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Air Pollution Potential: Regional Study in Argentina

MARÍA I. GASSMANN*
NICOLÁS A. MAZZEO
Department of Atmospheric Sciences
Faculty of Sciences
University of Buenos Aires
Piso 2—Pabellón II—Ciudad Universitaria
(1428) Buenos Aires, Argentina

ABSTRACT / Air pollution potential is a measure of the atmospheric conditions that are unable to transport and dilute pollutants into the air, independently of the existence of sources. This potential can be determined from two atmospheric parameters: mixing height and transport wind. In this paper a statistical analysis of the mixing height and transport wind, in order to determine the areas with high or poor atmospheric ventilation in Argentina, is presented. In order to achieve this, meteorological data registered during 1979–1982 at eight meteorological stations were used. Daily values of the maximum mixing height were calculated from observations of daily temperatures at different heights and maximum surface temperature. At the same time as the maximum mixing height, the values of the transport wind were determined from the surface windspeed and the characteristics of the ground in the surroundings of each meteorological station. The mean seasonal values for both parameters were obtained. Isopleths of the mean seasonal of the maximum mixing heights were drawn. The percentage of seasonal frequencies of poor ventilation conditions were calculated and the frequency isopleths were also drawn to determine areas with minor and major relative frequencies. It was found that the northeastern and central–eastern regions of Argentina had a high air pollution potential during the whole year. Unfavorable atmospheric ventilation conditions were also found in the central–western side of the country during the cold seasons (37.5% in autumn and 56.9% in winter). The region with the greatest atmospheric ventilation is located south of 40°S, where the frequency of poor ventilation varies between 8.0% in summer and 10.8% in winter.

Air pollution may be defined as ‘‘the presence in the atmosphere of pollutants or combinations of them in such quantities and of such duration as may be or may tend to be injurious to human, plant, or animal life, or property, or which unreasonably interferes with the comfortable enjoyment of life or the conduct of business.’’ One of the objectives of society is to have an appropriately clean atmosphere, obtained at an appropriate cost. To reach this goal, there are different air pollution control philosophies: emission standards, air quality standards, emission taxes, and cost–benefit standards. The implementation of these philosophies requires different control methodologies. Some of them consist in obtaining better pollutant dispersion in the lower atmosphere (high stacks, intermittent emission controls, placing industrial plants far from populated areas), reducing emissions by changing industrial processes, or installing control devices.

The improvement of natural dispersion and self-purification conditions of the atmosphere requires the knowledge of the lower atmosphere’s characteristics. Air pollutants reach the receptors after they are transported and/or transformed in the atmosphere. The air pollution concentration at the receptor depends on the location of the receptors in relation to the sources, on the source height, and on the emission rate. Furthermore, the sensitivity of the receptors towards pollutants in conjunction to its concentration will determine the effects.

Once polluted, the atmosphere can only be cleansed by natural processes. Thus, knowledge of atmospheric processes is useful in the management of the atmospheric environment. Meteorological information and knowledge can contribute to establishing the bases for decisions regarding the control of emissions. In this way, high air pollution potential can be related to the atmospheric conditions, which, given the existence of sources, are conducive to the occurrence of high concentrations of pollution. This definition is in terms of atmospheric conditions only and a high air pollution potential may occur even through the air quality is good.

An important meteorological variable for air pollution potential is the mixing height. This height is defined as the thickness of the atmospheric layer near the ground in which relatively vigorous convective and turbulent mixing take place. This height can range from virtually zero at night to several kilometers in the afternoon. Some authors in different countries have evaluated and analyzed mixing height (Popovics and

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*Author to whom correspondence should be addressed.

Szepesi 1970, Holzworth 1972, Tuna 1972, Raman and Kelkar 1972, Portelli 1977, Myrick and others 1994, Ulke and Mazzeo 1998). Another important variable in the estimation of air pollution potential is the average wind speed through the mixing layer or transport wind. If the mixing layer is thin, a strong transport wind has the same effect on air's ventilation as a lighter transport wind associated with a larger mixing layer. The frequency of poor atmospheric ventilation or high air pollution potential conditions can be important in the evaluation of the impact on air quality that could be produced by future installation of industries.

