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Atmospheric monitoring and model applications at the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory detects high-energy cosmic rays with energies above $\sim 10^{17}$ eV. It is built as a multi-hybrid detector measuring extensive air showers with different techniques. For the reconstruction of extensive air showers, the atmospheric conditions at the site of the Observatory have to be known quite well. This is particularly true for reconstructions based on data obtained by the fluorescence technique. For these data, not only the weather conditions near ground are relevant, most important are altitude-dependent atmospheric profiles. The Pierre Auger Observatory has set up a dedicated atmospheric monitoring programme at the site in the Mendoza province, Argentina. Beyond this, exploratory studies were performed in Colorado, USA, for possible installations in the northern hemisphere. In recent years, the atmospheric monitoring programme at the Pierre Auger Observatory was supplemented by applying data from atmospheric models. Both GDAS and HYSPLIT are developments by the US weather department NOAA and the data are freely available. GDAS is a global model of the atmospheric state parameters on a 1 degree geographical grid, based on real-time measurements and numeric weather predictions, providing a full altitude-dependent data set every 3 hours. HYSPLIT is a powerful tool to track the movement of air masses at various heights, and with it the aerosols. Combining local measurements of the atmospheric state variables and aerosol scattering with the given model data, advanced studies about atmospheric conditions can be performed and high precision air shower reconstructions are achieved.

1. Introduction

The Pierre Auger Observatory is an installation for detecting ultra-high energy cosmic rays (CR) above several 10^{17} eV. CR entering the atmosphere can initiate a cascade of secondary shower particles called an extensive air shower. The observatory is located at the elevated plain *Pampa Amarilla* in the province Mendoza, close to the city of Malargüe, Argentina, at about 1.4 km a.s.l. The original instrumentation consists of 1 660 water-Cherenkov tanks forming the surface detector (SD) array of about 3 000 km^2 for detecting the secondary particles of CR-induced extensive air showers (EAS) at ground. Regular data taking started in 2004. Later, a smaller infill array was added to the original SD array to increase the detection statistics towards the lower energy threshold.

As a hybrid detector, the SD is supplemented by five fluorescence detector (FD) stations with a total of 27 telescopes. The four original stations house six telescopes each, the HEAT (High Elevation Auger Telescopes) extension features three additional fluorescence telescopes with an elevated field of view. This enables HEAT to record lower energy EAS that develop higher up in the atmosphere. Each telescope measures the longitudinal EAS profile via the induced fluorescence and Cherenkov light.

The main physics goal of the Pierre Auger Observatory is the determination of the spectrum of ultra-high energy cosmic rays with high energy resolution. Questions about the origin of these cosmic rays, whether they have their sources within our galaxy or are of extra-galactic origin, at which energy the transition from galactic to extra-galactic origin takes place, and about the type of the primary particles are also of interest. To address these enigmas, the energy and chemical composition of the cosmic rays at highest energies have to be determined with highest possible resolution and statistics. The Pierre Auger Observatory aims for combining the striking advantages of all installed detection methods. The SD delivers EAS events with high statistics because of its duty cycle of almost 100%. The FD offers an almost model-independent and calorimetric energy determination together with a direct measure of the position of the shower maximum X_{max} which is defined as the position in the atmosphere where the most secondary particles in the EAS are present. X_{max} is a good estimator for the composition of cosmic rays. However, FD data taking is possible only about 13% of the time, because night conditions with low moon illumination and fair weather conditions are required for these measurements.

In particular the FD detection technique requires a good knowledge of the condition of the atmosphere at the site at altitudes between ground level and $\sim$10 km and at the time when the EAS event took place. Thus, a sophisticated atmospheric monitoring programme has been installed at the Pierre Auger Observatory.

In south-east Colorado, balloon soundings were performed as part of an atmospheric R&D project. The ground station used for the soundings was a mobile version of the equipment used in Argentina. The launches were performed at two sites, the Atmospheric Monitoring

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Telescope (AMT) and the Distant Raman Laser Facility (DRLF) [1]. The sites are about 40 km apart and are equipped with identical weather stations.

Predicting the aerosol content of the atmosphere is an inherently difficult process. It is not easy to measure, much less track, the aerosols in the air. Air shower observatories tend to only measure the scattering caused by aerosols rather than their content and composition. Local aerosols typically have several sources, some of them nearby and some in places very far from the observatory site. HYSPLIT is a tool to track air masses as they travel from one location to another, depending on wind and other atmospheric conditions. By backtracking the air masses from the Observatory the correlation between their origin (i.e. from the ocean or from desert) and the measured aerosol scattering at the site can be investigated and possible sources could be determined.

2. Atmospheric influences

For the FD detection technique, the excitation of atmospheric nitrogen molecules by secondary particles and subsequent electrons of the EAS is exploited. The nitrogen molecules isotropically emit fluorescence light in a spontaneous de-excitation, mainly in the wavelength region between about 280 and 430 nm (cf. [2]). The radiative process is proportional to the amount of energy deposited by the EAS (cf. [3]). At higher pressure, as in the Earth's atmosphere below 10 km, collisional quenching of excited nitrogen molecules by different air molecules competes with the radiative de-excitation and becomes significant. This collisional quenching depends on local atmospheric conditions and it reduces the detectable radiative emission. Thus, atmospheric state variables temperature T, pressure p, and relative humidity u have to be known at the place of the light emission to determine the deposited energy of the EAS correctly (cf. [4]).

