Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 149-155.

# AEROSOL LOADING OVER SANTIAGO DE CHILE (33º.3'S 70º.5'W, 500 m.a.s.l.): A COMPARISON BETWEEN SATELLITE AND IN SITU MEASUREMENTS.

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## ABSTRACT

We analyze aerosol data (partially -PM10- and fully inhalable –PM2.5- particles) collected in situ at Santiago de Chile, a city with more than 6 million inhabitants who are frequently exposed to severe air pollution. We use these data to estimate aerosol loading expressed as optical depth. For this purpose we assume a well mixed boundary layer and model calculated boundary layer height. In addition, we make use of the aerosol optical thickness derived from a ground based sunphotometer located in Santiago between August 2001 and October 2002 to validate the satellite data. Particular attention is paid to the most extreme winter and fall pollution events, which occur when the subsident regime of the Pacific high is further enhanced by coastal lows (CLs) bringing down the base of the subsidence inversion. We find a poor correlation between satellite and in situ data, which may be partially attributed to biases in the retrieval algorithm linked to an inadequate characterization of surface reflectivity, and wrong assumptions regarding the aerosol vertical distribution. Under the extreme stable conditions that prevail in connection with CLs, the optical thickness appears to depend to a larger extent on the boundary layer height than on the aerosol concentration near the surface. Thus, the use of optical depth as a proxy for air quality seems not adequate for Santiago de Chile.

**Key-words: optical depth, MODIS, AERONET, air quality**

## INTRODUCTION

Remote sensing of aerosol might become a powerful tool for air quality monitoring and control over populated urban areas, lessening costs and reducing the number of required in situ stations (Wang and Christopher, 2003; Engel-Cox et al., 2004). However, it must be well understood that remote sensing cannot replace in situ measurements and furthermore it requires such measurements for validation (e.g., Remer et al., 2005). Typically, the retrieval algorithms used for estimating aerosol optical depth from satellites have been validated by comparison with in situ, ground based sunphotometer measurements from the Aerosol Robotic Network (AERONET), which cover varied situations (biomass burning, city pollution, etc.) with encouraging results (e.g., Chu et al 2003; Wang and Christopher, 2003).

In this work, we assess the applicability of remote sensing of aerosol loading in the boundary layer for Santiago de Chile (33º.3'S 70º.5'W, 500 m.a.s.l.). Santiago is one of the most polluted cities in South America and although great efforts have been carried out to improve air quality (CONAMA, 2000) the 6 millions inhabitants of Santiago are still exposed to dangerous air pollution levels. Previous works (e.g., Garreaud et al, 2002 and references therein) have shown the connection between the severe air pollution episodes and the so called coastal lows (CLs). The most intensive air pollution events are associated with so called A type CLs. The synoptic scale circulation in a A type event is characterized by a midlevel midlatitude ridge drifting eastward, weaker than a normal midlevel westerly flow over subtropical Andes and a anticyclonic anomaly with its center at about 45ºS that results in a stretching of climatological subtropical anticyclone into continent. The main characteristics in a developing coastal low are the elongated trough along the subtropical coast, the enhancement of temperature inversion which reduces the boundary layer height, resulting in severe air pollution episodes in Santiago during

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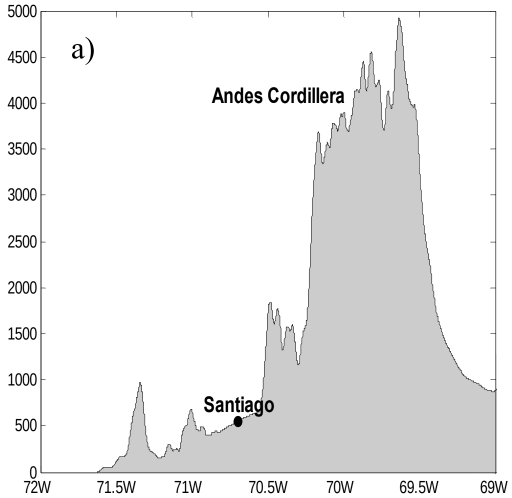
austral winter. We focus our analysis on such events.

