

Strengthening of the Air Quality Information System

Working area 2: Application of a regional-scale model over the central part of Chile

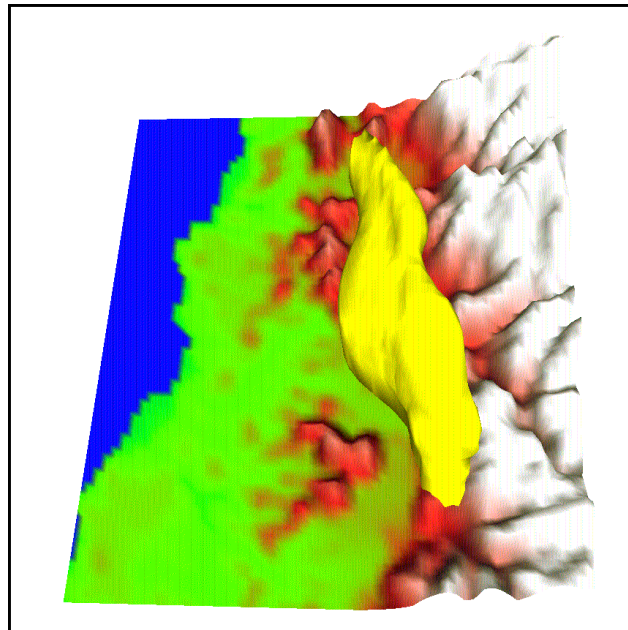
REGIONAL DISPERSION OF OXIDIZED SULFUR OVER CENTRAL CHILE USING THE HIRLAM-MATCH SYSTEM

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Sulfur dioxide plume (15 ppbv surface) over Central Chile during an A-type episode in early July 1999 as simulated by HIRLAM-MATCH

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ABSTRACT

When assessing air pollution problems, no single tool, in spite of accuracy and/or complexity, may give satisfactory answers regarding process understanding and efficient attainment measures. Hence, like any other environmental issue, dealing with air pollution requires of a systemic approach in which suites of tools ranging over a broad span of disciplines and considerations are applied. Dispersion modeling is one of the necessary tools to assess air pollution. Again, suites or batteries of dispersion models might be required. This work corresponds to the first attempt to assess the regional distribution of oxidized sulfur by means of a regional-scale modeling system. This is a cooperation project between the National Commission for the Environment (CONAMA) and the Swedish Meteorological and Hydrological Institute (SMHI) initiated in 1999. Several reasons justify the application of regional-scale modeling tool. Nearly one third of the population of Chile (i.e., about five million people) is found in the Metropolitan area of Santiago. This brings industries, private and public transportation, domestic and industrial energy consumption and other activities that result in large emissions of pollutants. From other cities and some large point sources in Central Chile emanate other pollutants and pollutant precursors. Of particular interest are the large copper smelters: Caletones, Ventanas and Chagres, which stand for ca. 95% of the total sulfur emissions in this part of Chile. The combination of meteorological conditions adverse to the ventilation and of large emissions of pollutants to the atmosphere promotes the occurrence of high concentrations of pollutants, which pose a risk for the population and the vegetation. Due to their physical and chemical characteristics many of the pollutants (inhalable particles, oxidized sulfur, oxidized nitrogen, hydrocarbons, ozone, etc.) are likely to be dispersed on a regional scale, i.e., over hundreds of kilometers downstream from the sources. Altogether, these considerations make it meaningful to apply a regional modeling tool with the purpose to determine the influences of different sources on the air quality of the central part of Chile. Particularly in view of the fact that urban areas and infrastructure in Central Chile, including interregional highways and trains, are expected to grow and develop further. To implement and evaluate such a tool has been the overall objective of this project. This project has provided a regional-scale dispersion model, a suite of validated meteorological data sets covering various typical meteorological conditions that affect Central Chile, including extreme conditions under El Niño and La Niña years. It has given valuable insights regarding the regional dispersion of oxidized sulfur in this part of the country, and an assessment of the contribution of the smelters to the air quality in the heavily populated Metropolitan area of Santiago. Furthermore it has produced relevant inputs for establishing a regional monitoring network. At last but not least, it has provided strongly needed Chilean know-how in dispersion modeling. Altogether, this project has strengthened the air quality information system, improving our understanding of the intricate processes that govern the regional dispersion of pollutants and therefore of our environmental managing capabilities for facing and hopefully preventing those problems.

1. INTRODUCTION

In the last years, efforts have been made to establish emission inventories, meteorological and air quality networks in urban areas, especially in Santiago (33.5° S, 70.8° W). These data begin to make modeling applications for meso- and regional scale air pollution problems a meaningful exercise. Here we present a first attempt to assess the regional distribution of man-made pollutants, mainly oxidized sulfur, in Central Chile (See Figure 1) using a regional-scale modeling tool. This effort is part of a cooperation project between the National Commission for the Environment (CONAMA) and the Swedish Meteorological and Hydrological Institute (SMHI) initiated in 1999, which has been developed within the framework of a cooperation agreement between the Regional Government of Santiago in Chile and the County Administration of Västra Götaland in Sweden (See <http://www.swe-chile.com> for details).

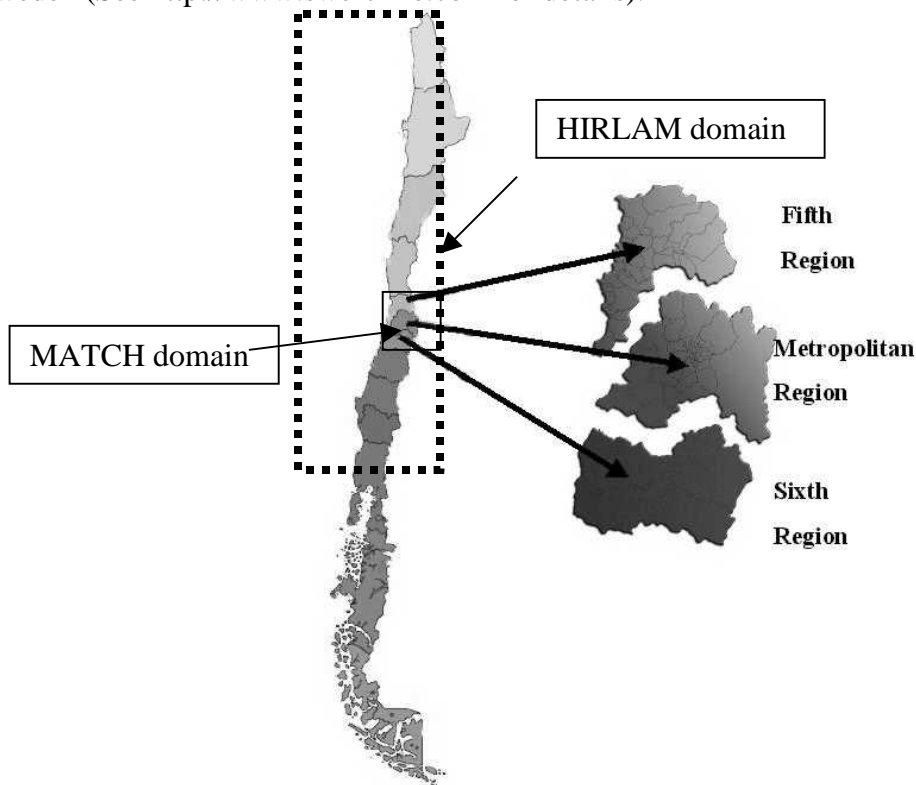


Figure 1. Political regions of Chile for which the model is applied, i.e., 5th(V), 6th(VI) and Metropolitan. Also, the model domains for which HIRLAM-MATCH was applied are shown.

Several reasons justify the application of regional-scale modeling tool. Nearly one third of the population of Chile (i.e., about five million people) is found in the Metropolitan area of Santiago. This brings industries, private and public transportation, domestic and industrial energy consumption and other activities that result in large emissions of pollutants. From other cities and some large point sources in Central Chile emanate other pollutants and pollutant precursors. Of particular interest are the large copper smelters: Caltones (34°05'S, 70°27'W, 2400 m.a.s.l.), Ventanas (32°44'S, 71°29'W, 10 m.a.s.l.) and Chagres (32°40'S, 70°53', 600 m.a.s.l), which stand for ca. 95 % of the total sulfur emissions in this part of Chile. The combination of meteorological conditions adverse to

the ventilation and large emissions of pollutants to the atmosphere promotes the occurrence of high concentrations of pollutants, which constitute a risk for the population and the vegetation (Ostro et al., 1996; Ilabaca et al., 1999; García-Huidobro et al., 2000). Due to their physical and chemical characteristics many of the pollutants (inhalable particles, oxidized sulfur, oxidized nitrogen, hydrocarbons, ozone, etc.) are likely to be dispersed on a regional scale, i.e., over hundreds of kilometers downstream from the sources. Besides, external reviewers of the attainment plan for Santiago stressed that it was necessary to count on a regional scale dispersion model (CONAMA-RM, 1999). Altogether, these considerations make it meaningful to apply a regional modeling tool with the purpose to determine the influences of different sources on the air quality of the central part of Chile. This is a model able to reproduce regional patterns of dispersion, seasonal changes and long-term trends. To implement and evaluate such a tool has been the overall objective of this project.

To assess 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 only 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. Furthermore, we chose to focus on oxidized sulfur since, on one hand, it is an environmental issue of concern, and on the other hand, the emissions and atmospheric concentrations of oxidized sulfur have been regularly monitored at several places over several years making it easier to bracket the model outputs than for other pollutants. Figure 2 shows the location of the air quality monitoring stations used in the model evaluation as well as the main cities and the copper smelters (The Figure also shows the complex topography of the area). From the beginning we were aware that the available monitoring stations were designed to assess health-effects and that a regional network was needed to provide baseline measurements and to assess secondary effects as those on vegetation and agriculture (García-Huidobro, 1999; García-Huidobro et al, 2000). Particularly in view of the fact that urban areas and infrastructure in Central Chile, including interregional highways and trains, are expected to grow and develop further (PRDU, 1999). Therefore, a part of this project has been to use the model outputs in order to provide insights in the design of a regional monitoring network, which we hope could be set in place in the near future.