In this paper we present a statistical analysis of the mixing height and of the transport wind to evaluate the air pollution potential in Argentina. Daily values of maximum mixing height and of transport wind were calculated for different areas of the country. The mean seasonal values for these parameters were analyzed and the seasonal frequencies for poor ventilation condition were calculated. We include the isopleths of the mean seasonal frequencies of poor ventilation conditions in Argentina. We could not study the evolution of the nocturnal ground-based inversion because the last of the two daily rawisonde observations is done at 8 p.m. (0 UTC) under diurnal conditions during the warm seasons and at the evening during the cold ones.

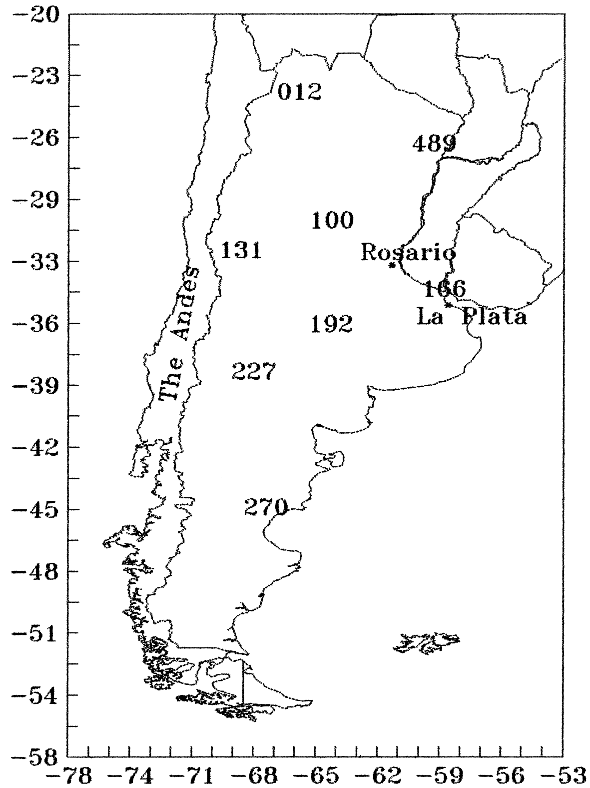

Figure 1. Location of the meteorological stations: Salta (012), Resistencia (489), Córdoba (100), Mendoza (131), Ezeiza (166), Santa Rosa (192), Neuquén (227), Comodoro Rivadavia (270), Rosario City, and La Plata City. Numbers in parentheses indicate meteorological station number.

Descriptive Aspects

Argentina has an area of almost 3 million km^2 and extends from 22°S to 55°S and from 75°W to 55°W, in other words, from the subtropic to the subpolar region (Figure 1). The eastern portion of the country is essentially plain, rising gradually from east to west. On the western side of the country there are the Andes mountain range, the most important topographic feature in South America. Mountains in Argentina have heights greater than 4000 m up to 40°S. Beyond this latitude, the height of the mountains decreases appreciably. Argentina has a population of 36 million people. Almost 34% of this population lives in the Buenos Aires Metropolitan Area (BAMA), an area of 4082 km^2 around Buenos Aires City. The most industrialized region of the country stretches from the Rosario City (32°55′S; 60°47′W) to the La Plata City (34°55′S; 57°56′W), enclosing the BAMA (see Figure 1). In general, there are few observational studies of air quality in Argentina.

For this study, daily information of air temperature at different heights and the maximum air temperature at ground level observed at eight meteorological stations (see Table 1 and Figure 1) belonging to the National Meteorological Service were used to obtain the daily maximum mixing height. Likewise the surface wind speed measured at 10 m height and the topographic characteristic of the surroundings of each station were used to estimate the transport wind. The seasonal amount of meteorological data used in this paper varied between 466 and 934 and was obtained in the period 1972–1982. The data corresponding to rainy days were not take into account, because in these cases the methodology used to calculate the mixing height is not

Table 1. Meteorological station characteristics

Station	Station number	Height (m)	Latitude	Longitude	z_0 (m)
Salta	012	1226	24°51′S	65°29′W	1.00
Resistencia	489	52	27°27′S	59°03′W	0.05
Córdoba	100	474	31°19′S	64°13′W	0.20
Mendoza	131	704	32°50′S	68°47′W	0.07
Ezeiza	166	20	34°40′S	58°32′W	0.03
Santa Rosa	192	189	36°34′S	64°16′W	0.30
Neuquén	227	270	38°57′S	68°08′W	0.07
Comodoro Rivadavia	270	61	45°47′S	67°30′W	0.03

applicable. Table 1 shows the location of the meteorological stations, their identification number, their height over sea level and their surface roughness length (z_0) (see Panofsky and Dutton 1984).