Considering the complex topography of the Santiago basin, surrounded by the Andes Cordillera (figure 1), and the particular meteorological phenomena involved in the critical pollution episodes, it is relevant to explore how the satellite measurements agree with in situ data and aerosol optical thickness variability for pollution episodes.



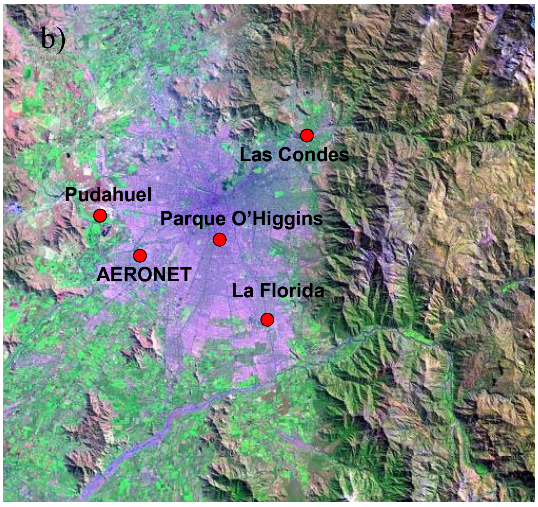




Figure 1: a) Profile of terrain elevation at 33.5ºS, b) Santiago basin: topography and monitoring stations.

| Station | Location |
|---|---|
| La Florida | 33º31'S , 70º34'W |
| Las Condes | 33º22'S , 70º31'W |
| Pudahuel | 33º26'S , 70º44'W |
| Parque O'Higgins | 33º27'S , 70º39'W |
| AERONET | 33º.28'S 70º.42'ºW |

Table 1: Location of the air quality stations and AERONET station considered in this study.

## DATA AND METHODS

We use aerosol optical thickness (AOT) data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument (Remer et al, 2005), and from a sunphotometer of the AERONET network (Holben et al., 1998). While MODIS (aboard TERRA satellite) provides 2 measurements per day in the region, AERONET gives measurements every 15 minutes in sunlight hours. Also, we use hourly aerosol concentrations from four stations of the Santiago air quality network run by the Metropolitan Health and Environment Service (SESMA, http://www.asrm.cl/sitio/pag/aire/indexjs3aireindices.asp), where both PM10 and PM25 were collected over the period 2000-2001. Data for the period 2002-2004 was kindly provided by the National Center for the Environment (CENMA). The locations of the in situ stations whose data we considered in this study are presented in Table 1.

## RESULTS

### a) MODIS vs. AERONET

The MODIS AOT time series, measured in a 10x10 $km^2$ area located in the same region that AERONET, exhibit an annual cycle (figure 2.b) with minimum values in the cold season (June-September). This time of the year shows the least number of MODIS observations as often cloudy conditions associated with middle latitude perturbations occur in the austral winter (June to August). The MODIS signal shows a high variability in the warm season (November-March), with values between 0.1 and 0.8, which may be explained by the MODIS signal contamination (Gao et al, 2002) due to the frequent presence of cirrus clouds over this area. The annual cycle shown by the MODIS data is not observed in AERONET data, which show maximum values in the cold season in the range between 0.1 and 0.4. The annual cycle in the AERONET AOT series might be obscured though by the scarcity of measurements in the cold period.

