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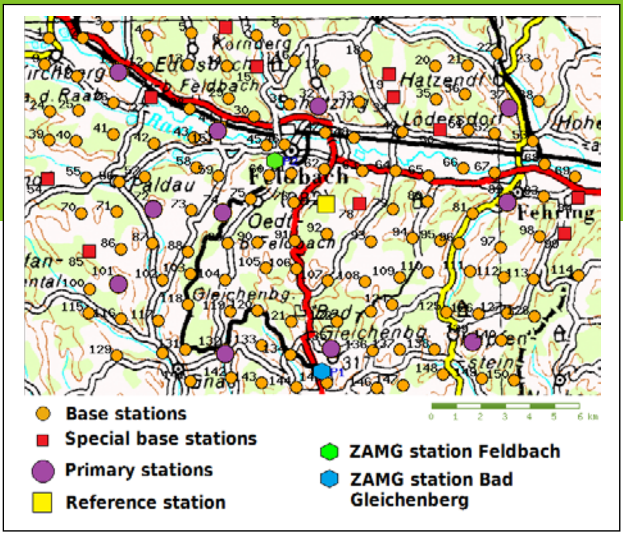

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Analysis of WegenerNet Precipitation Data and Quality Evaluation for Case Studies and Climatologies

Katalin Szeberényi

March 2014

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The **Wegener Center for Climate and Global Change** combines as an interdisciplinary, internationally oriented research institute the competences of the University of Graz in the research area "Climate, Environmental and Global Change". It brings together, in a dedicated building close to the University central campus, research teams and scientists from fields such as geo- and climate physics, meteorology, economics, geography, and regional sciences. At the same time close links exist and are further developed with many cooperation partners, both nationally and internationally. The research interests extend from monitoring, analysis, modeling and prediction of climate and environmental change via climate impact research to the analysis of the human dimensions of these changes, i.e., the role of humans in causing and being effected by climate and environmental change as well as in adaptation and mitigation. (more information at www.wegcenter.at)

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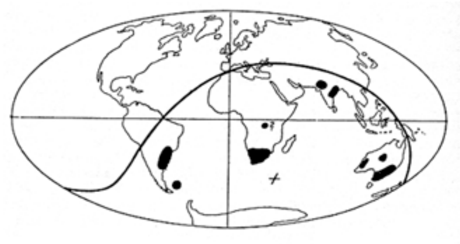

Alfred Wegener (1880-1930), after whom the Wegener Center is named, was founding holder of the University of Graz Geophysics Chair (1924-1930). In his work in the fields of geophysics, meteorology, and climatology he was a brilliant scientist and scholar, thinking and acting in an interdisciplinary way, far ahead of his time with this style. The way of his ground-breaking research on continental drift is a shining role model—his sketch on the relations of continents based on traces of an ice age about 300 million years ago (left) as basis for the Wegener Center Logo is thus a continuous encouragement to explore equally innovative ways:
paths emerge in that we walk them (Motto of the Wegener Center).

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Katalin Szeberényi

Master Thesis

for the academic degree of
Master of Science
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Finally I would like to thank my family, who, in the first place, made my studies and this thesis possible. Not only the financial support but also the mental encouragement helped me through.

Last but not least I thank Sascha for his constant support and assistance.

Abstract

The WegenerNet, which is a network of meteorological stations in the region of Feldbach (in south-eastern Styria, Austria), is considered as a “pioneering experiment for long-term observations at very high resolution” (Kabas [2012]). Essential meteorological parameters are measured in 5-minute intervals by 151 meteorological stations which are arranged in a grid pattern over an area of about 20 × 15 km^2.

In this thesis the WegenerNet precipitation data have been analyzed and evaluated in order to obtain information about the quality of the current measuring system. All precipitation gauges are based on the principle of the “tipping bucket”, which records the precipitation amount by counting tiltings of a seesaw bucket via a reed contact.

The base instrument in the WegenerNet is model 7041.2000 from Theodor Friedrichs & Co which can be found at 139 stations. It is not provided with a heating system and is therefore only reasonable for the measurement of liquid precipitation. The two other instruments, model 52202 from R.M. Young (11 stations) and the reference model MR3H from Kroneis Meteoservis (1 station) can also be applied to solid precipitation as they are equipped with a heater.

The quality analyses of the data have been carried out by directly comparing the data sets at the reference station (equipped with all three sensor systems), by doing homogeneity evaluations across the whole network and by performing case studies. Climatological aspects have been considered by studying seasonal and annual precipitation data throughout the network. Comparison of the same data sets at difference processing steps provided information about weaknesses in the WegenerNet processing system.

The analyses delivered detailed insight into the WegenerNet precipitation data quality and demonstrate deficiencies in the current system that are taken as a basis for further improvements.

Zusammenfassung

Das WegenerNet, das als Pionierexperiment für Langzeitbeobachtungen mit sehr hoher zeitlicher und räumlicher Auflösung fungiert, ist ein Netzwerk von meteorologischen Stationen im Raum Feldbach in der Südoststeiermark (Kabas [2012]). Insgesamt 151 Stationen, die in einer Gitterstruktur über ein Gebiet von ca. $20 \times 15\ \mathrm{km}^2$ angeordnet sind, liefern Daten über eine Reihe meteorologischer Parameter in 5-Minuten-Intervallen.

Thema der vorliegenden Arbeit ist die Auswertung der WegenerNet Niederschlagsdaten, sowie eine Qualitätsanalyse der verschiedenen Niederschlagssensoren. Alle verwendeten Regenmesser arbeiten nach dem Prinzip der Kippwaage, wobei das Kippen eines kleinen Behälters bei einer vorgegebenen Füllmenge über einen Reedkontakt registriert wird.

Das Basisinstrument ist das Modell 7041.2000 von Theodor Friedrichs & Co, welches an insgesamt 139 Stationen zu finden ist. Dieses Instrument ist nicht mit einem Heizungssystem versehen, weshalb es für die Messung von festen Niederschlägen ungeeignet ist. Die beiden anderen Niederschlagsmesser, Modell 52202 von R.M. Young (12 Stationen) und das Referenzmodell MR3H von Kroneis MeteoServis (eine Station) können auch für die Messung fester Niederschläge herangezogen werden, da sie mit Heizungen ausgestattet sind.

Die Qualitätsanalysen der Daten wurden durch direkten Vergleich der Datensätze an der Referenzstation (mit allen drei Sensoren ausgestattet), durch Homogenitätsbetrachtungen des gesamten WegenerNets und durch Betrachtung einzelner Fallstudien durchgeführt. Klimatologische Aspekte wurden durch die Analyse der Jahres- und Saisondaten näher betrachtet. Um Informationen über das WegenerNet Processing System zu erhalten, wurden die Daten nach verschiedenen Prozessierungsschritten verglichen.

Die Analysen geben einen detaillierten Überblick über die Qualität der WegenerNet Niederschlagsdaten und zeigen Schwächen im laufenden System auf, die auf dieser Basis nun verbessert werden können.

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1. Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) which will be released in 2014, recently presented the Summary for Policymakers from Working Group I (Stocker et al. [2013]). The message of this report is clear: "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased." (Stocker et al. [2013], p. 2 therein). The climate change and its various consequences have become part of our everyday lives as it has been commonly accepted as a significant challenge of the current and future generations.

Together with increasing greenhouse gas concentrations and increasing global surface temperature, which cause changes in the radiation and energy balance of the atmosphere, also extreme weather events are becoming more frequent. One of the key components in the current climate change debate is besides the temperature the hydrological cycle and the related meteorological parameters. Precipitation, with its high temporal and spatial variability, will change in terms of intensity, frequency and also in the amount (Schoenwiese [2013a]). The AR5 assesses that dry areas will even get drier and wet areas will experience more rainfall (Stocker et al. [2013]).

This thesis deals with the quality of precipitation measurements in the WegenerNet, a network of 151 meteorological stations arranged in a grid pattern over an area of about 20×15 km^2. The network, which is a pioneering experiment of its kind, has been installed in 2006 by a group of researchers from the Wegener Center for Climate and Global Change at the University of Graz, Austria. The main idea behind the project was to create a long-term platform for small-scale climate observations (Kirchengast et al. [2008], Kabas et al. [2011], Kabas [2012], Kirchengast et al. [2014]).

For accurate forecasts and model studies a reliable knowledge of all parameters is required on reasonable scales. The WegenerNet is a flagship project with its novel way of "downscaling" meteorological observations. In Chapter 2 an introduction into the WegenerNet, the data stream and the processing chain, the measurement systems and the weather and climate characteristics of the investigation area is given.

As precipitation is the core parameter in this thesis, Chapter 3 deals with the conditions for cloud formation and the development of precipitation in general. A precipitation classification should help to classify rainfall and snowfall events discussed later on. The different precipitation types, which differ in intensity and spatial extent, will also be explained in some detail in this chapter.

For accurate measurements, accurate sensor systems and carefully selected station sites are relevant. In Chapter 4 the precipitation sensor systems used at the WegenerNet stations are introduced. All stations use tipping bucket rain gauges for precipitation measurments. A total of three different models is in use at the 150 stations whereof two types are equipped with a heating system and are therefore also applicable for solid precipitation measurements.

In this chapter also frequently occurring errors and correction options for rain gauges are discussed.

The results of the different analyses and evaluations are presented in Chapters 5, 6 and 7. In order to determine the quality of the precipitation measurements in the WegenerNet one reference station has been equipped with three sensors from different companies. A direct comparison of the basis data as well as the investigation of data products (monthly, annual and seasonal data) reveals differences in the measurements of the three instruments. As these three sensors are used in the WegenerNet as part of different station types, it is of interest whether results at the reference station are representative for the whole network. A determination of homogeneity and consistency of the measured precipitation data across the entire WegenerNet inspecting the seasonal and annual data for all 150 stations, which are equipped with rain gauges, is therefore also performed. Defective stations with frequently blocked funnel orifices or problems with heating systems are as well detected by the analyses, adding to the valuable information for guiding next steps of improvement in the network.

A summary and conclusions gathers the main results and two appendices inform on the results of rain gauge tests in the field and the data gaps within 2007 and 2013 found by the work, respectively.

2. WegenerNet Climate Observation Network

2.1. The WegenerNet

The WegenerNet is an international pioneering experiment concerning long-term weather and climate observations at very high resolution. The network which consists of 151 meteorological stations in Feldbach, a region in the southeast of Styria (Austria), is arranged in a grid pattern which covers an area of about 20 × 15 km^2 (Kabas [2012], Kirchengast et al. [2014]). Each grid cell has an extent of 1.4 km × 1.4 km, thus about 2 km^2. The high spatial resolution of this rather small area is achieved by the short distance between the individual stations. High temporal resolution is guaranteed by a measurement set-up with 5-minute data sets. Figure 2.1 shows a map of the WegenerNet region covering 27 municipalities in the county of Feldbach. The Raab valley which crosses the WegenerNet region from west to east devides the investigation area into a northern and southern part.

The WegenerNet has been installed in 2006 in the framework of a dissertation at the Wegener Center for Climate and Global Change, University of Graz, Austria. First data has been delivered at the end of 2006. Since 2010 the system is fully operational after a three-year phase of testing and demonstration. The motivation behind the WegenerNet project was to establish a core region for weather and climate research for better risk assessment concerning environmental purposes and as a consequence also social and economic issues. It is also of great value to questions of land use regulation, water and energy supply, emergency management as well as regional development in the investigation area.

The 151 meteorological stations, which can be found in the WegenerNet region, are equipped with different meteorological instruments. Their set-up can be subdivided into two categories, each with two sub-categories. In Table 2.1 an overview of the different station types is shown (WegCenter [2014]). The 139 base stations measure only the three core parameters (air temperature, air relative humidity and precipitation) with additional measurement of soil temperature and pF-value for the special base stations. Beside these essential meteorological parameters the 12 main stations supply data for wind and solid precipitation measurements, and among them one primary station is equipped with net radiation and air pressure sensors. The result is a complete characterization of the investigation area.

2.2. WegenerNet Data Stream and Sensor Systems

The measuring instruments in the WegenerNet Observation Network are equipped with selected sensors for each of the meteorological parameters. For complete climatological observations the application of the following sensors is necessary:

- **Temperature and humidity sensor:**
  Temperature and relative humidity are measured with a combined sensor (single chip multisensor module from Driesen+Kern GmbH, Sensirion) for both parameters. Bene-

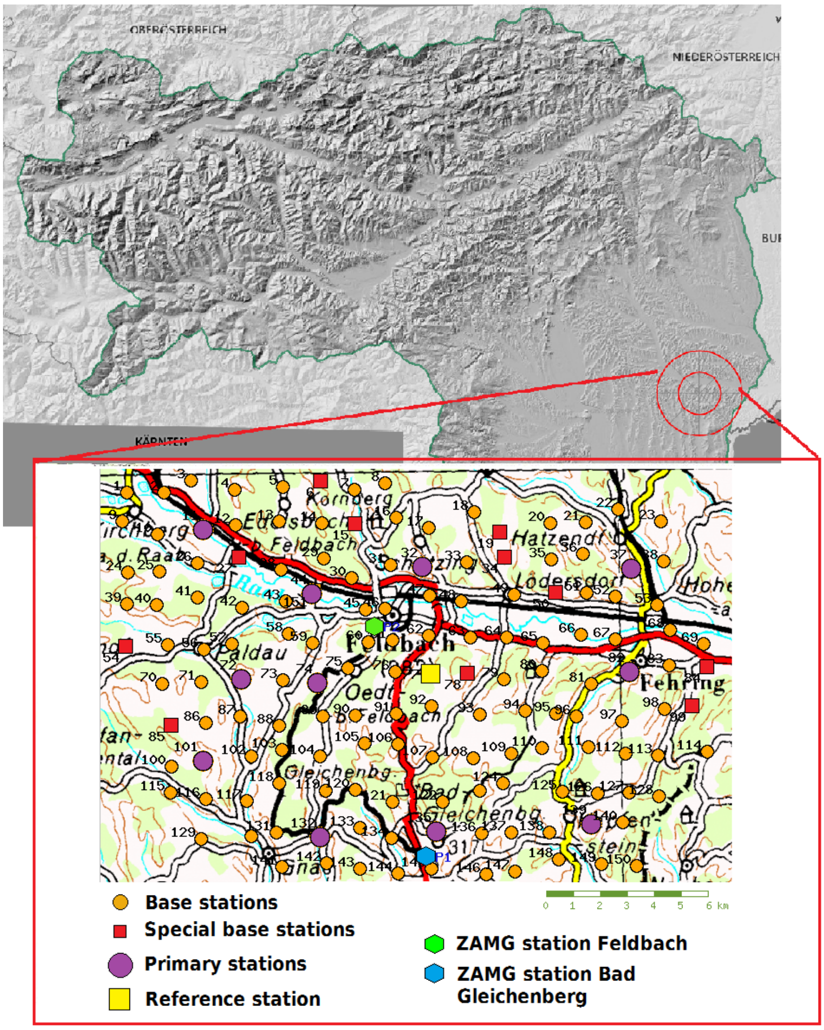

Figure 2.1.: WegenerNet region Feldbach with the 151 stations aligned in a grid pattern (WegNet [2013]).

ficial are the low power consumption, the long-term stability and the easy integration. Further information can be found at the Sensirion web page[1].

- **Precipitation sensor:**
  All precipitation measurement systems are based on the principle of the "tipping bucket rain gauge". In Chapter 4 detailed information on the used sensors and their specifications can be found.

- **Wind sensor:**
  The wind parameters are measured by WindSonic[2], a sonic anemometer from Gill Instruments. Ultrasonic sound waves sent and received by four transducers are used to determine wind speed and wind direction. The principle of operation is based on changes in the travel time of the sonic pulses due to air movements.

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[1] `http://www.sensirion.com/de/produkte/feuchte-und-temperatur/feuchtesensor-sht71/`

[2] `http://www.gill.co.uk/data/datasheets/WindSonic-Web-Datasheet.pdf`

Table 2.1.: Overview of the WegenerNet stations and the measured meteorological parameters. The + sign indicates that the parameters are additional to the base station parameters. Stations denoted with a – sign measure the base station parameters without the given parameter (WegCenter [2014]).

Type	**Subtype**	**Meteorological Parameter**	**Station Number**
Base stations (139 stations)	Base stations (B) (127 stations)	air temperature, air relative humidity, precipitation	all stations except other types
	Special base stations (BS) (12 stations)	+ soil temperature, pF-value	6, 15, 19, 27, 34, 50, 54, 78, 84, 85, 99
		– precipitation	151
Main stations (12 stations)	Primary stations (P) (11 stations)	+ solid precipitation, wind parameters	11, 32, 37, 44, 72, 74, 82, 101, 132, 135, 139
	Reference station (R) (1 station)	+ solid precipitation, wind parameters, air pressure, net radiation	77

- **Soil sensor:**
  For measuring soil parameters a combinated sensor for soil temperature and the pF-value is used (pF-Meter[3] from GeoPrecision). The pF-value gives information about the soil moisture content, which is available as a derived parameter.

- **Radiation balance sensor:**
  The radiation balance is given by the net radiometer NR LITE[4] from Kipp&Zonen. It measures the net radiation which is the balance between incoming and outgoing radiation. The sensor technology is based on the principle of the thermoelectric pile.

- **Air pressure sensor:**
  Air pressure is measured by a capacitive pressure sensor (Barometric Pressure Sensor Model 315 K[5] from Kroneis) which determines changes in electrical capacity due to air pressure changes.

For data collection and transfer the WegenerNet System uses a data logger which guarantees automatic communication. The advantage of the applied internet logger (i-Log from GeoPrecision) is the possibility of remote control and remote alignment. Data transfer works using General Packet Radio Service (GPRS) via a mobile communication network. Data is collected in 5-minute intervals and every hour the logger transmits the stored data to the WegenerNet Server. This data is called *Level 0 data* and is further processed by the so-called Quality Control System (QCS). To ensure high quality results the transmitted data passes through the QCS in seven steps. Each of the QCS layers tests the data for special errors (see

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[3] `http://www.geoprecision.com/en/products/pf-meter.html`

[4] `http://s.campbellsci.com/documents/us/manuals/nr-lite.pdf`

[5] `http://www.kroneis.at/images/stories/Englisch/ProdInf/barosensor_315ke.pdf`

Table 2.2). In the first layer with ID 0 for example the operation of the sensor is checked. If operation can be confirmed - so the check is negative - the data is passed on to the second layer and so on. If a check is positive the data is marked with a corresponding quality flag (QF) which is defined as $QF = 2^{LayerID}$. If the data fails at more than one layer, the QF results from the sum of the QF values for the non-passed levels. Faultless data get a QF of 0. The most frequent combination for nonzero-QF precipitation data is QF=64 which indicates failure at level 6, thus a too high deviation from the median of at least five neighboring stations. The data marked with quality flags is now called quality-controlled or *Level 1 data.*

Table 2.2.: Seven-layer structure of the WegenerNet quality control system and the correspondent quality control flags (Kabas [2012], Kirchengast et al. [2014])

Layer ID	QCS layer	QC flag
0	operation check	1
1	availability check	2
2	sensor check	4
3	climatological check	8
4	time variability check	16
5	intra-station consistency check	32
6	inter-station consistency check	64
7	external reference check	128

In the last step of the processing chain, which provides the desired *Level 2 data*, the data passes through the Data Product Generator (DPG), where it is interpolated as needed (either temporally or spatially, dependent on the availability of the data) and merged into data products. The WegenerNet Data Portal (available at `www.wegenernet.org`) allows the download of half-hourly, hourly, daily, monthly, seasonal and annual data which are generated from the 5-minute basis data.

For special applications also 2-dimensional grid data in Network Common Data Format (NetCDF-Files) are available, at 200 m × 200 m spatial resolution.

For this thesis the Level 1 data has been observed and studied. For further information on the QCS, please refer to Kirchengast et al. [2008], Kabas et al. [2011], Kirchengast et al. [2014] and the master's thesis of Scheidl [2014].

In Table B.1, in Appendix B, logger outages with a duration of more than 24 hours are listed for each station. These data missings, which are due to failures of the data logger, can lead to significant losses at the corresponding stations as all parameters measured are not documented during these downtimes.

2.3. Weather and Climate in the WegenerNet Region Feldbach

The investigation area is located in Feldbach in the south-east of Styria (federal state of Austria) and is referred to as *WegenerNet region* in this thesis. To get a better understanding of the local weather and climate conditions and processes, respectively, a discussion about the characteristics of the WegenerNet region will be conducted in this section.
The WegenerNet is located in the south-eastern part of the foothills of the Alps which include the Styrian hills and southern Burgenland (federal state of Austria). Lieb [1991] subdivides

the Styrian bio-geographic region into two main categories and 28 sub-units, which again can be subdivided into several sub-categories. This classification states the complex structure of the bio-geography of the versatile mountainous and hilly region. Figure 2.2 shows Lieb's division of the natural spaces in Styria.

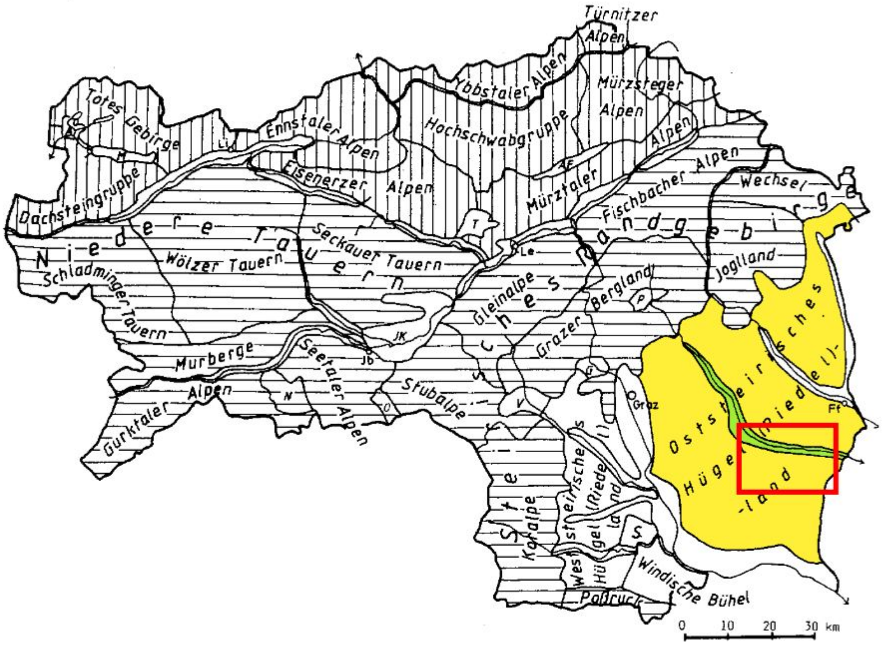

Figure 2.2.: Bio-geographic structure of Styria with the WegenerNet region (red square) in the East-Styrian Alpine foreland (yellow). The hatching pattern displays the North-Alps of Styria (vertical) and the Central Alps (horizontal) (Kabas [2012], adapted from Lieb [1991]).

The region in the Alpine foothills which contains the WegenerNet is referred to as *East-Styrian Riedelland* and is part of the foreland. The "Riedel" that characterize the landscape of this region, are long-drawn low mountain ridges with typically more steep western and more flat eastern hillsides. They are composed of tertiary loose sediments and have a height of up to about 400 m. Some isolated elevations which are higher than the Riedel ridges are remnants of tertiary volcanism (Buchgraber [1989]). The highest elevations are the *Steinberg* with 470 m height in the south-east of Feldbach and the Kleichenberg Kogel with 600 m height.

The Raab valley (marked green in Figure 2.2) separates the investigation area into a nothern and a southern part of the Styrian Riedelland (Kabas [2012]).

Regarding climatic conditions in the WegenerNet region the valleys in the East-Styrian Riedelland are affected by continental climate conditions. Cold winters and warm summers are the consequence. The occurrence of inversions and fog is more frequent than on the higher located ridges, as there is hardly no possibility for the outflow of cold air pockets.

On the ridges climate is thermally balanced with less important differences between winter and summer temperature. The Riedel-climate is characterized by warm summers and mild winters due to better aeration. Positive consequences are higher sunshine duration in the winter months and smaller frost risk. On the other hand storms or convective precipitation (see

Chapter 3) and hail events during summer are more frequent than in the valleys (Wakonigg [1978]). In Figure 2.3 the mean annual temperature for Styria is shown. The WegenerNet region is located in the mildest part of the federal state.

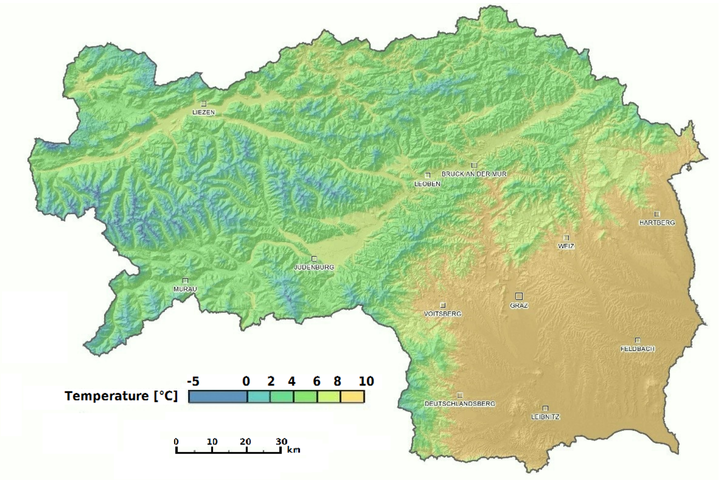

Figure 2.3.: Mean annual temperature, given in °C (Breitfelder [2012]).

Figure 2.4 shows the mean precipitation amount per year in Styria. The mountainous region in the north-west of the federal state has up to three times higher annual precipitation amounts than the foreland in the south-east. The reason for this north-south gradient is the increase of orographically induced precipitation (with increasing altitude). The north-western part of Styria is located in the influence area of northern weather conditions (atlantic origin), whereas the south-east is more influenced by the low pressure conditions over the Mediterranean. In addition, local relief structures can cause accumulative effects of moist air masses, which can provide large precipitation amounts (Breitfelder [2012], Schulatlas Steiermark).

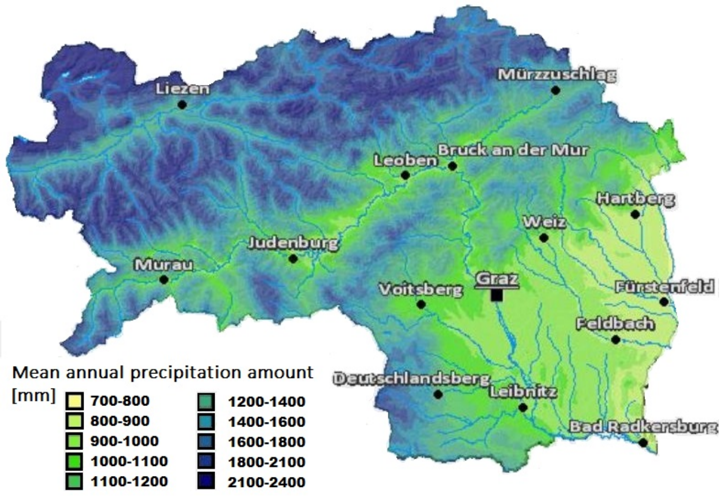

Figure 2.4.: Mean Precipitation amount per year, given in mm (GIS [2013]).

2.4. ZAMG Stations in Bad Gleichenberg and Feldbach

The Central Institute of Meteorology and Geodynamics (*Zentralanstalt für Meteorologie und Geodynamik (ZAMG)*) is the national meteorological and geophysical service in Austria with its head office in Vienna (Hohe Warte). Besides the daily weather forecast and the preparation of climate statistics, also consulting services, research in the fields of meteorology and geophysics, the monitoring of pollutant dispersal and the earth quake alert service are part of the daily routine.
The monitoring network of the ZAMG is the only comprehensive meteorological network in Austria with 250 stations providing data from all climate regions and altitude levels. Most of these stations are semiautomatic weather stations (Teil-Automatische Wetterstation, TAWES), which record the data of the weather parameters and transmit them in real-time to the Hohe Warte.

In Figure 2.5 an overview of all ZAMG stations in Austria is shown. The two stations which will serve as reference stations in this thesis are marked with a red square. They are located in the WegenerNet region around Feldbach, directly in Feldbach close to station no. 60 and in Bad Gleichenberg close to station no. 145 (see Figure 2.1) and are equipped with tipping bucket rain gauges. As they are official stations of the ZAMG network they are a good reference for the WegenerNet stations.

2.5. Specifications of Stations Used for the Evaluations

For the evaluations in the Chapters 5 - 6 mainly the reference station 77, the two ZAMG stations located in the WegenerNet region (in Feldbach and Bad Gleichenberg) and their surrounding four WegenerNet stations will be analyzed. In this section the specifications of these eleven stations are summarized in order to get an idea of the ambient conditions of the stations. Table 2.3 shows for each of these stations the geographical coordinates, the altitude (above sea level) and the type of station.

Table 2.3.: Stations mainly used in the quality evaluations.

Station	**Latitude [°N]**	**Longitude [°E]**	**Altitude [asl]**	**Station Type**
77	46.9330	15.9071	302 m	Reference station
ZAMG FB	46.9489	15.8797	323 m	TAWES[1]
ZAMG BG	46.8722	15.90361	269 m	TAWES[1]
45	46.9542	15.8762	289 m	Base station
46	46.9547	15.8857	280 m	Base station
60	46.9434	15.8775	351 m	Base station
61	46.9442	15.8892	322 m	Base station
134	46.8787	15.8878	316 m	Base station
135	46.8807	15.9090	305 m	Primary station
144	46.8668	15.8903	269 m	Base station
145	46.8682	15.9066	279 m	Base station

[1] TAWES = semiautomatic weather stations

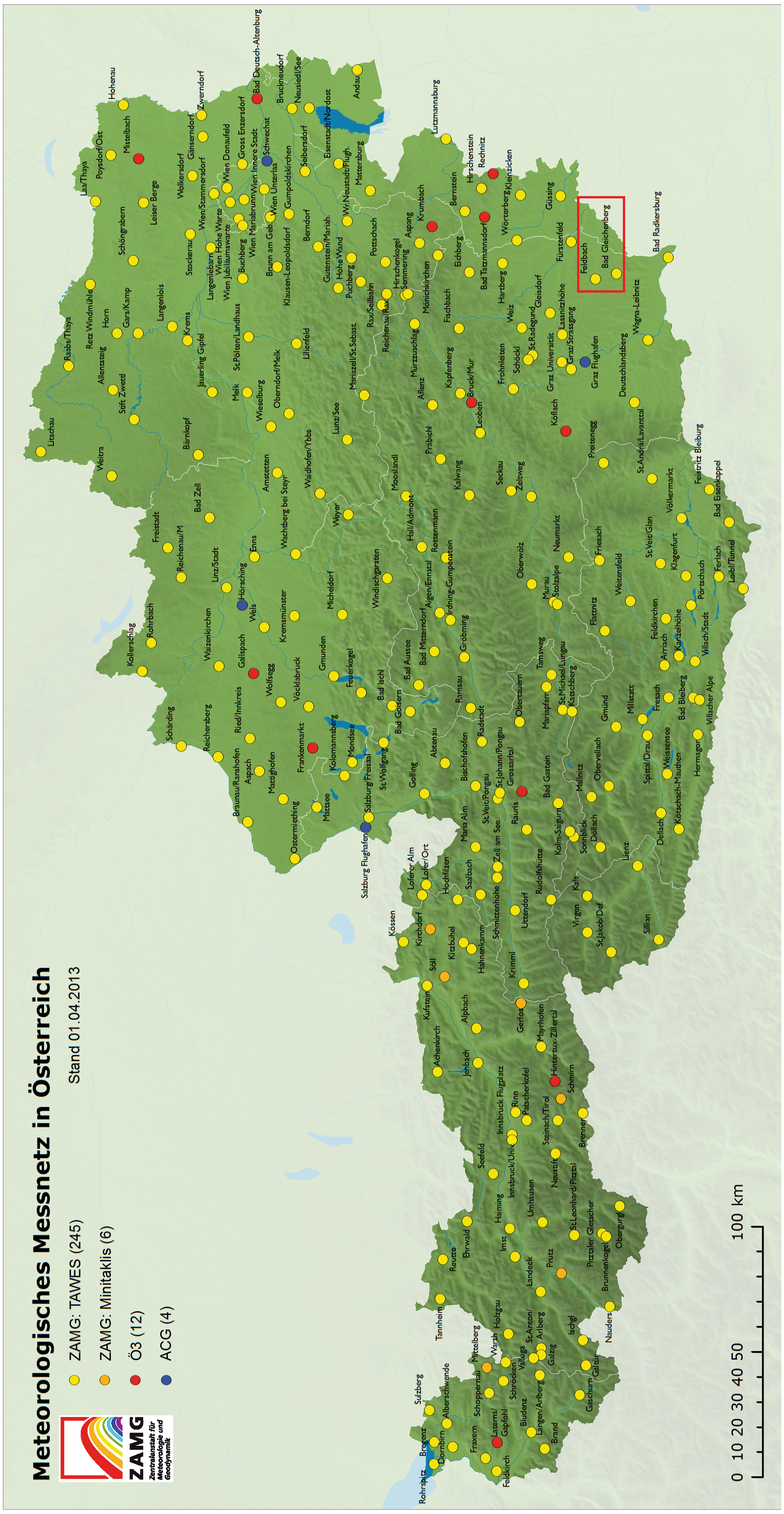

Figure 2.5.: ZAMG-network of meteorological stations in Austria. The two stations *Bad Gleichenberg* and *Feldbach* (red square) have been used as reference stations in this thesis (ZAMG [2013a]).

