3. Meteorological influence.

Diurnal to seasonal cycle changes in wind conditions and humidity probably have a large influence on the aerosol peaks recorded in Arica, either through influencing specific sources or by changing the aerosol properties. Arica presents year-round low cloud cover that often breaks in the afternoon, particularly in late austral spring-summer. Typically, clear skies prevail between 11:00 and 20:00 LT in November-December, but only between 14:00 and 17:00 in June-August.

3.1 Surface winds

Surface winds, atmospheric pressure, air and dew point temperatures and low-cloud cover are reported by the Chilean Weather Service every 3-hours at the Chacalluta airport in Arica. Surface winds peak at 14:00-16:00 LT (19:00 UTC) at the time of minimum low-cloud cover, with maximum seasonal strength in November (~ 4 ms^{-1}) and SSW direction in the afternoon. Minimum speeds are observed by 7:00-9:00 LT (12 UTC) particularly during July-August (< 0.7 ms^{-1}), coinciding with a seasonal maximum in low cloud- cover. Prevailing wind directions at this time of the year are from the E in the morning and from the SW in the afternoon (CORFO-EOLO Report, 200).

Thus, coarse sea salt aerosols could be advected on to the Arica area at the time when photometric observations are available (clear afternoon periods). To assess their possible contribution to the coarse aerosol loading, daily anomalies for the peak of aerosol episodes (AOT > 0.7) have been calculated based on 30-year synoptic weather observations at Chacalluta (DMC). Tables 3.1 and 3.2 summarizes these results separately for austral summer and winter, respectively: WD is the wind direction, WS is the maximum afternoon windspeed in knots, MWS is the long-term mean windspeed and AWS is the windspeed anomaly.

Table 3.1

Date (Summer)	WD	WS	**MWS**	AWS	Date (Summer)	WD	WS	**MWS**	AWS
* 1999 01 29	210	7.2	**6.9**	+0.3	* 2000 01 03	190	9.3	**6.9**	**+2.4**
* 1999 02 11	210	7.7		+0.8	* 2000 01 13	200	7.7		+0.8
* 1999 02 14	210	6.7		-0.2	* 2000 01 21	200	6.7		-0.2
* 1999 02 24	200	6.7		-0.2	* 2000 02 21	210	5.7		-1.2
* 1999 03 18	200	9.3		**+2.4**	* 2000 03 04	190	9.3		**+2.4**
* 2000 11 30	200	6.7		-0.2	* 2000 12 14	200	7.7		+0.8
* 2000 12 20	210	5.7		-1.2	* 2000 12 30	210	6.7		-0.2

Only in 3 out of the 14 episodes considered here, the MWS was significantly exceeded by about 1.2 ms^{-1}. Therefore marine aerosols (coarse sea-salt particles) within the MBL do not seem to be important contributors to the maxima in AOT in austral summer.

Table 3.2

Date (Winter)		WD	WS	**MWS**	AWS
*	1998 08 12	220	6.2	**5.4**	+0.8
*	1999 08 11	210	6.2		+0.8
*	2001 08 31	230	5.1		-0.3
*	2001 09 12	220	7.2		**+1.8**
*	2003 08 16	220	5.1		**+2.4**

For the 5 winter cases, positive anomalies of the order of ~ 1 ms^{-1} seem important in the two last ones.

Although DMS is another possible marine fine aerosol (sulphate) contributor in late spring at the time of phytoplankton blooms, the DMS emissions have not yet been assessed there.

3.2 Upper air winds

At this latitude, winds aloft show a pronounced seasonal cycle, being immersed in the easterlies in austral summer, in particular when the core of the upper troposphere Bolivian High is over the southwestern Andes Highlands (Altiplano), and in the westerlies in the opposite season. Above the marine boundary layer and the subsidence inversion, westerlies bring dry air into the continent while the opposite stands during the peak season of the South American monsoon in austral summer.

The upper air circulation at the key levels of 700 and 500 hPa has been assessed through back trajectories for particular events (12 UTC) available since year 2000 from the AERONET site: http://www.aeronet.gsfc.nasa.gov. More detailed back trajectories could be made available through regional models as the MATCH (e.g. Huneeus et al., 2006), MM5 and WRF.

In order to cover events prior to year 2000 and compare one-day trajectories with actual upper-air winds measured at Antofagasta (23°S), daily radiosonde data at 12 UTC (08:00 LT) has been obtained from the U. of Wyoming site http://weather.uwyo.edu/upperair/sounding.html. Daily wind profiles were analyzed for June and July 1999 and for January-February 2000 focusing on those days with maxima in AOT (episodes) and also the corresponding days before each episode. The analyses concentrate in levels around 700 hPa (~ 3000 m amsl) and 500 hPa (~5500 m amsl), corresponding the emissions at the Chuquicamata copper smelter, 500 km to the SSE from Arica, and volcanic emissions spanning from 200 to 600 km from Arica, covering directions from ENE to SSE, respectively.

3.2.1 Austral Summer 2000. During this season 5 events were recorded in January-March 2000 and 4 in November December 2000. The first five present low windspeeds and easterly wind components at 500 hPa, covering the area in which volcanic emissions can have an impact. Although 700 hPa trajectories advect air from the SSE they fail to pass over Chuquicamata within the previous 7 days because of the extremely low windspeeds.

As seen from the Antofagasta radiosonde data, the first event of the season occurred January 3 when strong SSE winds were present between 700 and 450 hPa the two previous days. On the 3rd they begin to turn SSW at 575 hPa although speeds in the SSE winds below peaked at 15 m/s. Something very similar although less intense occurred on Jan 12 and 13 (AOT 0.85 on the 13th). On the 18. 19 and 20th, a similar pattern of SSE winds occurred with AOT = 0.72 on the 21st. In fact easterly wind components prevailed throughout the whole troposphere during those days.

