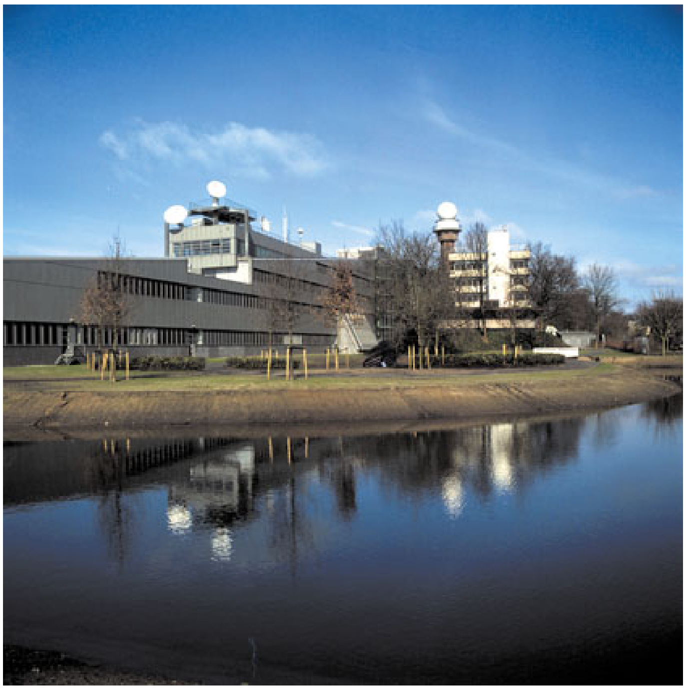

The relation between temperature and precipitation

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Internship report

Contents

CHAPTER 1

Introduction

The environment we live in plays a dominant role in our lives. The difference between rain and sun on a day changes many peoples decisions for that day. But compared to the importance of the atmosphere, our knowledge about it is limited. Many aspects of the atmosphere (temperature, wind, precipitation) may change due to greenhouse gas induced warming. It is expected that the intensity of the hydrological cycle will increase as the climate warms. In particular the intensity of precipitation extremes is expected to increase. An important relation to understand the changes in precipitation extremes is the Clausius-Clapeyron relation. This relation expresses the amount of water vapor in the atmosphere at saturation as a function of temperature and pressure. At constant pressure it is an exponential relation. Precipitation extremes are generally expected to increase at the same rate with temperature. The saturation amount is found to increase with 7 percent per degree Celsius. However data analysis of precipitation showed different behavior when the temperature becomes bigger than $12°C$ [2].

This is an internship report for the study Applied Physics of the Delft University of technology. The objective of this internship is to further investigate precipitation measurement data and get experience in working in a company.

1.1 Precipitation

Precipitation is the amount of water that falls down from clouds. In this study the precipitation measured by measurement stations is considered. The origin of precipitation is water vapour condensing around particles in the atmosphere. If these droplets grow and reach a critical size they will fall down due to gravitational force acting on its mass. The condensation rate is strongly dependent on temperature changes. Since warm air can contain more water vapour than cold air, condensation can be triggered by cooling a parcel of air. Roughly there are two types of precipitation: large scale precipitation events, which occur in frontal systems associated with synoptic low pressure systems, and convective precipitation which occur in relative small scaled convective clouds. It is expected that convective precipitation plays a more dominant role as temperature increases. How this influences the relation between temperature and precipitation has already been investigated [2, 4], but in this study the influence of multiple meteorological parameters on this relation is investigated.

1.2 The KNMI

The KNMI (Koninklijk Nederlands Meteorologisch Instituut) was founded in 1854 by Prof. C.H.D. Buys Ballot. Its mission is to provide information about the weather, seismology and climate. This consist of short term predictions, seismological information and climate modeling on multiple scales. Many measurement tools are used and developed in order to advance the knowledge about the weather together with the needs of current and future society. The organization structure is given by figure 1.1.