3. Precipitation

In times of climate change the monitoring of the hydrological cycle gets more and more relevant. This cycle induces the exchange of water between the Earth's surface and the atmosphere. The global average evaporation and precipitation rate, respectively, librate between 1000 mm to 1100 mm per year. As the average equivalent water column height of the atmosphere is about 25 mm, the average residence time of water in the atmosphere is about 10 days (Roedel and Wagner [2011]).

In this chapter the processes leading to precipitation events are discussed in some detail. Under which conditions does precipitation formation take place? What are the different types and forms of precipitation? What are the different modes and which processes determine precipitation intensity? These questions will be dealt with in the following sections.

3.1. Conditions for Precipitation Formation

Before we can treat the processes that lead to precipitation on the Earth's surface, we need to deal with the mechanisms of cloud physics. Simply put, clouds develop when warm moist air ascends, cools down due to expansion and enables condensation in saturated air masses (relative humidity exceeds 100 %). We call this process *adiabatic cooling*. Sheet clouds (*stratus*) form when warm air masses glide upon cold air layers. Heap clouds (*cumulus*) are the result of convective ascend of warm air. The presence of cloud condensation nuclei can promote the condensation process.

As "not all clouds precipitate" (Sumner [1988]) it is indispensable to think about the question of how water droplets or ice particles can grow large enough to overcome the updrafts in the cloud and the environment beneath the cloud, which is unsaturated (relative humidity less than 100 %). Too small particles only survive a few millimeters before they evaporate in the unsaturated environment (Roedel and Wagner [2011]). Figure 3.1 displays the range of cloud droplet sizes for a fair weather cumulus cloud (droplet size range: 2.5 µm to 15 µm) and for a cumulus cloud which instantaneously starts to precipitate (droplet size range: 2.5 µm to 25 µm). As one can see clearly the larger droplets become more numerous, obviously at the expense of the smaller ones.

There are two major mechanism in clouds that lead to the enlargement of cloud particles to sizes that allow precipitation:

- *coalescence:* droplet growth due to collisions between liquid particles
- *Wegener-Bergeron-Findeisen process*[1] *(WBF)*: describes the growth of ice crystals in mixed phase clouds (coexistence of water vapour, liquid supercooled droplets and ice crystals) (Korolev [2006])
    - *aggregation:* ice crystal growth due to collisions between solid particles

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[1] after A. Wegener, T. Bergeron and W. Findeisen

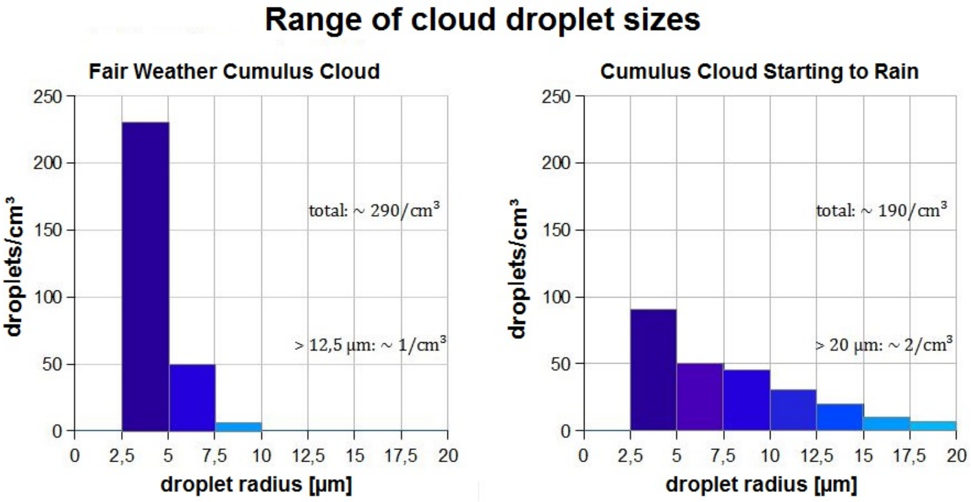

Figure 3.1.: Average range of droplet sizes. Left: for a fair weather cumulus cloud, right: for a cumulus cloud which starts to rain (Roedel and Wagner [2011]).

  - *accretion:* ice crystal growth due to mixed collisions between solid and liquid particles

As for this thesis a more detailed treatment of these processes is not required please access Sumner [1988] or Roedel and Wagner [2011] for further information.

3.2. Classification of Precipitation

For classification purposes Sumner [1988] suggests the distinction between forms, modes, intensities and types of precipitation. The types will be dealt with in Section 3.3. With *form* the appearance on the Earth's surface is meant:

- rain: liquid precipitation, diameter of drops > 0.5 mm
- drizzle: liquid precipitation, diameter of droplets < 0.5 mm
- snow: frozen precipitation, formed by accretion in the parent cloud
- hail: frozen pellets, diameter > 5 mm, occur in thunderstorm cells (Section 3.3.1)
- ice pellets: similar to hail but smaller
- graupel: frozen precipitation, forms when frozen particles and supercooled water droplets freeze together[2], diameter: between 2 and 5 mm

The *modes* refer to the continuity of the rain- or snowfall event and are defined by Sumner [1988] as follows:

- continuous: permanent rainfall duration > 1 hour

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[2] `http://www.weather.com/glossary/g.html` (Oct. 25th, 2012)

- intermittent: comes from continuous cloud cover but the rainfall periods are interrupted by dry periods
- occasional: the same as for intermittent rainfall but the dry periods exceed the wet periods
- shower: can usually be observed during thunderstorms and hence stem from heavily convective clouds

In Chapter 4 (Section 4.1.1) the definition of *precipitation intensity* and the corresponding units and scales will be explained in detail. For the moment we just have a look at the classification according to the magnitude of different precipitation forms. A distinction is made between light, moderate, heavy and - for showers - violent rainfall (see Table 3.1).

Table 3.1.: Definition of the precipitation intensity for different precipitation forms (Sumner [1988]).

	light	**moderate**	**heavy**	**violent**
Rain	< 0.5 mm h^{-1}	(0.5 ... 4) mm h^{-1}	> 4 mm h^{-1}	
Shower	< 2 mm h^{-1}	(2 ... 10) mm h^{-1}	(10 ... 50) mm h^{-1}	> 50 mm h^{-1}
Snow	< 0.5 cm h^{-1}	(0.5 ... 4) cm h^{-1}	> 4 cm h^{-1}	

For an accurate classification of a rain- or snowfall event, it is inevitable to know all the information defined above. There is a close interrelation between precipitation intensity, duration, form and mode. As an example, Sumner [1988] explains the relation between intensity, duration and scale of occurrence as follows: High intensities occur for short durations and in general on small scales, low intensities can occur for long durations - even for several days - and even up to continental scale.

3.3. Types of Precipitation

As the uplift of air masses, which can cause condensation and subsequently lead to cloud formation, can result from different mechanisms in the atmosphere and from different orographic conditions on the Earth's surface, the resultant precipitation can be divided into three types: *convective precipitation, cyclonic* or *frontal precipitation* and *orographic precipitation.* The three types are not mutually exclusive, but can occur in combination. In the following sections these types will be discussed in detail on the basis of Sumner [1988], Petersen et al. [2012] and Barry and Chorley [2003].

3.3.1. Convective Precipitation

The convective type of precipitation arises generally in combination with towering cumulus and cumulonimbus clouds. In the temperate latitudes this type of precipitation is common during summer time, when strong insolation heats the Earth's surface and the air layers above and reinforces evaporation. As warm air is less dense than cold air the heated moist air is lifted up and cools as a result of expansion in higher layers. This rapid uplift of air can subsequently lead to a local convective instability (Barry and Chorley [2003]).

Instabilities in the atmosphere occur as a result of distinctive vertical air movement which leads to convective activity. The reason for the development of an instability is the difference between the adiabatic lapse rate of the ascending airmass and the ambient lapse rate in the atmosphere. When the ambient lapse rate exceeds the adiabatic lapse rate the rising air parcel cools slower than the surrounding air and so the rising effect is enforced as warm air is less dense than cold air. This simple rising of air can effect significant turbulences and extensive vertical clouds (U.S. Dept. of Transportation [2008]). If the adiabatic lapse rate is larger than the ambient lapse rate or if the two lapse rates are equal, the atmosphere is referred to as stable. In these cases the uplift of the air mass is resisted.

The spatial extent of convective cells which develop in situ is limited to small and medium scale. The resulting precipitation is produced by the Wegener-Bergeron-Findeisen process (see Section 3.1) and can be classified in most cases as heavy or violent rainfall, sometimes even with hail. The duration is also limited and will typically not exceed 12 hours.

In Figure 3.2 the stages of development of a convective cumulus cloud are shown. Below the zero degree boundary, which is situated at about 5 km altitude, all particles are present in form of liquid water. Up to the −40 °C boundary (approximately at 10 km height) the particles can coexist in the form of supercooled water droplets or in the form of ice crystals. At temperatures beneath −40 °C the supercooled water droplets freeze spontaneously so that no liquid particles can exist anymore in those regions of the cloud.

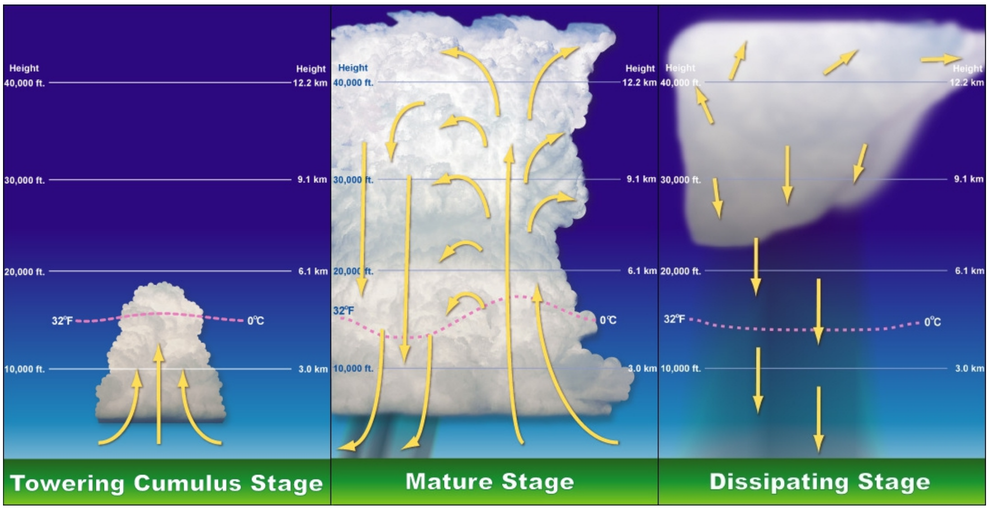

Figure 3.2.: Schematic illustration of the development of a convective cumulus cloud (NOAA [2013]).

3.3.2. Cyclonic and Frontal Precipitation

In contrast to convective precipitation, cyclonic (or frontal) precipitation results from large-scale circulations in the atmosphere (Sumner [1988]). The predominant mechanism is ascending motion of air masses through horizontal convergence of air streams (Barry and Chorley [2003]). The horizontal airflow in the atmosphere, which is leading to *fronts*, results from the inhomogeneous distribution of sources and sinks of energy in any form. Kraus [2004] describes a front as “a discontinuity surface that separates two homogeneous air masses from each other”. A front is called warm front, when it propagates from the warmer towards the

colder air (Figure 3.3). In the opposite case the front is called cold front (Figure 3.4). In both cases the warm air is raised above the cold air, as it is less dense. Due to this uplift the warm air expands and cools through adiabatic cooling (Guo [2006]).
Figure 3.3 illustrates how during a warm front the warm air is preceding towards the cold air mass and gliding upon it. It is also shown which type of clouds develop during the uplifting process of the warm air. At the outer edge of the front fog and precipitation, either liquid or solid, depending on the ambient temperature, form due to condensation of rising water vapor. Precipitation intensity resulting from these processes is in general slight or moderate.
The development and propagation of a cold front is shown in Figure 3.4. During the preceding movement the cold air forces the warm air to rise. The active zone concerning precipitation is located behind the preceding front where heavy showers and thunderstorms can develop.

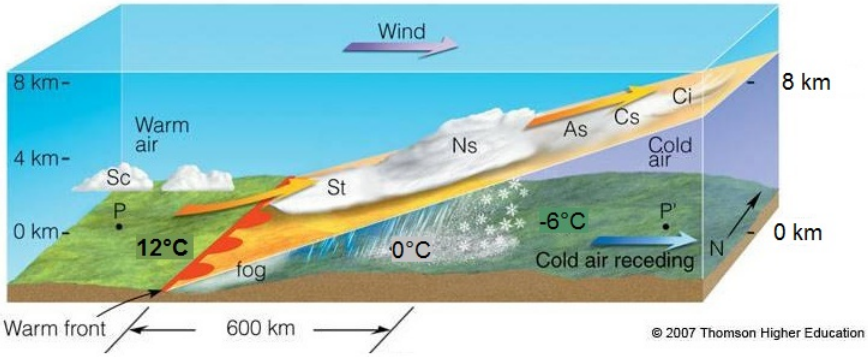

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Figure 3.3.: Development of a warmfront (Sc Stratocumulus, St Stratus, Ns Nimbostratus, As Altostratus, Cs Cumulostratus, Ci Cirrus) (Thomson Higher Education [2007b]).

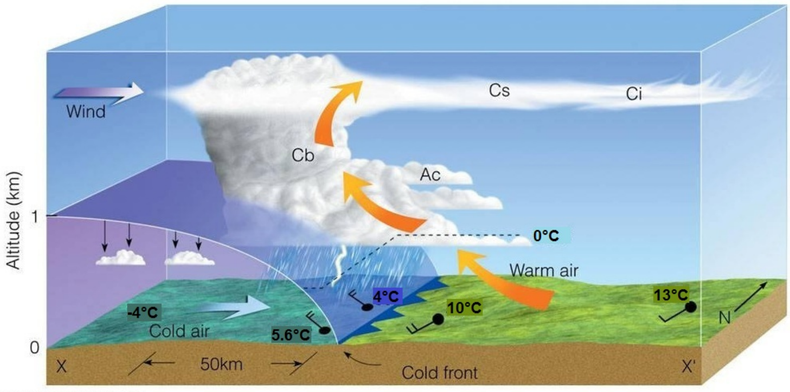

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Figure 3.4.: Development of a coldfront (Ac Altocumulus, Cb Cumulonimbus, Cs Cumulostratus, Ci Cirrus) (Thomson Higher Education [2007a]).

3.3.3. Orographic Precipitation

Orographic precipitation forms in mountainous or hilly regions when warm moist air transported by air streams hits a barrier and is lifted up along the mountain side (Figure 3.5). On the windward side of the hill or mountain the air cools adiabatically during the uplift

and condenses as latent heat is released. If the rising air parcel is cooling at a greater rate as the ambient air (stable conditions), the uplift is stopped and stratus cloud canopy forms. For an unstable air parcel (lapse rate smaller than in ambient air) the situation is different. The initial lift will not stop spontaneously but will even be amplified and reinforce instability (Petersen et al. [2012]). The result is cloud formation due to condensation and precipitation on the windward side of the mountain or hill.
Besides the above discussed mechanism hilly regions come under the influence of increased frontal precipitation as cyclonic systems are dammed in front of the mountain range. The so called rain shadow, which is the leeward side of the orographic barrier, is in general a dry region that is only sparsely covered by vegetation in contrast to the arboreous windward side (Barry and Chorley [2003]).

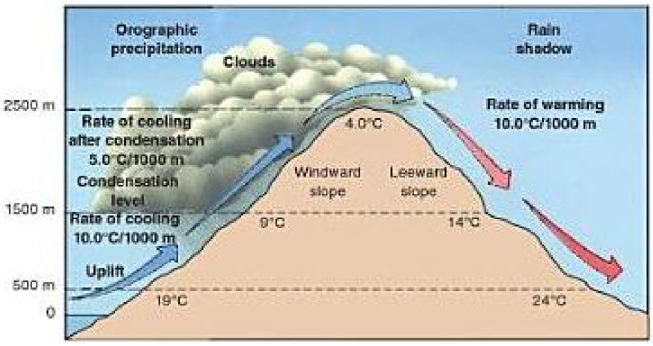

Figure 3.5.: Development of orographic precipitation at the windward side of a mountain and the shadow effect on the leeward side (Petersen et al. [2012]).

4. Precipitation Sensor Systems

The quality of measurements is dependent on many factors: good instruments, good attendance and a good quality control system are the main decisive factors for high quality data. To ensure reliability of the data the WegenerNet uses three different types of precipitation sensors. At the reference station no. 77 all three sensors measure the precipitation parameters alongside in a maximum distance of 0.5 meters.
All three systems are based on the principle of the "tipping bucket" (see section 4.1.2), which is the most common type of rainfall gauges. As the name suggests the major component of the measuring instrument is a bucket with two compartments aligned like a seesaw, which tips at a certain amount of collected water. This certain amount of water represents the systems resolution and sensitivity, respectively (WMO [2008]).

The base type is the unheated precipitation measurement system from Theodor Friedrichs & Co model 7041.2000 (section 4.2), which is only used for liquid precipitation. The two heated systems from R.M. Young model 52202 (section 4.3) and Kroneis MeteoServis model MR3H (section 4.4) enable additionally the measurement of solid precipitation like snow or hail. The differences between the three sensor systems and their specifications will be discussed in the following sections.

4.1. WMO Standards for Rain Gauges

The WMO Guide to Meteorological Instruments and Methods of Observation summarizes the fundamental definitions and requirements for the measurement of meteorological parameters. These standardizations serve as a rule for manufacturers of measuring systems for meteorological stations. In the following sections the standards for precipitation gauges are discussed.

4.1.1. Units and Scales

The unit for declaring precipitation amount is mm (equivalent to $\mathrm{l\,m^{-2}}$ or $\mathrm{kg\,m^{-2}}$). Precipitation rate is given per unit time in $\mathrm{mm\,h^{-1}}$. Brock [2001] defines the precipitation rate as follows: "Precipitation rate is the depth to which a flat horizontal surface would have been covered per unit time if no water were lost by run-off, evaporation, or percolation."
According to the WMO standards daily amounts should be given to the nearest 0.1 mm and 0.2 mm, respectively (depending on the resolution of the measuring systems). Amounts of rain (liquid precipitation) less than 0.1 mm are regarded as a trace.

4.1.2. Measurement Methods

The WMO Guide subdivides the measuring systems into two categories: non-recording precipitation gauges and recording precipitation gauges.

Gauges of the first group need an observer who reads the collected amount of water in regular intervals. In general, these systems consist of a collector, a funnel and a container, in which the water is collected between two observations. Recording gauges measure precipitation amounts continuously and therefore provide better time resolution than non-recording systems. The tipping bucket gauges used in the WegenerNet Observation Network are all of the second group together with weighing-recording gauges or so called float gauges. For further information on the principles of these instruments please refer to the WMO Guide of Instruments and Methods of Observation (WMO [2008]).

4.1.3. Tipping Bucket Raingauge

The principle of operation of the tipping bucket gauge in general is really simple (see Figure 4.1). A bucket consisting of two compartments aligned like a seesaw is placed beneath a funnel that conducts the water into one of the compartments. When the volume of collected water in one compartment reaches 0.1 mm or 0.2 mm respectively (predetermined by the producer) the bucket tips and records the tipping using a reed contact. The tips are counted by a microprocessor in the data logger. The filled compartment is emptied and the second compartment can be filled up. The WMO standard amounts to at least 0.2 mm for the resolution and to at least 200 cm^2 for the size of the collector orifice.

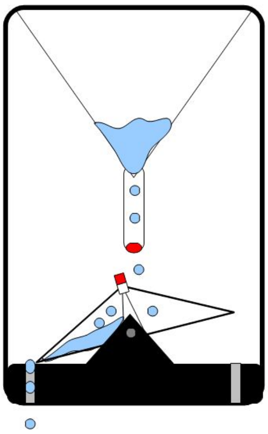

Figure 4.1.: Schematic illustration of the operation principle of tipping bucket precipitation gauges.

4.1.4. Errors and Correction Options

Lanza et al. [2006] introduce three categories for possible errors that occured during a laboratory test with many different tipping bucket rain gauges: sampling errors, catching errors and counting errors. The laboratory test analyzed mechanical and electronic errors as well as general uncertainties of rainfall intensity gauges. *Sampling errors* can be recognized as a dowry from the manufacturer. They relate to the bucket size and the sampling interval and are independent from rainfall intensity, which enables analytical evaluation.

Catching errors are more difficult to remedy as they occur due to weather conditions. Errors related to wetting, splashing or evaporation processes are also among this category. Lanza et al. [2006] define catching errors as the indicators for *"the ability of the instrument to collect* *the exact amount of water that applies from the definition of precipitation at the ground, i.e. the total water falling over the projection of the collector's area over the ground".* Wind is considered as the most problematic influence, particularly for light or moderate rainfall of the order of up to 10 mm/h or snowfall at low intensities. Sevruk et al. [1991] already investigated the problem of wind field deformation caused by the orifice rim. Dependent on the form of the rim wind speed can increase considerably directly over the orifice which can cause enormous losses. Nagy et al. [2013] introduce simulations of wind deformation around different types of rain gauges. They also found, that wind speed increases directly over the receiver between 20 % and 25 %. They conclude that wind has no significant influence on liquid forms of precipitation but for solid precipitation the errors are significant (Vuerich et al. [2009]).

Counting errors depend on the reliability of the instrument's sensor system. The WMO Laboratory Intercomparison showed that some of the gauges have problems during the tipping phase of the bucket. It is described that in some cases water still flows into the filled bucket compartment that has already reached the nominal volume (0.1 mm) and which is currently in the tipping movement. The amount of water which flows into the bucket compartment when it is already filled up with the nominal volume is not recorded by the system and gets lost. This problem especially occurs in cases of heavy rainfall and leads to an underestimation of precipitation amounts. Duchon et al. [2013] used high-speed photography to study exactly this effect of under-catching. With 500 frames per second they could observe the tipping movement in a very detailed manner. The analyses were carried out under laboratory conditions for two rain rates of 19.9 mm/h and 175.2 mm/h. For both cases the tipping of the bucket lasts in average 0.98 s - during that time the undercatch occurs. The constant time of tipping suggests that there is a linear relationship between the rain rate and the error (Figure 4.2) so that it could be accounted for in post-processing.

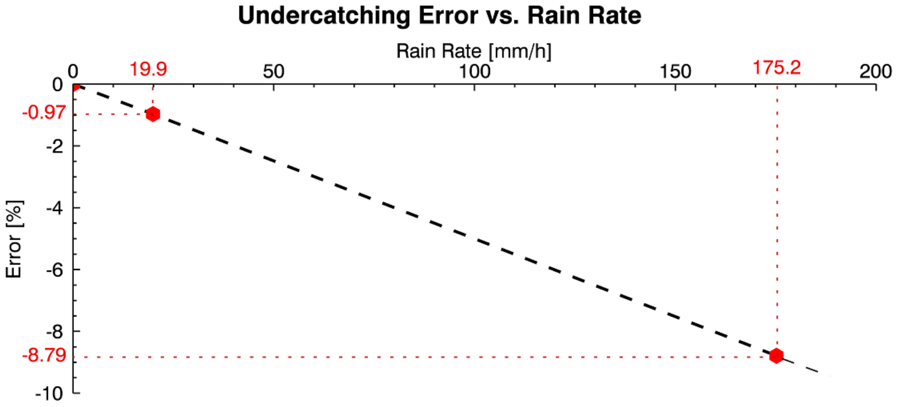

Figure 4.2.: Result of high-speed photography studies of tipping bucket rain gauges (Duchon et al. [2013]).

4.2. Model 7041.2000 (Theodor Friedrichs & Co)

Model 7041.2000 from Theodor Freidrichs & Co is the base type of tipping bucket gauges in the WegenerNet Observation Network. The instrument can be found at the 139 base and special base stations. As the instrument is not equipped with a built-in heating system, the measurement is limited to liquid precipitation. Measurements at temperature below 2 °C are marked with a quality flag. Figure 4.3 shows the structure of the instrument and the location of the individual components: collecting funnel (1), base plate (2), tipping bucket (3), reed switch (4), stop screws (5), cable outlet (6) and grids (7) (Friedrichs [2005]). The specifications of the instrument can be found in Table 4.1. The sensor meets the requirements of the WMO (Friedrichs [2005]).

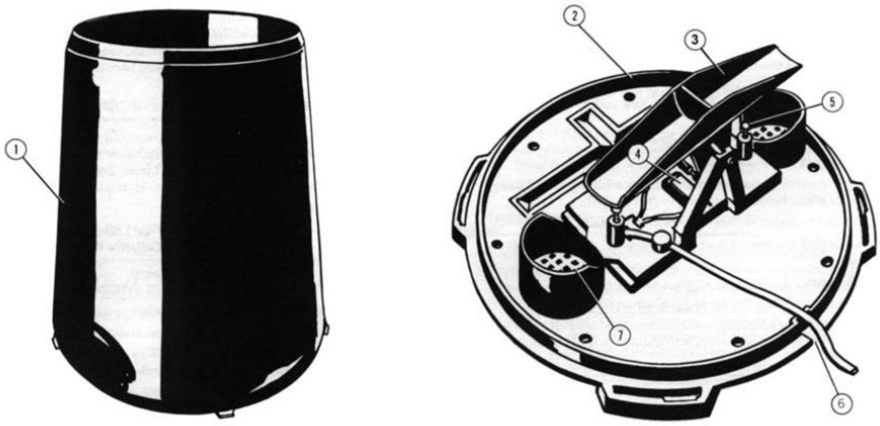

Figure 4.3.: Tipping bucket rain gauge model 7041.2000 from Theodor Friedrichs & Co (Friedrichs [2005]).

4.3. Model 52202 (R.M. Young)

Model 52202 from R.M. Young is a heated tipping bucket gauge and therefore also applicable for solid precipitation measurement, such as for snow or hail. Figure 4.4 displays the structure of the instrumentation and the sensing device. The components correspond to those of the Theodor Friedrichs gauge (see section 4.2). This model can be found at the 11 main stations and at the reference station (Nos. 11, 32, 37, 44, 72, 74, 82, 101, 132, 135, 139 and 77). The heating system which is adjusted to a switching temperature of 10 °C is composed of a thermostatic heating with a power consumption of 18 W. The device is suitable for operating temperature down to -20 °C. The specifications are listed in Table 4.1. The sensor meets the requirements of the WMO (Young [2005]).

4.4. Model MR3H (Kroneis MeteoServis)

The third sensor model MR3H from MeteoServis (with modifications by Kroneis GmbH) is also a heated version of tipping bucket rain gauge and is therefore also intended for both, liquid and solid precipitation measurements. In Figure 4.5 the cylindrical case and the base plate with the mounted tipping bucket are shown. The model from Kroneis MeteoServis can only be found at the reference station (No. 77) (up to October 2013, at this time it has been installed as well at all primary staions replacing the Young sensors).

The heating system consists of thermal resistors controlled by a thermostat which are placed under the funnel. The specifications are found in Table 4.1 and meet the requirements of the

Figure 4.4.: Tipping bucket rain gauge model 52202 from R.M. Young (Young [2005]).

WMO.
The MR3H instrument will act as reference instrument for the studies in the chapters 5-7.

Figure 4.5.: Tipping bucket rain gauge model MR3H from Kroneis MeteoServis (MeteoServis [2005]).

4.5. Model AP-23 (Anton Paar) at ZAMG stations

The two ZAMG stations located in the WegenerNet region use model AP-23 from Anton Paar for precipitation measurement. The device is a tipping bucket rain gauge with a resolution of 0.1 mm, thus the same type of instrument as used in the WegenerNet. The buckets are equipped with a heating system (switched on at a switching temperature of 4°C, additional heating systems for orifice rim at 5°C) and are therefore also applicable for solid precipitation measurements. Figure 4.6 shows the described instrument, mounted 1 m above ground (as required by the WMO). The specifications are given in Table 4.2.

Table 4.1.: Specifications of the three precipitation sensors used in the WegenerNet Observation Network.

	Theodor Friedrichs & Co	**R.M. Young**	**Kroneis MeteoServis**
Model	**7041.2000**	**52202**	**MR3H**
Operating principle	tipping bucket	tipping bucket	tipping bucket
Size (diameter, height)	165 mm, 241 mm	180 mm, 300 mm	278 mm, 336 mm
Catching area	211 cm^2	200 cm^2	500 cm^2
Resolution (precipitation per tipping)	0.1 mm	0.1 mm	0.1 mm
Specified Accuracy	±2% up to 25 mm/h ±3% up to 50 mm/h	±2% up to 25 mm/h ±3% up to 50 mm/h	$< -2\%$ up to 30 mm/h $< -10\%$ up to 100 mm/h $< -15\%$ up to 200 mm/h
Output	reed switch	reed switch	reed switch
Operating temperature	not specified	−20 °C to +50 °C	−30 °C to +60 °C
Power for heater	not heated	18 W	48 W to 57 W
Source of information	Friedrichs [2005]	Young [2005]	MeteoServis [2005]

Figure 4.6.: Tipping bucket rain gauge model AP-23 from Anton Paar (Vuerich et al. [2009]).

Table 4.2.: Specifications of the precipitation sensors used at the ZAMG stations in Feldbach and Bad Gleichenberg. (Vuerich et al. [2009], Anton Paar [1997])

	Anton Paar
Model	**AP23**
Operating principle	tipping bucket without correction
Size (diameter, height)	290 mm, 535 mm
Catching area	500 cm^2
Range of measurement	0-720 mm/h
Resolution	0.1 mm
Specified Accuracy	±1% from 6 mm/h to 150 mm/h
Output	reed switch
Power for heater	normal operation: 55 W extreme weather: additional 25 W additional heater for the interior (25 W) and the orifice rim (10 W)

5. Comparative Data Analysis

5.1. Data Intercomparison at the Reference Station No. 77

The reference station no. 77 (in Mühldorf, coordinates: 46.9330° N, 15.9071° E) in the center of the WegenerNet region is the only station that allows a direct comparison of the three sensor systems described in Chapter 4. This station is equipped with all of the three precipitation gauges (see Figure 5.1). All the other stations measure with either the gauge from Young (at the 11 primary stations [up to October 2013], Section 4.3) or the Theodor Friedrichs gauge (at the 138 base and special base stations, Section 4.2). The Kroneis MeteoServis instrument (Section 4.4) is exclusively available at the reference station and will act as the reference sensor. The two ZAMG stations in Feldbach (46.94889° N, 15.8797° E) and in Bad Gleichenberg (46.8722° N, 15.90361° E) will act as supplementary reference stations for further aiding the quality evaluation.

In a first step an analysis and a comparison of the data delivered by the three different sensors at the reference station no. 77 is performed in this chapter. This evaluation will show if there are systematic differences in the measured data sets of the different sensors. In the ideal case the measurement errors are within the margin of error which is specified by the manufacturer (see specified accuracy in Table 4.1). Conditions which can lead to deficient measurements have been described in Section 4.1.4.

A comparative analysis of the sensors can be carried out starting with June 2008. From that time on all three sensors and also the heating systems have been fully operational at the reference station. The data set will be investigated until and including February 2013. Thus, the investigation period covers 1734 days, 57 months and 19 seasons.

