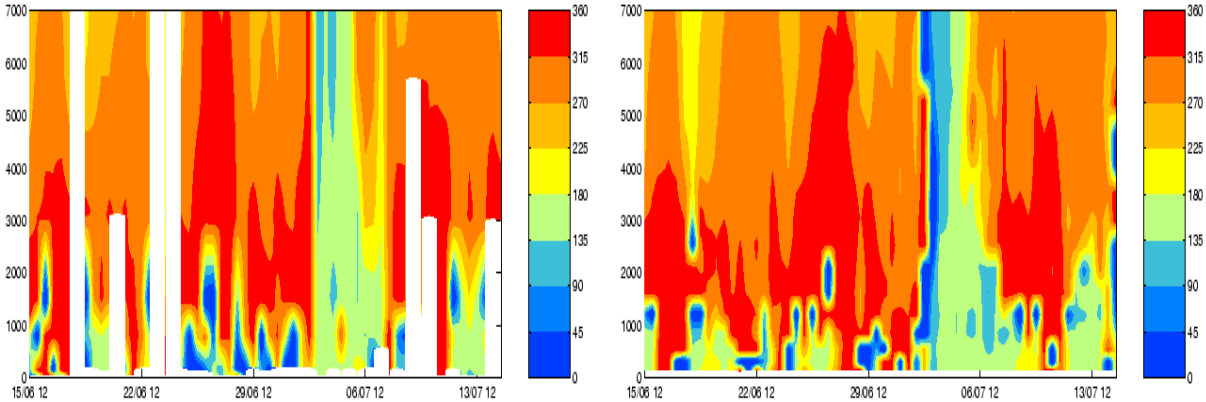


Fig. 3 Observed (left panels) and model simulated (right panels) vertical profiles of temperature (K), wind speed (m/s) and wind direction (deg) for the sounding station Santo Domingo at the coast of the central part of Chile in June-July 1999.

The validation of the MATCH model results has been limited by the fact that there is presently no regional monitoring network operating in Chile. Available SO_2 data are principally from the Santiago city monitoring network (named the MACAM network) and from some monitoring networks close to the copper smelters. Sulfate data are even more sparse. Fig. 4 shows comparisons of simulated and measured SO_2 at the MACAM station Parque O'Higgins, the station that appears most representative for the regional scale. The way the model handles wintertime episodes of the A-type is illustrated by the sulfur dioxide and sulfate leveles of Fig. 5and 6.

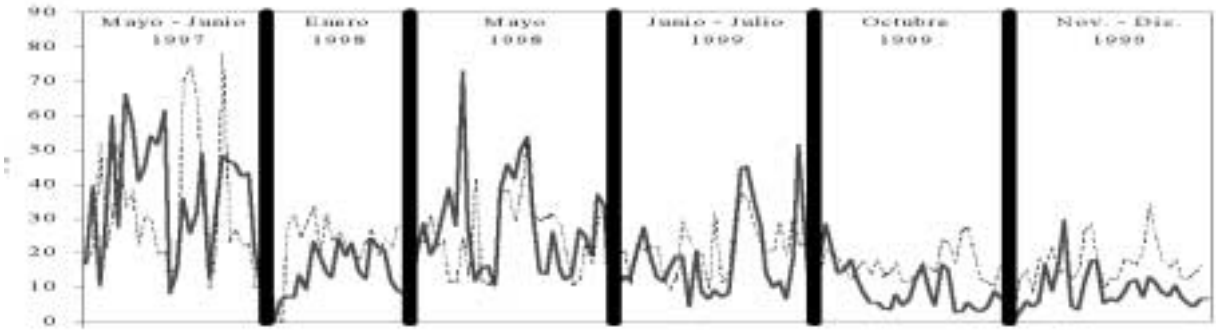


Fig. 4 Comparison between the simulated (blue/dashed) and observed SO_2 concentrations at Parque O'Higgins (EMD) in downtown Santiago for the six simulated periods. Units: μg/m^3.

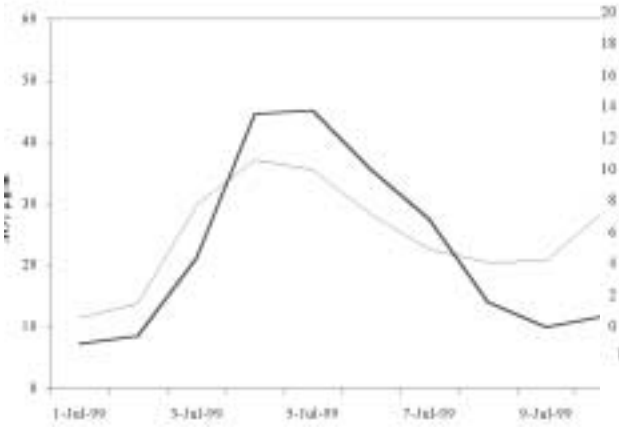


Fig. 5 Daily averages of SO2 concentrations measured (red/coarse) and simulated (blue/light) during an A type episode in July 1999. Units: μg/m^3.