Air pollution, on its multiple space and time scales, is determined by a suite of intricate factors, among others human behavior on individual and societal scales. Thus, it constitutes one of the most complex issues that scientists, technicians, decision-makers and people in general have to deal with. Given this complexity, no single tool, in spite of accuracy and/or complexity, may give satisfactory answers regarding process understanding and efficient attainment measures. Therefore, like any other environmental issue, dealing with air pollution requires of a systemic approach in which suites of tools ranging over a broad span of disciplines and considerations are applied. Dispersion modeling is one of the necessary tools to assess air pollution. Again, since atmospheric dispersion is also a multivariate and multiscale problem ranging from molecule-to-molecule interactions to synoptic scale weather systems, it must be addressed with batteries of models. This project has provided a regional-scale dispersion model, a suite of validated meteorological data sets covering various typical meteorological conditions that affect Central Chile, including extreme

conditions under El Niño and La Niña years. It has also given valuable insights regarding the regional dispersion of oxidized sulfur in this part of the country, and an assessment of the contribution of the smelters to the air quality in the heavily populated Metropolitan area of Santiago. Furthermore it has produced relevant inputs for establishing a regional monitoring network. At last but not least, it has provided badly needed Chilean know-how in dispersion modeling.

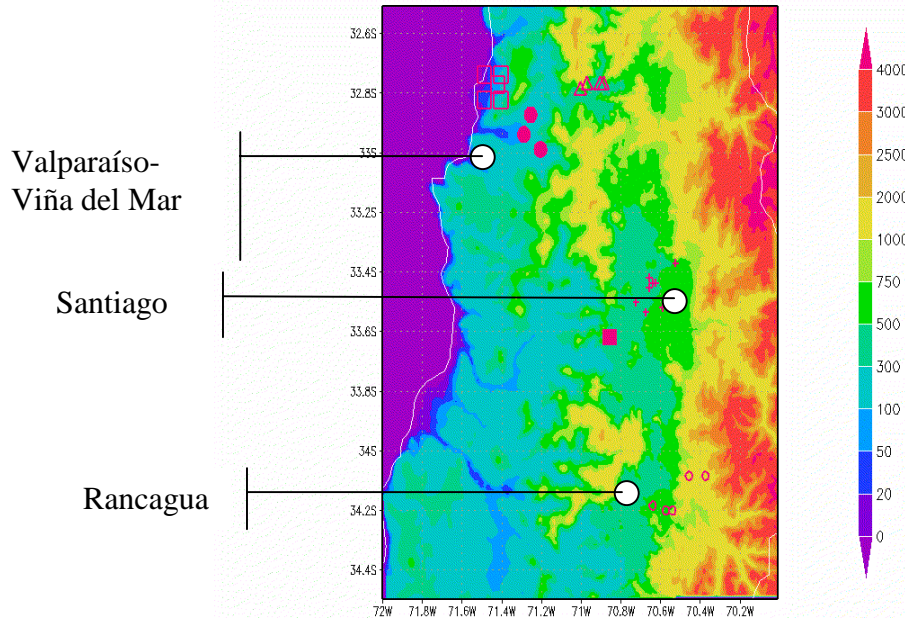


Figure 2. Location of air quality stations in the central part of Chile. The different networks are indicated with different marks: crosses correspond to the Santiago network, open circles indicate the Caletones network, filled circles are for the Quillota network, open squares correspond to the Ventanas network, open triangles indicate the Chagres network and the filled square correspond to the Talagante station. The locations of the major cities are also indicated. The topography of the area of interest is depicted on a resolution of ca. 800 m.

We highlight in Section 2 the issues addressed through this project and the main results. We review to which extent the objectives were accomplished. Section 3 summarizes the main conclusions. For a detailed description of the model set-up, the evaluation of the simulations and the conclusions the reader is referred to the technical appendix. The technical appendix summarizes all results including those presented in preliminary reports.

2. MODEL APPLICATION, EVALUATION AND RESULTS

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).

The implemented regional dispersion model is the Multiscale Atmospheric Transport and Chemistry Modeling System, MATCH, developed at SMHI (Robertson et al., 1999 and references therein). It has been applied to a suite of environmental assessments and as a research tool including sulfur and nitrogen deposition in Sweden and Southeast Asia, photochemical smog in Europe, etc. (Robertson et al., 1995; Bringfelt et al., 1997; Langner et al., 1998; Robertson et al. 1999; Engardt, 2000). Weather data are needed to drive the transport and deposition routines of MATCH. In this case, we use the outputs provided by a three-dimensional numerical weather prediction model, the High Resolution Limited Area Model (HIRLAM, <http://www.knmi.nl/hirlam/>). HIRLAM is the result of cooperation among the meteorological institutes in Denmark, Finland, Iceland, Ireland, The Netherlands, Norway, Spain and Sweden. Most of the participants use the HIRLAM numerical weather prediction system, partly or in its entirety, in their local routine weather forecasting procedures. Emission data required to drive the dispersion model were administrated through the database manager AIRVIRO (<http://www.indic-airviro.smhi.se/>). Figure 3 depicts the modeling system implemented for this project.

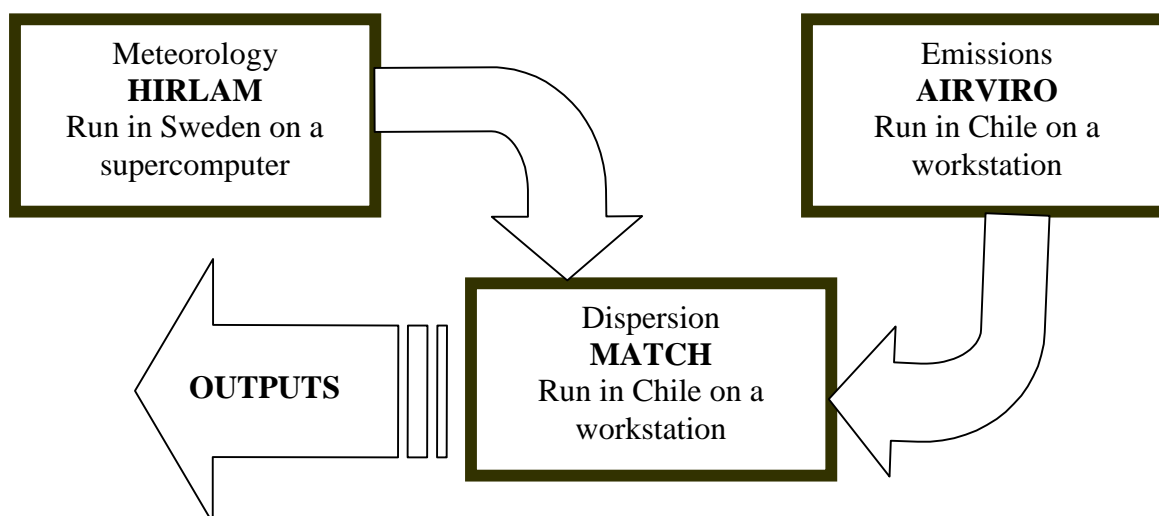


Figure 3. Scheme over the implementation of the modeling system.

A number of specific objectives were also proposed when initiating the project. Hereby we summarize to which extent those objectives were accomplished by the project:

- *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.*

This project has provided a suite of validated of meteorological data sets 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. The result is a validated three-dimensional data set with three-hour time resolution and ca. 11 km horizontal resolution that can be used in a variety of applications. This is illustrated in Figures 4 a) and 4 b). Notice the differences

in wind and cloud cover according to the differences in synoptical conditions typical for summer and winter seasons.

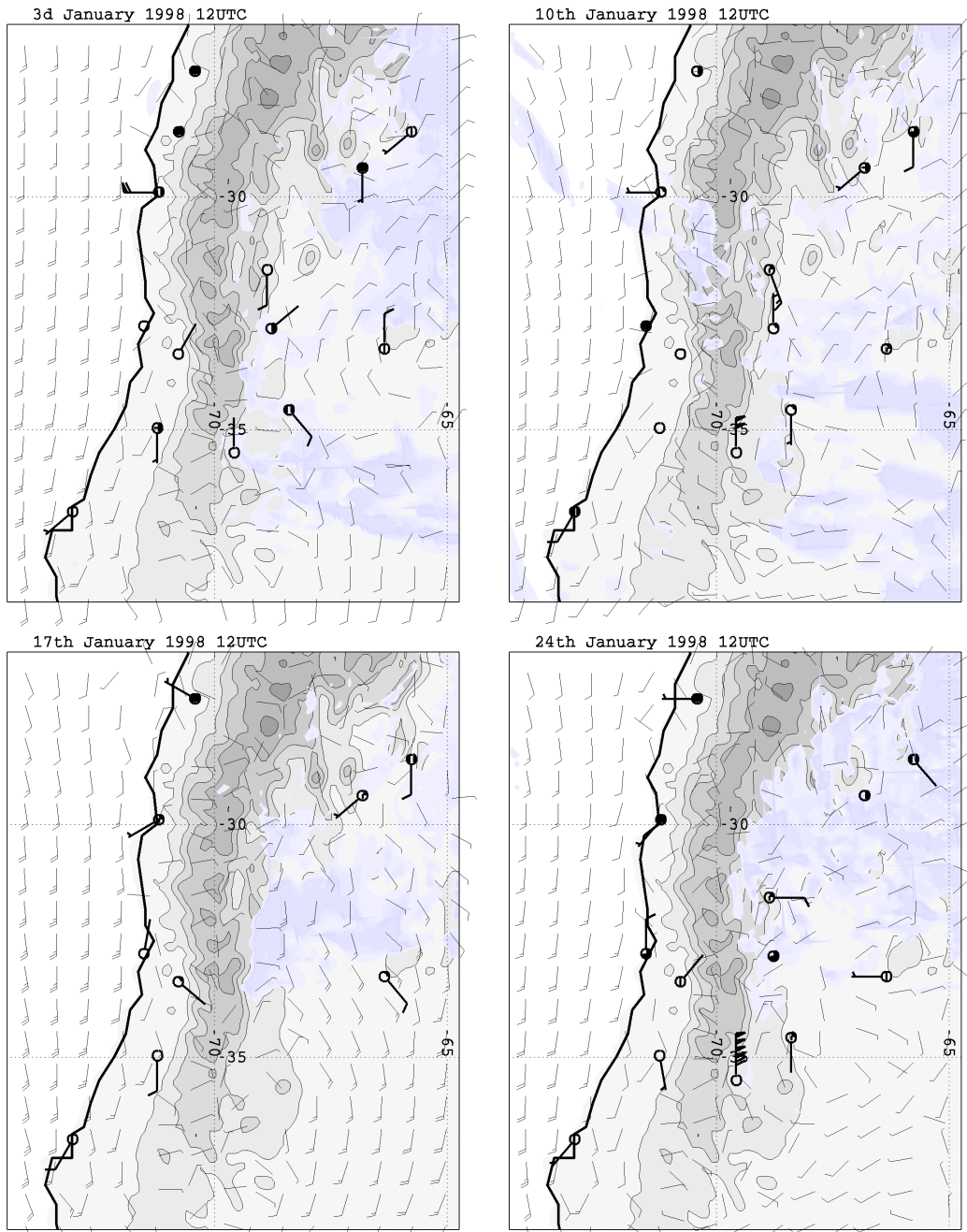


Figure 4 a) Maps of surface wind (10 meter) and cloud cover as simulated by HIRLAM for four different occasions during January 1998. Also shown is observed wind and cloud cover. The wind barb points in the direction the wind is blowing from. Speed is given in knots where half a barb represents 5 kts and a whole barb 10 kts (2 kts = 1 m/s). Note that the winds observed at the station close 35°S, 70°W seem to be in error. The filling of the station circle indicates observed cloud cover. A white circle corresponds to zero observed cloud cover while a filled circle indicates a completely cloud covered sky (eight octas).