After the emission of light along the path of the EAS through the atmosphere, all light reducing processes during the transmission towards the FD telescopes have to be taken into account. These processes are Rayleigh and Mie scattering, obscuration by clouds, and absorption. The latter is negligible for the given experimental conditions at the Pierre Auger Observatory site. The Rayleigh scattering of light can be determined analytically using the atmospheric state variables. For the Mie or aerosol scattering, only dedicated and almost real-time measurements of the effect can help to reconstruct the attenuation of light during transmission towards the telescopes (cf. [5]). Aerosol scattering is typically less strong than its molecular counterpart, however it can vary significantly on short timescales [6]. For high quality EAS events, a vertical aerosol optical depth at 3.5 km above ground of <0.1 is required. Furthermore, some dedicated campaigns were performed at the Pierre Auger Observatory to derive the overall aerosol conditions at the site of the experiment. These studies covered the aerosol phase function, the total horizontal attenuation across the array, and a characterisation of aerosol size and elemental composition of [7,8].

The third main aspect of atmospheric monitoring at the Pierre Auger Observatory is related to the presence and distribution of clouds across the array [9,10]. For determining the CR spectrum, the real observation time has to be known. Hence, the cloud cover in the field of view of the FD telescopes is recorded. Beyond this, for high quality EAS events, an actual cloud cover of less than 20% is required. In case of cloud identification in the direction of an EAS event, the height of cloud is extracted to evaluate possible light reduction or enhancement effects by scattering processes inside the cloud.

In the EAS reconstruction procedure of the Pierre Auger Observatory, an effort is made to include most atmospheric influences. Nevertheless, some known systematics cannot be avoided and are propagated into the given systematic uncertainties of the experiment [11].

An advanced description of the fluorescence emission recently resulted in a significant shift of the energy scale of the EAS data. The corrected fluorescence yield caused a shift of -8.2% in CR primary energy while other developments in the reconstruction procedure resulted in significant shifts in the opposite direction. A total shift of the CR primary energy of $+15.6\%$ was stated for the updated 2013 results of the Pierre Auger Observatory [11].

The overall systematic uncertainties for the CR primary energy were also updated in 2013 and are given as 14%. Here, uncertainties for the fluorescence yield, spectrum and quenching effects contribute with 3.6%. Other atmospheric uncertainties like the aerosol scattering and short-term variations of the atmospheric state variables below the temporal resolution of the implemented real data contribute with up to 6.2% [11].

3. Atmospheric monitoring devices and models at the Pierre Auger Observatory

At the site of the Pierre Auger Observatory, a sophisticated network of atmospheric monitoring devices has been in use over many years. An overview is given in Fig. 1.

3.1 Hardware installations

For many steps in the EAS reconstruction procedure, atmospheric state variables are necessary as described in Sect. 2. The Pierre Auger Observatory has installed several ground-based weather stations at the array, one at each FD station, one at the Central Laser Facility (CLF), and formerly one at the Balloon Launching Station (BLS). These weather stations from *Campbell Scientific* [12] record T, p, u, and wind information every 5 minutes. The data are collected in databases for physics analyses as well as for environmental control of nearby further instrumentation.

To assess the longitudinal development of EAS and for the reconstruction of the fluorescence light emission, atmospheric state variables have to be known at all altitudes below about 20 km [13,14]. For this purpose, meteorological radiosondes were launched at the Pierre Auger Observatory. Since 2002, more than 330 radio soundings have been performed. In 2005, a fixed station for launching meteorological radiosondes was set up at the south-western part of the array. The sondes and the receiver station are products from *GRAW* [15]. In the