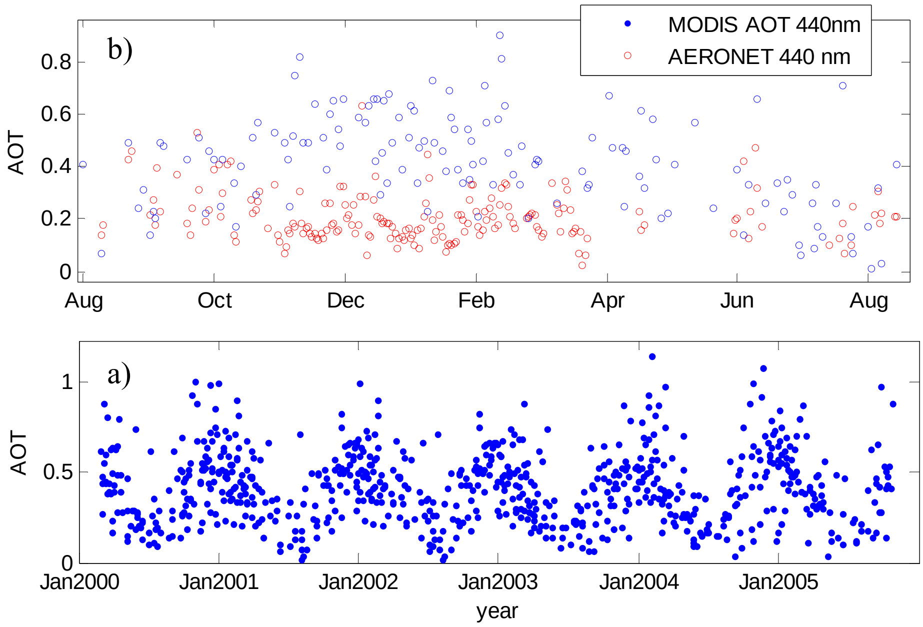



Figure 2: a) Time series of AOT estimated from MODIS and daily averaged AERONET AOT (2001-2002), b) Complete MODIS time series.

Even though it is possible to observe a correlation between AOT derived from MODIS and the one observed by the sunphotometer (figure 2.a), the linear correlation coefficient is poor (lower than 0.3). This can be partially explained by the high variability in the MODIS signal not represented in AERONET measurements. However, we cannot rule out problems with the sunphotometer operation. This correlation is similar to results from Levy et al (2005) for the Chesapeake Lighthouse Aircraft Measurements for Satellites (CLAMS) experiment in which correlations between 0.4 and 0.7 over continental regions were found. They point out that new industrial/urban aerosol models and correcting reflectance assumptions in MODIS algorithm should be developed to improve the relationships between satellite and ground-based AOT measurements. The frequent presence of cirrus clouds over Santiago may also contribute to the larger summer variability in the MODIS measurements of AOT than those of AERONET (e.g., Gao et al, 2002).

### b) AERONET vs. SESMA NETWORK

Figure 3.a shows the time series of fully inhalable particles, i.e., PM2.5, which exhibit an annual cycle with maximum values in austral winter (July-August) and minimum in summer (December-January). Additionally, PM2.5 time series present a diurnal cycle, and synoptic variability (figure 3.b). We compared the AERONET series with the PM10 and PM2.5 series collected at the SESMA network at all stations and also with their average. These comparisons were performed for daily (9-14 local time) and weekly time windows. Comparing the four PM2.5 stations with AERONET the best correlation (0.47) was found for Las Condes and Pudahuel stations (figure 4) that are located at the eastern and western bounds of the basin, respectively. These correlation values are lower than those found by Chu et al. (2003) in Milan (Italy) with correlations close to 0.8. Surprisingly, the minimum correlation (0.2) was found for the Cerrillos station that is placed closest to the AERONET site. This might reflect the fact that the aerosol loading measured by the sunphotometer not only retrieves aerosols in the boundary layer but also upper level aerosol layers. For example, Gallardo et al (2002) have suggested that in connection with CLs, a sulfate plume from a copper smelter located south of Santiago might be transported over the city. Also, the radiative circulation typical of the Santiago basin might result in an upper aerosol layer, partially decoupled from that reflected in the in situ PM10 and PM2.5 measurements. Another explaining factor for the mismatch between the sunphotometer measurements and the PM observations could be attributed to different emission patterns in Santiago, which are lower in Las Condes and Pudahuel stations than over Cerrillos (CENMA, 2000).