The time resolution for the used basis data is 5 minutes (Quality-controlled Level 1 data, see Section 2.2). For comparability with the ZAMG sensors, which only provide 10-minute data, 10-minute data products of the WegenerNet data have been produced, always adding up pairs of 5-minute data to 10 minutes.

For statistical purposes the relative differences are used for quantifying the occurring deviations between the data. The relative differences are defined as

$$RD_{FM} = \frac{x_F - x_M}{x_M} \cdot 100\ \% \tag{5.1}$$

$$RD_{YM} = \frac{x_Y - x_M}{x_M} \cdot 100\ \% \tag{5.2}$$

where x_F are the data of the Freidrichs sensor, x_Y of the Young sensor and x_M the reference data of the MeteoServis sensor.

5.1.1. Whole Measuring Period

Regarding the whole period from June 2008 to February 2013 we found that the Young sensor measured the highest total precipitation amount with 4414.7 mm, followed by the Meteoservis

Figure 5.1.: Precipitation measurement systems at the reference stations. From left to right: Kroneis MeteoServis, R.M. Young, Theodor Friedrichs & Co.

sensor with 4279.7 mm, the ZAMG station Bad Gleichenberg with 4162.4 mm, the ZAMG station Feldbach with 4108.2 mm and the Friedrichs sensor with 3926.2 mm.

This first analysis already gives a rough estimate of the relative behavior of the sensors. It shows that two of the WegenerNet sensors at the reference station measure more than the two ZAMG stations (Young: +6.1 % - +7.5 %, Meteoservis: +2.8 % - +4.2 %) and one sensor measures less (Friedrichs: –5.6 % - –4.4 %). In the following sections the relative behavior of different data products (seasonal data, monthly data, 10-minute data) will be investigated and discussed.

5.1.2. Seasonal Precipitation

The total precipitation amount per season was calculated from the basis data which has beforehand been manually controlled. Defective values, like negative values and too high values (higher than a meteorologically reasonable boundary value) have been detected and replaced by so called *not a number* values (NAN). In addition, only periods have been considered during which none of the three reference station sensors was affected by logger outages or missing data (see Table B.1, in Appendix B, for data gaps due to logger failures). The latter is important to avoid misinterpretations of distorted relative differences from using different time periods.

The months have been subdivided into seasons according to the definition by the SocMetPal [1783], which clearly defines the division as follows:

- *Spring:* from 1st of March to 30th of May
- *Summer:* from 1st of June to 31st of August
- *Autumn:* from 1st of September to 30th of November
- *Winter:* from 1st of December to 28th (or 29th) of February

For the seasonal precipitation the mean value of the relative differences with respect to the MeteoServis sensor and the two ZAMG sensors has been calculated. The primary objective was to determine seasonal dependencies of the deviations from the reference sensors. For the seasonal studies four springs, five summers, five autumns and five winters have been analyzed. In Table 5.1 the mean relative differences with respect to the MeteoServis sensor are shown.

Table 5.1.: Mean seasonal relative differences relative to the MeteoServis sensor (from summer 2008 to winter 2012/13).

	Friedrichs [%]	**Young [%]**	**ZAMG BG [%]**	**ZAMG FB [%]**
Spring	-13.84	14.44	-5.00	3.86
Summer	-12.11	5.35	4.34	5.13
Autumn	-17.26	-7.31	-14.90	-18.34
Winter	-12.93	0.14	4.59	-8.52

The Friedrichs sensor shows negative relative differences for all seasons what reveals a clear underestimation of seasonal precipitation amount relative to the reference sensor from MeteoServis. What might seem surprising is the fact that the unheated Friedrichs sensor does not have the highest absolute value of relative difference in winter but in autumn. The main reason for that is, that the snow, which accumulates in the unheated funnel of the Friedrichs sensor melts at rising temperatures and is simply measured delayed but is not lost. As the evaporation losses of heated instruments are considerably high, this fact can even lead to higher - but delayed - values in the unheated instruments compared to the heated ones.

The Young sensor is overestimating the seasonal precipitation amount in spring and summer. In summer the value is comparably small due to a two-day blockage during strong rain in June 2009, which caused a relative difference of –50 % within that month. The main reason for the lower values during autumn at the Young sensor are blockages and the fact that the heater was already activated. For low rain intensities the effect of evaporation due to the heating system, which is directly located underneath the funnel, prevents the collected water from reaching the orifice. In addition, as the orifice in the center of the funnel is smaller for the Young than for the other instruments, it is more easily blocked by seeds, leaves or other particles. Especially during autumn partly or totally blocked funnel orifices are quite likely due to leaves carried by the wind into the funnel.

The two ZAMG sensors show quite high negative relative differences in autumn with –15 % (Bad Gleichenberg) and –18 % (Feldbach). One main reason for these underestimations are station downtimes or blockages in October 2008, which lead to underestimations of about –70 % during that month. Another possible explanation are evaporation losses due to funnel heating. Also in the following autumn months the MeteoServis precipitation amount is underestimated by the two ZAMG stations but not at such a high relative value.

5.1.3. Monthly Precipitation

Figure 5.2 shows the precipitation amount per month from June 2008 to February 2013 for all three sensors. As mentioned before in June 2008 all three sensors started to measure consistently. The Friedrichs sensor already delivered data starting with October 2007. In this first overview the raw data (monthly sum of Level-1 data) delivered by the five sensors is shown. The only corrections were applied to negative values and too high values, which ex-

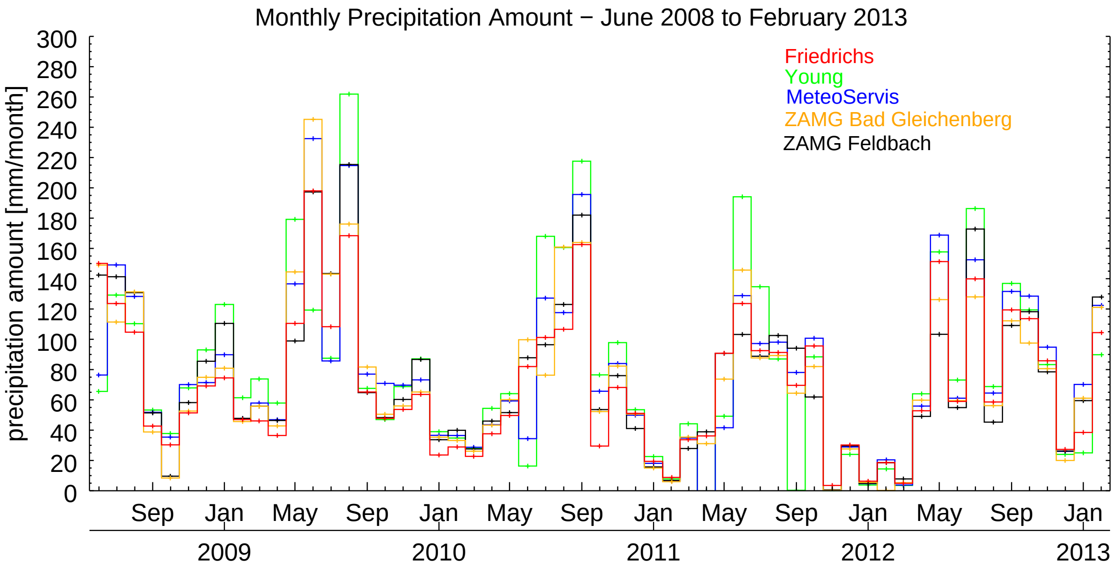

Figure 5.2.: Precipitation amount per month from June 2008 to February 2013 for all three sensors at the reference station and the two ZAMG station sensors at Bad Gleichenberg and Feldbach.

ceed an empirical maximum 5-minute value for precipitation Kabas [2012]. For other defective measurements and sensor failures many different reasons can be found. The most frequent problems that lead to unavailability of data are failures of the data logger. In these cases no measuring results are transmitted to the data portal and thus no data can be downloaded. As the Young sensor and the MeteoServis sensor share one channel in the data logger they always drop out simultaneously in case of logger channel failures. The Friedrichs sensor has its own logger channel which is less prone to outages. Table B.1 in Appendix B summarizes for each station the time periods of missing data due to logger outage and failures in the data processing, respectively. Blockages of the catching funnel constitute another frequent problem which gives rise to measuring and collecting errors. Such blockages are in general caused by leaves or dust and can be detected in the high-resolution basis data as a lack of data or a delayed flow through the funnel. For the Friedrichs sensor which is not equipped with a heating system, errors are unavoidable in the winter months during solid precipitation events. When temperature rises above the zero degree level again after a snowfall period the Friedrichs gauges also show the delayed flow due to melting of the accumulated snow which was gathered in the catching funnel. Most of these errors and uncertainties are detected by the quality control system (QCS) which marks defective data with quality flags (QF). However, it is advisable to check if the marks have been applied correctly. For further information on the WegenerNet Processing System (WPS) refer to Scheidl [2014], Kirchengast et al. [2014] and Kabas [2012].

For quantifying the differences between the sensors and the reference instruments the relative precentaged deviation has been calculated. The relative differences between Friedrichs and Young sensor respectively and the MeteoServis sensor are shown in Figure 5.3. The blue line represents the MeteoServis reference data, the dots mark the relative differences of each

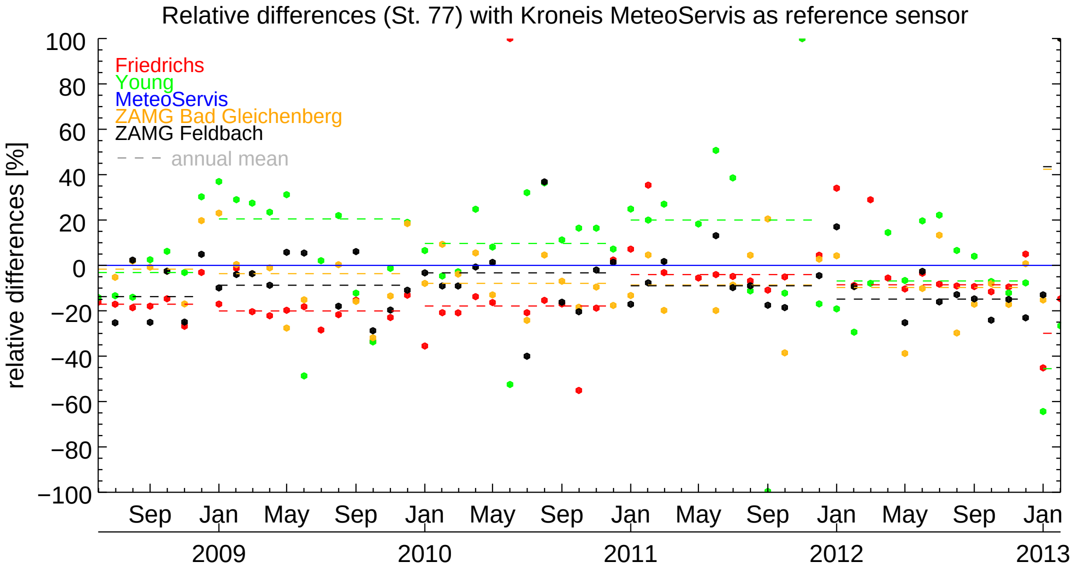

Figure 5.3.: Relative differences of all sensors with respect to the MeteoServis sensor. The dashed lines indicate the annual median relative difference for each sensor.

sensor type. The dashed lines represent the annual median of the relative differences. Between June 2008 and September 2010 the Friedrichs gauge underestimates the precipitation amount at an average of -17.5 %. Since January 2011 the relative deviation of the Friedrichs sensor decreased by more than 10 %. A conclusive reason for this could not be found by simple data analysis. A first assumption for the cause of this inconsistency was, that there may have been a change in the MeteoServis measurements. A sudden underestimation by the MeteoServis sensor would pretend higher Friedrichs measurements in the relative differences. However, what opposes this guess is the simultaneous decrease of the Young relative differences. If the first assumption was true, the relative differences of the Young sensor would have increased roughly by the same amount as the Friedrichs relative differences, assuming the Young being stable. Also the relation of the MeteoServis to the ZAMG stations does not support an appreciable change of the former sensor during this period.

Figure 5.4 shows the relative behavior of the sensors with respect to the sorted monthly MeteoServis precipitation amounts. The dashed lines indicate the ±20 % deviation from the reference. The lowest monthly precipitation amounts are in general measured in the winter months followed by spring and autumn. The highest values which are here in the range beyond 100 mm/month stem from the summer months which are strongly affected by convective precipitation events with high intensities and thus high amounts. In the left display of Figure 5.4 the absolute values are plotted against each other, on the right the relative differences are shown.

Table 5.2 summarizes the situation displayed in Figure 5.4. The relative number of values within defined percentaged deviation boundaries are listed. For the lowest precipitation amount range between (0...80) mm less than 60 % of the data are within the ±20 % interval around the reference. For months with precipitation amount between (80...160) mm the Friedrichs sensor is within the ±20 % with 93.8 % of the data (15 out of 16 events). The Young sensor which clearly tends to overestimate the precipitation amount in the range be-

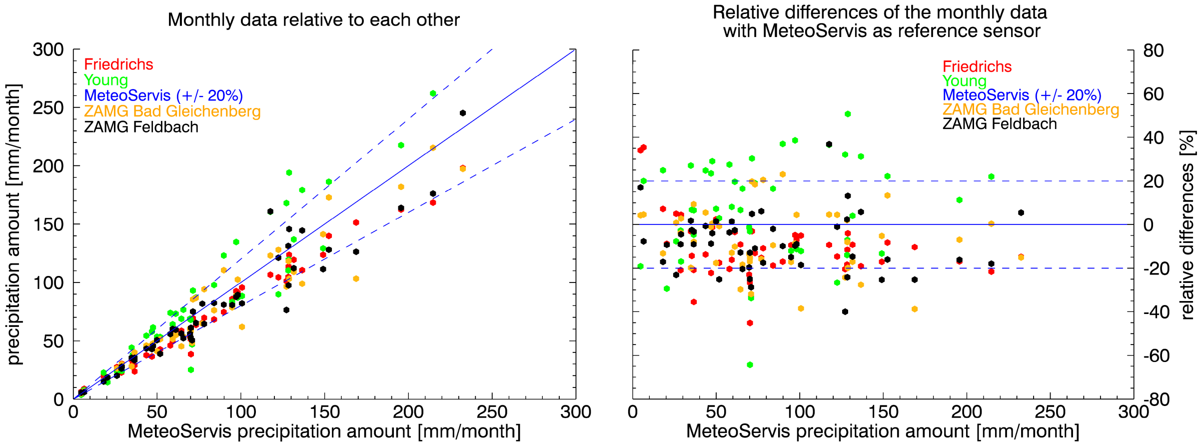

Figure 5.4.: Monthly precipitation amount relative to the reference sensor from Kroneis MeteoServis in ascending order. The blue line displays the reference exactly on the x=y line. Dashed lines: +/- 20% of the reference value.

tween (0...80) mm shows an interesting behavior in the intermediate category. 50 % of the data are within the ±20 % interval (mainly -20 %) and 50 % of the data are beyond the ±20 % boundaries (mainly beyond +20 %). As also shown in Table 5.1 the Young sensor underestimates precipitation amount especially in the autumn months October and November. These months have in average amounts exactly in the range between (80...160) mm. Regarding the whole range of 49 months investigated only 13 months are beyond the ±20 % range for the Friedrichs data but 20 months for the Young data.

The two ZAMG sensors show a quite good accordance with the MeteoServis data in the range between (0...80) mm with more than 80 % of the data within ±20 %. In the range between (80...160) mm only about 30 % of the ZAMG data are beyond the ±20 %, which indicates also a rather good consistency. In the highest precipitation range concerning months with a rainfall quantity of at least 160 mm 75 % of the data accumulate within the ±20 % interval relative to the MeteoServis data, which is valid for both ZAMG sensors. Considering the whole range of precipitation amount 18.4 % of the ZAMG data in Bad Gleichenberg are beyond the ±20 %, and 22.4 % of the ZAMG data in Feldbach.

5.1.4. 10-Minute Data

In Figure 5.5 the absolute 10-minute precipitation amounts of the Friedrichs and the Young sensor have been plotted against the reference values of the MeteoServis sensor. The right plot shows the according relative differences. The left visualization shows the comparative behavior of the sensors. The blue x=y line represents the MeteoServis data with the +/– 20 % deviation range (dashed lines).

For both sensors, Friedrichs and Young, a clear tendency relating to the reference sensor can be seen. The linear fit has been plotted for all values of at least 1 mm/10min, thus gives information about the high intensity 10-minute intervals. The linear regression of the Friedrichs data has an average slope of 0.80, what reveals an underestimation of –20 % with respect to the MeteoServis data, for the Young sensor the average slope is 1.27, what states an overestimation of +27 %. If the whole intensity range including low intensities is considered,

Table 5.2.: Relative number of values within the +/– 5 %, +/– 10 % and+/– 20 % deviation from the reference sensor (MeteoServis) shown in Figure 5.4 for different monthly precipitation amount ranges. The values are given in percent of the total number of events in that precipitation amount range. F ... Theodor Friedrichs & Co, Y ... R.M.Young

prec. amount [mm], (number)	**within ±5%**		**within ±10%**		**within ±20%**		**beyond ±20%**	
	F	**Y**	**F**	**Y**	**F**	**Y**	**F**	**Y**
0...80 (29)	24.1	17.2	34.5	37.9	58.6	55.2	41.4	44.8
80...160 (16)	12.5	6.3	50.0	12.5	93.8	50.0	6.2	50.0
> 160 (4)	0.0	0.0	0.0	0.0	75.0	50.0	25.0	50.0
whole range (49)	18.4	12.2	36.7	26.5	72.9	55.5	27.1	44.5

prec. amount [mm], (number)	**within ±5%**		**within ±10%**		**within ±20%**		**beyond ±20%**	
	BG	**FB**	**BG**	**FB**	**BG**	**FB**	**BG**	**FB**
0...80 (29)	34.5	37.9	48.3	58.6	89.7	82.8	10.3	17.2
80...160 (16)	18.8	12.5	43.8	37.5	68.7	68.7	31.3	31.3
> 160 (4)	25.0	0.0	50.0	25.0	75.0	75.0	25.0	25.0
whole range (49)	28.6	26.5	46.9	49.0	81.6	77.6	18.4	22.4

the Friedrichs value stays constant with –20 %, whereas the Young value decreases to +15 % due to the strong scattering around the reference in the lower intensity range (< 2 mm/10min, see right plot in Figure 5.5). The inhomogeneous jump of the mean relative differences between 2010 and 2011 (see Figure 5.3) for the two WegenerNet sensors can also be shown by a separate analysis of 2009/10 and 2011/12 with this kind of relative plot. The average slope of the Friedrichs sensor's data in 2009/10 is 0.76 (–24 %) and changes subsequently to 0.87 in 2011/12, which corresponds to a halved underestimation of –13 %. Also the values of the Young sensor change considerably. While the overestimation amounts to +34 % in 2009/10, it decreased to +19 % in 2011/12. For the Young sensor a stronger scattering around the mean value can be used as an explanation, which is not true in case of the Friedrichs sensor.

In the right plot the relative differences have been plotted instead of the absolute 10-minute values. Especially the behavior of the sensor at the low 10-minute rain rates becomes apparent in this type of illustration. Whereas the absolute difference is increasing with increasing rain rate, which can be seen in the left plot, the relative differences are converging at higher intensities. As an example for that two different intensities can be considered: If the reference sensor measures a 10-minute value of 0.5 mm and an other sensor measures 0.8 mm the absolute difference is quite small with 0.3 mm but the relative difference amounts to +60 %. At a higher 10-minute precipitation amount of, let's say, 7 mm at the reference sensor and 10 mm at the other sensor, we have 3 mm of absolute deviation, but only +43 % of relative difference. The Young sensor has a strong dispersion around the reference value of the MeteoServis sensor. For rain rates between 0.1 mm and 5 mm the values scatter into both the positive and negative percent range, whereas for higher intensities the tendency toward positive relative differences becomes apparent. The relative differences of the Friedrichs sensor are more well-behaved. As it shows already on the absolute differences plot on the left, the values are neatly situated around the –20 % deviation lines (lower dashed blue line).

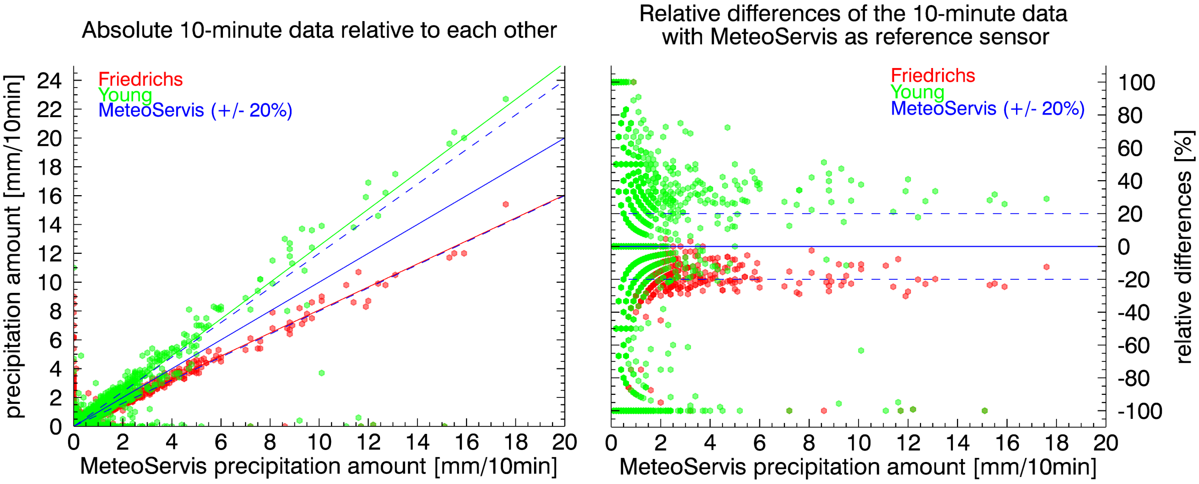

Figure 5.5.: Relative plots of the 10-minute data. The MeteoServis sensor data act as the reference.

5.2. Snowfall Events

5.2.1. Unheated Sensors

An example for delayed flow due to snow melting is shown in Figure 5.6. In this graph the total precipitation per day is plotted together with the temperature (5-minute basis data). The delayed flow due to snow and ice melting processes could be observed on the 9th and 10th of December 2012. As temperature rose above the zero degree boundary - which had not happened the days before - the snow and ice which had been collected in the funnel of the Friedrichs gauge melted and the sensor is (misleadingly) generating a precipitation event. For the other days with recorded precipitation the temperature is always above the freezing point, so that it can be assumed that there has not been solid precipitation. On the 15th of December (precipitation amount: 5 mm) the temperature even reaches 10 degrees Celsius at noon and does not fall below 2 degrees Celsius at night. Therefore all sensors, including the Friedrichs gauge, record similar precipitation amounts (within +/- 0.5 mm). On the 26th of December the situation is similar. Until late afternoon temperature lasts at about 5 degrees Celsius and then falls down to zero degrees at night. The precipitation event was recorded between 11:00 and 16:00 UTC which justifies the assumption that there has not been snowfall.

5.2.2. Heated Sensors

As solid precipitation forms cannot be measured with instruments without a heating system with the requested time resolution of 5 minutes, 13 stations with heated precipitation gauges have been installed in the WegenerNet. The 11 primary stations, equipped with a Young sensor (no. 11, 32, 37, 44, 72, 74, 82, 101, 132, 135, 139), provide data of solid precipitation with a thermostatic heating (power consumption of 18 W). The Reference station measures with a Young gauge as well as a MeteoServis gauge. The latter has a heating system consisting of thermal resistors which are placed beneath the collecting funnel. A thermostat controls the status of the gauge heating (power consumption of 48-57 W) (MeteoServis [2005]).

The base and special base stations which measure precipitation with the Friedrichs instru-

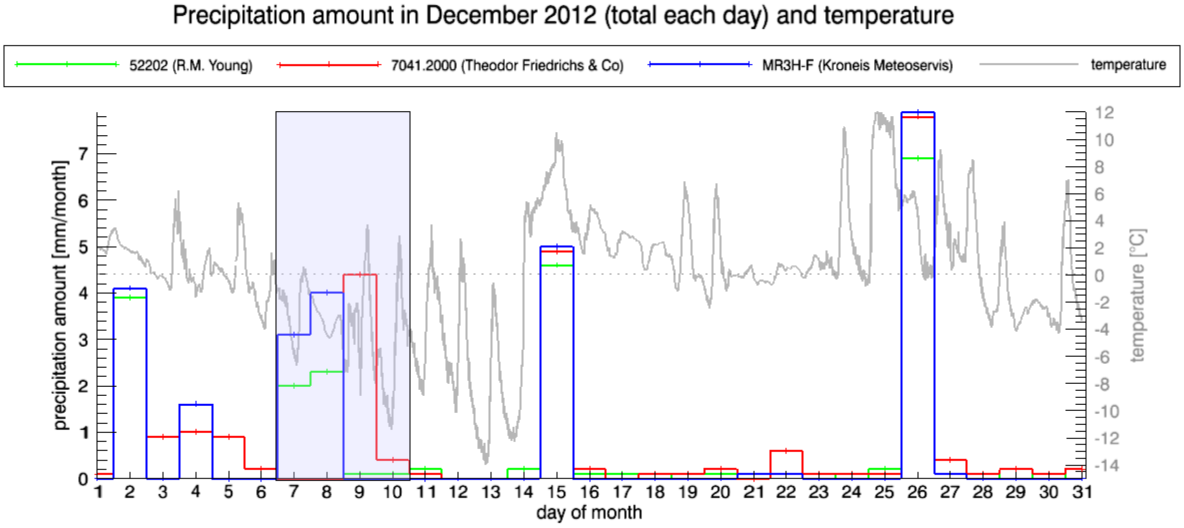

Figure 5.6.: Example for delayed flow of unheated precipitation gauges (Friedrichs) on December 9 and 10, 2012.

ment have no heating system. At snowfall events the snow accumulates in the collecting funnel. A delayed flow due to melting processes has been observed for most events with solid precipitation during winter, such as in the example shown in Figure 5.6.

For reliably measuring the water equivalent a flawless heater operation is required. For that reason the status of the 13 heated sensors in the WegenerNet has been analyzed and evaluated. The precipitation data measured by the two ZAMG stations and the MeteoServis sensor during snowfall events were used as a reference for the Young data. In order to determine whether an event has been a real snowfall event (not, e.g., graupel) the median and the maximum and minimum values of all Friedrichs sensors have been calculated. For medians larger than 0.2 mm the event has been discarded as *'not fully a snowfall event'*. Events with a median of 0.0 and temperature below –2 °C have been declared as *'prime examples'*.

According to information from the maintenance team all heated sensors were provided with power supply starting from June 2008. Hence five winters and 28 *real* snowfall events could be analyzed until spring 2013 in order to investigate the operation status of the 13 heaters. As there are no weather observers for the WegenerNet who document snowfall, those events had to be found through data analysis. For that purpose the data at the Reference station No. 77 were tested for events that show precipitation for the two heated sensors (Young and MeteoServis) but no precipitation for the un-heated Friedrichs sensor. The observations from the two ZAMG stations in Feldbach and Bad Gleichenberg were used as auxiliary information. Besides the amount of fresh snow and the total snow depth (both measured at 7:00 am), the ZAMG provides also information about the type of snow (e.g. powder snow, wet snow...).

To determine the operation status of the Young sensor heaters the amount of precipitation during the events declared as snowfall has been calculated. If the values found were less than 0.1 mm, the sensor was marked as either 'blocked' or 'sensor without operational heater'. In order to exclude blockages from the evaluation the behavior of the sensors at temperature rise above 0 °C was compared with the Friedrichs sensors. If the sensor shows the same behavior as the non-heated sensors at temperature rise or insolation, the operation status of the heater is beyond doubt *not operational.*

For documentation of the periods of heater operation, for each sensor the precipitation amount per snowfall event has been calculated and compared with the measured amount of the reference sensors (MeteoServis, ZAMG Bad Gleichenberg, ZAMG Feldbach). The results are summarized in Table 5.3. For every main station which is equipped with a heated precipitation gauge the times of heater drop out are noted. Since the actual date and time are not known exactly, a conventional point in time has been defined for making a reasonable allocation possible, then stored to the metadata part of the WegenerNet database. Accordingly, if the last time, when the heater was operational is known, the drop out time is defined as either

- the 1st of July of the current year (if the heater was operational throughout the entire preceding winter - from November to March) or
- the 1st of January of the following year (if the heater was operational until December of the preceding year).

For all stations the start of measurements was the 1st of January, 2007. The analysis showed that some heaters have been actually non-operational from the outset. From the beginning they show the same behavior as the unheated Friedrichs instrument. At temperature rise or at exposure to direct insolation they record precipitation. The heater of station 72 has been repaired during summer 2009.

Table 5.3.: Operation status of the 13 sensor heaters in the WegenerNet and time of heater drop out.

Station	Sensor Type	Heater drop out	Status (Apr. 2013)
11	Young	2008-07-01	not operational
32	Young	2008-07-01	not operational
37	Young	2008-07-01	not operational
44	Young	2011-07-01	not operational
72	Young	2008-07-01[1]	operational
74	Young	2009-07-01	not operational
77	Young	2013-01-01	not operational
77	MeteoServis	/	operational
82	Young	2011-07-01	not operational
101	Young	2009-01-01	not operational
132	Young	2008-07-01	not operational
135	Young	2009-01-01	not operational
139	Young	/	operational

[1] Heater at St. 72 repaired in summer 2009.

As a consequence of this unfavorable outcome, which revealed that 8 from 12 Young heaters have not worked properly early on and others failed later and due to the high liability to blockages of the funnel orifice, all Young instruments have been replaced by MeteoServis instruments (model MH3R, see Section 4.4) in October 2013. The measurements of the MeteoServis gauge at the Reference station turned out to be very reliable during snowfall events. In order to ensure automatic control of heater operation in future, all MeteoServis sensors are furthermore equipped in 2014 by a sensor continuously delivering status information on heater operation.

5.3. Wind Influence

A core area of investigation concerning precipitation gauges is the influence of different instrument designs on measurements results. Especially the deformation of the wind field around the measuring device due to its construction characteristics, can lead to significant losses during the measurement periods (Sevruk et al. [1991], Nagy et al. [2013]). Sevruk et al. [1991] discovered in wind tunnel tests that the deformation of the wind field is in particular dependent on size and shape of the orifice rim. Thick orifice rims lead to higher wind field deformation and higher losses in measurement. Bird protection rings which are not in use in the WegenerNet for precipitation gauges, also have a deforming effect on the wind field. Nagy et al. [2013] ascertained in wind field simulations around rain gauges, that the deforming effect is highest directly above the orifice in the center of the catching funnel. The latter causes an increase of the prevailing wind speed between 20 and 25%. Their simulations showed that this effect has no significant influence on liquid forms of precipitation but for solid precipitation the errors are significant. Strong wind speeds themselves can also bias precipitation measurements, in particular solid precipitation.

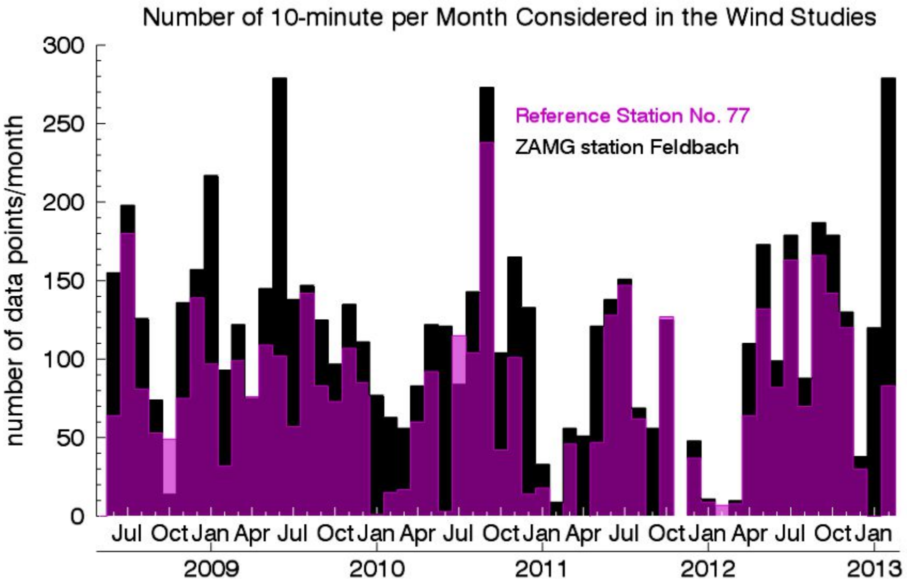

Figure 5.7.: Number of data points per month during June 2008 to February 2013, which have been taken into account for the wind studies. One data point corresponds to one 10-minute interval during which all sensors measured at least 0.2 mm.