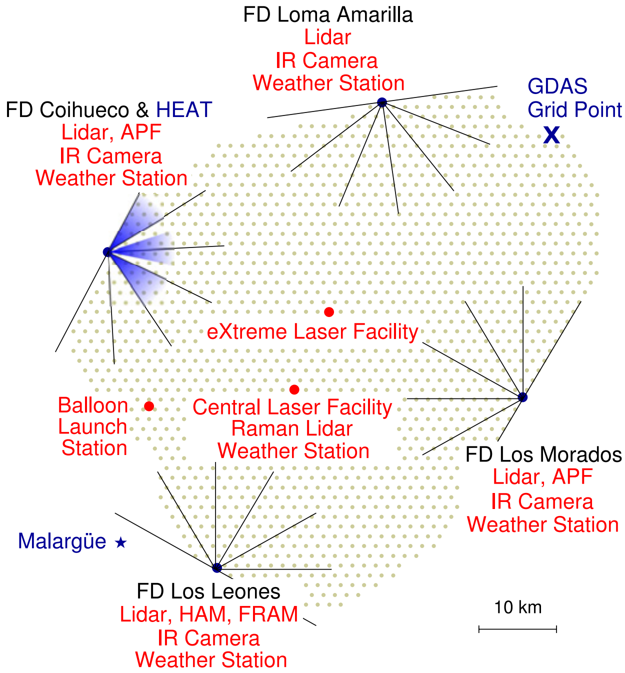

Figure 1. Schematic overview of the atmospheric monitoring devices installed at the Pierre Auger Observatory. At each FD building, there are a lidar station, a weather station, and an infrared camera for cloud detection. In addition, there are devices for measuring the Aerosol Phase Function (APF) at the Coihueco and Los Morados sites, a Horizontal Attenuation Monitor (HAM) and the ph(F)otometric Robotic Atmospheric Monitor (FRAM) at the Los Leones site. At central positions within the SD array, two laser facilities are installed. The Central Laser Facility (CLF) and the eXtreme Laser Facility (XLF) measure the vertical aerosol optical depth in the field of view of each FD telescope. The CLF also houses a Raman lidar. In the south-western part of the array, the Balloon Launching Station (BLS) is set up for launching weather balloons. The location was chosen so that the sondes are typically carried across the array by westerly winds. The GDAS grid point used for the Observatory is also indicated and is at 35° south and 69° west.

early years, sondes of the type DFM-97 were used and later DFM-06. With only 90 g, the more recent models are light-weight and are designed to provide reliable measurements up to an altitude of about 40 km. The sondes are equipped with temperature and humidity sensors. An on-board GPS provides the altitude and information about wind speed and direction through the relative movement of the sonde. The pressure is not measured directly but calculated using a ground value, the height information as well as the temperature and humidity profiles. With the weather balloons that were used, the atmospheric state profiles could be recorded up to about 25 km a.s.l. before the balloon would burst. From March 2009 until December 2011, weather balloon launches from the BLS were part of the *Rapid Atmospheric Monitoring* programme of the Pierre Auger Observatory, see Sect. 3.

To determine the optical transmission properties of the atmosphere at the Pierre Auger Observatory during FD data taking periods, the most important installations are the CLF and XLF (cf. Fig. 1). Here, a laser beam of 355 nm wavelength and of known intensity is shot into the atmosphere at fixed times. The scattered light is recorded by the FD telescopes and from comparisons with extremely clear so-called reference nights, in which only Rayleigh scattering occur, the vertical aerosol optical depth can be determined [6]. The CLF is positioned at about equal distance to the FD station Los Leones, Coihueco, and Los Morados. The fourth station, Loma Amarilla, is farther away, so that a second laser facility, the XLF, has been set up in 2009. In April 2013, the CLF was upgraded by a Raman lidar that was extensively tested and used for aerosol studies in Colorado as part of an Auger R&D effort.

At each FD station, an elastic lidar probes the atmosphere around the FD telescopes using a 333 nm pulsed laser beam. Scanning the atmosphere, the lidar can be used to measure the aerosol optical depth, but is also an important tool to detect clouds [16]. Due to its interference with the FD measurements it usually operates outside the field of view of the telescopes.

The Horizontal Attenuation Monitor (HAM) is used to measure the wavelength dependence of the aerosol attenuation close to ground. A high intensity discharge lamp shoots a broadband light beam from the Coihueco to the Los Leones FD site where a CCD camera detects the light. A filter wheel is used to measure the incoming light at five wavelengths between 350 and 550 nm. The attenuation is described by a falling power law with an exponential parameter γ. For the site of the Pierre Auger Observatory, a γ value of 0.7 ± 0.5 is found as an average which is implemented in the EAS reconstruction procedures. For determining the angular scattering distribution, the Aerosol Phase Function (APF) Monitor uses Xenon flash lamps of 350 nm wavelength that are installed close to two of the FD stations, Coihueco and Los Morados. The Xenon light crosses horizontally the field of view of these telescopes and the scattered part is recorded in dependence on the scattering direction. The Henyey-Greenstein function is used for the description [17] and an average value of the phase function asymmetry parameter g of 0.56 ± 0.10 is found [18]. The concentration, size distribution and chemical composition of the local aerosols are further investigated with an aerosol sampler and spectrometer [7, 8].

Clouds are of importance for the EAS reconstruction. To record the presence of clouds in the fields of view of the different FD stations, an IR cloud camera is installed at each station. These cloud information are investigated in combination with the lidar measurements and the application of satellite data by GOES-12/13. A detailed description is given in these proceedings [10].

3.2 Atmospheric model application

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) [19], a global atmospheric model, for the site of the Pierre Auger Observatory [14, 20]. GDAS data are publicly available free of charge via READY (Real-time Environmental Applications and

Display System). The National Centers for Environmental Prediction (NCEP) of the US National Weather Service run atmospheric computer analyses and forecasts multiple times per day. One of those systems is the Global Data Assimilation System (GDAS). GDAS combines current meteorological measurements from all around the world with predictions from numerical weather forecast models.

The GDAS data are available in 3-hourly, global, 1° latitude-longitude (360° by 180°) datasets. The position of the chosen GDAS grid point is marked in Fig. 1. Each dataset consists of surface data and data for 23 constant pressure levels (from sea level up to about 26 km). Among the meteorological fields are T, p and u. For the site of the Pierre Auger Observatory, the validity of GDAS data is given by comparisons with radio sounding data as well as with records from the ground-based weather stations.