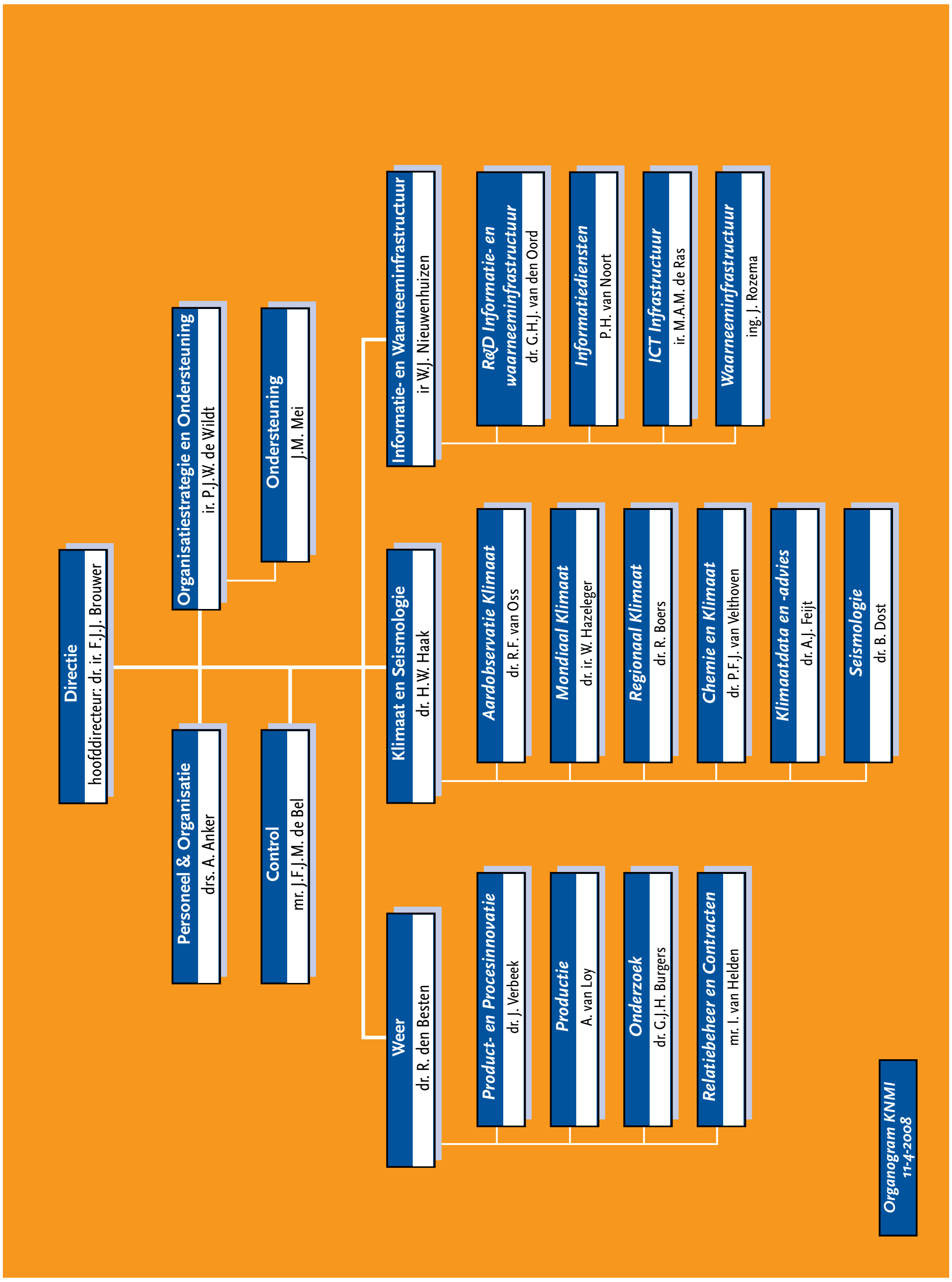


Figure 1.1: Organigram of the KNMI

1.3 Methods

This project is a data analysis of weather measurements in The Netherlands and particular De Bilt. An important assumption for the data analysis is that the last 5% of collected precipitation data sorted by the amount of precipitation can be described using a Generalized Pareto Distribution. Therefore for this internship the GPD algorithm from the Numerical Recipes [3] is translated into Ruby which is the language use for the data analysis. First the data is collected into a database to be able to create more advanced queries on the data. Almost all results are queries where the dependent variable is temperature. Data is collected in temperature bins of $3°C$ incremented by $1°C$. From these selections quantiles are taken [2] using a GPD fit on the last 5% of the sorted precipitation data. For more information on the methods used see the technical report [5].

CHAPTER 2

Analysis

To obtain a better understanding of the relation between temperature and precipitation, many variables and conditions are investigated. See for the complete set of figures the technical report [5]. In this chapter a selection is made that is found to be the most interesting.