Methodological Aspects

Mixing Height

The diurnal changes in solar radiation amounts set up a cycle of cooling and heating of the lower layer of the atmosphere. After sunrise, due to the heating of the ground by solar radiation, a diurnal atmospheric boundary layer (ABL) adjacent to the earth's surface is developed. This layer is known as the mixing layer since its turbulence of thermal origin is often sufficiently vigorous to mix pollutants. Movements inside this layer are dominated by updrafts, called thermals, that originate near the surface. The thermals penetrate the air layer over the atmospheric boundary layer, making possible a rapid growth of the mixing layer during the first morning hours. Once the maximum surface temperature is reached, this layer stops growing and its thickness remains practically constant for some hours. The thermals are surrounded by downdrafts of lower velocity, but covering a greater horizontal area. The result is a mixing of the air that is so strong in this layer that the vertical air temperature gradient is about $-0.01°C/m$. To obtain the daily maximum mixing height (H), Holzworth (1967) developed a method using the air temperature observed at different heights at 12 UTC (Universal Time Coordinate) and the daily maximum temperature observed at surface. The maximum mixing height is then estimated constructing a curve with a slope of $-0.01°C/m$ starting at the maximum surface temperature up to the height at which the vertical temperature variation is intersected.

Transport Wind

The transport wind (U_T) is defined as the average value of the windspeed through the mixing layer. The available amount of windspeed data observed at different heights at each meteorological station was not enough to evaluate the transport wind. For this reason we estimated the transport wind using the following expression:

$$U_T = \frac{1}{H - z_0} \int_{z_0}^{H} u(z)\, dz \tag{1}$$

where $u(z)$ is the wind profile and z is the height.

The wind profile functions used in equation 1, proposed by Ulke (1993), are based on considerations developed by Yokohama and others (1977a,b, 1979). They give a description of the turbulent structure of the ABL using an extension of the similarity theory developed for the surface layer (Monin and Obukhov 1954), which employs the local fluxes rather than the surface values as scaling parameters for the boundary layers' parameters.

Integration of equation 1 with the windspeed profile obtained by Ulke (1993) yields the following transport wind equations:

For neutral atmospheric conditions:

$$U_T = \frac{u_0^*}{k}\left[\ln\left(\frac{z}{z_0}\right) - \frac{3}{2}\right] \tag{2}$$

where u_0^* is the surface friction velocity (Panofsky and Dutton 1984), k is the von Karman constant, z is the height, z_0 is the surface roughness length, and H is the depth of the mixing layer.

For unstable atmospheric conditions:

$$\begin{aligned} U_T = \frac{u_0^*}{k(H - z_0)} \Bigg\{ & H \ln\left(\frac{H}{z_0}\right) - (H - z_0) \\ & + \frac{4L}{11}\left\{A(\mu)\Big|_{\mu_0}^{\mu} + B(\mu)\Big|_{\mu_0}^{\mu} + C(\mu)\Big|_{\mu_0}^{\mu} + D(\mu)\Big|_{\mu_0}^{\mu}\right\} \\ & + \Bigg[2 \ln(1 + \mu_0) + \ln(1 + \mu_0^2) \\ & - 2 \tan^{-1} \mu_0 - \frac{2}{33}\frac{L}{H}\mu_0^3\Bigg]\Bigg\} \end{aligned} \tag{3}$$

where

$$A(\mu) = [\tfrac{1}{4}(1+\mu)^4 - (1+\mu)^3 + \tfrac{3}{2}(1+\mu)^2 - (1+\mu)] \ln(1+\mu)$$

$$B(\mu) = -\tfrac{1}{16}(1+\mu)^4 + \tfrac{1}{3}(1+\mu)^3 - \tfrac{3}{4}(1+\mu)^2 + (1+\mu)$$

$$C(\mu) = \tfrac{1}{4}(\mu^4 - 1)[\tfrac{1}{2}\ln(1+\mu^2) - \tan^{-1}\mu]$$

$$D(\mu) = -\frac{1}{4}\left[\frac{\mu^4}{4} - \frac{\mu^3}{3} - \frac{\mu^2}{2} + \mu\right] - \frac{L}{33H}\frac{\mu^7}{7}$$

$$\mu = \left[1 - 22\left(\frac{z}{H}\right)\left(\frac{H}{L}\right)\right]^{1/4}$$

$$\mu_0 = \left[1 - 22\left(\frac{z_0}{H}\right)\left(\frac{H}{L}\right)\right]^{1/4}$$

and L is the Monin–Obukhov length (Monin and Obukhov 1954).