As there are no wind related studies yet concerning the three precipitation gauges used in the WegenerNet, in this section the influence of wind will be discussed based on a preliminary analysis. The basis for the studies are the 5-minute data of wind and precipitation from the reference station no. 77 and the 10-minute wind and precipitation data from the ZAMG station in Feldbach, respectively. For comparability purposes the 5-minute WegenerNet data have been transformed into 10-minute data products. Therefore, the precipitation rate is given in *mm/10min* and the wind speed as *10-min average wind speed*.

To figure out whether there is any correlation between wind speed and measured precipitation rate, wind speed has been grouped into four wind speed classes. The class boundaries have been found empirically by checking out typical maximum wind speeds during rain events. To ensure that all sensors measured during the observed periods, we have only selected 10-minute intervals with all sensors measuring at least 0.2 mm. In Figure 5.7 the number of data points (10-minute intervals) per month with a measurement value of at least 0.2 mm is shown. As the constraints were more sophisticated for the reference station sensors (all three had to measure at least 0.2 mm during the same 10-minute interval) than for the ZAMG station Feldbach (all 10-minute intervals with a precipitation amount of at least 0.2 mm were accepted), the number of data points is distinctly higher for the ZAMG station.

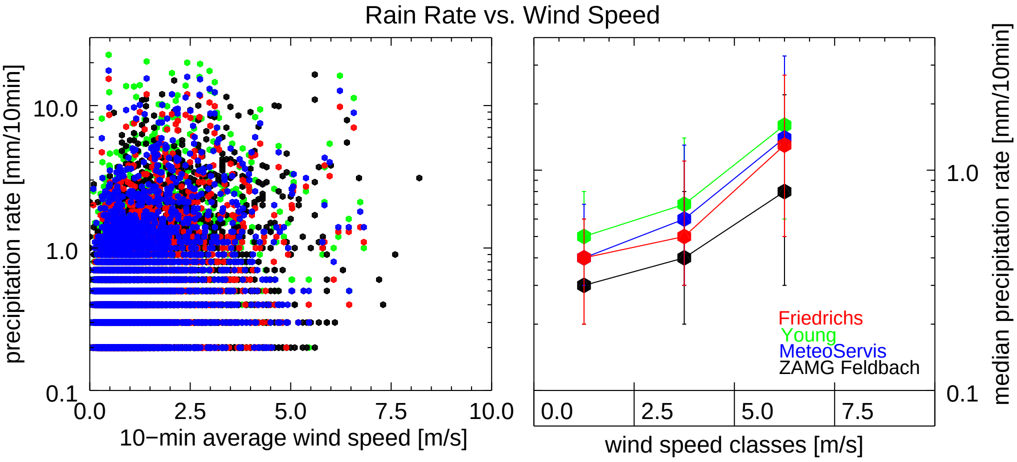

Figure 5.8.: Left: 10-minute precipitation rate as function of the 10-minute average wind speed. Right: median 10-minute precipitation rate per wind speed class, also indicating the interquartile range as vertical "uncertainty bars".

Figure 5.8 shows the 10-minute precipitation rate plotted against the 10-minute average wind speed for rain rates of at least 0.2 mm/10min. The scatter plot on the left gives information about the distribution of the different precipitation rates as a function of wind speed. As there is no linear relationship between the two parameters, the y-axis has been chosen logarithmic. The simple assumption that on an individual 10-minute data basis the highest rain rates come off at the higher wind speed classes, does not hold. In fact, the highest 10-minute rain rates with >20 mm/10 min have been reached in the lowest wind speed class between 0.0 m/s and 2.5 m/s, since there are much more data in this class than in the others. However, the median values per sensor and per wind speed class (right part of the picture) are clearly increasing. In the lowest class the median precipitation rate is between 0.3 mm/10min and 0.5 mm/10min whereas the values range between 0.8 mm/10min and 2 mm/10min in the highest class. Thus, even if the highest individual precipitation rates accumulate at low wind velocity, given the mass of data in this class, the rain intensity basically increases with higher wind velocity, which is physically plausible that these are the more convective situations.

When taking a look at the relative differences of the Friedrichs and the Young sensor relative

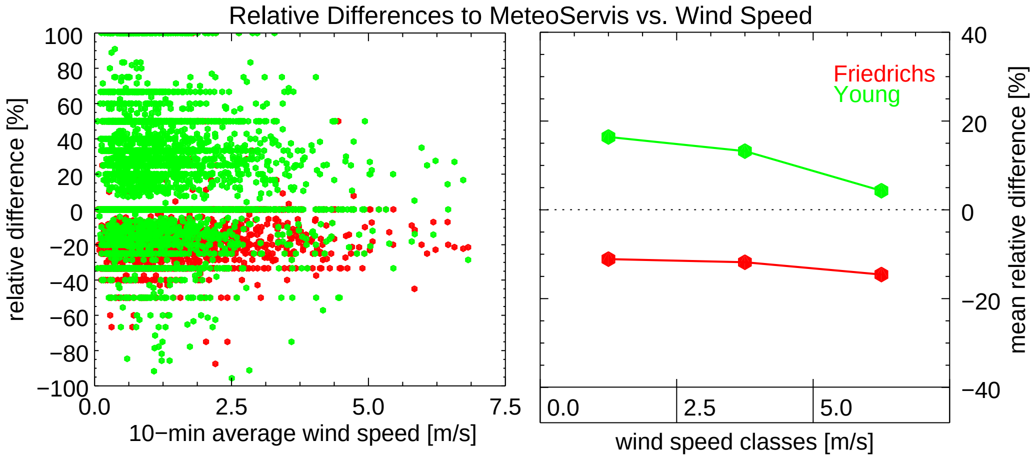

Figure 5.9.: Left: Relative differences of the 10-minute precipitation rate between the Friedrichs and Young sensor, respectively, and the MeteoServis sensor. Right: Mean relative differences per wind speed bin.

to the MeteoServis sensor, we get to Figure 5.9. All relative differences greater than 100 %, have been set to exactly 100 % to obtain a degree of clarity in the figure. The right plot shows the mean relative differences per wind speed class. As it begins to show up in the left plot, the relative differences of the Friedrichs sensor scatter in the negative percent range around –15 %. The deviation from the MeteoServis sensor is quite constant, apart from the slight decrease in the highest windspeed class. For the Young sensor the scattering is much stronger and spreads into the negative and positive areas of relative difference (left plot). The mean values per wind speed class show a clear decrease in relative difference from about +20 % to +5 %. This could be an indication of losses at high wind speeds. Since a direct comparison with the ZAMG sensor in Feldbach is not possible here due to the relatively large distance of 2.7 km and the difference between the data sets (concerning missing data, etc.), only more loose comparisons can be made.

Figure 5.10 shows the fraction of events in predefined precipitation rate intervals per wind speed class. The rain rate intervals have been chosen from Figure 5.8 in reasonable ranges. In the first two wind speed classes the rain rates < 1 mm/10min are dominant. In the last class the events with intensities between 1 mm/10min and 5 mm/10min are more frequent than the low intensity events. The highest precipitation intensities are considerably increasing with rising wind velocity. In the lowest class they only account for up to 2 % of all events, in the highest wind speed class they contribute up to about 10 %. The three WegenerNet sensors show a quite similar behavior, whereas for the ZAMG sensor the low intensity precipitation events remain dominant in all three wind speed classes, but the general dependance on wind speed class is similar. On the one hand the spatial separation of the stations of more than 2.5 m and the different ambient conditions are responsible for this. On the other hand the deviation is affected by the great difference in evaluated data points where the ZAMG station dataset includes more low intensity data (see Figure 5.7).

In summary, it is shown that physically high wind speeds are in general associated with high precipitation amounts, and that technically especially the Young sensor seems to be somewhat vulnerable to wind-induced precipitation losses.

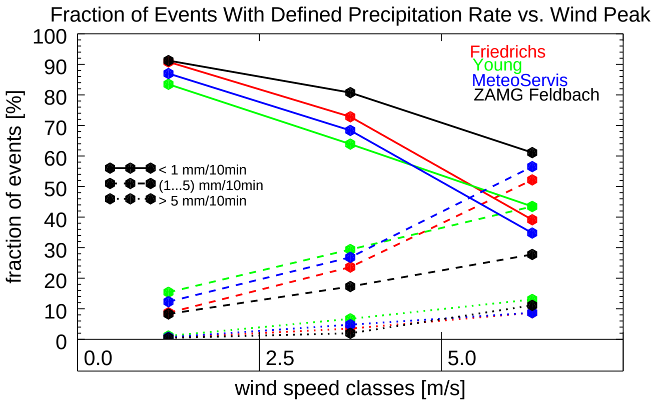

Figure 5.10.: Fraction of events in a defined precipitation rate interval per wind speed class.

5.4. Temperature Influence

In order to determine if there are any dependencies of precipitation rate and relative deviations on temperature, the same studies as for wind speed have been carried out. The analyzed data sets are the 10-minute precipitation sums and the 10-minute average temperature at the reference station no. 77. In Figure 5.11 the absolute 10-minute values are plotted against each other, whereas Figure 5.12 shows the according relative differences of the Friedrichs and the Young sensor with respect to the MeteoServis sensor. The right plots of both Figures show the median and mean values, respectively, for defined temperature classes (5°C intervals). It was required, that all three WegenerNet sensor must have a value of at least 0.2 mm for the same 10-minute interval at temperatures above 0°C and that both the Young and the MeteoServis sensor must have a value of at least 0.2 mm above −10°C in order to be evaluated.

The maximum precipitation rates which stem from convective showers are accumulated at temperatures between about 15°C and 22°C. For higher temperatures only a few precipitation events have been recorded, so this part is not reasonably covered by the dataset. For negative temperatures the maximum 10-minute precipitation rate is 1 mm at the ZAMG station Feldbach and 0.9 mm at the WegenerNet reference station. The median values per temperature class show an almost log-linear progression with increasing temperature,corresponding to a roughly exponential increase of rain rate with temperature, reflecting the Clausius-Clapeyron law (Berg et al. [2013]). Indeed, just by looking closer at Figure 5.11 whether there is, in accordance with Berg et al. [2013], a more stratiform part of lower-intensity precipitation for temperatures below about 15°C and a more convective part of high-intensity precipitation for temperatures above 15°C, this behavior can be considered well visible in Figure 5.11. Of course to more robustly qualify the rate of increase of precipitation with temperature, depending on stratiform and convective types, will need more thorough analysis.

The median of the Friedrichs sensor is always lower or equal to the MeteoServis median, whereas the median of the Young sensor is lower or equal to the MeteoServis median between −10°C and +10°C but higher for increased temperatures. As will be shown in Chapter 6 (Case Studies), the Young sensor induced overestimated precipitation amount at high precipitation rates such as during heavy rainfall or showers. The relative differences plot in Figure 5.12 shows a strong scattering of the Young sensor data into both the positive and the negative percentage range, the Friedrichs sensor data mainly scatters into the negative percentage area. The mean relative differences of the 10-minute precipitation rate with respect to the MeteoServis sensor per 5°C-interval can be seen in the right plot. Here the underestimation of the Friedrichs sensor becomes apparent. From a temperature of 10°C, the mean relative difference levels off at a value of about –15 %, at lower temperatures the mean relative deviation is higher with around –20 %. The relative differences of the Young sensor are also increasing with increasing temperatures and reach their maximum (with about 21 %) in the temperature range with maximum precipitation rate. Between 0°C and 15°C the mean relative differences are almost constant with near +15 %.

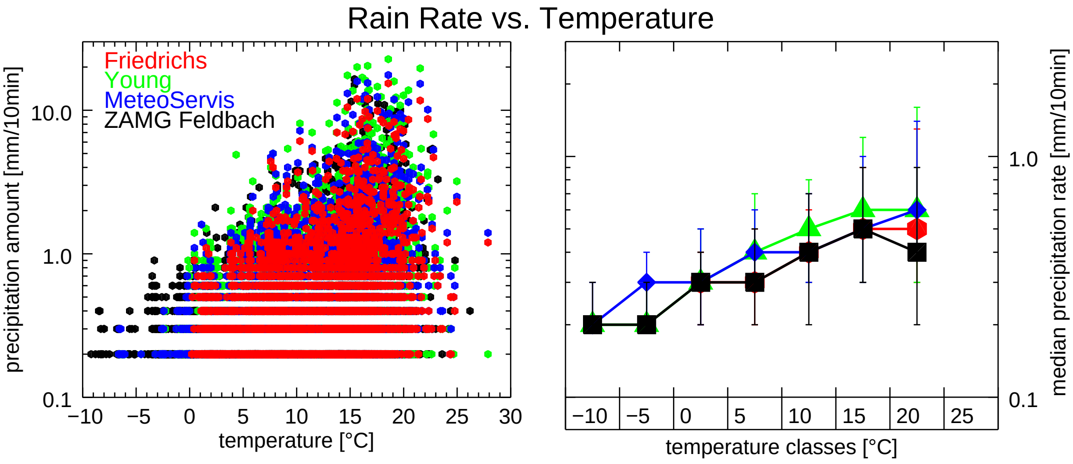

Figure 5.11.: Left: 10-minute precipitation rate as function of the 10-minute average temperature. Right: median 10-minute precipitation rate per temperature bin, also indicating the interquartile range as vertical “uncertainty bars”.

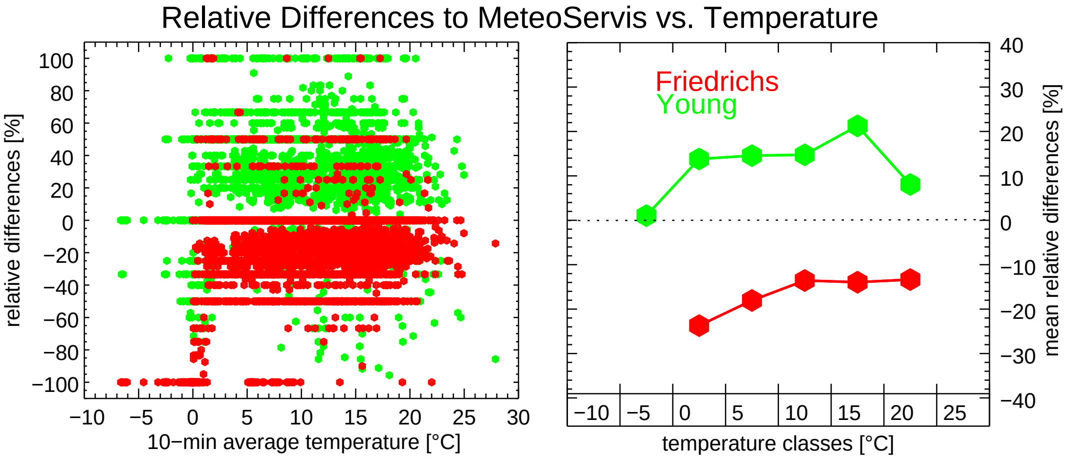

Figure 5.12.: Left: Relative differences of the 10-minute precipitation rate between the Friedrichs and Young sensor, respectively, and the MeteoServis sensor. Right: Mean relative differences per temperature class.

6. Case Studies

Measuring instruments are in most cases tested and evaluated under laboratory conditions. That means that measurements take place in a controlled environment and under controlled circumstances. The specifications which contain accuracy, resolution and dimensions of those instruments are derived in such laboratory tests (see Table 4.1). In nature, of course, we do not have laboratory conditions but have to deal with external effects and influences that cause unavoidable errors.

In this chapter the dependence of errors and uncertainties on different precipitation events (different forms and intensities) will be analyzed. In the following sections a distinction is made between light and moderate rainfall, heavy rainfall and snowfall. The definitions for precipitation intensity can be obtained from Table 3.1 (page 13). All case studies will be evaluated for all 150 stations in the WegenerNet and the two additional reference sensors from the ZAMG (Feldbach and Bad Gleichenberg). In the following studies the temporal and spatial distribution of the rainfall and snowfall events across the WegenerNet region will be analyzed and discussed. For better understanding of the situation the prevailing weather conditions will be discussed for each case study according to the records of the ZAMG in their monthly retrospects (ZAMG [2013b]).

Please note that time is always given, for consistency, in Coordinated Universal Time (UTC), which is Central European Time (CET) minus 1 hour and Central European Summer Time (CEST) minus 2 hours, respectively.

6.1. Light and Moderate Rainfall

Rainfall events with light or moderate intensities are in most cases attributable to steady or stratiform rain events. The two events which will be investigated in this context are November 5, 2012 (02:00 to 16:30 UTC) and November 12, 2012 (03:00 to 24:00 UTC). The first event has an average intensity of 5.0 mm/h, the second one of 1.7 mm/h, calculated for the reference sensor from MeteoServis at the reference station no. 77. In accordance with Table 3.1 the rain rate on 5th should rather be classified as heavy precipitation event but during the 14.5 hours of precipitation the intensity varied between very low and rather high values (see Figure 6.1), so we used this still as an example of a overall moderate event.

6.1.1. November 5, 2012

A depression over the British Isles brought dull weather to the regions south of the Alps between the 2nd and 4th of November 2012. On the 2nd 4.5 mm of precipitation are recorded at the reference station, the 3rd and 4th stay dry in the whole of Austria. During the night from the 4th to the 5th of November it begins to rain all over the country as the depression reaches the southern Alpine region. In Feldbach the first rain drops are recorded at about 2:00 UTC (see Figure 6.1). At 5:30 UTC the intensity suddenly increases from 1.2 mm/h to 22.8 mm/h within five minutes. Temperature reacts with a stronger recession from 16.5°C to 7.5°C within 6 hours. In contrast to the temperature, pressure reaches its minimum at around 5:00 UTC with 956 hPa and turns upward subsequently until it reaches its maximum of 988 hPa on the 7th of November (23:35 UTC). (ZAMG [2013b])

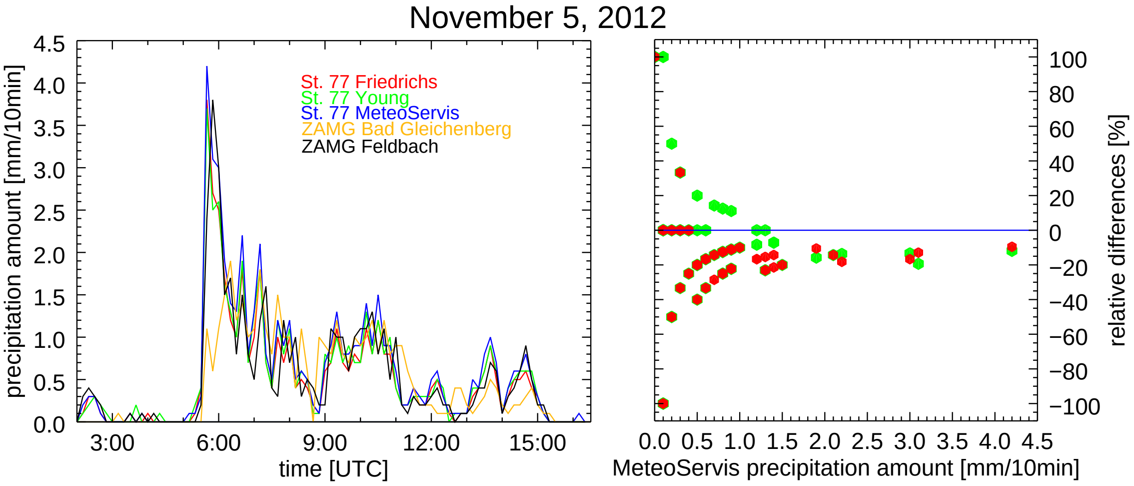

Figure 6.1.: Precipitation event on November 5, 2012. Right: Relative differences of Friedrichs and Young sensors relative to the MeteoServis sensor.

Figure 6.1 shows the progression of the precipitation event on November 5, 2012 for the reference station no. 77 and the two ZAMG stations in Feldbach and Bad Gleichenberg. A comparison of the maximum intensity peak at 5:30 UTC and the following side peaks of the different sensors indicates the distance between the stations. The peaks of the ZAMG station in Bad Gleichenberg, which is located at a distance of about 6 km south of the reference station, are delayed by more than 30 minutes. As the event moved across the WegenerNet region from the north-west to the south-east, the ZAMG station Bad Gleichenberg measured only half the maximum intensity of the reference station. Also the side peaks are shifted in time. The ZAMG station Feldbach, 2.6 km north-west of the reference station, only shows a maximum time shift of 10 minutes, which corresponds to one measuring interval.

The right plot in Figure 6.1 shows the relative differences of all sensors according to the MeteoServis sensor, which is indicated by the blue 0 %-line. The two WegenerNet sensors are underestimating the precipitation amount with mean relative differences of -16 ± 28 % (Friedrichs) and -8 ± 41 % (Young), respectively. The underestimation of the Young sensor, which is in contrast to the general overestimation in long-term observations, can be explained by the fact, that in November the sensor's heating system is already in operation which can cause evaporation losses especially for low intensity events. An interesting fact is that during the time of strongest precipitation intensity, between 6:00 and 8:00 UTC and 9:00 to 11:00 UTC, the relative differences of the WegenerNet sensors are within the –20 % range. The high differences occur at lower intensities.

Table 6.1 summarizes the total precipitation amount of the event for the three sensors at the reference station, the ZAMG sensors and their respective neighboring sensors. For each sensor the reference station and the according relative differences are given. The precipitation gauge at station 61 was obviously blocked during the event, as no rainfall has been measured.

Table 6.1.: Total precipitation amount of the WegenerNet reference station sensors (M ... MeteoServis, F ... Friedrichs, Y ... Young) and the ZAMG sensors (FB ... Feldbach, BG ... Bad Gleichenberg) and their surrounding station sensors for the precipitation event on November 5, 2012. The last column gives the relative difference to the corresponding reference sensor.

Station	**Total Precip. [mm]**	**Reference**	**Rel. Diff. to Ref. [%]**
77 M	51.9	/	/
77 F	43.6	MeteoServis	-16.0
77 Y	46.0	MeteoServis	-11.4
ZAMG FB	45.1	/	/
45 F	41.1	ZAMG FB	-8.9
46 F	35.5	ZAMG FB	-21.3
60 F	28.2	ZAMG FB	-37.5
61 F	0.0	ZAMG FB	-100.0
ZAMG BG	40.6	/	/
134 F	40.2	ZAMG BG	-0.5
135 Y	35.6	ZAMG BG	-12.3
144 F	37.8	ZAMG BG	-6.9
145 F	29.0	ZAMG BG	-28.6

The other stations show a typical underestimation of the precipitation amount. The high relative difference of station 60 is caused by a partial blockage of the instrument orifice.

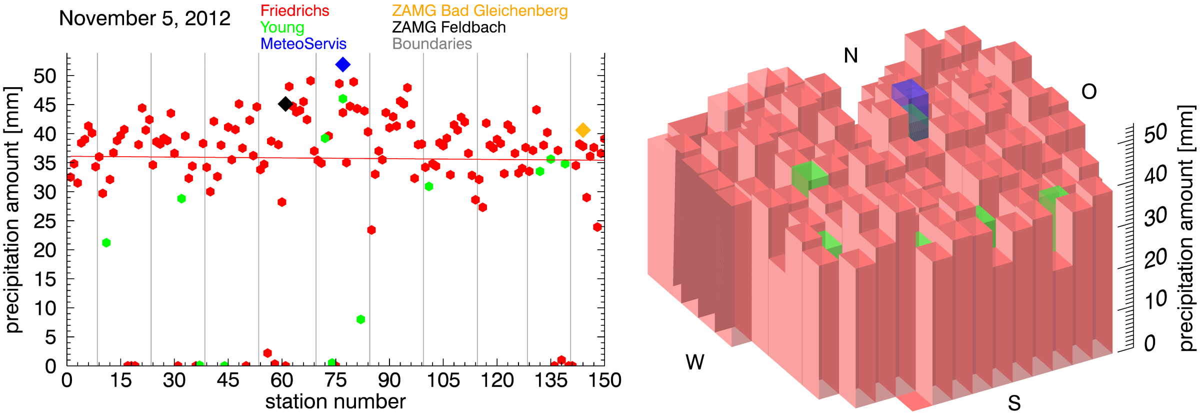

Figure 6.2.: Precipitation event on November 5, 2012 - field.

Figure 6.2 shows the precipitation event's amount regarding the whole WegenerNet field with all 150 stations equipped with rain gauges. The left plot shows the total precipitation amount of the event for each station. The grey vertical lines delimit the rows in the WegenerNet grid, thus a station directly left of a grey line is located at the eastern boundary of the field and a station directly right of a grey line is positioned at the western edge of the WegenerNet (at Figure 2.1, 4, Kirchengast et al. [2014]).

A linear fit of the Friedrichs values indicates the spatial precipitation amount gradient from north-west to south-east in the field. The right illustration is the corresponding surface plot which represents the total amount per grid cell. Station no. 1 is located in the upper left corner (north-west) and station no. 150 in the lower right corner (south-east). As precipitation is not always evenly distributed across the investigation area, the illustration should give a spatial view of the recorded amount.

Even though the rainfall on November 5, 2012 started off similar to a convective shower, the event was evenly distributed across the WegenerNet, which is typical for stratiform precipitation. Nevertheless, a slightly pronounced maximum in the center of the investigation area can be seen with up to 10 mm more rain than in the northern and southern regions. The technical side of view reveals that nine stations (nos. 17, 19, 31, 50, 75, 136, 140 and 141) had a problem with the data logger (logger outages with a duration of more than 24 hours are listed in Table B.1 in Appendix B). From these stations, which are all equipped with a Friedrichs rain gauge, no data has been transmitted to the WegenerNet database. Further four stations (no. 18, 36, 61 and 44), three with a Friedrichs sensor and one with a Young sensor, recorded a precipitation amount of 0 mm, thus were blocked during the event. The remaining 127 Friedrichs sensors measured a mean precipitation amount of 34 ± 12 mm, the 11 Young sensors measured an average of 23 ± 17 mm, the uncertainty range capturing the spatial variability.

6.1.2. November 12, 2012

The precipitation event on November 12, 2012 is preceded by a weeklong dry period. Especially on the 8th and 9th a high over west and central Europe caused mild weather conditions with temperatures up to 13°C in the WegenerNet region. During the 10th and the 11th a cyclone on its track from France to northern Germany and a depression over the Mediterranean caused high precipitation amounts in some parts of Austria. The south eastern region stayed dry. As the depression reached the area south of the Alps on the 12th of November the rainy weather also flashes over to the WegenerNet region and continues intermittently for about 24 hours (see Figure 6.3). (ZAMG [2013b])

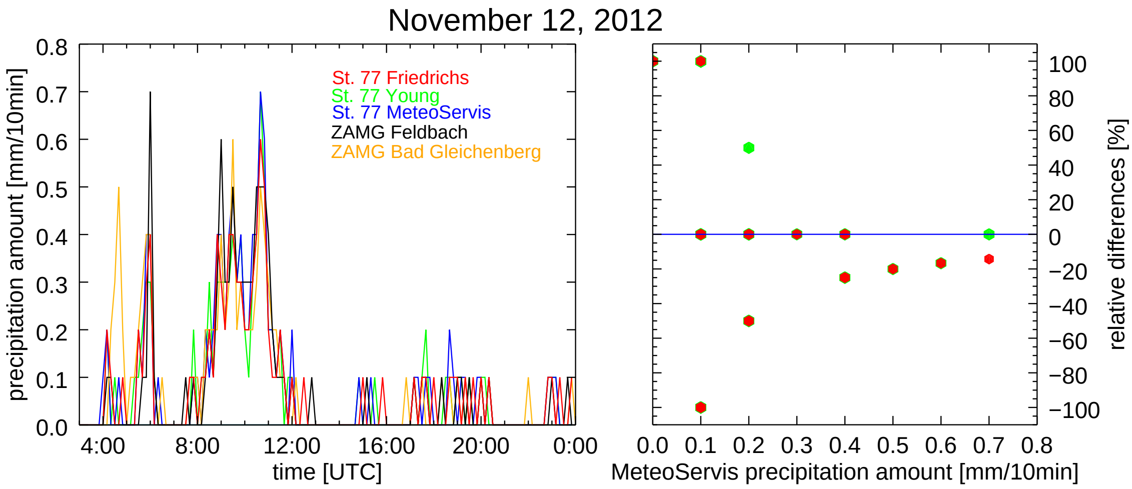

Figure 6.3.: Precipitation event on November 12, 2012.

Table 6.2.: Total precipitation amount of the WegenerNet reference station sensors (M ... MeteoServis, F ... Friedrichs, Y ... Young) and the ZAMG sensors (FB ... Feldbach, BG ... Bad Gleichenberg) and their surrounding station sensors for the precipitation event on November 12, 2012. The last column gives the relative difference to the corresponding reference sensor.

Station	**Total Precip. [mm]**	**Reference**	**Rel. Diff. to Ref. [%]**
77 M	10.2	/	/
77 F	9.2	MeteoServis	-9.8
77 Y	9.2	MeteoServis	-9.8
ZAMG FB	9.1	/	/
45 F	9.4	ZAMG FB	+3.3
46 F	7.4	ZAMG FB	-18.7
60 F	7.1	ZAMG FB	-22.0
61 F	8.4	ZAMG FB	-7.7
ZAMG BG	9.8	/	/
134 F	9.7	ZAMG BG	-1.0
135 Y	9.9	ZAMG BG	+1.0
144 F	9.4	ZAMG BG	-4.1
145 F	7.2	ZAMG BG	-26.5

The rainfall on the 12th of November 2012 can be described as a very light but long-lasting precipitation event. The maximum intensity during the 21 hours of duration was 0.7 mm/10min, thus 4.2 mm/h. This maximum precipitation rate is reached between 5:30 and 6:00 UTC and recurs at 11:00 UTC. In the first rainfall period between 4:00 and 6:30 UTC the front moves from the south-east of the WegenerNet region toward the north-west but does not cross the Raab river. The second precipitation phase moves from the west across the investigation area and brings rain to the whole WegenerNet. After three hours of interruption between 12:00 and 15:00 UTC, rainfall returns with a maximum intensity of 1.2 mm/h.

Comparing the maximum intensity peaks also indicates, that the front edge moved from the south to the north of the investigation area. The ZAMG station Bad Gleichenberg (6 km south of the reference station) has its first peak (at 4:30 UTC) about 1.5 hours before the reference station sensors. During the first high intensity peak at the reference station at 6:00 UTC the ZAMG station Feldbach measures its event maximum. Between 8:00 and 12:00 UTC the peaks occur in reverse order, as the front now moves from west to east and the reference station sensors are hit last and reach their maximum intensity at 10:40 UTC.

In the right plot of Figure 6.3 the relative differences related to the sorted MeteoServis sensor amounts are shown. As was the case for the event on the 5th of November, the relative differences show their maximum values at low precipitation rates. During the two stronger rainfall phases the relative differences are between –50 % and +50 %. The strong scattering on both sides around the reference sensor leads to low values for the mean relative differences but cause high standard deviations. For the WegenerNet sensors Friedrichs and Young the mean relative differencs amounts to -2 ± 67 % and -2 ± 71 %, respectively. However, it shows that for the light precipitation events the absolute differences are in a very small range. Thus the high relative differences at these only contribute to a minor part to the problematic relative differences regarding the whole investigation period.

In Table 6.2 the total precipitation amount of the rainfall event on November 12, 2012 are summarized for the sensors at the reference sensor, the two ZAMG sensors and their surrounding WegenerNet sensors. For each of the regarded sensors the relative difference to the nearest reference sensor is given. The neighboring stations of the ZAMG station Feldbach are within the ± 20 % range of relative difference, except station 60, which measured no precipitation during 8:00 and 12:00 UTC, so the whole second rainfall period is missing. Also the surrounding stations of the ZAMG station Bad Gleichenberg are very close to their reference, except station 145, which also had problems during the second rainfall period.

