Origin of atmospheric aerosols at the Pierre Auger Observatory using studies of air mass trajectories in South America

The Pierre Auger Collaboration\textsuperscript{a}, Gabriele Curci\textsuperscript{b}
\textsuperscript{a}Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina
\textsuperscript{b}CETEMPS, Department of Physics, University of L’Aquila, L’Aquila, Italy

Abstract

The Pierre Auger Observatory is making significant contributions towards understanding the nature and origin of ultra-high energy cosmic rays. One of its main challenges is the monitoring of the atmosphere, both in terms of its state variables and its optical properties. The aim of this work is to analyze aerosol optical depth $\tau_a(z)$ values measured from 2004 to 2012 at the observatory, which is located in a remote and relatively unstudied area of the Pampa Amarilla, Argentina. The aerosol optical depth is in average quite low – annual mean $\tau_a(3.5\text{ km}) \sim 0.04$ – and shows a seasonal trend with a winter minimum – $\tau_a(3.5\text{ km}) \sim 0.03$ –, and a summer maximum – $\tau_a(3.5\text{ km}) \sim 0.06$ –, and an unexpected increase from August to September – $\tau_a(3.5\text{ km}) \sim 0.055$). We computed backward trajectories for the years 2005 to 2012 to interpret the air mass origin. Winter nights with low aerosol concentrations show air masses originating from the Pacific Ocean. Average concentrations are affected by continental sources (wind-blown dust and urban pollution), while the peak observed in September and October could be linked to biomass burning in the northern part of Argentina or air pollution coming from surrounding urban areas.

Keywords: cosmic ray, aerosol, air masses, atmospheric effect, HYSPLIT, GDAS.

1. Introduction

Modelling of aerosols in climate models is still a challenging task, also due to the lack of a complete global coverage of long-term ground-based measurements. In South America, only few studies have been done, usually located in mega-cities (Carvacho et al., 2004; López et al., 2011; Morata et al., 2008; Reich et al., 2008; Zhang et al., 2012). Astrophysical observatories need a continuous monitoring of the atmosphere, including aerosols, and thus offer an unique opportunity to get a characterisation of aerosols in the same locations over several years. Here we report on seven years of aerosol optical depth measurements carried out at the Pierre Auger Observatory in Argentina.

The Pierre Auger Observatory is the largest operating cosmic ray observatory ever built (Abraham et al., 2004, 2010a). It is conceived to measure the flux, arrival direction distribution and mass composition of cosmic rays from $10^{18}$ eV to the very highest energies. It is located in the Pampa Amarilla (35.1° – 35.5° S, 69.0° – 69.6° W, and 1300 – 1700 m above sea level), close to Malargüe, Province of Mendoza. Construction was completed at the end of 2008 and data taking for the growing detector array started at the beginning of 2004. The observatory consists of about 1660 surface stations – water-Cherenkov tanks and their associated electronics – covering an area of 3000 km\textsuperscript{2}. In addition, 27 telescopes, housed in four fluorescence detector (FD) buildings, detect air-fluorescence light above the array during nights with low-illuminated moon and clear optical conditions. The atmosphere is used as a giant calorimeter, representing a detector volume larger than 30 000 km\textsuperscript{3}. Once cosmic rays enter into the atmosphere, they induce extensive air showers of secondary particles. Charged particles of the shower excite atmospheric nitrogen molecules, and these molecules then emit fluorescence light mainly in the 300 – 420 nm wavelength range. The number of fluorescence photons produced is proportional to the energy deposited in the atmosphere through electromagnetic energy losses undergone by the charged particles. Then, from their production point to the telescope, photons can be scattered by molecules (Rayleigh scattering) and/or atmospheric aerosols (Mie scattering). A small component (at shorter ultra-violet wavelengths) of the fluorescence light can be absorbed by some atmospheric gases such as ozone or nitrogen dioxide.

