Influence of South Pole atmosphere on cosmic rays observed by IceCube

by

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The figure on the titlepage shows the two objects under study in this work: an aerial view of the IceCube Neutrino Observatory, covered by the South Pole atmosphere. On the background, the Amundsen-Scott South Pole Station can be seen, positioned at the geographic South Pole. Picture taken in March 2011, thus after detector completion. (Edited by Haley Buffman to display the IceCube drilling holes.)
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Introduction

Exactly 100 years ago, the detection of “radiation which increased with increasing height” introduced a new field in physics and astronomy: astroparticle physics. This 100-year-old (or young) field studies subatomic particles originating out of space. In the 1930s, it was found that this radiation was actually originating from very energetic cosmic particles, creating a cascade of thousands or millions of particles during their propagation through the atmosphere of the Earth. Soon, it was realised that these cosmic particles might learn us more about the universe.

A century full of investigation and adventures, containing balloon flights and satellite experiments, underground detectors and large ground-based arrays, resulted in an overall composition and energy spectrum of these particles which is rather well known. However, the details might yield the most important information.

The details in the cosmic ray spectrum and the composition of the cosmic rays at these energies probably contains information about the source and acceleration mechanism of these cosmic particles. Since these particles reach very high energies, they must be produced in the most energetic sources present in our universe, hence yielding information about the formation, composition and evolution of these sources.

The last decades, the resolution of the cosmic ray experiments increased dramatically thanks to the strong rise of new technologies for the detection of charged and uncharged particles, together with their energy. Currently, the resolutions are reached at which the details are starting to become visible.

With increasing detector resolution, new effects arise which limit the resolution of today’s air shower measurements. The fact that these effects were not seen before, but are encountered in the current detectors, is no doubt a good sign. This means that the resolution indeed increases. However, if the resolution should increase further, which is of course desired, also these new effects should be taken into account.

In this thesis, the influence of the atmospheric variations on the measurements of the IceCube Neutrino Observatory, located at the South Pole, is studied. Chapter 1 shortly describes the knowledge of cosmic rays up to know, together with a description of the propagation of cosmic rays through our atmosphere. Furthermore, the IceCube Neutrino Observatory will be discussed, where the focus is on the surface array, IceTop (Chapter 2).

Chapter 3 yields a comprehensive description of the exceptional South Pole atmosphere. It will be shown that the influence of the giant ice sheet and the position close to the rotation axis of the Earth causes the South Pole atmosphere to behave and variate uniquely. The methods used for this study will be described in Chapter 4. Chapter 5 identifies the effect
of the atmospheric variations on observables at the surface. Furthermore, the effect on air
shower properties used for the reconstruction of the primary energy and particle type of the
shower is studied. This chapter also tries to find an explanation for the observed variations.
Finally, in Chapter 6 all the information is assembled. All observed effects are considered,
and possible correction formulas are proposed.
The discussion of the results and the outlook is the subject of Chapter 7.
Chapter 1

Cosmic rays

Probably astronomers exist as long as humankind; the fascination about the universe and the stars is known to be ancestral. Until the late 18th or early 19th century, visible light has been the only eye on the cosmos. Important contributions from Maxwell, Hertz and Roentgen initiated a broader use of the electromagnetic spectrum. In the 1930s, Karl Jansky detected the first radio waves coming from the Milky Way. Since the atmosphere of the Earth is opaque for certain photon wavelengths, astronomy using these parts of the spectrum is not possible from the surface of the Earth. X-ray astronomy emerged together with the rise of space sciences. Both X-ray, radio astronomy, as astronomy using other photon wavelengths revealed a surprising view of the mysterious universe.

Exactly 100 years ago, in 1912, Victor Hess initiated the start of another high-energy view of the cosmos. Aiming for clarifying the source of radiation which ionizes the air, Hess performed his famous balloon experiments. Using his electroscope, he measured the ionisation at different heights, up to 5300 m. The first 1000 m the radiation decreased with altitude. At these days, this was the expected behaviour, since radiation was thought to emanate from radioactive elements in the Earth itself. Therefore, measurements at higher elevations revealed a large surprise: from altitudes of 1000 m up to 5300 m, Hess discovered that the radiation increased. Shortly after his publications, the measurements were confirmed at higher altitudes. The source of this radiation should be found above our heads! Few years later, Robert A. Milikan named this radiation coming from above as ‘cosmic rays’. In 1936, Victor Hess received the Nobel Prize in Physics for the discovery of these cosmic rays (CRs).

Last 100 years, many studies were being performed to solve the mystery of cosmic radiation. What is this mysterious radiation? What is the nature and energy of the detected particles? Where do they come from and how do they get here? Since the discovery of the electron in 1897 by J.J. Thomson, a zoo of elementary particles has been discovered during the twentieth century. Because also particle accelerators were still in their infancy, certain elementary particles were discovered during the study of cosmic rays. Cosmic radiation was the only source of high-energy particles.

In the same year as Victor Hess, Carl Anderson was awarded with the Nobel Prize in physics for the identification of the positron in cosmic rays in 1932. Anderson identified the positron,
using a cloud chamber, as being a particle with the same mass as the electron, but with opposite charge [2]. The positron was the first antimatter particle ever detected. Four years after this discovery, Anderson detected, together with Seth Neddermeyer, the ‘mu-meson’ or muon. This particle had the same charge as the electron and proton, but was heavier than the electron and lighter compared to the proton. In 1947, Yukawas’s prediction of the existence of mesons was confirmed with the detection of pions in cosmic ray physics.

Using an array of counters and Wilson chambers, Pierre Auger discovered the existence of extended cosmic rays, since the separated detectors showed coincident events [3]. This indicated that the previously described particles are daughter particles produced by one single primary interacting in the atmosphere.

1.1 Cosmic rays on top of the atmosphere

1.1.1 Composition and spectrum

Cosmic radiation is a flux of primary particles originating from space, entering the atmosphere with high energy. 79% of all incident nuclei is hydrogen, while 70% of the rest are helium nuclei. The composition of cosmic rays is similar to the composition within the solar system, but small differences exist [4]. Larger abundances of lithium, beryllium and boron are observed in cosmic rays compared to the abundances in the solar system. This is surprising, since these nuclei are not produced in nuclear fusion reactions which provide the energy of stars. However, it is assumed that this is due to the interaction of carbon and oxygen with interstellar matter on their way to the Earth (this is called ‘spallation’). A similar fragmentation process of iron nuclei causes the larger abundance of nuclei with atomic numbers slightly less than 26, which are the secondary products of these fragmentation reactions. The carbon, oxygen and iron nuclei are fairly common in the universe, since they are produced in the nuclear fusion of stars. The production of iron is the last stage in the life of a heavy star before it implodes, since the production of iron is the last nuclear fusion reaction which is exothermic (‘creates energy’).

However, one can not really speak of ‘the’ cosmic ray composition, since the cosmic ray composition is energy dependent.

The energies of the primary particles cover a wide range, from $10^9$ eV$^1$ to $10^{20}$ eV, and follow a power law:

$$\frac{dN}{dE} \propto E^{-\alpha},$$

(1.1)

with the index $\alpha \approx 2.7$. This cosmic ray energy spectrum can be seen in Figure 1.1. However, the spectrum is found to steepen around a few PeV$^2$ (known as the knee), where the index grows to $\approx 3$. A second feature in the spectrum can be seen around 10 EeV, which is called the ankle. Around the ankle, the spectrum flattens, and the index decreases again to $\alpha \approx 2.7$.

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$^1$1 eV $\approx 1.602 \cdot 10^{-19}$ J
$^2$1 EeV$=10^3$ PeV$=10^6$ TeV$=10^9$ GeV$=10^{18}$ eV
Figure 1.1 – The cosmic ray energy spectrum [5]. At 1 GeV, fluxes of 1 particle per squared meter per second are observed, while at the knee region one particle per year per squared meter can be detected. Direct measurements are sufficient to scan the spectrum up to a TeV range. To detect one particle per year with energies in the ankle region, detectors with a surface of 1 km$^2$ are needed. Ground-based detectors which cover a large surface area, like IceCube, will be able to detect the high-energy particles through indirect measurements.
1.1. COSMIC RAYS ON TOP OF THE ATMOSPHERE

Figure 1.2 – The poly-gonato (Greek for “many knee”) model of the knee in the cosmic ray spectrum [7]. All dotted lines take the data of several experiments into account and describe the spectra of separate (groups of) elements. The solid line represents a fit of the sum of the various element spectra with \(1 \leq Z \leq 92\), while the bold dashed curve represents a fit of the spectra of all elements with \(1 \leq Z \leq 28\).

1.1.2 The knee

The first part of the spectrum, below the knee (\(E < 3-5\) PeV), is thought to emanate from within the Milky Way, comprising the galactic component of the CR spectrum [6]. The origin of the cosmic ray particles will be explained in Section 1.2. Although the existence of the knee is known for forty years, the actual shape and components of the knee remain a topic for investigation. Also the energy region above the knee is less known. The study of the detailed CR energy spectrum and composition around and above the knee requires measurements with large ground-level detector arrays, due to the steep decrease in flux with primary energy according to Equation 1.1. Before these high-energy particles reach the surface of the Earth, they will have undergone collisions with air nuclei, creating a cascade of secondary particles. The reconstruction of the primary particle and energy is complicated because of this indirect detection method.

Many different models to describe the knee region exist. Most of them assume that the knee is caused by a sudden decrease (or ‘cut-off’) in flux of one or more particle species (due to the limit of the cosmic acceleration), occurring at an energy around 3-5 PeV. This results in a change in slope in the CR spectrum. Figure 1.2 shows one of the most widely used models to describe the knee region.

1.1.3 The ankle

In the energy region above the knee, adjacent cut-offs of heavier elements are believed to take place. These subsequent cut-offs seem to result in a relatively smooth spectrum above the knee\(^3\). When the iron cut-off is reached, the CR flux decreases significantly. However, the evolution of the energy spectrum does not show a clear decrease in flux at a certain energy. Figure 1.1 rather shows the opposite behaviour: at an energy about 1 EeV, the CR energy spectrum seems to flatten again. This possibly indicates the presence of a (group of) weaker source(s) from extragalactic origin which would become the dominant source(s) at 1 EeV [8].

\(^3\)This behaviour is sometimes referred to as the Peters cycle, since it was first suggested by B. Peters.
CHAPTER 1. COSMIC RAYS

Figure 1.3 – (a) The flux of cosmic rays at energies in the neighbourhood of the GZK cut-off of both HiRes and AGASA, published by HiRes [12]. (b) The confirmation of the HiRes results by the Pierre Auger Collaboration [14].

Since the spectrum above 1 EeV can be described with a similar power-law spectrum as below the knee, it is believed that the sources below the knee and above the ankle should show similarities. The region in the CR spectrum between the knee and the ankle is often referred to as the transition region and indicates the energies at which a transition occurs from galactic to extragalactic cosmic rays.

1.1.4 The GZK limit

In 1966, Greisen[9] and Zatsepin and Kuz’min[10] independently predicted a significant steepening of the spectrum around $5 \times 10^{19}$ eV. Interactions with the cosmic microwave background (CMB) photons cause particles with energies higher than this cut-off to lose energy through the $\Delta^+$ resonance and drop below the cut-off:

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow N + \pi ,$$  \hspace{1cm} (1.2)

with $N = p, n$. At the energy of $5 \times 10^{19}$ eV, the interaction cross section of protons with CMB photons increases significantly because of this $\Delta$ resonance. Cosmic rays with energies higher than the GZK cut-off are called ultra-high-energy cosmic rays (UHECR).

In 2003, the AGASA (Akeno Giant Air Shower Array) experiment published results where 11 UHECR events were observed and it was claimed that the energy spectrum does not end at the GZK cut-off [11]. However, the HiRes (The High Resolution Fly’s Eye) experiment detected a flux suppression at the predicted energy [12]. The results of both experiments can be seen in Figure 1.3(a).

The Pierre Auger Observatory published only one year later (2008) results of the detection of 20,000 events with $E > 2.5 \times 10^{18}$ eV. The Pierre Auger Collaboration reports a suppression of the flux starting from the GZK limit, therefore confirming the results of the HiRes experiment (Figure 1.3(b)). It was also able to reject the assumption that the cosmic ray spectrum continues with the same index with a significance of 6$\sigma$ [13].
1.2 Origin of cosmic rays

So far we have discussed the energy spectrum of CRs incident on the atmosphere. But where do these particles come from? What is the mechanism (or mechanisms) producing this energy spectrum? These questions are definitely related and are briefly discussed in this section. The answers should include possible acceleration mechanisms, while the results should be in accordance with the observed CR spectrum.

One important first question is: Which particles are originated from within the Milky Way, and which ones have an extragalactic origin?

1.2.1 Galactic or extragalactic?

As already mentioned before, the particles with energies lower than 3-5 PeV are assumed to have a galactic origin. The knee in the CR energy spectrum would be caused by a sudden flux suppression of the lighter nuclei, probably proton or helium. Adjacent cut-offs of heavier elements will be encountered and characterize the transition region.

The above hypothesis is supported by the "leaky box" model [6]. This simplified model envisions the galaxy as being an empty cavity in which cosmic rays can propagate freely. At each boundary of the cavity, a cosmic ray particle has a certain chance to escape or "leak away" from the galaxy. The diffusion and propagation of the cosmic rays within our galaxy is mainly determined by the galactic magnetic field $B$, of which the strength is assumed to be $\sim 3 \mu G$. The magnetic rigidity $R$ is defined as:

$$R = B \cdot \rho = \frac{pc}{Ze},$$

where $\rho$ is the gyroradius, $p$ the momentum and $Z$ the atomic number of the cosmic ray particle. $c$ is the velocity of light and $e$ the elementary charge. Higher energy particles cause higher bending radii and higher rigidities compared to lower energy particles. This means that higher energy particles are more likely to escape from the galactic magnetic field, inducing a cut-off in the CR energy spectrum. Since the rigidity is inversely proportional to the charge, all particle species will reach their cut-off at another energy. Therefore, as the energy increases, the CR flux becomes dominated by heavier particles. This increase of the mean mass of cosmic rays with energy continues until the iron cut-off is reached. At this energy, the flux of cosmic ray particles originating from within our galaxy decreases dramatically and the flux of cosmic ray particles coming from outside our galaxy may become dominant [8]. Apparently, this induces again a softening of the CR energy spectrum around the ankle, which probably indicates the presence of a new extragalactic source with the same power law, but a lower flux.

1.2.2 Acceleration mechanisms

The cosmic rays originating from within our galaxy are believed to have supernova remnants as their most promising source, while more 'exotic' sources are possible places for the acceleration of higher energy particles. These 'exotic' sources may contain pulsars (spinning
magnetized neutron stars) or active galactic nuclei (AGNs) [15]. However, gamma-ray bursts (GRBs) are the most promising source of high-energy particles. It is believed that the cosmic ray acceleration at these sources is accompanied by the production of high-energy neutrinos. In [16], the IceCube collaboration was able to give a new upper limit of neutrinos coming from GRBs. The Hillas plot shows possible sources of UHECRs according to their size and magnetic field strength (Figure 1.4).

Figure 1.4 – Hillas plot showing the relation between the size of the possible sources of UHECRs and the magnetic field strength.

A large set of models describing possible acceleration mechanisms exist. This indicates that the acceleration mechanisms are certainly not completely understood and all possible observation methods (multi-wavelength photon telescopes, cosmic rays, neutrino detection,...) have to be employed to solve this mystery.

Supernova remnants

Galactic CRs are believed to be produced in supernova remnants (SNR). The energy of stars is provided by exothermic nuclear fusion reactions in the core. The internal pressure produced by these exothermic reactions has to withstand the gravitational pressure of all matter surrounding the core. Towards the end of live of a star, the fuel gets exhausted. Whether this situation will stay in balance, depends on the mass of the stars. Low and intermediate mass stars (< 8 M\(_{\text{sun}}\)) will end their fusion reactions if carbon or maybe oxygen is reached, because not enough mass is provided to initiate these reactions. These stars will become white dwarfs. If however, while the mass is high enough, nuclear reactions continue with heavier nuclei, iron will be reached at the end. Iron is the element with the highest binding energy, therefore nuclear fusion of iron does not generate energy. When the iron in the core is piling up, the degenerate pressure (due to the Pauli exclusion principle) cannot counteract the gravitational pressure and the star implodes under its own gravity. This gravitational collapse releases an enormous amount of energy, which blows the outer layers of the star into space, and is called a supernova. The star remains as a neutron star or a black hole, depending on its mass [17]. Another source of supernova explosions is the accretion of matter on white dwarfs. If the
mass of the white dwarf reaches the Chandrasekhar limit of $1.38 \, M_{\odot}$, the electron degenerate pressure cannot withstand the gravitational force, inducing a collapse of the white dwarf.

The expanding shells of the supernova is the supernova remnant. A famous supernova remnant is shown in figure 1.5.

**Fermi acceleration**

In 1949, E. Fermi considered the idea that these supernova remnants could be important candidates for the birth and acceleration of cosmic ray particles. The reason why this theory is currently regarded as very successful, is because it predicts naturally the desired power law of the cosmic ray spectrum [6, 18].

This can be derived as following: the CR acceleration can take place if kinetic energy is transferred from the source to the CR particle. A particle which is moving in a SNR encounters several collisions with moving magnetic fields. At each collision, a certain amount of kinetic energy is transferred from the source to the particle or opposite, and the particle gains an energy proportional to its energy $\Delta E = \xi E$, where $\xi$ is the relative gain.

After $n$ collisions, the energy becomes equal to $E_n$:

$$E_n = (1 + \xi)^n E_0,$$

where $E_0$ is the particle energy before entering the accelerating region. So the amount of encounters needed to reach an energy $E$ is given by:

$$n = \frac{\ln \left( \frac{E}{E_0} \right)}{\ln (1 + \xi)}.$$

In order to obtain the all-particle spectrum, one has to take the chance of leaving the accelerating region into account. At every collision, there is a certain probability $P_{\text{esc}}$ of escaping the accelerating region. The probability that a particle remains in this region is given by:
(1 - P_{esc})^n$. Therefore, the number of particles $N$ which are accelerated to an energy $E_n$ is given by:

$$N(> E_n) = N_0 \sum_{n=\infty}^\infty (1 - P_{esc})^n .$$

Inserting 1.5 leads to:

$$N(> E_n) \propto \frac{1}{P_{esc}} \left( \frac{E}{E_0} \right)^{-\gamma} ,$$

with

$$\gamma = \frac{\ln\left(\frac{1}{1-P_{esc}}\right)}{\ln(1+\xi)} \approx \frac{P_{esc}}{\xi} .$$

It can be easily seen that equation 1.7 leads to the desired power law spectrum.

In Fermi's paper, he suggested (elastic) collisions of charged particles with magnetic regions (caused by clouds of moving plasma) as being the source of particle acceleration. Currently, there are two types of Fermi acceleration known: first and second order Fermi acceleration. The acceleration mechanism described in Fermi’s paper is equivalent to the second order Fermi acceleration.

First order Fermi acceleration is also called ”shock acceleration”.

The expansion velocity of a SNR is supersonic and a shock front is created. When a charged particle enters the shock region, it can be scattered back and forth by the magnetized gas ahead and behind the shock front. The gas ahead of the shock front moves at the speed of the shock front $v_1$, while the gas behind the shock recedes from the shock with a velocity $v_2 < v_1$, relative to the shock front. The net effect of the head- and tail-on collisions will be an energy increase, which will be related to the difference in velocity between the shock front and the receding shocked gas as ($\beta = (v_1-v_2)/c$) [6]:

$$\xi \propto \beta$$

Shock acceleration seems a good candidate to produce energies observed at Earth. However, the first order Fermi acceleration suffers from the ‘injection problem’: particles already need to have a certain significant energy to be able to enter the region of acceleration. It is not known which source could provide this energy. One possible candidate is the second order Fermi acceleration. This acceleration mechanism is based on multiple stochastic reflections within a moving plasma cloud. When a particle enters the cloud, it will undergo many scatterings. After a few scatterings, the particle motion will on average concur with the magnetic cloud. Multiple scatterings inside the cloud occur, at which the particle can either gain or lose energy. However, since the particle motion concurs with the motion of the cloud, there will be a net gain of energy. This energy gain is only proportional to the velocity of the magnetic cloud squared [6]:

$$\xi \propto \beta^2$$

This process is thought to be to slow to provide the necessary energy spectrum observed. Further diffusion may happen during the propagation through the universe, probably resulting in the CR energy spectrum observed at Earth. However, many questions remain.
1.3. Extensive air showers

Balloon or satellite experiments, operating at the outer layers or above our atmosphere, can provide us with useful information about the low-energy region of the CR spectrum. However, as shown on Figure 1.1, the particle flux decreases fast with increasing energy. Thus, research of the CR spectrum from energies above hundreds of TeV up to the highest energies has to be performed with large detector arrays. Since these detector arrays are built at ground level, primary particles will undergo collisions with (air) nuclei in the atmosphere of the Earth before they can be detected, and induce extensive air showers (EAS).

CR particles will interact with the atoms in the atmosphere at a certain altitude, after having already crossed a certain amount of matter. After this first interaction a cascade is initiated, creating secondary, tertiary, etc. particles, and the information about the primary energy and mass is more and more spread out. When a number of these particles disappear through interactions with air molecules, part of the initial information is lost. The goal of every detector array must be to assemble the puzzle as good as possible, such that the energy and mass of the primary particle get extracted again. An example of an air shower is shown in Figure 1.6.

1.3.1 First interaction

The length or depth crossed before primary particles undergo their first collision is determined by the mean free path or interaction length:

\[
\lambda_{\text{int}} = \frac{A}{N_A \sigma_{\text{int}}} = \frac{m_{\text{air}}}{\sigma_{\text{int}}} \quad [g/cm^2],
\]

(1.11)
where $A$ is the mass number of the target nucleus and $N_A$ is Avogadro’s number. The ratio of the mass number and $N_A$ is given in the second equation by $m_{\text{air}} = A_{\text{air}}m_p^4$, the mean atomic mass of air [6]. The mean atomic number of air $A_{\text{air}}$ is known to be 14.54 (Table 3.1, [20]). The actual mean distance before interaction $l_{\text{int}}$ can be determined by multiplying this with the atmospheric density $\rho$:

$$l_{\text{int}} = \frac{m_{\text{air}}}{\sigma_{\text{int}}} \rho \ [\text{cm}].$$

The interaction length determines the mean path length or depth at which the number of particles is reduced by a factor of $1/e$ [21]:

$$\frac{I(X)}{I_0} = e^{X/\lambda_{\text{int}}},$$

with $I(X)$ the number of particles at a depth $X$ (in g/cm$^2$) and $I_0$ the number of particles on top of the atmosphere. At a certain altitude, this depth $X$ is given by the mass overburden, which is also named as ‘atmospheric depth’ or ‘thickness’.

Since collisions between the primary particle and the target nuclei are destructive, the $\sigma_{\text{int}}$ will be defined by the inelastic cross section $\sigma_{\text{inel}}$ (in mb$^5$). $\sigma_{\text{inel}}$ is the main source of uncertainties in the mean free path determination, or even more general, in the development of EAS. For detailed air shower simulations, hadronic cross sections are needed to determine particle collisions between every possible primary and the main air components. Even though this interaction cross section depends only weakly on the energy, the precise cross section is not well known at ultra high energies (up to $10^{21}$ eV). This is beyond the capabilities of today’s accelerators and the cross sections have to be determined using extrapolation methods. Cross sections and interaction lengths are model dependent and significant variations exist between different hadronic interaction models, especially at higher energies. Figure 1.7 shows the nucleus-air cross sections for various hadronic interaction models. Since the target and projectile (except for proton) nuclei are composed of several nucleons, many nucleons are participating in the reactions. These cross sections are calculated from the nucleon-nucleon cross section following Glauber theory [20, 22]. In the EAS simulation, the nucleon-air ($n$-air) cross section is determined by the weighted sum of the nucleon cross section of the air components $N_i$ (Section 4.1.1):

$$\sigma_{n-\text{air}} = \sum_i n_i \cdot \sigma_{n-N_i},$$

where $n_i$ are the abundances of the air components.