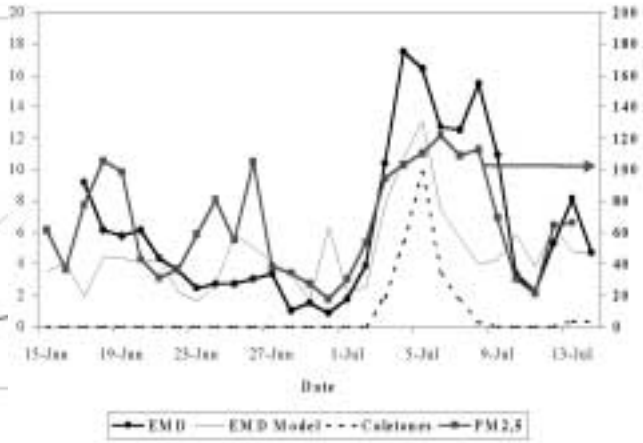


Fig. 6 Daily averages of sulfate concentrations measured (black/coarse) and simulated (blue/light) during June-July 1999. Also the measured PM2.5 concentrations (red/coarse) and the estimated contribution from the Caletones smelter are indicated. Units: μg/m^3.

The conclusions drawn from the MATCH model comparisons with data can be summarized as:

- On a monthly average basis the simulations reproduce the observed sulfur dioxide concentrations as well as the variance of the data in Santiago and Rancagua. Clear mismatches occur though in stations located in the immediate surroundings of the largest point sources, i.e., the copper smelters, partly because the model resolution is not enough to resolve local circulation patterns.
- The observed daily averaged SO_2 concentrations are well captured by the model in the Santiago basin. Also some features of the diurnal cycles are simulated. However, significant discrepancies occur in connection with shortcomings in the representation of the meteorological fields such as mismatches in wind direction due to topography effects or wind speed due to cloud cover effects.

- The simulated sulfate concentrations are consistent with the seasonal averages of the total sulfur content measured in aerosol filters for inhalable particle matter (PM_{10}) during winter 1998 in downtown Santiago. Moreover, the daily averaged values observed during a campaign in winter 1999 are also in good agreement with the simulations.

4.3 Analysis and synthesis of the regional dispersion model results

The regional model study of oxidized sulfur levels in Central Chile yields the following results:

- According to the model simulations, oxidized sulfur is regionally dispersed over Central Chile, i.e., there is a long-range transport of the sulfur emissions that affect the fifth, sixth and Metropolitan political regions where between one third and 50% of the country's population lives. This is illustrated in Figure 7.

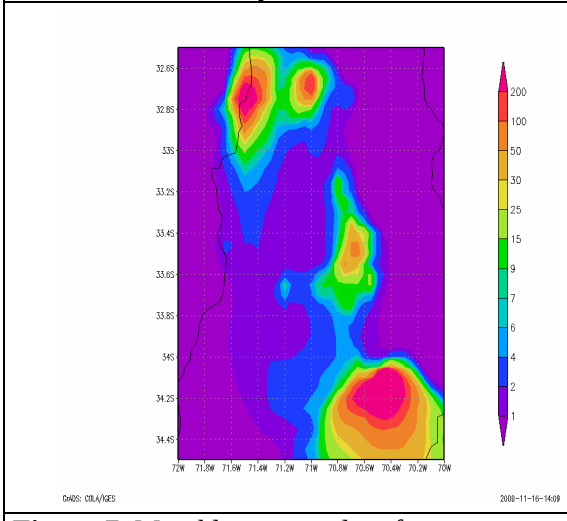
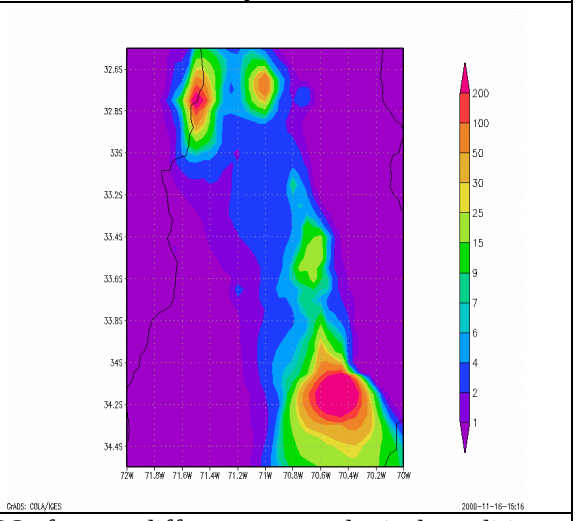
May-June 1997	May 1998
	

Figure 7. Monthly averaged surface concentration of SO_2 for two different meteorological conditions. May-June 1997 corresponds to a rainy month under El Niño conditions whereas May 1998 corresponds to a dry fall/winter month with nearly no precipitation (La Niña year). Unit: µg SO_2 m^{-3}.

