Global Atmospheric Models for Cosmic Ray Detectors

MARTIN WILL\textsuperscript{1,2} FOR THE PIERRE AUGER COLLABORATION\textsuperscript{2}

\textsuperscript{1} Karlsruher Institut für Technologie, Institut für Kernphysik, Karlsruhe, Germany
\textsuperscript{2} Full author list: http://www.auger.org/archive/authors_2013_06.html
\textsuperscript{*} now at: Instituto de Física d’Altes Energies, Bellaterra, Barcelona, Spain
martin.will@kit.edu

1 Introduction

A cosmic ray particle entering the atmosphere can initiate an extensive air shower. The secondary shower particles excite nitrogen molecules in the air which emit a characteristic, isotropic emission in the UV range as part of their de-excitation process. The light can then be observed by an optical telescope, typically consisting of a collecting mirror and a camera. To properly reconstruct the properties of such air showers, the atmospheric conditions at the site have to be known in order to correct for Rayleigh scattering effects and to estimate the fluorescence yield of the air shower \textsuperscript{1}. Height-dependent profiles of temperature, pressure and humidity as well as weather conditions near the ground are relevant.

The Pierre Auger Observatory \textsuperscript{2} is a cosmic ray detector located near Malargüe in the Mendoza province in Argentina. It consists of a Surface Detector (SD) array and five Fluorescence Detector (FD) buildings \textsuperscript{3}. Between 2002 and 2010, atmospheric conditions over the Observatory were measured by intermittent meteorological radio soundings. Additionally, ground-based weather stations measure surface data continuously in order to provide the atmospheric parameters to properly reconstruct the measured air showers.

In south-east Colorado, several balloon soundings were performed as part of an atmospheric R&D project. The aim of this effort was to study possible enhancements and performance improvements for the Pierre Auger Observatory, as well as explore technological advancements for a possible future ground-based observatory. The ground station used for the soundings was a mobile and slightly advanced version of the equipment used in Argentina. The launches were performed at two sites, the Atmospheric Monitoring Telescope (AMT) and the Distant Raman Laser Facility (DRLF) \textsuperscript{4}. The sites are about 40 km apart and are both equipped with identical weather stations.

Performing radio soundings imposes a large burden, both in terms of funds and manpower. We investigated the possibility of using data from the Global Data Assimilation System (GDAS) \textsuperscript{5}, a global atmospheric model, for the site of the Pierre Auger Observatory \textsuperscript{6,7}. GDAS data are publicly available free of charge via READY (Real-time Environmental Applications and Display System). Each data set contains all the main state variables as a function of altitude. The data gathered in Colorado were also compared to GDAS data in order to evaluate the possibility to use GDAS also in different locations and for a possible future ground-based cosmic ray detector.

2 Global Data Assimilation System

Data assimilation is a process in numerical weather prediction in which the development of a model incorporates the real behavior of the atmosphere as found in meteorological observations \textsuperscript{8}. The atmospheric models describe the atmospheric state at a given time and position. The first step in performing a full data assimilation is to collect data from meteorological instruments placed all over the world. Using the current atmospheric conditions, a future state – e.g. 3 hours ahead – is forecast using numerical weather prediction. Finally, data assimilation is used to adjust the model output to the measured atmospheric state, resulting in a 3-dimensional image of the atmosphere. At a given time, the value of a state variable is known from observations. For the same time, a model forecast for this variable from a previous iteration a few hours earlier exists. The data assimilation step combines observation and forecast. This analysis is the initial point for the weather prediction model to create the forecast for a later time, when this process is repeated.

The Global Data Assimilation System is an atmospheric model developed at the National Centers for Environment-
Global Prediction of the National Oceanic and Atmospheric Administration. The numerical weather prediction model used is the Global Forecast System. Data are available for every three hours at 23 constant pressure levels – from 1000 hPa (≈ sea level) to 20 hPa (≈ 26 km) – on a global 1°-spaced latitude-longitude grid (180° by 360°). Each data set is complemented by data for the surface. The data are made available online [5].