It was shown that the application of GDAS data are a low-cost and efficient replacement of local measurements of profiles of atmospheric state variables [21]. Since 2012, radio soundings are performed at the Pierre Auger Observatory only in short dedicated campaigns. GDAS data are used now in all analyses and reconstructions of the Pierre Auger Observatory, they are available from June 1st, 2005 and the database is updated once per week.

The radiosonde data gathered in Colorado were also compared to GDAS data in order to evaluate the possibility of using GDAS also in different locations and for a possible future ground-based cosmic ray detector. More details of this study are given in Sect. 4.

3.3 Rapid atmospheric monitoring

In 2009, some of the atmospheric monitoring devices at the Pierre Auger Observatory joined the so-called rapid atmospheric monitoring programme [21]. Ideally, the atmospheric conditions are known at the time when an extensive air shower is recorded at the Pierre Auger Observatory. However, this is not feasible for all events. With the rapid atmospheric monitoring programme, a fast online-reconstruction procedure has been developed. For some particularly interesting EAS events (e.g. very high-energetic showers or those with atypical longitudinal profiles) an alert is sent to some of the monitoring devices. The participating instruments are the lidar stations, the FRAM, and until end of 2011 the radio soundings.

Within minutes after such an interesting EAS event, the lidars probe the atmospheric optical properties within the field of view of the FD telescopes, causing a negligible deadtime of the regular FD data taking. The FRAM can derive the total extinction of the light in the field of view of the FD telescope by comparing of the apparent magnitude of stars with catalogued information. In the case of radio soundings, an operator was alerted by a short text message and drove to the BLS and launched a weather balloon within 2 hours after an EAS event.

4. Studies in Colorado

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 R&D project consisted of two sites, the Atmospheric Monitoring Telescope (AMT) and the Distant Raman Laser Facility (DRLF) [1]. The sites are about 40 km apart and are both equipped with identical weather stations. The R&D project was operated from early 2010 until middle of 2011. Recently the two sites were restored and new instrumentation was installed as part of the ARCADE project [22].

4.1 Weather balloon measurements

The radiosondes used for the weather balloon measurements are the same model as the sondes used at the southern site of the Pierre Auger Observatory (Sect. 3), the DFM-06 by *GRAW* [15]. The mobile ground station GS-E is used to be able to set up a balloon launch anywhere. The station receives the radiosonde signals and provides local GPS information. All functions of the GS-E are controlled by a standard PC through a USB port. The radiosonde signal is received by a narrow-band SDR receiver (400 MHz to 406 MHz) using an omni-directional antenna.

4.2 Weather stations

Environmental conditions including wind and rain are measured by Vaisala [23] model WXT520 weather transmitters at the AMT and the DRLF. If rainy or windy conditions above 7 m s^{-1} are detected, the door of the AMT and the roof hatch of the DRLF are closed or cannot be opened until the conditions are safe for operations. Besides capacitive sensors for temperature, pressure and humidity, an ultrasound sensor measures the wind speed and direction and an acoustic sensor measures precipitation.

4.3 Operations

Most of the balloons were launched at the DRLF building, although two sondes were flown from the AMT site. All attempts to launch from another site were unsuccessful. The prevailing wind direction at higher altitudes is west. The balloon usually ascends a few kilometres when high winds that come over the Rocky Mountains take the sonde over the Kansas state border and further east until the balloon bursts at an altitude of around 20 to 25 km.

In Fig. 2, balloon paths and height-dependent profiles of temperature, pressure, relative humidity and vapour pressure are shown. Shown in the two plots on top are two flights from 3 June, 2010. The first was launched from the AMT site, the other 4 hours later from the DRLF. The starting positions are almost 40 km apart, however, the balloon paths and the two profiles of the state variables suggest that the molecular atmospheric conditions are very stable over the course of a few hours and across the