The aerosol component is the most variable term contributing to the atmospheric transmission function. Thus, to reduce as much as possible the systematic uncertainties on air shower reconstruction using the fluorescence technique, aerosols have to be continuously monitored. An extensive atmospheric monitoring system has been developed at the Pierre Auger Observatory (Abraham et al., 2010b; Louedec and Losno, 2012). The different facilities and their locations are shown in Figure 1. Ae-
The CLF provides hourly altitude profiles for each fluorescence site during fluorescence data acquisition. In Figure 2(left), the distribution of the aerosol optical depth integrated from the ground up to 3.5 km above ground level, recorded at Los Leones, Los Morados and Coihueco is shown. Due to large distance to the CLF site, measurements from Loma Amarilla have not been included in this study. Only recently, data from the closer XLF have been used to measure the aerosol attenuation from Loma Amarilla (Valore et al., 2013). The mean value of $\tau_a(3.5 \text{~km})$ is about 0.04. Nights with $\tau_a(3.5 \text{~km})$ larger than 0.1, meaning a transmission factor lower than 90%, are rejected for air shower studies at the Pierre Auger Observatory. Systematic uncertainties associated with the measurement of the aerosol optical depth are due to the relative calibration of the telescopes and the central laser, and the relative uncertainty of the determination of the reference clear profile. The total uncertainty is estimated to 0.006 for an altitude of 3.5 km above ground level. Figure 2(right) displays the monthly variation of the aerosol optical depth integrated up to 3.5 km above ground level. The aerosol concentration depicts a seasonal trend, reaching a minimum during Austral winter and a maximum in Austral summer. This trend is typical and has already been observed in many long-term aerosol analy-
The relative frequencies month-by-month for clear conditions and hazy conditions are shown in Figure 3. Clear conditions are more common during the Austral winter than in the rest of the year. Furthermore, a clear increase for the population of hazy aerosol profiles from August to September can be seen in both Figures 2 (right) and 3, contrary to the overall seasonal trend. Table 1 lists the fraction of clear and hazy aerosol profiles for each year between 2005 and 2012. For each year, the two or three highest fraction values are indicated. Clear conditions are very common during the Austral winter throughout all years of this analysis. The unexpected peak in hazy conditions during September and October is almost as stable as the seasonal trend throughout the years, but not with the same statistical significance. It could be a consequence of biomass burning in the northern part of South America or closer pollution sources coming from the larger cities San Rafael and Mendoza in the North.

3. Backward trajectory of air masses

After having briefly presented the air-modelling programme used in this study and checked the validity of its calculations using meteorological radio soundings, this section aims for characterising the air masses crossing over the Pierre Auger Observatory.

3.1. HYSPLIT – an air-modelling programme

Different models have been developed to study air mass relationships between two regions. Among them, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, or HYSPLIT (Draxler and Rolph 2012, Rolph 2012), is a commonly used air-modelling programme in atmospheric sciences for calculating air mass displacements between two regions. Among them, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, or HYSPLIT (Draxler and Rolph 2012, Rolph 2012), is a commonly used air-modelling programme in atmospheric sciences for calculating air mass displacements between two regions. Among them, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, or HYSPLIT (Draxler and Rolph 2012, Rolph 2012), is a commonly used air-modelling programme in atmospheric sciences for calculating air mass displacements between two regions. Among them, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, or HYSPLIT (Draxler and Rolph 2012, Rolph 2012), is a commonly used air-modelling programme in atmospheric sciences for calculating air mass displacements between two regions. Among them, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, or HYSPLIT (Draxler and Rolph 2012, Rolph 2012), is a commonly used air-modelling programme in atmospheric sciences for calculating air mass displacements between two regions.

\[ \tau_{a}(3.5 \text{ km}) \leq 0.01 \quad (1126 \text{ trajectories}) \]

\[ \tau_{a}(3.5 \text{ km}) > 0.10 \quad (583 \text{ trajectories}) \]

\[ 0.03 < \tau_{a}(3.5 \text{ km}) \leq 0.05 \quad (1918 \text{ trajectories}) \]
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Table 1: Fraction and statistics of aerosol hourly profiles for clear and hazy aerosol conditions for each month between 2005 and 2012. For each year, the first line gives the fraction of profiles corresponding to the aerosol conditions in the whole set of profiles recorded during the corresponding month. The second line gives the number of profiles associated to their corresponding fraction. Months without data are indicated by “–”. For each year, the two or three months with the highest fraction of clear and hazy nights are coloured in blue and red, respectively. Colours in online version.

In this work, HYSPLIT will be used to get backward / forward trajectories by tracking air masses backward / forward in time. The resulting backward / forward trajectory indicates air mass arriving at a specific time in a specific geographical location (latitude, longitude and altitude), identifying the regions linked to it. All along the air mass paths, hourly meteorological data are used. Trajectory uncertainty for computed air masses is usually divided into three components: the physical uncertainty due to the inadequacy of the representation of the atmosphere in space and time by the model, the computational uncertainty due to numerical...
just slightly inside the array to the north-east (Abreu et al., 2012a). Lateral homogeneity of the atmospheric variables across the Auger array is assumed (Abraham et al., 2010b). Validity of GDAS data was previously studied by the Auger Collaboration: the agreement with ground-based weather station and meteorological radiosonde launches has been verified. The work consisted of comparing the temperature, humidity and pressure values with those measured by the monitoring systems at Auger. For instance, distributions of the differences between measured weather station data at the centre of the array and GDAS model data were obtained for temperature, pressure and water vapour pressure: $1.3 \text{ K} [\sigma = 3.9 \text{ K}], 0.4 \text{ hPa} [\sigma = 1.2 \text{ hPa}]$ and $-0.2 \text{ hPa} [\sigma = 2.1 \text{ hPa}]$, respectively (Abreu et al., 2012a). Thanks to their highly reliable availability and high frequency of data sets, it was concluded that GDAS data could be employed as a suitable replacement for local weather data in air shower analyses of the Pierre Auger Observatory. The agreement between GDAS model and local measurements has been checked only for state variables of the atmosphere. In the next section, wind data, a key parameter in the HYSPLIT model, are tested.