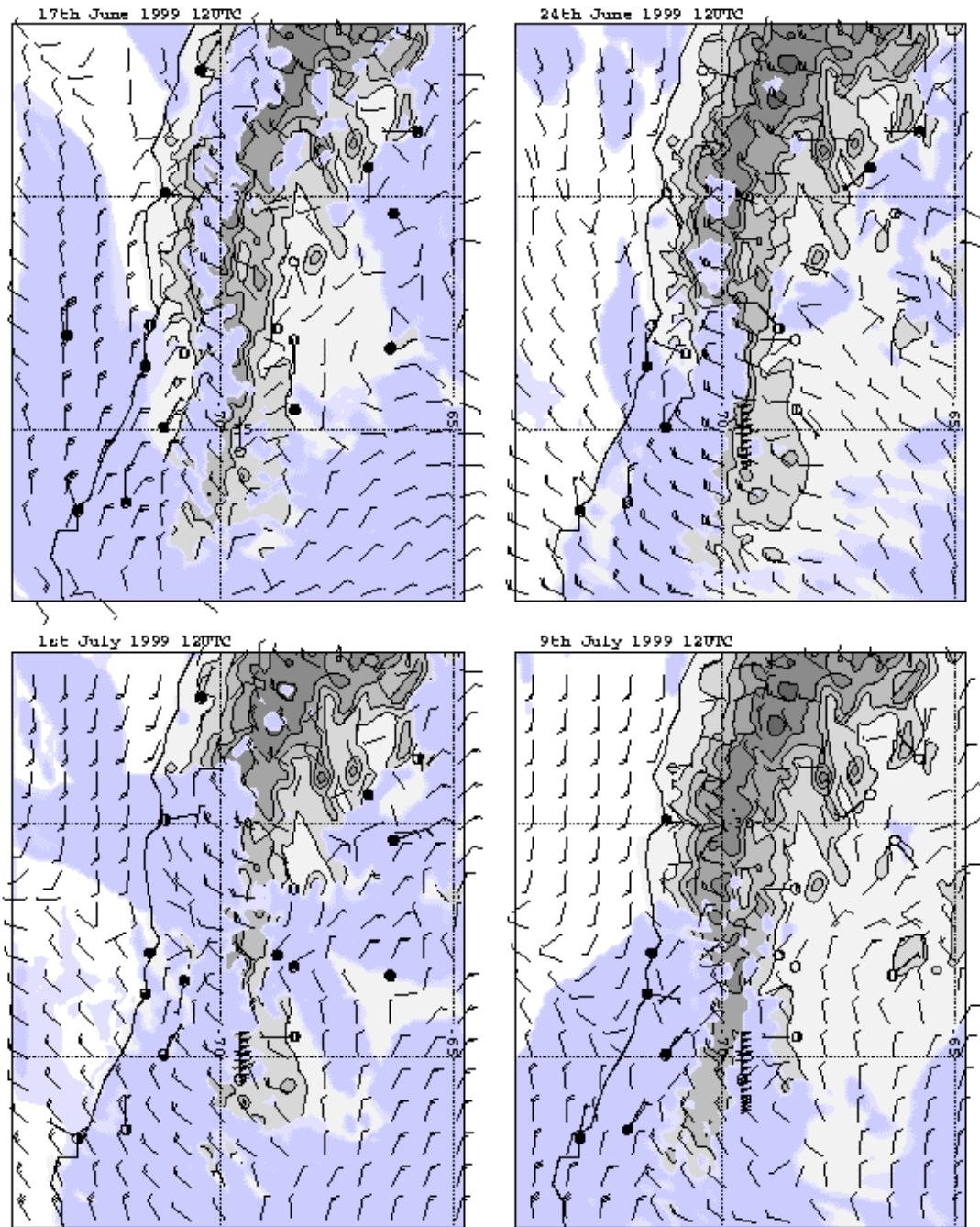
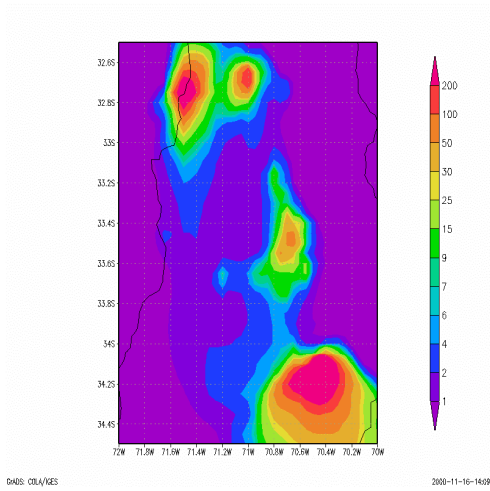


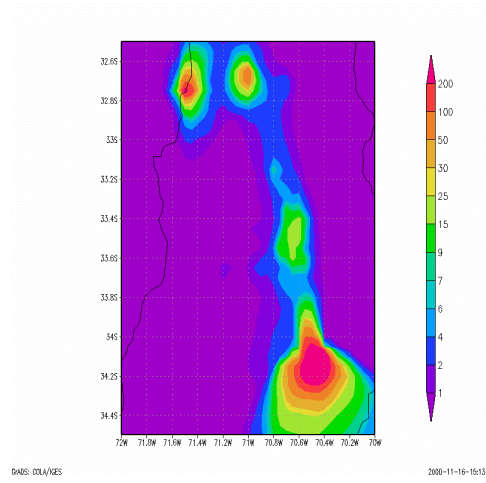
Figure 4.b) As in Figure 4a but for the period June-July 1999.

- To determine the temporal and spatial distribution of the pollutant deposition flows and concentrations in central Chile, including its physical and chemical transformation.
- The HIRLAM outputs have been used to drive the MATCH model for oxidized sulfur, i.e., for the sulfur dioxide and sulfate reservoirs. In this way, atmospheric concentrations, deposition and transformation fluxes of oxidized sulfur have been studied on annual, monthly, daily basis and in some cases on an hourly basis. Figure 5a shows the monthly average surface concentrations of sulfur dioxide for: May-June 1997, January and May 1998, June-July, October and November-December 1999. These scenarios span over a broad range of meteorological conditions including extreme situations under El Niño and La Niña years, which make them meaningful in a climatologic sense and therefore useful for long-term assessments. Figure 5b shows the corresponding fields of total deposition of oxidized sulfur. These figures (5a and 5b) show that 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. In addition, they show that there is a marked seasonal variation in the oxidized sulfur fields. Moreover, substantial amounts of sulfur are deposited in the area. These results make it necessary to enlarge the spatial coverage of the ongoing monitoring activity and also to begin a thorough analysis of impacts on agriculture and vegetation in general. Using the model outputs, we propose eight new sites to place air quality monitoring devices, including a few wet only collectors to analyze the rainwater composition (See Figure 5c). Of course, these approximate locations are to be evaluated *in situ*.
- Also a budget calculation has been performed on a monthly and annual basis over an area of ca. 200x400 km² around Santiago. 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 SO₂ 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 related to fine particles (radii < 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 elsewhere. 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.
- The simulated periods provide insights regarding the seasonal, synoptic and subsynoptic (day-to-day and week-to-week) variations, including recurrent extreme meteorological conditions, which make them useful for defining environmental strategies. Moreover, short-term simulations of specific events such a intensive coastal lows have confirmed or shed light on the mechanisms responsible for high-pollution episodes and, in general, on the regional patterns of dispersion in Central Chile.