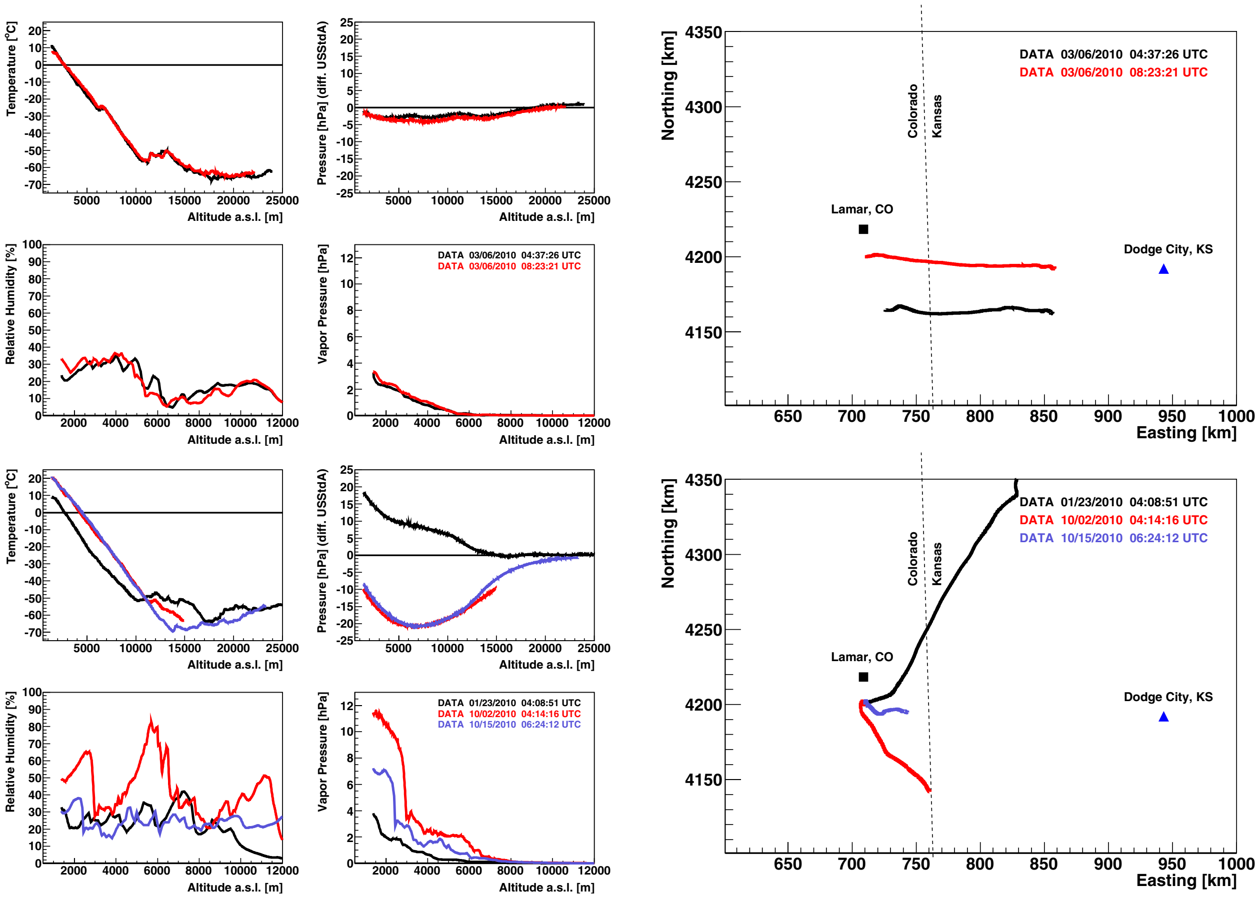

Figure 2. Profiles of temperature, pressure, relative humidity and vapour pressure versus height and flight paths of several balloons launches. The pressure profiles are shown as difference to the US Standard Atmosphere (USStdA) for better visualisation. In the two plots on top, data from two balloons launched from the DRLF building and the AMT site within 4 hours are shown. On the bottom, data are shown from balloons that deviate from the usual west-east flight path.

baseline of the R&D project. In the bottom two panels of Fig. 2, three ascents with paths that are unusual are shown. The first was caught in a very strong south-west wind that carried it in about 150 minutes over a distance of more than 180 km. The second balloon caught a north-west wind, barely crossing into Kansas. During the third ascent, almost no wind was present. In almost 2 hours of flight it reached an altitude of over 23 km but only covered a distance of less than 34 km.

4.4 Comparison of the weather data with models

The data collected by the weather balloon program and the two weather stations are compared to temperature, pressure and humidity values from the GDAS model (Sect. 3). A density profile is calculated using these data. The GDAS grid point for the Colorado R&D site is 38° N and 102° W, about 50 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. We compare the full profile to the measurements obtained by the weather balloons, and the weather station data with an interpolated data point at the height of the station.

In the top left panel Fig. 3, a comparison in temperature versus height for a single profile is shown. Around 2 km above sea level, a temperature inversion is observed. This inversion is very well described by the GDAS data. The accuracy of the GDAS data for the site in Colorado is remarkable, and better than similar comparisons done with balloon data from the Pierre Auger Observatory in Argentina [14]. This is due to the better coverage with atmospheric measurements of the northern hemisphere, and the United States in particular, resulting in a better basis for the model calculations the GDAS data is based upon. In 500 m height bins, the measured profiles and the profiles generated from GDAS data are interpolated and subtracted and filled into a histogram. In the top right and the bottom panels of Fig. 3, the means and RMS values at each height are shown for temperature, water vapour pressure and air density. The agreement is very good.

Similar to the results in Argentina, we conclude the description of the local atmospheric conditions by GDAS is adequate. Therefore, on-site balloon measurements which impose significant effort and costs can be substituted with this easily accessible and cost free model data.

