Studies of Antarctic precipitation statistics

Internship at the Laboratoire de la Glaciologie et Géophysique de l'Environnement (LGGE)

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The Antarctic is a key factor in the current issue of climate change. Great interest exists to understand the different relationships and processes affecting the climate system. Precipitation is an important but until now not well-known parameter of many processes and interactions. The Antarctic is a very dry region and under the hard conditions, accurate precipitation observations are difficult to obtain and temporally and spatially very limited. To understand the whole system other methods were developed such as climate models and mid-range forecasts. The various models are based on the same dynamical and physical laws but they are solved differently, so that each model developed its own solutions. The model accuracy has to be tested and a comparison under each other but also with the little amount of observation is important. In the following studies, such a comparison was done between the available observation data and different climate models and mid-range forecasts with the aim to gain more knowledge about the reality but also about the model`s and the observation`s quality.

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1. Introduction

The issues of the ongoing climate change let many scientists focus their investigation on the Antarctic. The climate system shows a complicated interaction of many physical and dynamical components. Climatic processes are based on a relationship between the atmosphere, the hydrosphere, the biosphere and the cryosphere. The Antarctic ice sheet represents 90% of the terrestrial ice. This large unit of the cryosphere and the close connection to the atmosphere as well as to the ocean make the sensitive region to one of the key factors of the complex climate system.

A better understanding of the complicated framework concerning processes linked to the ice sheet of the Antarctic is crucial to conclude on the climate evolution affecting our planet. It is important to study single components like temperature, wind patterns, CO_2 concentration, precipitation and so on in details but also their interplays and effects on each other need to be understood to set together a global picture.

By creating climate models, the understanding of the climate system and its effects on our environment is aimed. Models are constructed to represent as many processes and interactions as possible on a global but also on a local scale in order to best represent the real conditions. They should simplify the complexity of the system to let us see behind the confusing convolutions.

However to create an accurate model some physical and dynamical laws need to be respected and a link to the reality should be kept by using parameter values in a realistic range, what is not always simple. Every model developed its own ways of solving these problems.

Precipitation characteristics play an important role for the global water cycle but also for the ice accumulation in the Antarctic. It exists therefore a great interest to understand the local and global particularities of rainfall and snowfall. To calculate and model correctly the Surface Mass Balance of the big ice sheet of the Antarctic, income and output quantities and their distribution should be known to solve the equation of the balance. However, these factors are extremely difficult to estimate correctly. The more and the more accurate information about precipitation quantities and distribution the better such processes can be understood.
The Antarctic region is one of the driest regions in the world. Precipitation is very little in quantity and very variable in time and space. It is very difficult to collect an accurate data set of the precipitation characteristics. The spatial extent of the data is strongly limited combined with a very irregular distributed set of data over the ice sheet. Most direct measurements are not robust enough or the instruments are not well adapted to the extreme hard circumstances. Other solutions are explored to understand the precipitation patterns in this particular region better. Model predictions should produce an image representing a realistic climate. References for comparison are rare and many ongoing processes are not yet well understood. Different operators to find the best fitting prediction have run climate models as well as precipitation analysis. By improving the computational resolution but also the dynamic and physical process-integration, the models represent the climate system more and more accurate and even for such a special environment like the Antarctic a simulation become possible. Constant upgrading is aspired.
Additionally the various instruments and techniques used to collect precipitation data are continually tried to be enhanced. The network of observation is getting denser and more extended on the ice sheet. Despite all this effort, it remains very difficult to reach clear conclusion and a realistic simulation for the Antarctic is still hard to reach.

In these studies, different model predictions as well as a range of data collections of direct observation in the Antarctic should be tested on their accuracy and the inter-comparison should lead to conclusions about the effective precipitation characteristics. In a first step, the commonality and the differences of the models should become evident. The conclusion over the different model's quality is furthermore achieved by comparing the precipitation analysis and climate models to each other but also by comparing them with the different fragments of direct observation sets that are available. Besides, some conclusion might be made over the quality of the different techniques and instruments used for precipitation measurements at diverse Antarctic stations.

2. Model Methods

2.1 Model description:

The behavior of the atmosphere is governed by a set of physical laws, which can be expressed as mathematical equations (ECMWF, 2009). Apart from these physical aspects, a dynamical part is included into the modeling of the climate system. The equations concerning the dynamics are called primitive equations and display a simplification of the Navier-Stokes equation for a compressible fluid at the surface of a spherical planet with a rotational movement. By solving these primitive and physical equations, a future state of the atmosphere can be derived from a current state. The current state can be seen as the term “weather” in case of short and medium range forecasts (ECMWF, 2009). For modeling climate, the initial conditions are not significant and a model will be run for a time important enough that the starting input parameters looses their effects on the represented system. Nevertheless, a state close to the current conditions is generally chosen to begin a model run. Numerical models are used to solve the complex primitive equations (ECMWF, 2009). The different models thereby solve these equations with their own proceeding and their available funds and computer power. Here lies one of the major differences in the various model approaches and notable also in their results.

The models of the general circulation calculate the temporal evolution of different variables, which are determining for the meteorological and climate development in a 3D grid. The gird displays the entire atmosphere and the model is separated into two parts, a dynamical and a physical part (LMDZ 2004). The calculation concerning the dynamical part affects a three dimensional volume with horizontal and vertical process interactions, whereas the part treated by physical calculation can be seen like neighboring columns that are not interacting with each other. The two parts treat different variables and the temporal integration as well as the time steps are not the same and therefore treated by different numerical systems (LMDZ 2004).

All general climate models are derived from a large number of fundamental physical laws, which are than subjected to physical approximations appropriate for the large-scale climate system and then further approximated through mathematical discretization (Berrisford et al, 2009). Computational limits restrict the resolution in the discretized equations. The smaller the set of numbers, the coarser the discretization and the less detailed forecast of the atmospheric state is reached but the less computer strength is needed (ECMWF, 2009). The finer the discretization, the larger the amount of numbers, the more extended computer time, the more powerful and more expensive the solution becomes. The discretization that can be afforded depends on the power of the computer and how efficient its power is used.

Small-scale effects can often not be included due to a too coarse discretization. Nevertheless, they cannot be neglected so that their effects need to be taken in account what can be done by accounting their influence on the behavior of large-scale parameters. This parameterization is very important to be able to create an accurate forecast. A striking difference between the varying types of models can hereby be found. Not every model uses the same scheme and has the same funds for high quality solutions. Parameterization has to be proved and should be compared on observations and systematic research (Randall et al, 2007).

There have been ongoing improvements in order to computational methods, parameterizations and additional processes that have been included in most of the climate models. The improvement includes also reformulated dynamics and transport schemes as well as an increased horizontal and vertical resolution. Wave models but also terrestrial processes are included (Randall et al, 2007).

Models should be viewed critically for both weather predictions and climate predictions. Weather forecasts have the advantage that they are produced on a regular base and can be tested quickly against what actually happened and over time an important amount of statistics can be collected to give information about the performance of a particular model or a forecast system (Randall et al, 2007). Climate models are used to make projections into the future and run over a longer period of many decades. Confidence in a model can only be gained through historical record what is much more limited than the direct information available for weather forecasts. A long-term prediction cannot be verified with the actual happening (Randall et al, 2007).

The better a model simulates the complex spatial patterns and seasonal and diurnal cycles of present climate, the more confidence exist that all important processes are well represented and past and future simulation can be launched. The development of analysis methods was pushed forward by modeling groups that combined a set of standard experiments and the model outputs which have been analyzed by many researchers worldwide (Randall et al, 2007). These coordinated models like the ECMWF (European Centre of Mid Range Weather Forecast) and the NCEP (National Center for Environmental Predictions) lead to a more rapid identification and correction of errors, the creation of standardized calculations and a more complete and systematic record of modeling progress. The capability of this models were tested on time scales from weather forecasting to seasonal forecasting and an increasing confidence arises that this meteorological analysis simulate well some of the key processes and interactions of the climate system (Randall et al, 2007). There is currently no compromise found for an optimal way to divide computer resources among; finer numerical grids, which allow a better general simulation; greater numbers of observation projects and a larger amount of measurement data, which allows better statistical estimation of uncertainties; and the inclusion of more complete sets of processes (Randall et al, 2007).

Precipitation is not only strongly determined by insolation patterns, like temperature, also vertical movements of the air due to different atmospheric instabilities and the interaction with the topography are important (Randall et al, 2007). Precipitation patterns are linked to atmospheric humidity, evaporation, condensation and transport processes. To model the seasonal variation some processes such as condensation and transport have to be evaluated and simulated correctly what can be very challenging. Good observations for global evaporation patterns and local precipitation dispersions are not available and a problem of subscalling processes that dominate condensation and vertical vapor transports to a large extend remains unsolved (Randall et al, 2007). In general, it was concluded that the precipitation amount falling in extreme events are underestimated. Models tend to produce too many days with weak precipitation and too little rainfall overall in intense events (Randall et al, 2007).

2.1.1 ECMWF

The European Center of Mid Range Weather Forecast produces an operating meteorological model that is applicable in many different commercial and research areas. Forecasting the weather for the next few days helps for example to calculate shipping routes, pollution diffusion patterns, or simply helps to predict the weather in regions without own meteorological predictions (ECMWF, 2009). For research projects the meteorological analysis lead to a good climate model. Due to such purposes, the ECMWF forecast was used in the following investigation with an eye particularly set on the precipitation analysis of the Antarctic region. To give a better understanding of the ECMWF some details are discussed below.

The discretization for the ECMWF is equivalent to a regular grid with a distance of 40km from one gridpoint to the next around the globe (ECMWF, 2009). This grid is repeated on 60 levels in the vertical. In order to start a computer model, initial conditions are required. For the Analyses of the ECMWF, observation are used to calculate the “weather” (the current state) at each gridpoint throughout the model. The forecast is made in short steps of 15min what gives the starting conditions for the next forecast step and so on. Initial conditions for a global model are created by making a synthesis of observation values of the atmosphere for a time-period of 24 hours and short-range forecasts provided by the model itself (ECMWF, 2009). The synthesis leads to the integration of the observation into the model. A problem shows the irregular distribution and the varying quality of the observation data over the globe (ECMWF, 2009).

For these studies, the ERA-Interim archive of the ECMWF was used. This data set is produced through a reanalysis of the global atmosphere and includes a wave model. The ECMWF predicts the behavior of the atmosphere in the medium-range up to ten days ahead. The global atmosphere is included into the model to a height of 65km from the earth's surface. The data used covers a period from 1989 to June 2009. As ERA-Interim is a continuous series, updates of the data archive are done monthly (Berrisford et al, 2009). After ERA-40, this new reanalyzes should improve the representation of the hydrological cycle, the quality of the stratospheric circulation, the handling of biases and changes in the observing system (Berrisford et al, 2009). The parameters used for the model are stored either on pressure levels or on model levels and classified again into spherical harmonics and a Gaussian grid (Berrisford et al, 2009). Parameters are available both, from analysis and forecasts. A short-term forecast of a free atmospheric model with a 24h-time step for the total precipitation was launched for the entire period over the Antarctic region on a grid of 3°x3°.

2.1.2 LDMZ

Different to the ECMWF the LMDZ is a pure climate model with the purpose on climate research and not on forecasting weather conditions. The aim of this model is to produce statistics over the climate and to predict its evolution on a large time scale (Genthon, personal communication).

The LMDZ is the atmospheric model of the IPSL but with a difference in the resolution at the poles. The LMDZ model of the general atmospheric circulation allows a zooming of any region of the world due to a stretched hydrodynamic grid and a completed parameterization (LMDZ, 2004) whereas the IPSL climate model displays the worldwide representation better. The resolution of the ECMWF is on a global scale much finer but regarding the zooming possibility of the LMDZ on particular region; an equally high resolution for the area of interest is produced (LMDZ, 2004). The initialization of the model needs a certain amount of starting conditions what handles the temporal integration of the model components. The starting conditions for the LMDZ simulation are not based on observation but close to an actual state. These conditions are not important and the model is run until the initial state is not remembered in the represented system anymore. In general a model is run to make a climate prediction and the first modeled period, most commonly one year, is not considered in the prediction since the initialization may affects the modeled result (Genthon, personal communication).

For both models described in details above, the primitive equations are the same and based on physical laws. However, the way they are resolved divers. The dynamical processes are well known and to eliminate the largeness and complexity of these equations discratization is applied. For the physical components, problems in the model integration of very small processes occur but also the understanding of some physical interactions are still limited. To solve these problems parameterization schemes are introduced that vary strongly for the two models. As an example, the convection is completely different treated in the LMDZ climate model than in the mid-range forecast of the ECMWF. Some parameterization patterns are developed by one and overtaken by the other model. The radiation process is very similar in the both approaches the LMDZ and the ECMWF since it has been developed by the LMDZ and improved by the ECMWF afterwards (Genthon, personal communication).

2.1.3 GPCP

The precipitation analysis of the Global Precipitation Climatology Project (GPCP) was launched to gain a better understanding of the spatial and temporal pattern of the global precipitation (HUFFMAN et al, 2009). Thereby different type of precipitation measurements over the globe like rain gauge stations, satellite geostationary and low-orbit infrared as well as passive microwave and sounding observation have been combined to estimate the rainfall on a globe covering grid with a resolution of 2,5 degrees (HUFFMAN et al, 2009). The largest data set reaches from 1979 to the present. For the following investigation, data was used from 1996 to the present from the data set "GPCP One-Degree Daily Precipitation Data Set". This set of precipitation data is a first approach to estimate global daily precipitation at the 1°x1° scale strictly from observational (HUFFMAN et al, 2009). No model forecast was used. The very complete analysis for oceanic regions can be found due to the combination of the precipitation estimation of the different satellite data collection (HUFFMAN et al, 2009). The information about the rainfall gives additionally important spatial details for the analysis of precipitation over land regions. The spatial coverage is tried to be global, however a small scattering of points at the pole are missing. The missing values are filled by average-fillings values (HUFFMAN et al, 2009).