The large model-to-model variations of the nucleus-air cross section result in a large uncertainty in the interaction length (Figure 1.8). One approximation of the energy dependency of the inelastic proton-air cross section with is given by [23]:

$$\sigma_{\text{inel}}^{p-\text{air}}(E) = 290 \cdot E^{0.06\pm0.01} \ [\text{mb}],$$

with $E$ in TeV. This proton-air cross section dependency of the energy is consistent with the cross sections used in the various models used in the simulation of air showers (Figure 1.7). A

$5\text{mb} = 1 \text{ millibarn} = 1 \cdot 10^{-3} \text{b} = 10^{-31} \text{m}^2$
1.3. EXTENSIVE AIR SHOWERS

Figure 1.7 – The nucleus-air inelastic cross section as a function of momentum in the lab frame, for different nuclei in various hadronic interaction models used in the simulation of EAS [20].

cross section for a 1 PeV proton of about 440 mb is obtained, which corresponds to an interaction length of about 55 g/cm². Hence, if 100 1 PeV proton primaries would be inserted on top of the atmosphere, \( \frac{100}{e} = 36.8 \) of them would not have interacted after crossing 55 g/cm² of air. Figure 1.7 shows that the iron-air cross section \( \sigma_{\text{Fe-air}}^{\text{inel}} \) can be roughly estimated as \( 5 \cdot \sigma_{\text{p-air}}^{\text{inel}} \), therefore obtaining an interaction length of iron in air of approximately 11 g/cm². The bulk of the first interactions can be found at altitudes between 10 and 40 km above sea level (a.s.l.).

In the inelastic collision between a primary particle and a target nucleus, a number of secondary particles is produced. This particle multiplicity is highly energy dependent and, just like the cross section, not known at these high energies. Therefore, also the particle multiplicity is one of the major sources of uncertainties in air showers.

To give a qualitative description of air showers, it is important to distinguish between the different components of the air showers. Different components will develop in different ways and can be treated (almost) independently. The reaction products of the inelastic nucleon-nucleon collisions will be in 90 % of the cases pions (the other 10 % are kaons), together with the recoil nucleus and separate hadrons [15, 23]:

\[
p + N \rightarrow N + N + n_1 \pi^\pm + n_2 \pi^0 + X ,
\]

where \( N = p^+ \), \( n^0 \) and \( X \) stands for all possible additional reaction products, including hadrons. Protons are taken as the projectile nucleon, since protons will be the vast fraction of incoming nucleons [6]. Neutron induced interactions will produce the same reaction products. Produced \( K^\pm \) and \( K^0 \) mesons will behave similarly as pions and will not be handled separately.

The electromagnetic (EM) component contains electrons, positrons and photons and will be initiated by the produced \( \pi^0 \) mesons. The \( \pi^+ \) and \( \pi^- \) may contain both an EM and muonic component. The recoil nucleus and produced hadrons will be the core of further air shower production. Moreover, since these different components have varying properties, they
Figure 1.8 — A sketch of an air shower and its components. At the right side of the plot, the different components of the air shower, induced by a nucleus \( N \), are shown. The \( \pi^0 \) immediately decays to photons, inducing an electromagnetic part of the shower (green), while the charged pions will decay to muons (orange) or interact. Aside from this, also atmospheric neutrinos are created. The left side shows the shower development in number of particles as a function of the atmospheric depth, plotted for iron, proton and gamma induced showers of \( 10^{19} \) eV obtained from simulations. The different colours are due to the various hadronic models. Figure composed from presentations at the CORSIKA school 2008 [24, 25].

will have to be detected in diverse ways. The different components of an air shower are shown on Figure 1.8.

1.3.2 Electromagnetic component

The produced \( \pi^0 \) mesons will induce the EM component, considering the branching ratio (BR) of their main decay channel [4]:

\[
\pi^0 \rightarrow \gamma \gamma \quad (\text{BR} : 98.823 \pm 0.034\%)
\]  

(1.17)

Neutral pions will almost immediately decay to photons, without having a chance of interacting with another air molecule. Further development of the EM component can be well
1.3. EXTENSIVE AIR SHOWERS

approximated by the Heitler model of EM showers [26].

The radiation length describes the mean distance (or depth) over which an high-energy elec-
tron loses 1/e of its energy by bremsstrahlung. Furthermore, it is 7/9 of the mean free path
for pair production of an high-energy photon [4]. The radiation length for electrons, positrons
and photons in air is $X_0 = 36.66 \text{ g/cm}^2$ [15]. Therefore, only photons, positrons and electrons
produced close to the surface will actually reach the detector. The other ones will either pro-
duce more particles, or will be stopped in the atmosphere, depending on the particle energy.

Hence, each radiation length the amount of particles will be doubled, creating $N(X)$ par-
ticles after $n = X/X_0$ splitting lengths:

$$N(X) = 2^{X/X_0}, \quad (1.18)$$

where $X$ is the amount of matter crossed (in g/cm$^2$). During each multiplication, the energy
of the initial particle ($E_0$) is assumed to be equally divided between the two reaction products.

After $n$ splitting lengths, the particles have an energy of:

$$E_n = \frac{E_0}{N(X)}, \quad (1.19)$$

Multiplication continues until the particle energies $E_n$ fall below the critical energy $E_c$, where
collisional energy loss exceeds radiative energy loss. In air, $E_c \approx 85 \text{ MeV}$ [26].

This simple model overestimates the number of electrons and positrons compared to the
number of photons. As shown on Figure 1.10, the number of photons is about ten times
larger than the e$^\pm$ number for a 1 PeV vertical proton shower. This is mainly due to multiple
photon production by bremsstrahlung and e$^\pm$ range out in the air [26].

1.3.3 Muonic component

The hadronic cascade is the parent process or core of the air shower. Primaries, primary
fragments or energetic secondary particles are the projectiles in subsequent collisions with
air nuclei. At each stage, new EM and muonic cascades are created. This process continues
until the energy of the primary fragments or secondary hadrons reaches the energy threshold
below which no new pions are created. Below this energy, the hadrons undergo more scatter-
ing processes and nuclear collisions which will not influence the development of the air showers.

Muons in air showers originate from charged pion (or kaon) decays [4]:

$$\begin{cases} 
\pi^+ \rightarrow \mu^+ + \nu_\mu & (99.98770 \pm 0.0004\%) \\
\pi^- \rightarrow \mu^- + \bar{\nu}_\mu & (99.98770 \pm 0.0004\%) \end{cases} \quad (1.20)$$

The pion lifetime $\tau$ is roughly 26 ns, which allows them to travel a significant distance in the
atmosphere. Whether the pions decay or interact, depends on the ratio of the decay length
(with units cm) to the interaction length $l_{\text{decay}}/l_{\text{int}}$. The relativistic decay length $l_{\text{decay}}$ can be calculated using:

$$l_{\text{decay}} = \Gamma c \tau, \quad (1.21)$$

with $\Gamma$ the Lorentz factor and $c$ the velocity of light. The interaction length is determined
by Equation 1.12 and depends on both the air density and the $\pi^\pm$ cross section with air
molecules. When the $\pi^\pm$ interacts, new nucleon-nucleon interactions will induce more cascades, containing both EM and muon components.

A similar hypothesis for hadronic cascades as EM cascades can be applied to determine the muon energies (Equation 1.19). The most energetic pions are created high in the atmosphere, in the first interactions. Therefore, also the highest energy muons are created close to the first interaction.

Muons have a mass of 105.7 MeV/c$^2$, which is a more than 200 times the electron mass. This makes muon bremsstrahlung more than $(200)^2$ times less efficient [4]. Hence, muons can travel a large distance through matter without being absorbed.

Muons decay in almost 100 % of the cases to electrons [4] through the weak interaction:

$$\begin{align*}
\mu^- &\longrightarrow e^- + \bar{\nu}_e + \nu_\mu \\
\mu^+ &\longrightarrow e^+ + \nu_e + \bar{\nu}_\mu
\end{align*}$$

(1.22)

Due to the decay through the weak interaction, the $\mu^\pm$ lifetime is about 2200 ns [4]. This results in a long decay length: using Equation 1.21, it can be shown that most muons will reach the surface.

The bulk of the high-energy muons, which are created close to the first interaction, possess enough energy to travel a large distance in ice and can be detected by an underground detector (like IceCube).

In the Feynman scaling approximation [23], the average number of muons grows linearly with the energy $E_0$ of the primary proton. However, as explained in [27], the mesons are on average produced at larger depths in higher energy showers. At larger depths, the atmospheric density is larger (Chapter 3). Therefore, the $\pi^\pm$ interaction length decreases, resulting in a smaller amount of muons. When both the effects are taken into account, the muon multiplicity increases according to $E_0^\alpha$, where $\alpha$ is about 0.75 [27].

The calculation of the muon fluxes as a function of energy is further described in [6].

A large number of neutrinos is produced in air showers. These mainly originate from pion (Equation 1.20), kaon or muon (Equation 1.22) decays. The knowledge of the atmospheric neutrino flux is of great importance for cosmic neutrino measurements, since the atmospheric neutrinos constitute a large background.

1.3.4 Longitudinal profile

The electromagnetic and muonic development together form the total longitudinal profile of the EAS. An example of a longitudinal profile of an air shower is shown in Figure 1.9. Obviously, not every air shower profile is the same, but the average profile is typical for each primary and energy.

The number of electrons and photons increases fast until they reach the critical energy $E_c$. Below this threshold, the number of $e^+$, $e^-$ and $\gamma$ particles decreases. At the atmospheric depth where all particles have the critical energy, the shower reaches its maximum size ($X_{\text{max}}$).
1.3. EXTENSIVE AIR SHOWERS

Figure 1.9 – Longitudinal profile of 100 simulated showers in the July 2010 atmosphere above the IceTop detector (ground level=697.6 g/cm$^2$, see Chapter 3). The primary particle is a vertical 1 PeV proton. The red line shows the mean number of particles as a function of the atmospheric depth.

Figure 1.10 – Average profile of the different EAS components in the July 2010 atmosphere above the IceTop detector (ground level=679.6 g/cm$^2$, see Chapter 3). 100 showers initiated by a vertical 1 PeV proton are averaged.
CHAPTER 1. COSMIC RAYS

The number of particles at $X_{\text{max}}$ is [26]:

$$N(X_{\text{max}}) = \frac{E_0}{E_c}, \quad (1.23)$$

from which we can obtain the depth of the shower maximum (using Equation 1.18):

$$X_{\text{max}} = X_0 \frac{\ln E_0/E_c}{\ln 2}. \quad (1.24)$$

This EAS property is very important and will be used frequently in this work. The approximation for the number of particles and the depth of the shower maximum is also valid when considering air showers initiated by hadrons [6]. The longitudinal profile of the $e^\pm$ and $\gamma$ particles can be seen on Figure 1.10. This figure also shows the development of the muonic and hadronic component. Since the atmosphere is thin in the early stages of the EAS development, the pion and kaon interaction length is large and the number of muons quickly rises. When density increases, more pions and kaons will interact and the number of muons will rise more slowly. Because of the large decay length of muons, the number of muons almost doesn’t decrease before the surface is reached.

Due to the energetic collisions and nuclear fragmentation, also the number of hadronic particles rises in the young EAS. When more atmosphere is crossed, the number of hadrons stagnates and finally decreases.

Higher mass primaries

The average longitudinal profile of both a proton and an iron induced shower with an energy of 1 PeV is shown in Figure 1.11. Since proton and iron comparisons are going to be performed in this work, it is important to highlight the differences between the EAS development of the two primaries.

One simple principle which is widely used to describe showers induced by heavier primaries than proton, is the superposition principle. This principle assumes that a shower initiated by an atomic nucleus with mass number $A$ and energy $E_0$ is approximately equal to a superposition of $A$ showers with primary energy $E_0/A$ [18]. This approximation is valid since the binding energy ($\sim\text{eV}$) between the nucleons is much smaller compared to the energy of the primary. This assumption will help to understand some properties of iron showers compared to proton showers.

Due to the larger cross section (Figure 1.7), heavy nuclei interact more quickly compared to proton showers when entering the atmosphere. Furthermore, iron showers develop more quickly, due to the superposition principle. Both effects result in a lower depth of the shower maximum. This can be seen using Equation 1.24:

$$X_{\text{max}}^A = X - 0 \frac{\ln (E_0/A E_c)}{\ln 2} = X_{\text{max}}^p - X_0 \frac{\ln A}{\ln 2}, \quad (1.25)$$

where $X_{\text{max}}^A$ is the depth of the shower maximum with a primary of mass $A$. $X_{\text{max}}^p$ is the average $X_{\text{max}}$ of proton showers.
If measurements are performed at depths larger than $X_{\text{p max}}$, proton showers will contain more particles compared to iron showers, since iron showers are at a later stage in their development.

The profile of one shower initiated by a heavy primary describes the average of many individual showers (in the superposition principle), induced by the different nucleons. Hence, fluctuations in the longitudinal development are smaller in showers initiated by heavy nuclei compared to light nuclei (Figure 1.11). Furthermore, the showers initiated by heavy primaries are produced at smaller depths, where the atmosphere is less dense, which also induces smaller fluctuations.

Since the profile of showers induced by heavy primaries describes the average of many individual showers, the number of particles at $X_{\text{max}}$ is lower in these showers compared to proton initiated showers [6].

For higher mass primaries, the superposition principle can be used to determine the muon component. If a proton primary of $E_0$ produces on average $<N_\mu(E_0)>$ muons, the muon multiplicity will be on average $A<N_\mu(E_0/A)>$ for primaries with mass $A$ [27, 28]. When considering that the number in the showers scales with $E_0^{0.75}$, it can be seen that iron showers contain about $26^{0.25}$ (i.e. more than two times) more muons compared to proton showers of the same energy.
1.3.5 Lateral distribution

The lateral spread of the EM component is caused by the multiple Coulomb and Compton scattering and is characterized by the Molière radius $r_M$:

$$r_M = \frac{X_0 E_s}{\rho E_c} \text{[cm]}.$$  \hspace{1cm} (1.26)

In this equation, $E_s = m_e c^2 \sqrt{4\pi/\alpha} \approx 21 \text{ MeV}$ characterizes the energy loss due to multiple Coulomb scattering [4]. $E_c$ is the critical energy earlier defined in Section 1.3.2 [23]. $r_M$ determines the radius of a cylinder in which 90\% of the EM energy is contained.

A description of the entire lateral distribution of EM is given by the NKG (Nishimura-Kamata-Greisen) formula [6]. Though, since this formula does not include muons and hadrons, modifications to this formula are needed. Besides, the lateral distribution function (LDF) highly depends on the detection technique. Therefore, LDF’s are unique in most experiments, the IceTop LDF is described in section 2.7.1.

The transverse momenta obtained by the secondary particles emerging from the hadronic interactions, together with the meson decay to muons both dominate the muonic lateral spread.

1.4 Air shower detectors

During the twentieth century, many indirect detection methods of air showers have been developed. This was of great importance for the further evolution of the cosmic ray detectors, after the first coincident measurements of Pierre Auger in the 1930s.

Since the electromagnetic particles are not penetrating, they will be stopped in a very small amount of material and has to be detected with surface detectors. Compared to this, muons can penetrate a very large amount of matter. The energy loss of high-energy muons can be described as follows:

$$-\frac{dE_{\mu}}{dx} \approx a + b \cdot E_{\mu} \text{,}$$  \hspace{1cm} (1.27)

with $a$ and $b$ approximately constant and $E_{\mu}$ the muon energy. In order to have no electromagnetic background and to be able to determine the energy of the muons, muon detectors have to be located underground (or under a certain amount of ice, water or other absorbing material).

Various currently used detection methods can be seen in Figure 1.12 and are given below, together with a very limited selection of experiments using these methods:

- Large Cherenkov detectors, detecting the Cherenkov light emitted by muons in the surrounding medium, which is water or ice. The predecessor of IceCube, AMANDA (the Antarctic Muon and Neutrino Detector Array) used the ice at the South Pole as a natural medium of Cherenkov light production [29].

- Cherenkov tanks measure the energy deposition of the particles which pass through the tank. These tanks filled with water are for example used as the surface detectors of the Pierre Auger Observatory [30]. The IceTop array, more extensively described in Chapter 2, uses Cherenkov tanks filled with ice.
Scintillation counters at the surface. SPASE (South Pole Air Shower Experiment), the predecessor of IceTop, used these kind of detectors [29]. Also KASKADE (KArlsruhe Shower Core and Array DEtector [31]) uses the scintillation technique to detect particles at the surface.

Tracking detectors or calorimeters. The hadronic component of EAS is detected at the KASKADE array using calorimeters.

Air Cherenkov telescopes. Charged particles emit Cherenkov radiation when they travel faster than the speed of light in air. The MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes [32]) experiment and many others make use of this detection technique.

Air fluorescence detectors, where UV-light is emitted by the nitrogen molecules in the air when they are excited by collisions with air shower particles. The Pierre Auger Observatory includes four air fluorescence detectors [33].

**Measurement Techniques of Air Showers**

- First Interaction (usually several 10 km high)
- Air shower evolves (particles are created and most of them later stop or decay)
- Some of the particles reach the ground
- Measurement of Cherenkov light with telescopes or wide angle pmts
- Measurement with scintillation counters
- Measurement of low energy muons with scintillation or tracking detectors
- Measurement of high energy muons deep underground
- Measurement of fluorescence light

**Figure 1.12** – Diverse detection methods. The detectors enclosed by the green rectangle indicate the Cherenkov tanks, which are used as surface detectors of the IceCube Neutrino Observatory, while the red ellipse content is related to the in-ice component. Picture edited from [24].
Chapter 2

The IceCube Neutrino Observatory

Figure 2.1 – The IceCube Neutrino Observatory with all its components. The different colours of the IceTop stations indicate the year of deployment.
2.1 Detector: goals and location

The main goal of the IceCube Neutrino Observatory is to detect high-energy astrophysical neutrinos originating from extraterrestrial sources. As neutrinos are neutral particles, they are not affected by the magnetic field and point directly to their sources. Moreover, high-density regions which are opaque for photons do not affect neutrinos. Possible sources of high-energy cosmic neutrinos include gamma-ray bursts, galactic supernova remnants and active galactic nuclei. It is likely that these high-energy neutrinos are produced through interactions of accelerated charged particles with a target particle, like for example interstellar matter. Therefore, the sources of high-energy neutrinos might point back to the accelerating regions of high-energy cosmic rays.

Neutrinos produced in extensive air showers constitute a large background in the search for cosmic neutrinos. It is expected that these sources of neutrinos could be distinguished using their difference in spectra. In general, it is assumed that the atmospheric neutrinos have a harder spectrum [34]. However, to distinguish the lower flux of cosmic neutrinos from this background of atmospheric neutrinos, the atmospheric neutrino spectrum has to be completely understood.

Furthermore, a neutrino detector can be used in the search for possible dark matter candidates, like WIMPs (Weakly Interactive Massive Particles). These WIMPs could be gravitationally trapped in massive regions like the center of the Earth, Sun or Milky Way. If possible WIMPs, like the lightest supersymmetric particle, annihilate, particle pairs are produced which could annihilate to neutrinos. A statistical excess of neutrinos originating from these massive regions would point to possible dark matter candidates. Moreover, a neutrino detector can contribute in the search for other possible exotic particles, like supersymmetric taus (staus) [34, 35].

Since neutrinos are electrically neutral, weakly interacting particles, their cross-section with matter is only very small. Therefore, instruments have to be designed using a large detection volume. IceCube makes use of the clear ice at the South Pole (Figure 2.2) to be the surrounding medium. When neutrinos interact with matter, charged particles are created which will emit Cherenkov radiation when travelling faster than light. This light can propagate through the ice and is detected by optical sensors (Section 2.3). In IceCube, these optical sensors are distributed over 1 km$^3$. As will be shown in Section 2.2, muons created by the muon neutrinos will create the easiest signature in the detector.

The charged particles created by the original neutrinos are pointing in (approximately) the same direction as the initial neutrino and thus also point to the neutrino source. IceCube makes use of the Earth as an actual shield for atmospheric muons, which constitute a large background. Hence, IceCube is mainly looking at muons from neutrinos pointing to sources at the northern celestial sphere. These neutrinos are called upgoing neutrinos.

To deal with the large background of downgoing muons, an air shower array at the surface, called IceTop (Section 2.5), will be used as a veto. IceTop is also designed to study the EM component and low energy muonic component of cosmic rays. IceCube is ideally suited to detect the high-energy muonic component of EAS. Since both the muonic and EM component are detected, the IceCube Neutrino Observatory has many tools for the reconstruction of the energy and mass of the primary particle.
2.2 Detection mechanism

Because of the small cross section of neutrinos, very large detectors are required to detect a significant amount of neutrinos. Besides, the angular resolution is very important in neutrino telescopes and flavour identification is desired since $\nu_e$ and $\nu_\tau$ backgrounds are much lower compared to $\nu_\mu$ backgrounds. This is due to the pion or kaon decay to muons in EAS, hence the background for atmospheric electron and tau neutrinos is much lower.

When neutrinos interact with a nucleus in the ice, a charged lepton is produced through the exchange of a W boson:

$$\nu_\mu + X \rightarrow W \rightarrow \mu + X',$$

with X the original and $X'$ the recoil nucleus. When travelling faster than light in the medium, charged particles emit Cherenkov photons [36]. These photons have wavelengths in the UV-band of the electromagnetic spectrum, which makes the bluish color of Cherenkov radiation. Also, all the photons are radiated at a certain 'Cherenkov angle', all together determining the 'Cherenkov cone'. The Cherenkov angle only depends on the velocity of the particle in a certain medium (when assuming a non-dispersive medium, which is the case here):

$$\theta_c = \cos^{-1}\left(\frac{1}{n\beta}\right) = \cos^{-1}\left(\frac{c_n}{v}\right),$$

where $n$ is the refractive index of the medium. $\beta = v/c$ is the particle velocity.

The amount of Cherenkov photons per photon energy and path length is determined by the Franck-Tamm formula [4]:

$$\frac{d^2N}{dEdx} = \frac{\alpha Z^2}{hc} \sin^2 \theta_c,$$

where $\alpha$ is the fine structure constant $\approx \frac{1}{137}$, $Z$ is the charge of the particle and $\hbar$ is the reduced Planck constant. This results in approximately 32000 emitted photons in the 300-600
nm wavelength interval for a muon travelling through 1 meter of ice. Using the Antarctic ice as a propagation medium, Cherenkov radiation can be used to detect charged leptons. Difficulties may arise due to scattering and absorption of the Cherenkov photons in the ice. However, dedicated simulations and detector calibrations are performed to study the detailed ice properties.

Since the energy loss is many times smaller for muons than for taus or electrons, the muon signature (Figure 2.3) in the detector is one long track, compared to the taus or electrons, which deposit all their energy immediately. Figure 2.4 shows the created signal of the different neutrinos in the IceCube detector. Clearly, it is easier to reconstruct and to determine the properties of the long muon track.

![Figure 2.3](image1.png)

**Figure 2.3** – Cherenkov radiation emitted by a muon travelling faster than light in ice. This muon was produced by charged-current interactions from a neutrino with a nucleus. The muon signature is a (17 m) long track in the detector [37].

![Figure 2.4](image2.png)

**Figure 2.4** – The signal of (a) a simulated $\nu_e$, (b) a muon or muon bundle in IceCube-40, (c) a simulated $\nu_\tau$. Each dot is from a single hit DOM. The colours refer to the time when the PMT was hit, from red (early) to blue (latest). The magnitude of the signal is displayed in the size of the sphere [38].
CHAPTER 2. THE ICECUBE NEUTRINO OBSERVATORY

2.3 Detectors: Digital Optical Modules

The eyes of the IceCube Neutrino Observatory are Digital Optical Modules (DOMs), which detect the radiated Cherenkov photons. Figure 2.5 shows a DOM with all of its components. A DOM consists of a 35 cm diameter glass pressure vessel which surrounds a photomultiplier tube (PMT) together with the associated electronics and a data acquisition system (DAQ).