The atmospheric stability at the hour of maximum surface temperature was determined using the classification suggested by Turner (1964). We obtained the surface roughness length (z_0) using the topographic

Table 2. Mean seasonal transport wind (U_T) and seasonal standard deviations of transport wind (σ_{U_T}) and mixing height (σ_H)

Station	Statistic	Summer	Autumn	Winter	Spring
Salta	U_T (m/s)	8.9	6.0	6.9	11.9
	σ_{U_T}	5.6	4.4	4.9	6.3
	σ_H (m)	519	347	572	578
Resistencia	U_T (m/s)	3.9	3.2	4.4	5.0
	σ_{U_T} (m/s)	2.9	2.7	3.4	3.5
	σ_H (m)	541	443	414	516
Córdoba	U_T (m/s)	9.3	9.0	9.0	11.0
	σ_{U_T} (m/s)	5.5	5.7	6.4	6.1
	σ_H (m)	518	418	441	565
Mendoza	U_T (m/s)	5.3	3.5	3.0	5.0
	σ_{U_T} (m/s)	3.6	3.0	3.7	4.0
	σ_H (m)	729	514	484	763
Ezeiza	U_T (m/s)	6.9	5.8	6.3	7.3
	σ_{U_T} (m/s)	4.1	3.5	3.9	4.3
	σ_H (m)	547	438	365	512
Santa Rosa	U_T (m/s)	9.3	8.9	9.3	10.7
	σ_{U_T} (m/s)	5.9	6.0	6.8	7.0
	σ_H (m)	796	532	499	738
Neuquén	U_T (m/s)	8.9	6.9	8.8	10.5
	σ_{U_T} (m/s)	5.8	5.3	7.1	7.1
	σ_H (m)	667	604	543	757
C. Rivadavia	U_T (m/s)	16.2	13.3	14.0	16.0
	σ_{U_T} (m/s)	8.9	9.1	9.6	9.4
	σ_H (m)	901	761	677	919

characteristics and the land use at the surroundings of each station (Panofsky and Dutton 1984). The Monin-Obukhov length (L) was obtained using the methodology presented by Golder (1972) knowing the atmospheric stability and the surface roughness length. Finally, the windspeed observed at a height of 10 m was used to estimate the value of the surface friction velocity. In cases of calm winds, the windspeed was taken to be equal to the anemometers' threshold (0.5 m/sec).

Results and Discussion

Mixing Height

The daily maximum mixing height (H) was calculated using the methodology described above, and then we obtained the mean seasonal values and standard deviations of H (see Table 2). In general, the mean seasonal maximum mixing height (Figures 2–5) has a minimum value in winter and a maximum in summer in all meteorological stations, except in Salta. In this site there is a minimum value in autumn and a maximum in spring. This behaviour of H in Salta can be related to the occurrence of a northwestern low atmospheric pressure system during the warm month. This system produces rains during summer. In this way, the incident

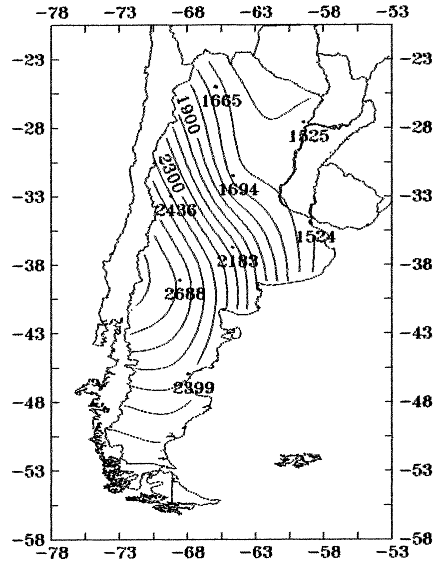

Figure 2. Isopleths of summer mean maximum mixing height (unit: m).