2.1.4 Other Models

Furthermore, some models contributing to the IPCC assessment report 2007 have been included for the investigation. For a first comparison additionally to the ECMWF and the LMDZ output, the IPSL_cm4, the MIUB_ECHO_G and the MRI_CGCM2_3_2a data sets have been treated for a period of 18 years from 1989 to 2007. All this mentioned, additional used models are purely orientated on climate research and do not incorporate observation into the analysis directly. They are purely climate models. The meteorological analysis of NCEP has been integrated as well in some of the studies. It is equivalently to the ECMWF, based on an observation-forecast-simulation combination.

2.2 Data Treatment and Modeling

With the software "Ferret", the NetCD-files originate from the different models that contain precipitation data for the Antarctic region, have been used and precipitation maps were produced. These figures show the precipitation quantities in meters per day for each gridpoint of the considered area. To reach a comparable result the precipitation quantities has been relativized by the following application:

daily precipitation [m/d] / daily precipitation average of 1989-2007 [m/d] = relative precipitation value

With Ferret, additionally, statistics has been extracted and compared to estimate the basic variation in precipitation quantities of the different model approaches such as the average precipitation amount as well as maximum and minimum values.

To know more about the precipitation patterns in the Antarctic region it is important to collect information about the quantities that are falling; about how the rain- and snowfall is distributed; and about the frequency, meaning the numbers of days with precipitation occurrence during the considered period. Therefore, next to the modeled precipitation-quantity, a frequency-distribution

was drawn by mapping the precipitation occurrence at every gridpoint for each model. The image was then produced by summing up all the days with a recorded precipitation event. The values are finally displayed in percentage.
A precipitation event is defined as followed in these studies: For every day (of the investigated period) when precipitation was predicted by the model for a certain gridpoint in between the same 24 hours, an event is set for this day at the certain location (gridpoint).
Such an illustration makes the precipitation frequency-distribution evident but does not include statements about the amount of rain- or snowfall during each event. The initial treatment does not include any thresholds on the quantity of precipitation needed during one day to be registered as an event. That means that a single crystal falling from the sky, is enough to state a precipitation event. A storm for several hours with a large quantity of precipitation accounts as the same single event for one day. A distinction of large and small events is therefore not possible with considering only these outputs.
The comparison between the ECMWF and the LMDZ was extended to a global scale and the two solutions were investigated more deeply for the Antarctic region. To understand better the difference in the partition of small and big events to the entire precipitation quantities, thresholds have been introduced. Thereby a limit of the numbers of precipitation events is set by introducing a threshold on the daily average of the precipitation quantity needed to count as an event. In other words, this means a certain amount of precipitation is required during one day to define an event. The differences of the LMDZ and the ECMWF models can be demonstrated.
With the software Ferret, maps of different quantity-events (different threshold limiting the mapped precipitation events) were drawn. Such illustrations were done for the ECMWF forecast and the LMDZ model, thereby the time from 1989 to 2007 was considered.

The GPCP precipitation data in a NetCD-format has been analyzed as well with the software Ferret for the same region but additional also on a global scale. A quantity map in meters per day and a frequency-distribution by mapping the precipitation events in percentage were demonstrated. The results are discussed in section 4.2.

3. Observation Methods

3.2 Observation description

To evaluate the accuracy of climate models a comparison to direct observation is very helpful. Unfortunately, only few measurements are available for the Antarctic region. Nevertheless, direct observation and measurements are established and tried to be improved again and again to reach some more information about the precipitation characteristics. Most commonly, the used instruments are established for milder conditions. They are not accurate enough in such extreme environments. Especially during the winter months, measurements are difficult to obtain.

On the French-Italian station at Dome C, people wintering at the station in 2009 measured precipitation characteristics along with other meteorological observation like wind conditions, atmospheric pressure, temperature, humidity, visibility and cloudiness. The available data starts in

November 2008 and ends in September 2009. The observations was done by indicating if precipitation was seen or not and by measuring the thickness of a snow layer on a plate every day. The plate with a size of ca. 1m x 1m was installed around 1m to 1,5m above the ground. Additionally, visual observation of hoar formation, crystal types and occurrence of single crystals in the air was carried out. Since the conditions do sometimes not allow the observation, some missing data can be found in the data set. Sometimes the precipitation seems not important enough in its quantity to give a thick enough layer on the plate that can be measured. Such cases are expected when there is a lack of the thickness value but an event is recorded. The collected data from this visual precipitation observation gives an estimation of the frequency but no exact quantitative values.

Furthermore, a Biral VPF-730 has been installed. This visibility sensor delivers data at Dome C since 2007 and at the coastal area at Cap Prud'Homme already since 2006. The Biral is based on the principal of a Nephelinometer. Near-infrared radiation are sent out and received by two receptors, which are installed with an angle of 35° and 130° (A. TOUVILLIEZ, 2009). The signal is only received if there are particles passing between the sensors, thus if there is precipitation or most likely also if there is blowing snow. This construction makes it possible to measure the size and the speed of particles in more than only one direction. A volume of 400 cm^3 is captured and solid as well as liquid precipitation is measured (A. TOUVILLIEZ, 2009). Proposed by the manufacturer (Biral, user guide) is the use of a matrix indicating the size and the speed of the particles as well as their ratio to make conclusions about precipitation conditions and transportation types (fig. 3.1). Snow particles are very small in the Antarctic. It appears therefore difficult that a ratio considering the size can be used to recognize the different transportation types (Genthon, personal communication). The speed of the particles depends on the wind. In the Antarctic, it is complicated to distinguish if the particles observed by the VPF-730 Biral are snowflakes that are carried by the wind or if it is mobilized snow from the ground. The instrument does measure particles before they reach the land surface and can therefore easily be perturbed (Genthon, personal communication). The suggested matrix might work in the region where the Biral was developed but under the hard conditions in the Antarctic, it is not very reasonable to extract information out of such a matrix.

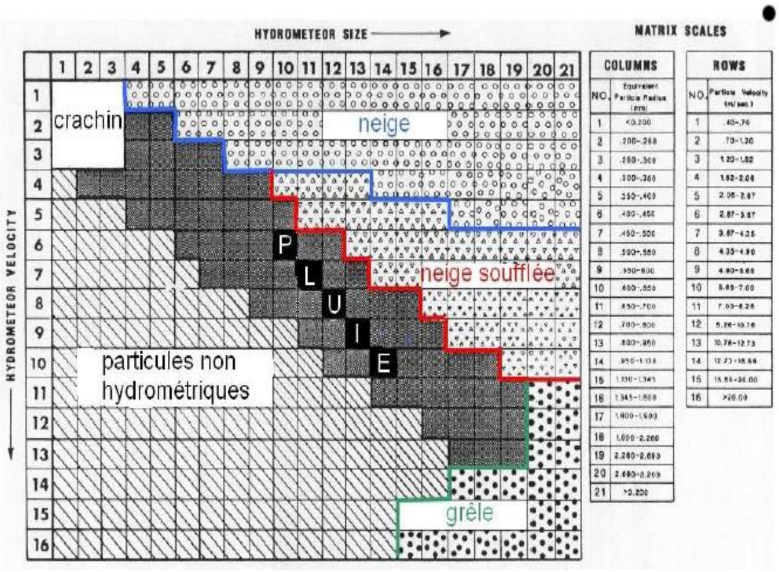


Fig. 3.1: Size-speed Matrix to estimate the hydrometeor type with the VPF-730 (Biral, user guide).

Another disadvantage of the instrument is the tendency to failure during the time, when no reparation is possible, manly during the Antarctic winter. For the coastal area, data was available for January, February, March, September and October in 2006 and only for February and December for the year 2007. In 2008 results could be collected for the months February, March, April and May and for 2009 data for January, February, May, June and July were available. At Dome C measurements were only obtained for the period January to July in 2009.
The Biral registers its measurements every hour. For the purpose of this study, daily values were calculated and further on used.

At Cap Prud`Homme a FlowCapt was installed in 2009. It is an acoustic sensor measuring the speed of the wind and the snow flux (V. CHRITIN, 1999). The instrument is built out of three tubes, each with a size of 1m and in this case the instrument is vertically installed (A. TOUVILLIEZ, 2009). Every tube contains a microphone and the particles carried by the wind create an acoustic pressure onto the tube (V. CHRITIN, 1999). Due to the high amount of particles carried by the wind, a certain frequency is typical. This allows the registration of blowing snow. The acoustic pressure is linked to the quantity of particles. The wind itself gives also a signal but with a much lower frequency. As a result, a distinction between the snow flux and the wind speed can be done (V. CHRITIN, 1999).
By earlier investigation (A. TOUVILLIEZ, 2009) it became evident that the bottom tube seems to be the most robust with the smallest noise. Therefore, the data measured by the lowest situated tube was used for my investigation. The data set covers the period from January to mid July and the month of October in 2009 but for comparisons in this work, only the records from January to February and May to June were used. The data is recorded every 30min. For the following investigation, a daily value was produced.

At the Dumont d'Urville station situated on an island in a distance of 5km from Cap Prud'Homme, Meteo France is doing some visual observation of precipitation occurrence. In 2009 people wintering at the station, indicate the occurrence and the duration of precipitation events for each day of the month. The observed data is separated into 6h-intervals. A day value is here used what means if there was precipitation seen during one day it counts as a precipitation event-day (explanation of precipitation event in section 2.2). Data was available from January to August in 2009. The result shows a good indication of the occurrence of precipitation event but they contain no quantity statement. This data can be compared to the appearance of a happening of precipitation by other measurement techniques. It is assumed, due to the little distance between the locations that the precipitation event data sets should be correlating between Dumont d'Urville's visual observation and Cap Prud'Homme's records of the Biral.

3.2 Data comparison

Plots of the different outputs of the measurement and the models have been done to get an overall estimation of the correlation of the different data sets. The results are discussed in more detail in section 5. The plots indicate the amount of precipitation in mm/day (y-axes) for each day of the year (x-axes) for all methods where such information was available. The FlowCapt data is plotted into the same scheme with the same x-axes scale but with a different y-axes scale of $g/m^2/s$. This was done to see if blowing snow indicated by the FlowCapt occurs coincidental with large precipitation events on the Biral records. The visual data was additionally compared with the plotted values.

To compare the different observation techniques and the modeled result at Cap Prud`Homme some data treatment has been applied to find the fraction of days where a correspondence of event and non-event could be quantified. All the days, where the result states the same information about the occurrence of precipitation events, are counted and then compared to the total number of days. In other words, every time one instrument shows an event-day or a non-event day of precipitation, the result of a second method was examined for the same day if it shows an equivalent result or not. The number of corresponding days of the different methods was then divided by the entire numbers of days that have been respected:

Corresponding days/total days = fraction of positive identifications

This value has been calculated for the Biral data in comparison with the model of the ECMWF and the visual observation of Meteo France at the coast. Furthermore, the fraction of days with precipitation and without precipitation in relation to the corresponding days was investigated. The same technique has been applied to make such a correspondence evident for Dome C, using the results of the visibility sensor located at Dome C, the ECMWF prediction and the visual observation on a plate.

Since it is not entirely clear if the Biral only measures precipitation or as well blowing snow the result of the FlowCapt at Cap Prud'Homme placed in 1km distance to the Biral should help to solve this problem. High FlowCapt values should give indication on the difference between precipitation and effects of wind interaction on the visibility sensor. The following modification of the Biral data could be done: For every case, where a high value in the FlowCapt data was found but no event was predicted by the ECMWF, the precipitation event at the Biral was assumed to be purely due to blowing snow but not to a precipitation event. A threshold of 1g/m^2/s was set for the FlowCapt data to make the data output more robust and to eliminate noise.

For the data used at Cap Prud'Homme, thresholds of 0,5mm/day and 1mm/day were introduced for the ECMWF. That means that only precipitation quantities greater than 0,5mm respectively 1mm during one day counts as a precipitation event. All smaller events are assumed to be due to noise and are therefore not considered. Different thresholds are used to find the best correspondence in the day-to-day comparison. When comparing the fraction of days with a corresponding event like described above for the ECMWF, the Biral data and the observation of Meteo France, some manual corrections have been applied. These corrections were done when the ECMWF missed the visually observed event for one day and when the visual observation missed an event but it was predicted by the model and seen by the Biral. Furthermore, only the events were counted for the ECMWF that are larger in quantity than 1mm per day. The results of these comparisons are described in the section 5.1.

The visual data of Meteo France has been further investigated by comparing it to the visibility sensor. The Biral data measuring precipitation at Cap Prud'Homme should therefore indicate the same pattern than the observation done by Meteo France since they are placed nearby. The fraction of positive identifications was calculated like described above. This has been done without considering the quantity of the precipitation.

At Dome C for the visual observation, some corrections for inaccurate data and eliminations of precipitation events have been done where the layer thickness on the plate was too small to be measured.

4. Results Models

The Antarctic is a very dry region. Especially the precipitation quantities at the plateau are assumed to be very little due to the dry and cold continental air. The amount of precipitation at the coast is expected to be more important since the moist air from the sea arrives at the colder continent and condensates close to the coastline. A decrease of the amount of precipitation from the coast towards the interior of the Antarctic seems to be reasonable. All the models correspond with lower quantities over a large part of the plateau (fig. 4.1).

The precipitation frequency (numbers of days with a recorded precipitation event divided by the total numbers of days) is calculated with the software Ferret for all mentioned models. The different solutions demonstrate similar results for the ocean and the coastal area. Over the sea, a frequency of the precipitation events up to a range of 90% to 100% (dark red) is shown for all models (fig. 4.1). In other words, that implies the registration of precipitation episodes daily for the considered period of 18 years. The frequency distribution does not give any indication about the quantity.

