Evolution of solar radiative effects of Mount Pinatubo at ground level

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ABSTRACT

The field research reported here contributes to the documentation on the effect of stratospheric aerosols produced by the 1991 eruption of Mount Pinatubo. Using ground-based data obtained at 2 radiometric stations, located at very different latitudes (Estonia and Spain), we have studied the evolution of the Pinatubo eruption effects. Following the eruption of Mount Pinatubo there is a significant reduction in direct solar radiation, of about 10% in Almería (Spain) and 7% in Tiirikoja (Estonia). The maximum reduction, of about 15% and 9% respectively, is measured during the 1991–92 winter. The aerosol optical depth in Almería presents, aside from the seasonal dependence, evident influences due to the volcanic aerosol cloud. We have tried to isolate this last effect. As a result, we have found that the 1991/1992 winter presented the maximum volcanic effects, with a decay along 1992 and a recovery in the 1992/1993 winter. These results are in agreement with more sophisticated studies of the aerosol cloud effects. By the 1993–1994 winter, our analysis shows evidence of a recovery of pre-eruption conditions confirmed by the aerosol optical depth behaviour during 1994. The analysis of Tiirikoja data set using an atmospheric integral transparency coefficient leads to similar results. The volcanic aerosol effect shows an exponential decay in both locations estimated at 8.6 ± 1.9 months for Almería and 8.9 ± 3.5 months for Tiirikoja.

1. Introduction

Recent volcanic eruptions have provided the opportunity for advancing the scientific knowledge in many areas of atmospheric science. The documentation and assessment of atmospheric effects are the crucial first step in the process of evaluating the different climatic change theories (Rosen et al., 1994).

The sulphur dioxide injected into the stratosphere by volcanic eruption, about 20 million tons for Mount Pinatubo eruption in June 1991 (Bluth et al., 1992), leads to the formation of sulphuric

acid droplets. These aerosols are responsible for scattering solar radiation back to space, thus leading to a decrease in the solar radiation input to the earth system. This effectiveness in the solar radiation spectrum is not accomplished by the effective absorption of sufficient outgoing thermal radiation and thus there is a contribution to surface cooling. For Mount Pinatubo, Stowe et al. (1992) have shown that these volcanic aerosols circled the globe in slightly less than one month, due to the westward transport by the stratospheric winds, enhancing the potential for global cooling. The latitudinal spreading of the stratospheric aerosol cloud, has been detected in the Almería radiometric station, a seashore location (36.83°N, 2.41°W, 10 m a.s.l.) during August 1991 (Olmo

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and Alados-Arboledas, 1995). By this date there is a sharp decrease in solar direct irradiance and associated increase in aerosol optical depth and diffuse irradiance.

The research reported here contributes to the growing world-wide documentation of the volcanic effects following the Mount Pinatubo eruption in June 1991. In this paper we extend temporally our previous study (Olmo and Alados-Arboledas, 1995), including also analysis performed on the radiometric data registered at Tiirikoja Lake Station (Estonia, 58.87°N, 26.97°E). Our goal is to follow the evolution of the volcanic effects in these two radiometric stations, located at different latitudes and affected by different climatic conditions. These processes are compared with the decay detected by Rosen et al. (1994), using balloon-borne backscatter-sondes observations of the stratospheric aerosols over two midlatitude locations. Also some parallelism has been drawn with the results obtained by Jäger et al. (1995) and by Osborn et al. (1995), using ground lidar systems, in north hemisphere stations covering subtropical and middle latitudes.

2. Data and measurements

The radiometric data used in this study have been measured in two different radiometric stations. Fig. 1 shows the location of the radiometric stations in Europe. The first one is located at the University of Almería, a seashore location (36.83°N, 2.41°W). Global and diffuse broadband horizontal solar irradiance (0.3–3 μm), have been continuously registered since the beginning of 1990, using Kipp & Zonen pyranometers, model CM-11. The measurements are registered at one minute intervals and stored at ten minutes averages until early 1993, when five minutes average intervals has been selected. The pyranometers are intercompared yearly against a reference CM-11, reserved for this purpose, and exposed to solar radiation only during these intercomparison campaigns. Temporal degradation of pyranometers is about a few tenths percent per year. Air temperature and relative humidity at two levels and other radiometric fluxes are also included among our continuous registers. From this data base, hourly values, covering the period from June 1990 to January 1995, have been generated for the present