In Fig. 4, the data from both stations are compared with GDAS data for the Colorado location. The GDAS grid point is about 50–60 km away from the two weather

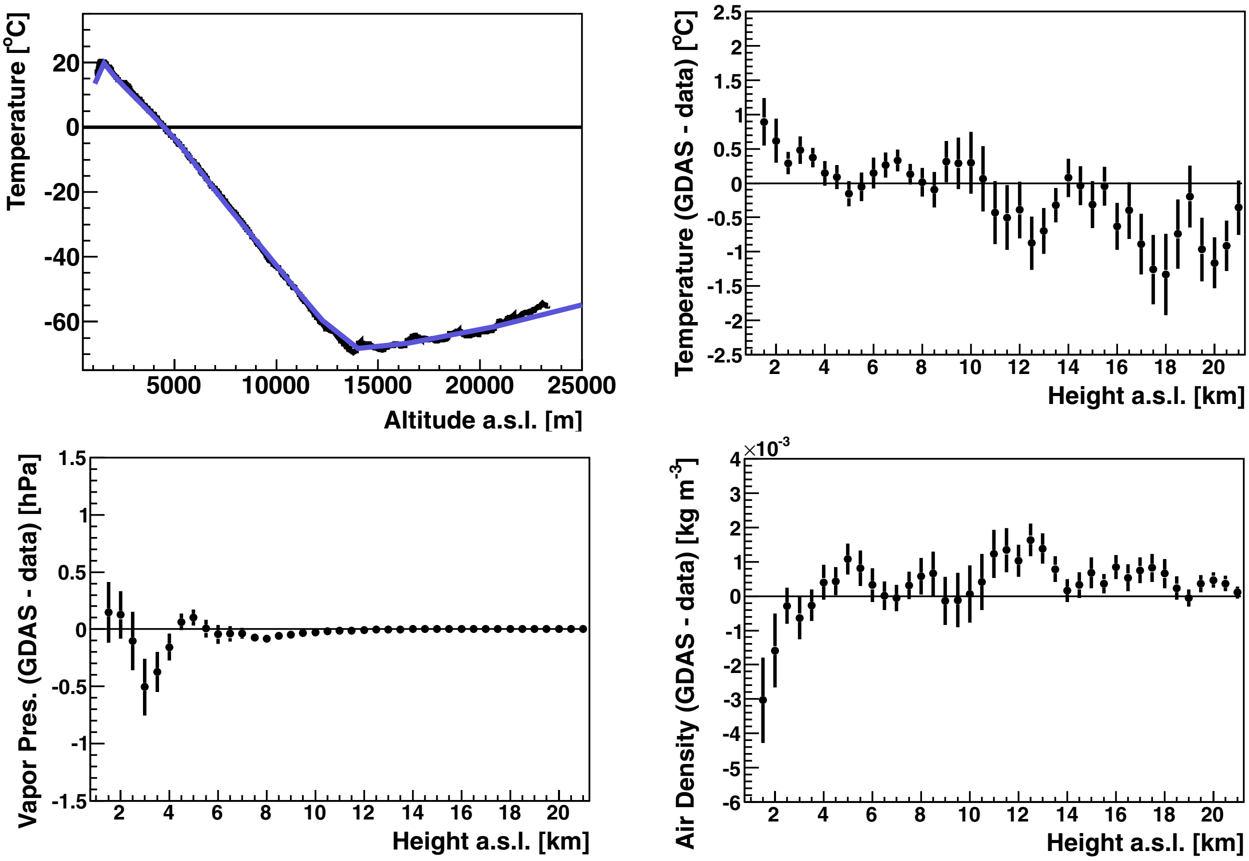

Figure 3. Top left: measured temperature profile from October 15, 2010, 6:24 UTC (black). Shown in blue is the GDAS profile for 6:00 UTC for the same day. A temperature inversion can be seen in both profiles at 2 km a.s.l. Top right, bottom: averaged profiles of difference between measured and GDAS data for temperature, water vapour pressure, and air density versus height.

station locations, for the comparison the GDAS data is evaluated at the height of the stations. The DRLF station recorded data from December 2009 until June 2011, but was defective from December 2010 until April 2011, a total of about 1800 hours of data are available. The AMT station was running since December 2009 until February 2012 with a longer interruption in December 2010, more than 4000 hours of data can be used for comparison. The histograms in the top panels of Fig. 4 are normalised for better visualisation. The difference in temperature between GDAS and AMT is −3.7 K with an RMS of 4.9 K, between GDAS and DRLF it is −1.7 K with an RMS of 5.4 K. It has to be noted that no negative temperatures are included in this comparison due to an error in the readout program. The means agree well, the spread is rather large. One reason for this is the placement of the stations very close to surfaces which can cause a residual heating effect. The mean differences in vapour pressure are −0.12 and 0.29 hPa with RMS of 2.2 and 2.8 hPa, respectively. Since the relative humidity is the quantity measured by the weather stations, the vapour pressure is calculated and the differences in temperature translate into the differences in vapour pressure. In pressure, the differences are −0.07 and 0.85 hPa with an RMS of 1.7 and 2.5 hPa. The differences are small, the data agree very well. The GDAS grid point is about 110 m higher than the DRLF and about 220 m higher than the AMT, resulting in an expected pressure difference of 11 and 22 hPa, respectively. Both the differences between GDAS and AMT and between GDAS and DLF are within expectations. In the bottom panels of Fig. 4, the data for temperature, pressure and vapour pressure of the AMT station and GDAS are again compared to each other. The missing negative values for the temperature can clearly be seen. The difference in density (not shown) is also rather small, as it is calculated from the three variables compared here.

The comparison between the weather stations and GDAS shows a rather good agreement across the baseline of the experiment, although the statistics are rather limited. At both sites, the GDAS data agree well with the weather station measurements.