4.1 The different models in more detail

The output of the MRI model demonstrates a strong simplification at high latitude where the precipitation event rate reaches almost everywhere a value of 90% to 100%. This is obviously an overestimation. The MRI model is not considered because of its low quality in the Antarctic region and therefore it is not displayed in Figure 4.1.

The model of MIUB and the IPSL show quite similar results for the polar region and on a world map. Nevertheless, differences are present due to the lower resolution of the MIUB approach. The statistics of the precipitation are in good agreement between the two models.

The LMDZ, shows a similar distribution than the two mentioned models above. Slightly more precipitation is falling in the coastal area and over the open sea in the LMDZ output. The frequency of the events does not appear lower. That means, for the LMDZ climate model, a somewhat higher average of the precipitation quantity is reached for the Antarctic region.

For the ECMWF, the precipitation events are more seldom than in the other simulations. Looking at the quantity distribution the amount of precipitation seems to be lower than elsewhere too. Considering again the statistical values extracted by Ferret, this assumption of lower quantities and lower frequencies of the events in the ECMWF result is confirmed. The daily average of precipitation for the Antarctic region of 0.7m/day for the ECMWF is well below the daily average of around 1.0 m/day for the other models.

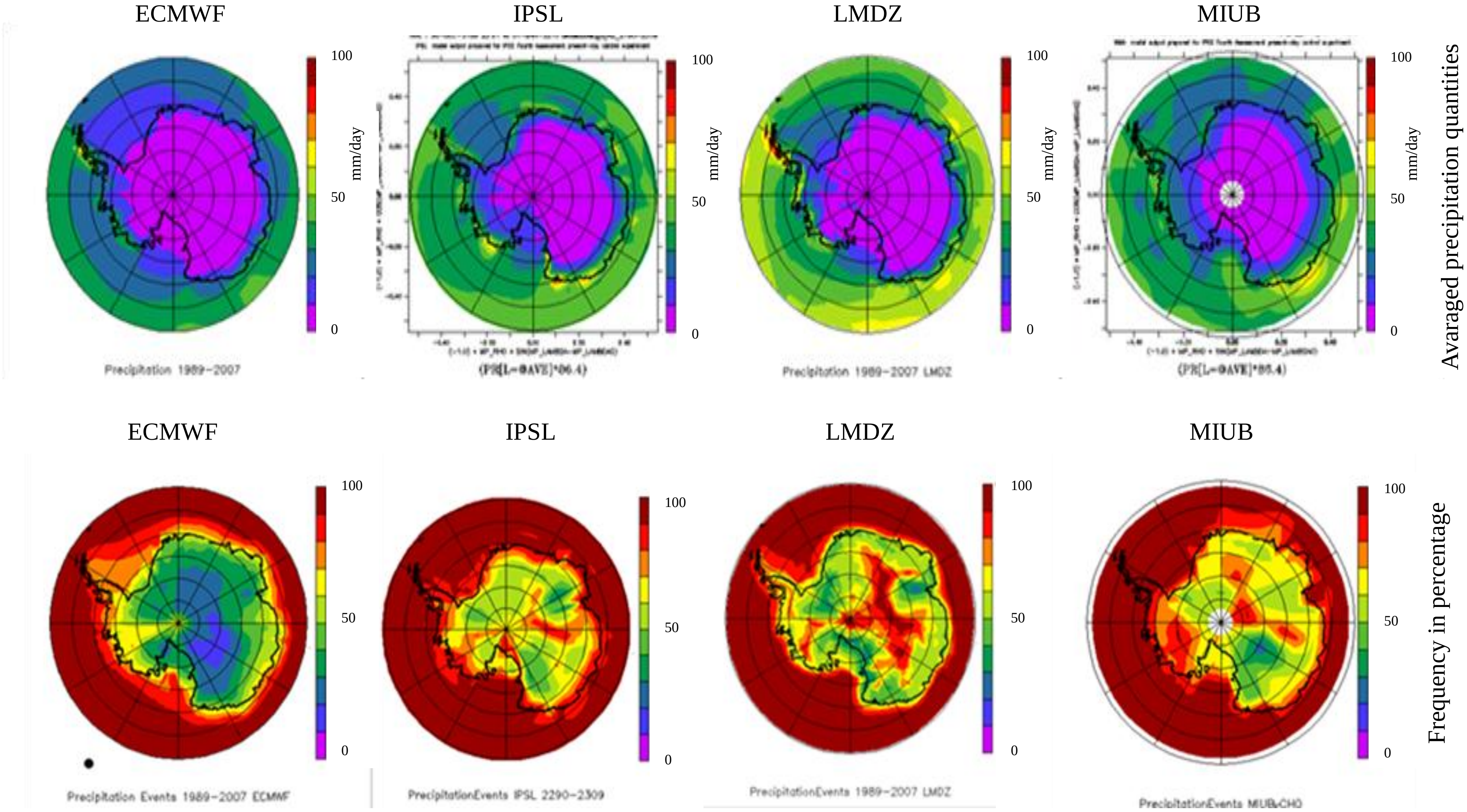


Fig. 4.1: On the top row, the precipitation quantities are daily averaged over the period 1989 to 2007 for the different models. On the bottom row, the frequency of the precipitation occurrence for the same period (number of days with a recorded precipitation event divided by the total number of days) is mapped in percentage.

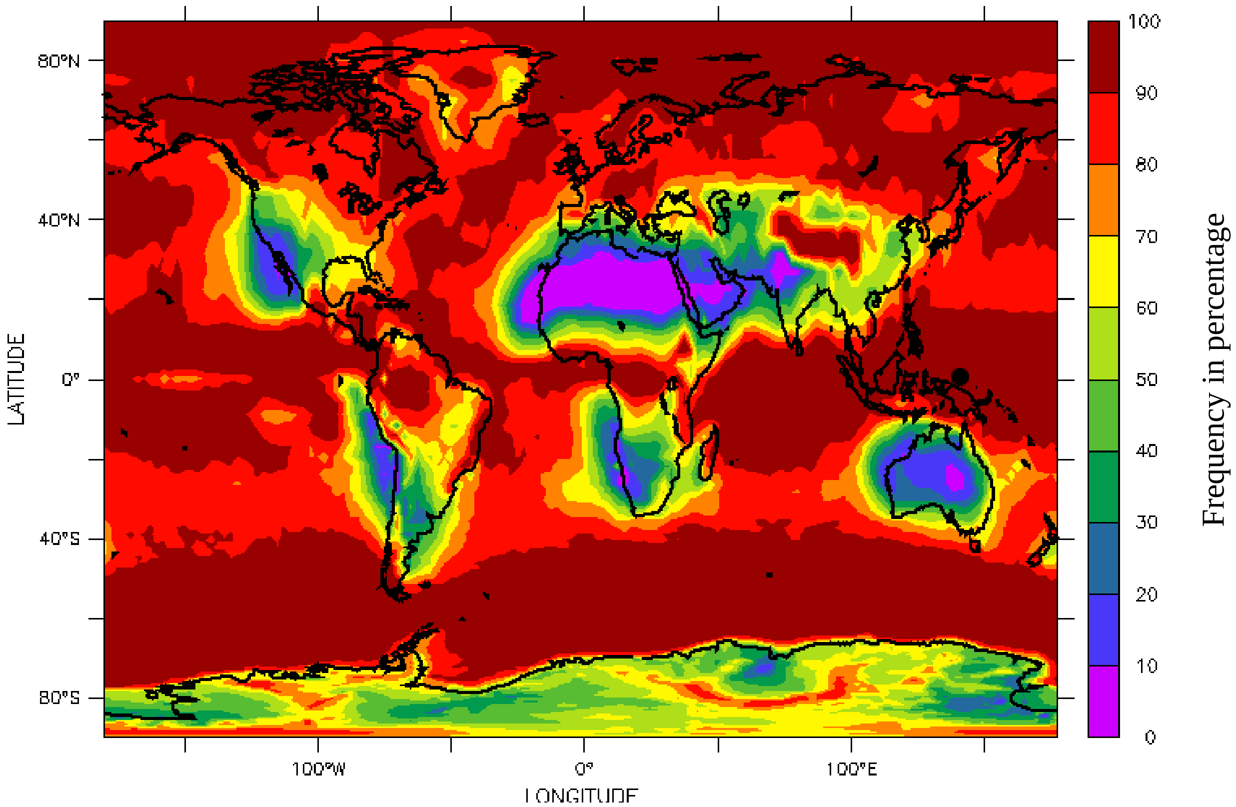
4.2 Global model: LMDZ vs. ECMWF

By modeling the precipitation events for one year (2003) over the entire globe, remarkable regional differences appear between the two considered models, the ECMWF and the LMDZ (fig.4.2). The precipitation frequency seems in general to be higher on the LMDZ. This characteristic is even more pronounced at high latitude and in the interior of continental areas. In the LMDZ climate simulation, Greenland, Mongolia and China show a very high occurrence of rain- and snowfall. With higher latitude than 40° N, the frequency map displays at least a value of 80% of all the days with precipitation but reaches easily up to 100% of event occurrence. For around 90% to 100% of the days in 2003 precipitation was recorded for the Alps. An overestimation seems evident. The model of LMDZ shows a low global resolution. It is based on regional improved simulations. A zoom should be applied on a certain region to increase the resolution quality. For this climate model run, the South Hemisphere and especially the Antarctic region seem better represented. If the IPSL global climate model is analyzed, the worldwide image is more or less identically to the result of the world map of the LMDZ but the IPSL does show a less precise simulation for the Antarctic.

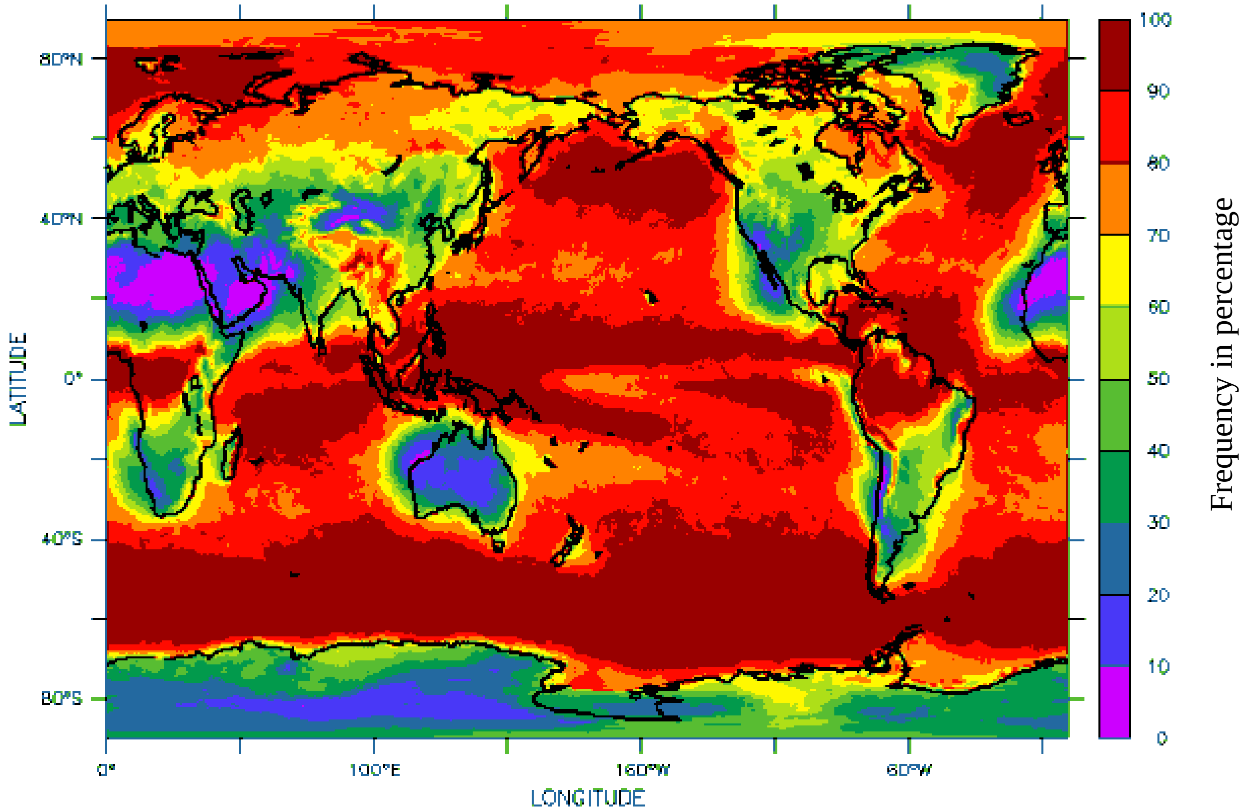
The ECMWF does show a much better resolved model for the frequency-distribution on the world map. The quite detailed and well represented solution in the mid-altitude region should be noted. For example, the plateau of China seems with a higher frequency to correspond well with the LMDZ but the distribution is much more detailed. Considering the precipitation events of the ECMWF, what might be the more appropriate model for the worldwide analysis since it is initialized by direct observation, the numbers of precipitation events in Greenland, Central Asia and for the Antarctic are much lower.

It seems to be evident that the inclusions of observations, which appear very precise for populated areas, lead to a good estimation of precipitation patterns. In regions where observation is less accurate like in the Antarctic, the ECMWF might show some problems when modeling.

Important to note is the good correlation between the two model`s solutions for Africa and the South of Asia. A good agreement is also reached for Australia, USA and for Middle and South America. The different distribution characteristics of the precipitation frequencies are over the globe recognized but much stronger pronounced at high latitude bands. The assumption, that the LMDZ tends to account the highest amount of precipitation out of smaller but more frequent events, whereas the ECMWF accounts small precipitation events less, was proved for the Antarctic region but might be also applicable worldwide.