Almería
36.83°N, 2.41°W
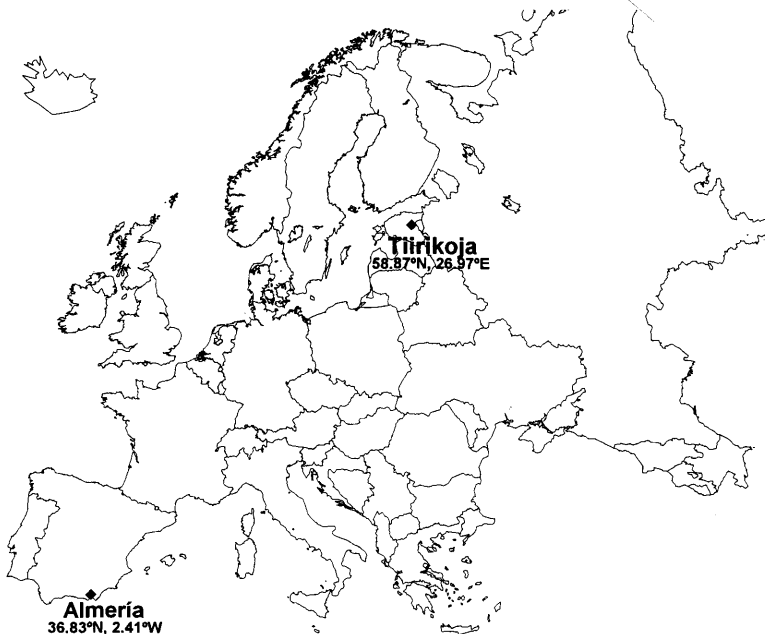
Tiirikoja
58.87°N, 26.97°E

Fig. 1. Locations of the 2 European radiometric stations used in this study.

study. Cloud cover data registered in the Almería Airport, located about 1 km away from the radiometric station, at 30 minutes intervals have been added to the data base.

The diffuse irradiance, measured by shadow-band, has been corrected using the model developed by Batlles et al. (1995). These corrected data and the global irradiance measurements have been used to evaluate the solar direct irradiance hourly values.

This radiometric station is located in the Mediterranean coast in South-eastern Spain and is characterised by the great frequency of cloudless days, and the persistence of a high humidity regime.

The Tiirikoja Lake Station is located in the western coast of the lake Peipus, Estonia (58.87°N, 26.97°E). Where an actinometer AT50 (developed at the Main Geophysical Observatory in Leningrad (St. Petersburg) was operated by solar tracker. A description of this device could be found at Kondratyev (1969). For the present study, only data acquired under no solar obstruction by clouds, as detected by human observer, have been used. The available data cover the period from 1956 until 1995 (Ohvril et al., 1995). In this study, we use instantaneous values registered at 12:00 True Solar Time (TST) since 1987 until 1995.