However, extensive SSE winds between ca. 700 and 500 hPa in February 9, 11, 12 and 16, 17 and 18, did not result in high AOT's in Arica. Generalized weak easterly winds from 680 to 350 hPa on the 15th February may have caused a volcanic contribution increasing AOT to almost 0.6.

The most important and last event of the season occurred on March 4, without any sign of easterly wind components in the intervening layers over Antofagasta, although back-trajectories indicate easterly winds at 500 hPa turning abruptly from a SSW direction before reaching Arica.

In three of the four cases at the end of 2000, NW winds at 700 hPa could have transported emissions from La Oroya smelter (central Peru) within the 2 to 3 days prior to the peak, although in two of them winds at 700 hPa at Antofagasta do not support these trajectories. On the other hand, 500 hPa trajectories indicate possible influence of sources from nearby volcanoes. In two cases back trajectories in 500 hPa suggest air from the Amazon basin, in one of them even a possible contribution of volcanoes from Ecuador.

It might be concluded that in austral summer the contribution of steady volcanic emissions is highly probable, although it seems very sensitive to heights, speeds and day to day changes in the prevailing easterly flow. Eventually, anticyclonic trajectories around the Bolivian High could bring aerosol contributions over Arica from La Oroya and from even farther into the Amazon region.

3.2.2 Austral winter 1999 and other episodes.

During the June-July 1999 time interval westerly wind components were generally found above 700 hPa (3000 m) over Antofagasta, preventing volcanic emissions to reach Arica. A relatively large AOT (>0.5) occurred on June 05, although westerly wind components were already present above 750 hPa, with NE (40 deg.) winds below. Conversely, on June 24, 1999 when the second most important peak in AOT in the 1999-2000 winter seasons occurred, westerly winds appear above 630 hPa, with relatively strong SE and E winds below. In this case contributions from the Chuquicamata copper smelter could have been important. However on July 30-31 SE winds were found below 580 hPa without any significant impact (no data on the 30th) on AOT values.

The most emblematic case during the 1999 austral winter season was the event in August 11, 1999. The August 10 radiosonde report indicated NE winds from 850 to 420 hPa that on the 12th (no data available for the 11th) switched to northerlies above 780 hPa. Therefore Chuquicamata and volcanic emissions should be completely disregarded. Again on the 11th and 12th August 1998, NW wind component were present above 780 hPa.

Three cases analyzed by means of back trajectories for August 2000 and August – September 2001 show N-NW wind components in both 700 and 500 hPa levels , two of them with a possible contribution from La Oroya. On August 30, 2001 NW winds prevailed above 720 hPa over Antofagasta. An extreme case occurred in September 11 and 12, 2001, when strong NW winds started at the surface and above 850 hPa respectively.

The last episode considered here took place on August 16, 2003. In contrast with the preceding cases in which northerly wind components prevailed, SSE winds blowed from the surface up to 850 hPa on the 15th, switching to SW between 900 and 700 hPa on the next day, with SE winds aloft. In this case certainly Chuquicamata could well have contributed to the aerosol burden measured over Arica. However the back trajectory analysis does not suggest such possible contribution.

In summary, most of the austral winter AOT peaks over Arica are concurrent with N-NW winds, possible bringing aerosol contributions from central Peru (La Oroya). However, Chuquicamata copper smelter contributions could sporadically contribute.

3.3 Atmospheric Circulation composites

The characterization of the atmospheric circulation during AOT events was performed via NCEP/NCAR 12 UTC Reanalysis:
http://cdc.noaa.gov/composites/hour

3.3.1 Austral summer

The following events were composited for this season:

• 1999 01 29	* 2000 01 03
• 1999 02 11	* 2000 01 13
• 1999 02 14	* 2000 01 21
• 1999 02 24	* 2000 02 21
• 1999 03 18	* 2000 03 04
• 2000 11 30	* 2000 12 14
• 2000 12 20	* 2000 12 30

The atmospheric circulation highlights, obtained from vector winds and their anomalies at 500 and 700 hPa, geopotential anomalies at 700 hPa to assess mid-latitude wave patterns, 850-500 hPa thicknesses and anomalies to assess anomalous heating pattern sin the lower troposphere, outgoing longwave radiation (OLR) to identify deep convective clouds and precipitable water anomalies (APW); are the following

- Low easterly wind anomalies at 500 and 700 hPa around the study area.
- Anomalous summer warming and convective cloudiness over the SW Altiplano.
- Troughing-ridging 700 hPa mid-latitude patterns favoring enhanced convection over the Altiplano.

- ***Positive anomalies in the column water vapor content over Arica (precipitable water).***

3.3.2 Austral winter

The following episodes in which AOTs > 0.7 (1998-2003) have been considered here:

* 1998 08 12
* 1999 08 11
* 2001 08 31
* 2001 09 12
* 2003 08 16

Although the 2003 episode was of a different nature compared with the previous ones, the composite analysis shows:

- Enhanced northerly wind components at 500 and 700 hPa around the study area.
- Colder lower-troposphere and cloud bands along southern Peru.
- Deep mid-latitude trough (leading edge) over the study area, reaching lower latitudes than usual.
- ***Positive anomalies in the column water vapor content along southern Perú (precipitable water).***

As a tentative hypothesis from this composite analyses, moisture convergence over Arica from the east in summer and from the NW along southern Peru seems a key factor in an area where several possible natural and anthropogenic aerosol precursors are most of the time fully available.

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