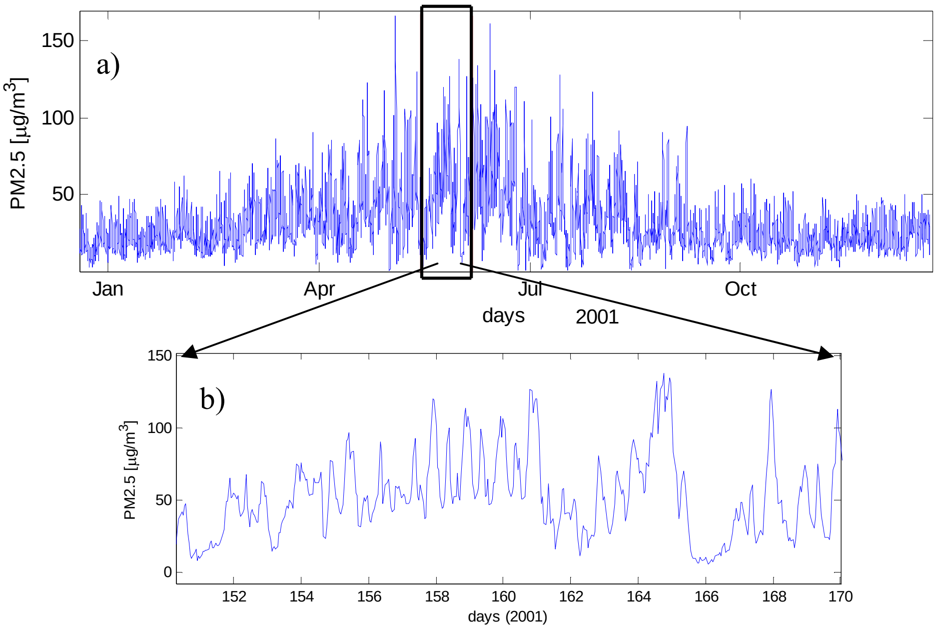



Figure 3: Stations average hourly particulate matter (PM2.5) for the 4 air quality stations indicated in Table 1 over Santiago area: a) year 2001, b) enlargement for a particular period (June, 2001).

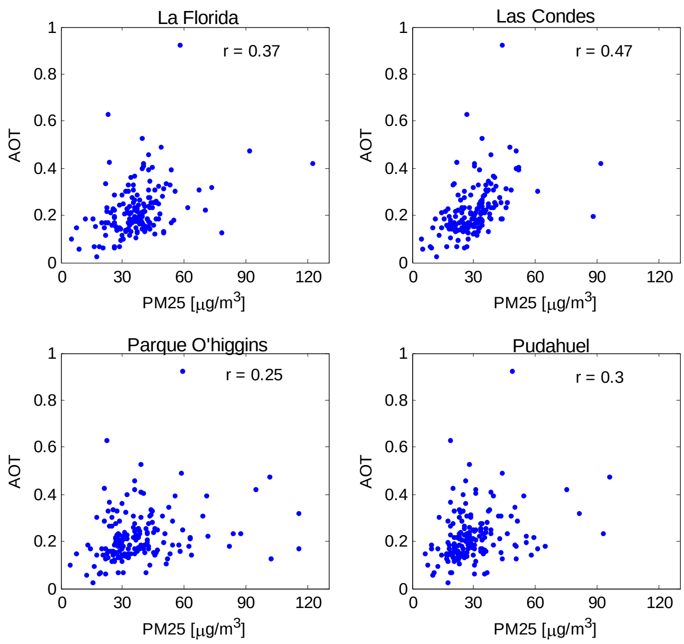



Figure 4: Scatter diagrams between daily PM 2.5 and AOT 440 nm derived from AERONET for the 4 air quality stations of Santiago area.

The correlation indexes between PM and AERONET AOT vary depending on the time window considered for producing the averages. The best correlation is found for 72 hours averages, .i.e. 3 days (figure 5). This indicates that synoptic and sub synoptic variability in weather patterns, and stability are the most important factors determining the variability in aerosol loading.

As expected, the higher PM values are associated to CL events (figure 6a). However we did not find a clear tendency in AERONET record (figure 6b), for which unfortunately only 30% of the data are representative of fall and winter conditions.