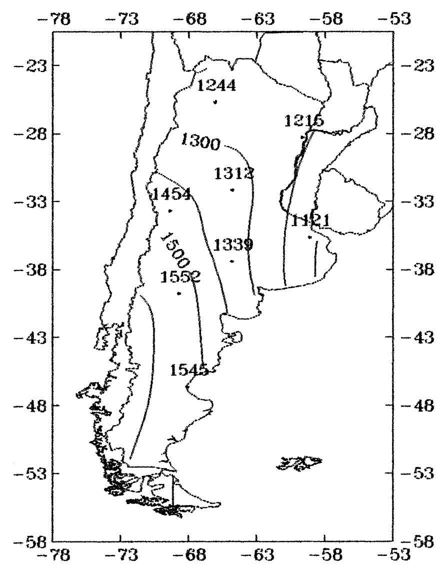

Figure 3. Isopleths of autumn mean maximum mixing height (unit: m).

solar radiation at the ground is reduced and the maximum of H does not occur in summer. The seasonal standard deviations of the mixing height (σ_H) generally have high values (see Table 2) due to the variability of H. The minimum standard deviation of H occurs in autumn or winter, while the maximum value occurs in spring or summer (see Table 2).

The highest mean seasonal maximum mixing height ($H \approx 2700$ m) is observed in summer (Figure 2) in

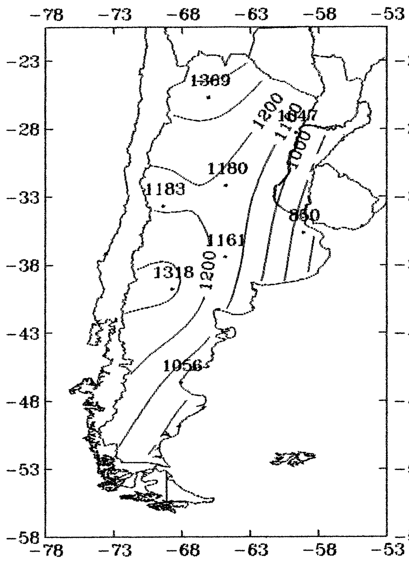

Figure 4. Isopleths of winter mean maximum mixing height (unit: m).

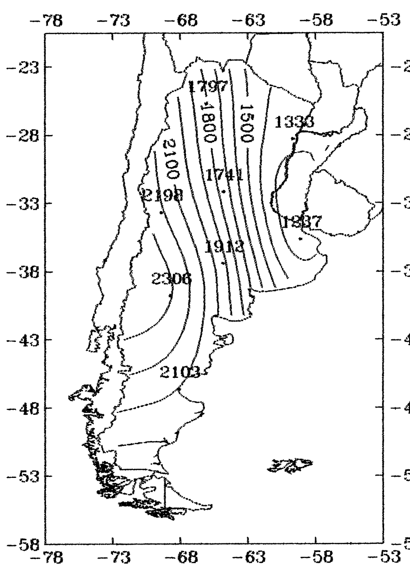

Figure 5. Isopleths of spring mean maximum mixing height (unit: m).

Neuquén. The values of H diminish towards the northeast of the country until they reach a value of about 1500 m in Resistencia. The high mean value of H obtained in Neuquén could be the result of a great amount of incident solar radiation, as a consequence of the slight cloud cover in the area (Crivelli and Pedregall 1972, Hoffmann and others 1987). The greatest horizontal gradient of H is in the southwest–northeast direction. The northeastern region of Argentina is affected by the presence of the Atlantic high pressure system that limits the growth of thermals. During autumn (Figure 3) the area with highest mean maximum mixing heights (1500 m) is still located in Neuquén. The area with the smallest values (1200 m) of H is located in the northeastern zone of the country. An important decrease of the mean mixing height gradient is observed during this season. In winter (Figure 4), the area with the lowest mean maximum mixing height is found in the northeast of the country, reaching its minimum value (850 m) over the BAMA and near the Rosario–La Plata industrialized zone. The minimum mean maximum value observed at Ezeiza could be related to the increase of the ground–ocean temperature difference. This difference contributes to the generation of the sea breeze that induces the development of an internal boundary layer (Lyons 1975, Venkatram 1977, Smedman and Högström 1983). In addition, an area with high values of mean maximum mixing height appears in the northwestern region, which might be caused by an increase of solar radiation due to the lack of cloud cover during this season. In spring (Figure 5), the conditions are similar to those of summer, but with less horizontal gradients of the mean maximum mixing height.