### 3.2. Validity of the HYSPLIT calculations using meteorological radio soundings

Above the Pierre Auger Observatory, the height dependent profiles have been measured using meteorological radiosondes launched mainly from the Balloon Launch Station (BLS, Figure 1). The balloon flight programme was terminated in December 2010 after having been operated 331 times since August 2002 (Abreu et al., 2012b; Keilhauer and Will, 2012). The radiosonde records data every 20 m, approximately, up to an average altitude of 25 km above sea level, well above the fiducial volume of the fluorescence detector. The average time elapsed during its ascent was about 100 minutes on average. The measurement accuracies are 0.2°C in temperature, 0.5 – 1.0 hPa in pressure and 5% in relative humidity.

As mentioned in Section 3.1, the HYSPLIT tool requires meteorological data from the GDAS model. Using the meteorological radio soundings performed at the Pierre Auger Observatory, a balloon track is available for each flight. In Figure 4, the average-vertical profiles of wind speed for each season are displayed, as measured during balloon flights at the observatory. Each of them is compared to the mean vertical profile extracted from GDAS data of the corresponding season. The wind speed fluctuates strongly day-by-day: the largest variations are measured in the Austral winter. In table 2, the mean values and the standard deviation values for the difference between measured radio sounding data and GDAS data for temperature, pressure, vapour pressure and wind speed are given. Concerning the wind speed which will be of primary interest in this work, we can see that its value is slightly underestimated by the GDAS model in the lower part of the atmosphere.

Figure 3: Monthly frequency over a year of clear hourly aerosol profiles ($\tau_v(3.5 \text{ km}) \leq 0.01$, solid line), average hourly aerosol profiles ($0.03 < \tau_v(3.5 \text{ km}) \leq 0.05$, grey filled) and hazy hourly aerosol profiles ($\tau_v(3.5 \text{ km}) > 0.10$, dotted line) at Los Morados. Data set between January 2005 and December 2012 is used here. Each bin is re-weighted to take into account the fact that not the same number of aerosol profiles is recorded in Winter (longer nights) or during Summer (shorter nights). Colours in online version.
Figure 4: Seasonal vertical profiles for wind speed using the radio soundings and the GDAS model at the Malargüe location. Radio soundings data (solid line) from August 2002 to December 2010 are used: 72 profiles in winter, 95 profiles in spring, 81 profiles in summer and 81 profiles in fall. GDAS data (dashed line) from January 2005 to December 2010 are used. Each seasonal profile contains approximately 4000 profiles. The curves represent the averaged profile of wind speed for the corresponding season. The dashed bands show the distribution of 68% of the measurements. Colours in online version.

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Table 2: Mean and standard deviation values for the differences between measured radio sounding (RS) data and GDAS model data. Values calculated for different probed altitudes. $T$: temperature, $p$: pressure, $e$: vapour pressure, $v_w$: wind speed. Data sets from January 2005 to December 2010.
To validate the wind directions used in HYSPLIT calculations, the agreement between the directions of the balloon flights and the directions of air mass paths estimated using HYSPLIT is checked. In Figure 5 (top), the distribution of balloon trajectories obtained at the Auger site is given. In this plot, the altitude evolution through the flight is not indicated. The corresponding directions of these balloon trajectories are given in blue in Figure 5 (bottom), tending roughly to a South-East direction (detailed explanations on how to obtain this plot are given in Sect. 3.3 where the steps here are given by the different data points recorded during the balloon flight). To exclude altitudes too much higher than the 500 m AGL computed by HYSPLIT, only the first 20 min of each flight is used to estimate the direction of a radio sounding. On the other hand, using the HYSPLIT tool, 48-h forward trajectories from an altitude fixed at 500 m are computed every hour, for the year 2008. Following the same method as the one explained in Sect. 3.3, the resulting distribution of air mass directions is plotted in red. The distributions for different initial altitudes will be shown later in Figure 8. Air mass directions are just slightly dependent on the altitude. The agreement between balloon trajectories and forward trajectories computed by HYSPLIT is once again very good: since a change in direction is not common for air mass trajectories at these probed altitudes, an agreement of directions along this short path can be extrapolated to larger distances travelled by air masses. Thus, after these two crosschecks, i.e. the vertical profiles for wind speed and the directions of air masses travelling above the Auger array, it can be concluded that air mass calculations for the location (35° S, 69° W) are suitable. This conclusion complements the analysis and results of the former study of GDAS data for the Pierre Auger Observatory [Abreu et al. 2012].