5. Advanced studies for aerosols

Unlike global models of atmospheric state variables like GDAS, models of aerosols are very hard to produce. This is mostly due to missing long-term monitoring and global coverage of dedicated aerosol measurements, especially in remote areas where ground-based CR observatories are located. Since 2004, the Pierre Auger Observatory has measured the the aerosol optical depth on an hourly basis during FD data taking nights. Also, several other studies

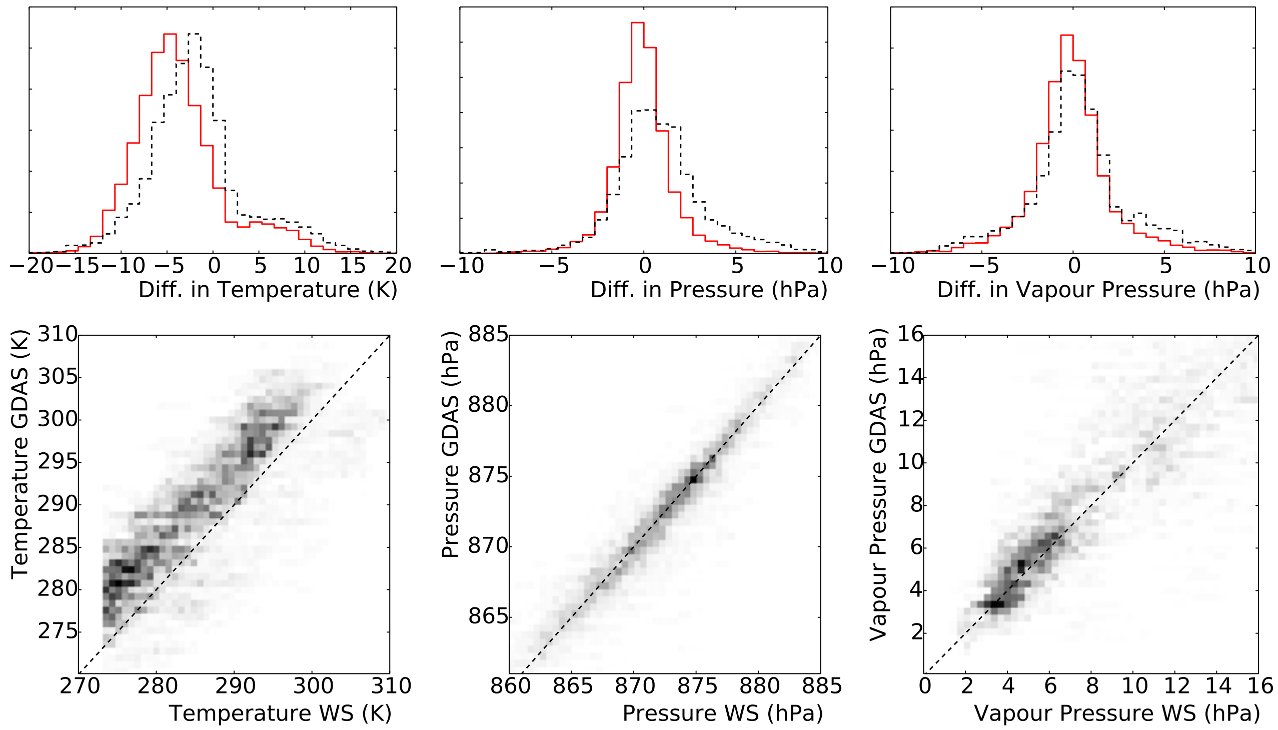

Figure 4. Comparison of temperature, pressure, and vapour pressure for data from the weather stations at the AMT and the DRLF and GDAS data. All histograms are normalised to correct for the different number of entries. Top: the difference of DRLF and GDAS are shown with a black dashed line, AMT and GDAS in red. The differences in pressure and vapour pressure are rather small, the difference in temperature is explained by the mounting of the weather stations close to surfaces that retain heat. Bottom: comparison of the same variables for the AMT and GDAS. No negative temperatures were recorded due to a software bug.

about the local aerosol content and scattering properties have been performed, see Sect. 3.

The HYbrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) [24,25] is a modelling programme in atmospheric sciences for calculating the displacement of air masses. HYSPLIT uses simulations of transport and dispersion of aerosols and can be used to track air masses forward or backward in time from a given starting location and altitude. To simulate the path of air masses, meteorological data from the GDAS model can be used to consider wind patterns and other relevant variables along their path. Using HYSPLIT, the aerosols at the Pierre Auger Observatory can be linked to different regions in South America. With the local measurements at the Observatory, a relationship between the scattering properties and chemical composition of the aerosols and the possible origins of the air masses can be investigated.

Although the aerosol optical depth at the Pierre Auger Observatory can fluctuate strongly on short timescales (cf. Sect 3), the atmosphere is typically much clearer in austral winter than in summer. It was found that during these clean conditions in winter, the air masses predominantly come from the Pacific Ocean, while during hazy conditions the air masses usually travel over continental areas, potentially picking up soil and dust [26]. A possible correlation of high aerosol optical depth in August and September with air masses coming from the direction of North Argentina and Bolivia, where biomass burning occurs frequently in these months, was found. However, it cannot be excluded that the higher aerosol content in the air masses coming from the North is of more local origin, e.g. pollution from bigger cities close to the Observatory. Future studies including satellite data or ground-level aerosol monitoring between the Observatory and the source regions in the North might resolve this issue.