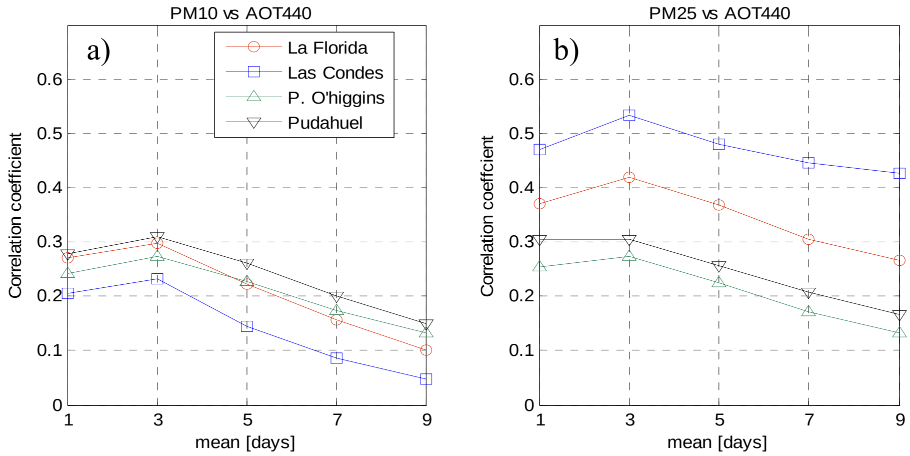



Figure 5: Correlation coefficient using different time period averaged values: a) PM10 vs. AOT 440 [nm], b) PM2.5 vs. AOT 440 [nm].

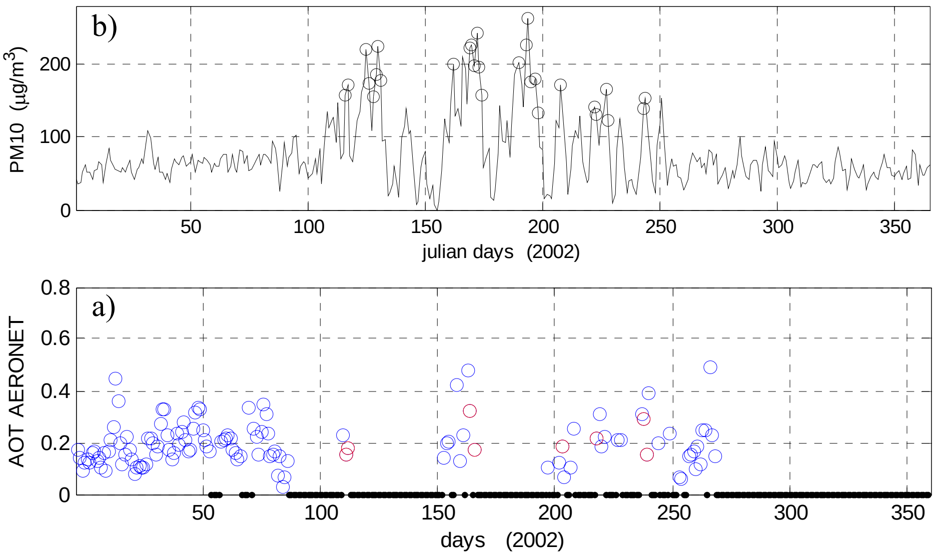



Figure 6: Time series year 2002: a) Daily PM10 time series recorded in Pudahuel station, the circles indicate the coastal lows events, b) AERONET AOT; the red circles indicate the coastal lows events and black dot with no AOT data.