Precipitation events in 2003 (LMDZ)

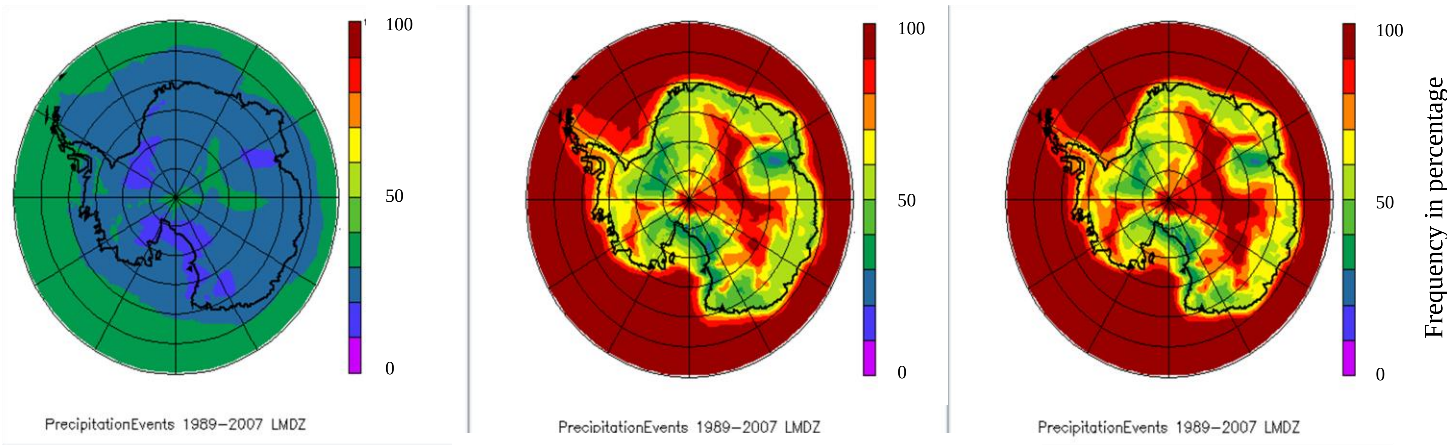


Precipitation events in 2003 (ECMWF)

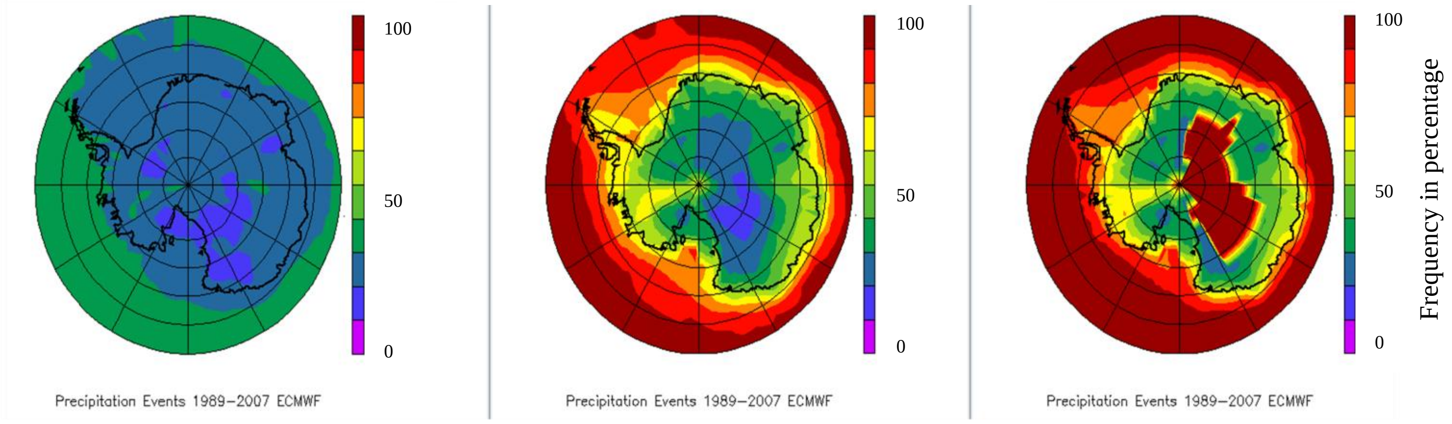
Fig.4.2: Top: the global precipitation occurrence for 2003 of the LMDZ climate model. Bottom: The forecast of the precipitation frequency for the world in 2003done by the ECMWF.

4.3 Comparison of the LMDZ and the ECMWF for the Antarctic Region:

Important to note is the difference of the LMDZ and the ECMWF on the Antarctic continent. The number of precipitation events with small quantities is recorded to be very high on the plateau. Temperature inversion at the surface can lead to a condensation of some crystals almost constantly. This inversion can occur in interaction to topographical characteristics, what might be well taken into account by the LMDZ, which displays a high frequency of small events over the plateau (described in more details in section 4.3.1). The analysis of the precipitation data of the ECMWF show a continuous decrease in precipitation frequency for medium size events the more inland in the Antarctic located. The model also seems to realize that the number of events increases for small events (fig. 4.3). The forecast of the ECMWF is not able to create a topographic differentiation on the interior of the Antarctic. It simply seems to fill out a more or less radial pattern of the precipitation event distribution outgoing from the South Pole.



Precipitation events 1989-2007 (LMDZ)



Precipitation events 1989-2007 (ECMWF)

Fig.4.3: The top row shows the frequency-distribution of the precipitation occurence in percentage for the LMDZ and the bottom row for the ECMWF. For the first column a threshold of 1, for the second of 0.01 and for the third of 0.00001 is set.

4.3.1 Topographical effect?

The LMDZ shows a particular distribution of the precipitation events what might display topographical interaction guiding the precipitation allocation. Unfortunately, no observation exists to prove this assumption.

The averaged quantity of the precipitation in the area is very little. Therefore, the quantity of each event must be extremely small. This phenomenon has been described as small, scattered crystals falling constantly from the sky. The question is now asked, if such small events contribute importantly or not to the total amount of precipitation at certain locations. Visual observation affirm an importance to these events and as we can see in figure 4.4 and 4.5 the amount of precipitation on the plateau due to such very small events makes up to 30% in the result of LMDZ.

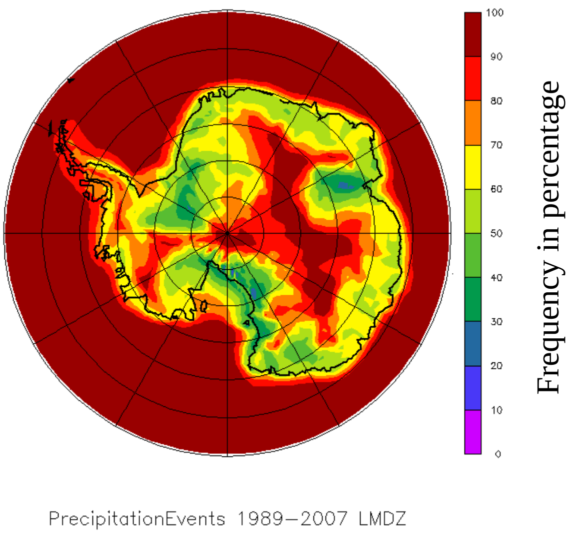


Fig. 4.4: All recorded precipitation event in percentage for the LMDZ. An increase of the frequency of the events becomes evident over the plateau. These distribution characteristics might follow a topographical relief.

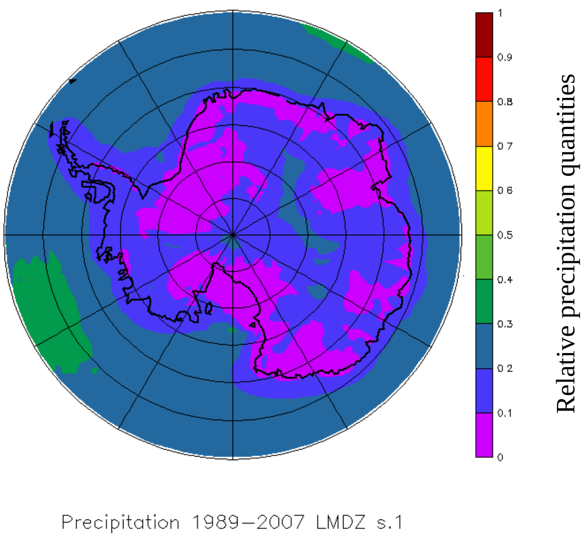


Fig.4.5: relative precipitation amount (daily precipitation/ average daily precipitation of 1989-2007) with a threshold of 1 (daily precipitation/average of the precipitation of all days = 1).
The precipitation smaller than the daily average precipitation over the period of 18 years contributes around 10% to 30% to the total precipitation recorded on certain locations on the plateau for the LMDZ.

The high number of precipitation events over the crests on the plateau could be due to the temperature inversion above the extremely cold surface of the Antarctic what creates catabatic winds blowing downhill along the flanks of a mountain. These winds pull warmer air from the atmosphere into the colder layer near the surface. When the warm air arrives, condensation of a few crystals takes place.

These particular features of the event distribution seem not to be respected for the precipitation event distribution in the ECMWF forecast (fig 4.6). The ECMWF does not show clear distinguished topographical details on the entire plateau. A more regular distribution is found. The ECMWF does not show significance for small quantity events considering the total precipitation (fig.4.7).

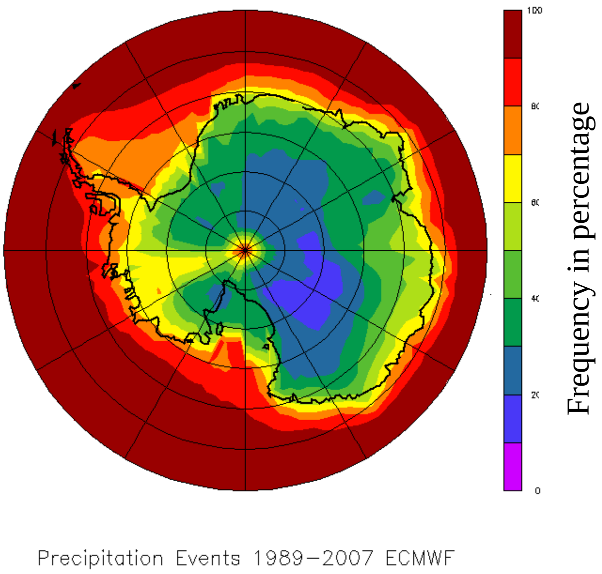


Fig.4.6: The precipitation event distribution modeled by the ECMWF in percentage does not show a clear topographic effect.

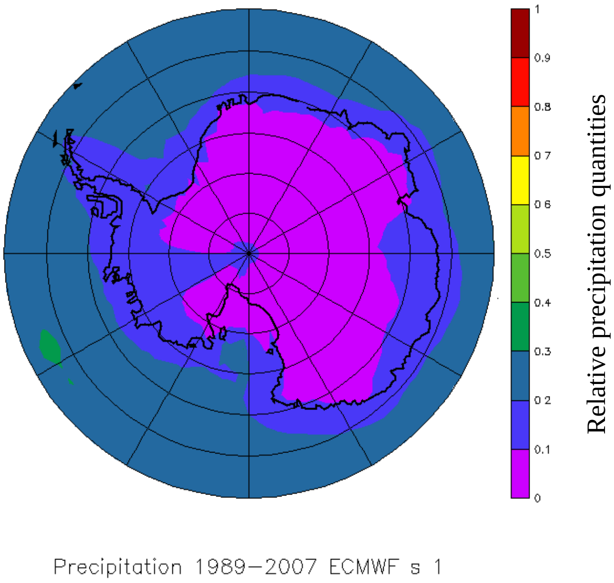


Fig.4.7: relative precipitation amounts with a threshold of 1 (daily precipitation/average of the precipitation of all days). The precipitation smaller than the daily average precipitation over the period of 18 years contribute not significantly to the total amount for the ECMWF. The contribution shows almost over the entire plateau less than 10%.

4.4 Big events vs. small events

By setting thresholds on the amount of precipitation that is needed to define a precipitation event the contribution of small and large events to the total registered amount of rain-and snowfall should be pointed out for each of the two models. A threshold of one signifies that the amount of precipitation at that certain day equals the daily averaged quantity of the period 1989 to 2007. With setting a threshold of one consequently all the events smaller than this mean value are analyzed (fig.4.5 & fig.4.7).