6. Summary

Several analyses of atmospheric conditions at the site of the Pierre Auger Observatory and studies of reconstructed air shower data have illustrated the necessity of a sophisticated atmospheric monitoring programme. Such a programme has been developed and installed at the Pierre Auger Observatory over the past years. Here, we presented the main installations and their purposes together with some advanced developments by replacing or supplementing local measurements with adequate atmospheric models. Mainly those parts of the atmospheric monitoring programme describing atmospheric state variables and aerosol scattering are able to improve the reconstruction resolution of air shower data significantly and reduced the systematic uncertainties of the reconstructed primary energy and the position of shower maximum of CR events detected at the Pierre Auger Observatory.

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References

[1] L. Wiencke et al. (for the Pierre Auger Collaboration), *Atmospheric "Super Test Beam" for the Pierre Auger Observatory*, in *Proc. 32nd ICRC* (Beijing, China, 2011), Vol. 3, pp. 141–144, [arXiv:1107.4806]

[2] F. Arqueros, J.R. Hörandel, B. Keilhauer, Nucl. Instr. Meth. **A597**, 1 (2008), [arXiv:0807.3760]

[3] M. Ave et al. (AIRFLY Collaboration), Nucl. Instr. Meth. **A597**, 46 (2008)

[4] B. Keilhauer, J. Blümer, R. Engel, H.O. Klages, Nucl. Instr. Meth. **A597**, 99 (2008), [arXiv:0801.4200]

[5] J. Abraham et al. (the Pierre Auger Collaboration), Astropart. Phys. **33**, 108 (2010), [arXiv:1002.0366]

[6] P. Abreu et al. (Pierre Auger Collaboration), JINST **8**, P04009 (2013), [arXiv:1303.5576]

[7] M.I. Micheletti et al., Nucl. Instr. Meth. **B288**, 10 (2012)

[8] M.I. Micheletti (for the Pierre Auger Collaboration), *Aerosol characterization at the Pierre Auger Observatory*, in *Proc. 33rd ICRC* (Rio de Janeiro, Brazil, 2013), p. 104, [arXiv:1307.5059]

[9] J. Chirinos (for the Pierre Auger Collaboration), *Cloud Monitoring at the Pierre Auger Observatory*, in *Proc. 33rd ICRC* (Rio de Janeiro, Brazil, 2013), p. 108, [arXiv:1307.5059]

[10] J. Chirinos (for the Pierre Auger Collaboration), *Remote Sensing of Clouds with Satellites, Lidars, CLF/XLF and IR Cameras at the Pierre Auger Observatory*, in *AtmoHEAD 2014* (this conference, 2014)

[11] V. Verzi (for the Pierre Auger Collaboration), *The Energy Scale of the Pierre Auger Observatory*, in *Proc. 33rd ICRC* (Rio de Janeiro, Brazil, 2013), p. 7, [arXiv:1307.5059]

[12] Campbell Sci., http://www.campbellsci.com

[13] B. Keilhauer, J. Blümer, R. Engel, H.O. Klages, M. Risse, Astropart. Phys. **22**, 249 (2004), [astro-ph/0405048]

[14] P. Abreu et al. (Pierre Auger Collaboration), Astropart. Phys. **35**, 591 (2012), [arXiv:1201.2276]

[15] GRAW Radiosondes, http://www.graw.de

[16] S. Benzvi et al., Nucl. Instr. Meth. **A574**, 171 (2007)

[17] L.G. Henyey, J.L. Greenstein, Astrophys. J. **93**, 70 (1941)

[18] S.Y. Benzvi et al., Astropart. Phys. **28**, 312 (2007), [astro-ph/0704.0303]

[19] NOAA Air Resources Laboratory (ARL), *Global Data Assimilation System (GDAS1) Archive Information* (2004), http://ready.arl.noaa.gov/gdas1.php

[20] M. Will (for the Pierre Auger Collaboration), *Implementation of meteorological model data in the air shower reconstruction of the Pierre Auger Observatory*, in *Proc. 32nd ICRC* (Beijing, China, 2011), Vol. 2, pp. 51–54, [arXiv:1107.4806]

[21] P. Abreu et al. (Pierre Auger Collaboration), JINST **7**, P09001 (2012), [arXiv:1208.1675]

[22] L. Valore, *ARCADE: Description of the Project and Setup of the LIDAR/AMT System*, in *AtmoHEAD 2014* (this conference, 2014)

[23] Vaisala, http://www.vaisala.com

[24] R.R. Draxler, G.D. Rolph, Tech. rep., NOAA Air Resources Laboratory, College Park, MD (2013), model Access via NOAA ARL READY website, http://www.arl.noaa.gov/HYSPLIT.php

[25] G.D. Rolph, Tech. rep., NOAA Air Resources Laboratory, College Park, MD (2013), http://www.ready.arl.nocbeaa.gov

[26] A. Aab et al., Atmos. Res. **149**, 120 (2014), [arXiv:1405.7551]