### c) Boundary layer height and optical depth

To estimate how the boundary layer height (BLH) relates with AOT measurements, we estimated the hourly evolution of BLH for an eight days period between June 16 and 24 2002, when a coastal low affected the Santiago area (June 19-23). For that purpose we used the Fifth generation Pennsylvania State University-NCAR Mesoscale Model, MM5) (e.g. Grell et al. 1994). The MM5 is a nonhydrostatic model which solves the primitive equations of movements with terrain-following vertical coordinates. The model captures the main characteristics of coastal lows with warming and drying of boundary layer. We estimated a rough boundary layer height (BLH) as the level with positive temperature gradient (δT/δZ > 0), that is, the height corresponding to temperature inversion base (with the upper layer statically stable). The typical characteristic of the BHL is the diurnal cycle with minimum at dawn and maximum in the afternoon (by radiative cooling-warming) and a reduction tendency during the period of the CL. A covariation is found between AOT and simulated BHL time series, showing that the reduction of AOT coincides with BLH reduction (figure 7.a), furthermore, the minimum AOT measurements (June 22-23) occur when BHL is minimum and with an almost collapsed boundary layer. On the other hand, the PM10 and PM2.5 time series present no significant trend over that period (figure 7.b). Thus, boundary layer height and not aerosol concentration is the determining factor for AOT variability.

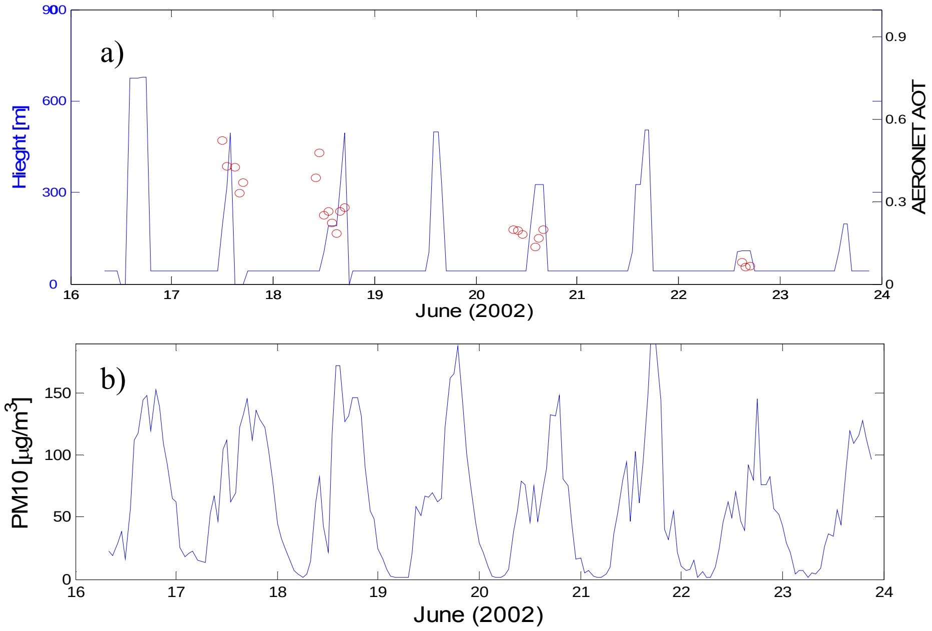



Figure 7: a) BHL from simulation and AOT from AERONET, in June 2002, b) PM10 at Las Condes station for the same period.

## CONCLUSIONS

We have explored the use of AOT measurements from in situ measurements (AERONET) and remote sensing as surrogates for aerosol concentrations for Santiago de Chile, a six million inhabitants urban center located in a basin in Central Chile surrounded by the high Andes.

The MODIS AOT data showed poor correlation with in situ data from an AERONET sunphotometer operated between August 2001 and October 2002, and no correlation with in situ measurements of aerosol concentrations was found. Thus, today's MODIS retrievals cannot be used as an index of air pollution for Santiago. As suggested by Levy et al. (2005), this may be partially attributed to biases in the retrieval algorithm linked to an inadequate characterization of surface reflectivity, and wrong assumptions regarding the aerosol vertical distribution. Further analyses should also pay attention the presence of the high variability in the MODIS AOT in the warm period, which is partly attributed to the cloud contamination caused by summer cirrus (Gao et al 2002).

The comparison of AERONET AOT and situ aerosol concentration measurements shows poor correlation as compared to correlations found in other studies (Wang and Christopher, 2003). Surprisingly, the minimum correlation (0.2) was found for the Cerrillos station that is placed closest to the AERONET site. This suggests that the aerosol loading measured by the sunphotometer not only measures aerosols in the boundary layer but also upper level aerosol layers such as industrial plumes, cirrus clouds, and aerosols lifted up during day in connection with up slope winds and then decoupled from the aerosol layer close to the surface reflected in the in situ PM10 and PM2.5 measurements. Future studies should address the existence of these multiple aerosol layers, typical of prevailing strong static stability conditions.