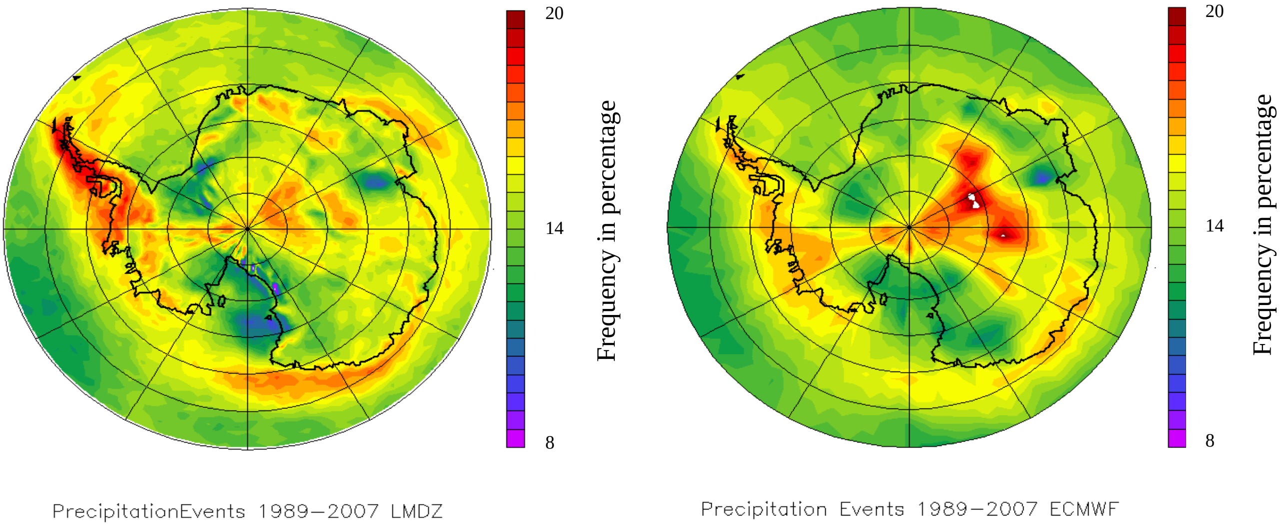
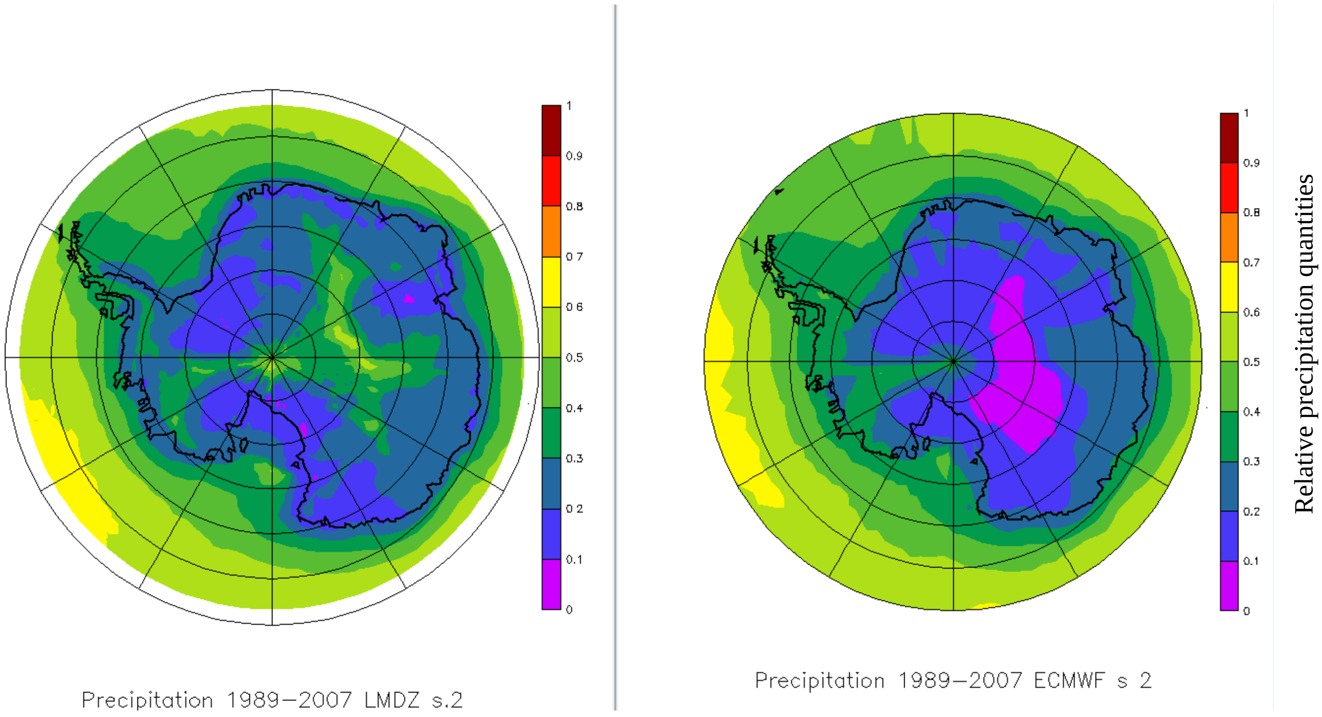


Fig.4.8: Precipitation event distribution for a threshold of 2 for the model of the LMDZ and the ECMWF. The simulations show a quite similar pattern. The scale reaches from 8% to 20% for both models.

For a medium threshold of up to 2 (events with double as much precipitation falling in one day than the daily average over the considered period) a comparable pattern of the frequency distribution for the two models is demonstrate (fig. 4.8). There are some incoherencies in the distribution of the frequency of the precipitation events found between the two models but the general trend is similar. Characteristic is the increase of events in the interior of the plateau for the LMDZ and for the ECWMF output (fig. 4.8). Medium and small events (smaller than two times the average) account for the LMDZ up to 60% of the entire precipitation in certain areas (fig. 4.9). The LMDZ register therefore small events with an important contribution to the total amount of precipitation. The ECMWF displays increasing frequency for smaller events over the plateau with a decreasing quantity (fig. 4.8 and 4.9). The quantity of the precipitation recorded by events smaller than the double of the daily average (threshold of 2) becomes extremely small for certain regions. High frequency is present but the amount of snowfall does not exceed more than 10% of the total precipitation quantity on the centre of the plateau. Already for medium size events, the quantity contribution does strongly differ between the both models. Apart from the medium values, the two models develop into an opposite tendency considering both, the frequency distribution and the quantity partition.

A small threshold of one seems to show the topographical guided distribution of the precipitation event for the LMDZ. For high thresholds (showing only the strong precipitation events) that feature is recognized too. At medium values, the distribution of the amount of precipitation is more homogenized and very similar to the one of the ECMWF, who is showing a more regular distribution for every event size.



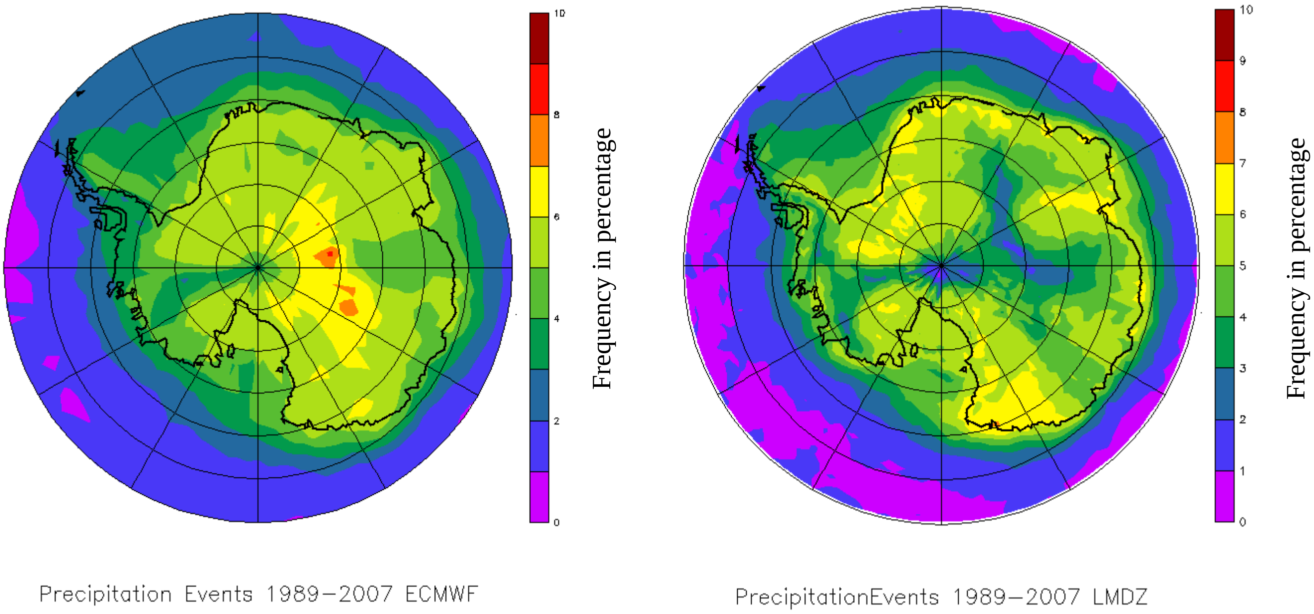
Precipitation 1989–2007 LMDZ s.2

Precipitation 1989–2007 ECMWF s 2

Fig.4.9: The quantity map of precipitation with a threshold of 2, shows that most amount of precipitation is due to events stronger than two times the daily average on a large part of the plateau. For the ECMWF very small events do not contribute to the entire amount of precipitation remarkably (purple area). For the LMDZ, small-scale events are influencing the quantity of precipitation in the interior importantly (green to yellow on the plateau).

If increasing the threshold we would assume a decrease of events certainly over the plateau (fig. 4.10). The models show a lower percentage for strong events. The LMDZ still shows that assumed topographical interaction but with an opposite trend: the number of large events is very low in the inland and especially over the mountain crests in the interior almost no big events occur and roughly nothing of the entire precipitation quantities is recorded from such large rain- and snowfall episodes (fig. 4.11). There are more strong events at the coast. Surprisingly the ECMWF model demonstrates the opposite and more strong events are predicted over the plateau than in the coastal region. These few but large events on the plateau contribute importantly to the total amount of precipitation in certain locations (fig. 4.10 and 4.11).

With the illustrations in the annex (section 9) the important differences in the trends of the models of the LMDZ and ECMWF considering the frequency distribution and the relationship of the quantitative contribution are pointed out.



Precipitation Events 1989–2007 ECMWF

PrecipitationEvents 1989–2007 LMDZ

Fig.4.10: The frequency distribution for events with large amount of precipitation shows a decreasing tendency for the LMDZ the more inland one goes. On the contrary, an increasing number of such strong events are counted for the ECMWF for the same location. A threshold of 5 was set (events with 5 times as much precipitation falling than the daily average). It should be noted that the scale only reaches from 0% to 10% that means the total occurrence of large events is rather small.

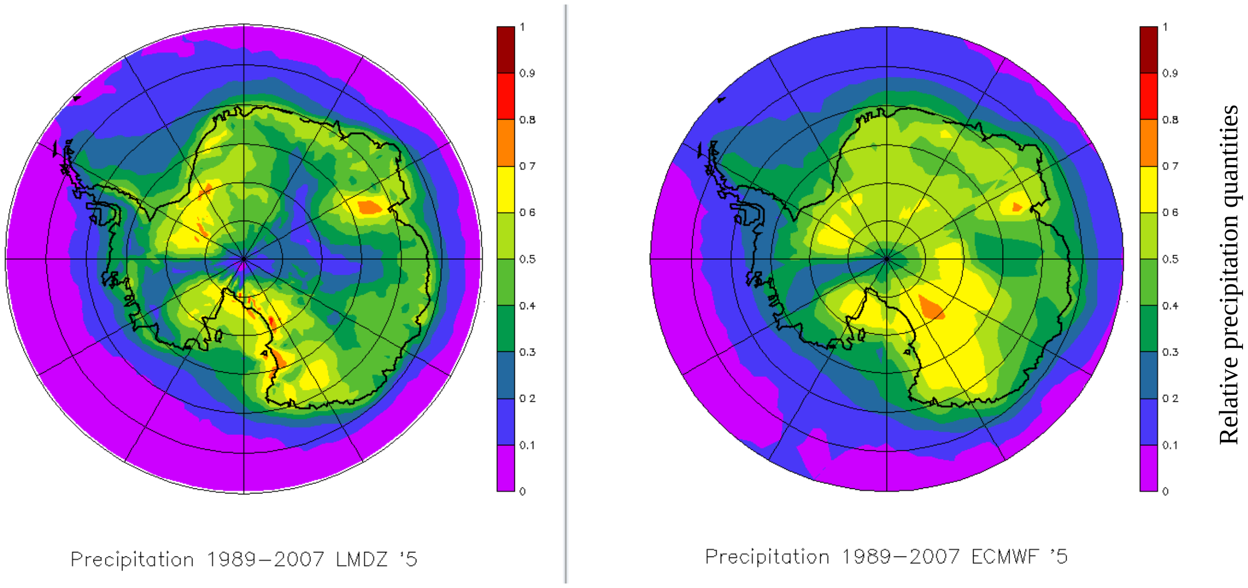


Fig.4.11: All the events larger than 5 times the daily average value from 1989 to 2007 are drawn on the figures. Large events contribute only around 20% for the interior of the plateau in the LMDZ climate simulation. For the EMCWF the contribution to the total quantity of such large events reaches at the same location conversely up to 60%.

4.5 GPCP

The precipitation data of the GPCP has been treated the same way as for the above-mentioned models. The used data are purely observation based. For region with a good satellite cover, the GPCP result seems to be very accurate. Since the quality and the quantity of measurements are rather poor in the Antarctic region, no striking results were expected.