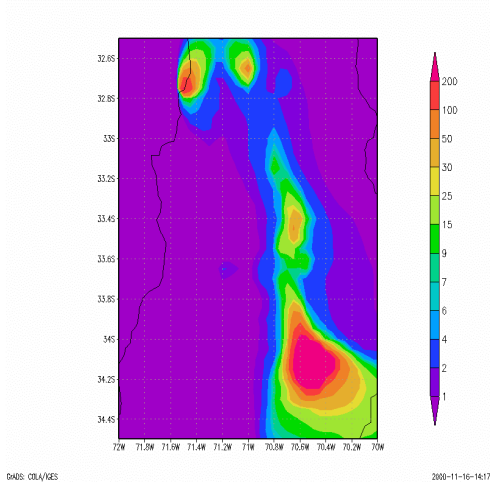
May-June 1997



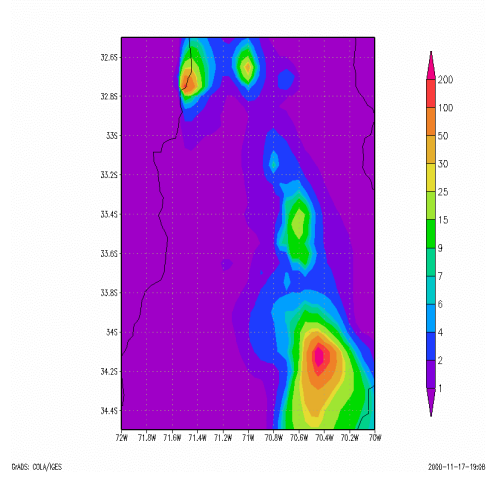
June-July 1999



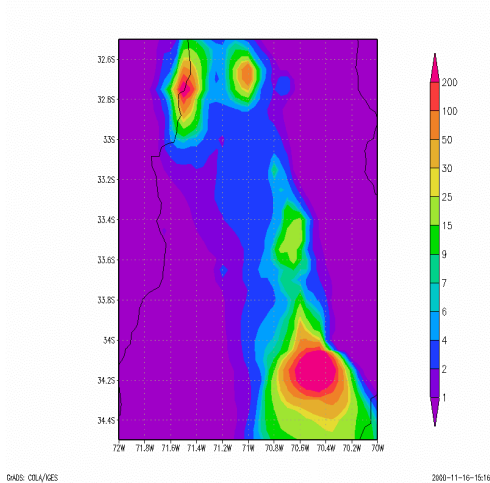
January 1998



October 1999



May 1998



November-December 1999

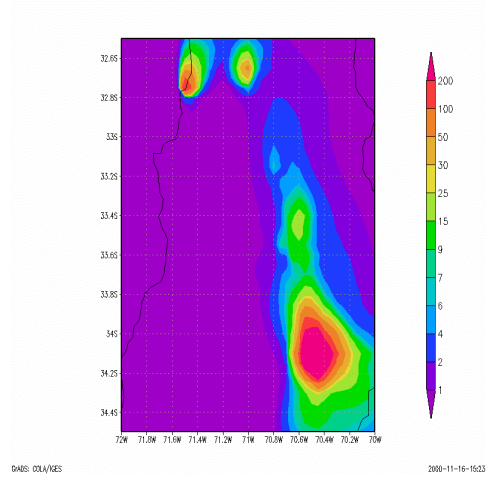


Figure 5a. Monthly average surface concentration of sulfur dioxide ($\mu\text{g}/\text{m}^3$) for six different meteorological conditions.

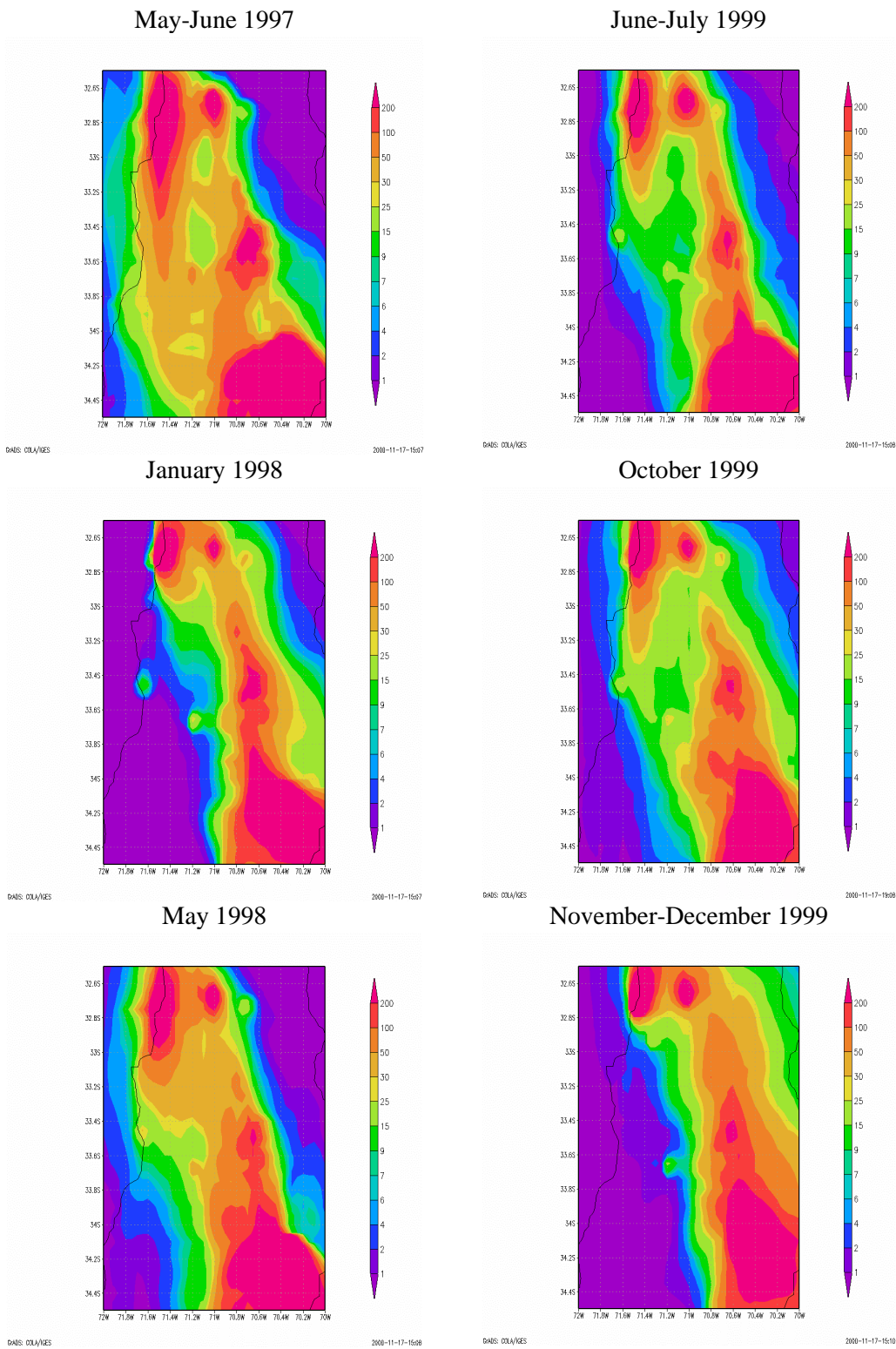


Figure 5b. Monthly sulfur total deposition (mgS/m^2) for six different meteorological conditions.

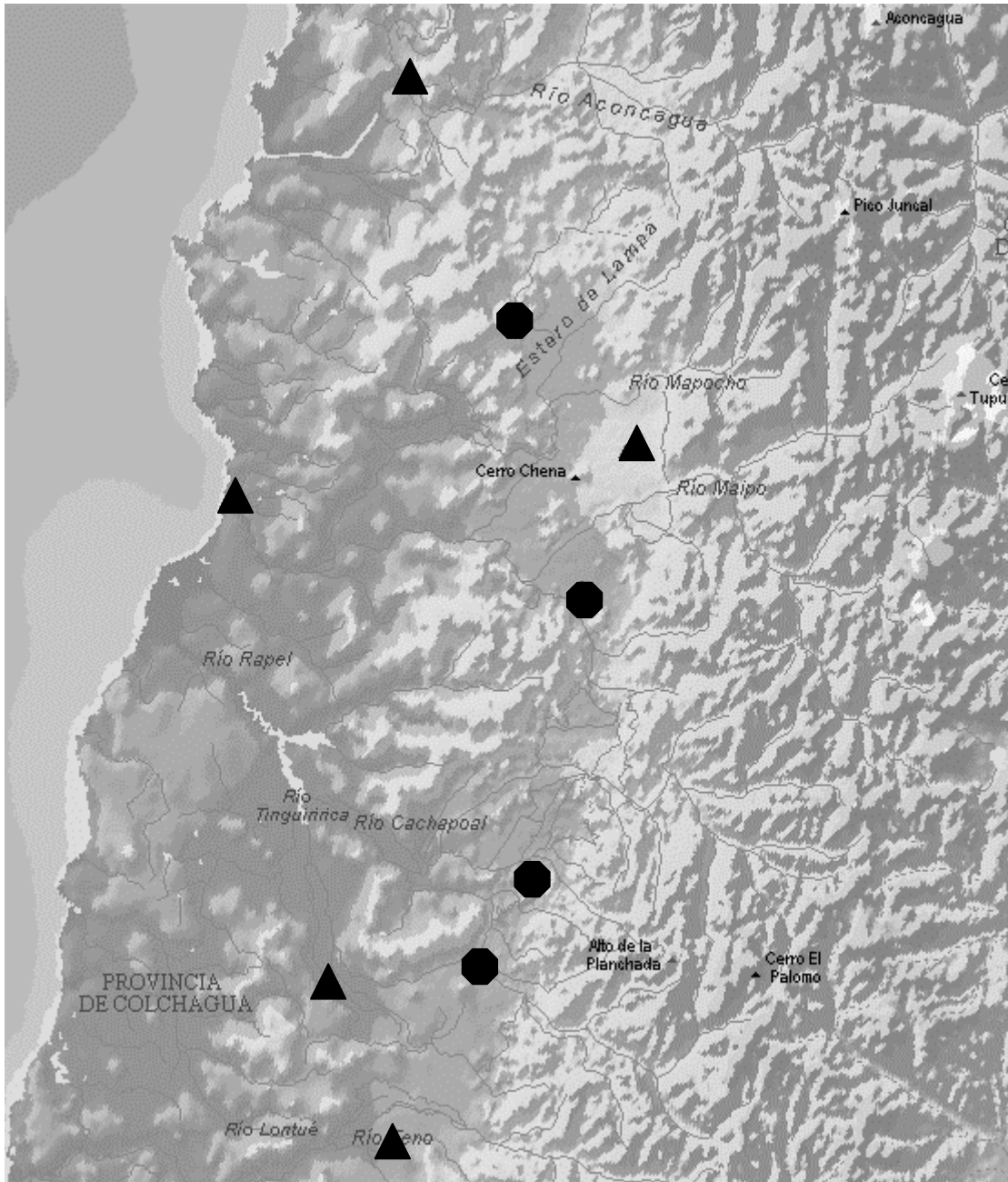


Figure 5c. Approximate location of proposed new monitoring sites. Triangles indicate sites where wet only collectors are proposed in addition to air samplers; circles indicate sites where only air sampling devices are proposed. A prioritized list of stations can be found in the technical appendix.