The PMT is the main component of the DOM. It is the part of the DOM which actually detects the Cherenkov photons. The model used for most IceCube and IceTop DOMs is a 10” (25 cm) Hamamatsu R7081-02 photomultiplier tube, which has a maximum quantum efficiency of about 25%. The amplifying part has ten dynodes and different gains are adapted for IceCube compared to IceTop DOMs. The anode operates at high voltage, which is provided by a Cockroft-Walton power supply, while the cathode is grounded [39].

The PMT is surrounded with a mu-metal grid to shield it from the Earth’s magnetic field. The upper half of the DOM is occupied by the DAQ system. The PMT anode is connected with the DAQ through a (bifilar wound) toroidal transformer. After this transformer, a discriminator trigger is placed into the circuit. If the threshold is not passed by the signal, the DAQ will not further analyse this signal. This is done in order to reduce the dark noise in the PMT. The PMT signal is then amplified by 3 different gains (0.25, 2, 16) to increase the dynamic range, after which the signal is digitized by the ATWD (Analog Transient Waveform Digitizer) and FADC (Fast Analog to Digital Converter). Before the digitization, the analog signal is delayed on the delay board, which contains a 70 ns long delay line. This is done in order to be able to initialize the digitizers and to make a trigger decision. This means that the two nearest-neighbour or next-to-nearest-neighbour DOMs recorded a signal above the discriminator threshold within a 1 μs window. A simplified diagram of the DAQ electronics

Figure 2.5 – A schematic view of a Digital Optical Module (DOM).
Figure 2.6 – A simplified block diagram of the electronics on the main board of the DOM [37].

is shown on Figure 2.6. The main board is supplied with two ATWDs to reduce dead time. The FADC and other electronics also house on the main board. Aside from this, the main board contains an "on-board" UV LED, which is used to determine the transit time through the PMT and electronics. This "on-board” LED may be flashed on command.

Above the main board, the DOM contains a flasher board with 12 LEDs mounted on the edges. These are for example used for charge and time calibration and the exact positioning of the DOMs.

It is important that all materials exhibit very low noise rates and reliable lifetime, since DOMs cannot be repaired once deployed and low noise rate is needed to reduce the background.

2.4 The in-ice component: IceCube

The in-ice component of the IceCube Neutrino Observatory, IceCube, consists of 5160 DOMs mounted on 86 strings. Each standard string contains 60 DOMs, which are spread over 1 km, corresponding to a separation of 17 m between two subsequent DOMs.

Seventy-eight ‘basic’ IceCube strings are situated on a triangular grid with a 125 m spacing (Figure 2.7(a)), which all together covers a surface area of 1 km$^2$. The three-dimensional 1 km$^3$ IceCube detector is deployed at a depth between 1450 and 2450 m beneath the ice surface (Figure 2.1). This depth ensures that the large background of low energy atmospheric muons is reduced. Besides, during the AMANDA data taking period, it was found that even at a depth of 1 km, air bubbles limited the scattering length of Cherenkov photons to about 50 cm. This was troublesome. However, these air bubbles mostly disappear at larger depths.

In the center of the array, 8 more strings are added. This part of the detector is called 'DeepCore'. Six of these strings are deployed on a 72 m triangular grid, while string 79 and 80 are placed at an intermediate position between these strings and the most central string.
CHAPTER 2. THE ICECUBE NEUTRINO OBSERVATORY

Figure 2.7 – The geometry of the IceCube and IceTop stations seen from the surface.

(string 36). All of these strings contain, similar to the other IceCube strings, 60 DOMs. However, 50 DOMs are located at the bottom of the string, with a 7 m spacing between subsequent DOMs. The other 10 DOMs are attached higher up. These 10 DOMs are used, together with the outer IceCube strings, to veto against events which are not contained in the detector [35]. The denser DeepCore extension lowers the energy threshold of IceCube by about a factor of 10, reaching a lower energy threshold of almost 10 GeV.

Recorded data is sent to the surface, where it is collected by a string hub, which is a standard industrial computer. One hub is used per string. These string hubs also distribute the power to the DOMs, calibrate the time stamps from the DOMs using a Master Clock, which receives GPS input. When this happened, information is sent to a trigger. Several IceCube triggers exist, of which the most important one is the SMT (Simple Majority Trigger). This trigger selects events with at least 8 hit DOMs within a time window of 5 µs. Triggered events are, together or separated from IceTop triggers, selected by an Online filter. This filtered data is directly transmitted over satellite to the data warehouse in Madison, Wisconsin. All triggered data is stored on tape and sent north during the Austral summer.

2.5 The surface component: IceTop

Next to the veto task which was discussed earlier, the IceTop detector is mainly a cosmic ray air shower array. IceTop is used to study the EM and low energy muonic component of EAS in the energy range between hundreds of TeV and 1 EeV.

The detector element for IceTop is a cylindrical Cherenkov tank, of which a schematic picture is shown on Figure 2.8. The IceTop tank is based on the Cherenkov principle, where the
Figure 2.8 – Schematic plot of an IceTop tank. A charged particle crossing the tank (red arrow) will radiate Cherenkov photons (purple cone and dotted lines). These photons can be detected directly, or will be detected after several reflections on the inner surface. This reflective surface is established by adding a 4 mm Zirconium or Tyvek coating. The HG DOM and LG DOM are separated by 58 cm. The tank diameter given on the plot is the inner tank diameter. Above the ice, the tank is filled with 40 cm perlite dust, in order to increase efficiency by reflecting the light, such that the light coming from below would stay within the tank and the light from outside the volume would be prevented from entering the tank.

medium in which the particles emit Cherenkov radiation is contained in the tank. This type of setup is known to be reliable from previous experiments like the Haverah Park experiment [40] and the Pierre Auger Observatory [30]. However, the IceTop tanks are filled with ice, while the surface tanks of the previously mentioned experiments were filled with water. The same optical sensors as used in IceCube are used for the detection of the Cherenkov photons. One tank will accommodate two DOMs, with PMTs operating at different gains, which serves to increase the dynamic range of possible signals. The DOM with a PMT operating at a gain of $5 \cdot 10^6$ is called the ‘High Gain’ (HG) DOM, while the ‘Low Gain’ (LG) DOM operates at a gain of $10^5$. A through-going particle will emit Cherenkov radiation, of which the photons will be directly detected by one of the DOMs or will be reflected on the inner surface of the tank before being detected.

The tank rests on a wooden pallet and is also protected for damage by a wooden lid. The dimensions of a tank can be seen on Figure 2.8. The deployment of a tank and the freezing of the water are shown on Figure 2.9.

In total, 162 ice-filled tanks are deployed in over a surface area of 1 km$^2$. IceTop tanks are positioned in pairs of two tanks, called a station, 10 m apart from each other. The two tank grouped in one station geometry is mainly important to distinguish between the individual event rate of particles passing through a tank ($\sim 2$ kHz) and small showers, originating from low-energy showers (typically several tens of TeV). Furthermore, one could possibly extend the sensitive energy range to lower energies, at which only the two tanks within one station trigger. Also fluctuations of reconstruction parameters can be measured by splitting the array
CHAPTER 2. THE ICECUBE NEUTRINO OBSERVATORY

Figure 2.9 – (a) The placing of an IceTop tank. The frame above the IceTop tank is only attached during the freezing process. The apparatus which can be seen at the back of the tank is the Freezing Control Unit (FCU) which monitors the freezing process, which is also removed after freezing completed. Picture by Bakhtiyar Ruzybayev. (b) A view inside the tank. The two DOMs can be seen during the freezing process. Picture by Tom Gaisser.

78 stations are placed on the same triangular grid as the 'basic' IceCube strings. The average distance between IceTop stations and IceCube strings which belong together is 25 m. Three additional stations are placed in the center of the array. Together with the closest stations, these stations provide an instrument to reduce the low energy threshold for the detection of cosmic rays to 100 TeV, which provides an overlap with direct measurements. The geometry of the IceTop stations can be seen in Figure 2.7.

The lowest possible energy to trigger 3 stations, which is needed for proper reconstruction, is approximately 300 TeV, depending on several environmental parameters and detector fluctuations. The CR flux decreases fast with increasing energy, which determines the high energy threshold of a squared kilometer detector array. Therefore, the maximum energy at which IceTop is able to collect enough statistics is about 1 EeV.

A very important benefit for composition and spectrum studies is the altitude of IceTop. The surface component of the IceCube Neutrino Observatory is located at a height of 2835 m above sea level (a.s.l.), which corresponds to an average atmospheric depth of approximately 680 g/cm². Compared to the height of the KASCADE experiment, which is located at an altitude of 110 m a.s.l., and the Pierre Auger Observatory, of which all detectors have altitudes between 1300 and 1500 m a.s.l. (∼ 880 g/cm²), the South Pole surface is located at a much higher altitude.

As a consequence, in the energy range sensitive for IceTop, this experiment is located at an atmospheric depth very close to the depth at which the showers of these energies reach their maximum size, so \(X_{\text{max}}\). This is shown in Figure 2.10. Being close to \(X_{\text{max}}\) means that more particles are detected, which reduces the fluctuations compared to the case when the shower is detected further away from \(X_{\text{max}}\) (Figure 1.11). This will result in a better energy resolution for the IceTop detector.
Figure 2.10 – $X_{\text{max}}$ as a function of energy for gamma-, proton- and iron induced showers. The full horizontal blue line denotes the average atmospheric depth at the South Pole station, the pale blue band shows the variation in atmospheric depth at the surface due to atmospheric variations. The accessible energy range for IceCube/IceTop is located between the two vertical blue dotted lines, while the IceTop array is sensitive in the energy region between the green dotted lines. This difference between IceTop only and coincident IceCube/IceTop measurements is mainly due to the decrease in the number of high-energy muons with decreasing energy. Furthermore, IceTop only measurements have a larger solid angle. Several hadronic interaction models and data points of other experiments are shown. Picture edited from [25].
2.6 Detector deployment

Detector construction took off during the 2004/2005 austral summer season. Since the deployment season is rather short, between mid-October and mid-February, and string construction is a critical job, seven seasons were foreseen for detector deployment. During the 2010/2011 season the final IceCube strings and IceTop DOMs were placed. The number of strings and stations used for data taking are given in Table 2.1.

Table 2.1 – Number of strings and stations used in analysis for each year during construction, together with the data taking period of these configurations. The configuration used in this work is (IC79-)IT73.

<table>
<thead>
<tr>
<th>Season</th>
<th>IceCube strings</th>
<th>IceTop stations</th>
<th>Configuration</th>
<th>Data Taking period</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>1</td>
<td>4</td>
<td>IC1 - IT4</td>
<td>-</td>
</tr>
<tr>
<td>2006</td>
<td>9</td>
<td>16</td>
<td>IC9 - IT16</td>
<td>-</td>
</tr>
<tr>
<td>2008</td>
<td>40</td>
<td>40</td>
<td>IC40- IT40</td>
<td>April 2008 - May 2009</td>
</tr>
<tr>
<td>2009</td>
<td>59</td>
<td>59</td>
<td>IC59- IT59</td>
<td>May 2009 - May 2010</td>
</tr>
<tr>
<td>2010</td>
<td>79</td>
<td>73</td>
<td>IC79- IT73</td>
<td>31 May 2010-13 May 2011</td>
</tr>
<tr>
<td>2011</td>
<td>86</td>
<td>81</td>
<td>IC86- IT81</td>
<td>May 2011 - ...</td>
</tr>
</tbody>
</table>

2.6.1 Construction of the IceCube detector

In order to deploy the IceCube strings into the ice, holes with a depth of 2500 m had to be drilled. This was established using hot water under high pressure. The diameter of the holes had to be 61 cm, which was needed to ensure that the holes remained wide enough during the refreezing to lower the DOMs. The water was heated to 88 °C, afterwards being transported through the hose reel to the Tower Operating System (TOS). When drilling was completed, the DOMs were attached to the cables in the TOS, after which they were lowered. Data taking started as soon as the hole refreezed, and the string was tested, commissioned and integrated in the DAQ. The drilling site and lowering of a DOM is shown in Figure 2.11.

2.6.2 IceTop construction

The assembly of IceTop tanks was done in the United States before transportation to the South Pole. DOMs were build at several places, but final testings were done at South Pole before deployment. This happened for both IceCube and IceTop DOMs. The IceTop station construction is shown on Figure 2.9(a). A crucial element in tank construction is the freezing of the 90 cm of water, since crack-free, clear ice is needed to obtain the best signals as possible. Air bubbles are undesirable guests in the ice. Therefore, a Freeze Control Unit (FCU) monitors the freezing process for each tank. Circulation of the water, degassing and the release of pressure due to the expansion of the water/ice volume are among the main tasks of the FCU. The total freezing process is finished in about 50 days and depends on the surface temperature. In order to reduce the freezing time as much as possible, sunshades were placed on top of the tanks and insulating snow on the surface has been removed continuously. After completion of the freezing process, the tanks were filled with perlite, after which they were closed. The last tanks were closed in February 2011.
2.7 Reconstruction of air showers

As explained before, a large benefit of the IceCube Neutrino Observatory as a cosmic ray detector is its capability of the simultaneous detection of the muonic and EM component. With the combination of muon and EM information, IceTop will, together with IceCube, be able to help in "solving" the cosmic ray mystery. In this section, the main techniques used to reconstruct the primary particle type, energy and zenith angle of the air shower will be described. The reconstruction of the EM component of the EAS by IceTop can be done by choosing a variable which is the most representative to determine the size of the EM shower. The amount of muons in the air shower could be determined using a similar technique in IceCube. As shown in Section 1.3, the size of the muonic and EM part characterizes the primary particle type and energy (Figure 2.12).

The main parameters of the air shower are the core position and direction. Furthermore, the lateral distribution will be important to reconstruct the energy of the primary particle and the stage in the shower development. Other possible parameters may be correlated with primary mass or energy, like for example total charge deposited, the IceTop muon content (which can be determined using SLC (Soft Local Coincidence) hits [41]), etc.

2.7.1 EAS reconstruction by IceTop

Reconstruction of the shower core

This reconstruction of the shower core, which is the position where the shower axis (defined by the direction of the primary) crosses the surface, is performed using an algorithm that calculates the 'Center of Gravity' (COG) of the shower. The COG of the shower is the weighted average of the signals ($S_i$) detected by the DOMs at a distance from the shower axis $r_i$:

$$r_{\text{COG}} = \frac{\sum_i r_i \cdot \sqrt{S_i}}{\sqrt{S}} ,$$  

(2.2)
CHAPTER 2. THE ICECUBE NEUTRINO OBSERVATORY

Figure 2.12 – The number of muons in the deep detector versus the number of electrons at the high Antarctic plain. Since shower maximum approaches the surface at higher energies, fluctuations will become less visible and the distribution is narrowing. The superposition principle explains the difference in the number of muons and the change in $X_{\text{max}}$ with primary mass, which determines the number of electrons at the surface [42].

where $i = 1 \rightarrow 7$ to avoid a bias from elongated showers [43]. Certain (mainly high-energy) showers which trigger the array, may have their core position outside the detector. In this case, the reconstruction of the COG will still be done. However, it will never be reconstructed outside the array and larger deviations from the true core position are possible.

Reconstruction of the shower direction

The reconstruction of the shower direction happens through a ‘plane-fit’. This fitting procedure uses the assumption that the incoming shower front is approximated as a plane wave propagating with the speed of light $c$. The expected arrival times $t_i^{\text{exp}}$ in the DOMs (at a position $(x_i, y_i)$) are given by:

$$t_i^{\text{exp}} = T_0 - \frac{ux_i + vy_i}{c}, \quad (2.3)$$

with $T_0$ the mean arrival time of the particles. A $\chi^2$ fitting procedure minimizes the difference between the real arrival times $t_i^{\text{real}}$ and the arrival times calculated in Equation 2.3:

$$\chi^2 = \sum_i \left( \frac{t_i^{\text{real}} - t_i^{\text{exp}}}{\sigma} \right)^2. \quad (2.4)$$

The fitting is done to $u$ and $v$, which describe the direction of the shower:

$$\mathbf{n} \equiv \left( u, v, -\sqrt{1 - u^2 - v^2} \right). \quad (2.5)$$
2.7. RECONSTRUCTION OF AIR SHOWERS

Figure 2.13 – The combined LDF fit to a simulated air shower detected by the IceTop-73 array. This particular event is a 10 PeV vertical proton shower. (a) The footprint of the shower in the IceTop-73 array. The signal detected by each tank is displayed through the size of the circle, the timing is given by the color of the (half)round. The reconstructed shower core is indicated by the black star, while the dotted line represents the direction of the incoming shower (azimuth). The vertical direction of the shower is clearly visible in the spherical symmetric timing circles around the shower core. (b) The lateral fit to the tank signals. The signal size at 125 m of the shower axis (S125) and the slope of the LDF at 125 m (β) are given.

σ = 5 ns, which is found to be the best value for this fitting procedure. After the first iteration, the actual tank heights are taken into account, since tank height differences can vary with a maximum of about 6 m, and a second iteration is performed.

Advanced fitting: the lateral distribution

Both first fitting procedures serve as a seed for the final fitting algorithm. This includes charge, time and unhit stations to perform a negative log-likelihood minimization. Several iterations are done minimizing charge and time terms. The algorithm also takes the signal attenuation due to snow into account.

The result of this procedure is the ‘Lateral Distribution Function’ (LDF), which describes the signal at a certain distance from the shower axis (Figure 2.13). Dedicated Monte-Carlo simulations were done to derive the functional form of this particular IceTop LDF [44]. The functional form is not a simple exponential, but has a slope which is slightly and constantly changing. The following function is used to describe the LDF:

\[ S(R) = S_{R_0} \cdot \left( \frac{R}{R_0} \right)^{-\beta - \kappa \log_{10} \left( \frac{R}{R_0} \right)} \]  

This function is referred to as the ‘Double Logarithmic Parabola’ (DLP) and describes the signal S as a function of the distance R. The LDF uses one reference distance from the shower axis R₀. From simulations, κ seems to be quite stable for IceTop, fluctuating about its mean value (0.30624) and seems not correlated to a physical variable like energy or mass of the primary. However, κ still has to be studied more extensively. The slope of the parabola is determined by β and is correlated with the stage in the shower development. Showers detected in a later stage of their longitudinal development have smaller β values, while β will be larger.
if the shower is detected at an earlier stage. This can be understood qualitatively, since this means that the later the shower is detected, the more the particles are spread out. 

\( \beta \) should be energy dependent and smaller when the atomic number of the primary particle increases, due to the change in longitudinal development. Since the zenith angle of the incoming cosmic particle changes the stage at which the shower is detected, \( \beta \) also shows a zenith angle dependency.

As shown in Section 1.3, the shower size is highly energy dependent, which will be reflected in the LDF and thus the signal at \( R_0 \). In order to obtain an ideal energy estimator, this reference distance should be chosen such that the signal at this position is highly energy dependent, but independent of the primary particle type of the shower. In IceTop, this distance is determined to be 125 m. Therefore, the signal at 125 m of the shower axis (S125) will be used as the standard energy estimator in IceTop. Furthermore, 125 m is found to be the distance of the shower axis at which the signal is the most stable. Fluctuations start to dominate at larger distances to the core due to the decrease in statistics, while smaller distances are highly affected by misreconstructions of the shower core and more uncertainty due to saturation.

### 2.7.2 IceCube reconstruction

Signals of CRs detected in IceCube are originating from single muons or muon bundles. Single muons are products of neutrinos originating from air showers with typical primary energies of the order of a few to tens of TeV, as shown in Figure 2.14. This figure also shows the amount of muons created in an air shower as a function of the muon threshold energy. Since all these high energy muons are created close to the first interaction at about the same time, they will be detected in IceCube as muon bundles. Muons contained in muon bundles possess only small transversal momenta. Therefore, all muons are moving approximately parallel to each other and a bundle can be approximated as one central track.

The number of muons is only indirectly measured in the IceCube detector, through the emitted Cherenkov radiation which is detected by the DOMs. This Cherenkov radiation is mainly coming from energy loss processes along the track of the muon or muon bundle. The muon radiative processes include bremsstrahlung and pair production, which initiate a secondary electromagnetic cascade close to the muon track, and emit also Cherenkov radiation. This energy loss depends on the muon energy, as shown in Equation 1.27.

Hence, the amount of Cherenkov radiation scales with the energy loss along the track, which is a convolution of the energy loss of one muon, the number of muons in the bundle and the muon energy spectrum. If this energy loss can be reconstructed precisely, the number of muons and their energy can be determined. As shown in Section 1.3, the muon multiplicity depends highly on the mass of the particle initiating the air shower. Therefore, the reconstructed energy loss can be used to determine the mass of the primary particle.
2.7. RECONSTRUCTION OF AIR SHOWERS

Figure 2.14 – The amount of muons and the muon spectrum coming from air showers initiated by proton primaries with energies between $10^{14}$ eV and $10^{18}$ eV. Heavier primaries will create more muons with lower energies compared to proton primaries. Also rates for these coincident events per year are shown. The energy threshold for muons to reach the top of the deep IceCube detector is about 500 GeV [35].
Chapter 3

The atmosphere

In air shower arrays, the atmosphere in which the EAS develops is part of the detector. Since the atmosphere is not a static volume but undergoes a continuous change, this can affect the air shower measurements and the reconstruction of the mass and energy of the primary particle. The main goal of this thesis is to study how atmospheric variations affect the air shower properties. We want to study the effects of all atmospheric changes to IceTop observables like S125 and the number of high-energy muons detected by the deep detector. However, if an influence is observed in other observables, these would provide us with a more complete view of what the atmosphere does to an EAS observed by the IceCube Neutrino Observatory.

As we know, from experiencing both the cold winter months and the (hopefully) warm summer months, the temperature of the air above us is able to vary within a certain range. In each case, this variation will significantly influence our mood. But what will this difference in temperature do to extensive air showers? When the temperature is higher, are there more particles that (want to) reach the surface? Or are air shower arrays able to detect more secondary particles during the winter months? Maybe different particle types show a different seasonal behaviour? And what about their energy? Does a higher temperature mean more energetic particles? Can we even speak of one single surface temperature to describe the entire atmosphere? What are the effects of temperature changes higher in the atmosphere? Is temperature the only variable that specifies the atmospheric condition?

A comprehensive description of the atmosphere is the subject of this chapter, while the effect of the atmosphere on the IceTop measurements is going to be extensively discussed in the following chapters.

3.1 Atmosphere structure

3.1.1 Composition and state of matter

The atmosphere consists of a composition of atoms and molecules, all subject to gravity and therefore bound to our earth. All mass above a certain layer contributes to the gravitational pressure on this layer. Since densities and pressures in the atmospheric gas are rather low, the atmosphere can be approximately described as an ideal gas.

The ideal gas law is given by:

$$ P \cdot V = nRT $$

(3.1)
where \( P \) is the pressure, \( V \) the volume, \( T \) the temperature and \( n \) the number of moles enclosed in this volume. \( R \) is the universal gas constant, being the product of Avogadro’s constant and Boltzmann’s constant:

\[
R = N_A \cdot k = 8.314 \frac{J}{K \cdot \text{mol}}.
\]

(3.2)

Pressure, temperature and volume are expressed in the usual units, respectively: pascal (Pa), Kelvin (K) and kg/m\(^3\). The ideal gas law can be transformed to:

\[
P = \frac{RT}{V} \cdot n = \frac{R m}{M V} \cdot T \quad \text{since} \quad n = \frac{m}{M}.
\]

(3.3)

(3.4)

This shows that the universal gas constant divided by the molar mass \( M \) is the specific gas constant \( R_{\text{spec}} \), which takes the exact composition of the volume into account. This formula is very useful since volume is included in density and it links this density with pressure and temperature. Pressure and temperature are easy to measure, while the density is the important variable for determining the mean free path of particles travelling through our atmosphere.

Although variations of atmospheric composition may seem large due to the current problems like the ozone hole, the composition of our atmosphere is actually rather stable. The percentage values of the main components are given in table 3.1. This table also shows the molar masses of the components. The molar mass of atoms is equal to their atomic weight multiplied with the molar mass constant, which is equal to 1 g/mol.

Therefore, the molar mass of each component can be calculated when considering that the molecular weight is equal to the number of atoms of each compound multiplied with its atomic mass.