Transport Wind

Daily values of the transport wind were obtained according to the methodology described above and the mean seasonal values and standard deviation of U_T (σ_{U_T}) were calculated (see Table 2). The greatest mean seasonal value of transport wind occurs in spring at all sites, except in Comodoro Rivadavia and Mendoza, where it occurs in summer (see Table 2). This could be related to an increase of the meridional atmospheric pressure gradient in the southern hemisphere during the summer (van Loon 1964, Prohaska 1976) in 50°S. In Mendoza, the occurrence of the maximum value during summer could be related to effects on local atmospheric circulation caused by the presence of the Andes mountain range. The minimum mean seasonal values of the transport wind are observed during autumn at all sites, except in Mendoza where it occurs in winter. Table 2 shows that Resistencia has the smallest mean seasonal values of the transport wind, while Comodoro Rivadavia has the highest ones. The values obtained in Resistencia may be related to the high frequency of calms. In Mendoza, light transport wind values are obtained, particularly in winter. The seasonal standard deviations (σ_{U_T}) of the transport wind generally show a maximum in spring and a minimum in autumn (see Table 2). The highest seasonal values of the standard deviation of U_T are in Comodoro Rivadavia.

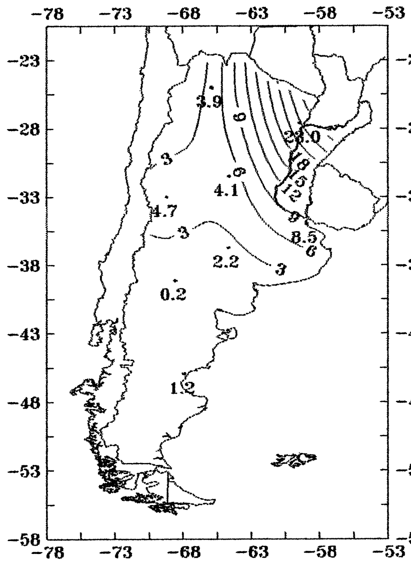

Figure 6. Isopleths of the summer low ventilation conditions ($\Delta = 3\%$).

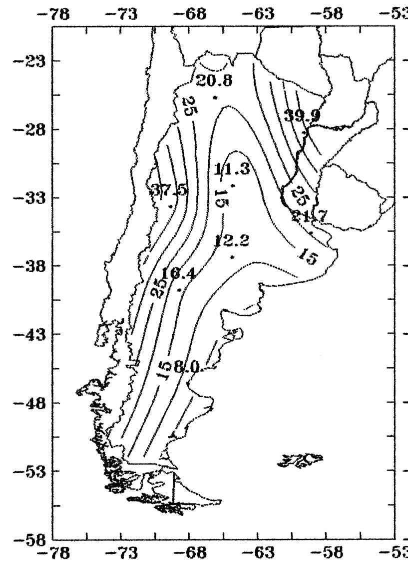

Figure 7. Isopleths of the autumn low ventilation conditions ($\Delta = 5\%$).

Air Pollution Potential

It is well known that many of the principal air pollution episodes are generally associated with high air pollution potential. In other countries some authors (Stackpole 1967, Gross 1970, Dobbins 1979) have determined the following conditions for poor atmospheric ventilation or high air pollution potential: $H \leq 1500$ m and $U_T \leq 4.0$ m/s for days without rain. As can be observed, during the cold seasons (Figures 3 and 4) practically the whole country has mean seasonal values of mixing height below 1500 m. Even so, during most of the year, the mean seasonal values of the transport wind exceed 4.0 m/s in almost all sites. These results do not allow one to infer the occurrence of conditions for low or high atmospheric ventilation.

From the calculated values of mixing height and transport wind, the seasonal frequencies of poor ventilation at each station were obtained. The isopleths of the seasonal frequencies were drawn (Figures 6–9). Figure 6 shows that during summer the air pollution potential in Argentina is generally low, because the mixing height shows its maximum values during this season. The lowest frequency of poor atmospheric ventilation occurs in Neuquén (0.2%), while the maximum occurs in Resistencia (23.0%). At this site low transport wind values are a consequence of the influence of the Atlantic high pressure system, which also limits the growth of the mixing layer. The Buenos Aires Metropolitan Area (BAMA) has an 8.5% frequency of low ventilation conditions. During autumn (Figure 7) the frequency of these conditions increases considerably in the whole country, specially in Mendoza (37.5%) and Resistencia (39.9%). In Mendoza, this increase could be related to the fact that in autumn the westerly winds (usually located south of 40°S) shift towards the north, producing a spill of air over this site after they cross the Andes mountain range (Rutlland 1981, Minetti and Vargas 1983). This air spill creates an upper boundary that prevents the vertical evolution of thermals. The minimum frequency of poor atmospheric ventilation (8.0%) is found in Comodoro Rivadavia showing the good ventilation conditions in this site. In winter (Fig-