3. Analysis and results

To analyse the Mount Pinatubo aerosol effect at Almería, only data recorded in cloudless conditions were used for the study, for this purpose we have used the cloud observations registered in the Meteorological Office of Almería Airport. In the 1st part of our study, we have used data registered within 2 h of local noon. Fig. 2 represents the hourly direct solar irradiance time series plot for cloudless days, including data registered within two hours of local noon. There is an evident decreasing tendency starting in 1991 summer. In our previous study (Olmo and Alados-Arboledas, 1995), we have applied the sequential version in time of the Mann–Kendall rank statistic proposed by Sneyers (see for example, Sneyers, 1992) over the radiation fluxes time series registered in Almería radiometric station. As a result we have found the existence of a sharp change in solar radiation, direct and diffuse components during the first week of August 1991. According to e-folding time of the conversion of SO_2 to aerosol estimated by McPeters (1993) of 24 days, by the time the Pinatubo aerosol effect has been detected in our radiometric station the gas to particle conversion would have been largely completed. The direct irradiance values presented a reduction
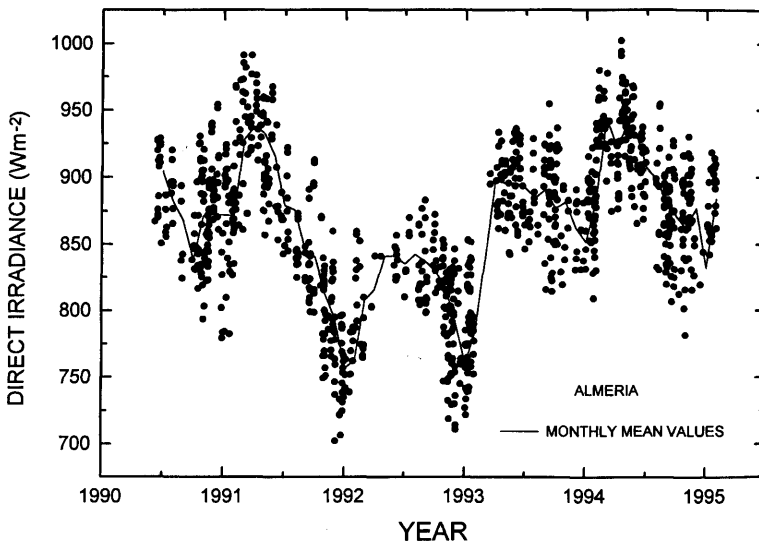

Fig. 2. Time series plot of direct solar radiation hourly values for clear days within 2 h of local noon for Almería (Spain). The solid line represents the trend of monthly average hourly values for data within 2 h of local noon.

of about 10% by these dates. Diffuse irradiance presented an increase of about 43%, while solar global irradiance shows a reduction of about 4%. The study of the temporal radiometric series reveals the combination of the seasonal variation with the volcanic effects. After the sharp change suggested by the Mann–Kendall test (Olmo and Alados-Arboledas, 1995), the volcanic aerosol extinction at Almería increased during 1991 autumn and 1991–92 winter. At this time the aerosol extinction reached its maximum value, with an hourly direct solar radiation reduction of about 15%, for values within two hours of local noon. Afterwards, during 1992 summer, there is a decay of the volcanic aerosol extinction, as a consequence the direct irradiance reduction reached values close to 6%. Nevertheless, at the end of 1992 there is a recovering of the extinction process, with a reduction of direct solar irradiance around 9% with reference to pre-eruption autumn values. This result is similar to the detected by Michalsky et al. (1994) in their analysis of Mt. Pinatubo eruption effects, where they found a similar decay of volcanic aerosol effects interrupted by the presence of a recovery at the end of 1992. Previous analyses of El Chichon eruption effects (Michalsky et al., 1990) have revealed a similar pattern, with winter extinction recovery. This fact has been justified by the possible winter transport of stratospheric aerosols from a tropical reservoir, which it is slowly decreasing (Michalsky et al., 1990). For the 2nd semester of 1993 the direct irradiance values approached the pre-eruption levels. Since these dates the volcanic effects present a negligible contribution, as revealed by the comparison with the pre-eruption conditions.

The reduction in solar direct irradiance detected after the volcanic eruption is followed by an important increase in solar diffuse irradiance due to the presence of volcanic aerosols. Following the decay of the direct irradiance reduction, shown in Fig. 2, we detect a decrease in the anomalous high values of diffuse irradiance. This modification in the partitioning of the solar global irradiance received at surface level has been responsible of efficiency loss in solar energy conversion systems (Michalsky et al. 1994). The highly variable effects of tropospheric aerosols, water vapour and clouds effects complicate the detection of the volcanic decreasing effects in the solar global horizontal

irradiance. In spite of the forward scattering effect, the volcanic aerosols are responsible for a reduction in the ratio of global horizontal irradiance at surface level to extraterrestrial horizontal irradiance. This fact suggests a reduction in the solar global horizontal irradiance availability starting in 1991 August and finishing by the end of 1993. We have found a peak decrease of about 4% during August 1991, for cloudless conditions limited to hours close to local noon. Dutton and Christy (1992) have found maximum decreases of 5% in clear sky total irradiance at solar zenith angle of 60° when the Pinatubo volcanic aerosol effects presented their maximum at Samoa Islands and Boulder, Colorado. On the other hand after analysing the daily solar global irradiance for completely cloudless days at Mauna Loa, these authors (Dutton and Christy, 1992) found an average 2.7% decrease. After the comparison of daily solar global irradiance for cloudless days, before and after August 1991, we found an average decrease about 2.5%. This is an important result considering the latitudinal differences between our station and Mauna Loa (19°N), and provides more information about the radiative forcing of volcanic aerosols.