Using the component abundances and their molar masses, the mean molar mass of dry air can be calculated:

\[
M_{\text{air}} \approx 28.97 \frac{g}{\text{mol}}.
\]

(3.6)

From which one can obtain the specific gas constant of dry air:

\[
R_{\text{spec}} = \frac{8.314 \frac{J}{K \cdot \text{mol}}}{28.97 \frac{g}{\text{mol}}} = 287.04 \frac{J}{Kg \cdot K}.
\]

(3.7)

### 3.1.2 Atmospheric depth

The "thickness" or atmospheric depth of the atmosphere is widely used in the description of extensive air showers, as this value is a good measure of the amount of matter crossed. Besides, it is a parameter which is easier to visualize than pressure, and they only differ by a constant:

\[
X(z) = \frac{P(z)}{g(z)},
\]

(3.8)

where \( g(z) \) is the gravitational acceleration. The altitude dependency of \( g(z) \) is very weak and will be ignored in every calculation performed in this work. Its value is taken equal to
CHAPTER 3. THE ATMOSPHERE

Table 3.1 – Percentage composition of our terrestrial atmosphere, together with the molar mass of the components. Percentage composition values obtained from [46], while atomic weights are given in [47]. Due to uncertainty and variations, numbers do not add up to 100 %. Water (vapour) is variable and typically has a contribution of about 1% with a molar mass of 18.0153 g/mol. Nitrogen and oxygen are clearly the main constituents of our atmosphere. Also ozone ($O_3$) and little dust particles are present in the atmosphere. However, they only have abundances of 1 ppm (particle per million).

<table>
<thead>
<tr>
<th>Component</th>
<th>Abundance (%)</th>
<th>Molar mass (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen ($N_2$)</td>
<td>78.08</td>
<td>28.0137</td>
</tr>
<tr>
<td>Oxygen ($O_2$)</td>
<td>20.95</td>
<td>31.9988</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>0.934</td>
<td>39.9480</td>
</tr>
<tr>
<td>Carbon Dioxide ($CO_2$)</td>
<td>0.038</td>
<td>44.0094</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>0.0018</td>
<td>20.1797</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>0.0005</td>
<td>4.0026</td>
</tr>
<tr>
<td>Methane (CH$_4$)</td>
<td>0.0002</td>
<td>16.0425</td>
</tr>
<tr>
<td>Krypton (Kr)</td>
<td>0.0001</td>
<td>38.7980</td>
</tr>
<tr>
<td>Hydrogen (H$_2$)</td>
<td>0.00005</td>
<td>2.0160</td>
</tr>
</tbody>
</table>

the gravitational acceleration at the South Pole surface, 9.83 m/s$^2$ [48].

A more intuitive description of atmospheric depth is given when it is calculated as the weight of the atmosphere above a certain altitude. This mass overburden can be calculated by integrating over the entire density profile above a certain altitude $z$:

$$X(z) = \int_{z_0}^{z} \rho(z')dz' ,$$  \hspace{1cm} (3.9)$$

where $z_0$ is the altitude at which the atmospheric density is approximately zero. When the cosmic ray particle is not propagating vertically through the atmosphere, its track through the atmosphere will be longer and the amount of atmosphere crossed will be higher compared to the vertical case. In this case, the term 'slant depth' $X_s$ is used:

$$X_s(x) = \int_{x_0}^{x} \rho(x')dx' ,$$  \hspace{1cm} (3.10)$$

where the zenith angle $\theta$ is included in the path length $x$:

$$x = \frac{z}{\cos \theta} .$$  \hspace{1cm} (3.11)$$
3.1.3 Atmospheric profile

Pressure, density and atmospheric depth

In the formulae for calculating the atmospheric depth (Equations 3.8 and 3.9), pressure and density are altitude dependent. Since the pressure at a certain height describes the gravitational force per unit area exerted by the weight of the part of the atmosphere above this height, the pressure increases with decreasing altitude.

The mass within a certain atmosphere layer between altitudes $z$ and $z + \delta z$ with a unit area is given by $\rho \delta z$.

The vertical pressure gradient, due to the decrease in pressure with height, is acting upwards on the atmospheric layer. Since the atmospheric layer is in (hydrostatic) balance, this upward acting force will be equal but opposite to the downward gravitational pressure. Therefore, the pressure change when going from a height $z$ to $z + \delta z$ can be calculated as:

$$\delta P(z) = -\rho(z)g \delta z,$$  \hspace{1cm} (3.12)

with $\delta P(z)$ the pressure variation. When the limit $z \to 0$ is taken, this becomes:

$$\frac{dP(z)}{dz} = -\rho g.$$  \hspace{1cm} (3.13)

This is the hydrostatic equation. Using the ideal gas law (Equation 3.5), this can be transformed to:

$$dP(z) = -\frac{P(z)}{R_{\text{spec}}(z)T(z)} g dz.$$  \hspace{1cm} (3.14)

The composition of the atmosphere (thus $R_{\text{spec}}$) is more or less stable up to 80-90 km [48]. To simplify the equation further, we will only consider one small layer, in which we can assume a constant temperature. When integrating between $z_1$ and $z_2$ we obtain:

$$\frac{P_2}{P_1} = \frac{\int_{z_1}^{z_2} dP'}{P(z)} = \frac{\int_{z_1}^{z_2} \frac{g}{R_{\text{spec}}T} dz'}{z_2 - z_1},$$  \hspace{1cm} (3.15)

which results in an exponential pressure profile:

$$P_2 = P_1 \exp \left( -\frac{g}{R_{\text{spec}}T} (z_2 - z_1) \right).$$  \hspace{1cm} (3.16)

This is a very important result. Equation 3.8 indicates that also the thickness decreases exponentially with height (Figure 3.3(a)). Similarly, the density profile decreases exponentially (Figure 3.3(b)). This can be easily seen when assuming constant temperature, since then density and pressure are linearly correlated through the ideal gas law (Equation 3.5).

The assumption of a constant temperature is of course only valid within a small vertical layer. When assuming non-constant temperatures, the above equations become more complicated.

At a height of 100 km, the atmospheric depth is more than one million times smaller compared to the surface thickness. This means that 99.9999 % of the atmosphere can be found below 100 km height.
CHAPTER 3. THE ATMOSPHERE

Temperature profile

Figure 3.1 shows that the temperature structure of the entire atmosphere is definitely not constant. Several layers can be distinguished, each layer is bounded by ”pauses”, where the largest changes of density and composition occur [17, 48].

- **Troposphere:**
  This layer starts at the surface of the Earth and extends up to 6-20 km. This upper bound altitude is different at the poles compared to the equator and depends on the time of the year. Almost all weather phenomena happen in this layer.
  Due to the heating of the Earth, the temperature decreases (constantly) with increasing altitude. The tropopause is the upper boundary of this layer, where the temperature gradient changes.

- **Stratosphere:**
  The stratosphere starts at the top of the tropopause and ends in the stratopause, at a height of about 50 km. The main component of this layer is the ozone layer. In this layer, which can be found on average at the lower stratosphere (15-35 km), most of the ozone of our atmosphere is contained. This ozone is very important for life on Earth because it absorbs UV-radiation originating from the Sun. The re-assembly of ozone causes the stratosphere to heat, thus inducing a temperature increase with increasing height. While the temperature of the tropopause typically can be found around -90 °C, it may reach almost freezing point in the stratopause.
  The ozone layer has a variable size throughout the year and also depends on geographical position.

- **Mesosphere:**
  The mesosphere is the atmospheric layer which can be found above the stratopause. In this layer, temperature will again decrease with increasing altitude. The top of the mesosphere, the mesopause, which can be found at 80-90 km up in the air, is the coldest place in the atmosphere. At these heights, it may cool down to temperatures below −100 °C. Even though the atmosphere is getting thinner, the density is still large enough to burn meteorites and create shooting stars.

- **Above the mesosphere, the thermosphere and the exosphere are also referred as atmospheric layers. However, density is extremely low and as such, variations within these layers will never affect extensive air showers. Most often, the atmosphere is said to end somewhere around 100 km, in the lower thermosphere. The temperature increases significantly in the lowest 200 km of the thermosphere, due to the very low densities and solar heating. However, temperature changes are only reflected in changing velocities of particles. Satellites will not experience these extreme temperatures. The solar heating causes the ionisation of the particles in the atmosphere and induces large fluctuations in the temperature of the thermosphere. The International Space Station orbits in the thermosphere.**

**Atmospheric variations**

Seasonal variations are the major source of temperature changes in our atmosphere. When spring is knocking on the door, the duration of the night decreases and solar radiation starts
Figure 3.1 – A sketch of the atmospheric temperature profile together with the mean molar mass and the electrical structure. At the right hand side, an extensive air shower is shown [49].

To heat up the outer layers of the atmosphere. During spring and summer, the entire atmosphere will warm up together with the surface of the Earth. Maximum temperatures will be reached at the end of the summer. After this period of warming, the atmosphere will slowly cool down. This process starts again at the outer layers during fall and reaches its minimum at the end of the winter. Atmospheric temperature variations will be reflected in pressure and density variations.

Next to these seasonal variations, daily fluctuations also occur. Sometimes days are full of sunshine and we experience a pleasant warmth. Other days can feel rather cold. These daily temperature variations induce a change in the lower atmosphere, furthermore resulting in a change in surface pressure.

Using the same mechanism as the seasonal temperature cycle, a daily temperature cycle exists also. During the day, the surface of the Earth heats up due to solar radiation. The maximum temperature on Earth can not be found at the solar maximum elevation, but occurs 2-3 hours later, due to the heat captured by the Earth’s surface. After sunset, temperature decreases due to a heat transfer from the warm Earth to the rather cold atmosphere. Temperature minima can be found around sunrise.

The temperature exchange between surface and lower atmosphere occurs mainly in one small layer: the Planetary Boundary Layer (PBL). During the night-time cooling, the surface emissivity of the surface of the Earth will cool the part of the atmosphere closest to the Earth. Therefore, a small layer may arise in which temperature will increase with height [48], called an inversion layer.
3.2 South Pole atmosphere

It is obvious that a place near one of the rotation poles of the Earth is a special place. The fact that the magnetic pole is nearby is responsible for the origin of auroras in the thermosphere. However, the extreme circumstances typical for those places is not due to the magnetic field of the Earth, but mainly due to the tilted position of the Earth’s axis compared to the ecliptic plane. This special position has a major influence on variations of the South Pole atmosphere.

The South Pole is located on a large ice sheet, which has an important impact on the atmosphere. As explained in Chapter 2, the height of the Antarctic plateau, being between 2600 and 4000 m \([48]\) (the altitude of the IceCube Neutrino Observatory is 2835 m) is very important for air shower measurements with IceTop. While the mean surface pressure at sea level is 1013.25 hPa, the mean pressure at the IceTop surface is only 667 hPa. This is equivalent to a mean atmospheric depth of 680 g/cm\(^2\) (Figure 2.10). Furthermore, the high elevation of the South Pole plateau and the presence of the ice sheet will be important in explaining the behaviour of the exceptional South Pole atmosphere.

3.2.1 Seasonal variations

Seasonal atmospheric variations at the South Pole are completely different compared to variations at for example 51\(^\circ\) 3’ N, the latitude of Ghent. Due to the tilted axis of the Earth, the length of each day (from sunrise to sunset) varies during the year at most places. Close to the celestial poles, the most extreme situations can be found: during the austral summer, the sun is always above the horizon, while austral winter is a period of six months when it is completely dark. This will be reflected in extreme differences in temperature.

Due to the semi-annual alternation between polar day and polar night, seasonal atmospheric variations will be combined with the daily temperature cycle. The air temperature close to the surface will increase with height since the ice and snow at the surface will cool down the air, when no solar radiation heats up the surface \([50]\). Therefore, this inversion layer is very important at the South Pole surface. Strong inversion layers exist during austral winter: from the surface level up to an altitude of 500 m, a temperature increase of about 20 °C is measured. During austral summer less significant inversion layers are present \((T_{500 \text{ m}} - T_{\text{surface}} \approx 10 \text{ °C})\). The mean temperature difference between summer and winter is shown in Figure 3.2. Since February is the time of the year when the summer season is just past half-way, February will be one of the warmest months of the year. July is included in the core of the coldest winter months, thus exhibiting the other extreme compared to February. However, throughout the year, the surface temperature never reaches freezing point.

Together with the surface temperature changes, the magnitude of the seasonal temperature difference will be largest in the lower stratosphere. During austral springtime, solar radiation ensures that UV-absorption by ozone increases. Consequently, the heat release in the stratosphere grows, which increases the temperature (Figure 3.2) \([51]\).

These temperature changes influence the pressure and density profile of the South Pole atmosphere. During the austral winter, the tropospheric temperature is lower than in summer. As shown on Figure 3.3(d), this is reflected in an increase in density close to the surface
3.2. SOUTH POLE ATMOSPHERE

Figure 3.2 – The mean temperature profile between surface (2835 m) and the top of the stratosphere (~ 50 km) in both July 2010 and February 2011. Data is supplied by the AMRC and AIRS satellite. In July, when it is cold and dark and sometimes no data taking is possible, data is obtained up to smaller altitudes compared to February data. This is the reason for the unstable behaviour around 45 km in July. The temperature is plotted on the x-axis to have a clear view of the different atmosphere layers. Prominent inversion layers are visible, being largest in July. Aside from this, also the height of the tropopause varies: it can be found around 22 km during winter, compared to a height of 9-10 km during summer. The mean surface temperature is -36.2 °C in February 2011, while July 2010 has a mean surface temperature of -57.1 °C.

during winter (as expected through the ideal gas law (Equation 3.5)). The density between \( z \) and \( z + \delta z \) (take \( \delta z > 0 \)) determines the difference between the atmospheric depths at these altitudes \( (X(z) - X(z + \delta z)) \) (Equation 3.9). Thus, a higher density implies a larger change in thickness. Therefore, the thickness profile is steeper in winter than in summer (Figure 3.3(a)). This figure also shows that, because of this steepening at the lowest altitudes, the atmospheric depth and pressure are smaller at all altitudes during winter compared to summer.

Intuitively, it can be thought that the density at a certain altitude is lower during summer, when the atmosphere is warmer, compared to winter. Figure 3.3(b) shows that this is valid close to the surface, but at higher altitudes, the opposite behaviour can be seen. This can be explained by taking also the effect of the pressure change on density into account. During summer, the effect of the higher temperature on density is completely counteracted and even reversed by the higher pressure, resulting in a larger density during summer.

However, the reason for the higher density in winter than in summer at (almost) every altitude is not evident, since this means that the atmosphere should contain more matter in summer than in winter. When the atmosphere contains more mass, as is the case in summer, the surface pressure and thickness should be higher. Indeed, this can be seen in Figure 3.3(c).

The mechanism for the increase in total mass in the column of air above the surface during springtime is not trivial and can not be explained using only the ideal gas law. For the surface pressure to increase, a net transport of mass into this column of air should take place.
Figure 3.3 – Atmospheric depth (a) and density (b) profile in the lowest 45 km of the mean July 2010 and February 2011 atmosphere. The thickness at an altitude of 2850 m a.s.l. (the lowest data point) is 678.4 g/cm² in July, the density at that altitude is $1.074 \times 10^{-3}$ g/cm³. In February, this thickness is 698.5 g/cm², while the density is $1.007 \times 10^{-3}$ g/cm³. Since the y-axis is plotted on log scale, the exponential decrease of atmospheric depth and density is shown by the linear decreasing function. The lower figures show the difference between the two atmospheres, for thickness (c) and density (d).
3.2. SOUTH POLE ATMOSPHERE

This mass transport and corresponding surface pressure change is due to a strong interplay between the temperature changes and the South Pole wind regime. At the South Pole, the wind regime near the surface is mainly determined by the geographical configuration. Due to the cooling of the atmosphere through temperature exchange with the ice sheet, the density close to the surface is higher compared to places without the presence of the ice sheet. At lower latitudes, where no ice mass is present, the density at a height of 2.6 - 4 km (the altitude of the Antarctic plateau) is lower. This horizontal change in density induces a horizontal pressure gradient, which is the motivating force for the horizontal movement of air. Due to the high elevation of the Antarctic plane compared to the subpolar regions, this horizontal movement of air is also subject to gravity and results in large katabatic winds in the lower troposphere, blowing from the South Pole to the subpolar regions. Furthermore, the elevation of the Antarctic plateau prevents large winds originating from the subpolar regions to move southwards [51].

This horizontal movement of air in the lower troposphere implies that a circulation of air must occur between the South Pole and the subpolar regions. A weak but broad flow of air returns to the South Pole in the middle and higher troposphere [51]. The strong lower troposphere wind carries mass from the high density region at the South Pole to the subpolar latitudes. If the circulation is perfectly balanced, the broad high troposphere wind would carry the same amount of mass back to the South Pole. Therefore, the net amount of mass in the air volume above the Antarctic plateau would remain constant.

As shown above, a large surface temperature difference between austral summer and winter exists. This can be seen through the difference in the strength of the inversion layer between February 2011 and July 2010 (Figure 3.2). At the subpolar regions, no ice sheet is present and hence temperature differences at the same altitude as the Antarctic plateau are smaller between the seasons. This is clearly shown in Figure 3.4.

During austral autumn (January to April), the South Pole surface temperature is decreasing (by \(-20^\circ\)C), while the temperature at an altitude of 2.6-4 km decreases slower in the subpolar regions (by about \(-4^\circ\)C). This induces an increasing density difference between those regions, strengthening the horizontal pressure gradient and corresponding wind. Since this lower troposphere wind carries mass from the South Pole to the subpolar latitudes, a growth in matter transport away from the South Pole occurs. At the same time, the return wind at the higher troposphere altitudes still blows a smaller amount of matter back to the Antarctic plateau. Therefore, the net amount of mass contained in the air volume above the South Pole grows during autumn. Since the wind circulation occurs over a large distance (from 90° latitude to 50°), it is assumed that the increase of the return flow of matter is delayed by a few months.

Between September and December (austral spring) the opposite effect takes place. Due to the solar heating, the temperature in the inversion layer increases and the inversion strength decreases. The increase in surface temperature at the South Pole is larger than the corresponding temperature change at the subpolar latitudes. This results in a decrease of the lower troposphere wind flow, therefore carrying less mass away from the South Pole, while the return wind flow carries still the same amount of mass back inside the air volume above the South Pole. During spring, the net amount of mass in the atmosphere above the South Pole grows.

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Figure 3.4 – The temperature variation from January (warmer) to April (colder) in the troposphere and lower stratosphere at latitudes between 50° (subpolar regions) and 90° (South Pole) [51]. The inversion layer (green) and stratosphere (red) above the South Pole show the largest temperature differences between January and April. Also the strong katabatic wind (long arrow) from the polar to the subpolar region and the weak but broad return wind (broad arrow) are shown.

It can be concluded that the difference in surface pressure between the summer and winter months can be explained by the interplay between the wind regime and the atmospheric temperature variations, hence by the exceptional geographic configuration of the South Pole.

Appendix A gives the monthly variations in thickness in the troposphere and stratosphere for the IT-73 data taking period. Differences with the CORSIKA July 01, 1997 (MODATM 12) MSIS-90-E model are given (see Chapter 4). The blue line represents the monthly average atmosphere, while the grey band indicates the daily variations.

3.2.2 Daily variations

As on any other place on Earth, daily (24 hours) variations also occur at the South Pole, in addition to seasonal effects. These changes mainly take place in the lower atmospheric layers, in particular in the troposphere, and are associated with weather (wind and clouds). Temperature variations can be seen in Figure 3.5 and are also reflected in density, thickness (Figure 3.6) and pressure changes. Larger pressure variations exist during austral winter. Pressure changes may go up to 20 or even 25 hPa, while during summer maximum pressure changes of 10 hPa are measured.

3.2.3 Atmosphere data

The data used in this analysis are provided by both balloon and satellite measurements. Balloon data are available from the Antarctic Meteorological Research Center (AMRC), a research center at the University of Wisconsin-Madison [52]. These balloon flights are performed twice a day at the South Pole. During the flight, every two seconds many observables are measured by a radiosonde, including temperature, pressure and height. Balloon flights are not performed when the weather is too bad. The maximum altitude reached by the balloon
3.2. SOUTH POLE ATMOSPHERE

**Figure 3.5** – Daily temperature variations in July 2010 (a) and February 2011 (b). Different days are represented by different colors. The transition from balloon data (wiggly line) to (interpolated) satellite data (stable line) can be very clearly seen. This transition occurs earlier in July compared to February. A smaller set of days are visible in July due to the bad weather conditions when balloon flights were not possible.

**Figure 3.6** – Daily atmospheric depth variations in July 2010 (a) and February 2011 (b). This plot shows the difference in atmospheric depth between these atmospheres and the CORSIKA July 1, 1997 South Pole atmosphere (Chapter 4).
also depends on the weather. Maximum altitudes reached during the austral summer are about 25 or 30 km, while during austral winter the balloon flights reach maximum heights of about 15 km. Radiosonde data can be found at [53].

For simulations using the real atmospheric profiles, atmospheric data is needed up to larger altitudes than the highest balloon measurements. Therefore, balloon data is supplemented with satellite data at heights above the maximum balloon altitude, up to 50 km high. Satellite data are obtained from the NASA Aqua research satellite [54], one of the six instruments on board is the AIRS (Atmospheric Infrared Sounder). Using infrared technology, AIRS is able to scan the temperature profile of the entire troposphere and stratosphere. Different wavelengths are used to scan different heights. Other variables measured are the humidity, water vapour, pressure and density profiles of certain components of the atmosphere.

In order to be able to simulate the entire atmosphere, data is extended using a fitting procedure up to heights above 100 km.

3.3 Influence of the atmosphere on EAS

If the atmosphere stayed constant throughout the year, the average longitudinal profile of a shower of a certain energy, primary and zenith angle would be the same each day of the year. As shown above, this is not the case. During the year, large atmospheric variations are observed at the South Pole. Pressure or thickness variations at the surface change the observation level at which we probe the longitudinal profile of the shower. The EAS will be detected in another stage of its development, at which it will contain a different amount of particles. Furthermore, also the atmospheric density profile changes. Density changes in one layer might affect the air shower differently compared to a change in density in another layer. Since the atmosphere is the detector volume in which the EAS develops, it is important to know the entire atmospheric profile change.

IceTop and IceCube reconstruct the primary particle type and its energy using its relation with the signal strength at the surface, dominated by the EM particles, and number of muons underground. If this relation changes through the year, this might lead different reconstructions in the different seasons. Moreover, if the signal dependency of the atmospheric variations is not known, these effects should be taken into account in the systematics, hence reducing the resolution of energy and composition measurements.

Low energy showers which are detected when the surface pressure is low, will be totally absorbed in high pressure atmospheres. The mean surface pressure is higher during austral summer, which raises the energy threshold for shower detection by IceTop. This results in a detection rate decrease.

Thus, the IceTop DOM count rate is anti-correlated with the surface pressure. This relation is given by

\[ \Delta \ln R = \beta \Delta P , \]

where \( \Delta \ln R \) is the natural logarithm of the IceTop rate change, \( \Delta P \) the pressure change and \( \beta \) the barometric coefficient [55, 56]. The number of air showers detected by IceTop varies by 17% with the surface pressure, resulting in a barometric coefficient of -77%/hPa. A barometric pressure correction can be applied, which corrects for the rate changes given
3.3. INFLUENCE OF THE ATMOSPHERE ON EAS

by Equation 3.17. As can be seen on Figure 3.7, this pressure correction does not explain the entire seasonal variation of the IceTop DOM count. In [55], (anti-)correlation with lower stratospheric (60-80 g/cm$^2$) changes was found. The reason for this correlation is not clear yet and will be further investigated in this thesis. Also the barometric pressure correction is currently further under study.

Next to this rate change, the signal of the showers triggered by IceTop will be affected by the atmospheric variations [57].

When the density decreases, the $\pi^\pm$ and $K^\pm$ interaction length, given by Equation 1.12, increases. The high energy muons detected by the underground detector are created close to the first interaction. A density decrease at the pressure levels close to the first interaction would lead to more high-energy muons detected by IceCube, since the ratio of the interaction length over the decay length changes in favour of the decay length. As explained in Section 3.2.1, counter-intuitively, density increases at (almost) every altitude during summer. However, at fixed pressure levels, the density is lower in summer than winter, due to the increase of temperature at every altitude during summer. Since the stage in the shower development is determined by the atmospheric depth, not by the altitude, more high-energy muons will be created in summer than in winter.