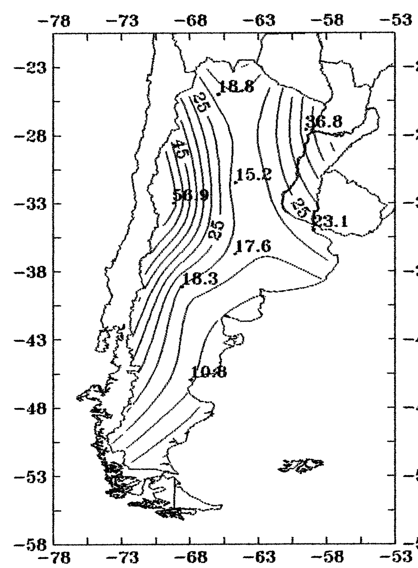

Figure 8. Isopleths of the winter low ventilation conditions ($\Delta = 5\%$).

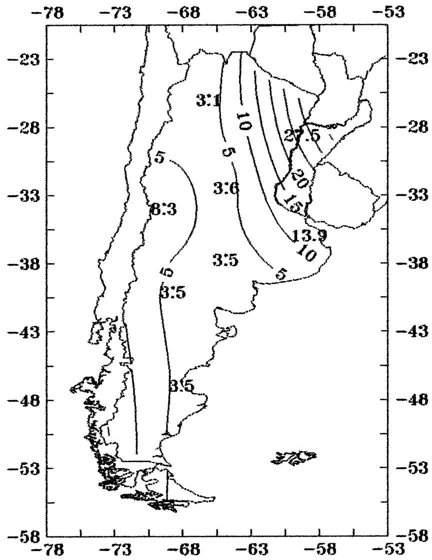

Figure 9. Isopleths of the spring low ventilation conditions ($\Delta = 5\%$).

ure 8) the effects mentioned for autumn increase, making Mendoza the site with the highest frequency of low atmospheric ventilation (56.9%). In Resistencia, the frequency (36.8%) decreases with respect to that of autumn. The minimum frequency (10.8%) is again observed in Comodoro Rivadavia. In spring (Figure 9), the frequency of low ventilation decreases substantially in the central western region of the country.

Summary

One of the aspects to take into account in air pollution control is the self-cleansing capacity of the atmosphere. This capacity can be determined by evaluating two atmospheric parameters: the mixing height (H) and the transport wind (U_T). A criterion usually applied to determine conditions of low ventilation or high air pollution potential is given by $H \leq 1500$ m and $U_T \leq 4.0$ m/s. This paper presents a statistical analysis that includes temporal and spatial distributions of the mean seasonal values of the mixing height and the transport wind in Argentina. The regions of the country with low or high air pollution potential are also determined.

In general, in Argentina the mean seasonal maximum mixing height shows a maximum in summer and a minimum in winter, with the exception of Salta. The spatial distribution of this variable shows a relative minimum in the region located between the northeastern and the central–eastern region of the country. In addition there is a relative maximum in Neuquén. Both the minimum and the maximum values persist during the four seasons. Only during winter, a second relative maximum appears in Salta. In this season, the mean seasonal maximum mixing heights are lower than 1500 m.

In general, the mean seasonal values of the transport wind show a minimum in autumn and a maximum in spring. The mean seasonal values of transport wind were, in general, greater than 4.0 m/s. The smallest mean seasonal values were found in Resistencia and Mendoza.

The isopleths of seasonal frequencies of cases with $H \leq 1500$ m and $U_T \leq 4$ m/s show greater values in the northeastern region of the country throughout the year. The exception is winter, during which the highest frequencies appear in Mendoza due to the influence of its geographical location and topographic characteristics.

According to this analysis, we conclude that in Argentina there are two zones with a poor atmospheric self-cleansing capacity. One of them is located from the northeast to the central east of the country, involving the area with the highest population and industrial density (Rosario–La Plata area). In this area, the frequency of low ventilation ranges between 23.1% and 36.0% in winter and 8.5% and 23.0% in summer. The other zone is located in the central west (Mendoza), where the low ventilation is notorious during the cold seasons (37.5% in autumn and 56.9% in winter). On the other hand, good atmospheric ventilation appears south of parallel 40°S.

Acknowledgments

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