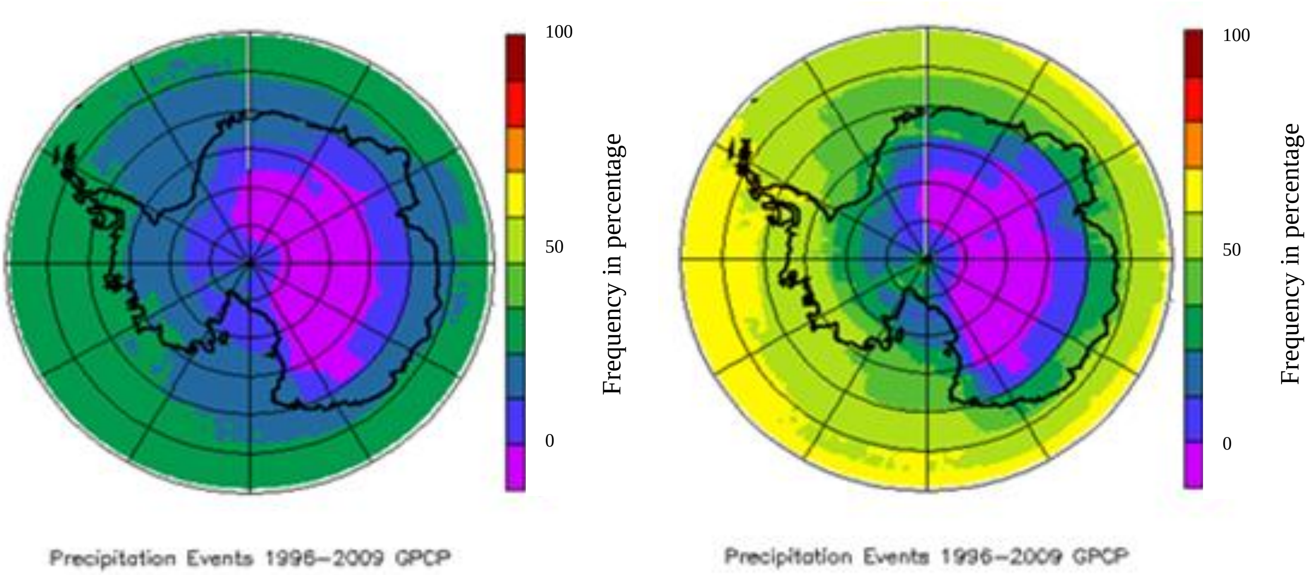
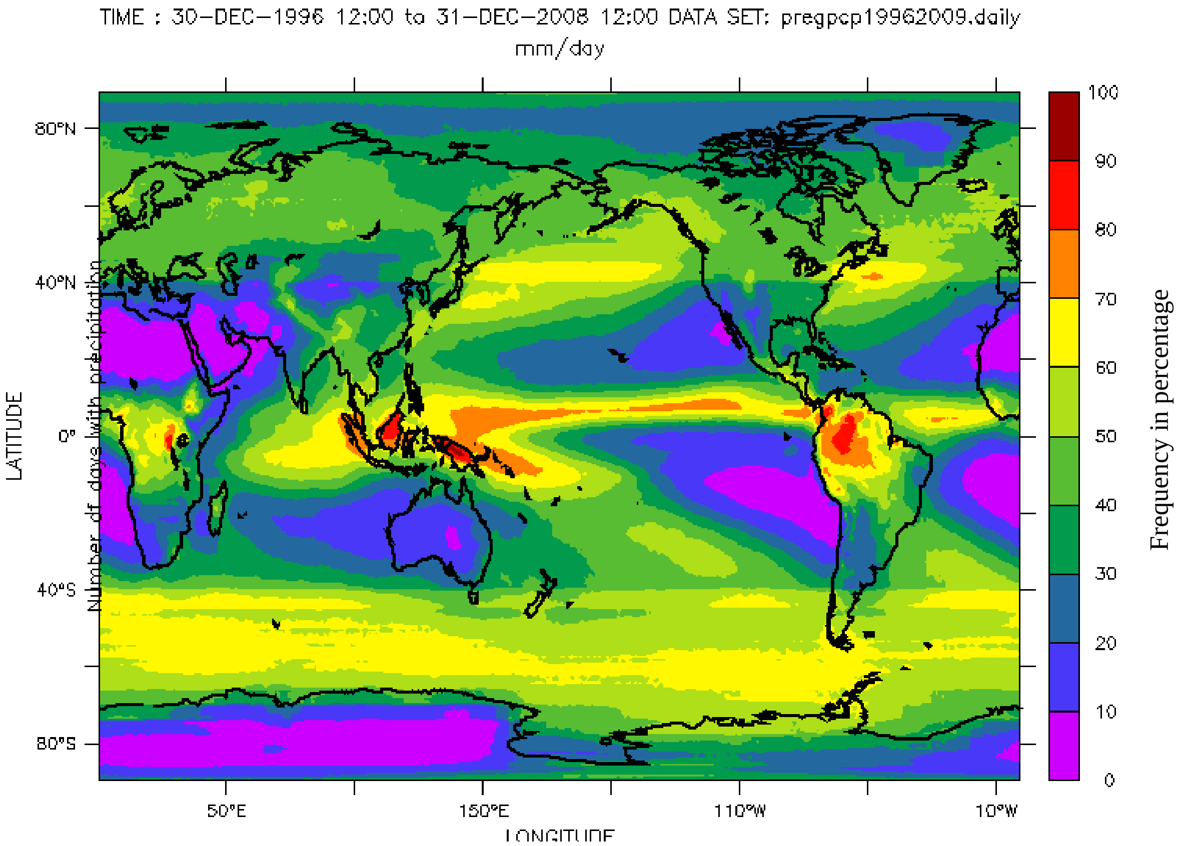


Fig. 4.12: The precipitation event distribution predicted by the GPCP with a threshold of 1,0 and 0,00001.

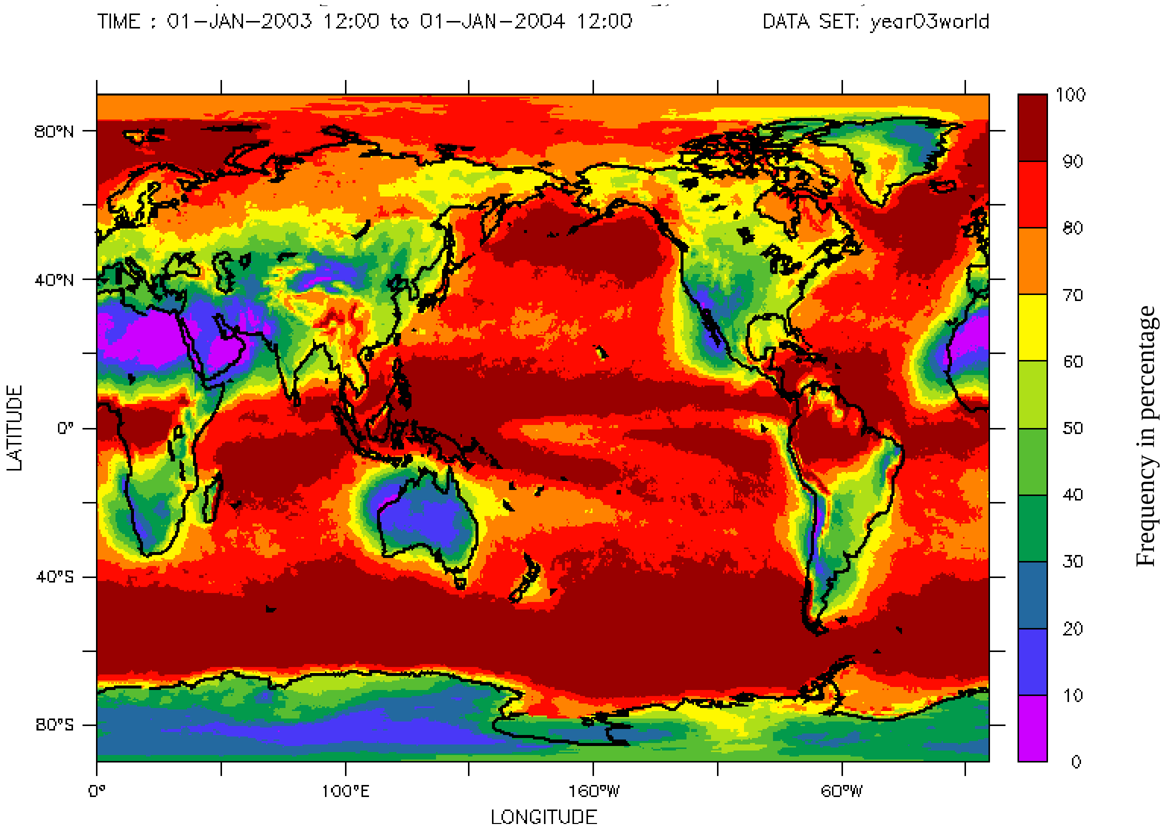
The Figure above shows the GPCP mapped data for the Antarctic. The number of precipitation events averaged for the period 1996 to 2009 in figure 4.12 seem to be underestimated compared to the before treated models. Especially over the ocean the numbers of events only reaches up to 70% averaged over a time period going from 1996 to 2009 whereas in all other models a value of 90% to 100% over almost the entire oceanic surrounding of the Antarctic continent was calculated. The estimation for the plateau appears much lower, where as the coastal area might not be too much out of range but still lying around 10% under the expected values by the other models. The interior of the plateau shows only 10% of all the days considered to have recorded precipitation events. This should be too low and an underestimation over the plateau of the precipitation frequency can be assumed. If we consider other models that show an increasing number of events with low quantities in the inland, the GPCP leads to an opposite conclusion of a very dry plateau with extremely little amount of precipitation occurrence. Such an image however is not surprising since the observation data must be very scarce for the Antarctic.

More surprising are the modeled values of the ocean what clearly demonstrate lower frequency than all model predictions considered earlier in these studies. The same can be discovered for the image of the entire world (fig. 4.13). Especially the frequency of precipitation events over the ocean shows up to 80% less precipitation than the ECMWF solution. On the globe, a good agreement is found for continental regions of the mid-latitude like Africa, Australia, Central America, Southern USA and the northern part of South America. The high latitude bands show a strong disagreement between the GPCP output with the ECWMF and the LMDZ model. The GPCP data shows much less precipitation events.

Some locations show an opposite trend such as the equatorial oceanic region. The GPCP shows a very high frequency in the Atlantic around 0° latitude whereas the ECMWF and the LMDZ explain a tendency for decreasing numbers of event. For China and Mongolia, the GPCP simulates a very low number of events for these dry areas. The other two models show a very high frequency almost reaching a range of 90% to 100% over the same area. The strong differences are illustrated in figure 4.13.



Precipitation events average of 1996-2009 (GPCP)



Precipitation events in 2003 (ECMWF)

Fig.4.13: The global model of the precipitation frequency. On the top for an average of the period 1996 to 2009 of the GPCP data and on the bottom side for the ECMWF a prediction for the year 2003.

5. Results Observation

5.1 Observation Cap Prud'Homme

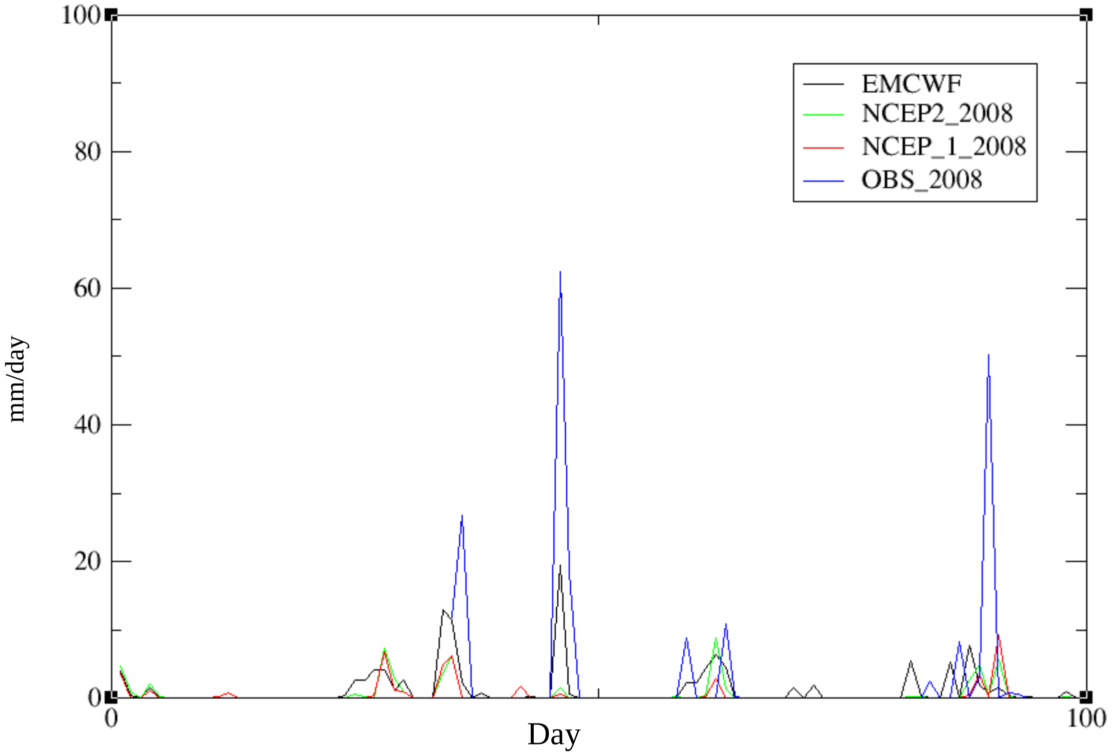


Fig. 5.1: Comparison of the precipitation occurrence at Cap Prud`Homme predicted by the ECMWF (black) and the NCEP (red and green) as well as measured by the Biral ((OBS_2008), blue) in the first 100 days in 2008.

In the plot (fig. 5.1) the observed data and model predictions have been traced to test the correspondence of the model results and the direct measured data that origins from the visibility sensor (Biral VPF-710(730) VISIBILITY SENSOR) installed close to the coast at Cap'Prud Homme. Primarily, the model of the European Center of Mid-Range Weather Forecast (black) has been chosen to be plotted with the data of the Biral (blue). To see the difference to another precipitation analysis the data of NCEP (green and red) has been included. The values of the NCEP seem to be underestimated in direct comparison with the EMCWF. The amplitude of the precipitation amount per day measured by the Biral and predicted by the ECMWF in mm/day is not good correlated. A strong underestimation in comparison with the extracted values of the Biral can be found for the ECMWF and even a greater miss-correlation occurs for the NCEP model. The values of the observed precipitation amounts with the visibility sensor are much higher than the model predictions. A measured maximum value by the visibility sensor for 2009 reaches up to more than 250mm per day at Cap Prud`Homme, whereas the highest modeled value (for both models EMCWF and NCEP) not even reaches 50mm per day for the same year and the same location.