For the site of the Pierre Auger Observatory, applicable GDAS data are available starting June 2005. Because of the lateral homogeneity of the atmospheric variables across the Auger array [1], one location is sufficient to describe the atmospheric conditions. The grid point at 35° S and 69° W was chosen, at the north-eastern edge of the Observatory. The grid point for the Colorado R&D site is 38° N and 102° W, about 40 km to the east of the DRLF and 60 km to the north-east of the AMT. Since the terrain is very similar to the Argentinian high desert, horizontal uniformity can be assumed. This assumption was verified by radiosonde launches at different starting positions.

For the air shower analyses of the Pierre Auger Observatory, the main state variables of the atmospheric – temperature, pressure and relative humidity – are needed at several altitudes. They are provided directly by the GDAS surface and upper air data. From those, air density and atmospheric depth profiles are calculated.

3 GDAS vs. Measurements

To validate the quality of GDAS data and to verify their applicability to air shower reconstructions for the Pierre Auger Observatory, we compare the GDAS data with local soundings from weather balloons and ground-based weather stations. Comparisons using the data from the Colorado site are also shown.

3.1 GDAS vs. Weather Balloon Soundings

Local radio soundings are performed above the array of the Pierre Auger Observatory since 2002, but not on a regular basis. To provide a set of atmospheric data for every measured event, the profiles from the ascents were averaged to obtain local models, called Malargüe Monthly Models (MM) [9]. The MM have been compiled using data until the end of 2008. The uncertainties for each variable are given by the standard deviation of the differences within each month together with the absolute uncertainties of the sensors measuring the corresponding quantity.

Compared to the MM models with ascent data until the end of 2008, the comparison displayed in the top panels of Fig. 1, radiosonde data from 2009 and 2010 are used to illustrate the strength of the GDAS data, the data set of local soundings being independent of the MM. The error bars denote the RMS of the differences at each height. These uncertainties are larger for the MM than for GDAS data. In contrast, the GDAS data represent the local conditions in 2009 and 2010 much better and the intrinsic uncertainty is consistently small. For earlier years, the GDAS data fit the measured data equally well or better than the MM which were developed using the data from these years.

In the bottom panels of Fig. 1, the same comparison is shown between the radiosonde data measured in Colorado and the corresponding GDAS data. The differences are of the same order and the error bars are similar to the results at the Pierre Auger Observatory site.

The GDAS data fit the radiosonde data in the upper part of the atmosphere, especially in the field of view of the fluorescence detectors. Possible inconsistencies between local measurements and GDAS data close to the ground are investigated using weather station data.

3.2 GDAS vs. Ground Weather Stations

Five ground weather stations continuously monitor atmospheric values at the Pierre Auger Observatory. They are mounted between about 2 to 5 m above ground level at four FD stations, and one was set up near the center of the array at the Central Laser Facility (CLF). For the Colorado R&D site, two identical weather stations were set up, one at the DRLF laser facility and one at the AMT telescope.

Figure 1: Top: Difference between measured individual radiosonde data and the corresponding GDAS data (black dots) and MM (red squares) versus height for all ascents performed at the Pierre Auger Observatory in Argentina in 2009 and 2010. Bottom: Difference between radiosonde data and the GDAS data (blue dots) versus height for all ascents performed at the Colorado R&D site in 2009 and 2010.
site. To make sure that the GDAS data describe the conditions at the ground reasonably well, the values provided by the GDAS data set are compared to all available weather station data. The profiles built using GDAS data are interpolated at the height of the station.

In Fig. 2, the differences between measured weather station data and GDAS data are shown. For the stations at the CLF and FD site Loma Amarilla (LA) all data measured in 2009 were used (top panel). For the Colorado R&D site, data taken between January 2010 and June 2011 were used for both the AMT and DRLF sites. Temperature, pressure (not shown), and vapor pressure are in similar agreement as GDAS data with local sounding data close to ground (cf. Fig. 1). The mean difference in temperature is 1.3 K for the CLF, −0.3 K for the LA, 0.5 K for the DRLF and 0.7 for the AMT station. For vapor pressure, the means are −0.2 hPa (CLF), −0.7 hPa (LA), 0.2 hPa (DRLF) and 0.4 hPa (AMT). The differences between the GDAS and the weather station data are of the same order as the difference in data of two different stations [6].