This is extensively investigated in data and described in [55]. A 10% seasonal modulation in the high energy muon event rate is observed (Figure 3.7), which is highly correlated with the effective temperature $T_{\text{eff}}$. $T_{\text{eff}}$ is the weighted average of the temperatures at all pressure levels in the atmosphere [58]. Weights to pressure levels are given according to their contribution in muon production. The pressure levels in the middle stratosphere (30-60 g/cm$^2$) obtain the highest weighting factors, since these pressure levels are close to the first interaction. It was found that the surface pressure difference does not affect the IceCube muon rate in first order. The reason for this can be seen in Figure 1.10. Since the number of muons is relatively constant close to the surface, their distribution will be only slightly affected if the mass overburden above the surface would increase or decrease.

Although the effect of atmospheric changes on the muon rate is well known, further investigation of the influence of atmosphere changes on the number of muons and their energy spectrum is needed. As explained earlier, this is important in order to obtain an accurate reconstruction of the mass and energy of the primary particle. As such, also the atmospheric influence on the number of muons is studied in this thesis.
Figure 3.7 – (a) The temperature variation at pressure levels between 20 and 10 hPa from May 2007 to April 2009. (b) The surface pressure together with the IceTop DOM count before and after barometric correction. (c) The effective temperature and the IceCube muon trigger rate [55].
Chapter 4

Simulation

In this thesis, the effect of the atmosphere on IceTop measurements and the number of high energy muons is studied using simulations. Studying the atmospheric effects through simulations has many benefits: the primary energy, particle type and zenith angle are known. This is favoured when the effect of atmosphere on the composition and energy spectrum is being studied. Furthermore, the atmospheric profile is known and can be chosen or adjusted, which creates the possibility to separate the effects of different atmosphere layers.

4.1 Simulation of extensive air showers

4.1.1 CORSIKA

The simulation of EAS in the atmosphere is performed using CORSIKA (COsmic Ray SImulations for KAascade) version 6.980 [20]. This FORTRAN code tracks high energy particles through the atmosphere while they undergo reactions with air nuclei or decay. The high energy hadronic interaction model used in the simulations is SYBILL 2.1 [59]. Low energy (< 80 GeV) hadronic interactions are treated using FLUKA [60, 61]. The electromagnetic part of the cascade is modelled using the EGS4 code [62].

High-energy particles are inserted on top of the atmosphere and create an EAS. The initial primary particle type, energy and zenith angle can be chosen. The higher the energy, the higher the number of particles which has to be tracked, hence increasing the computer time. Therefore, the highest primary energy used in this study is 50 PeV. The other primary energies used are 1, 5, 10 and 30 PeV. The zenith angle dependency is studied by simulating both vertical showers and showers with zenith angle $\theta = 20^\circ$, while the azimuth angle $\phi = 0^\circ$. This fixed azimuth angle is chosen in order to reduce the number of possible effects on measurements. Air showers induced by both proton and iron primaries are studied. The amount of showers generated for one particular atmosphere, energy, zenith angle and primary is (in most cases) equal to 100. Though, more simulations are performed for 1 and 5 PeV protons, since fluctuations in low energy proton initiated showers are large. The simulation time of these showers is rather short, hence it was feasible to add more statistics.

Hadronic particles and muons are tracked until their energy falls below 50 MeV. The $e^-$ and $e^+$ threshold is 10 MeV, while photons are tracked until their energy reaches the lower energy threshold of 2 MeV.
The selected options are specified in the CORSIKA steering file. The steering file used in this study is given in Appendix B.

The seeds determine the shower to shower fluctuations. Therefore, each shower in the array of showers simulated for each atmosphere, primary particle type, \( \theta \) and energy uses different seeds. Since effects aside from the atmosphere effect should be reduced, the same sequence of seeds is chosen for each sequence of 100 simulated showers. The seeds are determined as a function of their run number and of the first run number in the sequence:

\[
\begin{align*}
\text{SEED1} &= 45003 + (\text{RUNNR} - \text{STARTRUN}) \\
\text{SEED2} &= 45004 + (\text{RUNNR} - \text{STARTRUN}) \\
\text{SEED3} &= 45005 + (\text{RUNNR} - \text{STARTRUN})
\end{align*}
\]

where \( \text{STARTRUN} \) is the first run number in the sequence.

In one sequence, the first seed ranges from 45003 to 45103. The second and third seeds behave similar. However, CORSIKA does not use the third seed for this type of study. The additional simulated atmospheres for the 1 and 5 PeV protons use seeds starting from 46003, 46004 and 46005.

The atmospheric composition adopted by CORSIKA consist of 78.1 % \( \text{N}_2 \), 21.0 % \( \text{O}_2 \) and 0.9 % \( \text{Ar} \) nuclei. This is in agreement with the realistic values (Table 3.1).

CORSIKA models the density and thickness profile of the atmosphere in 5 layers [20]. The profile adopted in the lower four is exponential. The mass overburden \( X(h) \) at a certain height \( h \) is determined by:

\[
X(h) = a_i + b_i e^{-h/c_i} \quad i = 1, ..., 4.
\]

The fifth layer uses a linear decrease of thickness with height:

\[
X(h) = a_5 - b_5 \frac{h}{c_5}.
\]

The parameters \( a_i, b_i \) and \( c_i \) are given in [20] and are determined such that \( X(h) \) is continuous and can be differentiated continuously. From the above equations, density can be calculated using Equation 3.13:

\[
\rho(h) = -\frac{\text{d}X(h)}{\text{d}h}.
\]

This results in an exponential decrease of density in the lower four layers. The density in the fifth layer is constant. However, the fifth layer only starts at high altitudes and the density is low. Therefore, this constant density, which is a deviation of reality, does not influence the development of EAS. The layer boundaries in the CORSIKA atmospheres are fixed at 0, 4, 10, 40, 100 km and the altitude where the atmospheric depth vanishes. This highest boundary can be calculated by inserting \( X = 0 \text{ g/cm}^2 \) in Equation 4.5 and is, when using CORSIKA atmospheres, always equal to an altitude of 112.8 km.

CORSIKA includes 6 standard South Pole atmospheres, which can be chosen using the ATMOD keyword in the steering file (Appendix B). These atmospheres are listed in table 4.1. The CORSIKA MODATM 12 atmosphere is the standard atmosphere used in IceTop simulations (later referred to as CORSIKA July).
Table 4.1 – The 6 South Pole atmospheres included in CORSIKA [20]. MODATM is the argument which has to be set in the ATMOD keyword.

<table>
<thead>
<tr>
<th>MODATM</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>March 31, 1997 South Pole atmosphere (MSIS-90-E)</td>
</tr>
<tr>
<td>12</td>
<td>July 01, 1997 South Pole atmosphere (MSIS-90-E)</td>
</tr>
<tr>
<td>13</td>
<td>Oct. 01, 1997 South Pole atmosphere (MSIS-90-E)</td>
</tr>
<tr>
<td>14</td>
<td>Dec. 31, 1997 South Pole atmosphere (MSIS-90-E)</td>
</tr>
<tr>
<td>15</td>
<td>South Pole atmosphere for January after Lipari</td>
</tr>
<tr>
<td>16</td>
<td>South Pole atmosphere for August after Lipari</td>
</tr>
</tbody>
</table>

As can be seen in table 4.1, a South Pole atmosphere is available for every season. Performing simulations using all these atmospheres would give the possibility to study the seasonal atmospheric effect on IceTop data. The drawback of these atmospheres is that the atmosphere cannot be adjusted at will. Moreover, the atmosphere varies every day and significant differences with realistic atmospheres are observed (Appendix A).

4.1.2 External atmospheres

The Bernlöhrr package (version 1.44) creates the possibility of using external tabulated atmospheres [63]. The atmospheres are described by density, thickness and index of refraction profiles from the surface up to the highest altitudes. The index of refraction is important for Cherenkov telescopes, but is not used in this study. Hence, each external atmosphere is characterized by density and thickness values at 50 well chosen heights. These heights should be chosen in such a way that every detail in the atmospheric profile is visible. The different atmospheres used in this study are listed in Table 4.2.

The Bernlöhrr package fits the 4 piecewise exponential layers and one linear layer used in CORSIKA to the 50 tabulated atmospheric depths values. The real (tabulated) and fitted atmospheric depths at 2850 m are given in Table 4.2 for comparison. 2850 m is the altitude at which the lowest data point of the real atmospheres is available. The table also lists the surface atmospheric depth obtained from the fit. The fitting procedure describes the realistic thickness values in an acceptable way, especially in the lowest ~ 25 km, which are the most important altitudes for IceTop (Figure 4.1(a)). However, one important remark should be made: since the density values depend on the standard fit performed to the thickness values, fitted densities will deviate significantly from the realistic values (Figure 4.1(b)). These thickness and density fits are used in the electromagnetic part of the air showers, while the muonic and hadronic part uses an interpolation of the tabulated values. Therefore, the electromagnetic part of the air shower might be influenced by this, which can cause a problem in the atmosphere studies.

The external atmosphere can be specified through the ATMOSPHERE keyword in the steering file (Appendix B).
Table 4.2 – The external atmospheres used in this study. The second column lists the corresponding real atmospheric depth values at 2850 m a.s.l. Also the fitted thickness values at this height and at the surface (2835 m a.s.l.) are given.

<table>
<thead>
<tr>
<th>Description</th>
<th>$X_{2850\text{m}}$ (g/cm$^2$) real</th>
<th>$X_{2850\text{m}}$ (g/cm$^2$) fit</th>
<th>$X_{\text{surface}}$ (g/cm$^2$) fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average July 2010</td>
<td>678.4</td>
<td>678.1</td>
<td>679.6</td>
</tr>
<tr>
<td>Average February 2011</td>
<td>698.5</td>
<td>698.9</td>
<td>700.3</td>
</tr>
<tr>
<td>July 17, 2010</td>
<td>660.2</td>
<td>660.0</td>
<td>661.4</td>
</tr>
<tr>
<td>made-up</td>
<td>/</td>
<td>701.0</td>
<td>702.5</td>
</tr>
</tbody>
</table>

Figure 4.1 – The relative thickness (a) and density (b) difference between the real average July 2010 profile and the fit to the tabulated values. Disagreements of the order of 30% exist. At the layer boundaries, sharp edges can be seen.
CORSIKA July vs real July 2010

The difference in density and thickness between the average July 2010 atmosphere and the South Pole CORSIKA July 01, 1997 (MODATM 12) atmosphere is shown in Figure 4.2. Also the difference between the CORSIKA July and the fit to the average July 2010 atmosphere is plotted. These plots show that the CORSIKA July atmosphere deviates significant from the real July atmosphere. This is very important for further studies, since data - simulation relations should take these deviations into account!

Furthermore, Figure 4.2(b) shows that the density difference is not a continuous function. This is caused by the sudden change of density at the layer boundaries. As discussed before, the fit difference (red line) deviates from the realistic difference (blue line). The difference between the CORSIKA July atmosphere and the real July atmosphere seems to decrease at higher altitudes. However, this is mainly due to the exponential decrease of density and thickness with altitude. The variations at higher altitudes are not visible due to the low absolute values, but can be observed on plots of the relative difference.

The behaviour of the density close the surface seen in the blue line is due to the inversion layer. This inversion layer is present in the real July atmosphere (Figure 3.5(a)), not in the CORSIKA July atmosphere. The low surface temperature in the real July atmosphere causes the density to increase, therefore obtaining large negative values for the difference between CORSIKA July and the real July atmosphere. However, this inversion layer is not well fitted (red line). As explained earlier, this will mainly affect the EM part of the air showers. Therefore, we should pay attention on this deviation in the further analysis.

The relation between the thickness and density plot is given by Equation 4.6. When the density difference is negative, the thickness difference increases. The opposite is true for a positive density. Since we want to study the real atmospheric behaviour, comparisons will be made with the realistic July atmosphere from now on.

Seasonal difference: July 2010 vs February 2011

Figure 4.3 shows the difference between the July 2010 and the February 2011 atmosphere. Since the seasonal variations cause large temperature differences in the stratosphere, a significant density difference is observed at these altitudes. These densities may even differ by more than 100%. The density at a fixed altitude is larger during austral summer. This seems in violation with the ideal gas law, since also the temperature is larger in summer than winter. However, as explained in Chapter 3, this is due to the pressure increase during summer. Figure 4.3(b) also shows that the inversion layer is larger during the winter months compared to the summer months. This has been discussed in Chapter 3 and can also be seen on Figure 3.2.

Daily: Average July 2010 vs July 17, 2010

The (extreme) daily variations are shown on Figure 4.4. This figure shows the thickness and density profile difference between the average July 2010 atmosphere and the atmosphere of one specific day of that month (the 17th). This day has been chosen because of the large difference
in surface pressure with the average July (July 17 is the upper pink line on Figure 3.6). Since this particular day is known to have extreme weather conditions (strong winds) [64], the inversion layer is less prominent. Daily atmosphere variations only influence the atmosphere up to altitudes of about 20 km.

**Stratosphere effect: Made-up vs July 2010**

Figure 4.5 shows the difference between the average July 2010 atmosphere and the only made-up atmosphere. In this final atmosphere, the July 2010 and February 2011 atmospheres are merged. Up to 8 km, the density is approximately the same as the July atmosphere. Above this altitude, the made-up atmosphere is similar to the February atmosphere. This atmosphere serves to separate the effects induced at the (lower and middle) stratosphere from the effects at lower altitudes.

As described above, the modelling of the atmospheric density profile is not perfect. However, to perform quantitative and qualitative analyses on IceTop measurements, which are influenced by the EM part, one can compare the fits to the different atmospheres.

![Figure 4.2](image-url)  
**Figure 4.2** – The profile difference in atmospheric depth (a) and density (b) between the CORSIKA July atmosphere (MODATM 12) and the average July 2010. The blue line shows the difference between the CORSIKA atmosphere and the real average July 2010 values. The difference between CORSIKA July and the fitted average July 2010 atmosphere is shown in red. Also the inversion layer is shown, which is present in the real July 2010 atmosphere but not in the CORSIKA July atmosphere.
CHAPTER 4. SIMULATION

Figure 4.3 – Atmospheric depth (a) and density (b) profile difference between the average July 2010 and the average February 2011 atmosphere. The blue line shows the difference between the real tabulated values, while the red line shows the difference between the fits to the two atmospheres.

Figure 4.4 – Atmospheric depth (a) and density (b) profile difference between the average July 2010 atmosphere and the atmosphere on July 17, 2010.
4.2 IceTop simulation

Each simulated CORSIKA shower is 100 times resampled with the shower core of each sample at a random position in a circle of 400 m radius around the center of the IceTop array. This way, the array will see different footprints of the same shower, in order to have a realistic detector response. The 400 m radius is chosen in order to produce no showers with the core outside the IceTop array, which could possibly lead to bad reconstructions of the shower core position, direction and LDF. The simulations are done using the IT-73 geometry.

The IceTop tank height varies on a tank-by-tank basis, with a maximum of 6 m. The air between the tank and the detector level specified by CORSIKA (2835 m) is simulated using the GEANT-4 simulation \cite{65}. This GEANT-4 code is also used for the full IceTop tank simulation. Particles are tracked through the tank and the number of emitted Cherenkov photons is calculated. Furthermore, the GEANT-4 simulation accounts for the snow, which can be found on top of and at the sides of each tank and varies per tank. A full simulation of the DOM and PMT response is performed. The produced signal consists of waveforms produced in each hit DOM, which will be used in the IceTop reconstruction.

4.3 IceTop standard processing

Air showers trigger the IceTop array if the IceTop SMT (Simple Majority Trigger) trigger condition is fulfilled. This condition requires 6 HLC (Hard Local Coincidence) hits in IceTop DOMs within a time window of 6 $\mu$s. When this trigger condition is passed, all hit DOMs are read out and the waveforms are sent to the IceCube Lab, which is the counting house at the center of the IceTop array. Events are only kept if also the filter condition is passed. The filter used in this study is the basic IceTopSTA3 filter, which requires the IceTop SMT trigger and at least 3 stations with an HLC hit \cite{56}. The bulk (> 90 %) of the lowest energy (1 PeV) air showers simulated in this study pass both the trigger and filter condition.
The shower reconstructions are described in section 2.7, and are only done for showers which have hit at least 5 IceTop stations.

It is important to mention that in this study snow correction is applied in the lateral distribution fit. The amount of snow varies on a tank-by-tank basis and will mainly reduce the EM component of the air showers, since EM particles quickly lose energy when crossing material. The distribution of the X positions of the reconstructed shower cores without snow correction is shown in Figure 4.6. This figure illustrates the simulated influence of snow on the number of detected showers. The part of the detector deployed in the first years of detector installation is already covered by a larger snow depth compared to the new part of the detector. This reduces the signal significantly in the old part, resulting in a decrease in detection rate. Figure 4.7 shows the influence of snow on the signal at 125 m of the shower core. In the old part of the detector, the signal is shifted to lower values since more snow is present. The difference in number of triggered showers in the old part and new part is due to the surface area covered by both parts. The snow height varies (little) during the year, which possibly contributes to the seasonal variation in detection rate. The snow correction is currently under study [43].

The attenuation due to snow is modelled using GEANT-4. Hence, the snow correction factor is known in simulation. To disentangle atmospheric effect from the snow effect, a snow correction is applied here. However, the snow effect behaves differently compared to the atmosphere effect: snow is different between the old and new part of the detector, while atmosphere is the same for the entire detector. This allows for a separation of the snow and atmosphere effect in data.

Number of showers

Appendix C lists the number of showers used in this study per atmosphere, for every particle type, energy and zenith angle.

These tables show the number of showers which were generated, including the 100 resamples. Furthermore, the number of showers which passed the IceTopSTA3 filter, hence triggered at least 3 stations (with an HLC hit), are given. The showers which passed this filter are included in the histograms of the first interaction height, number of hit stations, the secondary particle energy spectrum and the number of high-energy muons contained in the showers (see following chapter).

The tables also list the showers for which the reconstruction of the LDF is performed (correctly). As explained above, this requires 5 hit stations. Furthermore, also bad reconstructions are excluded, which is done by performing cuts on $S_{125}$ and $\beta$: $S_{125} > 0; 1.55 < \beta < 4.95$. Hence, these reconstructed showers contribute to the $S_{125}$ and $\beta$ histograms described in Chapter 5.
Figure 4.6 – The distribution of the reconstructed X positions of the shower cores from vertical 1 PeV proton simulated showers in the July 2010 atmosphere. The number of showers included in this plot is 9988: 100 CORSIKA showers 100 times oversampled reduced by the ones which did not trigger the detector. The green stroke indicates the difference between the “old half” of the detector and the “new half”. As a rough approximation, one can assume that the tanks in the old part of the detector where placed in the first years of detector deployment (2005-2007). The new half of the detector contains the tanks deployed after 2007. However, the transition at an X position of 200 m is only a rough approximation. Instead, the transition occurs smoothly [56].

Figure 4.7 – The S125 distribution of 10000 simulated (100 CORSIKA showers 100 times resampled) vertical 10 PeV proton showers in the July 2010 atmosphere. The number of entries is equal to the number of triggered showers. The histogram is shown, together with a double Gaussian fit to the data. The green stroke indicates the difference between the "new half" and "old half".
Chapter 5

Atmospheric effect on observables

As shown in Chapter 3, large atmospheric variations exist at the South Pole throughout the year. Using simulations of the propagation of EAS through the atmospheres described in Chapter 4, the effect of these atmospheric changes on the air shower properties is studied. Furthermore, the influence on IceTop measurements and the number of high-energy muons at the South Pole surface is considered. The main three atmospheres which will be used are the July 2010, February 2011 and July 17, 2010 atmosphere, because their atmospheric density and thickness profile is known to be very different. The July 2010 atmosphere will be used as the reference atmosphere. The made-up atmosphere is mainly used in the next chapter, when the separate effects of the stratospheric and tropospheric changes will be considered.

5.1 Shower Development

Since this study is performed using simulations, it is possible to investigate systematically the influence of the atmosphere on the development of the air shower. This will help to understand and try to explain the observations made by IceTop and IceCube. The energies considered in this chapter are mainly 1 and 30 PeV. As can be seen in Figure 2.10, both proton and iron showers with these energies have reached their $X_{\text{max}}$ before detection. This means that the number of particles has already started to decrease, which is important for the explanation of the observed changes.

5.1.1 First interaction height

The height of the first interaction of the impinging nucleus is determined by the interaction length, which depends on the air density and nucleus-air cross section. As explained in Section 1.3, the measurement of these cross sections is one of the major goals of present day accelerators.

The estimated interaction length for a 1 PeV proton in air is about 55 g/cm$^2$, while the 1 PeV iron interaction length is estimated as approximately 11 g/cm$^2$. Using Equation 1.15 to calculate the proton-air cross section and Equation 1.11 to calculate the corresponding interaction length, the interaction length for a 30 PeV proton is estimated to be approximately 45 g/cm$^2$. In Section 1.3, we assumed that the iron-air cross section is 5 times larger than the proton-air cross section, based on Figure 1.7. Hence, the interaction length for a 30 PeV
5.1. SHOWER DEVELOPMENT

![Diagram](attachment:figure5.1.png)

**Figure 5.1** – The distribution of first interaction heights of vertical 1 PeV proton and iron primaries in different atmospheres. The vertical dotted line indicates the height $h_{int}$ at which $1/e$ of the primary particles have survived. The values are given in Table 5.1. Figures (a) and (b) compare the July 2010 and February 2011 atmosphere for respectively proton and iron. The lower two figures compare the average July 2010 atmosphere with the atmosphere on July 17, 2010, also for proton (c) and iron (d). For each atmosphere, 200 proton and 100 iron induced showers have been used. Also the resamples are used to make this figure. However, since the 100 resamples of one shower have the same first interaction height, a scaling of 1/100 has been done. Only the resampled showers which triggered the IceTop detector are included. This causes the integral being slightly lower than 200 for proton or 100 for iron.

Iron primary in air is about 9 g/cm$^2$.

Since the atmospheric density and depth profile changes throughout the year or even on a day-by-day basis, the first interaction of the primary particle might occur at a different height. This is shown in Figure 5.1 for 1 PeV primary particles and in Figure 5.2 for 30 PeV primaries. The variation of the height at which 36.8% of the initial particles have not yet interacted is shown by the vertical dotted lines and listed in Table 5.1.

For both proton and iron primaries, the interaction height is the same for the average July 2010 and the July 17, 2010 atmosphere. This can be explained by Figure 4.4: the difference between these two atmosphere only occurs in the lower layers, below 15-20 km.
Figure 5.2 – The distribution of first interaction heights of vertical 30 PeV proton and iron primaries in different atmospheres. The height \( h_{\text{int}} \) at which \( 1/e \) of the primary particles have survived is indicated by the vertical dotted line and given in Table 5.1. For each atmosphere, 100 proton and 100 iron induced showers have been used. However, also the resamples are taken into account. The reason for the integral being larger than 100 for certain distributions is given in Section 5.2.1.

On the other hand, the July and February atmospheres are particularly different at the higher altitudes, between 15 and 40 km (Figure 4.3). In that region, the density is higher in February. This imposes that during the austral summer, the first interaction will be earlier than in winter.

Due to higher Fe-air than p-air cross section, the iron induced showers interact at higher altitudes, where the density is lower. Hence, a density change causes a certain thickness value to shift over a larger (vertical) distance compared to lower altitudes, where the density is higher. This causes the larger shift in the first interaction length in the iron induced showers (iron showers) than in the proton induced showers (proton showers).