3.3. Origin and trajectories of air masses arriving at the Pierre Auger Observatory

The trajectories of air masses arriving at the Auger Observatory have been evaluated for eight years (2005–
2012). In this way, the seasonal variations in the origin of air masses can be shown by the analysis. A 48-h backward trajectory is computed every hour, throughout the years. Also, the evolution profiles of the different meteorological quantities can be estimated and recorded. The key input parameters for the runs are given in Table 3. In Figure 6, an example of a 48-h backward trajectory from HYSPLIT is shown for altitudes fixed at 500 m, 1000 m or 3000 m above the Malargüe location. A 2-day time scale is a good compromise with respect to aerosol lifetime, air mass dispersion and computing time. Each run provides the geographical location of air mass trajectories (arriving at different altitudes) at the Auger Observatory and the evolution (along the trajectories) of the relevant meteorological physical parameters (temperature, relative humidity, etc). Some geographical locations of air masses show significant changes of direction during the previous 48 hours. Two different methods have been used to display air mass origin and mean trajectory.

The first visualisation is a two-dimensional diagram, longitude versus altitude. From this display, it is possible to extract regional influence on air quality at the Auger site. Also, changes in direction are obvious. Therefore all regions that an air mass path traversed during its entire 48-h travel period towards the Pierre Auger Observatory are displayed. In Figure 7, the distribution of the backward trajectories for each month during the year 2008 is displayed, for a start altitude fixed at 500 m above ground level. The polar histograms are normalised to one, i.e. the sum of the height entries corresponding to the height directions is equal to one. Most of the months have air masses with a North-West origin. Air masses coming from the East are particularly rare. The observations remain the same when the start altitude of the backward trajectories is modified. For the highest initial altitude (1000 m above ground level at the observatory), the fluctuations trajectory-to-trajectory are larger and the air masses travel faster; their endpoint is farther from the Pierre Auger Observatory.

### Table 3: Input parameters used for all HYSPLIT runs.

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4. Interpretation of aerosol measurements using backward trajectories of air masses

As described in Section 2, aerosol concentrations measured at the Pierre Auger Observatory can fluctuate strongly night-by-night. Nevertheless, a seasonal trend with a minimum in Austral winter is found. The computed HYSPLIT trajectories are given in Figure 8 (top) for the conditions described in Section 2 (clear, hazy and average hourly aerosol profiles). During clear conditions, the air masses come mainly from the Pacific Ocean as already observed in Allen et al. (2011). For hazy conditions, these air masses travel principally through continental areas during the previous 48 hours. Following the conclusion of a chemical aerosol analysis performed at the Auger site by Micheletti et al. (2012), NaCl crystals are detected in aerosol samplings during Austral winter, the period with mostly clear conditions and trajectories pointing back to the Pacific Ocean. Thus, these NaCl crystals could come from the Pacific Ocean, even if we cannot exclude another main origin as salt flats as main origin. Snow is another phenomenon that has to be taken into account here. As explained in Micheletti et al. (2012), even though snowfalls are quite rare during winter in this region, the low temperatures conserve the snow on ground for long periods. An aerosol source (soil) blocked by snow, combined with air masses coming from Pacific Ocean, are probably...
Figure 7: Distribution of 48-h backward trajectories from the Malargüe region by month. Paths estimated with HYSPLIT for the year 2008, for a start altitude fixed at 500 m AGL. The black star represents the Pierre Auger Observatory. The black line represents the South American coast. Colours indicate the frequency of a region, from red (more likely) to blue (less likely). Colours in online version.
Figure 8: Direction of air masses influencing the Auger atmosphere for each month. Direction of trajectories estimated using HYSPLIT for the year 2008, with input parameters given in Table 3, at two different start altitudes: 500 m AGL (solid line) and 1000 m AGL (dashed line). Each distribution is normalised to one. Colours in online version.
Paragraphs of text and diagrams...
do not have the same origin throughout the year. Aerosol concentrations measured at the observatory depict two notable features: a seasonal trend with a minimum reached in Austral winter, and a quick increase occurring yearly just after August. The first can be explained by air masses transported from the Pacific Ocean and travelling above snowy soils to the observatory. The peak in September and October could be interpreted as air mass transport from biomass burning occurring in the northern South America (mainly in the northern of Argentina and Bolivia) during dry season. However, another cause such as air pollution transported from closer urban areas, also located to the north of the observatory, cannot be excluded. Future studies that include satellite data or ground-level monitoring between the observatory and possible pollution source regions could resolve this issue. However, for both cases, air mass transport plays a key role in the aerosol component present above the Pierre Auger Observatory.

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Appendix A. Supplementary data

Supplementary data to this article can be found online.

References