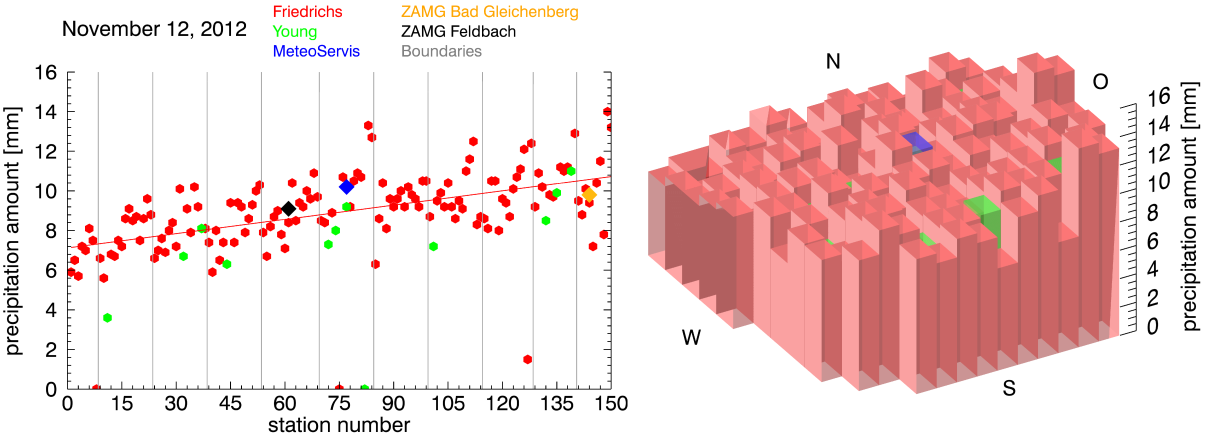

Figure 6.4.: Precipitation event on November 12, 2012 - field.

Figure 6.4 shows the spatial distribution of the precipitation event on November 12, 2012. The left plot presents the total rain amount of the event for each WegenerNet station in a two-dimensional manner which shows a representative increase of precipitation amount from the north-west to the south-east of the investigation area. In the right plot the spatial sense of the formation can be seen even more distinctly. During this event only one station (no. 75 - Friedrichs) had a logger outage and thus did not transmit any data to the database. Two stations in all (nos. 8 and 82), a Friedrichs and a Young sensor, measured a total precipitation amount of 0 mm. Besides these three defective or blocked sensors, two further sensors measured values less than 4 mm (nos. 11 and 127, Young and Friedrichs) and can therefore be classified as partially blocked.

6.2. Heavy Rainfall and Shower

Heavy rainfall and showers are mainly the consequence of convectional updrift of air masses due to strong insolation and heating of the atmosphere. Thus these events occur in general in late spring, summer or early autumn. The events which will be analyzed are May 18, 2009 (20:00 to 22:00 UTC) and August 3, 2011 (20:00 to 24:00 UTC) as convective precipitation events and May 3 to 4, 2012 (22:30 to 10:30 UTC) as stratiform heavy rainfall event.
The average intensities of these three events are 32.9 mm/h, 12.2 mm/h and 4.9 mm/h, respectively, with mean 10-minute precipitation amount of 5.4 mm, 2.0 mm and 0.8 mm.

6.2.1. May 18, 2009

This day has been chosen as a case study for further investigation as it is the day with the highest 10-minute precipitation amount in the history of the WegenerNet. May 2009 was as far as the weather concerned a very active month: above-average lightening occurrence, wild storms, thunderstorms with heavy rainfall and floods, mud and snow slides. Because of the preferential location of the WegenerNet, precipitation reaches the region relatively late compared to other Austrain regions. The 17th stays dry with temperature up to 24°C, on the 18th even temperatures of 27°C were reached. Weak gradient conditions with low horizontal pressure gradients and thus low wind velocity as well as local convective instabilities resulted in strong convective activity at night (see Figure 6.5) (ZAMG [2013b]).
The track of the thunderstorm cell can be followed across the WegenerNet in weather radar images in Figure 6.13 on page 54.

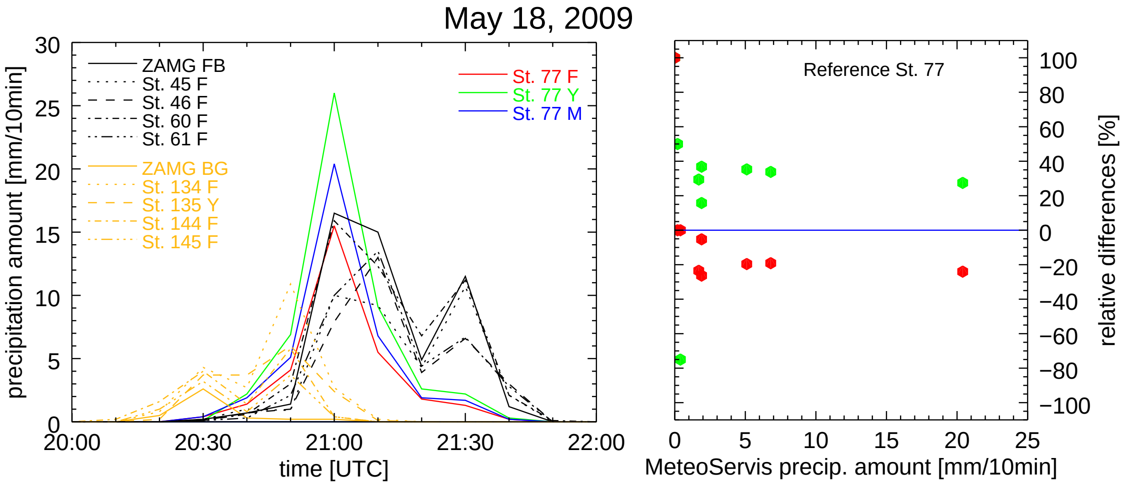

Figure 6.5.: Precipitation event on May 18, 2009.

Figure 6.5 shows the progression of the high intensity precipitation event on May 18, 2009. As for convectional precipitation events great spatial differences occur on very small scales, also the neighboring stations of the ZAMG sensors are included into the plot. The neighbors of the ZAMG station Feldbach are drawn in black, the neighbors of the station in Bad Gleichenberg are orange as their reference. The high spatial separation of 6 km between the reference sensor 77 and the ZAMG sensor Bad Gleichenberg leads to a completely different progression of the event at the two stations. The ZAMG station Feldbach, which is located at a distance of 2.6 km from the reference station, shows the maximum intensity peak at the same time as the reference station sensors, but has a side peak at 21:30 UTC, which is not that distinctly developed at the reference station.

The relative differences plot on the right side of Figure 6.5 shows a very constant distribution of the two WegenerNet sensors around the MeteoServis reference values. As the intensity increased abruptly between 20:50 and 21:00 UTC and declined again after this 10-minute shower, the right plot shows a gap between 7 mm/10min and 20 mm/10min. The mean relative differences for the WegenerNet sensors are -15 ± 11 % (Friedrichs) and 19 ± 39 %

Table 6.3.: Total precipitation amount of the WegenerNet reference station sensors (M ... MeteoServis, F ... Friedrichs, Y ... Young) and the ZAMG sensors (FB ... Feldbach, BG ... Bad Gleichenberg) and their surrounding station sensors for the precipitation event on May 18, 2009. The last column gives the relative difference to the corresponding reference sensor.

Station	**Total Precip. [mm]**	**Reference**	**Rel. Diff. to Ref. [%]**
77 M	38.4	/	/
77 F	30.2	MeteoServis	-21.4
77 Y	49.4	MeteoServis	+28.6
ZAMG FB	51.4	/	/
45 F	38.4	ZAMG FB	-25.3
46 F	36.2	ZAMG FB	-29.6
60 F	52.1	ZAMG FB	+1.4
61 F	39.9	ZAMG FB	-25.3
ZAMG BG	3.8	/	/
134 F	21.6	ZAMG BG	+468.4
135 Y	16.1	ZAMG BG	+323.7
144 F	13.4	ZAMG BG	+252.6
145 F	9.1	ZAMG BG	+139.5

(Young).

Table 6.3 summarizes the total precipitation amount of the three WegenerNet sensors at the reference station 77, of the two ZAMG stations and of their eight neighboring stations. For each station also the relative difference to the nearest reference sensor is given. The WegenerNet sensors show the typical under- and overestimations, respectively. For the ZAMG station Bad Gleichenberg the relative differences of the surrounding stations are very high, which results from the missing peak at 20:50 UTC. At that time all neighbors measure between 4 mm and 11 mm, whereas the ZAMG sensors measures only the minimum resolvable value of 0.1 mm. The second ZAMG station is underestimated by three out of four neighbors by -25 % to -30 %. Only station 60 shows a slightly higher total precipitation amount.

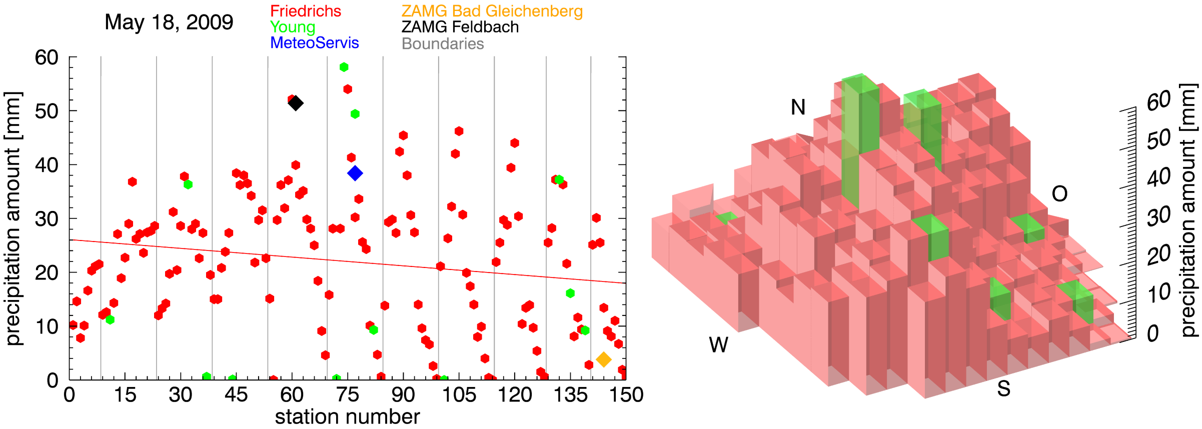

Figure 6.6.: Precipitation event on May 18, 2009 - field.

The precipitation amount on May 18, 2009 shows a strong spatial dependence. Since it was a convective rainfall event resulting from a convective cell with a certain track across the investigation area, not all stations were equally affected by the precipitation. Some stations, particularly in the south-east of the WegenerNet region, did not record any rain at all. At the time of the event none of the stations had a logger outage, thus all sensors were operational during the two-hour shower. The maximum values have been recorded on a track from the south-west to the north of the region. The mean precipitation quantity of the Friedrichs sensors amounts to 22.0 mm whereas the Young sensors measured an average of 19.0 mm. One Friedrichs sensors (station 55) and one Young sensor (station 101) were totally blocked during the event, the sensor of station 37 (Young) was partially blocked. The two ZAMG sensors and the MeteoServis sensor fit nicely into the distribution of the Friedrichs sensors.

6.2.2. August 3, 2011

The ZAMG describes August 2011 with "hot, sunny and even precipitation balance". On the 1st of August an occlusion front provided for small precipitation amounts in the east of Austria, some regions are met by thunderstorms because of weak gradient conditions. Due to a ridge of high pressure the 2nd is sunny and dry throughout the country with temperatures of 26°C in the WegenerNet region. The following days from the 3rd to the 7th of August are under the influence of a low over the British Isles. On the 3rd of the month a cold front crosses over Austria and provides for fierce thunderstorms in the regions south of the Alps. The WegenerNet region is hit by precipitation at 18:00 UTC with, for the first, light intensities. At 21:45 UTC as the thunder cell crosses over Feldbach the intensity increases abruptly. (ZAMG [2013b])
The track of the cell, which first moves from north to south and then from south-west to north-east is seen in Figure 6.14.

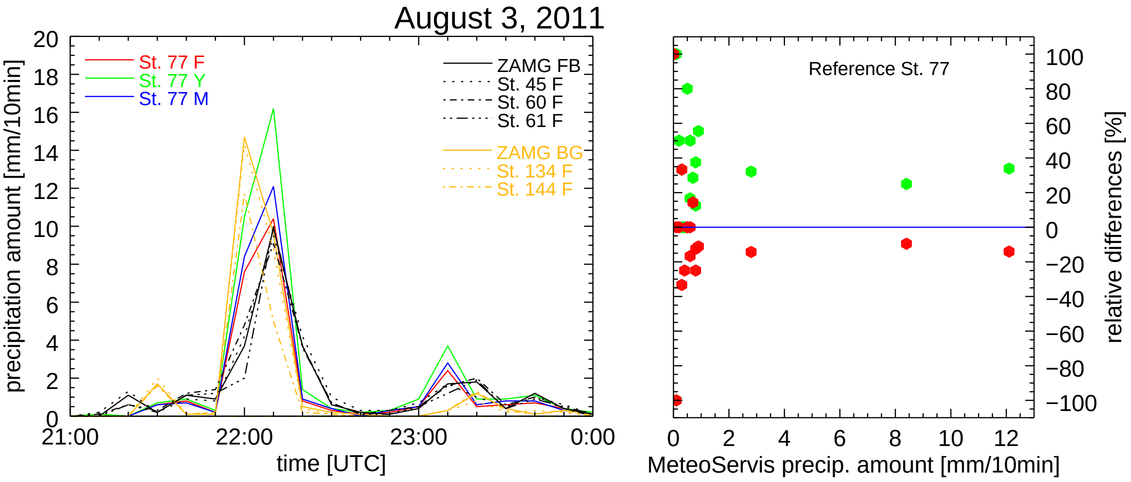

Figure 6.7.: Precipitation event on August 3, 2011.

In Figure 6.7 the progression of the high intensity precipitation event on August 3, 2011 is shown for the three sensors at the reference station 77 and the two ZAMG station sensors each

Table 6.4.: Total precipitation amount of the WegenerNet reference station sensors (M ... MeteoServis, F ... Friedrichs, Y ... Young) and the ZAMG sensors (FB ... Feldbach, BG ... Bad Gleichenberg) and their surrounding station sensors for the precipitation event on August 3, 2011. The last column gives the relative difference to the corresponding reference sensor.

Station	**Total Precip. [mm]**	**Reference**	**Rel. Diff. to Ref. [%]**
77 M	29.6	/	/
77 F	26.3	MeteoServis	-11.1
77 Y	39.1	MeteoServis	+32.1
ZAMG FB	27.5	/	/
45 F	28.6	ZAMG FB	+4.0
46 F	0.0	ZAMG FB	-100.0
60 F	28.4	ZAMG FB	+3.3
61 F	25.2	ZAMG FB	-8.4
ZAMG BG	29.5	/	/
134 F	27.8	ZAMG BG	-5.8
135 Y	0.0	ZAMG BG	-100.0
144 F	21.2	ZAMG BG	-28.1
145 F	0.0	ZAMG BG	-100.0

with its neighboring station. The neighbors have been considered in the evaluation because convective precipitation events can show very differing progressions for stations with large relative distances. As shown in the radar images on page 55 the convective cell moves from the north-western edge of the investigation area to the south-west and subsequently crosses the WegenerNet to the north-east. Also in the progression plot the west-to-east-motion of the thunder cell can be tracked. The maximum intensity peak at the ZAMG station Bad Gleichenberg reaches the reference station and the ZAMG station Feldbach with a time delay of 10 minutes. The side peak at 23:10 UTC is measured by all sensors, but delayed at the ZAMG station Bad Gleichenberg and devided into two intervals by the ZAMG station Feldbach.

The situation according the relative differences resembles the distribution of the event on May 18, 2009. The WegenerNet sensors show very constant relative differences across the reference intensities.The mean relative differences of the Friedrichs and Young sensor amount to -1 ± 45 % and 36 ± 47 %, respectively.

In Table 6.4 the total precipitation amount of the rainfall event on August 3, 2011 is given for all station regarded. The WegenerNet sensor MeteoServis and the two ZAMG sensors act as reference in the table for their neighboring sensors. As already shown for the precipitation event on May 18, 2009 the Young sensor at the reference station shows a comparably strong overestimation at high intensity rainfall events. The underestimation of the Friedrichs sensor is not as pronounced as in May 2009. Three of the ZAMG neighbors did not record the rainfall event at all, which was most probably caused by total blockages of the instruments, as no logger malfunction could be detected at the event time.

The precipitation event on August 3, 2011 was also a convective rainfall and therefore shows a strong spatial dependence. One can easily see both on the left and on the right plot of Figure 6.8 the decrease of total precipitation amount from the north-west to the south-

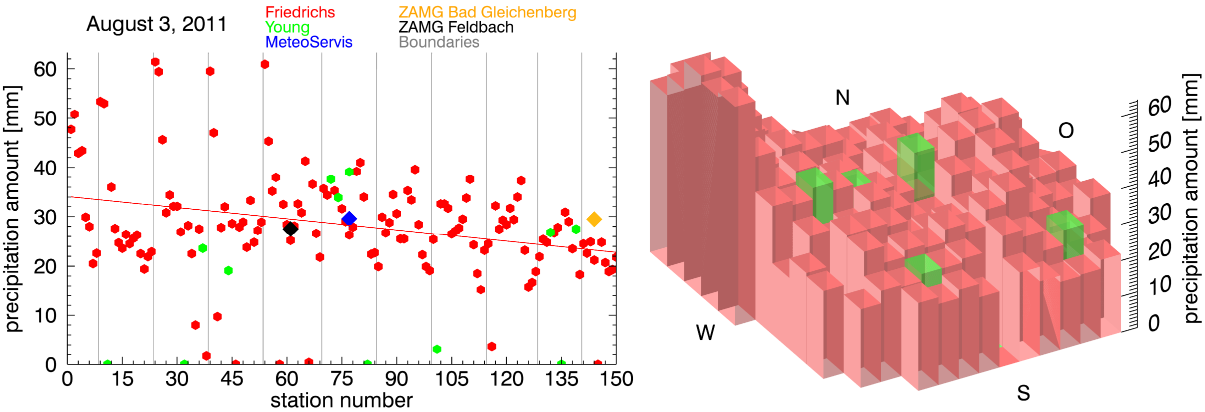

Figure 6.8.: Precipitation event on August 3, 2011 - field.

east of the WegenerNet region. The maximum values are accumulated in the top left corner of the surface plot and directly right of the grey boundary lines in the 2-dimensional plot, respectively. A total of seven stations (nos. 11, 32, 46, 58, 82, 135 and 145), three Friedrichs sensors and one Young sensor, was totally blocked during the precipitation event. Further five Friedrichs sensors (nos. 35, 38, 41, 66 and 116) and one Young sensor (no. 101) can be considered as partially blocked. The average amounts for the two sensor types are 28.4 mm (Friedrichs) and 17.6 mm (Young), respectively.

6.2.3. May 3 to 4, 2012

The first week of May 2012 is affected by thundery weather. A continental depression arranged for rainfall throughout Austria. Temperature fell down from a daily maximum of 31°C (on May 1 and 2) to a maximum of 21°C. Throughout most of Austria May 2012 was too dry. Some stations only recorded 25 % of the long-term average precipitation amount. The north-east of Lower Austria, some parts of Tyrol and Eastern Tyrol were particularly affected by the drought. In contrast, the south-east of Styria, which contains the WegenerNet region, was blessed with 75 % more rain than in the long-term mean (ZAMG [2013b]). The first shower arrives at the WegenerNet on the 3rd of May at 22:30 UTC and arranges for a total of 55.2 mm (reference station). 20 % of the precipitation which has fallen between the 3rd of May, 22:30 UTC and the 4th of May, 10:00 UTC, were recorded in the first hour with a maximum intensity of 5 mm/10min (MeteoServis), thus 30 mm/h. In the following 10 hours the mean intensity is 0.8 mm/10min, which equates to 4.8 mm/h.

Figure 6.9 shows the progression of the precipitation event in May 2012. The first peak arrived with high intensity simultaneously at all regarded stations (23:10 UTC). A look at the grid data reveals that the front propagated from the south-east and spread over the whole investigation area in 30 minutes. After 12 hours of duration it disappeared in north-eastern direction. While the ZAMG station sensor has its maximum at the same time as the reference station sensors but with a lower intensity (–40 % compared to MeteoServis) the ZAMG sensor Feldbach shows a double peak with the maximum intensity at 23:40 UTC, thus 30 minutes delayed compared to the other sensors. After this first shower the curves are very consistent with slight differences in intensity.

The plot on the right shows the relative differences related to the sorted MeteoServis pre-

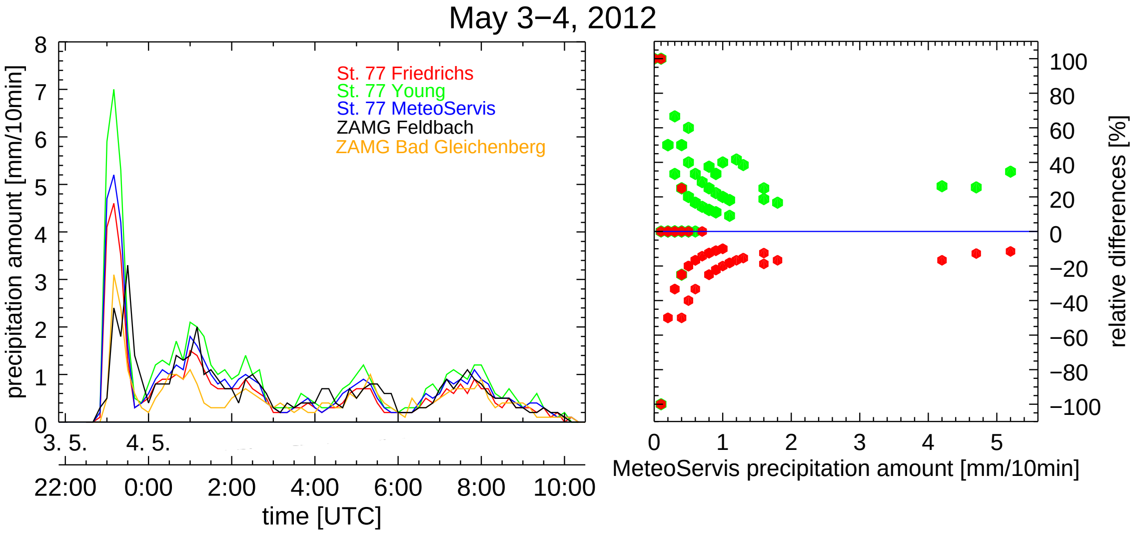

Figure 6.9.: Precipitation event on May 3 to 4, 2012.

cipitation rate. For the lower intensities between 0.1 mm/10min and 2 mm/10min the WegenerNet sensors show a mirrored behavior according to the MeteoServis sensor. In both cases the absolute value of the relative differences is decreasing with increasing precipitation rate. For the higher intensities between 4 mm/10min and 5.5 mm/10min the relative differences of both sensors are within a range of ±40 %. The mean relative differences are -15 ± 22 % for the Friedrichs sensor and 21 ± 26 % for the Young sensor.

In Table 6.5 the total precipitation amounts of regarded precipitation event in May 2012 are given for the three sensors at the reference station 77, the two ZAMG sensors and their corresponding four neighboring stations. The values at the reference station for the Friedrichs and Young sensor are within their typical under- and overestimation range, respectively (also shown in the right plot of Figure 6.9. Station 60 again shows a very different progression than its neighbors which indicates a partial blockage of the instrument. The remaining three neighbors of the ZAMG station Feldbach are in good accordance with their reference sensor. As is the case for the sensor at station 60, also station 135 shows a defective behavior which indicates a blockage of the funnel orifice. The high relative difference at station 145 results from the fact, that the sensor measured 0.1 mm in all 5-minute intervals between 0:00 UTC and 2:00 UTC. Again, one can assume a partial blockage.

In contrast to the precipitation event on November 12, 2012, the May-event shows a falling gradient from the north western part of the investigation area to the south-east of the region (see Figure 6.10). The linear fit of the Friedrichs sensors is the best indicator for the sloping amounts. During the event one station (no. 32), which is equipped with a Young sensor, had a data logger outage, thus no data is available. None of the further stations was totally blocked at the event time, but 7 sensors (four Friedrichs sensors and three Young sensors) can be classified as partially blocked as they measured less than 10 mm. The maxmum precipitation amount, 68.2 mm, was measured by the Young sensor at the reference station no. 77 which can be considered as an overestimation. The average rainfall of the Friedrichs sensors amounts to 40.9 mm, whereas the Young sensors only recorded an average of 29.2 mm. The MeteoServis sensor fits nicely into the sinuslike curve progression of the Friedrichs sensors.

Table 6.5.: Total precipitation amount of the WegenerNet reference station sensors (M ... MeteoServis, F ... Friedrichs, Y ... Young) and the ZAMG sensors (FB ... Feldbach, BG ... Bad Gleichenberg) and their surrounding station sensors for the precipitation event on May 3 to 4, 2012. The last column gives the relative difference to the corresponding reference sensor.

Station	**Total Precip. [mm]**	**Reference**	**Rel. Diff. to Ref. [%]**
77 M	55.2	/	/
77 F	46.5	MeteoServis	-15.8
77 Y	68.2	MeteoServis	+23.6
ZAMG FB	48.3	/	/
45 F	46.5	ZAMG FB	-3.7
46 F	41.3	ZAMG FB	-14.5
60 F	36.5	ZAMG FB	-24.4
61 F	45.0	ZAMG FB	-6.8
ZAMG BG	36.1	/	/
134 F	39.7	ZAMG BG	+10.0
135 Y	15.7	ZAMG BG	-56.5
144 F	36.6	ZAMG BG	+1.4
145 F	24.6	ZAMG BG	-31.9

6.3. Snowfall

6.3.1. February 6 to 7, 2012

The first half of February 2012 is with a mean temperature of –7°C significantly colder than the long-term average that lies between –2°C and +2°C. From the beginning of the second half of the month temperature levels off around the freezing point. After a depression south of the Alps that brings some rain to Carinthia and some parts of southern Styria on the 4th of February a high over Fennoscandia brings sunny weather with a maximum temperature of –6°C. A continental depression finally brings snowfall to the whole country on the 6th and 7th of the month (ZAMG [2013b]). The event hits the WegenerNet region on the 6th at

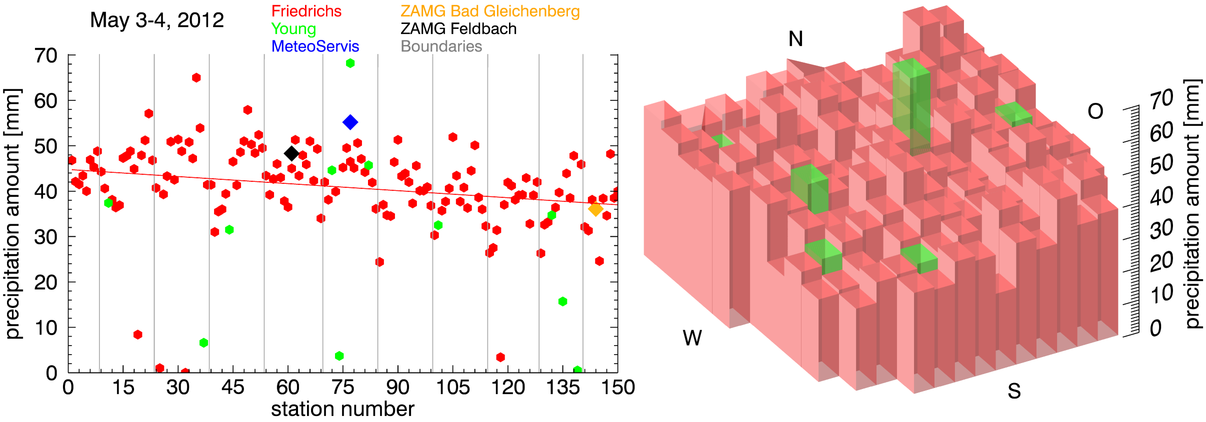

Figure 6.10.: Precipitation event on May 3 to 4, 2012 - field.

18:00 UTC and ends after 26 hours of snowfall on the 7th at 20:00 UTC. The snowfall event can be classified as a low intensity event with a maximum intensity of 0.3 mm/10min (snow water equivalent).

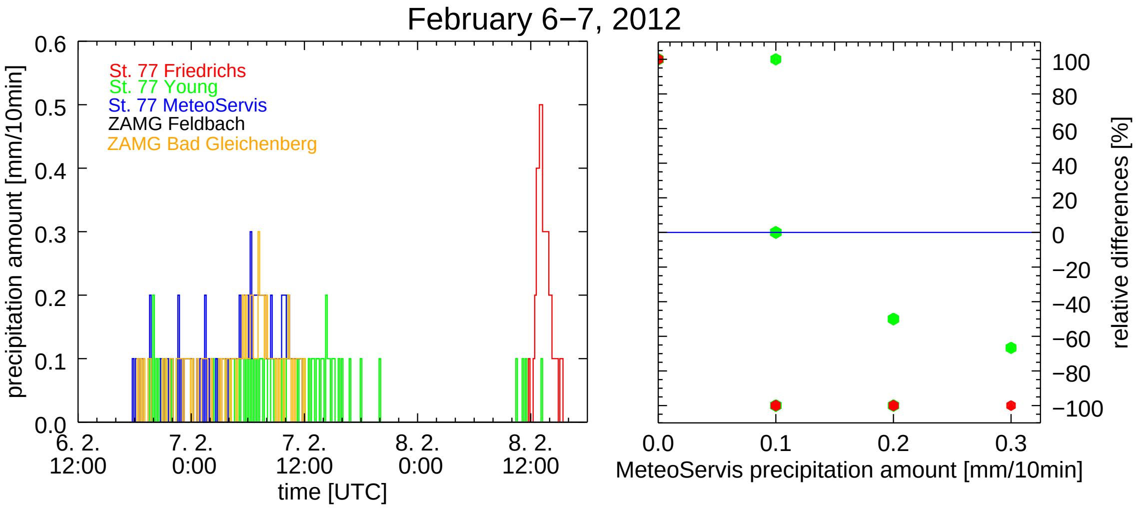

Figure 6.11.: Snowfall event on February 6 to 7, 2012.

In Figure 6.11 the development of the event is displayed. The red curve in the right part of the plot shows the melting of the snow in the unheated Friedrichs sensor which is recorded on the 8th at 12:00 UTC. Further information on snowfall events and the differences between heated and unheated precipitation measurement systems can be found in Section 5.2. The ZAMG station Feldbach did not measure the snowfall event at all. Also the melting process on the 8th of Februrary at 12:00 UTC was not recorded. The outage of the ZAMG sensor in Feldbach can not be explained without detailed information on the sensor and heater operation status.

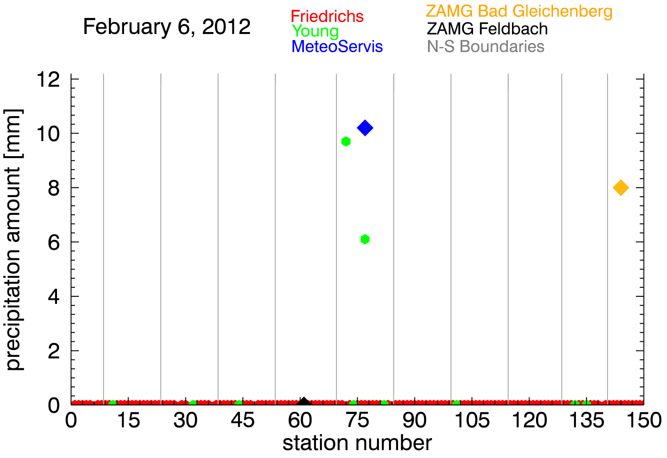

Figure 6.12.: Snowfall event on February 6 to 7, 2012 - field.

The relative differences plot of the snowfall event between the 6th and the 8th of February 2012 shows a rather sparse distribution as only three different 10-minute values have been measured. The Friedrichs and ZAMG Feldbach sensors did not record the snowfall event, which is not surprising in case of the unheated Friedrichs sensor.