Aerosol optical depth provides a measure of the aerosol contribution to the extinction in direct irradiance as it passes through the atmosphere. This parameter can be obtained from direct solar spectral irradiance or by the combination of direct solar total irradiance and a radiative transfer model. In our case we have derived the aerosol optical depth from the direct solar total irradiance using a relatively simple parametric model. We have used the Gueymard and Iqbal C models (Iqbal, 1983; Gueymard, 1993), obtaining similar results in both cases. In this way we have excluded the water vapour effect, evaluated by means of relative humidity and temperature measured at screen level. For the contribution due to gases we have used climatological values.

The temporal series of aerosol optical depth presents a pattern similar to that observed in the direct irradiance. To remove the seasonal effects we have evaluated the aerosol optical depth anomaly respect to the complete year available before the volcanic eruption, Fig. 3. The maximum anomaly in aerosol optical depth appeared in March 1992, at the end of winter. Starting at this maximum, the aerosol optical depth decreased with
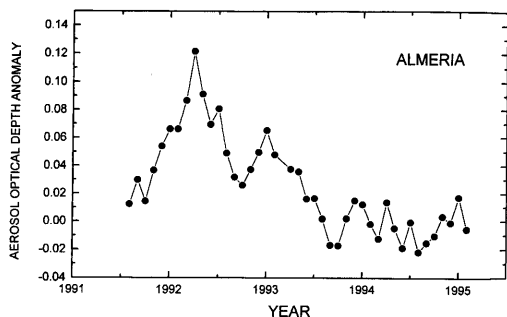
Fig. 3. Aerosol optical depth anomaly normalised by the pre-eruption values in Almería (Spain).

an average 1/e decay time around 8.6 ± 1.9 months. For this computation we have considered the period since March 1992 until January 1995. Rosen et al. (1994) have analysed the decay of the Pinatubo aerosol at Laramie (Wyoming, 41°N) and Lauder (New Zealand, 45°S) using balloon-borne scatterosondes. They obtained an e-folding decay time for the stratospheric aerosol optical depth (tropopause to 30 km) of 495 ± 105 days and 381 ± 41 days, respectively, without removing the annual cycle effects. On the other hand Jäger et al. (1995) have detected e-folding decay times for the stratospheric aerosol effects between 8.3 and 10.3 months in the northern latitude stations included in their study.

Osborn et al. (1995) using a ground-based lidar system at NASA Langley Research Center in Hampton, Virginia, have found that the maximum stratospheric aerosol effects were measured on 20 February 1992. After decreasing during the spring and summer of 1992, the aerosol burden increased significantly during the winter of 1992–93, reaching a secondary maximum on 19 February 1993, almost one year after the absolute maximum. These winter maxima are evidence of the significant volcanic aerosols poleward winter transport from the equatorial reservoir (Kent, 1986). The enhancement in the winter of 1992/1993 was followed by a sudden, dramatic clearing in the spring of 1993. We found a similar pattern in our analysis of aerosol optical depth. After the 1992 March maximum there is a substantial decay in the aerosol optical depth, with a local minimum in this anomaly at the end of 1992 summer. This feature is similar to that found for the aerosol optical depth from above the tropo-

pause by Jäger et al. (1995) in their lidar study. From the autumn of 1992 there is a recovery of the aerosol optical depth anomaly, that reaches a secondary maximum during December 1992, also consistent with the results of Jäger et al. (1995) for Japanese and German stations. Our results show that conditions close to that prevailing in the pre-eruption period have been reached for the second semester of 1993. The aerosol optical depth obtained by Rosen et al. (1994) over Laramie also presents this behaviour. In addition, Osborn et al. (1995) using the integrated aerosol backscatter, defined as the integral of the aerosol backscattering coefficient from the tropopause to 30 km, which provides a good measure of stratospheric aerosol column loading, obtained this pattern of primary and secondary maximum during the 1991–92 and 1992–93 winter, with a local minimum at the end of 1992 summer.