The GDAS data fit the measured data at the Observatory and the R&D site very well and are better suited for use in air shower reconstructions and simulation than monthly mean models. This reduces the need for laborious and costly radiosonde launches to sporadic checks of the consistency of the GDAS data.

4 Air Shower Reconstruction

To study the effects caused by using GDAS data in the air shower reconstruction of the Pierre Auger Observatory, all air shower data between June 1, 2005 and the end of 2010 were used. The change of the description of the atmosphere will mainly affect the reconstruction of the fluorescence data. Varying atmospheric conditions alter the fluorescence light production and transmission [11]. The fluorescence model we use determines the fluorescence light as a function of atmospheric conditions [10], parameterized using results from the AIRFLY experiment [11, 12].

4.1 Data Reconstruction

The following analysis is based on three sets of reconstructions. The first set, FY, is the reconstruction applying an atmosphere-dependent fluorescence yield calculation without temperature-dependent collisional cross sections and humidity quenching [13]. The MM are used in the calculations. For the second set, FY_mod, all atmospheric effects in the fluorescence calculation are taken into account. Again, the MM are used. For the third set, FY_GDAS, the MM are exchanged with the new GDAS data in combination with the modified fluorescence calculation. Comparing the reconstruction sets with each other, the variation of the reconstructed primary energy E and the position of shower maximum $X_{max}$ can be determined, see Fig. 3.

Using GDAS data in the reconstruction instead of MM affects E only slightly. The mean of the difference FY_GDAS minus FY_mod is 0.4% with an RMS of 1.4%. For the reconstructed $X_{max}$, only a small shift of −1.1 g cm$^{-2}$ is found with an RMS of 6.0 g cm$^{-2}$. Comparing the full atmosphere-dependent reconstruction FY_GDAS with FY, a clear shift in E can be seen: an increase in E by 5.2% (RMS 1.5%) and a decrease of $X_{max}$ by −1.9 g cm$^{-2}$ (RMS 6.3 g cm$^{-2}$). These modified fluorescence settings are now used in the Auger reconstruction, in conjunction with other improvements to the procedure, see [14].

The description of atmospheric conditions close to ground is very difficult in monthly mean profiles since the fluctuations in temperature and humidity are larger below 4 km than in the upper layers of the atmosphere. Consequently, a more precise description of actual atmospheric conditions with GDAS than with MM will alter the reconstruction for those air showers which penetrate deeply into the atmosphere. The full atmosphere-dependent fluorescence calculation alters the light yield for conditions with very low temperatures, corresponding to higher altitudes. Showers reaching their maximum in the altitude range between 3 and 7 km show a difference in E around 5%, see Fig. 3 upper right. However, showers with very shallow or
very deep $X_{\text{max}}$ are reconstructed with a 7–8% higher energy than using the atmosphere-independent fluorescence calculation. The $X_{\text{max}}$ sensitivity to the different parameterizations of the atmosphere and fluorescence yield (Fig. 3, lower right) is consistent to what has been reported in [15].

4.2 Impact on Reconstruction Uncertainties

To study the effect that GDAS data have on the uncertainties of air shower reconstructions, air showers induced by protons and iron nuclei are simulated with energies between $10^{17.5}$ eV and $10^{20}$ eV. The fluorescence light is generated using temperature-dependent cross sections and water vapor quenching. The times of the simulated events correspond to 109 radio soundings between August 2002 and December 2008 so that realistic atmospheric profiles can be used in the simulation. All launches were performed at night during cloud-free conditions. After the atmospheric transmission, the detector optics and electronics are simulated. The resulting data are reconstructed using the radiosonde data, as well as the GDAS data.

Some basic quality cuts are applied to the simulated showers. The same study has been performed to determine the uncertainties of the MM [16]. The systematic error due to different atmospheres was found to be less than 1% in $E$ and less than 2 g cm$^{-2}$ in $X_{\text{max}}$. Between $10^{17.5}$ eV and $10^{20}$ eV, energy-dependent reconstruction uncertainties of $\pm 1\%$ and $\pm 5$ g cm$^{-2}$ for low energies and up to $\pm 2\%$ and $\pm 7$ g cm$^{-2}$ for high energies were found.