For the illustration of the spatial distribution of the snowfall event (see Figure 6.12) only the time span between the 6th of February, 12:00 UTC and the 8th of February, 00:00 UTC have been taken into account. This was done to avoid misinterpretations due to the melting of the snow in the Friedrichs funnels which occurred on the 8th of February, 12:00 UTC, as shown in Figure 6.11. It shows that only three of the WegenerNet sensors recorded the snowfall at all. For the 139 Friedrichs sensor, which are not equipped with a heating system, this fact is not surprising, as the snow accumulated in the funnel and stayed there until temperature exceeded the melting point. However, what was suprising, is that ten of the supposedly heated Young sensors did also not record the snowfall. As already stated in Section 5.2 at the beginning of 2012 only the heater of station no. 72 and the two heaters at the reference station no. 77 were operational. This is also confirmed within the scope of this case study. For this reason it was not considered useful to plot the three-dimensional surface plot of the event's total snow amount.

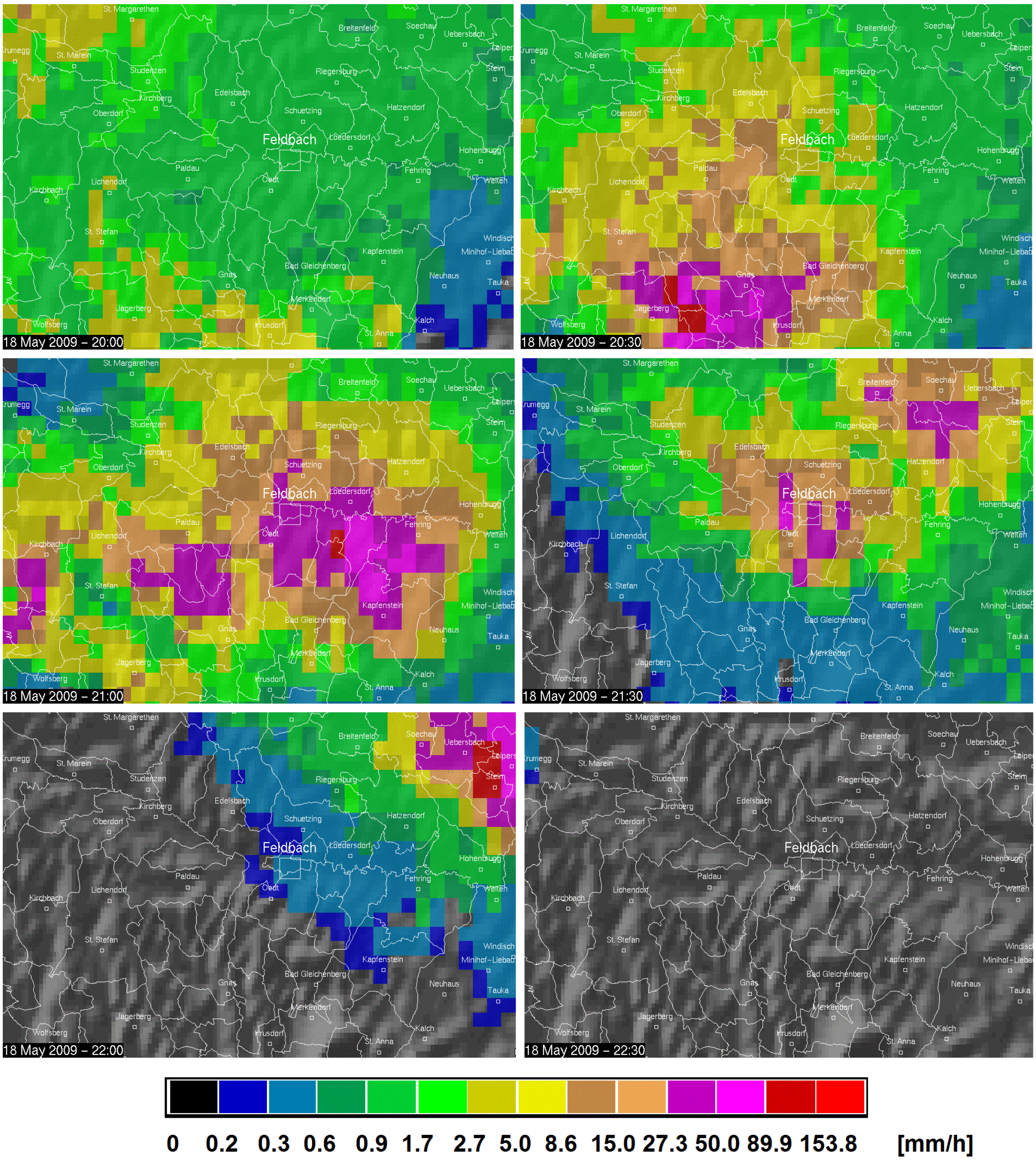

Figure 6.13.: Radar Image of May 18, 2009 - 20:00 to 22:30 UTC. (Austrocontrol / TU-Graz, IHF)

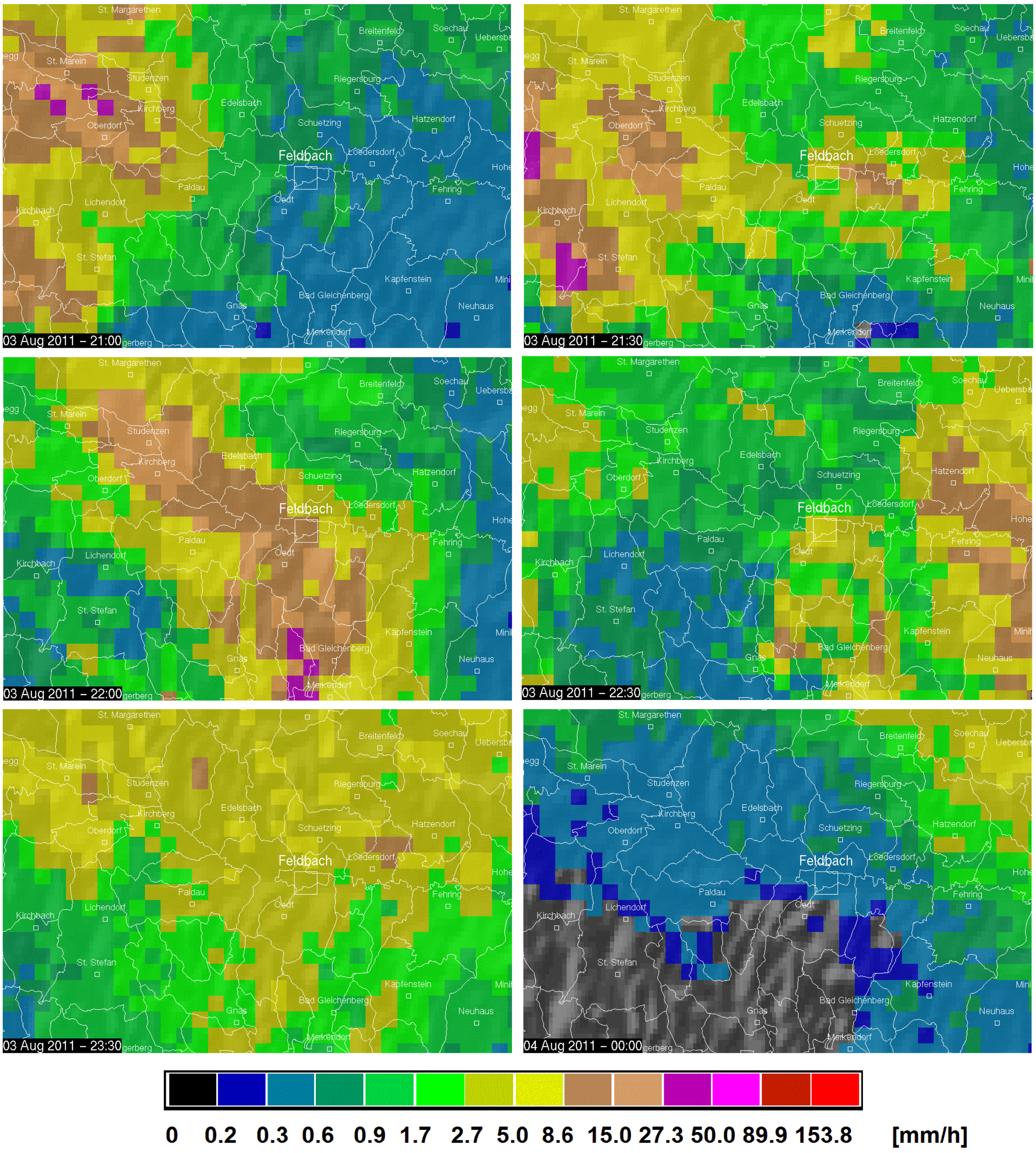

Figure 6.14.: Radar Image of August 3, 2011 - 21:00 to 00:00 UTC). (Austrocontrol / TU-Graz, IHF)

7. Climatological Evaluation

For climatological evaluations seasonal and annual precipitation amount per sensor type have been regarded. In contrast to the results in Chapter 5 all precipitation gauges in the WegenerNet are subject of analyses in the following sections. The mean seasonal and annual precipitation amounts and the relative differences to a reference sensor have been calculated per instrument type (Section 7.1). The basis of the calculations are the 5-minute data sets from June 2008 to February 2013 (summer 2008 to winter 2012/13).

The sensor types are divided in 139 Friedrichs sensors at the 138 base and special base stations and at the reference station and 12 Young sensors at the 11 primary stations and the reference station. The MeteoServis sensor at the Reference station will again act as reference sensor as well as the two ZAMG station sensors - Feldbach and Bad Gleichenberg. The objective is to detect variabilities of relative deviations during the course of the year. This could possibly reveal a dependency of data quality on different precipitation amount or on different weather conditions. As a mean value is a rather bad representation of individual phenomena, Sections 7.2.2 and 7.2.1 deal with homogeneity considerations across the WegenerNet. One primary objective is to find out if there are stations with frequently blocked precipitation gauges or frequent logger failures. The other motive of investigating homogeneity issues is our climatological interest. The following sections will reveal if there are small scale differences in precipitation distribution across the WegenerNet region and if climatological gradients of precipitation amount can be discovered.

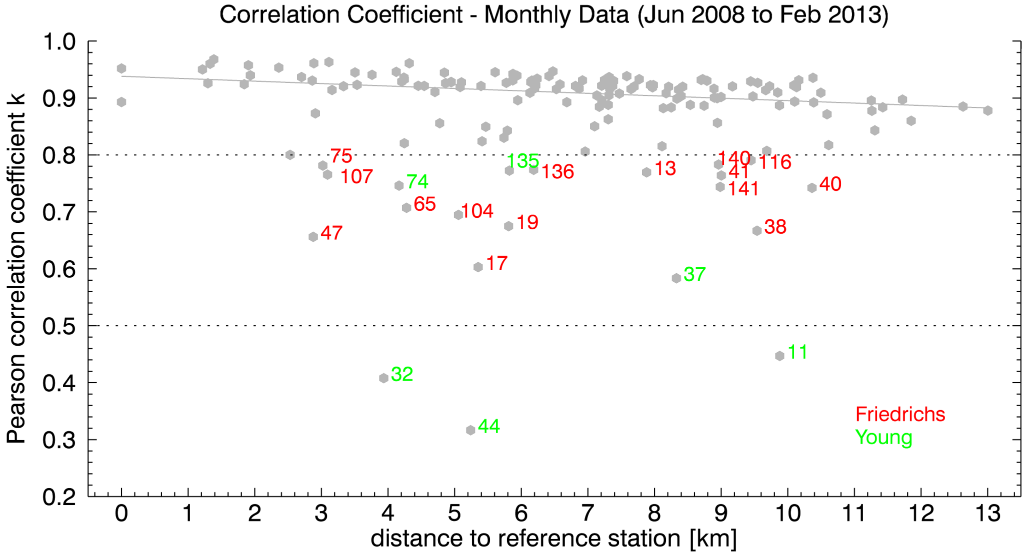

Figure 7.1.: Correlation between the monthly data of Young and Freidrichs sensors and the MeteoServis sensor as function of the distance to the reference station no. 77. For all stations with k less than 0.8 the station number is given.

Figure 7.1 shows the Pearson correlation coefficient k, which is a dimensionless measure for the linear dependence between two variables and may have any value between –1 and 1. A correlation coefficient of $|k| = 1$ indicates a complete (positive or negative) correlation between the two variables, whereas $k = 0$ means that they are not linked by a linear dependence. The correlation coefficient is positive ($k > 0$ if the slope of the linear regression line, when the variables are plotted against each other, is positive, whereas $k < 0$ if the regression line has a negative slope (Schoenwiese [2013b]).

The correlation between the monthly data of the Friedrichs and Young sensors, respectively, and the MeteoServis sensor gives a first estimate of the homogeneity of the data across the WegenerNet. A correlation coefficient of $k > 0.8$ suggests a good correlation between the data, whereas $k < 0.8$ may indicate a frequently blocked funnel opening or logger outages. For 130 stations the correlation coefficient is greater than 0.8 but nevertheless shows a slight decrease with increasing distance to the reference sensor. The remaining 21 stations with $k < 0.8$ are marked with their station numbers. Particular problems show up for the precipitation gauges at the following stations: 11, 32 and 44. Those three - all Young sensors - have a correlation coefficient even smaller than 0.5, which indicates a bad correlation between the data.

7.1. Seasonal and Annual Precipitation

Calculations of the mean seasonal and annual totals of precipitation amount per sensor type will give information about tendencies to over- or underestimation of the selected instruments. The mean value was assessed by summing up the seasonal totals of all Friedrichs and Young sensors respectively and dividing the resulting value by the number of stations equipped with that sensor type (139 for Friedrichs and 12 for Young).
The seasonal sum is the defined total of three months which are composed like outlined in Section 5.1.2. Starting the analyzes with summer 2008 and ending up with winter 2012/13 a total of 19 seasons (5 summers, 5 autumns, 5 winters and 4 springs) could be evaluated. The relative differences have been calculated in order to obtain a reasonable comparability of the results. The annual sums have directly been assessed from the 5-minute basis data.

Figure 7.2 shows the mean seasonal precipitation amount per sensor type in absolute values. The grey bars are the Level 2 data which have been calculated from the "Monthly Area-mean Precipitation Amount" (long name of the variable in netCDF grid file). These data are generated by the *Data Product Generator* (DPG) from the quality controlled Level 1 data (see Section 2.2 for further information). As these data sets are relevant for the data user at the end of the data acquisition and quality control chain, they have been included into the considerations. Even if only half a decade has been evaluated, an annual cycle of precipitation amount can be seen. Summer and autumn are the seasons with highest precipitation amount, followed by spring and winter. An order which is valid for every year, does not exist. In 2008, 2009 and 2011 the summers were pronounced with relativly high quantities of rainfall, whereas in 2010 and 2012 the maximum amount of precipitation was recorded in autumn. On average spring precipitation has a share of 20 % in the total annual rainfall quantity, summer precipitation has a share of 40 %, autumn precipitation of 28 % and winter precipitation of 12 %.

In Figure 7.3 the relative differences to the MeteoServis sensor are displayed. All averages have been calculated without the four primary stations 11, 32, 37 and 44 as their values have already been determined as defective due to long-term blockages and lack of maintenance (see Figure 7.1 and find detailed explanation and demonstration in Section 7.2.1). The high relative values measured in spring 2011 are due to repeated logger outages in April and May at the reference station: In April no data are available from the Young and the MeteoServis sensor, in May no data have been recorded from the 1st to the 7th and from the 10th to the 23rd of the month. An interesting finding in the seasonal relative differences plot is that during autumn all sensor types, even the two ZAMG station sensors are underestimating relative to the MeteoServis sensor data. Evaporation losses due to the heating systems which are already turned on during autumn, can be used as the most reasonable explanation for this fact.

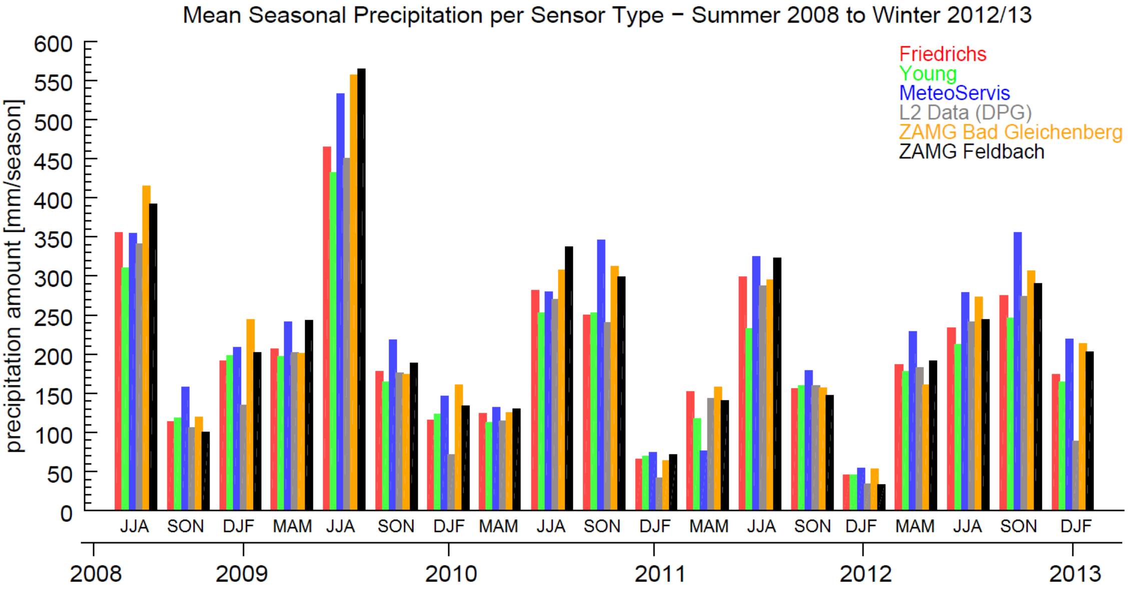

Figure 7.2.: Mean seasonal precipitation amount per sensor type (Young, Friedrichs) with the MeteoServis sensor as reference. The grey bars are the Level 2 data which are generated by the Data Product Generator (DPG).

The mean relative differences for all sensor types relating to MeteoServis are summarized in Table 7.1. Spring 2011 was not included into the calculations due to the lack of data in April and May. The mean relative differences obtained from the seasonal data show a negative tendency toward the MeteoServis sensor. The underestimations amount to between –6 % at the ZAMG stations in Bad Gleichenberg and –19 % at the Young sensor stations. In this calculations also the three defective Young sensors (nos. 11, 32 and 44) have been taken into account in order to show the actual status of the WegenerNet measurements. The Level 2 data which are generated from the unflagged (QF=0) 5-minute data, even show an underestimation of near –25 %. Especially the high negative relative difference in winter is alarming. To understand this value, we have to check some steps in the processing chain of the data: At temperatures less than +2°C (average temperature of the past 5 hours) all Friedrichs data greater than 0 mm are marked with a quality flag as they are classified as untrustworthy due to the fact that they have no heating system. Now, when it starts to snow and the Young (if heater is operational) and MeteoServis sensors start to measure the water equivalent (melted snow) all Friedrichs sensor measure 0 mm and get not flagged by the QCS - as the value is not greater than 0 mm - and therefore get passed to the DPG. The same is

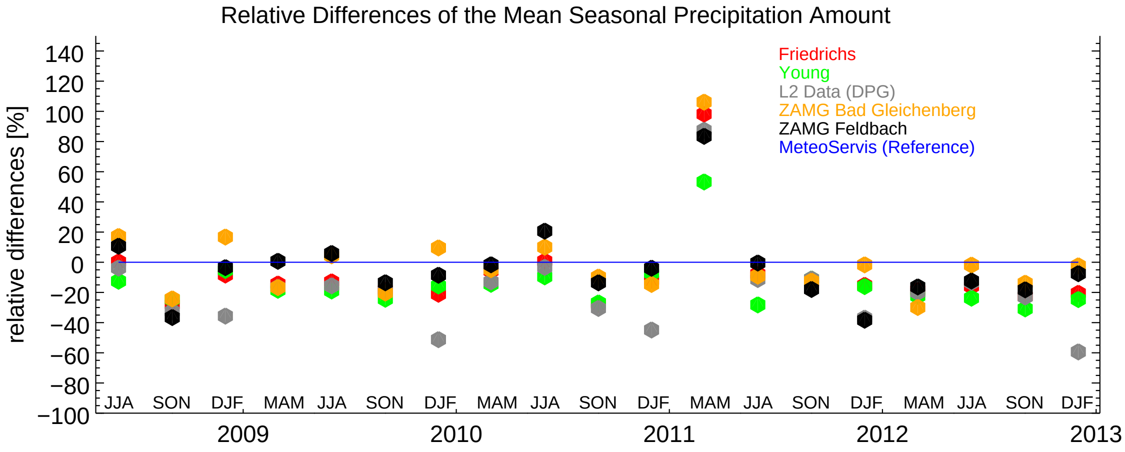

Figure 7.3.: Relative differences of the mean seasonal precipitation amount per sensor type (Young, Friedrichs) with the MeteoServis gauge as reference sensor.

valid for the Young sensors with defective heaters. As an example, at the reference station no. 77 this problem caused high losses in the Level 2 data during winter, especially since the drop-out of the heating system of the Young sensor. When the MeteoServis sensor measured 0.1 mm in one 5-minute interval while the Young and the Friedrichs sensor measured nothing, the average, which was handed over to the DPG, was 0.03 mm.

Table 7.1.: Mean relative differences of Friedrichs and Young sensors and the Level 2 data with MeteoServis as reference sensor. The values have been calculated from summer 2008 to winter 2012/13.

	F [%]	**Y** [%]	**L2** [%]	**BG** [%]	**FB** [%]
Spring[1]	-12.9 (±6.6)	-18.5 (±3.9)	-16.5 (±3.6)	-17.2 (±12.5)	-5.7 (±9.2)
Summer	-7.1 (±7.6)	-18.6 (±7.7)	-9.5 (±5.6)	4.1 (±10.2)	4.9 (±12.3)
Autumn	-21.9 (±6.4)	-23.6 (±7.4)	-23.3 (±8.8)	-16.1 (±6.0)	-20.0 (±9.6)
Winter	-15.4 (±5.5)	-13.8 (±7.8)	-45.6 (±9.9)	1.6 (±12.1)	-12.4 (±14.7)
Whole period	-14.5 (±8.3)	-18.6 (±7.6)	-24.5 (±16.1)	-5.8 (±13.6)	-8.6 (±14.7)

Figure 7.4 shows the mean annual precipitation amount for each sensor type in the WegenerNet. As for the seasonal data also the Level 2 data (grey bars) are plotted. Please note, that for the year 2008 only the months starting from June have been considered in the evaluations, in 2013 only January and February have been taken into account. For the Friedrichs and Young sensors a mean annual value calculated from all 139 and 12 stations respectively has been determined. As these values, in contrast to the MeteoServis sensor and the two ZAMG station sensor, contain also spatial variations and gradients, the values can differ more or less strongly from the reference sensors. However, what seems rather conspicuous is that the mean annual precipitation measured by the Young sensors lags behind the other sensor measurements. Only the generated Level 2 data are lower in 2009, 2010 and 2013.

Considering climatological aspects, without regarding 2008 and 2013 (as not all months of the year have been taken into account), it seems that precipitation amount is declining since 2009. However, it should be taken into account that the annual rainfall amount of 2009 was between 30 % to 50 % above the long-term average. The years 2010 and 2012 correspond to the long-term mean, whereas 2011 is with 10 % to 30 % below the average. In any cae, the record is much too short to draw any climatological conclusionson long-term changes.

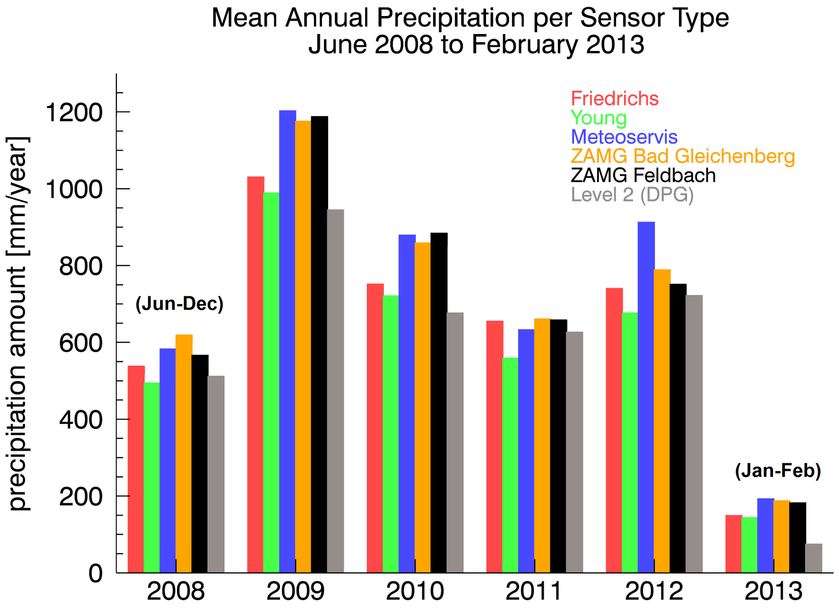

Figure 7.4.: Mean annual precipitation amount per sensor type (Young, Friedrichs) with the MeteoServis sensor and the two ZAMG station sensors as reference (2008 only Jun-Dec, 2013 only Jan-Feb). The grey bars are the Level 2 data which are generated by the Data Product Generator.

The latter is also shown in the relative difference plot, Figure 7.5. The underestimation of the Young sensors, amounts to between –12 % in 2011, where the data missings in April and May are visible through the high relative values of the ZAMG sensors and the Friedrichs sensor, to up to –26 % in 2012 and 2013. The high deviations for 2013 are not surprising, as only January and February have been considered in the calculations and from 12 Young-heaters only two have been operational. In 2012 all sensor types lag behind the MeteoServis value with more than -10 %. The reason for this are high underestimations with respect to the MeteoServis sensorduring autumn and spring 2012. The relative differences of the Friedrichs values are between +4 % in 2011 and –23 % in 2013, with an average of –12 % regarding all years.

7.2. Homogeneity Considerations

7.2.1. Spatial Homogeneity of the Annual Data

As the WegenerNet region covers an area of about 20 × 15 km^2, which can be observed on a very small scale, homogeneity analyzes can be carried out in a rather high-resolution manner.

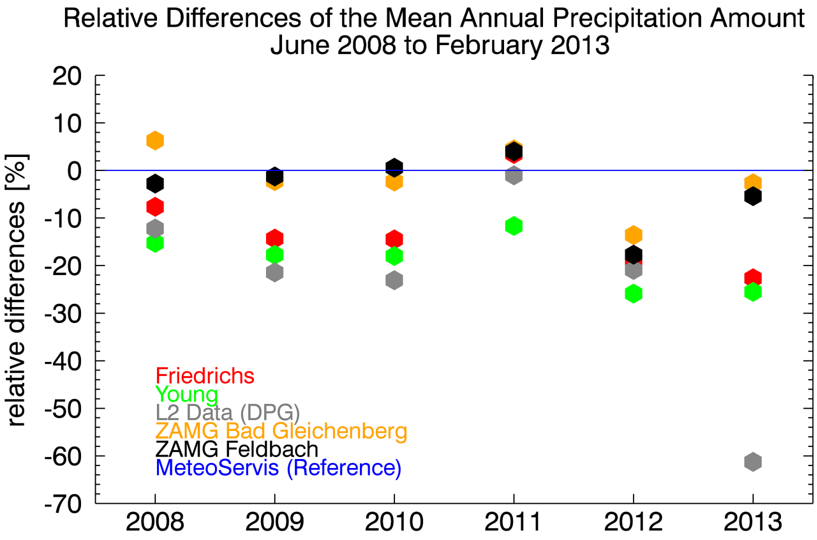

Figure 7.5.: Relative differences of the mean annual precipitation amount per sensor type with the MeteoServis gauge as reference sensor.

The contemplation of the annual total precipitation amounts allows for a consistency check of the measured rainfall quantities across the WegenerNet. For the following evaluations the annual totals of precipitation amount have been calculated from the basis data for all 150 stations (152 precipitation gauges). The first homogeneity testing was performed by the analysis of scatter plots with the 150 stations on the x-axis and the precipitation amount on the y-axis. The grey lines indicate the western and eastern borders of the WegenerNet region.

Figures 7.6 - 7.9 show the annual precipitation amount per station. The different sensor types are displayed in different colors. The reference sensors from the ZAMG have been plotted near to stations in their surroundings. The red lines indicate the linear fit of the Friedrichs sensors and permit a rough estimation of spatial gradient effects in the WegenerNet. For all years the linear fit of the annual data has a negative gradient which indicates lower precipitation amounts in the south-eastern regions of the WegenerNet compared to the north-west. The most pronounced negative tendency towards increasing station number can be found in 2009 with 14.8 % less precipitation in the south-eastern part compared to the north-western area. In 2011 and 2012 the relative differences are between -5.3 % and -5.5 %. In 2010 precipitation was rather evenly distributed with only 1.4 % less precipitation in the south-east.

This effect can be explained with the orographic and topographic conditions of the WegenerNet region. In Figure 2.4 on page 8 the north-west to south-east gradient in Styria due to the mountainous region in the north is shown. The map shows that in the area around Feldbach, where the WegenerNet is located, there is also a change between different levels of precipitation amount (900 to 1000 mm and 800 to 900 mm respectively). Four Young sensors (at stations 11, 32, 37, 44) in the northern part of the WegenerNet region show a defective behavior in all years, which has already been shown in Figure 7.1 which represents the correlation with the MeteoServis sensor. Detailed analyzes have shown that these sensors have been blocked over long periods of time without being freed from the clogging of the orifice. In 2009 the annual sums of the Friedrichs sensors are very consistent with very few exceptions

Table 7.2.: Comparison of the annual total precipitation amount of the three WegenerNet sensors at the reference station 77 (F...Friedrichs, Y...Young, M...MeteoServis), the two ZAMG stations sensors (FB...Feldbach, BG...Bad Gleichenberg) and their corresponding four neighboring stations. The relative differences to the nearest reference sensor are given.

	2009		**2010**		**2011**		**2012**	
Station	**Total [mm]**	**Rel.Diff. [%]**	**Total [mm]**	**Rel.Diff. [%]**	**Total [mm]**	**Rel.Diff. [%]**	**Total [mm]**	**Rel.Diff. [%]**
77 M	1202.5		879.1		632.8		912.6	
77 F	1019.6	-15.2	763.6	-13.1	695.2	+9.9	837.5	-8.2
77 Y	1234.5	+2.7	1010.5	+14.9	652.4	+3.1	935.2	+2.5
ZAMG FB	1187.4		884.1		658.2		751	
45	1112.2	-6.3	746.9	-15.5	722.5	+9.8	817.9	+8.9
46	927.8	-21.9	760.4	-14.0	388	-41.1	673.5	-10.3
60	1098.9	-7.5	477.1	-46.0	682.7	+3.7	701.9	-6.5
61	1002.4	-15.6	811.3	-8.2	625.5	-5.0	662.4	-11.8
ZAMG BG	1175.6		858.7		660.8		788.6	
134	1001.5	-14.8	730.2	-15.0	629.5	-4.7	808.1	+2.5
135	1117.7	-4.9	718.7	-16.3	449.6	-32.0	525.6	-33.4
144	976.1	-17.0	865.8	+0.8	622.6	-5.8	790.9	+0.3
145	806.7	-31.4	604	-29.7	403	-39.0	604.7	-23.3

as station 17 or station 122.

Table 7.2 summarizes the annual sums for the three sensors at the reference station 77, the two ZAMG sensors (in Feldbach and Bad Gleichenberg) and the corresponding neighboring station. The second column per year lists the relative differences to the nearest reference sensor. The three reference sensors used are the MeteoServis sensor at the reference station and the two ZAMG station sensors. The annual sums of the other stations are shown in the Figures 7.6 to 7.9.

7.2.2. Spatial Homogeneity of the Seasonal Data

The seasonal totals per station have been calculated and plotted in the same way as in the previous section for the annual data. The seasonal data gives information about variations in the annual cycle across the observation area. The four Figures 7.11 - 7.10 show the total precipitation amount of all 19 seasons analyzed. The different sensor types are represented by different symbols, the colors relate to one year each. In order to study possible gradients in dependence on seasonal variability a linear fit has been drawn for each season.