Tiirikoja direct irradiance temporal series shows just the same pattern observed at Almería (Fig. 4). For this study we used data acquired at 12:00 TST. To detect the existence of an abrupt change in this radiometric data serie, we have applied the sequential version in time of the Mann–Kendall rank statistics proposed by Sneyers (Sneyers, 1992). This test, that have been previously applied to the Almería data set (Olmo and Alados-Arboledas, 1995), allows the detection of the approximate beginning of change through a graphical technique which uses the forward and backward trend analyses of the Mann–Kendall statistic. In this case, we found an intersection between the two resulting lines in the region of 5% significance level, thus suggesting the existence of an abrupt change in the solar direct irradiance measured at Tiirikoja during the third August week. This implies a delay of about a week in comparison with the results obtained at Almería (Olmo and Alados-Arboledas, 1995).

A maximum reduction of about 9% has been found in Tiirikoja during the 1991–92 winter. During the second winter following the volcanic eruption a reduction about 5% over the pre-eruption conditions has found, while the inter-mediate summer shows only a reduction about 3%. This pattern is similar to that found in Almería.

For Tiirikoja data base, it is not possible to evaluate the aerosol optical depth for the complete period. For such reason we used the direct irradi-
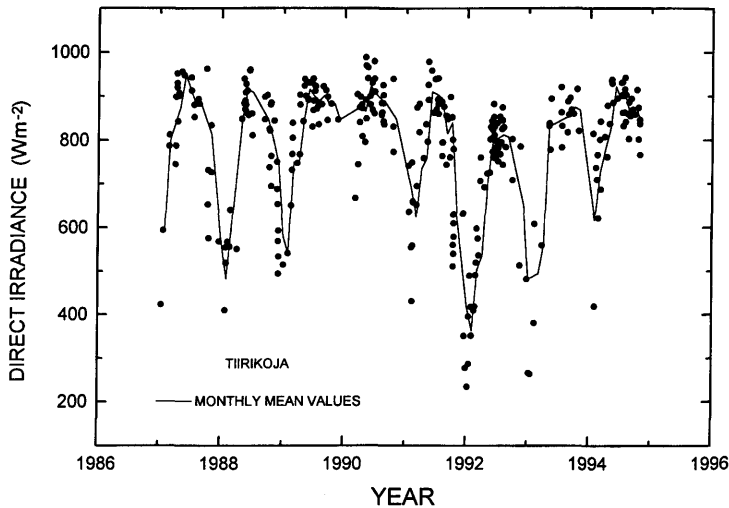
Fig. 4. Time series plot of instantaneous direct solar irradiance, registered at local noon, at Tiirikoja (Estonia).

ance measurements to evaluate the atmospheric transparency by means of the coefficient p_m

$$p_m = (I_m/I_o)^{1/m},$$

which may be considered as an Atmospheric Integral Transparency Coefficient — AITC, where I_m represents the direct beam at surface level measured at relative optical air mass m, and I_o represents the extraterrestrial solar irradiance. Due to simplicity of the AITC p_m, many actinometrists tried from 1920s to introduce it as a general character of turbidity for all atmospheric layers (Kondratyev, 1969). Unfortunately because of the Forbes effect (caused by the selective spectral attenuation of direct solar beam in the atmosphere) the AITC depends on solar elevation even for stationary and azimuthally homogeneous atmosphere. Methods to reduce the Forbes effect were in principal solved in 1960s by Sivkov (1965, 1968) and Mürk (1959a, 1959b). Methods were upgraded by Yevnevich and Savikovskij (1989), Mürk and Ohvril (1988, 1990) and Ohvril and Mullamaa (1993). It is generally accepted to reduce the AITC p_m from the actual air mass m to p_2 that corresponds to air mass $m=2$ (solar elevation 30°). We have used the most recent formula of Mürk and Ohvril:

$$p_2 = p_m \left(\frac{2}{m}\right)^{(\log p_m + 0.009)/(\log m - 1.848)},$$

described by Ohvril and Mullamaa (1993). This formula allows easy calculation of AITC, normalised to 30° solar elevation.