A comparison between the first interaction heights of the 1 and 30 PeV showers confirms that the cross section change with energy is only small, as indicated by Equation 1.15. As shown in Table 5.1, the obtained interaction lengths are very similar between the different...
5.1. SHOWER DEVELOPMENT

Table 5.1 – The heights $h_{\text{int}}$ and corresponding depths $\lambda_{\text{int}}$ at which $1/e$ of the primary particles has interacted, for 1 PeV and 30 PeV proton and iron primaries in different atmospheres. The values are computed using the histograms in Figures 5.1 and 5.2 with 600 bins instead of 30. Furthermore, the estimated interaction length $\lambda_{\text{int}}^{\text{est}}$ is given.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Primary</th>
<th>Energy (PeV)</th>
<th>$h_{\text{int}}$ (km)</th>
<th>$\lambda_{\text{int}}$ (g/cm$^2$)</th>
<th>$\lambda_{\text{int}}^{\text{est}}$ (g/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2010</td>
<td>p</td>
<td>1</td>
<td>17.45</td>
<td>57.18</td>
<td>55</td>
</tr>
<tr>
<td>February 2011</td>
<td>p</td>
<td>1</td>
<td>19.65</td>
<td>57.26</td>
<td>55</td>
</tr>
<tr>
<td>July 17, 2010</td>
<td>p</td>
<td>1</td>
<td>17.35</td>
<td>57.31</td>
<td>55</td>
</tr>
<tr>
<td>July 2010</td>
<td>Fe</td>
<td>1</td>
<td>26.65</td>
<td>10.49</td>
<td>11</td>
</tr>
<tr>
<td>February 2011</td>
<td>Fe</td>
<td>1</td>
<td>31.15</td>
<td>10.63</td>
<td>11</td>
</tr>
<tr>
<td>July 17, 2010</td>
<td>Fe</td>
<td>1</td>
<td>26.55</td>
<td>10.62</td>
<td>11</td>
</tr>
<tr>
<td>July 2010</td>
<td>p</td>
<td>30</td>
<td>18.85</td>
<td>44.08</td>
<td>45</td>
</tr>
<tr>
<td>February 2011</td>
<td>p</td>
<td>30</td>
<td>21.45</td>
<td>43.87</td>
<td>45</td>
</tr>
<tr>
<td>July 17, 2010</td>
<td>p</td>
<td>30</td>
<td>18.75</td>
<td>44.25</td>
<td>45</td>
</tr>
<tr>
<td>July 2010</td>
<td>Fe</td>
<td>30</td>
<td>27.05</td>
<td>9.79</td>
<td>9</td>
</tr>
<tr>
<td>February 2011</td>
<td>Fe</td>
<td>30</td>
<td>31.55</td>
<td>10.05</td>
<td>9</td>
</tr>
<tr>
<td>July 17, 2010</td>
<td>Fe</td>
<td>30</td>
<td>26.95</td>
<td>9.92</td>
<td>9</td>
</tr>
</tbody>
</table>

Atmospheres. At first sight, this is surprising, since the first interactions are statistically determined. However, the sequence of seeds used for the simulations in every atmosphere is the same. Since this seed determines the atmospheric depth at which the first interaction occurs, this probably explains the very similar values. A distribution of the first interactions as a function of the atmospheric depth should look the same for a certain energy, particle type and zenith angle in every atmosphere, and could confirm this. Furthermore, the obtained interaction lengths are close to the estimated values. This is expected, since the hadronic interaction model used in the simulations are based on cross-section models like Equation 1.15.

The values for the interaction heights $h_{\text{int}}$ are obtained by integrating over the distribution of interaction heights starting from ground level. The altitude at which the integral is equal to 36.8% of the total number of showers in the distribution, is taken as $h_{\text{int}}$. $\lambda_{\text{int}}$ is the atmospheric depth at this height $h_{\text{int}}$.

It can be concluded that a seasonal variation of the first interaction height is observed. This might influence the air shower properties at the South Pole surface. However, since the shower-to-shower variations in the further development of the shower are large, it is assumed that the influence of a change in first interaction height is small.

5.1.2 Number of particles at ground level

The number of particles at ground level will determine the signal detected by IceTop. Therefore, if atmospheric variations affect this number, this will influence the IceTop measurements. The daily (average July 2010 and July 17, 2010) and seasonal (July 2010 and February 2011) variation in particle number at ground level for vertical 1 PeV proton and iron showers is
CHAPTER 5. ATMOSPHERIC EFFECT ON OBSERVABLES

shown in Figure 5.3.

At the energies considered here (1 PeV - 50 PeV), the stage of the air shower development at which the shower is detected is already passed $X_{\text{max}}$ for both proton and iron showers. Furthermore, $X_{\text{max}}$ is smaller in iron showers compared to proton showers at all energies (Figure 1.11). Hence, the number of particles is larger in proton showers compared to iron showers of the same energy and zenith angle, as can be observed in Figure 5.3.

The shower-to-shower fluctuations in the number of particles at ground level originating from proton showers is larger compared to iron showers. This is a consequence of the superposition principle and is also shown by Figure 1.11.

The difference in particle number between the various atmospheres is mainly determined by the change in surface thickness $X_{\text{surface}}$ (Table 4.2). $X_{\text{surface}}$ is closer to $X_{\text{max}}$ in the July 2010 ($X_{\text{surface}}=679.6 \text{ g/cm}^2$) compared to the February 2011 atmosphere ($X_{\text{surface}}=700.3 \text{ g/cm}^2$), which results in more particles at surface level during the austral winter (July) than summer (February). This is clearly visible for 1 PeV iron showers. Due to the large shower-to-shower fluctuations, the change in particle number is less visible in 1 PeV proton showers.

The surface thickness at July 17, 2010 is 661.4 g/cm$^2$. Therefore, $X_{\text{max}}$ is closer to the surface than in the average July 2010 atmosphere. This results in more particles at the surface on this particular day than on average during July. Again, this effect is less visible for proton showers compared to iron showers, which is due to the large spread in proton showers.

As can be seen by comparing Figures 5.3(b) and 5.3(d), the difference in particle number is larger between the seasons than between the daily atmosphere variations. However, the change in surface pressure is approximately the same in the two cases, respectively 20.7 g/cm$^2$ and 18.2 g/cm$^2$. This probably indicates that not only the change $\Delta X_{\text{surface}}$ is important and some other effect should be taken into account. One plausible explanation for this can come from the seasonal difference in the number of high-energy muons. As will be explained in Section 5.3, the number of high-energy muons is larger in austral summer than winter. This means that, during summer, less energy will be contained in the EM part of the shower, which will decrease the number of particles at the surface even further. No daily variation of the number of high-energy muons in air showers is present (Section 5.3). Hence, the daily variation of the number of particles will be smaller than the seasonal variation.

Figure 5.4 shows the variation in number of particles for 30 PeV proton and iron showers. As expected, and explained in Section 1.3, the number of particles is larger in 30 PeV than 1 PeV showers. Similar conclusions as in the 1 PeV case can be made for the differences between various atmospheres.

As can be seen on Figures 5.4(a) and 5.4(c), a few of the 30 PeV proton showers contain significantly less particles than the mean number of particles in the shower (around 55 million instead of 95 million). These are the showers which interacted at low altitudes (Figure 5.2(a) and 5.2(c)). They are detected at surface much before they would reach $X_{\text{max}}$. Therefore, they contain significantly less particles at the surface than the mean 30 PeV proton shower. It will be shown below that this is also visible in the distribution of the signals at 125 m (S125).
Figure 5.3 – The distribution of the total number of particles in a shower detected at the Antarctic plateau, for vertical 1 PeV proton and iron showers in different atmospheres. These total particle numbers are obtained from the CORSIKA simulations (before the detector simulation), hence, for each atmosphere, 200 proton and 100 iron showers are included.

The number of particles detected by the IceTop array is only a subset of the above described particles at ground level. While all particles at surface level are included in the above plots, IceTop will only detect the ones which hit the tanks.
CHAPTER 5. ATMOSPHERIC EFFECT ON OBSERVABLES

5.2 Effect on IceTop observables

5.2.1 Number of hit stations

Intuitively, the number of hit stations reflects the number of particles at surface level: the more particles contained in the shower, the more stations will be hit. Figure 5.5 shows the distribution of the number of hit stations for vertical 1 and 30 PeV proton and iron showers in both the July 2010 and February 2011 atmosphere. As shown in Section 5.1.2, the number of particles at ground level is higher during winter than summer. Hence, one would also expect the amount of hit stations to increase in winter. Indeed, this is the behaviour that can be seen in Figure 5.5(c), which shows the comparison for a 1 PeV iron shower.

However, in Figures 5.5(a), 5.5(b) and 5.5(d), the number of hit stations changes in the direction opposite to the direction seen in Figure 5.5(c), while the number of particles is larger during winter compared to summer. This unexpected behaviour can not be clarified by only taking the number of particles into account.
5.2. EFFECT ON ICETOP OBSERVABLES

Table 5.2 – The mean number of hit stations for vertical proton and iron showers with a primary energy of 1, 5, 10 or 30 PeV. The mean number of hit stations is given for the average July 2010 ($<N_{hit}^{July}>$) and February 2011 ($<N_{hit}^{February}>$) atmosphere, the atmosphere on July 17, 2010 ($<N_{hit}^{July17}>$) and the made-up atmosphere ($<N_{hit}^{made-up}>$) (Section 4.1.2). No simulation of the development of 30 PeV iron showers in the made-up atmosphere has been done. The number of showers used in this table is equal to the number of triggered showers, given in Appendix C. However, a few extra entries (with number of hit stations = 2) in the histogram compared to the number of triggered showers are present, and are due to the showers which contained a possible "bad" station.

<table>
<thead>
<tr>
<th>$E_0$ (PeV)</th>
<th>primary</th>
<th>$&lt;N_{hit}^{July}&gt;$</th>
<th>$&lt;N_{hit}^{February}&gt;$</th>
<th>$&lt;N_{hit}^{July17}&gt;$</th>
<th>$&lt;N_{hit}^{made-up}&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fe</td>
<td>6.85</td>
<td>6.57</td>
<td>6.98</td>
<td>6.45</td>
</tr>
<tr>
<td>5</td>
<td>Fe</td>
<td>18.96</td>
<td>18.77</td>
<td>19.17</td>
<td>18.57</td>
</tr>
<tr>
<td>10</td>
<td>Fe</td>
<td>26.51</td>
<td>26.50</td>
<td>26.51</td>
<td>26.26</td>
</tr>
<tr>
<td>30</td>
<td>Fe</td>
<td>40.48</td>
<td>40.84</td>
<td>40.53</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>p</td>
<td>7.36</td>
<td>7.44</td>
<td>7.40</td>
<td>7.33</td>
</tr>
<tr>
<td>5</td>
<td>p</td>
<td>17.99</td>
<td>18.26</td>
<td>17.92</td>
<td>18.05</td>
</tr>
<tr>
<td>10</td>
<td>p</td>
<td>24.56</td>
<td>24.97</td>
<td>24.42</td>
<td>24.65</td>
</tr>
<tr>
<td>30</td>
<td>p</td>
<td>36.48</td>
<td>37.46</td>
<td>36.62</td>
<td>37.36</td>
</tr>
</tbody>
</table>

Table 5.2 shows the evolution of the mean number of hit stations with energy, for vertical proton and iron showers after propagation through the various atmospheres. As explained above, the average number of hit stations for a 1 PeV iron shower is larger after propagation through the July atmosphere than through the February atmosphere. Table 5.2 shows that this difference decreases with increasing primary energy, and the effect even reverses. For a 1 PeV proton shower, the mean number of hit stations is already larger in the average February 2011 atmosphere than in the average July 2010 atmosphere and this difference increases further at higher energies.

This shows that the mean number of stations does not only depend on the surface pressure change. The difference in density close to the surface causes a possible effect. Since the whole inversion layer reaches lower temperatures during austral winter compared to summer (Figure 3.2), density will be highest in winter (Figure 4.3(b)). This will result in a smaller Molière radius (Equation 1.26) and thus a smaller spread of the particles with enough energy to trigger a station during austral winter compared to summer. The abundance of the particles (which have enough energy to trigger) at larger radii is higher during summer than in winter. Therefore, less stations will be hit during the winter. The shower lateral spread depends on the primary energy, which might explain the evolution with energy. Besides, this lateral spread also depends on the primary particle type. It should also be considered that the effect of the surface pressure might be different for different energies and primaries.

The surface pressure is lower in the July 17, 2010 atmosphere than in the average July 2010 atmosphere. Therefore, on average, more stations are triggered after the propagation of a 1 PeV iron shower through the atmosphere on July 17. The density close to the surface is larger in the average July atmosphere, as is shown by the fit on Figure 4.4(b). It is assumed
Figure 5.5 – The distribution of the number of hit stations for vertical 1 and 30 PeV proton and iron showers in both the July 2010 and February 2011 atmospheres. 20000 showers (200 showers 100 times resampled) are generated for the 1 PeV proton distribution, while each of the other samples contain 10000 showers. Only the showers which triggered the detector are included (Appendix C). Although the IceTopSTA3 filter has been used, which requires 3 stations to be hit, a small fraction of showers resulted in only 2 hit stations. This is probably due to a possible “bad” station, which can be excluded. The 30 PeV showers contain a few showers where the shower reconstruction disconnected one hit station from the other stations which where hit. Therefore, the shower is split, which causes the few extra entries with only one hit station. These showers will be rejected for further IceTop shower reconstruction because the requirement of 5 hit stations is not fulfilled. These extra showers also cause the integral to be larger than the amount of simulated showers.
that the effect of the lateral spread is less, due to the smaller difference in density close to the surface than between the July 2010 and February 2011 atmosphere. The combination of the two effects results in small differences in mean number of stations between the two atmospheres for all energies and both proton and iron (Table 5.2). (This is also the reason why no comparison plots of these differences are shown here.)

Also the mean number of stations in the made-up atmosphere is shown in Table 5.2. This atmosphere has been made in order to separate the stratospheric effect from the effect of the density close to the surface. The density in the lowest 8 km is equal to the density of the average July atmosphere. This means that the effect of the lateral spread is not present in the comparison of the number of hit stations between the average July and made-up atmosphere. The density at higher altitudes agrees with the February atmosphere (Figure 4.5), which results in a surface thickness of 702.5 g/cm$^2$. The mean number of hit stations is, at every energy and for both primaries, smaller than this mean in the February atmosphere, which confirms the influence of the density close to the surface. $X_{\text{surface}}$ is further from $X_{\text{max}}$ in the made-up atmosphere than in the average July 2010 atmosphere, for all energies and primaries considered here. Hence, at all energies, the number of particles at the surface is higher in the July 2010 atmosphere. This means that the mean number of hit stations should always be higher in the July atmosphere. However, still an evolution with energy can be seen and the effect reverses for proton showers with energies of 5 PeV and higher. This indicates that, aside from the effects of the surface pressure and the density close to the surface, also the density in the stratosphere should be taken into account. However, further study is needed.

With the amount of simulations performed in this work, not enough statistics was obtained to investigate the lateral distribution. A detailed study of the number of particles and their lateral distribution at various pressure levels could possibly help to find out where and why the differences between the various atmospheres arise.

### 5.2.2 Energy spectrum of secondary particles

From now on, only particles which pass through a circle on the surface of 25 m around one of the tanks are considered. These particles potentially create a signal in the tank.

As shown above, the atmospheric variations cause a change in the number of particles at the surface. Changes in the atmosphere might possibly also alter the energy distribution of the particles at ground level. All particle species present in the shower contribute to this total energy spectrum of the secondary particles at the surface. Moreover, a change in energy spectrum of the secondaries could even lead to a different signal measured by the IceTop detector.

Figure 5.6 shows the mean energy spectrum at ground level of 20000 vertical 1 PeV proton showers. A comparison of this spectrum after propagation through either the July 2010 or February 2011 atmosphere has been made. The upper plot shows the mean number of particles (averaged over all triggered showers) at each energy bin. The full black lines show the total particle number per energy bin after propagation through the winter (July) atmosphere, while the dotted black lines show this to-
tual particle number after a shower development in the summer (February) atmosphere. Also
the energy spectra of the separate particle species are shown.

For each particle type, a lower energy cut-off is present. This is due to the chosen energy
cut-offs for the various particle species in the CORSIKA steering file (ECUTS, Appendix B).
It can be seen that photons are the most abundant particles. This is explained in Section 1.3
and shown by Figure 1.8. These photons dominate the low energy signal. Though, at energies
of approximately 1 GeV and above, electrons and positrons contribute as much to the signal
as the photons. At about 10 GeV, the number of muons becomes of the same order as the
number of photons and $e^{\pm}$ particles. The produced hadrons become important at energies of
100-1000 GeV and even start to dominate.

The lower plot shows the February 2011 over July 2010 ratio of the total number of par-
ticles in each energy bin, for an average 1 PeV proton shower. As explained earlier, the total
number of particles at the surface is larger in winter. This figure shows that this is true for
all secondary particle energies. However, a certain energy dependency is visible. The energy
dependence of this ratio is determined by the most abundant particles at the different ener-
gies. For all particle species, a small energy dependence of the ratio seems to be present.

Figure 5.7 depicts the secondary particle energy spectrum of an average 1 PeV iron shower,
again after propagation through either the July 2010 or February 2011 atmosphere. As ex-
plained before, the total number of particles (integrated over all energies) is smaller in iron
showers than proton showers. Furthermore, the muon component is more present and is the
dominant secondary particle type with energies above a few GeV. This is both due to the
larger number of muons and lower number of EM particles at the surface for iron compared
to proton showers (Section 1.3). This dominance in muon number induces a bump in the
total secondary particle spectrum of a 1 PeV iron shower.

At low secondary particle energies, the difference in number of particles at the surface between
the two atmospheres is larger for iron than proton showers, as expected (Section 5.1.2). Since
the muon contribution in this spectrum for 1 PeV iron showers becomes large at energies
larger than a few GeV, the increase of the ratio (up to above 1) is caused by the increase of
the ratio in muon number with energy between the two atmospheres.

The ratio of the number of muons of the summer over the winter atmosphere seems to increase
slightly with secondary particle energy: at the lowest muon energies observed, the ratio is
smaller than 1, while it becomes larger than 1 at higher muon energies. The energies are
related to the height at which the particles were formed: on average, higher energy particles
are formed closer to the first interaction (Section 1.3). The density at these pressure levels
might indicate why this spectrum is obtained. As explained in Section 3.3, the density in
summer is lower at fixed pressure levels in the stratosphere. Hence, more high-energy muons
are formed in summer than winter. This causes the ratio of these muon energies from Febru-
ary over July to be above 1. However, the evolution of the ratio as a function of energy is
not yet well understood for most secondary particle types and needs more investigation.
Figure 5.6 – The mean secondary particle energy spectrum of 20000 (200 simulated showers, 100 times resampled) vertical 1 PeV proton showers. Plotted both after propagation through either the average July 2010 (full lines) or average February 2011 atmosphere (dotted lines). The different colours show the different particle species. Only the errors on the total number of particles are plotted. The bottom plot shows the ratio of the all particle spectrum of the February 2011 over July 2010 atmosphere.

5.2.3 Shower size: S125

All the above described effects contribute to the variation of the detected signal at 125 m of the shower core (S125), due to the atmospheric changes. At this moment, S125 is the main IceTop variable to estimate the energy of the primary particle (Section 2.7.1) [56]. Therefore, seasonal and daily changes in S125 would change the energy spectrum in the winter compared to the summer or even from day to day [57]. Furthermore, the change in S125 might depend on the primary energy, particle type and zenith angle.

Figure 5.8 shows the obtained S125 distribution for 1 and 30 PeV proton and iron showers,
after propagation through either the austral winter or summer atmosphere. Also a Gaussian function is fitted to the distribution. The fit describes the data points well (good $\chi^2$ values) and will be used in the next chapter.

Since S125 is designed as an energy estimator, the difference in S125 between 1 and 30 PeV showers is large, while the difference between different primaries is small. This is the expected (and desired) behaviour.

A first important result is that the observed S125 difference between the various atmospheres is about an order of 10 smaller than the influence of snow on S125 (Figure 4.7).

The difference in S125 between summer and winter is larger for iron than proton showers. This is expected, since also the number of particles shows a larger difference for iron showers.

Figure 5.7 – The mean particle energy spectrum of 10000 (100 simulated, 100 times resampled) vertical 1 PeV iron showers.
5.2. EFFECT ON ICETOP OBSERVABLES

The mean S125 for 1 PeV proton and iron showers and 30 PeV iron showers is larger in winter than in summer. This can be explained by the larger number of particles at ground level in winter. However, the mean S125 for 30 PeV proton showers is higher during summer. Hence, the same conclusion can be made as when the number of hit stations was studied: also the atmospheric density at various heights should be taken into account, which influences the lateral spread of the particles. However, from these plots, it can not be determined which heights should be considered. This will be more extensively discussed in the Chapter 6.

The showers induced by 1 PeV primaries do not all trigger the detector, and even less of them are fully reconstructed. This is reflected in the integral being significantly lower than 20000 for 1 PeV proton showers and 10000 for 1 PeV iron primaries. In the 1 PeV iron case, it is clearly visible that less showers trigger 5 stations or more during austral summer than in winter. This is expected since more atmosphere has to be crossed in summer (Section 4.1.2), hence more showers are absorbed. This effect is smaller in 1 PeV proton showers, since $X_{\text{max}}$ is closer to the surface for proton showers, which results in more particles at the surface level, and shower to shower variations are larger.

Also the integral of the S125 distribution for the 30 PeV showers is not exactly equal to 10000, which is due to possible events that have S125 values outside the plotted region.

The long tails of smaller values in the S125 distributions of the 30 PeV protons for both atmospheres are due to these particular showers which interacted very late, close to the surface. This was already mentioned in Section 5.1.2. These showers contain a smaller amount of particles, which results in smaller signals at 125 m of the shower core. Since these showers are 100 times resampled, a distribution of low S125 values is obtained. These tails are not visible in the iron showers, which can be due to the fact that the first interaction of iron showers are higher in the atmosphere. Furthermore, the fluctuations in iron showers are much smaller (Figure 1.11 shows this for 1 PeV showers).

The 1 PeV proton showers already exhibit larger fluctuations than the 30 PeV showers, because of the smaller number of particles contained in 1 PeV showers. Therefore, the tail for 1 PeV showers is broader.

Figure 5.9 depicts the S125 comparison between the average July 2010 and July 17, 2010 atmosphere. The same conclusions as above can be drawn about the comparison of the atmospheres. It seems that, at all energies (except the 30 PeV proton case), the difference in mean S125 between the summer and winter atmosphere is about equal to the difference between the average July and July 17 atmosphere. However, Chapter 6 will look into more detail about the different atmospheric effects on S125.

5.2.4 Beta

Beta ($\beta$) describes the slope of the lateral distribution of the shower (at the surface) at 125 m of the shower axis (Section 2.7.1). This parameter has not yet been extensively studied or used before, due to large observed fluctuations. However, studies concerning this parameter are ongoing and current reconstructions seem to result in a more stable $\beta$ value. Therefore, the atmospheric influence on $\beta$ will be studied in detail here.
Figure 5.8 – The S125 distribution for 1 and 30 PeV proton and iron primaries in the average July 2010 and average February 2011 atmosphere. The number of showers included in these plots is equal to the number of reconstructed showers, as given in Appendix C. A Gaussian function is fitted to each distribution, except for the tails if these deviated significantly from the Gaussian distribution.

\( \beta \) shows a significant difference between proton (\( \beta \approx 3.15 \)) and iron showers (\( \beta \approx 2.97 \)) of primary energies between 1 and 30 PeV. Possibly, also a small increase of \( \beta \) with energy can be observed, being of the order of 0.05 between 1 and 30 PeV, which is confirmed by other (ongoing) studies [43]. Both effects are more or less expected, since \( \beta \) is correlated with the stage in the shower development at which the shower is detected (Section 2.7.1). Furthermore, also a zenith angle dependency is expected, which is not used and studied in this section. However, we will not go further into detail about the precise process why and
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Figure 5.9 – A similar figure as Figure 5.8. However, now the S125 comparison between the average July 2010 and July 17, 2010 atmospheres is shown.

how $\beta$ changes, this would go beyond the scope of this thesis. It has to be noted that, since $\beta$ seems a parameter which is sensitive to the primary particle type, it could be used together with S125 (a good energy estimator) to perform energy and composition measurements using only IceTop.

From both Figures 5.10 and 5.11, it can be observed that the $\beta$ distribution is much narrower for the 30 PeV showers (it has to be noted that the range on the x-axis for 30 PeV showers is even smaller). Probably, this can be explained by the larger amount of particles in 30 PeV showers. Furthermore, the distribution is (slightly) broader for proton than iron.
showers, which might be explained by the superposition principle.