- The predominance of the copper smelters as contributors to the burden of oxidized sulfur in Central Chile has been shown according to the MATCH simulations. In all scenarios, the emissions from the copper smelters dominate the overall horizontal and vertical distributions of sulfur in Central Chile. Thus if measures are to be taken to avoid or to diminish the impacts on agriculture and vegetation those should be related to the copper smelter's emissions.
- Additionally, the copper smelters contribute episodically to oxidized sulfur burden inside Santiago. During summer, the impact seems to be related to the strong vertical mixing that takes place during the afternoon at hours of highest insolation. In the fall and dry winter cases, the impact appears to be related with the strong general subsidence associated with the configuration of strong coastal lows (A type episodes). Besides, there is a connection between the episodic impact of the copper smelters and the appearance in downtown Santiago of aged air masses with higher sulfate to SO_2 ratios, i.e., associated with secondary aerosols or fine particles (diameter <2.5 µm).
- The urban emissions, particularly those of Santiago, only affect significantly the city surroundings. The contribution to the oxidized sulfur burden of the urban sources at rural sites outside Santiago, as well as above the boundary layer, is estimated to be less than 10%.
- A first assessment of the regional oxidized sulfur budget over Central Chile, i.e. some 200x200 km^2 around Santiago, has been presented. This budget shows that Central Chile is a net source of sulfur and that the most abundant reservoir is sulfur dioxide with ca. 95% of the total atmospheric burden. Only a smaller fraction (<5%) of the emitted SO_2 is converted to sulfate within the area under consideration. Nevertheless, since the emissions are so large (ca. 40 kton S/yr), this together with primary sulfate emissions give rise to a significant atmospheric burden of sulfate tightly related to fine particles (diameter < 2.5 µm).

- The budget calculations show that the most important removal mechanism is by far dry deposition. However, in rainy winters wet deposition can add up to 50% of the total deposition.
- Most part of the emitted sulfur is exported outside the model domain. Even though the dominant feature of the atmospheric circulation in Central Chile, i.e., the Pacific high, produces an overall south-to-north transport pattern, a significant fraction of the emitted sulfur (ca. 40%) is exported south of the largest point source in the area, namely Caletones.
- These results make it necessary to enlarge the spatial coverage of the ongoing monitoring activity and also to begin a thorough analysis of impacts in agriculture and vegetation in general both within the area under consideration in this study and to the south of it.

The model study clearly shows the dominant role of copper smelter emissions for the atmospheric sulfur burden over Central Chile, and the necessity to reduce those emissions in order to avoid e g damages on vegetation in the region. In a parallel study, initiated by CONAMA and concerning the impact of Arsenic emissions, the copper smelters was shown to be the dominating sources of airborne arsenic all over the Central and North Chile territory.

A specific and key issue for the CONAMA regional authority in Santiago to handle in the PPDA plan is to separate out the different contributions to the elevated levels of partially and completely inhalable particles, PM_{10} and $PM_{2.5}$ respectively, found in the city, both the sources contributing with primary particles as well as those emitting gases that participate in the secondary formation of particulate matter. The following discussion will only build on the smelters contribution to sulfate levels, this as the regional model study focused on oxidized sulfur. The regional impact of the other parts has not yet been assessed.

The MATCH model results for the Santiago inner areas gave an average impact of total oxidized sulfur (sulfur dioxide + sulfate) of up to 15% originating from the copper smelters surrounding Santiago. Thus, 85% of the impact is associated with the city emissions. However, the model results also indicate that the impact of the smelters, mainly Caletones– the smelter south of Santiago -, during A-type episodes, can be as high as 50% of the total sulfur burden in the Santiago basin.

Speciation analyses of particulate matter and source receptor modelling in Santiago show sulfate contents of about 20% of total mass for $PM_{2.5}$ and 8% for PM_{10}. Hence, other sources probably related to fossil fuel combustion and transportation sources in Santiago are responsible for the remaining 80% and 92% of the mass in $PM_{2.5}$ and PM_{10} particles, respectively. In other words, the copper smelter emissions will contribute to approximately 3% ($PM_{2.5}$) and 1% (PM_{10}) of the average particulate levels. Altogether, in order to improve the air quality of Santiago with respect to pollution by oxidized sulfur and particulate matter, one has to focus on a reduction of local emissions. However, since there is a significant impact of the smelters, especially Caletones in connection with high concentration episodes associated with coastal lows, this source's influence should not be disregarded in the control plans for particulate matter in Santiago (particularly when discussing fine particles). Still the major control efforts must be oriented towards urban transportation sources and fossil fuel combustion.