Figs. 5, 6 show the temporal series of p_2 evaluated over Tiirikoja and Almería data set for the sake of comparison. To put in evidence the volcanic aerosol effects we have evaluated the p_2 anomaly following the Mt. Pinatubo eruption. For this purpose we have evaluated a mean p_2 pattern using data since 1988 until 1990, available at Tiirikoja. The background aerosol level preceding the eruption of Pinatubo was lower than that preceding El Chichon, due to the absence of important volcanic eruption since the 1985 eruption of Nevado del Ruiz. Similar procedures have been followed at Almería, although in this case the pre-eruption conditions are limited to data acquired since 1990. For the sake of comparison, we have considered the convenience of analysing the relative anomalies, using the anomaly to the mean background value ratio. Fig. 7 shows the relative anomalies in p_2, both for Almería and Tiirikoja. It is interesting to note that the results obtained at Almería are similar to those obtained in the aerosol optical depth analyses. This could be considered as an evidence of the convenience of p_2 for this study. Concerning Tiirikoja, after the detection of the abrupt change, the p_2 coefficient presents a pattern similar to that found at Almería.
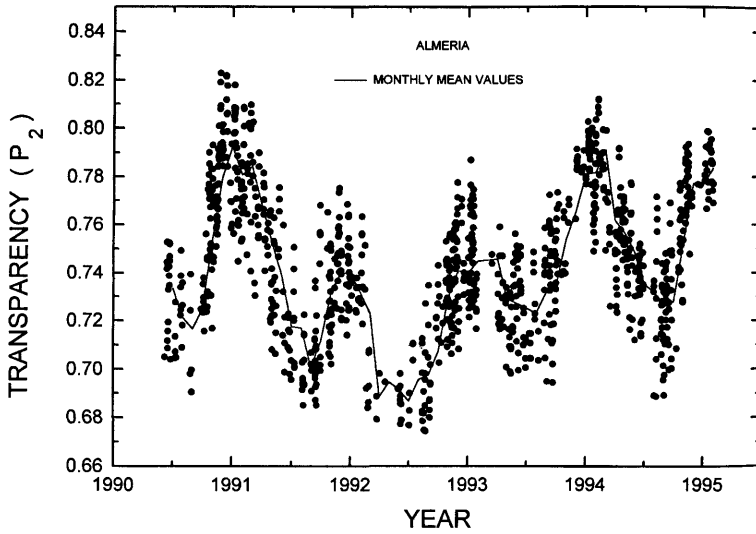
Fig. 5. Time series plot of atmospheric integral transparency coefficient p_2, evaluated for clear days within 2 h of local noon at Almería.
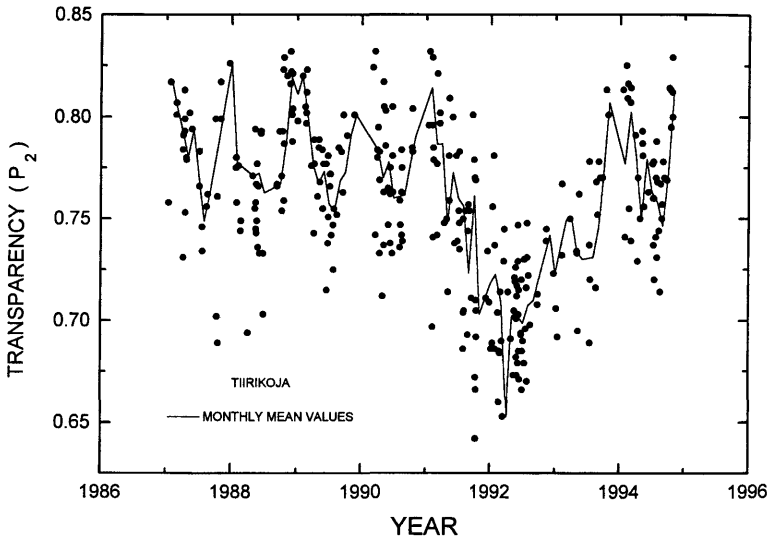

Fig. 6. Time series plot of atmospheric integral transparency coefficient p_2, evaluated for clear days at local noon at Tiirikoja.