- To validate the simulations through a systematic comparison of the results with available observations.
- In the case of the meteorological aspects, the validation of the model simulations has been performed by a systematic comparison of the simulations with data on wind speed and direction and temperature from a subset of the ca. twenty-two stations that have been installed in the Santiago basin, including a vertical profiler at La Platina in the southern outskirts of Santiago. Available data from synoptic meteorological stations in the whole model area have also been utilized. The location of these stations is given in Figures 6a and 6b.

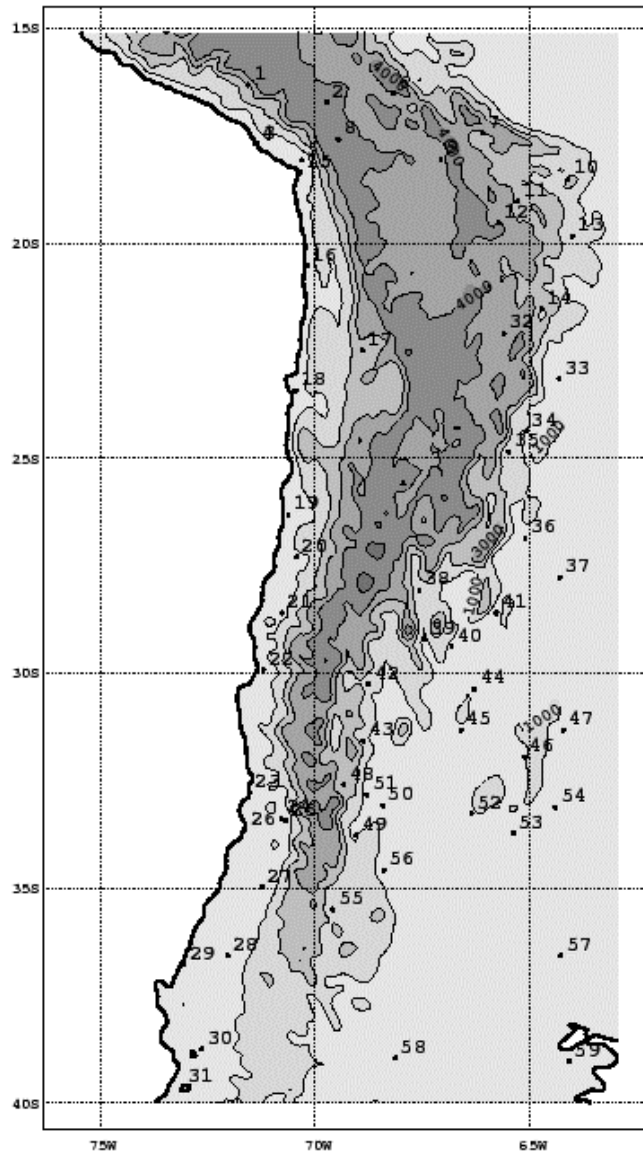


Figure 6a. The model domain and synoptic stations reporting to the World Meteorological Organization (WMO), which have been used for model validation (For details see appendix).

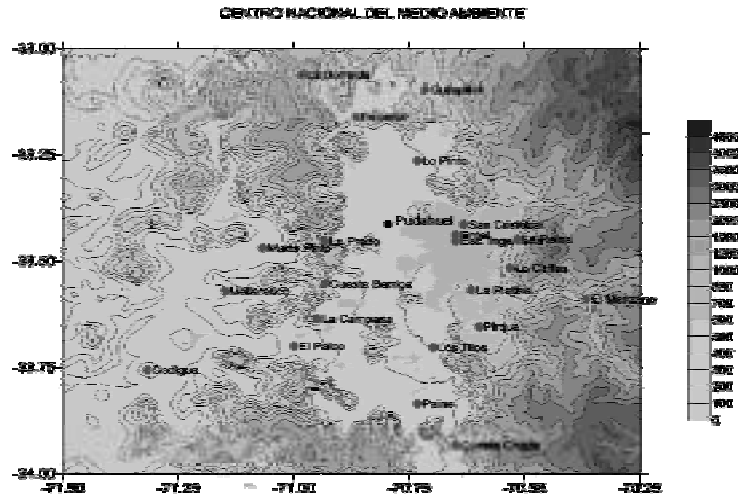


Figure 6b Map of the stations in the Santiago area used for model evaluation. These stations are managed by the National Center for the Environment (CENMA). For details see appendix. Also, Pudahuel (WMO-station number 24) is marked in the map.

- The HIRLAM 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 (e.g. fronts). Furthermore, HIRLAM is able to capture 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. The main exception to this is the period May-June 1997, which is poorly simulated. In Figure 6c we illustrate these features by showing a comparison between the model simulations and the observations at three synoptic stations for two different seasons.
- In addition, the model simulates well surface wind speeds in the Santiago region. However, with a tendency towards too high values during winter and a too low values during summer. This relates to the fact that the model has a tendency to underestimate low-level cloudiness in the central Chile region during winter periods, which occasionally 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 because then there is generally little cloudiness. These features are illustrated in Figure 6d, where a comparison in wind speed for four different areas in the Santiago basin is shown. 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 ($11 \times 11 \text{ km}^2$) and that small-scale topographic effects govern the differences seen. Comparisons of vertical profiles at La Platina show that the agreement

between simulated and observed wind direction and speed is much better at one hundred meters above the surface than at the surface. This supports the conclusion that the model simulations provide a good description regional-scale transport patterns in central Chile.

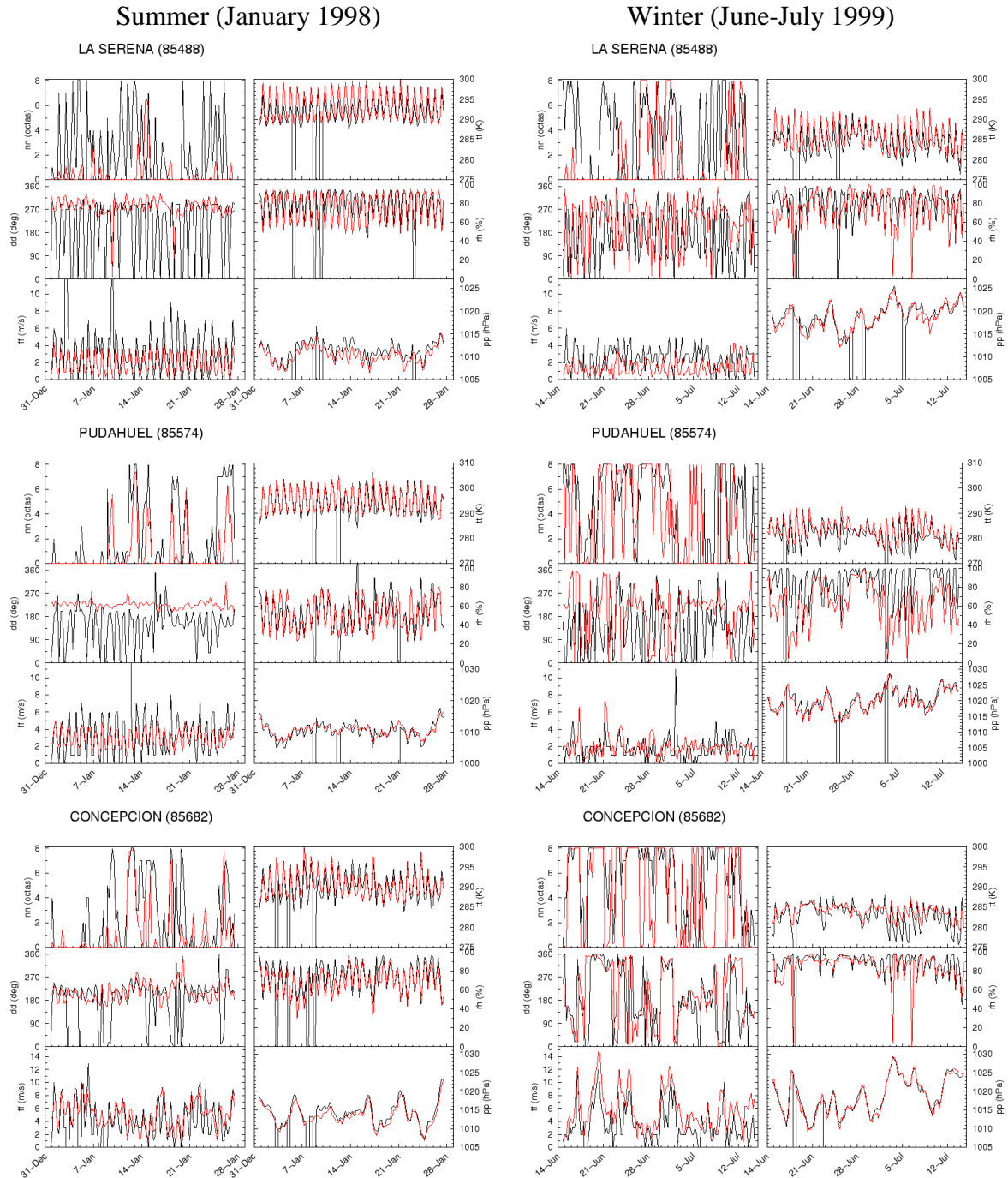
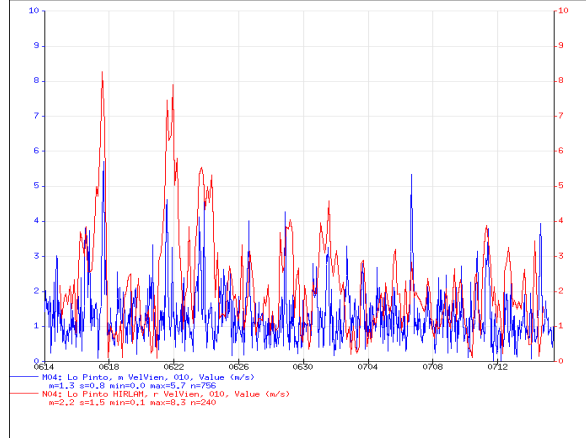
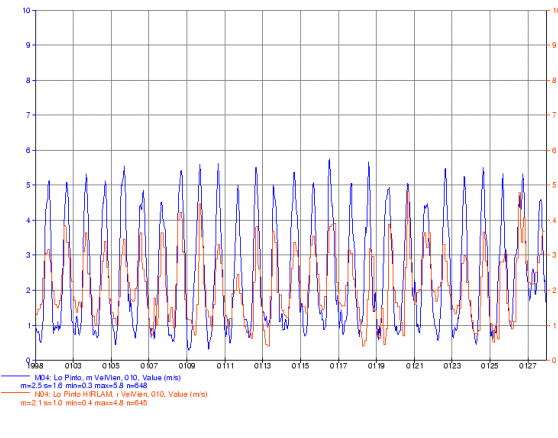


Figure 6c Observed (black) and simulated (red) cloud cover (octas), 2-meter temperature, 10-meter wind direction (deg), 2-meter relative humidity (%), 10-meter wind speed (m/s) and surface pressure reduced to mean sea level (hPa) for three synoptic meteorological stations in the central part of Chile in January 1998 and June-July 1999.