However, the correlation of the appearance and the timing of precipitation occurrence lasting for a period of 2 to 3 days or longer are surprisingly good (fig. 5.1). In the beginning of the year for January to March, the indicated precipitation events by the different models and the observation results show a good agreement so that the graphs lie more or less on top of each other. Later in the year, the accordance decreases strongly.

Since the NCEP model does not give a more convincing image then the ECMWF, it was not considered in further investigation. The model does neither especially correlate with one of the other investigated models, nor with the observation data.

Unfortunately, it is very difficult to make significant statements about the distribution by interpreting the results of the direct measurements for one year since there is a great lack of data because of problems and several breakdowns of the VPF-730. On Figure 5.2 no data was registered between day 57 and 140 and with day 199 the data series stops for the Biral measurements at Cap Prud`Homme for 2009. Considering the small pieces of complete data, it can be concluded that the observed precipitation events by the Biral are less frequent but an event occurs with a higher quantity than predicted by the models. The results of the mid-range forecast show a higher frequency of smaller and more regular events.

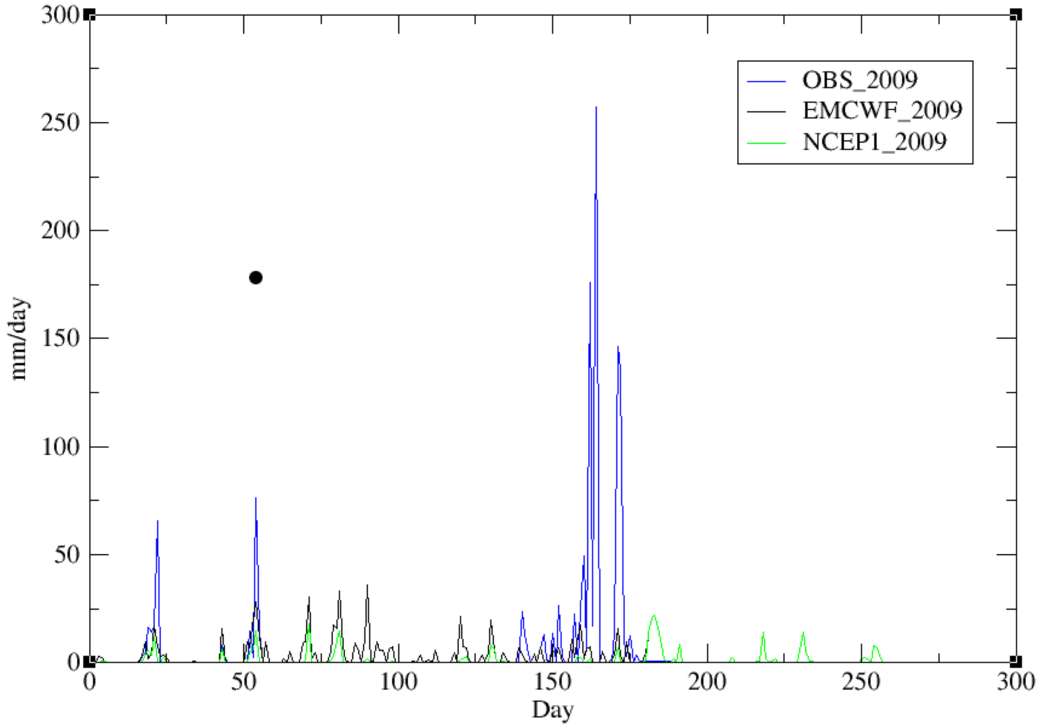


Fig.5.2: Considered for 2009 are the models of EMCWF (black) and NECP (green) for comparison with the results of the direct measurements of the Biral ((OBS_2009) blue). Especially for the beginning of the year a good correlation in the timing of the events seems to be achieved.

The calculated fraction of days with a correspondence on the events for the Biral and the ECMWF are shown in Table 1. This comparison should draw out how good the accordance of the methods appears. First, no threshold was set what led to a very weak day-to-day correspondence of 52% between the Biral data and the ECMWF prediction. With introducing a threshold for the ECMWF of 1mm/day on the amount of the daily precipitation, the fraction of positive identifications increased only slightly to 55%. For this location, the corresponding days of the ECMWF and the Biral show an equilibrate fraction of precipitation-days and non-precipitation-days with 45 days with recorded precipitation and 47 days with no listed precipitation event for 92 corresponding days in total.

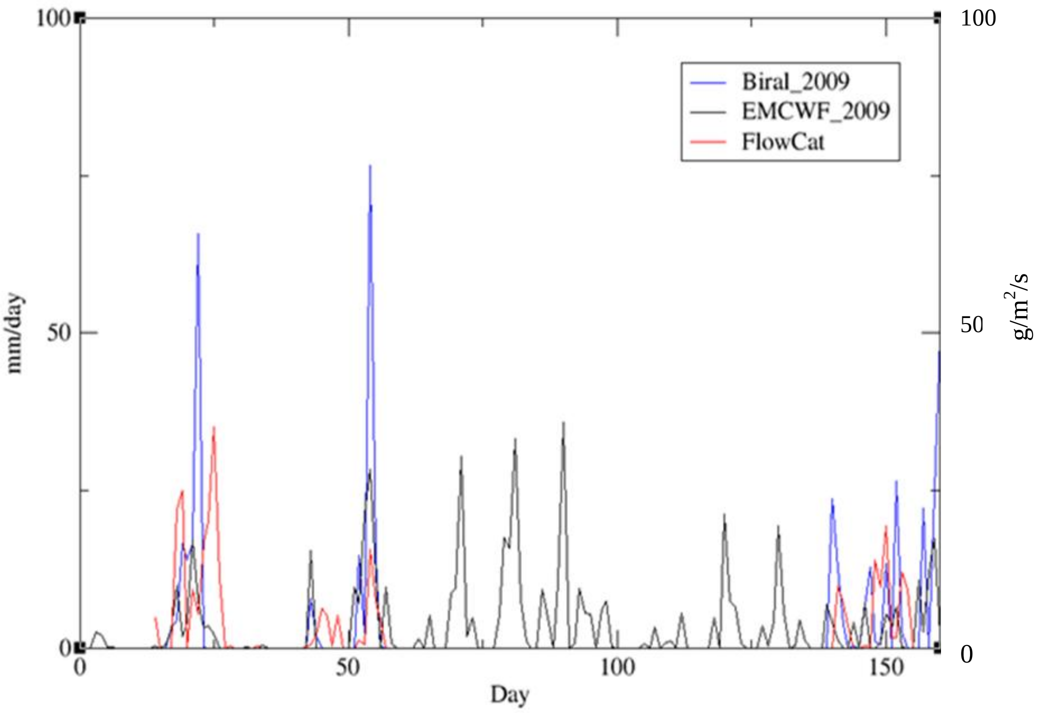


Fig.5.3: In addition to the models and the Biral correlation, as well the data of a FlowCapt in red in g/m^2/s was included in to the plot for the study site of Cap Prud`Homme for 2009.

Additionally collected data of a FlowCapt, that measures the blowing snow, should lead to conclusion about the overestimated amplitude of the Biral measurement (fig. 5.3). For every high FlowCapt value, it is assumed that the Biral next to the precipitation quantities also measured the blowing snow and could therefore show much higher amplitude than the prediction of the ECMWF. After some correction of the Biral data by comparing them with the FlowCapt and the ECMWF data (applied corrections are described in section 2.2) the fraction of corresponding days increased importantly to 86% (table.1). The interpretation after these corrections needs to be handled carefully since they cannot be proved but only assumed.

Cup Prud'Homme: **Fraction of positive identifications**	Pure Correspondence	Threshold for the ECMWF 0.5 mm/day	Threshold for the ECMWF 1.0 mm/day	Correction on occurrence and threshold for the ECMWF 1.0 mm/day
ECMWF-Biral	0.52	0.54	0.55	
ECMWF-Biral corrected with the FlowCapt (threshold for the FlowCapt: 1g/m^2/s)	0.65	0.70	0.86	
ECMWF-Visual Observation (Meteo France)	0.57			0.82
Biral-Visual Observation (Meteo France)	0.72			

Table.1: Day-to-day correlation of the different observation and the ECMWF for 2009 at Cap Prud`Homme.

Additional to the FlowCapts and to the Biral data some visual observation of precipitation events has been done at Dumont d'Urville by Meteo France. The correlation of the data set with the ECMWF and the data of the Biral give a good correspondence in the timing of the event in 2009. The day-to-day correlation without any treatment gives a first value of 57% corresponding cases between the visual data and the ECMWF. Out of this 57%, for 22% of the days, precipitation has been observed by Meteo France and by the model predicted. The other 35% show days where no precipitation was observed by both methods. The ECMWF shows many more cases. There might be some missed events by the visual observation of Meteo France and a tendency of the ECMWF for more frequent smaller and regular events. To avoid noise for too small events a threshold of 1mm/day was introduced for the ECMWF as well as some manual corrections have been done described in section 2.2. For events during 3-4 days or longer the ECMWF predicts successively a day with no precipitation in such longer during precipitation occurrences, whereas the observation shows that also on that day at least a small quantity of precipitation occurred. In such cases, a mistake in the model has been assumed. This problem might be regarded as a weak point of the ECMWF analysis. The final 82% of correlating days considering all this corrections shows therefore a quite good correspondence in the timing of the events between the visual observation and the ECMWF (table 1). The amplitude of the events was only considered to set thresholds on the data. That value has to be handled carefully, since quite strong corrections were applied.

The correlation of the visual observation of Meteo France and the Biral data shows that without any treatment, 72% of all days correspond with the same event information, of which 27% of the days recorded a precipitation event on both sets and 45% of all cases are non-event days (table 1).

5.2 Observation at Dome C

The occurrence of the precipitation events visually observed at Dome C are compared with the data from the Biral installed at the same location and from the ECMWF precipitation analysis for 2009. The visual observation at Dome C indicates slightly more events than the measured values of the Biral. In a first step, comparisons have been done without setting a threshold. The fraction of the days with a correspondence was calculated to be less than 30% for all three data sets, a day-to-day correlation of 48% between the ECMWF and the visual observation and only a 51% correlation between the Biral and the visual precipitation observation could be found. If a threshold of 1mm/day for ECMWF was introduced the correlation between the ECMWF and the Biral increases as far as 65% for the fraction of positive identification.

The final correlation for the adjusted and corrected data shows a correspondence of 69% of all days between the ECMWF with the visual observation and value of 65% between the observation and the Biral data. Amelioration can be recognized for the correlation of the Biral and the visual data set.

To see the contribution of the fraction of the days with precipitation and the days without precipitation in relation to the total corresponding days, further investigation were done. Unfortunately, only two events of the 46 corresponding cases showed a precipitation event for the result with a threshold of 1mm/day for the ECMWF data and after applying the above mentioned correction of the other data sets. All other days correspond in no recorded precipitation. This does not speak for a good day-to-day correspondence and unfortunately, the final conclusion shows that we cannot use one or another method to confirm or correct the models or the instruments observation at Dome C. The correlation between the results is not well enough to make concrete statements.

6. Conclusion

After these studies, important differences of the model solutions became evident. So far, the observation data that was available do not represent accurate sets of precipitation characteristics and remain restricted on a small spatial extension with an irregular distribution. They cannot be used to judge over the model's quality. Conclusions only can be done on the order of magnitude-estimates. Clearness is not allowed since the accuracy of the data is too uncertain and the data set is temporally and spatially too limited.

Two kinds of models were tested. On the one hand pure climate models were analyzed, which show in between each other already dissimilarities. On the other hand short-term predictions initiated by observation were used. The main difference of these two ways of modeling the climate is this initialization of the simulation by observation versus pure modeling. The inclusion of observation seems clearly to improve the results for regions were accurate direct measurements are available. For territories like the Antarctic were good observations are seldom and rather low in quality such an inclusion does not remarkably improve the model.

The investigation was focused on the climate model of the LMDZ and the precipitation analysis of the ECMWF. A striking difference was found in the opposite way of the treatment of small, frequent precipitation events and more seldom big events. The ECMWF does attribute a large part of the precipitation quantities to big events whereas the LMDZ underlines the important contribution of extremely small precipitation events. The two models state the contrary of the characteristics of precipitation, what shows that at least one of the two simulations does not represent the real conditions very well. Unfortunately, a judgment of the two solutions is very difficult and only based on speculation since there is not enough precise information available to reach clarity.

A third type of precipitation reconstructions considers the solution provided by the GPCP. This displays only observation data. By comparing the global GPCP distribution to the data of the LMDZ and the ECMWF, a surprising different result is shown. It seems that the climate models and the precipitation analyses overestimate the precipitation frequency globally if we assume that the GPCP does show the real conditions registered in its observation. The correctness of the GPCP can be doubted for regions with a scarce amount of observation data but for regions with good measurement sets, a good approach can be expected. Nevertheless, the so far available data does not allow a clear conclusion about the accuracy and incoherency of the different models.

The various observation techniques considered can unfortunately not be used to make significant argumentations. It needs to be accepted that the observation techniques displays too variable results in comparison with each other and the correspondence with the model prediction is limited. It might be more significant if a larger collection of data could be obtained in the future. Until now, some suggestions and estimations over the quality of the different instruments and methods can be done but these are only supposition and cannot be doubtlessly proved.

The FlowCapt, indicating blowing snow seems to work quite well for the information if blowing snow is present or not. The quantities cannot be measured.

The visibility sensor, Biral VPF-730 seems to deliver quite good data in order to count precipitation events and blowing snow together. A problem is still present in distinguishing precipitation from blowing snow by measuring speed and size of the particles. In general, the frequency seems underestimated and the amplitude overestimated or the other way around that the model overestimate the precipitation occurrence and underestimate the quantity of each event.