Thus it is evident that during the 1991–92 winter the volcanic aerosol effect presents their maximum. After that there is a decay until the summer and autumn months, interrupted for the presence of a secondary maximum in the 1992–93 winter. The differences in the relative importance of the strato-spheric aerosol effect are evident from Fig. 7. The peak effect represents a reduction in p_2 above 10% in Almería, while for Tiirikoja this maximum effect is above 4%. The 1992–93 winter secondary max-imum represents a p_2 reduction around 7% in Almería and close to the 3% in Tiirikoja. During the second semester of 1993 the p_2 values reach conditions close to the pre-eruption conditions.
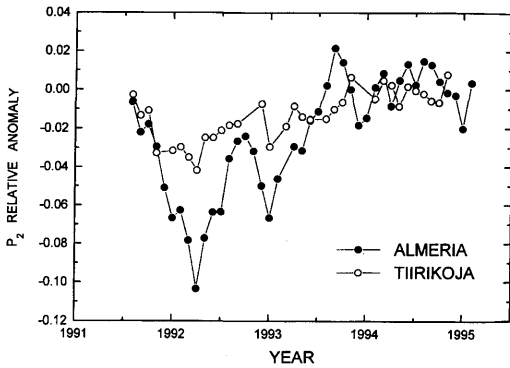
Fig. 7. Anomaly in atmospheric integral transparency coefficient p_2, at Almería and Tiirikoja. The anomaly is represented in relative terms, showing the ratio between the reduction in p_2 and the seasonal pattern obtained for pre-eruption conditions at both places.

Concerning the *e*-folding decay of the volcanic aerosol effects on p_2 we found a value of 8.9 ± 3.5 at Tiirikoja, while for Almería we found a value of 8.6 ± 2.4. This last result is similar to that found in the aerosol optical depth except the higher error, consequence of the p_2 differences with the aerosol optical depth.

4. Summary

The study of the radiation fluxes temporal series registered in two radiometric stations, Almería (36.83°N, 2.41°W) and Tiirikoja (58.87°N, 26.97°E), suggests the existence of a sharp change in solar radiation, direct and diffuse components, coincident with the arriving of the Pinatubo aerosols cloud to the respective latitudes. The direct irradiance values at a sea level location, in Southeastern Spain, present a reduction of about 10% a few weeks after the Pinatubo eruption, while for Tiirikoja we found a reduction close to 7%. Diffuse irradiance at Almería presents an increase of about 43%, with a minor effect on global irradiance, which shows a reduction of about 4%. The effects of the aerosol cloud are evident during 1992, reaching their maximum extinction levels during winter and decaying in summer. Nevertheless, there is a recovering of the extinction process at the end of 1992.

We have found similar direct radiation extinction effects to those obtained by Michalsky et al. (1994) for various mid latitude stations, but with some differences with those obtained by Blumthaler and Ambach (1994) for a high-Alpine station in Switzerland.

The temporal series of aerosol optical depth in Almería shows a maximum anomaly, after the volcanic eruption, in March 1992, at the end of winter. Starting at this maximum, the aerosol optical depth decreased with an average $1/e$ decay time around 8.6 ± 1.9 months. This $1/e$ decay is smaller than that encountered by Rosen et al. (1994) in Wyoming (41°N) and New Zealand (45°S) using balloon-borne scatterosondes, though it is close to the results of Jäger et al. (1995) for the northern latitude stations included in their study. In any case these differences in the *e*-folding decay times are not relevant considering the uncertainties involved in their computations.

In agreement with the results obtained by Osborn et al. (1995) and Jäger et al. (1995) we found that after the maximum volcanic aerosol effect, detected at the end of 1992 winter, there is a decreasing tendency. This tendency is interrupted during the 1993 winter when we found a maxima that evidences the significant poleward winter transport of stratospheric aerosols from the equatorial reservoir (Kent, 1986). The enhancement in the winter of 1992/1993 was followed by a sudden, dramatic clearing in the spring of 1993. Following the 1992 March maximum there is a local minimum in this anomaly at the end of the 1992 summer. This feature is similar to that found for the aerosol optical depth from above the tropopause by Jäger et al. (1995) in their lidar study. It appears that conditions close to those prevailing in the pre-eruption period have been reached for the second semester of 1993.

5. Acknowledgements

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