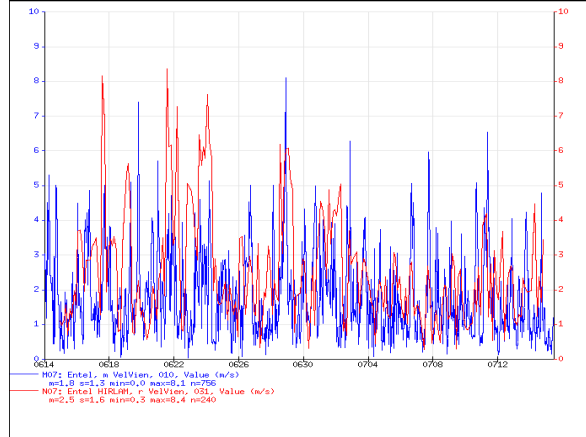
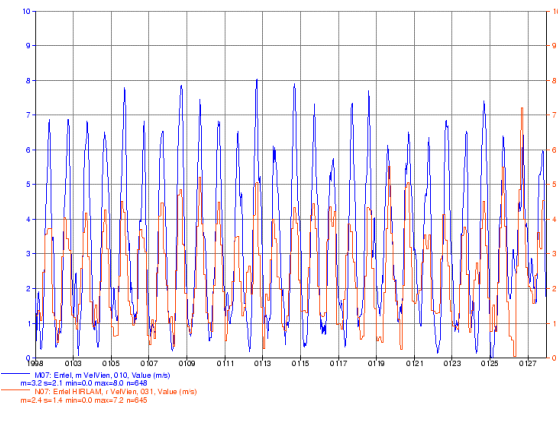
Summer (January 1998)

Winter (June-July 1999)

Lo Pinto 10 meter



Entel 120 meter



La Platina 10 meter

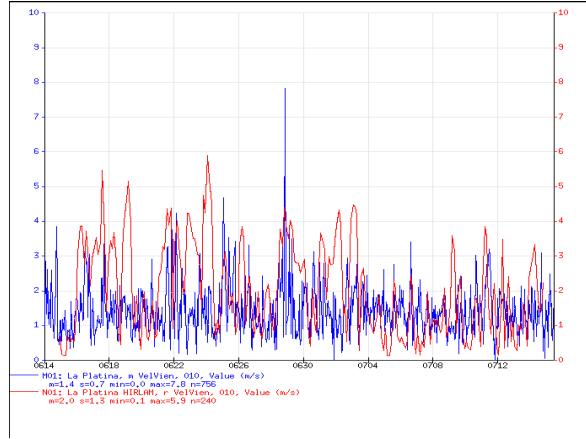
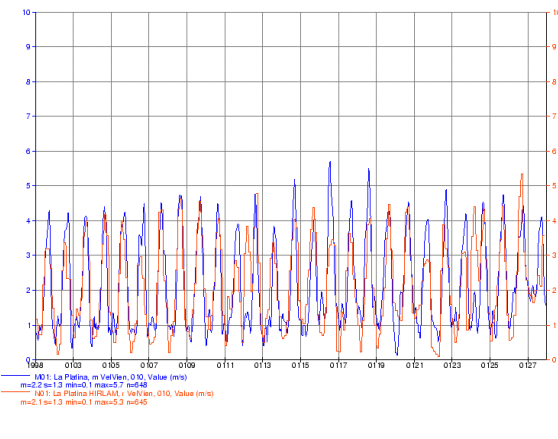


Figure 6d. Observed (blue) and simulated (red) time series of wind speed (m/s) for three meteorological stations in the Santiago region in January 1998 and June-July 1999.

- o Further, the model is able to capture the meteorological conditions during the two major winter episodes in May 1998 and July 1999 (coastal lows). 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. These coastal lows intensify the subsidence inversion, which results in inhibited dispersion and mixing that give rise to extreme pollution episodes for several pollutants in fall and winter. The model captures the large-scale characteristics of these episodes as well as the sub-synoptic characteristics. These features are illustrated in Figure 6e and Figure 6f. Figure 6e shows the observed and simulated vertical profiles from surface up to 2 km of temperature, wind for La Platina within the Santiago basin in June-July 1999. Figure 6f shows analogous information for the sounding station at Quintero, some 100 km northwest from Santiago. Notice that during the episode, in the first week of July, the inversion becomes stronger and the winds weaker than in other periods, with a pronounced easterly component in the layer below the inversion. Thus the model confirms the characteristic patterns described by Rutllant and Garreaud (1995). A similar pattern is found for May 1998 (not shown here).

June-July 1999

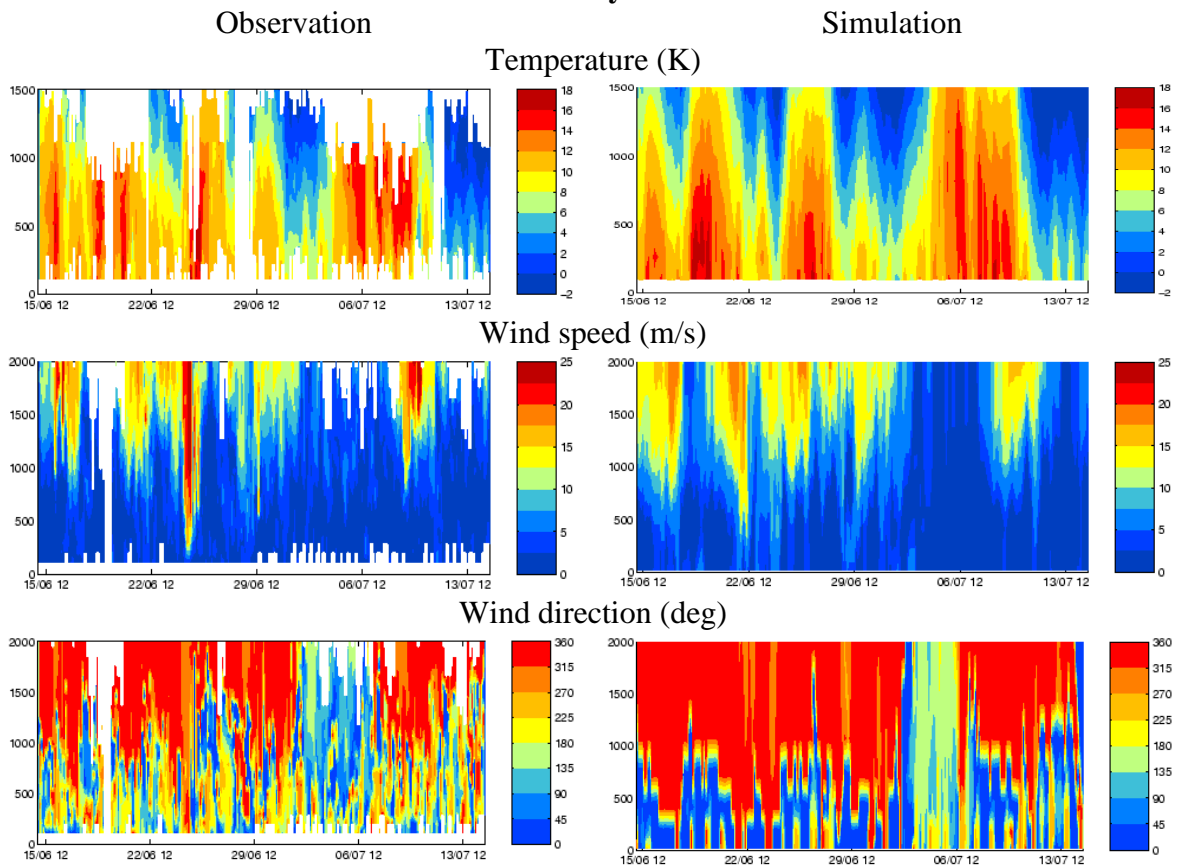


Figure 6e. Observed (left panels) and model simulated (right panels) vertical profiles of temperature (K), wind speed (m/s) and wind direction (deg) for the acoustic sounding station at La Platina, south of Santiago in June-July 1999.

- In the case of air pollutants, data provided by monitoring networks in Santiago and in the surroundings of industrial complexes have been compiled and analyzed for evaluating the model performance (See Figure 2). When compiling the information, we found a lack of systematic analysis of the data gathered through these measurements. Probably hereto the efforts have been focused towards specific subjects, e.g., high-concentration episodes of particulate matter in Santiago or attainment of a given environmental standard, whereas a more comprehensive and process-oriented analysis and description has received less attention. Still, it appears much desirable to complete the data with a thorough description that includes representativity, trends, quality assurance, etc.. We have also found inconsistencies in the data collected in various networks, which makes it necessary to review and standardize the data compilation and reporting protocols. Moreover, strong links should be promoted and implemented among the various monitoring networks. This could be useful in terms of data reliability and in terms of costs. Of course, model exercises like this help in making such analyses.
 - As it was already pointed out, the majority of the available monitoring stations have been placed to assess mainly local impacts, especially health effects. Therefore it cannot be expected that a regional model like HIRLAM-MATCH will be able to reproduce all the features of such observations. Nevertheless, 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. The observed daily averaged SO₂ concentrations are generally 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, for instance when cloud cover is underestimated inducing too strong surface winds (e.g. first half of May 1998) or when frontal disturbances are not captured by the meteorological model (e.g. May-June 1997). In addition to this, since wind direction at surface level is poorly represented in conditions of local circulations driven by topography effects, the redistribution of local emissions within the Santiago basin is not well simulated. Particularly in summer when local topography effects become strongest. These features are illustrated in Figure 7a that shows a comparison between observed and simulated daily averaged SO₂ concentrations in Santiago downtown at the Parque O'Higgins station for all six month-long periods simulated. Emphasis is put on comparisons with measurements at Parque O'Higgins since it is located in a relatively flat area of the basin, not too close to large point sources, which suggests that it is most representative of the regional patterns of dispersion of oxidized sulfur. The largest mismatch occurs in January 1998 when the impact of a large point source (a molybdenum smelter), located just two model grid-boxes away from the station, is clearly overestimated in connection with southerly winds that prevail in that period. The second largest mismatch takes place in May-June 1997 when the meteorological simulation is poorest. Nevertheless, the model reproduces satisfactorily the most outstanding SO₂ high-concentration episodes associated with strong coastal lows that determine stagnant dispersion conditions (See Figure 7b). Figure 7b shows daily average

concentrations as observed and simulated for two A-type episodes in May 1998 and July 1999.