It is suggested that the Biral data shows a too low number of events with too high amplitudes. In contrary, the climate models and the forecasts seem to model a too large number of events with an underestimated quantity of precipitation. A simulation showing the middle value of these two solutions might be a reasonable way to represent the real conditions.

To sum up the main conclusion of the work, a final statement can be formulated saying that we do not know if the direct measurements of the precipitation and its observed distribution patterns are doubtlessly correct. We also do not know if and which of the models show the best approach to represent the real conditions in the Antarctic. What we know is that the models show fundamental differences in their solutions but keep their results in more or less realistic ranges. An improvement of such models should be focused. It seems convincing that such comparisons help to identify problems of certain models but also advantages and disadvantages of the individual simulation can be discovered. It is important to keep improving the measurement techniques to find a possibility to collect accurate data sets of longer duration to verify the climate models and mid-range forecasts.
Investigating the precipitation distribution is a difficult task but a task with very interesting aspects. The complexity of the system becomes evident and it is aimed to capture an understanding of this complicated system. Neither the observation alone nor pure modeling or forecasting seems to lead to a complete result. The combination of the different methods might lead to better understanding in the future.

7. Acknowledgment

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8. Bibliography

Berrisford P., D. Dee, K. Fielding, M. Fuentes, P. Kallberg, S. Kobayashi, S. Uppala, 2009, The ERA-Interim archive, Version 1.0, ERA report series,

Bindschadler, R., H. Choi, Ch. Shuman, T. Markus, 2005, Detecting and measuring new snow accumulation on ice sheets by satellite remote sensing, Remote Sensing Environment 98, p.388-402,

Chitrin V., 1998, FlowCapt: un capteur dans le vent. Neige et Avalanches, 81, p. 13-15,

Chitrin V., R. Bolognesi, H. Gubler, 1999, FlowCapt: a new acoustic sensor to measure snowdrift and wind velocity for avalanches forecasting. Cold Regions Science and Technology, p.125-133,

ECMWF, 2009, Medium-range forecasts, technical report, ECMWF,

Eisen O., M. Frezzotti, Ch. Genthon, E. Isaksson, O. Magand, M.R. van den Broeke, D.A. Dixon, A. Ekaykin, P. Holmlund, T. Kameda, L. Karlöf, S. Kaspari, V.Y. Lipenkov, H. Oerter, S. Takahashi, D.G. Vaughan, 2008, Ground-Based Measurements of Spatial and Temporal Variability of

Snow Accumulation in East Antartica, Review of Geophysics, 46, RG2001/2008,

Genthon Ch., M.S. Town, D. Six, V. Favier, S. Argentini, A. Pellegrini, 2009, Meteorological atmospheric boundary layer measurements and ECMWF Analyses during summer at Dome C, Antarctica, Revision submitted to Journal of Geophysical Research,

Genthon Ch., G. Krinner, H. Castebrunet, 2009, Antarctic precipitation and climate-change predictions: horizontal resolution and margin vs plateau issues, Annals of Glaciology 50, p.55-60,

Genthon Ch., G. Krinner, M. Sacchettini, 2003, Interannual Antarctic tropospheric circulation and precipitation variability, Climate Dynamics 21, p. 289-307,

Gravaud I., 2008, Détection des événements de précipitation en Antarctique par télédétection micro-onde passive, Rapport de Projet Personnel,

Huffman G., D.T. Bolvin, 2009, GPCP One-Degree Daily Precipitation Data Set Documentation, technical report, Laboratory for Atmospheres, NASA Goddard Space Flight Center and Science Systems and Applications, Inc,

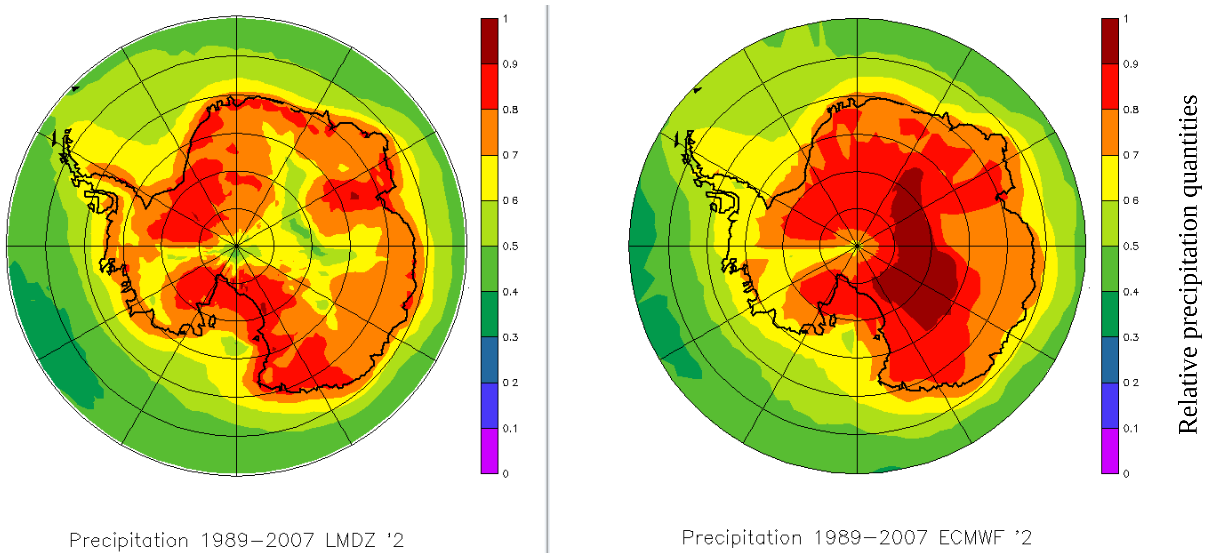
LMDZ, 2004, documentation, techincal report, LMDZ,

Magand O., Ch. Genthon, M. Fily, G. Krinner, G. Picard, M. Ffrezzotti, A.A. Ekaykin, 2007, An up-to-date quality-controlled surface mass balance data set for the 90°-180°E Antarctica sector and 1950-2005 period, Journal of Geophysical Research, vol. 112, D12106,

Randall D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007: Cilmate Models and Their Evaluation. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Trouvilliez A., 2009, Modelistation et Quantification de la Neige Soufflée en Antarctique, rapport du stage,

9. Annex



Precipitation 1989–2007 LMDZ '2

Precipitation 1989–2007 ECMWF '2

Fig.9.1: Regarding the quantity distribution of the events greater than 2 times the average, the different trends of the LMDZ and the ECMWF are very well displayed. The tendency of the LMDZ shows a weaker contribution of 40% to 60% by larger events of the entire quantity falling in the interior of the plateau. On the right side, the ECMWF prediction assumes a precipitation contribution of more than 90% for the same region by events greater than two times the average.

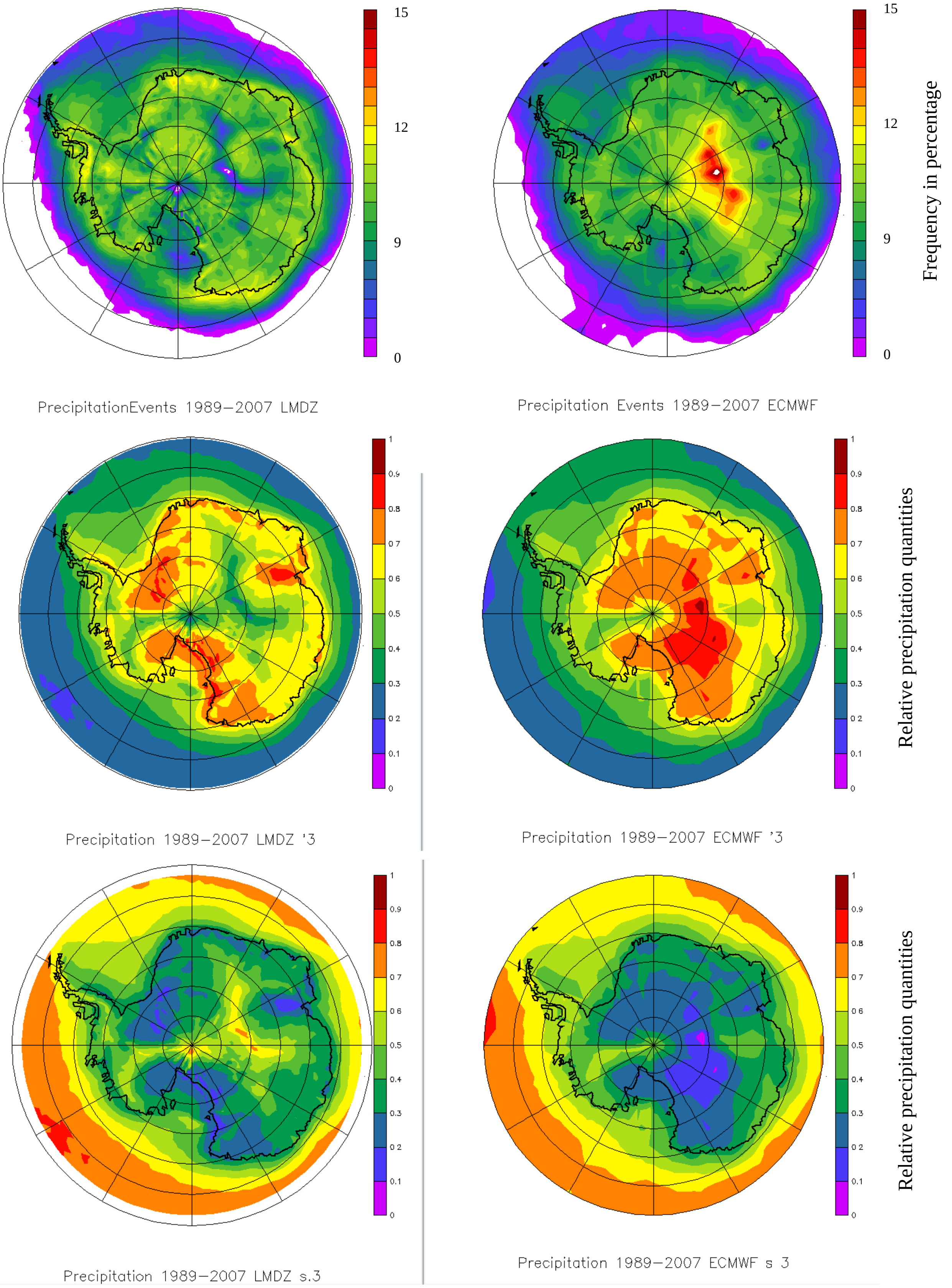


Fig.9.2: The same characteristics displayed for a threshold of 2 are also visible for the number of events with a quantity 3 times greater than the average (threshold of 3). On the top row, the distribution of the precipitation events is demonstrated. In the middle, the maps show the contribution to the total quantity of precipitation for events greater than three times the average and on the bottom for events smaller than three times the average.

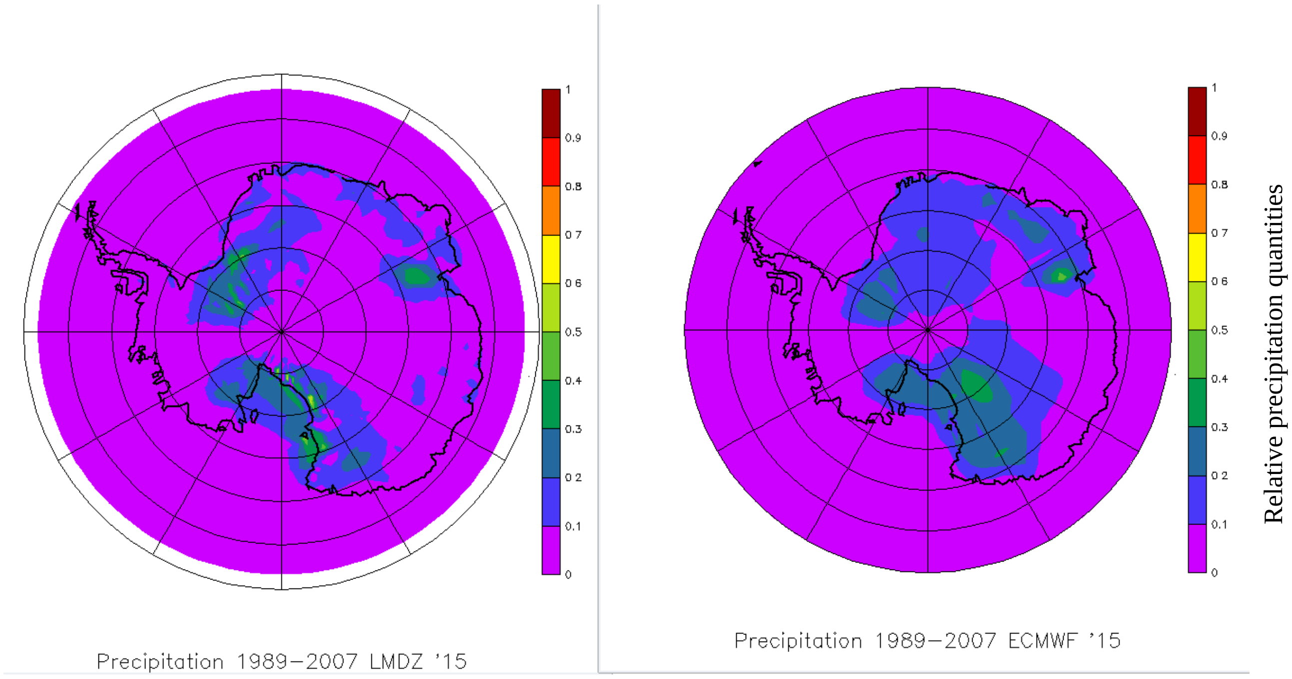


Fig.9.3: The quantity contributed by very large events (threshold of 15) is very little. Such big events are seldom in both models and occur manly at the west coast.