As can be seen, the maximum effect of the atmosphere on \( \beta \) is of the order of 0.02 for both primaries at (almost) all energies. The difference between the July 2010 and February 2011 atmosphere is opposite to and seems larger than the difference between the average July 2010 and July 17, 2010 atmosphere. These differences are most clear for the 30 PeV showers, because these \( \beta \) distributions are narrower than the distributions for 1 PeV showers.

It is described in Section 2.7.1 that \( \beta \) decreases when the shower is detected in a later stage of the longitudinal development, because the particles are more and more spread out. This explains the most important effect on \( \beta \), that can be seen on Figures 5.10 and 5.11. Since \( X_{\text{surface}} \) is larger in February 2011 than in July 2010 (Table 4.2), the shower is detected in a later stage in February 2011, which results in a smaller \( \beta \). The same argumentation can be used to explain the daily change in \( \beta \): because of the extreme weather on July 17, \( X_{\text{surface}} \) decreased by approximately 18 g/cm\(^2\) compared to the average July 2010 atmosphere. Hence, the average \( \beta \) is larger on this particular day than during the average July 2010 atmosphere. It has to be noted that the above hypothesis is only valid when \( X_{\text{max}} \) is above surface level, which is the case in all showers considered here.

When we compare Figures 5.10 and 5.11, it can be seen that the seasonal difference in \( \beta \) is larger than the daily variation, although that the differences in \( X_{\text{surface}} \) are similar. This effect, which apparently is smaller than the \( X_{\text{surface}} \) effect, can be explained by the difference in density close to the surface, or more precise, at the thickness level two (EM) radiation lengths \( 2 \cdot X_0 \approx 73 \text{ g/cm}^2 \) (Section 1.3) above the surface [23]. This density influences the Molière radius \( r_M \) (Equation 1.26) and therefore the lateral spread of the secondary particles.

At the altitude corresponding to the thickness level of 2 radiation lengths above the surface (\( \sim 750 \text{ m above surface, } \sim 3.6 \text{ km a.s.l.} \)), the density \( \rho_{2X_0} \) is larger in July than in February (Figure 4.3). Therefore, \( r_M \) is smaller in July, which results in a steeper slope of the LDF, thus a higher \( \beta \) value. This means that this density effect increases the difference in \( \beta \) between the seasons.

Due to the extreme weather on July 17, 2010, a transport of matter originating from the South Pole troposphere away from the Antarctic plateau took place. Therefore, the density in the entire troposphere on this day was lower than the average tropospheric density during July (Figure 4.4). Due to this decrease in \( \rho_{2X_0} \), the lateral spread of the particles grew (larger \( r_M \)), resulting in a lower \( \beta \) value on July 17. Hence, the \( \beta \) difference between the average July atmosphere and July 17, caused by the variation in \( X_{\text{surface}} \), decreases due to in the increase in wind strength on July 17 (Figure 5.11).

In Chapter 6, the change is \( \beta \) is studied for all energies and primaries in the various atmospheres.
5.2. EFFECT ON ICETOP OBSERVABLES

Figure 5.10 – The beta distribution for 1 and 30 PeV proton and iron primaries in the average July 2010 and average February 2011 atmosphere. The number of showers included in these plots is equal to the number of reconstructed showers, as given in Appendix C. A Gaussian function is fitted to each distribution.
Figure 5.11 – The beta distribution for 1 and 30 PeV proton and iron primaries in the average July 2010 and July 17, 2010 atmosphere.
5.3 IceCube muons

As explained in Section 3.3, a change in the density at atmospheric depth levels of 30 – 60 g/cm² influences the IceCube trigger rate. This is expected, since the number of high-energy muons depends on the ratio $\frac{\lambda_{\text{decay}}^{\pi^\pm,K^\pm}}{\lambda_{\text{int}}^{\pi^\pm,K^\pm}}$, and $\lambda_{\text{int}}^{\pi^\pm,K^\pm}$ is related to the density. If the density at these pressure levels increases, the charged pion and kaon interaction length $\lambda_{\text{int}}^{\pi^\pm,K^\pm}$ decreases with respect to the decay length $\lambda_{\text{decay}}^{\pi^\pm,K^\pm}$, which remains constant. This results in an increase of $\pi^\pm$ and $K^\pm$ collisions with atmospheric nuclei, hence less charged pions and kaons decay to muons. It is clear that this will not only influence the IceCube trigger rate, but also the mean number of muons in the shower (and maybe their energy). The number of muons in the shower is closely related to the primary composition (Section 1.3). Therefore, the mean reconstructed mass of the primary particles will be different in summer compared to winter (Section 2.7.2). Obviously, this behaviour is undesired.

Figures 5.12 and 5.13 show the distribution of the number of high-energy muons ($> 273$ GeV, which is determined to be the minimum muon energy to cause a signal in the IceCube detector) in respectively 1 and 30 PeV proton and iron showers. The upper plot compares the different seasons, while the lower plots describe the daily variations. A Gaussian function that will be used in Chapter 6 has been fitted to the data points.

For 1 PeV protons, the high-energy muon number distribution is similar for all atmospheres, which might be due to the small number of muons in these showers, hence a small amount of statistics. The 1 PeV iron showers contain more than 2 times more muons than proton showers. This is explained in Section 1.3. As can be seen, for 1 PeV iron showers, the number of muons experiences a seasonal modulation, but no daily variation. For 30 PeV proton and iron showers, the difference in number of muons between winter and summer grows, which is mainly due to the larger number of muons present in those showers. Also for 30 PeV shower, no daily variation is visible.

These differences can be easily explained by Figure 1.8. As shown by this figure, the largest change in the longitudinal development of muons in a 1 PeV proton shower occurs at very small depths. These depths are located in the stratosphere. Because of the large temperature difference between summer and winter (due to the heating mechanism of the ozone layer, Section 3.2.1), the density at fixed atmospheric depths is smaller during summer. Therefore, more high-energy muons are created during summer.

The daily differences occur mainly in the troposphere (Figure 4.4). Figure 1.8 shows that the muon number does not vary significantly with atmospheric depth at these altitudes or thickness levels ($> 100$ g/cm²). Therefore, a change in density at these thickness level will not influence the number of high-energy muons significantly. The difference in number of high energy muons as a function of the primary energy of the shower after propagation through various atmospheres is more extensively discussed in Chapter 6.

As shown in Figures 5.6 an 5.7, a small energy dependence of the difference in number of secondary muons between summer and winter is present. However, the amount of statistics was too low to study the energy spectrum of high-energy muons. Also this energy spectrum of the high-energy muons will be important, since the energy loss of muons depends on their
Figure 5.12 — The high-energy (> 273 GeV) muon number distribution in vertical 1 PeV proton and iron showers after propagation through either the average July 2010, average February 2011 or July 17, 2010 atmosphere. For each atmosphere, 200 proton and 100 iron showers have been used, after which each shower is 100 times resampled. A scaling of 1/100 has been done, since all resamples contain the same number of high-energy muons. However, the showers which didn’t trigger the IceTop detector are not included. A Gaussian has been fit to the histogram.

energy, and this energy loss is measured by IceCube (Section 2.7.2).
Figure 5.13 – The muon number distribution in vertical 30 PeV proton and iron showers after propagation through either the average July 2010, average February 2011 or July 17, 2010 atmosphere.
Chapter 6

Comparison of the atmospheric effects

In Chapter 5 we learned that the atmospheric variations described in Chapter 3 cause significant changes in the IceTop and IceCube measurements. Here, the results collected before will be used and extended to obtain a complete view of the atmospheric effects on the IceTop measurements and the number of high-energy muons. Particularly, the effects of atmospheric variations on the signal and slope of the IceTop lateral distribution function at 125 m from the shower axis are studied more detailed, and possible corrections are described.

Also the CORSIKA July and made-up atmosphere are discussed, which is done in order to have more (reliable) data points. Furthermore, the made-up atmosphere helps to obtain a separation of the stratospheric and tropospheric effects.

6.1 Shower size: S125

The upper plots of Figures 6.2 - 6.5 show the signal at 125 m of the shower core (S125) as a function of the energy of the primary particle, for both iron and proton showers with zenith angles 0° and 20°. The S125 values are shown after the propagation of the showers through various atmospheres, indicated by the different colours. These mean values are obtained from the fits of the Gaussian function to the S125 distribution, as described in Section 5.2.3. The plots clearly show that S125 is an ideal energy estimator. Besides, S125 seems independent of the primary particle type and zenith angle.

The plots in the middle of each figure show the S125 difference (ΔS125) between the July 2010 atmosphere and the other atmospheres. As described in Chapter 5, the difference in atmospheric depth (ΔX_{surface}) between the atmospheres determines the number of particles at ground level. Since none of the showers have already reached their X_{max} before detection, the number of particles at ground level will be larger when the surface thickness X_{surface} is lower (i.e. closer to X_{max}). It is expected that the signal at 125 m is proportional to the number of particles, hence S125 should be larger when X_{surface} is smaller.

The surface thickness is lowest on July 17, 2010, which causes S125 on this particular day to be larger than S125 on average during July 2010 (austral winter). Opposite, X_{surface} is larger
6.1. SHOWER SIZE: S125

in summer (February 2011) and in the CORSIKA July and made-up atmospheres, which 
induces lower S125 values than during winter. In most cases, this is the behaviour that 
can be observed on the middle plots. As can be seen on Figure 6.2, the vertical proton showers 
are clearly an exception to this rule. This already indicates that the story is more complex 
than only the effect of the surface pressure. Although, this surface pressure effect is very 
important and can be considered as the major influence on S125.

In order to investigate the magnitude of the surface pressure effect, the lower plots show 
the S125 variation divided by the atmospheric depth change at the South Pole surface 
($\Delta$S125/$\Delta$$X_{\text{surface}}$). These plots also show whether the surface pressure is the only effect. 
If this would be the case, all the points obtained for the various atmospheres would coincide 
at every energy. Furthermore, if the surface pressure effect would be identical for all energies, 
these points would lie at one horizontal line. Obviously, both assertions are not valid. These 
lower plots clearly show that a certain difference between the various atmospheres exist, which 
is energy, particle type (and possibly also zenith angle) dependent. This means that several 
effects have to be taken into account to explain the observed S125 variations. The energy and 
particle type dependency of a possible correction factor is obviously not preferable, since the 
mass and energy of the shower are unknown in data!

In the following, all of the known possible effects are discussed, which will be used to try to 
give an explanation for most of the obtained results.

The influence of the surface pressure might depend on the energy of the primary particle, 
since the difference between $X_{\text{surface}}$ and $X_{\text{max}}$ varies with primary energy. This is due to the 
change in $X_{\text{max}}$ with energy (Section 1.3). For example, at the energies where $X_{\text{max}} \geq X_{\text{surface}}$, 
the effect of the surface thickness on the number of particles reverses, hence also a change in 
the effect on S125 is expected. This pressure effect might also depend on the zenith angle 
and type of the primary particle.

To determine the magnitude of the pressure effect, we will follow a similar approach as [66]. 
The Gaisser-Hillas function describes the longitudinal development of the EM component 
(number of EM particles $N_\text{e}$) of an air shower [67]:

$$
N_\text{e}(X_s) = N_{\text{e, max}} \left( \frac{X_s - X_0}{X_{\text{max}} - X_0} \right)^{X_{\text{max}} - X_0} \exp \left[ \frac{X_{\text{max}} - X_s}{\lambda} \right] . \quad (6.1)
$$

$X_s$ is the slant depth (Equation 3.11), $N_{\text{e, max}}$ is the number of EM particles at $X_{\text{max}}$ and $\lambda$ is 
a primary energy and mass dependent parameter, which describes the effective attenuation 
length of the air shower after $X_{\text{max}}$. Also $X_0$ depends on the mass and energy of the primary 
particle, and is related (but not equal!) to the first interaction depth [68].

As illustrated in Figure 6.1, the evolution of the EM signal along the shower development at 
125 m of the shower core is delayed compared to the signal at the shower core. Using the 
Gaisser-Hillas function, it can be seen that the longitudinal development of the shower at 
125 m of the shower core can be parametrized as:

$$
S_{125\text{EM}}(E_0, X_s) \propto X_{\text{max}}^{\hat{X}_{\text{max}} / \lambda} \exp \left[ (\hat{X}_{\text{max}} - X_s) / \lambda \right] , \quad (6.2)
$$

where $E_0$ is the initial particle energy, $\hat{X}_{\text{max}}$ is the average maximum depth of the shower 
maximum at 125 m of the shower core ($\hat{X}_{\text{max}} = X_{\text{max}} + \Delta$, Figure 6.1).
Figure 6.1 – Sketch of the number of particles in a shower during the longitudinal development. The black line denotes the total number of particles. The number of particles in the center of the shower is shown by the blue curve, while the longitudinal development of the particle number at 125 m of the shower core is given by the red curve. The atmospheric depth at which the total number of particles reaches its maximum is indicated by $X_{\text{max}}$. $X_{\text{max}}$ gives the atmospheric depth at which the number of particles at 125 m of the shower core is maximum. $\Delta$ denotes the thickness difference between the two.

Consequently, to determine the energy dependence of the signal at 125 m, we should take $\hat{X}_{\text{max}}$ into account instead of $X_{\text{max}}$. Since $\hat{X}_{\text{max}} > X_{\text{max}}$, the energy at which the surface pressure effect on $S_{125}$ reverses will be lower than the energy at which $X_{\text{surface}} = X_{\text{max}}$.

Equation 6.2 shows that a change in surface thickness affects $S_{125EM}$ (using $dX_s = \sec \theta \, dX$, with $\theta$ the zenith angle):

$$\frac{dS_{125EM}}{dX} \approx - \left[ 1 - \frac{\hat{X}_{\text{max}}}{X_s} \right] \frac{\sec \theta}{\lambda} S_{125EM}.$$  \hspace{1cm} (6.3)

Hence, the change of $\log_{10}(S_{125})$ with $dX$ is given by:

$$\frac{d \log_{10}(S_{125EM})}{dX} = \frac{d \log_{10}(S_{125EM})}{dS_{125EM}} \frac{dS_{125EM}}{dX} \approx \frac{1}{S_{125EM} \ln(10)} \left[ 1 - \frac{\hat{X}_{\text{max}}}{X_s} \right] \frac{\sec \theta}{\lambda} S_{125EM}$$

$$\approx - \frac{\sec \theta}{\lambda \ln(10)} \left[ 1 - \frac{\hat{X}_{\text{max}}}{X_s} \right] = \alpha_X.$$  \hspace{1cm} (6.4)

Thus, this equation gives $\alpha_X$, which is the change of $\log_{10}(S_{125EM})$ with a unit change of the surface thickness.

As shown on Figure 1.8, the number of muons is not affected by a change in the surface thickness. Therefore, $d \log_{10}(S_{125}) \approx d \log_{10}(S_{125EM})$ and we will drop the subscript. The influence of the surface thickness on $\log_{10}(S_{125})$ can be parametrized as:

$$\log_{10}(S_{125}) = \log_{10}(S_{1250}) + \alpha_X(X_{\text{surface}} - X_{\text{surface}}^0),$$  \hspace{1cm} (6.5)
where $S125^0$ is the signal at the reference thickness $X_{\text{surface}}^0$ and $\alpha_X$ is a parameter which might depend on the primary energy and particle type of the shower.

However, next to the primary energy and zenith angle, $\alpha_X$ also depends on $\lambda$ and $\Delta$. $\lambda$ is given in [67] to be around 70 g/cm$^2$. As stated above, it depends (slightly) on the primary energy and particle type of the shower [68]. $\Delta$ has to be found using a large number of air shower simulations, during which the lateral distribution has to be measured at many atmospheric depths. This was not possible. Using the values given in [66], $\Delta$ is roughly estimated to be 20 g/cm$^2$.

Using these values, we have tried to calculate the magnitude of this pressure effect, which is shown as the full line on the lower plots. $\alpha_X$ is calculated to be about 0.0007 g$^{-1}$cm$^2$ for 1 PeV vertical proton showers and approximately 0.0019 g$^{-1}$cm$^2$ for 1 PeV vertical iron showers. It can be seen that the theoretical influence of the surface thickness effect reasonably approximates the observed $\alpha_X$ values. However, significant deviations are visible. This disagreement between the computed value and the value obtained from simulations might be caused by two reasons. Either, the assumed values of $\lambda$ and $\Delta$ differ substantial from the actual values. A second possibility might be that, on top of the pressure effect, certain other effects become important. It is clear that this pressure effect needs more investigation, maybe with the help of input from theory.

It has to be mentioned that the observed evolution of $\alpha_X$ (obtained from our simulations) with energy supports the proposed correction formula (Equation 6.5). In Section 1.3, it is shown that $X_{\text{max}} \propto \ln(E_0/A)$. When we insert this is in Equation 6.4, it can be seen that $\alpha_X$ should increase linearly with $\log_{10}(E_0)$:

$$\alpha_X \propto a + b \ln(10) \cdot [\log_{10}(E_0) - \log_{10}(A)] ,$$

where $a$ and $b$ are determined by Equation 6.4. $a$ will be certainly negative, while $b$ is a positive parameter. The $\ln(10)$ factor is due to the conversion from ln to $\log_{10}$. Figures 6.2 - 6.4 show this linear increase of $\alpha_X$ with $\ln E_0$.

If all the atmospheres would show a similar evolution of the signal with energy, we would be able to determine $a$ and $b$. However, the lower plots of these figures show that this evolution is very different for seasonal (red) compared to daily (green) variations. This shows that also other sources of variation in S125 are energy dependent. At this moment, we are not able to separate these effects. Hence, we will not infer $a$ and $b$, since these can variate strongly, dependent on the magnitude of the other effects.

One first important feature which is seen, is the difference between the $\alpha_X$ values obtained from the seasonal variations and those obtained from the difference between the made-up and July 2010 atmosphere (pale blue). Both on Figures 6.2 and 6.4, $\alpha_X$ between winter and summer atmosphere is higher than $\alpha_X$ between winter and made-up atmosphere. This might be due to the smaller density close to the surface in summer than winter, caused by the variation in inversion layer (Figure 4.3). Due to this smaller density, less EM particles are absorbed or energy is lost in this layer. Since the density in the approximately lowest 8 km is equal in the July and made-up atmosphere (Figure 4.5), this density difference is not present. Therefore, the signal is higher after propagation through the February atmosphere than through the made-up atmosphere. As shown on Figure 4.4, the (fitted) difference in density close to the surface between the average July atmosphere and the atmosphere on July 17, 2010 is only
CHAPTER 6. COMPARISON OF THE ATMOSPHERIC EFFECTS

small. Therefore, this effect will be (almost) not visible in the S125 difference between these
two atmospheres.

This difference between the seasonal S125 variation and the S125 change between the July and
made-up atmosphere can be seen at all energies, for both proton and iron showers. Furthermore,
this effect might be energy and particle type dependent, since this affects the number
of secondary particles. Higher energy showers contain more secondary particles, therefore,
it seems that this effect is larger for higher energy primaries. This might be confirmed by
the strong increase of $\alpha_X$ for the seasonal variation, which is not seen in the daily variation.
However, also a strong increase of $\alpha_X$ between the made-up and average July atmosphere is
observed, which seems to point to a contradiction. Hence, this has to be investigated further.

It can be noticed that this larger density is included in the surface pressure or thickness, hence we
should not account separately for it. However, EM particles which reach the surface
are created at low altitudes (Section 1.3). Therefore, a sudden change in density close to the
surface might affect the signal at ground level more significantly than indicated by the change
in surface pressure.

The S125 variation between the winter atmosphere and both the summer and made-up atmos-
phere might be influenced by the number of muons. As shown in Section 5.3, the air showers
contain more high-energy muons during summer than winter, due to the density variation in
the stratosphere between the seasons. This means that less energy is contained in the EM
part of the shower during summer, which might result in a smaller signal at the surface. This
influence of the stratospheric density is more important for iron showers than proton show-
ers, since iron showers contain more muons. Furthermore, this could cause that this effect
decreases with increasing energy, because the ratio of the number of muons over the number
of EM particles decreases. This is shown by Figure 2.12, and explained in Section 1.3, which
indicates that the number of EM particles in the shower roughly increases proportional to $E_0$,
while the number of muons increases following approximately $E_0^{0.75}$. Hence, with increasing
energy, this stratospheric density effect is supposed to decrease. It seems that this can be
mainly seen for 1 and 5 PeV iron showers: due to the larger muon content of the showers
propagated through either the made-up or February atmosphere, the S125 difference with the
July 2010 atmosphere is larger.

All these described effects might influence the signal at 125 m of the shower core. Fur-
thermore, even more unknown sources which might induce variations in S125 exist. Hence,
more extensive study is needed, for example to investigate why the evolution of $\alpha_X$ for daily
changes is very different from this evolution for the seasonal variations.

A study which compares for example two atmospheres which are identical at all altitudes
except at the inversion layer might be useful. Moreover, also an increase in the number of
shower simulations to study the lateral distribution might help to explain the observed dif-
ferences.

The figures which show the proton and iron showers with zenith angle 20° seem to confirm
the previous results. The lower plots of these figures show the measured S125 difference di-
vided by the variation in slant depth (compared to the surface atmospheric depth previously).
Hence, these data points should show no significant differences with the results obtained for
the vertical showers. This is indeed observed.

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Figure 6.2 – Upper: the mean signal at 125 m of the shower core (S125) as a function of the energy, for vertical proton showers after propagation through the various atmospheres (indicated by the different colours). Middle: the difference in S125 in July 2010 ($S_{\text{Jul10}}$) and S125 after propagation through one of the other atmospheres ($S_{\text{atm}}$). Lower: the same difference divided by the variation in surface atmospheric depth between that particular atmosphere and the July 2010 atmosphere. Furthermore, the solid line shows the evolution of the calculated surface thickness correction factor ($X$) as a function of the energy. The mean values and errors are obtained by splitting the set of reconstructed showers (given in Appendix C) in 5 subsets. The mean shown here is the average of the mean values of the Gaussian fit to each subset, while the error bars indicate the RMS of the distribution of the mean values of the separate subsets. The division into 5 subsets is chosen because more subsets would cause the errors to blow up because of the limited amount of statistics. Less subsets would simply not be useful for the goal of the division in subsets, which was the estimation of reliable errors. The different data points are horizontally shifted around energies 1, 5, 10, 30 and 50 PeV, in order to show all the points.
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Figure 6.3 – This figure shows the (similar to the previous figure) S125 difference between various atmospheres, for several energies, initiated by proton showers with zenith angle 20°. In this case of non-vertical showers, the difference in slant depth is considered in the lower plots, instead of the difference in surface atmospheric depth. The data points are horizontally shifted around energies 1, 5 and 10 PeV.
Figure 6.4 – The mean signal at 125 m of the shower core (S125) as a function of the energy, for vertical iron showers after propagation through the various atmospheres. The different data points are horizontally shifted around energies 1, 5, 10 and 30 PeV.
Figure 6.5 – S125 for 1 and 5 PeV iron showers with zenith angle 20°, after propagations through either the average July 2010, average February 2011 or July 17, 2010 atmosphere. The various plots are explained in Figure 6.2
6.2 Beta

Figures 6.6 - 6.9 compare the mean $\beta$ values as function of the energy after propagation through the various atmospheres, for both proton and iron showers with zenith angles $0^\circ$ and $20^\circ$. These average values are obtained using the Gaussian fits to the $\beta$ distribution, as described in Section 5.2.4.

The upper plots show the evolution of the average $\beta$ with increasing energy, for each atmosphere. It can be seen that $\beta$ decreases from proton to iron, so with primary mass. Furthermore, also the zenith angle dependency of $\beta$ is clearly visible. Both effects are simply due to the decrease of $\beta$ when the stage in the development at which the shower is detected increases (Section 2.7.1). In the case that $X_{\text{max}}$ is above surface level (which is true for all showers considered here), this means that $\beta$ decreases with increasing thickness difference between $X_{\text{max}}$ and $X_{\text{surface}}$. Air showers with a larger zenith angle have to cross more atmosphere. Therefore, at the energies considered here, $X_{\text{max}}$ will be further above the surface, thus $\beta$ will be smaller. Furthermore, $X_{\text{max}}$ is smaller for iron showers, hence $\beta$ will be smaller for iron showers.