In Fig. 4 the influence on the reconstruction due to GDAS data is shown. A deviation from zero indicates a systematic error, the gray error bands denote the true RMS spread of all simulated events and are a measure of the reconstruction uncertainty due to the atmospheric parameterization using GDAS. The red bands indicate the same RMS spread for the reconstructions using the MM. The systematic shifts in $E$ are below 1%, and the shifts in $X_{\text{max}}$ are less than 0.5 g cm$^{-2}$. The RMS spread for GDAS is considerably smaller than for the MM, $\pm 0.9\%$ and $\pm 2.0$ g cm$^{-2}$ for low energies, $\pm 1.3\%$ and $\pm 3.5$ g cm$^{-2}$ for high energies. The $E$ uncertainty at low energies is comparable to that introduced by the MM. At high energies, the uncertainty is almost half. For $X_{\text{max}}$, the uncertainties at all energies are halved.

This study of the reconstruction uncertainties using different atmospheric parameterizations further demonstrates the advantages of GDAS data over the MM.

5 Conclusion

The comparison of GDAS data for the site of the Pierre Auger Observatory in Argentina with local atmospheric measurements validated the adequate accuracy of the 3-hourly GDAS data. An air shower reconstruction analysis confirmed the applicability of GDAS for Auger reconstructions and simulations, giving improved accuracy when incorporating GDAS data instead of MM. Also, the value of using an atmosphere-dependent fluorescence description has been demonstrated. For the Colorado R&D site, the differences between the measured radiosonde data and GDAS are of the same order as in Argentina, further supporting the general validity of GDAS data as an atmospheric description to be used in current and future cosmic ray observatories.

Acknowledgment: We would like to thank the organizers of the workshop AtmoHEAD: Atmospheric Monitoring for High-Energy Astroparticle Detectors in Saclay, France, 2013 for the inspiring meeting. Part of these investigations are supported by the Bundesministerium für Bildung und Forschung (BMBF) under contracts 05A08VK1 and 05A11VK1. Furthermore, these studies would not have been possible without the entire Pierre Auger Collaboration and the local staff of the Pierre Auger Observatory.

References

[1] The Pierre Auger Collaboration, Astropart. Phys., 2010, 33: 108–129.
[2] The Pierre Auger Collaboration, Nucl. Instr. Meth., 2004, A523: 50–95.
[3] The Pierre Auger Collaboration, Nucl. Instr. Meth., 2010, A620: 227–251.
[4] L. Wiencke for the Pierre Auger Collaboration, Proc. 32nd ICRC, Beijing, China, 2011, 3: 141–144.
[5] NOAA Air Resources Laboratory (ARL), 2004, http://ready.arl.noaa.gov/gdas1.php, Tech. rep.
[6] The Pierre Auger Collaboration, Astropart. Phys., 2012, 35: 591–607.
[7] M. Will for the Pierre Auger Collaboration, Proc. 32nd ICRC, Beijing, China, 2011, 2: 51–54.
[8] P. Müller and H. von Storch, Computer modeling in atmospheric and oceanic sciences, Springer Verlag, 2004.
[9] B. Keilhauer, M. Will for the Pierre Auger Collaboration, Eur. Phys. J. Plus, 2012, 127: 96.
[10] B. Keilhauer for the Pierre Auger Collaboration, Astropart. Phys. Sci. Trans., 2010, 6: 27–30.
[11] The AIRFLY Collaboration, Astropart. Phys., 2007, 28: 41–57.
[12] The AIRFLY Collaboration, Nucl. Instr. Meth., 2008, A597: 50–54.
[13] F. Arqueros, J. Hörandel, B. Keilhauer, Nucl. Instr. Meth., 2008, A597: 1–22.
[14] V. Verzi for the Pierre Auger Collaboration, Proc. 33rd ICRC, Rio de Janeiro, Brazil, 2013.
[15] B. Keilhauer, J. Blümer, R. Engel, H. Klages, Nucl. Instr. Meth., 2008, A597: 99–104.
[16] B. Keilhauer, M. Unger, Proc. 31st ICRC, Łódź, Poland, 2009, arXiv:0906.5487 [astro-ph].