The plot of the summer precipitation (Figure 7.11) shows a large difference in rainfall quantity for the different years. According to the monthly review of the ZAMG (ZAMG [2013b]), in summer 2009 precipitation was 25 % to 75 % higher than the long-term average. In contrast summer 2012 recorded only about 50 % of the long-term reference value. The figure manifests for all years the negative gradient from the north-west to the south-east, as shown for the annual totals. This regional difference was most pronounced in summer of 2011 with a relative difference of –22.5 % (–75.9 mm). For the other years the relative differences range between –4.6 % (2008) to –11.6 % (2009). Overall, the summer precipitation recorded a difference of –195.5 mm (–11.3 %) in the south-eastern part of the WegenerNet compared to the north-west. In the plot the problematic Young sensors at the five primary stations 11, 32, 37, 44 and 74 show their typical conspicuous behavior. The main reason for the underestimation of the precipitation amount are long-term blockages.

In autumn (see Figure 7.12) the north-west to south-east gradients are positive for 2008, 2010 and 2011, whereas in 2009 and 2012 they are negative. The highest deviation was recorded in autumn 2011 with a relative difference of +39.1 mm (+28.7 %) followed by 2009 with –52.4 mm (–25.7 %). The total autumn gradient amounts to +8.3 mm (+0.9 %). In the annual cycle this slight positive tendency in autumn is compensated by the high negative gradients during summer. Autumn 2012 recorded the highest precipitation amount of all autumns and so filled the summer deficit of 2012 again. 2009, which had the highest summer rainfall amount, is at an average for autumn. For 2008 and 2011 the autumnal precipitation is below average, which is mainly caused by low September and October rainfall in 2008 and the absence of precipitation in November 2011.

As small scale precipitation events, such as convective rainfall with locally defined tracks, are very unusual in winter the total amounts are rather evenly distributed across the WegenerNet (see Figure 7.13). The total deviations between the north-west and the south-east range between –9.4 mm (2012/13) to +7.9 mm (2011/12). The two driest winters 2010/11 and 2011/12, respectively, recorded only 25 % to 75 % of the long-term average winter precipitation (according to the ZAMG). Winter 2009/10 is at an average with 75 % to 125 % of the long-term regional mean. 2008/09 and 2012/13 recorded precipitation amounts beyond the regional average. Particularly noteworthy is January 2009 with 325 % to 375 % of the common precipitation amount.

In spring (see Figure 7.10) the situation is comparable to summer, as all gradients are negative with absolute differences between north-west and south-east range from –52.6 mm (– – 22.6 %) in 2009 to –8.1 mm (–5.2 %) in 2011. The plot shows that the total spring precipitation amount was similar in all years investigated. Spring 2009 was according to the ZAMG at an average with 75 % to 125 % of the long-term mean, whereas the precipitation amount in 2010 and 2011 was slightly below average with about 75 % of the mean areal precipitation. In 2012 a relatively moist April and May (125 % to 225 % of the long-term mean) compensated a very dry March with less than 25 % of the long-term average precipitation amount.

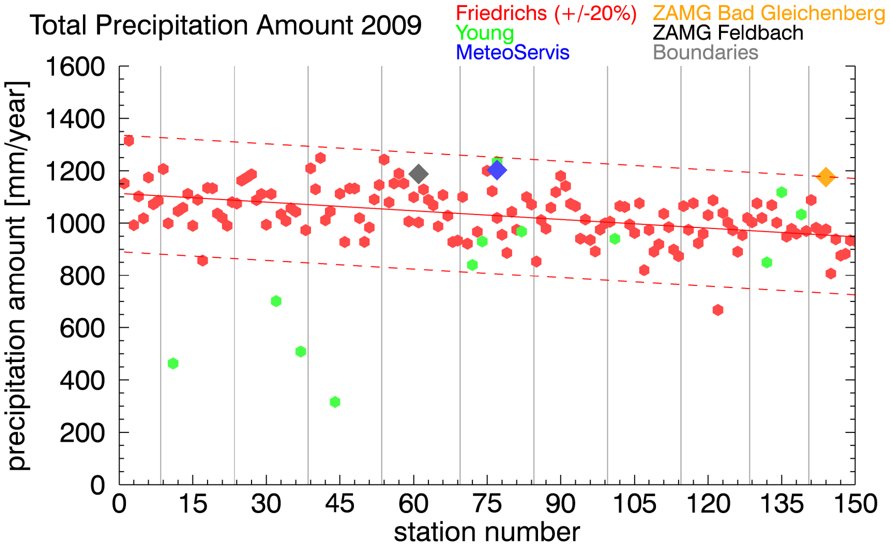

Figure 7.6.: Annual precipitation amount 2009 per WegenerNet station and the two ancillary stations from the ZAMG in Feldbach and Bad Gleichenberg. Red line: linear fit of Friedrichs sensors.

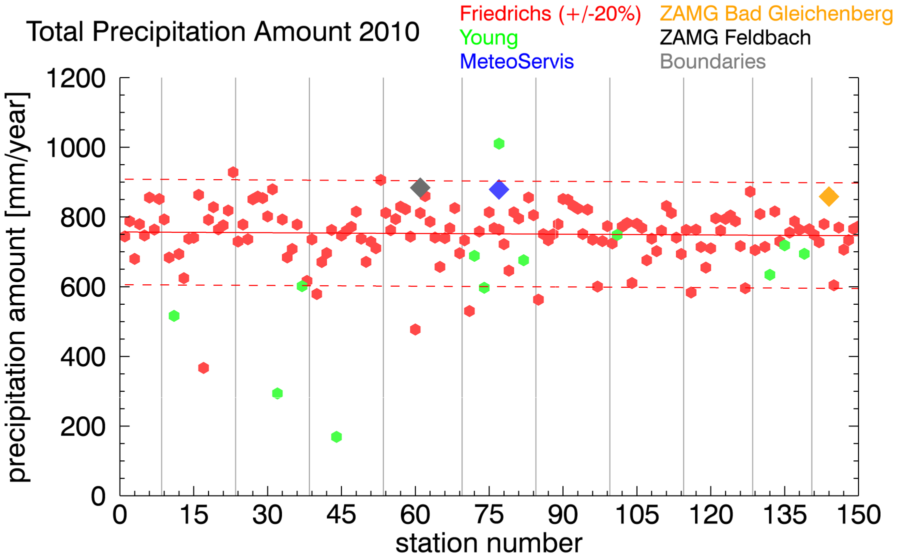

Figure 7.7.: Annual precipitation amount 2010 per WegenerNet station and the two ancillary stations from the ZAMG in Feldbach and Bad Gleichenberg. Red line: linear fit of Friedrichs sensors.

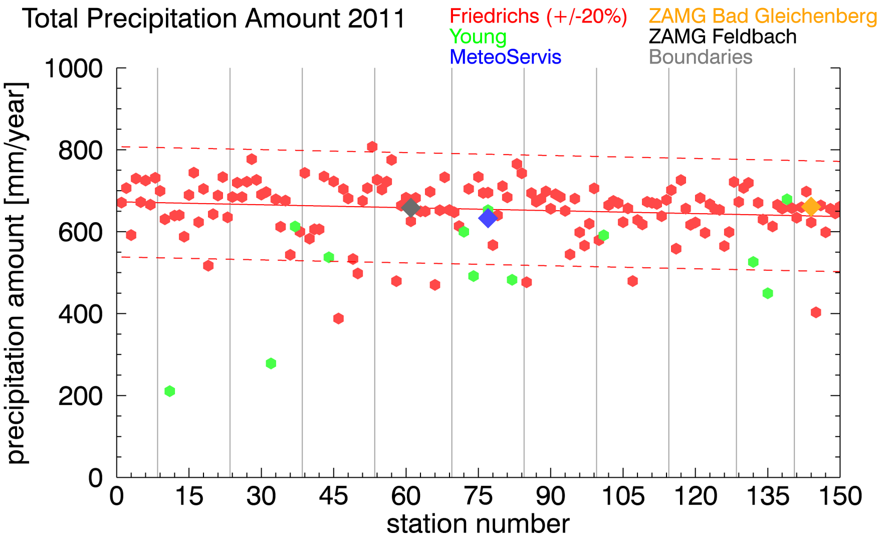

Figure 7.8.: Annual precipitation amount 2011 per WegenerNet station and the two ancillary stations from the ZAMG in Feldbach and Bad Gleichenberg. Red line: linear fit of Friedrichs sensors.

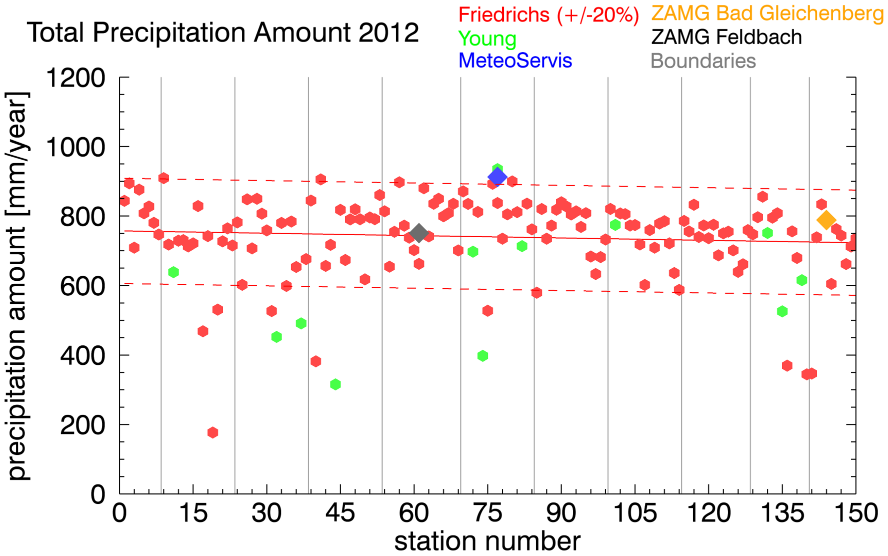

Figure 7.9.: Annual precipitation amount 2012 per WegenerNet station and the two ancillary stations from the ZAMG in Feldbach and Bad Gleichenberg. Red line: linear fit of Friedrichs sensors.

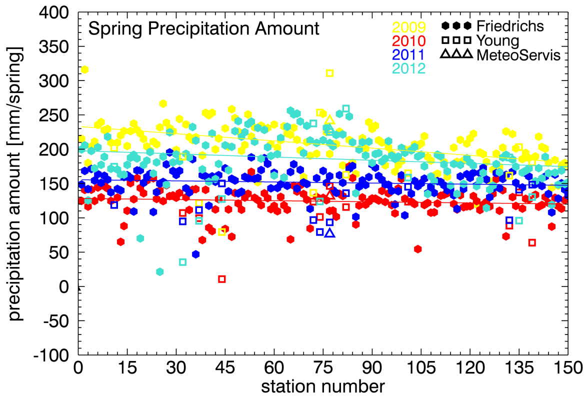

Figure 7.10.: Total precipitatation amount for spring (2009 to 2012).

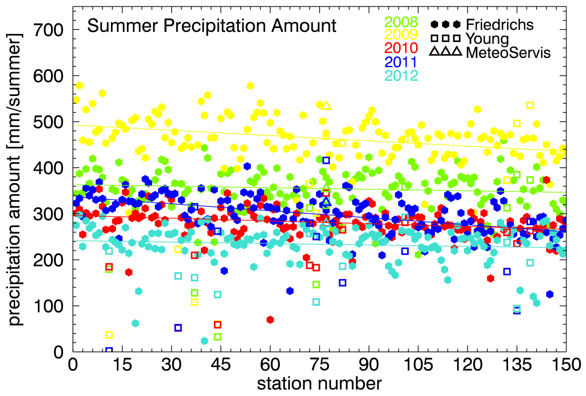

Figure 7.11.: Total precipitatation amount for summer (2008 to 2012).

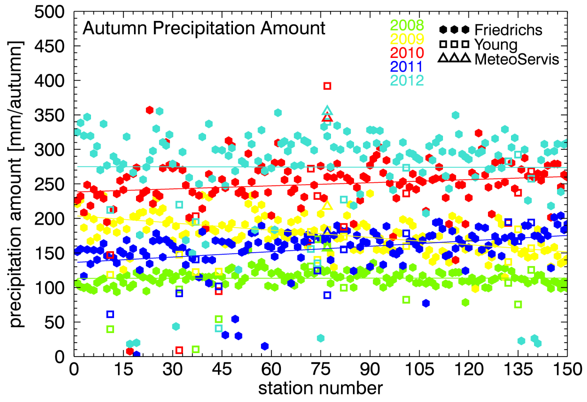

Figure 7.12.: Total precipitatation amount for autumn (2008 to 2012).

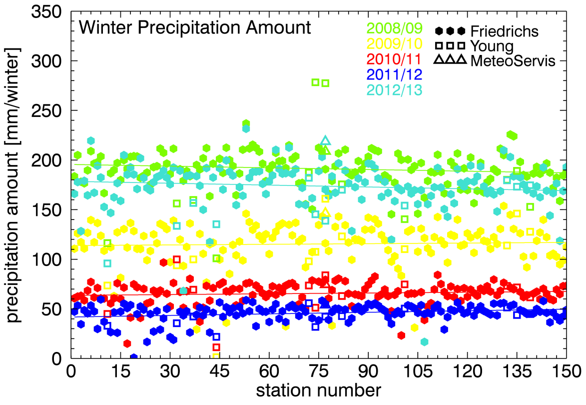

Figure 7.13.: Total precipitatation amount for winter (2008 to 2013).

8. Summary and Conclusions

In this thesis, the WegenerNet precipitation data have been analyzed and evaluated. The first four chapters give an overall introduction (Chapter 1), an introduction to the WegenerNet region and the meteorological network itself (Chapter 2), background information to precipitation and its meteorological characteristics (Chapter 3) and a description of the sensor systems used and their technical characteristics (Chapter 4).

The subsequent Chapters 5 to 7 contain the evaluations of the quality-controlled precipitation data. The main results from the comparative analyses between different sensors (Chapter 5) are the following.

The analysis at the reference station no. 77, which is the only station equipped with all three different rain gauges used in the WegenerNet, allowed first insights to the quality of the measurements. The MeteoServis sensor and the two ZAMG station sensors acted as reference instruments for the comparative evaluations. A direct investigation of the 10-minute data (produced from the 5-minute basis data) showed that the two sensors, from Friedrichs and Young, show systematic deviations relative to the MeteoServis sensor data. The Friedrichs sensor underestimates the precipitation amount by about –20 % (considering all 10-minute intervals with an amount of at least 0.1 mm), whereas the Young sensor overestimates the rainfall amount by about 15 %. If only the 10-minute intervals with measurements with at least 1 mm are taken into account, the under- and overestimation amounts to about –20 % and 27 %, respectively, which reveals a rather constant deviation of the Friedrichs sensor and a deviation which is highly dependent on precipitation rate of the Young sensor. The separate analysis of the time series of 2009/10 and 2011/12 revealed that the underestimation of the Friedrichs sensor decreased from about –24 % to –13 %, the overestimation of the Young sensor decreased from about +34 % to +19 %. A reason for this inhomogeneity could not be ascertained due to a insufficient maintenance information. A conclusion from this is that regular calibration is advisable, at least of the sensor at the 12 primary stations to serve as anchor points, even to replace all these sensors by reliable Kroneis MeteoServis sensors. The latter upgrade was then indeed implemented in fall 2013 (see below).

The study of snowfall events, which has been carried out in order to analyze the heater operation of the instruments from Young and MeteoServis, revealed significant degradation of the heaters over the years since 2007. By the end of 2012 only two out of 13 heaters in the WegenerNet were still operational. Five of them had dropped out by the end of winter 2007/08, three in winter 2009/10, two in the winter 2011/12 and the Young sensor at the reference station by the end of 2012. Early in 2013 therefore only the heater of the Young sensor at station no. 72 and the heater of the MeteoServis gauge were operational. The data losses due to these heater failures during snowfall events are particularly noticeable in the Level 2 data. As a consequence of these outages and their vulnerability to blockages, and also of the deviations found above, all precipitation gauges from Young (at 11 primary stations) have been replaced by instruments from Kroneis MeteoServis in October 2013. The measurements of the three sensors at the reference station will continue as before (with the existing MeteoServis sensor also receiving calibration), whereas the current Young sensor has been replaced by the Young sensor of station no. 72. The decisive factor for this decision was the high MeteoServis reliability over the years and the robust heating system. It also cannot be ruled out that the considerable scattering of the relative differences of the Young sensor with respect to the MeteoServis sensor was due to a questionable robustness of the reed contact, as overestimations of that kind are in general unusual for tipping bucket rain gauges.

A significant physical dependence of the data on wind speed or temperature could be confirmed as a robust feature; the sensor performance generally does not depend much on these parameters. However, there is undoubtedly a decrease in the relative differences of the Young sensor with increasing wind speed, which can also be attributed to the fact, that high wind speeds are associated with higher rain rates and therefore in general lower relative differences. For the Friedrichs sensor the relative differences are relatively constant in the range of about ± 5 %. Since only a fairly preliminary analysis was done into this direction, the subject of this rate dependencies on other meteorological parameters such as temperature and wind speed clearly deserves further study.

In chapter 6 the dependence of deviations on different types of precipitation events has been investigated. The main target was to find out whether there are differences in the behavior of the sensors with changing rainfall intensity. The analyses included light and medium rainfall intensity, showers with high precipitation rates and snowfall events. Altogether six events have been studied for their progression in time, the relative differences related to the MeteoServis sensor and the two ZAMG sensors, and regarding the homogeneity of all stations across the WegenerNet. At the reference station no. 77 the two low intensity events as well as the snowfall event are underestimated by both the Friedrichs and the Young sensor, whereas the high intensity events show an overestimation by the Young sensor and an underestimation by the Friedrichs sensor. The mean relative difference of all six events are –10 % (Friedrichs) and +8 % (Young), respectively. The negative relative differences of the Young sensor at the low intensity events can be explained by the fact that both events have been chosen in autumn when the heating systems are turned on and therefore evaporation losses are a source of underestimations. The homogeneity checks across the WegenerNet enable to spot blocked gauges and otherwise was generally governed by the spatial variability of individual precipitation events.

The climatological homogeneity across the WegenerNet region has been analyzed in chapter 7. The mean seasonal and annual precipitation amounts per sensor type have been calculated in order to get an averaged information about the relative behavior of all sensors. An interesting finding was that the average amount of all Young sensors, for all time ranges studied, is always lower than the MeteoServis amount. The average of the Friedrichs sensors shows the same underestimation relationship as in the preceding chapters. Field information was obtained by analyzing the seasonal and annual totals of each station. A first approach in order to get homogeneity information was to calculate the correlation of the monthly data. For 130 out of the 151 sensors the correlation with the MeteoServis data is high ($k > 0.8$), for three stations (all from Young) the correlation is less than 0.5 which indicates low correlation. The direct comparison of the seasonal and annual totals per station showed that these three sensors were deficient from the outset. The reasons for this deficient behavior were long-term blockages and insufficient maintenance. This was a further motivation to replace the Young sensors by MeteoServis sensors in October 2013.

Another climatological finding was, that the investigation area exhibits a negative gradient in precipitation amount from the north-west to the south-east. The difference between the north-western and south-eastern regions of the WegenerNet area was particularly pronounced in 2009 with a difference of −15 % (−166 mm). The average relative difference of all years investigated (2008 to 2013) amounted to about –8 % (–61 mm).

In conclusion, the quality analysis of the WegenerNet precipitation data has shown, that already with constant correction factors the systematic deviations of the instruments can be corrected to a reasonable degree towards a common reference. Accounting to some degree for time depence of correcting factors ("postprocessing calibration") can further improve the quality of the available precipitation dataset. Additionally, the installation of the new reference devices from MeteoServis at all primary stations will lead to a significant quality improvement of the data and thus the measurement network. It is also foreseen to regularly (at least bi-annually) perform calibration measurements for the sensors, particularly at the primary and reference stations, in order to enable trustworthy information on the accuracy of the reference instruments.

Overall with its unique high-resolution coverage of the 1 - 10-km-scale range with long-term precipitation data, the WegenerNet has a decent perspective to serve users with very valuable data for weather and climate research and applications.

A. Comparative Test Measurements in the Field

Precipitation gauges evidently are - as all measuring systems - not immune to measurement errors. In section 4.1.4 on page 18 a short overview of the different types of measuring errors according to rain gauges was given. The manufacturer points to these deviations by quantifying the maximum uncertainties in the devices specifications. In case of tipping bucket rain gauges these uncertainties are dependent on the rain intensity, or rain rate, thus the precipitation amount per unit time. This means that at higher rain rates the deviations from the actual value may be larger. The specifications of the used sensors are given in Table 4.1 on page 22. In order to get a better understanding of the measuring systems at different rain rates and to get an improved estimate of expected deviations, a field study has been carried out by the WegenerNet team on November 29, 2013, at the reference station no. 77 and one primary station (no. 11). In preparation of this field test many measurements with different dropping funnels were made to find three reproduceable rainfall intensities. Since the ZAMG is experienced in the field of comparative test measurements, we considered their advice for such a project.

The aim was to measure in a repeatable manner and with a reproduceable technical setting, three different precipitation intensities. The proposal of the ZAMG was to simulate the following three rain rates:

1. 10 mm in 3 minutes (intensity: 33 mm/10min)
2. 10 mm in 10 minutes (intensity: 10 mm/10min)
3. 10 mm in 20 minutes (intensity: 5 mm/10min)

A.1. Test Measurement Assembly

The measurements have been carried out with a dropping funnel from *Lenz Laborglas GmbH* with a capacity of 500 ml and a bore of 4 mm. For constant flow rates and for the ability to vary the intensity a medical infusion hose has been used. In Figure A.1 the measurement assembly is shown: the dropping funnel was fixed with a construction of foam panels which ensured a freely suspended infusion hose. As the scale of the dropping funnel was assumed to be too inaccurate (marks in 10 ml intervals) the funnel was accurately refilled with the aid of a 100 ml syringe (on the left in Figure A.1). The simulated rainfall intensity was estimated from the drop rate, which could be controlled by the roller clamp. The highest intensity proposed by the ZAMG could not be realized with this assembly, as it lies in a range between the loosest clamping and the open clamp. Therefore the highest intensity was measured with open roller clamp. One important requirement for the comparative measurements was constant intensity during one measurement run. The lab test runs, which have been carried out beforehand, showed that the use of an infusion hose can ensure constant flow rates. Without the hose the

Figure A.1.: Measurement assembly.

flow rate became gradually slower with each 100 ml interval in the dropping funnel. Figure A.2 shows the times per 50 ml interval (not recorded for the first measurement run '1 F') for each measurement run carried out at the reference station. The numbers indicate the number of measurement run, the uppercase letters the tipping bucket model.

Except for the second measurement at the Friedrichs gauge (labeled '2 F') the deviation was within ± 30 seconds for all runs, which represents a rather good realization of constant flow rates.

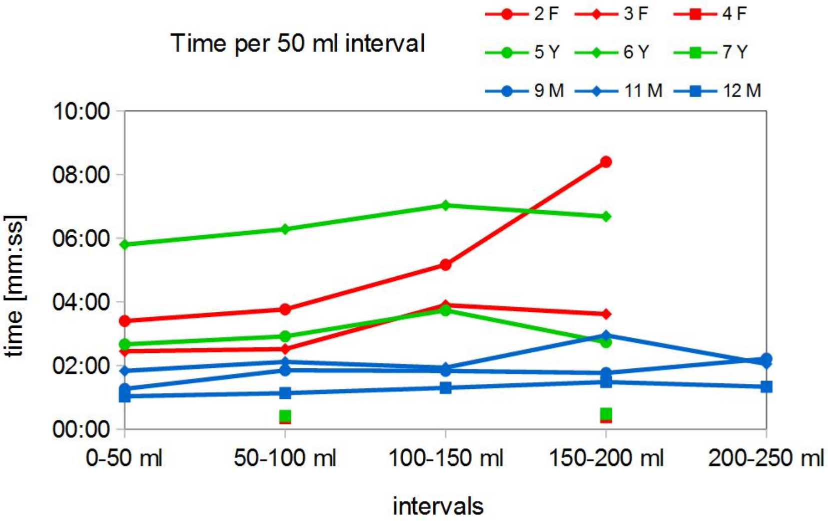

Figure A.2.: Lap times per 50 ml interval given for each measurement run. F ... Friedrichs, Y ... Young, M ... MeteoServis

A.2. Test Measurement Results

Table A.1 summarizes the results of the comparative measurements at the reference station 77. The intensity of the simulated rainfall event was calculated on the basis of the quantity of water in the dropping funnel and the catching area of the tipping bucket, which is 211 cm^2

Table A.1.: Results from the comparative test measurements at the reference station 77. F ... Friedrichs, Y ... Young, M ... MeteoServis

no.	**model**	**filling quantity [ml]**	**filling quantity [mm]**	**duration [mm:ss]**	**intensity [mm/10min]**	**measured quantity [mm]**	**deviation [%]**
1	F	200	**9.48**	12:26	7.62	**9.10**	-4.0
2	F	200	**9.48**	20:44	4.57	**9.20**	-2.9
3	F	200	**9.48**	12:29	7.59	**9.20**	-2.9
4	F	200	**9.48**	00:44	129.25	**5.50**	-42.0
5	Y	200	**10.00**	12:03	8.30	**10.10**	+1.0
6	Y	200	**10.00**	25:48	3.88	**10.50**	+5.0
7	Y	200	**10.00**	00:54	111.11	**6.70**	-33.0
8	M	500	**10.00**	06:15	16.00	**10.10**	+1.0
9	M	250	**5.00**	08:56	5.60	**5.80**	+16.0
10	M	500	**10.00**	01:35	63.16	**9.80**	-2.0
11	M	250	**5.00**	10:53	4.59	**6.00**	+20.0

for the Friedrichs gauge, 200 cm^2 for Young and 500 cm^2 for MeteoServis.

$$filling\ quantity\ [mm] = \frac{filling\ quantity\ [l]}{catching\ area\ [m^2]} \tag{A.1}$$

In the last column the relative differences between the filling quantity and the measured quantity are given. Figure A.3 shows the relation between the relative differences and the intensity. It is important to mention at this point that the maximum quantity of rainfall which has fallen within 10 minutes in the WegenerNet was about 25 mm, thus the highest simulated intensities have only been carried out in order to test the instruments under extreme conditions.

The Friedrichs instrument shows with –2.9 % to –4.0 % a rather low underestimation for the low and the medium intensity. At the high intensity, where the clamp roller was completely opened, the strong underestimation of –42.0 % is not surprising. The main reason for this high loss is that the compartements of the tipping buckets are still filled up with water during the tipping movement (detailed explanation in section 4.1.4 on page 18).

The Young sensor, which has been moved from station 72 to the reference station 77 in October 2013, shows a slight overestimation of +1.0 % to +5.0 % for the two low intensities and the typical undercatching error for the high intensity.

The measurements at the MeteoServis sensor revealed considerably high overestimations for the low intensity, of +16.0 % and +20.0 %. The two higher intensities show only very small relative differences between –2.0 % and +1.0 %. As the MeteoServis instrument was assumed to be the most accurate measuring device, and because of the fact that at all primary stations the Young sensors have been replaced by MeteoServis sensors, the team decided to carry out the measurements at one further primary station. The choice fell on the nearby located station 11. In Table A.2 the results of the two measurements are listed. The instrument showed a slight underestimation of –6.0 % which indicates a well calibrated device. Also the high intensity was measured quite accurately with an underestimation of –5.0 %. The latter suggests that the MeteoServis sensor at the reference station shows an offset which originates from a lack of calibration within the last 7 years of WegenerNet existence.

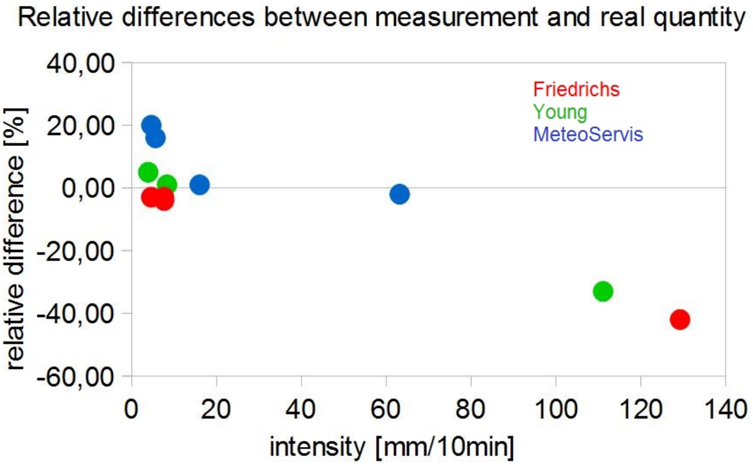

Figure A.3.: Relative differences between real quantity and measured quantity as function of the intensity.

Table A.2.: Results from the comparative measurements at the primary station 11. M ... MeteoServis

no.	model	filling quantity [ml]	filling quantity [mm]	duration [mm:ss]	intensity [mm/10min]	measured quantity [mm]	deviation [%]
12	M	250	**5.00**	06:17	7.96	**4.70**	-6.0
13	M	500	**10.00**	01:16	78.95	**9.50**	-5.0

A.3. Discussion

The comparative test measurements at the reference station 77 have been carried out in order to get some basic quality information about the precipitation sensors used in the WegenerNet. They showed that the Friedrichs sensor, which is in use at 139 stations, shows a rather accurate behavior for intensities in the medium range, which are common in the WegenerNet region. Also the Young sensor, which is - since October 2013 - only in use at the reference station, shows just a slight overestimation which is also within the +5 % range. The only surprise were the results of the MeteoServis sensor which showed quite high overestimations between +16 % and +20 %. Preliminary evidence from the climatological evaluation over 2008 to 2013 indicates that this overestimation exceeding 10 % was not occuring before September 2013, but re-calibration is anywy important. Further evaluations will be necessary to more exactly determine the evolution of this offset. A calibration of the instrument is foreseen in spring 2014 in order to maintain its status as reference instrument in the WegenerNet. Cross-check measurements for one of the new MeteoServis sensors at station 11 showed that those results exhibit offsets of only near –5 %.

B. Record of Data Gaps within Jan. 2007 - Sep. 2013

Table B.1 summarizes data gaps in the quality controlled WegenerNet data series (Level 1, processing version 2) between January 1, 2007 and September 30, 2013. The data voids which have been listed are due to logger failures or problems in the data processing chain at the corresponding stations and in the processing system, respectively. Only gaps with a duration of more than 24 hours (more than 288 missing data points) have been accounted for in this overview. As most of the missing data points are the result of logger failures, they generally affect all parameters. At the reference station no. 77 the Young and the MeteoServis sensor use a different logger channel than the other parameters (and the Friedrichs sensor). Usually only one channel is affected by such a failure but nevertheless there have been periods, where no data is available at the reference station. In Table B.1 such events can be detected by checking if a failure period occurs at the Friedrichs sensor as well as at the two other sensors. By a postprocessing of the WegenerNet data in January 2014 to the newest *Level 1 version 3* data most of the missing data could be restored. This new dataset, also with the *Level 2 version 4* data (data products, see Section 2.2 at page 3 for further information on the processing chain) will be available by the end of February 2014.

The subsequent Table B.2 shows the total period of station downtime and the total number of missing data points in the Level 1 data (processing version 2) between January 1, 2007 and September 30, 2013. Additionally the total time of outages originating from failures with a duration of less than 24 hours and the total time originating from failures of more than 24 hours are stated separately.

Table B.1.: Data gaps due to logger failures between January 1, 2007 and September 30, 2013 in the Level 1 data (version 3). Logger outages of less than 24 hours are not listed. The times given in the list are the last available (from) and the following available (to) data points. The last two columns give the number of missing data points and the corresponding time span.