The difference in $\beta$ between proton and iron showers is about 0.15, while $\beta$ decreases by approximately 0.05 when the zenith angle increases from $0^\circ$ to $20^\circ$ ($\cos \theta = 1$ to $\cos \theta = 0.94$). Also a very small increase of $\beta$ with the primary energy is present. This is expected due to the increase in $X_{\text{max}}$ with energy, following Equation 1.24. Although, this energy dependence seems to be smaller than the effect of the atmosphere on $\beta$.

The difference of $\beta$ between the July 2010 atmosphere and the other atmospheres is shown on the middle plots. As explained in Section 5.2.4, the main variation originates from the change in $X_{\text{surface}}$ between the various atmospheres, given in Table 4.2. The smaller $X_{\text{surface}}$ on July 17, 2010 than on average during July 2010 causes this daily variation to be positive, while the three other atmospheres (February 2011, made-up and CORSIKA July) have a larger surface pressure and thus smaller $\beta$ values.

It is important to see that this seems valid at (almost) all energies, primaries and zenith angles. Furthermore, this variation in $\beta$ also seems approximately constant!

The variation in $\beta$ between July 17, 2010 and on average during July 2010 becomes zero at 30 and 50 PeV vertical proton showers. This might be explained by the fact that $X_{\text{max}}$ is around $X_{\text{surface}}$ on July 17.

In order to investigate the magnitude of the pressure effect ($\Delta X_{\text{surface}}$) on $\beta$ and, at the same time, search for an extra effect on $\beta$, the lower plots are created. These plots show $\Delta \beta$ divided by $\Delta X_{\text{surface}}$, therefore the change in $\beta$ per unit change in surface atmospheric depth. For showers with zenith angle $20^\circ$, the slant depth (Equation 3.11) is taken into account instead of the atmospheric depth.

In the case that $\beta$ would be only determined by the surface atmospheric depth, all the points at one certain energy should coincide. As can be seen, almost all points agree within each others error bars. However, some (small) systematic effects are visible, which might become significant with more statistics. Therefore, they will be highlighted here.

For vertical showers, also data for the made-up atmosphere is available, depicted by the
blue dots. At most energies, the data points of the made-up atmosphere on the lowest plot seem to be closer to the winter data points than for the summer atmosphere (red dots). While the summer atmosphere deviates from the winter atmosphere by large density differences in both the troposphere and stratosphere, the variation in density between the made-up atmosphere and the July atmosphere is only present in the stratosphere (Figures 4.3 and 4.5).

As discussed in Section 5.2.4, this tropospheric density change between summer and winter probably induces an increased difference in $\beta$. This extra difference is not present for the made-up atmosphere (pale blue), since the density in the lowest 8 km is equal between this atmosphere and the July 2010 atmosphere. As explained in Chapter 5, the density at two radiation lengths above the surface $\rho_{2X_0}$ is probably the most important density that affects the Molière radius at the surface, and thus the lateral spread of the secondary particles.

This influence of the tropospheric density is confirmed by the position of the data points for the July 17, 2010 atmosphere (green) on the lower plots, with respect to the data points of the summer atmosphere. At (almost) every primary energy, particle type and zenith angle, the difference between $\beta$ on July 17, 2010 and the average $\beta$ during July is smaller than the winter-summer $\beta$ variation, even still after taking the $\Delta X_{surface}$ effect into account. In this case, the density variation $\rho_{2X_0}$ reduces the $\beta$ difference between the two atmospheres, as explained in Section 5.2.4.

If $\beta$ will be used for composition measurements using an entire year of data (which is desired), corrections should be applied for the atmospheric variations. Otherwise, the $\beta$ values would be more spread out, hence reducing our resolution.

When we take the two above described effects into account, the difference in $\beta$ between two atmospheres can be described as:

$$\beta_1 - \beta_2 \approx a(X_{surface}^1 - X_{surface}^2) + \Delta \beta_{\rho_{2X_0}}.$$  (6.7)

The first term describes the influence of the surface pressure (or atmospheric depth), where $a$ will give the change in $\beta$ per change in atmospheric depth of 1 g/cm$^2$. Hence, $a$ has units g$^{-1}$ cm$^2$. It is assumed that this first term does not depend on the energy. This can be seen by considering that $\beta$ is related the stage in which the shower is detected:

$$\beta \sim -(X_{surface} - X_{max}).$$  (6.8)

Therefore, the difference in $\beta$ due to the change in surface thickness does not depend on $X_{max}$ (since both $X_{max}$ terms cancel out in Equation 6.7), hence not on the energy of the primary particle.

An increase in $\rho_{2X_0}$ results in a smaller Molière radius, which steepens the LDF, thus increasing $\beta$. Hence, the density term $\Delta \beta_{\rho_{2X_0}}$ may possibly look like:

$$\Delta \beta_{\rho_{2X_0}} \approx b(\rho^1_{2X_0} - \rho^2_{2X_0}),$$  (6.9)

or another possible form is:

$$\Delta \beta_{\rho_{2X_0}} \approx -b \left(\frac{1}{\rho^1_{2X_0}} - \frac{1}{\rho^2_{2X_0}}\right).$$  (6.10)
The parameter $b$ describes the change of $\beta$ when $\rho_{2X_0}$ variates by 1 g/cm$^3$. Therefore, it has units g $^{-1}$ cm$^3$. Possibly, $b$ depends on the primary particle type and energy. This is determined by the lateral distribution function for the different primaries and primary energies, which would go beyond the scope of this thesis and needs to be investigated further. Since no significant change of the $\beta$ difference with energy is observed (Figures 6.6 - 6.9), it is assumed here that $b$ is constant. It is important to note that this is only a rough approximation based on the figures!

Equation 6.10 might seem more logical thanks to its relation to the Molière radius. However, the relation of $b$ to the Molière radius is not straightforward [44]. For simplicity, we will consider Equation 6.9 to be the density correction factor for $\beta$ to make an estimation for $b$.

We will use the difference in $\beta$ between winter and summer (red) and between winter and made-up atmosphere (pale blue) to (roughly) estimate the size of $a$ and $b$. Since the made-up atmosphere and the average July atmosphere have the same $\rho_{2X_0}$, the density term becomes zero. Therefore, the magnitude of this variation in $b$ might allow us to estimate $a$. It is roughly estimated that $\beta_{\text{made-up}} - \beta_{\text{Jul}} \approx -0.015$ for all energies, particle types and zenith angles. Therefore, $a$ is approximated as (Table 4.2):

$$a = \frac{\beta_{\text{made-up}} - \beta_{\text{Jul}}}{X_{\text{made-up}} - X_{\text{Jul}}} \approx \frac{-0.015}{702.5 \frac{g}{cm^2} - 679.6 \frac{g}{cm^2}} \approx -6.6 \cdot 10^{-4} \frac{g}{cm^2}.$$  \hspace{1cm} (6.11)

As explained above, the February atmosphere differs from the made-up atmosphere only by the density close to the surface. Therefore, this difference allows us to estimate the size of the density term. Using Equation 6.9, we obtain:

$$b = \frac{\rho_{\text{Feb}} - \rho_{\text{made-up}}}{\rho_{2X_0} - \rho_{\text{made-up}}} \approx \frac{-0.005}{8.865 \cdot 10^{-4} \frac{g}{cm^3} - 8.887 \cdot 10^{-4} \frac{g}{cm^3}} \approx 2 \cdot 10^3 \frac{g}{cm^3}.$$  \hspace{1cm} (6.12)

Using these values, we will estimate the daily (July 17 vs average July) and seasonal (February vs July) $\beta$ differences:

$$\beta_{\text{Jul17}} - \beta_{\text{Jul}} = -6.6 \cdot 10^{-4} \frac{cm^2}{g} \left(661.4 \frac{g}{cm^2} - 679.6 \frac{g}{cm^2}\right) + 2 \cdot 10^3 \frac{cm^3}{g} \left(8.875 \cdot 10^{-4} \frac{g}{cm^3} - 8.887 \cdot 10^{-4} \frac{g}{cm^3}\right) \approx 0.010$$  \hspace{1cm} (6.13)

$$\beta_{\text{Feb}} - \beta_{\text{Jul}} = -6.6 \cdot 10^{-4} \frac{cm^2}{g} \left(700.3 \frac{g}{cm^2} - 679.6 \frac{g}{cm^2}\right) + 2 \cdot 10^3 \frac{cm^3}{g} \left(8.865 \cdot 10^{-4} \frac{g}{cm^3} - 8.887 \cdot 10^{-4} \frac{g}{cm^3}\right) \approx -0.018$$  \hspace{1cm} (6.14)
Figure 6.6 – Upper: the mean $\beta$ for vertical proton showers as a function of the energy, after propagation through the various atmospheres. Middle: the difference between $\beta$ after propagation through a certain atmosphere ($\beta_{\text{atm}}$) and $\beta$ in July 2010 ($\beta_{\text{Jul0}}$). Lower: the same difference divided by the difference in surface atmospheric depth between a certain atmosphere and the July 2010 atmosphere. The mean values and errors are obtained in the same manner as S125, which is described below Figure 6.2. The different data points are horizontally shifted around energies 1, 5, 10, 30 and 50 PeV.

These are indeed the values which can be roughly seen in respectively Figures 5.11 and 5.10. It has to be noted that these values are only rough estimates and further investigation is needed when $\beta$ is going to be used in future composition measurements! Aside from the above described effects, possibly some other effects might contribute to the change in $\beta$, which are not clearly seen in these plots.
Figure 6.7 – This figure shows the evolution of $\beta$ as a function of the energy, for proton showers with zenith angle $\theta = 20^\circ$, after propagation through the various atmospheres. The middle plot shows the differences in $\beta$ between the various atmospheres, while the lower plot shows this difference divided by the difference in slant depth between the atmospheres. The different data points are horizontally shifted around energies 1, 5, and 10 PeV.
CHAPTER 6. COMPARISON OF THE ATMOSPHERIC EFFECTS

Figure 6.8 – The mean $\beta$ for 1, 5, 10 or 30 PeV vertical iron showers after propagation through different atmospheres. A more extended explanation of the various plots is given in Figure 6.6.
Figure 6.9 – This figure is similar to the previous \( \beta \) figures, but shows the \( \beta \) difference between various atmospheres for 1 and 5 PeV iron showers with zenith angle 20°.
CHAPTER 6. COMPARISON OF THE ATMOSPHERIC EFFECTS

6.3 IceCube muon number

The influence of the atmosphere on the number of high-energy muons which are detected by the IceCube detector is described in Section 5.3 for 1 and 30 PeV iron and proton showers. The upper plots in Figures 6.10 - 6.13 show the variation in the number of high energy muons as a function of the energy of the primary particle for proton and iron showers with zenith angles 0° and 20°.

As described in Section 5.3, the number of muons is larger in summer (February) than winter (July), due to the smaller density at fixed pressure levels in the stratosphere during winter. It is expected that also showers which developed in the made-up atmosphere contain more muons than in July, since the stratospheric densities of the made-up atmosphere are equal to the densities in the austral summer atmosphere. The stratospheric density difference between the CORSIKA July, July 17, 2010 and average July 2010 atmosphere is approximately zero, hence no difference in the number of muons is expected. This expected behaviour is indeed shown on the lower plots of Figures 6.10 - 6.13, which shows the fractional difference in number of high-energy muons at the South Pole surface between showers propagated in the July 2010 atmosphere and showers which developed in one of the other atmospheres.

These figures show that this relative difference remains about constant with energy, certainly within the error bars, which are rather prominent due to the large fluctuations of the number of muons. These large fluctuations are possibly due to the variation in interaction height, as described in Section 5.1.1. Furthermore, this relative difference is expected to increase for showers with zenith angle 20° compared to vertical showers. Although, this effect is only seen in 1 and 5 PeV and might be invisible for iron showers and 10 PeV proton showers due to the large error bars.

From the plots, it is roughly estimated that the number of muons in proton showers increases with slightly less than 10 % during summer compared to the winter. The iron showers contain approximately 10-15 % more muons in summer. However, the differences between proton and iron are small and within the error bars. From atmosphere data, it is found that the effective temperature $T_{\text{eff}}$ in July 2010 is about 193 K, while $T_{\text{eff}}$ is on average approximately 230 K in February. Hence, a change of about 37 K in effective temperature induces a change of about 10 % in the number of high-energy muons. We can try to calculate the temperature coefficient $\alpha_T$ for a change in muon number, similar as applied to the IceCube rate change [55]:

$$\frac{\Delta N_{\mu}}{< N_{\mu} >} = \alpha_T \frac{\Delta T_{\text{eff}}}{< T_{\text{eff}} >} ,$$

(6.15)

where the mean values of both the muon number and $T_{\text{eff}}$ are obtained as the mean between February and July. This results in a temperature coefficient $\alpha_T \approx 0.54$, which is of the same order as $\alpha_T$ for a change in IceCube detection rate [55].

In order to investigate the temperature coefficient more extensively, more data points are needed. This can be done by choosing different months during the year, because the effective temperature changes continuously (Figure 3.7). It might be important to study both months during the spring and autumn, however that the effective temperature would be the same. This is motivated by the fact that the atmosphere varies different in autumn than in spring.
6.3. ICECUBE MUON NUMBER

Figure 6.10 – Upper: the mean number of muons ($N_\mu$) as a function of the energy, for vertical proton showers, after propagation through the various atmospheres. Lower: the fractional difference between $N_\mu$ after propagation through a certain atmosphere ($N_\mu^{\text{atm}}$) and $N_\mu$ in July 2010 ($N_\mu^{\text{Jul10}}$). The averages and errors are obtained from the Gaussian fits described in Section 5.3. The error estimation by splitting the one distribution in subsets was not feasible since the number of data points in the Gaussian fits was only 100. The different data points are horizontally shifted around energies 1, 5, 10, 30 and 50 PeV.

(Chapter 3, this can also be seen on the upper plot of Figure 3.7). However, it is expected that the differences are small.

The approximately constant relative difference in number of high-energy muons might result in an energy independent correction factor. However, the energy spectrum at the surface of these high-energy muons might still be energy dependent. In order to obtain a correction factor for the energy deposition in IceCube, both the number of muons and the muon energies should be taken into account, where a propagation of the muons through the ice should be done [69].

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Figure 6.11 – The mean number of muons ($N_{\mu}$) for proton showers with $20^\circ$ zenith angle, after propagation through the various atmospheres. The studied energies are 1, 5 and 10 PeV.
Figure 6.12 – A similar plot as Figure 6.10. In this case, the studied showers are initiated by vertical iron primaries at the different energies.
**Figure 6.13** – The mean number of muons for 1 and 5 PeV iron showers with the initial zenith angle equal to 20°. A more comprehensive description of the figure is given in Figure 6.10.
Chapter 7

Discussion and outlook

The systematic study performed in this work was started to investigate and try to understand the atmospheric variations observed by the IceCube Neutrino Observatory. Since the air showers develop in the atmosphere, changes in the atmospheric structure can influence the properties of the air shower at the surface. Hence, if a whole year of data would be used, the measurements would be smeared out and resolution would decrease. Moreover, the presence of a clear seasonal variation in (the energy related) shower size highlighted the importance of the need to correct for these atmospheric changes.

The variations observed in the atmosphere above the IceCube Neutrino Observatory can be explained by the exceptional geographical configuration of the South Pole. The semi-annual alternation between polar day and polar night causes large temperature variations in the atmosphere. Due to the absorption of solar radiation by the ozone in the stratosphere, at altitudes between 15 and 35 km, this layer heats up during summer by about 50 °C compared to austral winter. Also the strength of the inversion layer close to the South Pole surface shows large seasonal variations. These temperature changes are reflected in corresponding variations in the atmospheric density in these layers. Furthermore, the presence of the high Antarctic ice plateau induces strong katabatic winds. The variation of this wind strength during the year, caused by the large temperature changes close to the surface, is the reason for large pressure variations at the surface level of the Antarctic plateau.

Daily differences due to weather also occur, resulting in an increase or decrease of the surface pressure and tropospheric temperature and density.

The influence of these seasonal and daily variations on the slope of the lateral distribution (β) and the signal at 125 m of the shower axis (S125) have been studied, together with the influence on the number of high-energy muons.

Both the seasonal and daily β changes are found to be about 0.02 for proton and iron showers, and seems to be independent of the energy and zenith angle. The largest change of β can be explained by the change in surface pressure. To a lesser extent, β is subject to variations caused by a change in density close to the surface. Moreover, both effects seem independent of the energy of the primary particle which initiated the air shower. Since the sum of these two effects explains the main observed behaviour of β, the atmospheric effects on β are rather...
The influence of the atmospheric effects on $\log_{10}(S125)$ is also of the order of 0.02, but is highly energy, zenith angle and particle type dependent and seems to be different for seasonal compared to daily changes. As for $\beta$, S125 changes are dominated by the pressure effect. On top of this pressure effect, S125 seems to be subject to influences of various atmospheric changes, like the variation in the inversion layer or the change in stratospheric density. All these effects might contribute to the zenith angle, energy and particle type dependent change of S125. Furthermore, it has to be considered that possible unknown influences of atmospheric variations could be present. This remarkable behaviour is not yet completely understood, hence S125 definitely needs a more detailed study.

Ongoing studies using data, which investigate the effect of the surface pressure on S125, seem to confirm the magnitude of $\alpha_X$, which describes the change of S125 when a change in the surface pressure of 1 g/cm$^2$ occurs. This supports the obtained results. However, it has to be considered that the real (data) measurements might be subject to more seasonal changes than studied here. Only a few of the examples are the detailed composition of the atmosphere, the wind strength and the DOM mainboard temperature. Also the effect of snow on the IceTop measurements is currently under study, where it is important to remark that the atmospheric effect on S125 is significantly smaller than the effect of snow.

A first systematic study of the high-energy muon content in air showers of different primaries, zenith angles and primary energies has been performed. These results confirm the expectations that more muons (about 10%) are found in the air showers during austral summer than in winter. This is an important result for the mass and energy determination of the primary particle using the IceCube detector. However, the density change in the stratosphere also seems to affect the energy of the muons. Since the deposited signal in the IceCube detector depends on both the number of muons and their energy, a more detailed study that also propagates the muons through the ice is currently performed.

One of the possible next steps to clarify the observed phenomena is a systematic simulation study where various detector levels through the EAS development are specified. This is possible in CORSIKA, and might yield information of the particle number, lateral spread, energy deposition, etc. Furthermore, 2 ”made-up” atmospheres could be created which only differ in one certain small layer. This can learn us more about the effect on S125 and $\beta$ of this particular layer. Especially, this might be important to investigate the influence of the inversion layer, which is vastly present at South Pole.

In order to obtain a full and comprehensive study of the influence on the number and energy of the high-energy muons, more atmospheres of various months throughout the entire year are needed. Moreover, more zenith angles and larger primary energies could be studied, which could possibly point to an energy or zenith angle dependence.

In summary, the effects of the atmosphere are roughly known and understood, and possible correction factors are introduced. However, the results certainly require more study using both data and simulation, which might be supported by some theoretical input. In each case, a first step is made in the quest to understand the influence of the variations of the South Pole atmosphere on measurements performed by the IceCube Neutrino Observatory.
Appendix A

Atmospheric depth variation during the IT-73 data taking period

Absolute difference

![Graphs showing atmospheric depth variation for different months and years](image-url)
October 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

November 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

December 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

January 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

February 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

March 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model
APPENDIX A. ATMOSPHERIC DEPTH VARIATION DURING THE IT-73 DATA TAKING PERIOD

April 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

May 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model
Relative difference

June 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-86-E model

July 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-86-E model

August 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-86-E model

September 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-86-E model

October 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-86-E model

November 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-86-E model
APPENDIX A. ATMOSPHERIC DEPTH VARIATION DURING THE IT-73 DATA TAKING PERIOD

December 2010 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

January 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

February 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

March 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

April 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model

May 2011 data vs July 01, 1997 (MODATM=12) CORSIKA MSIS-90-E model
Appendix B

CORSIKA steering file

RUNNR \{RUNNR\} Number of run, each run will be one shower
EVTNR 1 Number of first shower event
NSHOW 1 One shower per run
PRMPAR \{PRIM\} Primary particle
ESLOPE -2.7 Slope of primary energy spectrum (not used)
ERANGE \{E\_GEV\} \{E\_GEV\} Primary energy
THETAP \{THETA\} \{THETA\} Zenith angle
PHIP 0 0 Azimuth
SEED \{SEED1\} 0 0 Seed 1: first sequence for hadron shower
SEED \{SEED2\} 0 0 Seed 2: second sequence for EGS4
SEED \{SEED3\} 0 0 Seed 3: not used
OBSLEV 2835.e+02 Observation level: IceTop at SouthPole
ELMFLG F T EM flags: NKG and EGS
RADNKG 2.e+05 Outer radius for NKG lateral density
ARRANG -119. Rotation angle from CORSIKA to I3
FIXHEI 0. 0 First int. height and particle NOT fixed
FIXCHI 0. Starting altitude (g/cm^2)
MAGNET 16.59 -52.79 Magnetic field at South Pole (uT)
HADFLG 0 1 0 1 0 2 Flags hadronic interaction & fragmentation
SIBYLL T 0 Use Sibyll
SIBSIG T Use Sibyll cross sections
ECUTS .05 .05 .01 .002 Low energy cuts on (had/mu/e/gamma, GeV)
MUADDI T Additional muon info
MUMULT T Muon multiple scattering angle
LONGI T 1. F T Longit. distr., step size and fit
MAXPRT 2 Max. number of printed events (>1)
ECTMAP 100 Cut on gamma factor for printout
STEPFC 1.0 Mult scattering step length fact.
DEBUG F 6 F 1000000 Debug flags
DIRECT ./CORSIKA/ Output dir
ATMOSPHERE \{ATMOS\} F Only for real atmospheres!
ATMOD \{MODATM\} Only for CORSIKA atmospheres!
EXIT Terminates input

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The run number (RUNNR) is chosen to be uniquely for each shower. The primary particles (PRIM) used here were proton (h) or iron (fe). The energies (E GEV) used in these simulations were 1, 5, 10, 30 and 50 PeV, while the zenith angles used were 0° and 20°. The used seeds (SEED1, SEED2, SEED3) are given in Section 4.1.1. Furthermore, a real atmosphere (Table 4.2) is specified through ATMOS, while the MODATM is set to 12 to simulate the CORSIKA July atmosphere.
## Appendix C

### Number of simulated, triggered and reconstructed showers

**Table C.1** – The number of showers of each primary particle type, energy and zenith angle $\theta$ in the average July 2010 atmosphere which were simulated (including the resamples), passed through IceTopSTA3 filter (number of hit stations $\geq 3$) and reconstructed (number of hit stations $\geq 5$).

<table>
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<th>Type</th>
<th>Energy (PeV)</th>
<th>$\theta$ (°)</th>
<th>Generated</th>
<th>Filtered/Triggered</th>
<th>Reconstructed</th>
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<td>0</td>
<td>20000</td>
<td>19950</td>
<td>18667</td>
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<tr>
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<td>20000</td>
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<td>19996</td>
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<tr>
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Table C.2 – The number of showers of each particle type, energy and zenith angle in the CORSIKA July atmosphere which were simulated, passed through the filter and reconstructed. It is assumed that an error occurred in the simulation of 3 vertical 10 PeV proton showers, which could cause the number of triggered showers to be only 9700.

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy (PeV)</th>
<th>θ (°)</th>
<th>Generated</th>
<th>Triggered/Filtered</th>
<th>Reconstructed</th>
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Table C.3 – The number of simulated, triggered and reconstruction proton and iron showers of each energy and zenith angle in the average February 2011 atmosphere.

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</table>
Table C.4 – The number of generated proton and iron showers of each energy and zenith angle in the July 17, 2010 atmosphere. Also the number of showers which passed through the filter and which were reconstructed are given.

<table>
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<th>$\theta$ (°)</th>
<th>Generated</th>
<th>Triggered/Filtered</th>
<th>Reconstructed</th>
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Table C.5 – The same table, but after propagation through the made-up atmosphere.

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<th>$\theta$ (°)</th>
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</tbody>
</table>
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