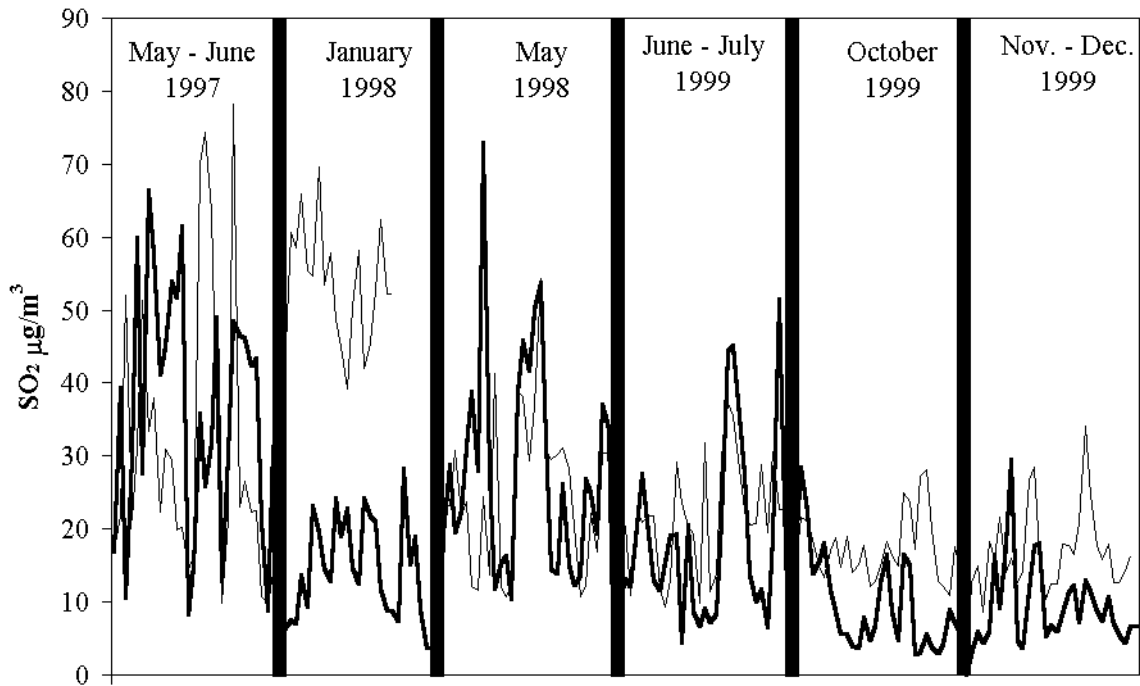
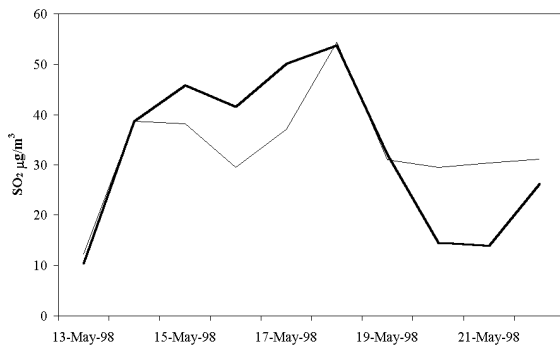


Figure 7a. Daily averaged sulfur dioxide concentrations in the Santiago basin (Parque O'Higgins) for six month-long periods. The dark line indicates the observed values whereas the light line indicates the simulated ones. For details see text.

May 13th – 22nd 1998



July 1st – 10th 1999

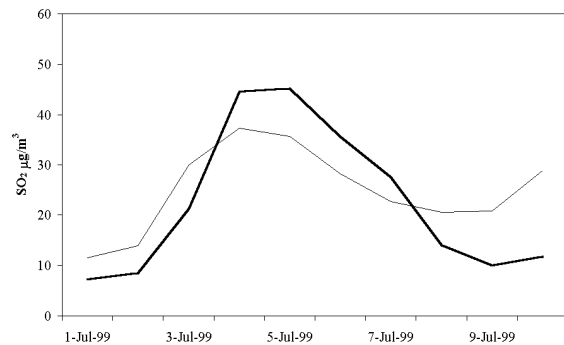


Figure 7b. Daily averaged sulfur dioxide concentrations in the Santiago basin (Parque O'Higgins) for two high-concentration (A type) episodes during May 1998 and July 1999. The dark line indicates the observed values and the light lines indicate the simulated ones.

- The simulated sulfate concentrations are consistent with the seasonal averages of the total sulfur content measured in aerosol filters for inhalable particle matter (PM₁₀) during winter 1998 in downtown Santiago. Moreover, the daily averaged sulfate values observed during a campaign in winter 1999 are also in good agreement with the simulations, particularly during a high-concentration episode observed in early July 1999 (See Figure 7c). According to the model simulations, during this type of episodes there is an enhanced contribution of the smelters to the burden of oxidized sulfur in the boundary layer of the Santiago basin, especially in the form of sulfate and thus associated to fine aerosols (radii < 2.5 μm). The model results suggest that the smelter's contribution, specifically that of Caletones, can be as high as 50% of the sulfate concentrations in the Santiago basin during such intensive episodes. The consistency between the simulated concentrations and the observations of both SO₂ and sulfate, in addition to the evidence provided by independent assessments (e.g. Artaxo, 1998), strongly supports the idea that on an episodic basis there is a significant contribution of the Caletones smelter in terms of oxidized sulfur and secondary aerosols. A similar contribution is simulated for summer conditions when, in connection with high insolation, strong vertical mixing occurs in the afternoon hours bringing down sulfur rich air, associated with the smelter's plume, from aloft.

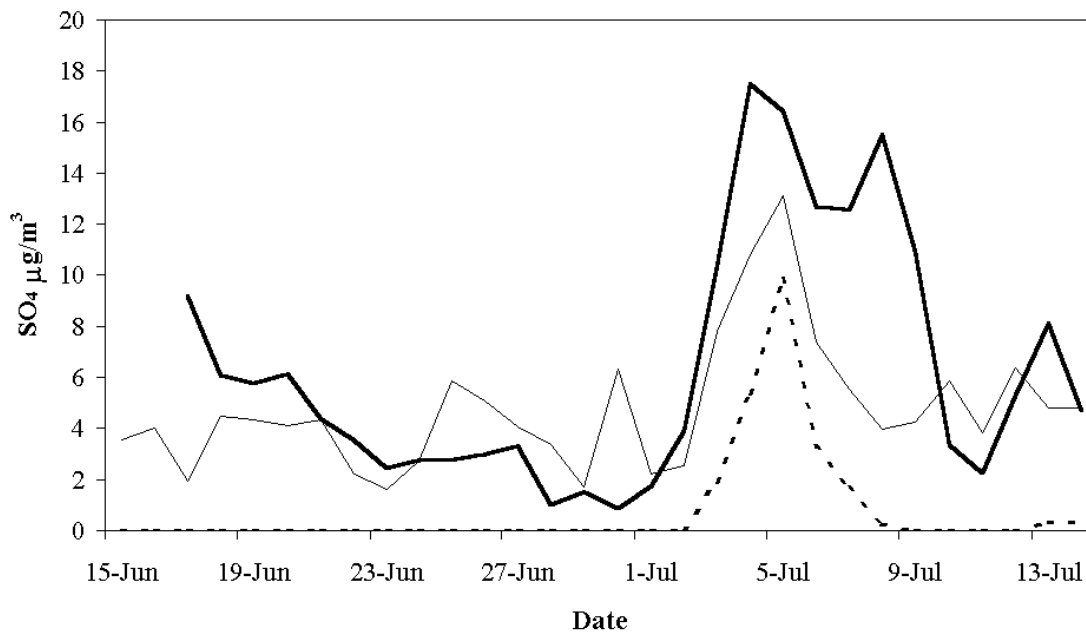


Figura 7c. Daily averaged sulfate concentration at Parque O'Higgins as observed (continuous black line) and as simulated (continuous light dark line). The contribution of the Caletones smelter as estimated by the model is also indicated (dashed line).

- The validation of any model is a step-by-step, complex and in some respects never-ending process through which one can quantitatively and qualitatively assess the suitability of a model for a number of applications. At this stage, we cannot say that the dispersion model applied to assess the regional dispersion of oxidized sulfur has been exhaustively validated. Nevertheless, the model reproduces consistently all the regional-scale characteristics that can be derived from available observations. It might be in place to repeat that when designing this project we were aware that the few available observations of the regional patterns of dispersion should not be enough to provide a comprehensive or detailed validation of the dispersion model results. However, we were also aware that a regional monitoring network was badly needed for assessing a suite of environmental problems and baseline requirements for regional planning. Moreover, we knew that a systematic revision of the available information as well as the insights given by the model simulation would be helpful in establishing a regional monitoring network. We expect the observations compiled through that network to confirm or disprove these model results, resulting in improvements of our understanding of the intricate processes that govern the regional dispersion of pollutants and therefore of our environmental managing capabilities for facing and hopefully preventing those problems.
- *To evaluate the contribution of different anthropogenic sources to the air pollution levels.*
 - The pattern of relative contribution of the copper smelters to the sulfur burden and deposition fluxes in Central Chile has been assessed for six individual month-long periods (not shown here). In all scenarios, the emissions from the copper smelters dominate the overall horizontal and vertical distributions of sulfur in Central Chile. The urban emissions, particularly those of Santiago, only affect significantly the city surroundings. The contribution of urban sources at rural sites as well as above the boundary layer is estimated to be less than a 10%. 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. Moreover, in order to improve the air quality of Santiago with respect to pollution by oxidized sulfur, in the long-term, one has to focus in decreasing the urban emissions.
 - Also, we have assessed the contributions of the copper smelters to the oxidized sulfur burden inside Santiago during summer and winter episodes of a few days. 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. Under these conditions, 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 SO₂ ratios, i.e., associated with secondary aerosols or fine particles (radii <2.5 μm). Thus, since there is a significant impact of Caletones in connection with high-concentration episodes and secondary aerosols this source's influence should not

be disregarded when discussing fine particles and high-pollution episodes in fall and winter.