Not surprisingly, our analyses indicate that synoptic and sub synoptic variability in weather patterns, and stability are the most important factors determining the variability in aerosol loading over Santiago. MM5 simulations for a coastal low period in June 2002 showed that AERONET AOT is positively correlated with BLH. Thus the use of AOT as a proxy for air quality (aerosol concentrations) seems not adequate for Santiago de Chile, particularly under extreme stable conditions that prevail in connection with CLs in the cold season. On the other hand, under those circumstances, AOT appears to be a straightforward index of BLH.

ACKNOWLEDGEMENTS. This work has been developed within the framework of ECOS Sud collaboration agreement (C03U04). We appreciate the kind help in retrieving air quality data provided by Manuel Merino and Andrea Rivera at the National Center for the Environment (CENMA). We are grateful to Omar Cuevas for his help with MM5 simulations.

## REFERENCES

CENMA, 2000: Mejoramiento de inventario de emisiones de la región Metropolitana. Reporte final. Avai.

CONAMA-RM, 2000: Plan de prevención y descontaminación atmosférica de la Región Metropolitana.Comisión Nacional del Medio Ambiente, Región Metropolitana de Santiago.

Chu, D. A., Y. J. Kaufman, G. Zibordi, J. D. Chern, J. Mao, C. Li, and B. N. Holben, 2003: Global Monitoring of Air Pollution over Land from EOS-Terra MODIS. *J. Geophys. Res.*, *108(D21), 4661, doi: 10.1029/2002JD003179*

Engel-Cox, J.A., C.H. Holloman, B.W. Coutant, and R.M. Hoff, Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality, *Atmos. Environ.*, *38*, 2495-2509, doi:10.1016/j.atmosenv.2004.01.039, 2004.

Gao, B. C., Y. J. Kaufman, D. Tanré, and R. R. Li, 2002: Distinguishing tropospheric aerosols from thin cirrus clouds for improved aerosol retrievals using the ratio of 1.38-µm and 1.24-µm channels. *Geophysical Research Letters*, *Vol. 29, No. 18, 1890, doi:10.1029/2002GL015475*

Gallardo, L., Olivares, G., Langner, J. and Aarhus, B., 2002: Coastal lows and sulfur air pollution in Central Chile. *Atmos. Env.* 36, 23, 3829-3841

Garreaud, R., J. Rutllant and H. Fuenzalida, 2002: Coastal lows in north-central Chile: Mean structure and evolution. *Mon. Wea. Rev.*, 130**,** 75-88.

Grell, G. A., J.Dudhia, and D. R. Stauffer, 1994: A description of the fith-generation Penn State/NCAR Mesoscale Model (MM5). NCAR. Tech. Note NCAR/TN-398+STR, 122 pp.

Holben, B. N., et al., 1998: AERONET-A federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ*., 66, 1-16.

Levy, R. C., L. A. Remer, J. V. Martins, Y. J. Kaufman, A. Plana-Fattori, J. Redemann and B. Wenny. 2005: Evaluation of the MODIS Aerosol Retrievals over Ocean and Land during CLAMS. *Journal of the Atmospheric Sciences*: Vol. 62, No. 4, pp. 974–992.

Remer, L. A., Y. J. Kaufman, D. Tanré, S. Mattoo, D. A. Chu, J. V. Martins, R-R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, & B. N. Holben, 2005: The MODIS Aerosol Algorithm, Products and Validation. *Journal of the Atmospheric Sciences*, Special Section. Vol 62, 947-973.

Wang, J., and Christopher, S. A., 2003: Intercomparison between satellite-derived aerosol optical thickness and PM2.5 mass: implications for air quality studies. *Geophysical Research Letters*, 30, 21, 2095, doi:10.1029/2003/GL018174.