Based on model results, a design of a future regional monitoring network has been incorporated in the project activities. A total of eight stations, including a couple of wet only collectors, have been proposed. The need for one or more regional background stations has been appointed also by an international expertise group while auditing the PPDA plan. In 2001 a preliminary evaluation of the proposed observation sites was initiated by means of passive samplers for sulfur dioxide, nitrogen dioxide and ozone. The evaluation forms part of the recently started five-year program to assess the sustaintability of the atmosphere in Central Chile, a program driven by CONAMA.

4.4 Publications and seminars

The project has generated the following official reports:

- Regional dispersion of oxidized sulfur over Central Chile using the HIRLAM-MATCH system Progress report March 2000 (main document in Spanish, appendices in English)
- Regional dispersion of oxidized sulfur over Central Chile using the HIRLAM-MATCH system Final report December 2000 (executive summary in English and Spanish, technical appendix in English)

In addition the project has generated the following technical reports (initiative taken by CONAMA):
- Gallardo, L., Olivares, G., Aguayo, A., Langner, J, Braahus, B., 1999: Regional Dispersion of Oxidized Sulfur over Central Chile: A summer Case. Comisión Nacional del Medio Ambiente (main document in English, summary in Spanish).
- Olivares, G., Gallardo, L., Aguayo, A., Langner, J, Braahus, B., 1999: Regional Dispersion of Oxidized Sulfur over Central Chile: A fall Case. Comisión Nacional del Medio Ambiente (main document in English, summary in Spanish).

Those reports constitute the technical documentation of the project work and were presented on two seminars organized in Santiago, each counting 30-50 participants from various Chilean authorities and Academia (Available at tralka.dcc.uchile.c/match). CONAMA has also, based on the results of the Swedish project, presented a scenario assessment for the reformulation of the National sulfur dioxide standard and prepared a document concerning the impact of the Caletones smelter:

- Dispersión de azufre oxidado en Chile central y escenarios de emisiones: Apoyo a la revisión de la normativa ambiental vigente. Gallardo, L., Aguayo, A. y Olivares, G., CONAMA, July 2000 (in Spanish)
- ¿Cuánto impacta Caletones en la cuenca de Santiago? – Una estimación para azufre oxidado y una inferencia para PM2.5Laura Gallardo, CONAMA, April 2001 (in Spanish)

In April 2000, preliminary results were presented at the 6th International Conference on Southern Hemisphere Meteorology and Oceanography, 6th ICSHMO, organized by the American Meteorology Society:

- Gallardo, L., Olivares, G., Aguayo, A., Langner, J., Engardt, M., Aarhus, B. and Gidhagen, L., 2000: *Application of a regional scale model over Central Chile*, in the Conference Proceedings.

Also, two manuscripts have been prepared and will be submitted to scientific journals with editorial committees:
- Gallardo, L., Olivares, G., Langner, J. and Aarhus, B., 2001: Coastal lows and sulfur air pollution in Central Chile.
- Olivares, G., Gallardo, L**.,** Langner, J. and Aarhus, B., 2001: Regional dispersion of oxidized sulfur in Central Chile.

Finally, this work has resulted in a M.Sc. thesis in Chemical Engineering (Universidad de Chile) by Gustavo Olivares, which will be defended in July 2001.

The final technical report was submitted to approximatively 50 representatives from Chilean authorities and Academia. Observations and comments on the reports and scientific manuscripts have been provided by several experts.

4.5 Future use of the regional model system

This modeling system as well as the results provided hereto can be of use for a variety of environmental problems that must be faced in Central Chile, where about 50% of the population lives and where a significant agriculture activity takes place. Especially in view of the needs of long-term planning posed by the fact that urban areas and infrastructure in Central Chile, including interregional highways and trains, are expected to grow and develop further.

Furthermore, this tool can be utilized in other areas of Chile, particularly in the northern part of the country, to assess other important environmental issues. The same system has indeed been applied to assess the regional dispersion of arsenic in Central and Northern Chile. Altogether, this project has strengthen the air quality information system and improved our understanding of the intricate processes that govern the regional dispersion of pollutants, and therefore we hope it will improve our environmental managing capabilities for facing and hopefully preventing those problems.

It is important to stress that the MATCH dispersion model is not exclusively dependent on meteorological input data from the HIRLAM model currently in operation at SMHI. In future applications for the Santiago Region it will be possible to use wind fields calculated by either HIRLAM with higher horizontal resolution or some other weather forecast model e.g. MM5. Also, diagnostic procedures are being implemented to improve the resolution of the simulations in connection with applications in the Aconcagua valley (Fifth region) and the Talcahuano area (Eigth region) where attainment plans are under evaluation.