- To evaluate the efficiency of the measures contained in the attainment plans applied in central Chile (Metropolitan Region, Caletones and Ventanas copper smelters).

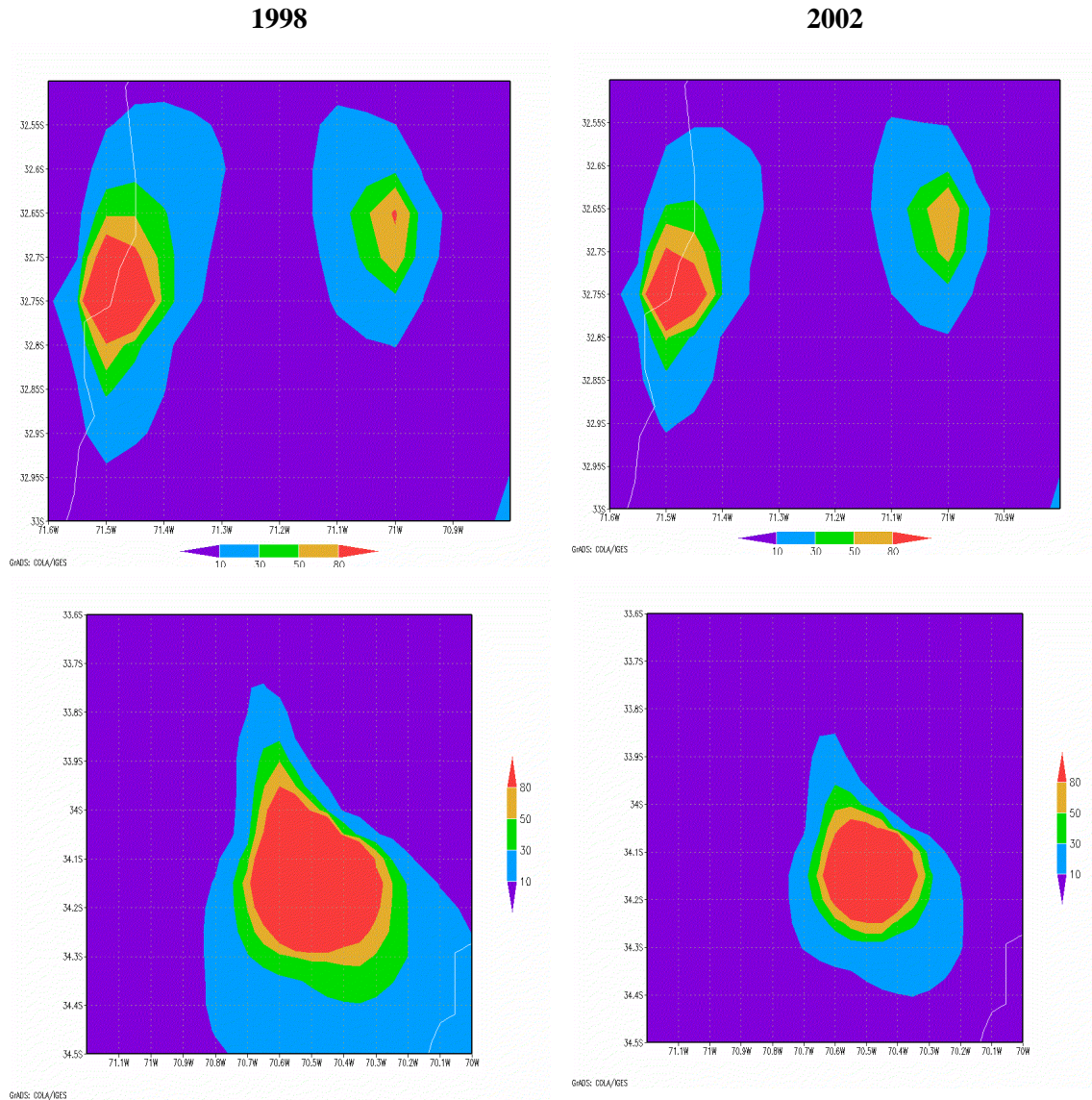


Figure 8. Annual mean SO_2 surface distribution (in $\mu\text{g}/\text{m}^3$) for two emission scenarios for 1998 and 2002. Areas around the copper smelters (Ventanas and Chagres in the upper panel and Caletones in the lower panel) with values that exceed the Chilean annual primary standard ($80 \mu\text{g}/\text{m}^3$) are shown, as well as those compared with the World Health Organization ($50 \mu\text{g}/\text{m}^3$) and the threshold of $30 \mu\text{g}/\text{m}^3$ recommended in Europe to protect vegetation.

Environmental authorities have enforced attainment plans for the two largest copper smelters in the area, Caletones and Ventanas, and for the Santiago region. The smelters have built sulfuric acid plants in order to reduce the atmospheric emissions of sulfur dioxide, which result from the processing of copper mineral. The Ventanas smelter reduced its emissions from ca. 42 kton S/yr in 1997 to ca. 15 kton S/yr in 1999, while Caletones implemented a reduction of ca. 30% from ca. 370 kton S/yr in 1997 to 240 kton S/yr in 1999. These plans have resulted in improvements of air quality as indicated by the available measurements. The attainment plan for Santiago has put a lot of effort in the reduction of emissions of inhalable particulate matter. This has in turn implied the reduction of sulfur emissions by heaters in intensive industrial processes due to the large-scale introduction of natural gas. This has brought down the Santiago emissions from about 21 kton SO₂/yr in 1997 to about 9 kton SO₂/yr in 2000. The model outputs have been used to evaluate emission reduction scenarios as considered in the attainment plans for Caletones and Ventanas. These scenarios have been evaluated with respect to the attainment of the sulfur dioxide standards. As an example of such an application we show in Figure 8 an estimate of the area affected by annual mean concentrations that exceed environmental standards for two emission scenarios valid for 1998 and 2002.

3. CONCLUSIONS AND PERSPECTIVES

Air pollution, on its multiple space and time scales, is determined by a suite of intricate factors, among others human behavior on individual and societal scales. Thus, it constitutes one of the most complex issues that scientists, technicians, decision-makers and people in general have to deal with. Given this complexity, no single tool, in spite of accuracy and/or complexity, may give satisfactory answers regarding process understanding and efficient attainment measures. Therefore, like any other environmental issue, dealing with air pollution requires of a systemic approach in which suites of tools ranging over a broad span of disciplines and considerations are applied. Dispersion modeling is one of the necessary tools to assess air pollution. Again, since atmospheric dispersion is also a multivariate and multiscale problem ranging from molecule-to-molecule interactions to synoptic scale weather systems, it must be addressed with suites or batteries of models. This project has provided a regional-scale dispersion model, a suite of validated meteorological data sets covering various typical meteorological conditions that affect Central Chile, including extreme conditions under El Niño and La Niña years. It has also given valuable insights regarding the regional dispersion of oxidized sulfur in this part of the country, and assessing the contribution of the smelters to the air quality in the heavily populated Metropolitan area of Santiago. Furthermore it has produced relevant inputs for establishing a regional monitoring network. At last but not least, it has provided badly needed Chilean know-how in dispersion modeling. Hereafter, the main technical conclusions drawn from the modeling work are summarized.

A meteorological model has been set up for an area covering central Chile, HIRLAM. The model has been executed for six month-long periods in 1997, 1998 and 1999 and a validated three-dimensional data set with three-hour time and 11 km horizontal resolution has been produced. Based on comparisons with available observed meteorological data the following conclusions are drawn:

- 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. 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 coastal 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 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.

The HIRLAM outputs have been used to drive a dispersion model, MATCH, for oxidized sulfur over an area of about 200x400 km² around Santiago in the central part of Chile. The simulated periods cover a suite of typical meteorological conditions that affect Central Chile, including extreme conditions under El Niño and La Niña years. These periods provide insights regarding the seasonal variations, including recurrent extreme meteorological conditions, which make them useful for defining environmental strategies. According to the model simulations and the comparison made with available observations, we conclude that:

- 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 at 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 SO₂ 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 (PM₁₀) 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.
- 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.
- 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.
- The copper smelters contribute episodically to the 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). 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 SO₂ ratios, i.e., associated with secondary aerosols or fine particles (radii <2.5 μm).
- The urban emissions, particularly those of Santiago, only affect significantly the city surroundings. The contribution of urban sources at rural sites as well as above the boundary layer is estimated to be less than a 10%. Hence, in order to improve the air quality of Santiago with respect to pollution by oxidized sulfur in the long-term one has to focus in decreasing the local emissions. However, since there is a significant impact of Caletones in connection with high-concentration episodes and secondary aerosols this source's influence should not be disregarded, particularly when discussing fine particles and high-pollution episodes.
- A first assessment of the regional oxidized sulfur budget over Central Chile, i.e. 400x200 km² 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 SO₂ 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 (radii < 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. This statement finds support in a newly published risk assessment study by García-Huidobro et al. (2000).
- We have used the model's simulations that cover a broad range of meteorological situations to propose the installation of air quality monitoring devices, including a few wet only collectors, at eight new locations. Of course, these approximate locations are to be evaluated *in situ*.

We have hereby presented the first assessment of the regional distribution of man-made oxidized sulfur, in Central Chile by using a regional-scale modeling tool. 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 strengthened 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. We foresee that an adequate management of regional dispersion problems will require of a coordinating activity in which monitoring and modeling of air quality and meteorology are closely integrated. Such an activity should be a part of an overall regional strategy, which using a systemic, long-term approach, may define efficient attainment and preventing measures.

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