Station	**from [UTC]**	**to [UTC]**	**# missings**	**duration** [D HH:mm:ss]
4	2007-11-24 05:15:00	2007-11-29 07:10:00	1462	5 01:50:00
5	2013-09-20 14:10:00	2013-09-22 00:00:00	405	1 09:45:00
6	2013-06-18 16:35:00	2013-08-04 00:00:00	13336	46 07:20:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-28 00:00:00	2231	7 17:55:00
8	2012-01-27 23:20:00	2012-01-29 06:15:00	370	1 06:50:00
	2012-01-29 09:10:00	2012-02-23 23:00:00	7365	25 13:45:00
9	2007-06-01 11:05:00	2007-06-05 07:10:00	1104	3 20:00:00

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Table B.1 – *Continued from previous page*

Station	**from [UTC]**	**to [UTC]**	**# missings**	**duration** [D HH:mm:ss]
	2007-11-03 05:05:00	2007-11-07 12:55:00	1245	4 07:45:00
13	2007-12-18 17:15:00	2007-12-28 01:30:00	2690	9 08:10:00
	2010-01-03 20:10:00	2010-04-13 23:00:00	28833	100 02:45:00
14	2007-11-02 11:15:00	2007-11-07 14:00:00	1472	5 02:40:00
	2007-11-27 11:10:00	2007-12-04 22:10:00	2147	7 10:55:00
	2011-06-11 20:15:00	2011-06-12 23:00:00	320	1 02:40:00
15	2013-06-19 15:40:00	still out of order	29763[1]	103 08:15:00
17	2011-08-30 04:12:59	2011-08-31 23:00:00	512	1 18:42:01
	2011-09-01 17:00:00	2011-09-05 23:00:00	1223	4 05:55:00
	2012-09-10 06:00:00	2012-10-01 00:00:00	5975	20 17:55:00
	2012-11-02 00:00:00	2012-11-07 00:00:00	1439	4 23:55:00
18	2010-12-04 14:25:00	2010-12-07 23:00:00	966	3 08:30:00
	2010-12-09 17:25:00	2010-12-10 23:00:00	354	1 05:30:00
	2010-12-12 17:40:00	2010-12-14 23:00:00	639	2 05:15:00
	2010-12-16 02:30:00	2010-12-17 23:00:00	533	1 20:25:00
	2010-12-21 05:30:00	2010-12-22 23:00:00	497	1 17:25:00
	2010-12-24 23:25:00	2011-01-01 23:00:00	2298	7 23:30:00
19	2012-06-30 18:40:00	2012-07-05 00:00:00	1215	4 05:15:00
	2012-09-10 06:00:00	2012-10-01 00:00:00	5975	20 17:55:00
	2012-11-02 00:00:00	2012-11-07 00:00:00	1439	4 23:55:00
	2013-06-19 09:00:00	2013-08-04 00:00:00	13139	45 14:55:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-28 00:00:00	2231	7 17:55:00
20	2007-04-09 23:35:00	2007-06-01 19:40:00	15216	52 20:00:00
	2009-12-05 09:30:00	2009-12-12 23:00:00	2177	7 13:25:00
	2011-10-10 01:55:00	2011-10-17 23:00:00	2268	7 21:00:00
21	2010-12-17 11:30:00	2011-01-08 00:00:00	6197	21 12:25:00
	2011-01-13 06:00:00	2011-02-09 23:00:00	7979	27 16:55:00
23	2009-12-16 16:30:00	2009-12-18 23:00:00	653	2 06:25:00
	2011-11-21 11:30:00	2011-12-28 14:00:00	10685	37 02:25:00
	2012-03-24 20:30:00	2012-04-10 23:00:00	4925	17 02:25:00
25	2012-01-18 07:00:00	2012-01-29 06:15:00	3158	10 23:10:00
	2012-01-29 09:10:00	2012-02-16 23:00:00	5349	18 13:45:00
26	2013-09-12 12:00:00	2013-09-15 00:00:00	719	2 11:55:00
27	2011-06-11 09:35:00	2011-06-12 11:05:00	305	1 01:25:00
	2012-01-09 05:35:00	2012-01-24 23:00:00	4528	15 17:20:00
	2012-02-07 22:35:00	2012-02-23 23:00:00	4612	16 00:20:00
	2013-06-19 10:45:00	2013-08-04 00:00:00	13118	45 13:10:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-29 00:00:00	2519	8 17:55:00

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[1] number of missing data until 2013-10-01 00:00:00

Table B.1 – *Continued from previous page*

Station	**from [UTC]**	**to [UTC]**	**# missings**	**duration** [D HH:mm:ss]
	2013-08-30 06:05:00	2013-09-07 00:00:00	2230	7 17:50:00
28	2011-06-11 08:10:00	2011-06-12 23:00:00	465	1 14:45:00
	2012-02-07 14:10:00	2012-02-16 23:00:00	2697	9 08:45:00
	2012-06-21 05:10:00	2012-06-23 17:05:00	718	2 11:50:00
30	2007-11-02 11:25:00	2007-11-07 13:20:00	1462	5 01:50:00
31	2011-08-27 11:25:00	2011-09-08 23:00:00	3594	12 11:30:00
	2012-02-07 19:25:00	2012-02-11 23:00:00	1194	4 03:30:00
	2012-03-24 11:25:00	2012-04-10 23:00:00	5034	17 11:30:00
	2012-06-07 17:25:00	2012-06-09 17:05:00	571	1 23:35:00
	2012-09-10 06:00:00	2012-10-01 00:00:00	5975	20 17:55:00
	2012-11-02 00:00:00	2012-11-07 00:00:00	1439	4 23:55:00
32	2007-03-30 23:25:00	2007-04-10 17:20:00	3094	10 17:50:00
	2012-04-21 07:55:00	2012-04-26 23:00:00	1620	5 15:00:00
	2012-04-28 10:25:00	2012-05-07 04:30:00	2520	8 18:00:00
	2012-05-07 06:25:00	2012-06-27 00:00:00	14610	50 17:30:00
33	2011-10-15 05:55:00	2011-10-17 23:00:00	780	2 17:00:00
34	2013-02-17 10:40:00	still out of order	64959[2]	225 13:15:00
36	2010-11-27 14:30:00	2010-12-04 23:00:00	2117	7 08:25:00
	2010-12-16 12:30:00	2010-12-17 23:00:00	413	1 10:25:00
	2010-12-27 14:35:00	2010-12-28 23:00:00	388	1 08:20:00
	2010-12-30 12:30:00	2011-01-01 23:00:00	701	2 10:25:00
	2011-01-26 15:30:00	2011-01-27 23:00:00	377	1 07:25:00
	2011-01-29 12:30:00	2011-02-01 23:00:00	989	3 10:25:00
	2011-02-12 13:30:00	2011-02-17 23:00:00	1553	5 09:25:00
	2011-02-19 19:30:00	2011-02-21 23:00:00	617	2 03:25:00
	2011-11-16 14:30:00	2011-11-25 23:00:00	2693	9 08:25:00
	2012-01-29 09:10:00	2012-02-23 23:00:00	7365	25 13:45:00
37	2012-03-19 07:30:00	2012-04-10 23:00:00	6521	22 15:25:00
38	2009-12-18 17:30:00	2010-04-13 23:00:00	33473	116 05:25:00
40	2010-12-18 17:00:00	2010-12-20 23:00:00	647	2 05:55:00
41	2008-07-08 04:00:00	2008-07-10 08:45:00	632	2 04:40:00
	2010-01-03 16:05:00	2010-04-15 19:30:00	29416	102 03:20:00
	2011-07-10 17:00:00	2011-07-14 23:00:00	1223	4 05:55:00
42	2007-10-31 05:15:00	2007-11-07 11:50:00	2094	7 06:30:00
	2011-06-11 18:10:00	2011-06-12 23:00:00	345	1 04:45:00
	2012-01-10 07:10:00	2012-01-29 06:15:00	5460	18 23:00:00
	2012-01-29 09:10:00	2012-02-16 23:00:00	5349	18 13:45:00
	2012-06-13 14:10:00	2012-06-22 23:00:00	2697	9 08:45:00
43	2011-06-11 05:10:00	2011-06-12 23:00:00	501	1 17:45:00
	2012-01-07 23:10:00	2012-01-26 23:00:00	5469	18 23:45:00

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[2] number of missing data until 2013-10-01 00:00:00

Table B.1 – *Continued from previous page*

Station	**from [UTC]**	**to [UTC]**	**# missings**	**duration** [D HH:mm:ss]
	2012-06-07 12:10:00	2012-06-26 17:30:00	5535	19 05:15:00
44	2007-04-07 23:15:00	2007-04-10 23:10:00	862	2 23:50:00
	2012-01-10 14:10:00	2012-01-24 23:00:00	4137	14 08:45:00
	2012-02-13 12:10:00	2012-02-23 23:00:00	3009	10 10:45:00
	2012-03-09 04:10:00	2012-03-28 23:00:00	5697	19 18:45:00
45	2007-06-01 05:25:00	2007-06-05 20:40:00	1334	4 15:10:00
	2009-10-19 16:25:00	2009-10-20 23:00:00	366	1 06:30:00
	2012-01-12 23:25:00	2012-01-24 23:00:00	3450	11 23:30:00
	2012-01-29 09:10:00	2012-01-30 23:00:00	453	1 13:45:00
	2012-11-23 06:25:00	2012-11-27 00:00:00	1074	3 17:30:00
46	2011-09-27 11:25:00	2011-10-10 23:00:00	3882	13 11:30:00
47	2009-12-17 17:25:00	2010-04-13 23:00:00	33762	117 05:30:00
48	2010-01-03 14:25:00	2010-01-23 23:00:00	5862	20 08:30:00
	2011-07-21 17:25:00	2011-07-23 23:00:00	642	2 05:30:00
	2012-02-09 23:25:00	2012-02-15 23:00:00	1722	5 23:30:00
	2012-03-24 11:25:00	2012-04-10 23:00:00	5034	17 11:30:00
49	2007-12-21 18:35:00	2007-12-24 17:30:00	850	2 22:50:00
50	2007-01-01 00:00:00	2007-01-04 11:30:00	1001	3 11:25:00
	2007-01-15 11:35:00	2007-04-10 17:30:00	24550	85 05:50:00
	2007-04-11 11:35:00	2007-06-21 17:30:00	20518	71 05:50:00
	2011-08-07 19:35:00	2011-08-08 23:00:00	328	1 03:20:00
	2011-09-06 22:35:00	2011-10-22 23:00:00	13252	46 00:20:00
	2012-11-02 00:00:00	2012-11-08 13:20:00	1887	6 13:15:00
	2013-06-19 06:25:00	2013-08-04 00:00:00	13170	45 17:30:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-28 00:00:00	2231	7 17:55:00
54	2008-01-01 03:20:00	2008-01-22 18:00:00	6223	21 14:35:00
	2012-06-06 13:35:00	2012-06-12 17:05:00	1769	6 03:25:00
	2012-11-22 16:40:00	2012-11-26 00:00:00	951	3 07:15:00
	2013-06-19 11:55:00	2013-08-04 00:00:00	13104	45 12:00:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-29 00:00:00	2519	8 17:55:00
58	2011-06-11 21:10:00	2011-06-12 23:00:00	309	1 01:45:00
59	2012-06-07 05:10:00	2012-06-10 17:05:00	1006	3 11:50:00
	2012-06-21 08:10:00	2012-06-26 17:25:00	1550	5 09:10:00
61	2012-06-20 22:25:00	2012-06-23 23:00:00	870	3 00:30:00
62	2010-12-17 07:15:00	2010-12-26 23:00:00	2780	9 15:40:00
63	2007-11-22 11:35:00	2007-11-26 05:00:00	1072	3 17:20:00
	2007-12-01 05:30:00	2007-12-04 11:35:00	936	3 06:00:00
	2011-07-21 23:25:00	2011-07-23 23:00:00	570	1 23:30:00
	2012-01-30 20:25:00	2012-02-16 23:00:00	4926	17 02:30:00

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Table B.1 – *Continued from previous page*

Station	**from [UTC]**	**to [UTC]**	**# missings**	**duration** [D HH:mm:ss]
	2012-03-25 02:25:00	2012-03-30 08:55:00	1517	5 06:25:00
	2012-03-30 10:50:00	2012-04-03 11:55:00	1164	4 01:00:00
	2012-04-03 13:50:00	2012-04-17 23:00:00	4141	14 09:05:00
65	2009-12-19 21:30:00	2010-04-13 23:00:00	33137	115 01:25:00
66	2010-08-22 23:30:00	2010-09-13 23:00:00	6329	21 23:25:00
71	2008-07-04 16:20:00	2008-07-10 11:55:00	1674	5 19:30:00
	2010-10-12 17:20:00	2010-10-17 23:00:00	1507	5 05:35:00
	2011-07-10 17:20:00	2011-07-14 23:00:00	1219	4 05:35:00
	2013-05-24 14:20:00	2013-05-26 00:00:00	403	1 09:35:00
	2013-07-06 20:20:00	2013-07-08 00:00:00	331	1 03:35:00
	2013-07-16 05:20:00	2013-07-17 08:00:00	319	1 02:35:00
72	2008-01-22 13:40:00	2008-01-26 10:55:00	1118	3 21:10:00
74	2007-10-07 02:30:00	2007-10-12 16:45:00	1610	5 14:10:00
	2007-11-14 11:55:00	2008-02-28 13:45:00	30549	106 01:45:00
75	2007-11-21 11:50:00	2007-11-29 12:50:00	2315	8 00:55:00
	2010-07-29 03:05:00	2010-07-31 23:00:00	814	2 19:50:00
	2012-02-02 03:25:00	2012-02-16 23:00:00	4266	14 19:30:00
	2012-09-10 06:00:00	2012-10-01 00:00:00	5975	20 17:55:00
	2012-11-02 00:00:00	2012-11-26 00:00:00	6911	23 23:55:00
76	2010-08-21 04:05:00	2010-09-15 14:45:00	7327	25 10:35:00
77 (F)	2007-01-01 00:00:00	2007-10-19 16:05:00	84000	291 16:00:00
	2012-03-27 17:35:00	2012-03-28 23:00:00	352	1 05:20:00
	2012-03-30 10:35:00	2012-04-10 23:00:00	3316	11 12:20:00
77 (Y)	2007-01-01 00:00:00	2007-10-19 16:05:00	84000	291 16:00:00
	2007-11-07 16:10:00	2008-06-10 11:10:00	62147	215 18:55:00
	2012-03-27 17:35:00	2012-03-28 23:00:00	352	1 05:20:00
	2012-03-30 10:35:00	2012-04-10 23:00:00	3316	11 12:20:00
77 (M)	2007-01-01 00:00:00	2007-10-19 16:05:00	84000	291 16:00:00
	2007-11-07 16:10:00	2008-06-10 11:10:00	62147	215 18:55:00
	2012-03-27 17:35:00	2012-03-28 23:00:00	352	1 05:20:00
	2012-03-30 10:35:00	2012-04-10 23:00:00	3316	11 12:20:00
78	2007-01-01 00:00:00	2007-07-05 17:10:00	53485	185 17:05:00
	2008-11-27 15:35:00	2008-12-03 08:40:00	1644	5 17:00:00
	2013-06-19 05:50:00	2013-08-04 00:00:00	13177	45 18:05:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-29 00:00:00	2519	8 17:55:00
83	2007-07-05 05:40:00	2007-07-27 18:40:00	6491	22 12:55:00
84	2007-07-05 05:45:00	2007-07-10 11:40:00	1510	5 05:50:00
	2013-06-18 21:30:00	2013-06-24 00:00:00	1469	5 02:25:00
	2013-06-25 17:10:00	2013-08-04 00:00:00	11313	39 06:45:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00

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Table B.1 – *Continued from previous page*

Station	**from [UTC]**	**to [UTC]**	**# missings**	**duration** [D HH:mm:ss]
	2013-08-20 06:00:00	2013-08-28 00:00:00	2231	7 17:55:00
85	2013-06-19 12:55:00	2013-08-04 00:00:00	13092	45 11:00:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-29 00:00:00	2519	8 17:55:00
88	2007-10-30 11:50:00	2007-11-07 17:40:00	2373	8 05:45:00
91	2010-10-12 10:05:00	2010-10-13 23:00:00	442	1 12:50:00
92	2007-03-15 11:15:00	2007-06-01 07:40:00	22420	77 20:20:00
99	2010-01-06 19:35:00	2010-01-13 12:50:00	1934	6 17:10:00
	2010-01-13 12:50:00	2010-01-14 23:00:00	409	1 10:05:00
	2010-01-21 04:40:00	2010-01-23 13:05:00	676	2 08:20:00
	2013-06-18 16:00:00	2013-08-04 00:00:00	13343	46 07:55:00
	2013-08-05 06:00:00	2013-08-19 00:00:00	3959	13 17:55:00
	2013-08-20 06:00:00	2013-08-28 00:00:00	2231	7 17:55:00
100	2011-12-25 00:20:00	2011-12-27 23:00:00	847	2 22:35:00
104	2009-12-19 20:45:00	2010-04-15 11:05:00	33579	116 14:15:00
110	2013-03-11 06:05:00	2013-03-20 00:00:00	2518	8 17:50:00
113	2011-06-27 01:40:00	2011-06-29 23:00:00	831	2 21:15:00
	2012-01-31 16:40:00	2012-02-21 23:00:00	6123	21 06:15:00
119	2008-08-03 11:20:00	2008-08-19 16:45:00	4672	16 05:20:00
	2009-04-08 17:00:00	2009-04-09 18:05:00	300	1 01:00:00
130	2011-09-09 17:20:00	2011-09-10 23:00:00	355	1 05:35:00
131	2011-09-09 14:45:00	2011-09-10 23:00:00	386	1 08:10:00
132	2011-06-17 04:45:00	2011-06-29 23:00:00	3674	12 18:10:00
	2011-09-09 16:45:00	2011-09-10 23:00:00	362	1 06:10:00
	2012-04-01 09:45:00	2012-04-09 23:00:00	2462	8 13:10:00
135	2007-08-29 00:10:00	2007-11-08 17:15:00	20652	71 17:00:00
136	2012-09-10 06:00:00	2012-10-01 00:00:00	5975	20 17:55:00
	2012-11-02 00:00:00	2012-11-08 00:00:00	1727	5 23:55:00
140	2012-09-10 06:00:00	2012-10-01 00:00:00	5975	20 17:55:00
	2012-11-02 00:00:00	2012-11-08 00:00:00	1727	5 23:55:00
141	2011-06-17 05:45:00	2011-06-29 23:00:00	3662	12 17:10:00
	2011-09-09 14:45:00	2011-09-10 23:00:00	386	1 08:10:00
	2012-09-10 06:00:00	2012-10-01 00:00:00	5975	20 17:55:00
	2012-11-02 00:00:00	2012-11-08 00:00:00	1727	5 23:55:00
142	2011-06-19 06:50:00	2011-06-21 23:00:00	769	2 16:05:00
	2011-06-26 05:55:00	2011-06-29 23:00:00	1068	3 17:00:00
148	2012-04-27 22:15:00	2012-04-28 23:00:00	296	1 00:40:00
150	2010-06-09 04:15:00	2010-06-10 23:00:00	512	1 18:40:00
	2010-07-14 04:15:00	2010-07-16 17:05:00	729	2 12:45:00

Table B.2.: Total number of data gaps in the Level 1 data (version 3) and according duration of the failure between January 1, 2007 and September 30, 2013, for each station. The last two columns give the share of missing data points coming from outages with a duration of less than 24 hours and more than 24 hours, respectively.

Station	**total** **# missings**	**total time** [D HH:mm:ss]	**total** <24 h	**total** >24 h
1	10	0 00:50:00	0 00:50:00	0 00:00:00
2	185	0 15:25:00	0 15:25:00	0 00:00:00
3	88	0 07:20:00	0 07:20:00	0 00:00:00
4	1472	5 02:40:00	0 00:50:00	5 01:50:00
5	405	1 09:45:00	0 00:00:00	1 09:45:00
6	19529	67 19:25:00	7 18:10:00	60 01:15:00
7	25	0 02:05:00	0 02:05:00	0 00:00:00
8	8043	27 22:15:00	1 01:40:00	26 20:35:00
9	1114	3 20:50:00	0 00:50:00	3 20:00:00
10	1327	4 14:35:00	0 06:50:00	4 07:45:00
11	569	1 23:25:00	1 23:25:00	0 00:00:00
12	0	0 00:00:00	0 00:00:00	0 00:00:00
13	31604	109 17:40:00	0 06:45:00	109 10:55:00
14	4064	14 02:40:00	0 10:25:00	13 16:15:00
15	30403	105 13:35:00	2 05:20:00	103 08:15:00
16	230	0 19:10:00	0 19:10:00	0 00:00:00
17	9329	32 09:27:01	0 15:00:00	31 18:27:01
18	5632	19 13:20:00	1 04:45:00	18 08:35:00
19	28275	98 04:15:00	1 02:25:00	97 01:50:00
20	19810	68 18:50:00	0 12:25:00	68 06:25:00
21	14325	49 17:45:00	0 12:25:00	49 05:20:00
22	10	0 00:50:00	0 00:50:00	0 00:00:00
23	16271	56 11:55:00	0 00:40:00	56 11:15:00
24	319	1 02:35:00	1 02:35:00	0 00:00:00
25	8539	29 15:35:00	0 02:40:00	29 12:55:00
26	740	2 13:40:00	0 01:45:00	2 11:55:00
27	31296	108 16:00:00	0 02:05:00	108 13:55:00
28	4165	14 11:05:00	0 23:45:00	13 11:20:00
29	0	0 00:00:00	0 00:00:00	0 00:00:00
30	1477	5 03:05:00	0 01:15:00	5 01:50:00
31	18129	62 22:45:00	1 02:50:00	61 19:55:00
32	21961	76 06:05:00	0 09:45:00	75 20:20:00
33	1005	3 11:45:00	0 18:45:00	2 17:00:00
34	65934	228 22:30:00	3 09:15:00	225 13:15:00
35	12	0 01:00:00	0 01:00:00	0 00:00:00
36	20491	71 03:35:00	11 09:10:00	59 18:25:00
37	6521	22 15:25:00	0 00:00:00	22 15:25:00
38	33485	116 06:25:00	0 01:00:00	116 05:25:00

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Table B.2 – *Continued from previous page*

Station	**total** **# missings**	**total time** [D HH:mm:ss]	**total** <24 h	**total** >24 h
39	30	0 02:30:00	0 02:30:00	0 00:00:00
40	667	2 07:35:00	0 01:40:00	2 05:55:00
41	31808	110 10:40:00	1 20:45:00	108 13:55:00
42	15985	55 12:05:00	0 03:20:00	55 08:45:00
43	11537	40 01:25:00	0 02:40:00	39 22:45:00
44	13713	47 14:45:00	0 00:40:00	47 14:05:00
45	6950	24 03:10:00	0 22:45:00	23 04:25:00
46	3918	13 14:30:00	0 03:00:00	13 11:30:00
47	33767	117 05:55:00	0 00:25:00	117 05:30:00
48	13786	47 20:50:00	1 19:50:00	46 01:00:00
49	866	3 00:10:00	0 01:20:00	2 22:50:00
50	81470	282 21:10:00	1 23:50:00	280 21:20:00
51	66	0 05:30:00	0 05:30:00	0 00:00:00
52	13	0 01:05:00	0 01:05:00	0 00:00:00
53	36	0 03:00:00	0 03:00:00	0 00:00:00
54	28941	100 11:45:00	1 10:40:00	99 01:05:00
55	163	0 13:35:00	0 13:35:00	0 00:00:00
56	165	0 13:45:00	0 13:45:00	0 00:00:00
57	137	0 11:25:00	0 11:25:00	0 00:00:00
58	346	1 04:50:00	0 03:05:00	1 01:45:00
59	2580	8 23:00:00	0 02:00:00	8 21:00:00
60	16	0 01:20:00	0 01:20:00	0 00:00:00
61	919	3 04:35:00	0 04:05:00	3 00:30:00
62	2790	9 16:30:00	0 00:50:00	9 15:40:00
63	15714	54 13:30:00	4 19:40:00	49 17:50:00
64	118	0 09:50:00	0 09:50:00	0 00:00:00
65	33137	115 01:25:00	0 00:00:00	115 01:25:00
66	6795	23 14:15:00	1 14:50:00	21 23:25:00
67	118	0 09:50:00	0 09:50:00	0 00:00:00
68	202	0 16:50:00	0 16:50:00	0 00:00:00
69	569	1 23:25:00	1 23:25:00	0 00:00:00
70	6	0 00:30:00	0 00:30:00	0 00:00:00
71	5504	19 02:40:00	0 04:15:00	18 22:25:00
72	1188	4 03:00:00	0 05:50:00	3 21:10:00
73	42	0 03:30:00	0 03:30:00	0 00:00:00
74	32180	111 17:40:00	0 01:45:00	111 15:55:00
75	20299	70 11:37:17	0 01:32:17	70 10:05:00
76	7363	25 13:35:00	0 03:00:00	25 10:35:00
77F	88434	307 01:30:00	2 15:50:00	304 09:40:00
77Y	150532	522 16:20:00	2 11:45:00	520 04:35:00
77M	150532	522 16:20:00	2 11:45:00	520 04:35:00

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Table B.2 – *Continued from previous page*

Station	**total # missings**	**total time** [D HH:mm:ss]	**total** <24 h	**total** >24 h
78	74825	259 19:25:00	0 03:25:00	259 16:00:00
79	27	0 02:15:00	0 02:15:00	0 00:00:00
80	160	0 13:20:00	0 13:20:00	0 00:00:00
81	24	0 02:00:00	0 02:00:00	0 00:00:00
82	78	0 06:30:00	0 06:30:00	0 00:00:00
83	6675	23 04:15:00	0 15:20:00	22 12:55:00
84	20498	71 04:10:00	0 01:20:00	71 02:50:00
85	19660	68 06:20:00	0 07:30:00	67 22:50:00
86	72	0 06:00:00	0 06:00:00	0 00:00:00
87	199	0 16:35:00	0 16:35:00	0 00:00:00
88	2452	8 12:20:00	0 06:35:00	8 05:45:00
89	11	0 00:55:00	0 00:55:00	0 00:00:00
90	26	0 02:10:00	0 02:10:00	0 00:00:00
91	452	1 13:40:00	0 00:50:00	1 12:50:00
92	22450	77 22:50:00	0 02:30:00	77 20:20:00
93	21	0 01:45:00	0 01:45:00	0 00:00:00
94	45	0 03:45:00	0 03:45:00	0 00:00:00
95	47	0 03:55:00	0 03:55:00	0 00:00:00
96	18	0 01:30:00	0 01:30:00	0 00:00:00
97	20	0 01:40:00	0 01:40:00	0 00:00:00
98	38	0 03:10:00	0 03:10:00	0 00:00:00
99	22920	79 14:00:00	1 06:40:00	78 07:20:00
100	847	2 22:35:00	0 00:00:00	2 22:35:00
101	17	0 01:25:00	0 01:25:00	0 00:00:00
102	72	0 06:00:00	0 06:00:00	0 00:00:00
103	12	0 01:00:00	0 01:00:00	0 00:00:00
104	33593	116 15:25:00	0 01:10:00	116 14:15:00
105	49	0 04:05:00	0 04:05:00	0 00:00:00
106	232	0 19:20:00	0 19:20:00	0 00:00:00
107	18	0 01:30:00	0 01:30:00	0 00:00:00
108	10	0 00:50:00	0 00:50:00	0 00:00:00
109	9	0 00:45:00	0 00:45:00	0 00:00:00
110	2518	8 17:50:00	0 00:00:00	8 17:50:00
111	22	0 01:50:00	0 01:50:00	0 00:00:00
112	20	0 01:40:00	0 01:40:00	0 00:00:00
113	7040	24 10:40:00	0 07:10:00	24 03:30:00
114	10	0 00:50:00	0 00:50:00	0 00:00:00
115	6	0 00:30:00	0 00:30:00	0 00:00:00
116	128	0 10:40:00	0 10:40:00	0 00:00:00
117	156	0 13:00:00	0 13:00:00	0 00:00:00
118	36	0 03:00:00	0 03:00:00	0 00:00:00

Continued on next page

Table B.2 – *Continued from previous page*

Station	**total** **# missings**	**total time** [D HH:mm:ss]	**total** <24 h	**total** >24 h
119	4984	17 07:20:00	0 01:00:00	17 06:20:00
120	136	0 11:20:00	0 11:20:00	0 00:00:00
121	238	0 19:50:00	0 19:50:00	0 00:00:00
122	227	0 18:55:00	0 18:55:00	0 00:00:00
123	0	0 00:00:00	0 00:00:00	0 00:00:00
124	40	0 03:20:00	0 03:20:00	0 00:00:00
125	14	0 01:10:00	0 01:10:00	0 00:00:00
126	176	0 14:40:00	0 14:40:00	0 00:00:00
127	177	0 14:45:00	0 14:45:00	0 00:00:00
128	189	0 15:45:00	0 15:45:00	0 00:00:00
129	6	0 00:30:00	0 00:30:00	0 00:00:00
130	663	2 07:15:00	1 01:40:00	1 05:35:00
131	743	2 13:55:00	1 05:45:00	1 08:10:00
132	6760	23 11:20:00	0 21:50:00	22 13:30:00
133	225	0 18:45:00	0 18:45:00	0 00:00:00
134	195	0 16:15:00	0 16:15:00	0 00:00:00
135	20847	72 09:15:00	0 16:15:00	71 17:00:00
136	7703	26 17:55:00	0 00:05:00	26 17:50:00
137	7	0 00:35:00	0 00:35:00	0 00:00:00
138	14	0 01:10:00	0 01:10:00	0 00:00:00
139	461	1 14:25:00	1 14:25:00	0 00:00:00
140	7892	27 09:40:00	0 15:50:00	26 17:50:00
141	12156	42 05:00:00	1 09:50:00	40 19:10:00
142	2011	6 23:35:00	0 14:30:00	6 09:05:00
143	227	0 18:55:00	0 18:55:00	0 00:00:00
144	47	0 03:55:00	0 03:55:00	0 00:00:00
145	14	0 01:10:00	0 01:10:00	0 00:00:00
146	14	0 01:10:00	0 01:10:00	0 00:00:00
147	14	0 01:10:00	0 01:10:00	0 00:00:00
148	343	1 04:35:00	0 03:55:00	1 00:40:00
149	14	0 01:10:00	0 01:10:00	0 00:00:00
150	1972	6 20:20:00	2 12:55:00	4 07:25:00

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Abstract:
The WegenerNet, which is a network of meteorological stations in the region of Feldbach (in south-eastern Styria, Austria), is considered as a "pioneering experiment for long-term observations at very high resolution" (Kabas 2012). Essential meteorological parameters are measured in 5-minute intervals by 151 meteorological stations which are arranged in a grid pattern over an area of about 20×15 km².
In this thesis the WegenerNet precipitation data have been analyzed and evaluated in order to obtain information about the quality of the current measuring system. All precipitation gauges are based on the principle of the "tipping bucket", which records the precipitation amount by counting tiltings of a seesaw bucket via a reed contact.
The quality analyses of the data have been carried out by directly comparing the data sets at the reference station (equipped with all three sensor systems), by doing homogeneity evaluations across the whole network and by performing case studies. Climatological aspects have been considered by studying seasonal and annual precipitation data throughout the network. Comparison of the same data sets at difference processing steps provided information about weaknesses in the WegenerNet processing system.
The analyses delivered detailed insight into the WegenerNet precipitation data quality and demonstrate deficiencies in the current system that are taken as a basis for further improvements.

Zum Inhalt:
Das WegenerNet, das als Pionierexperiment für Langzeitbeobachtungen mit sehr hoher zeitlicher und räumlicher Auflösung fungiert, ist ein Netzwerk von meteorologischen Stationen im Raum Feldbach in der Südoststeiermark (Kabas 2012). Insgesamt 151 Stationen, die in einer Gitterstruktur über ein Gebiet von ca. 20×15 km² angeordnet sind, liefern Daten über eine Reihe meteorologischer Parameter in 5-Minuten-Intervallen.
Thema der vorliegenden Arbeit ist die Auswertung der WegenerNet Niederschlagsdaten, sowie eine Qualitätsanalyse der verschiedenen Niederschlagssensoren. Alle verwendeten Regenmesser arbeiten nach dem Prinzip der Kippwaage, wobei das Kippen eines kleinen Behälters bei einer vorgegebenen Füllmenge über einen Reedkontakt registriert wird.
Die Qualitätsanalysen der Daten wurden durch direkten Vergleich der Datensätze an der Referenzstation (mit allen drei Sensoren ausgestattet), durch Homogenitätsbetrachtungen des gesamten WegenerNets und durch Betrachtung einzelner Fallstudien durchgeführt. Klimatologische Aspekte wurden durch die Analyse der Jahres- und Saisondaten näher betrachtet. Um Informationen über das WegenerNet Processing System zu erhalten, wurden die Daten nach verschiedenen Prozessierungsschritten verglichen.
Die Analysen geben einen detaillierten Überblick über die Qualität der WegenerNet Niederschlagsdaten und zeigen Schwächen im laufenden System auf, die auf dieser Basis nun verbessert werden können.

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