At first the result produce by Lenderink et.al [2] is reproduced in figure 2.1. The difference between the graph shown in this report and produced by Lenderink et al. is due to different values for the temperature bin size and bounds. The qualitative result is the same. In this graph the 95, 99 and 99.9 precipitation percentiles are shown as function of the daily average temperature. This figure is created using temperature bins of $3°C$ which are incremented by $1°C$. To obtain the percentile value, a GPD fit is done on the last 5% of the precipitation data. Some dotted lines are added to be able to make a better comparison with other figures created using similar parameters. Figure 2.1 shows the increase of slope in the temperature region between $10°C$ and $15°C$ as discussed by Lenderink et al. [2]. The aim of this research is to gain a better understanding in the reason of this increase in slope and to understand why and under which conditions a slope larger than the Clausius-Clapeyron relation (a super Clausius-Clapeyron slope) can be found. It is assumed that the increase of convective precipitation events can be responsible for this increase. A central question is whether the super Clausius-Clapeyron slope is caused by an increase in the number of convective precipitation events as compared to the number of large scale precipitation events, or whether it is a property of convective events only. A major question is whether due to an increased number of convective events a transition appears towards higher levels of precipitation with the convective events obeying the Clausius-Clapeyron relation or that convective precipitation events have a mechanism that causes the increase of extreme precipitation events per degree Celsius to be bigger than 7%. It might be even as big as 14%. As visual aid to compare graphs lines with a slope of 7 and 14 percent precipitation increase per degree Celsius are added.

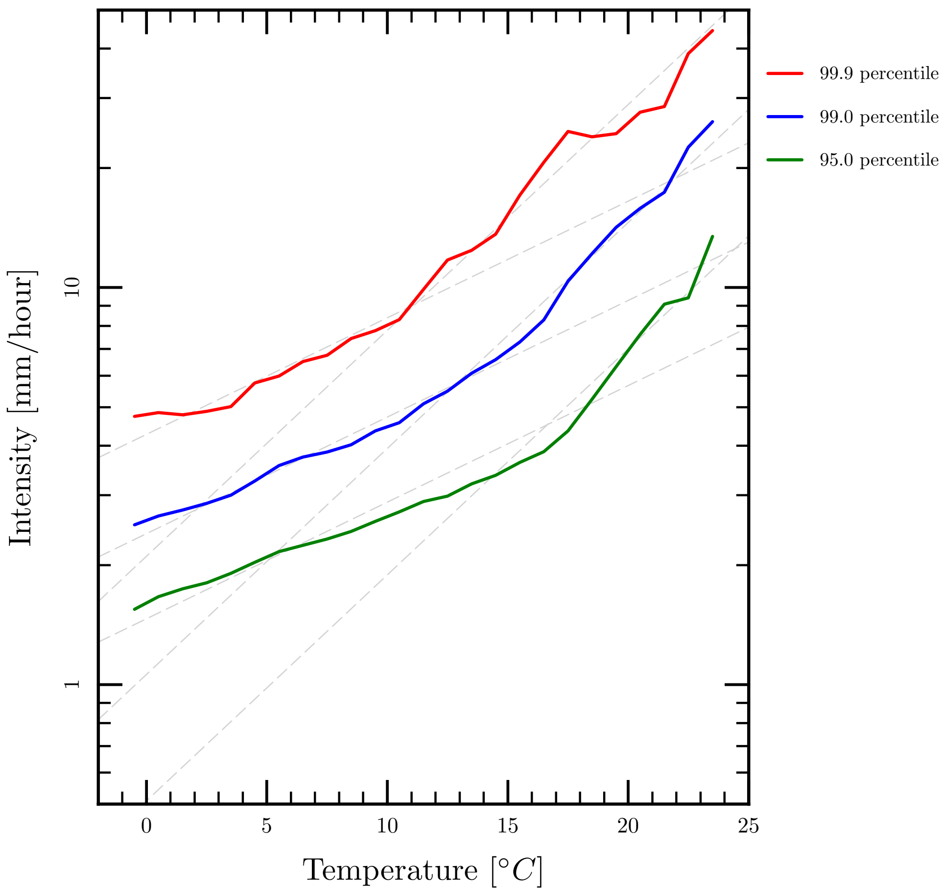


Figure 2.1: 95, 99 and 99.9 percentiles for all precipitation hours created using a gpd fit on the last 5% of the data. The fit is done on temperature bins of 3°C which are incremented by 1°C

In the attempt to separate convective and large scale events, the weather code (ww code) variable is used for analysis [1]. A weather code is a number between 0 and 100 representing the weather type. This representation might enable the separation of convective and large scale precipitation events. For this research the weather codes are separated into two groups, one group of ww ≥ 80 and one group containing the other ww codes. Since the ww codes 13, 17, 18 and 19 also indicate convective precipitation events, they are counted as above 80. In figure 2.2 the ratio of weather codes above or equal to 80 (including ww codes 13, 17,18 and 19) to all events in a bin is plotted for all hours in the temperature bin, for all precipitation hours and for the top 10% precipitation hours. From this figure it can be seen that the weather code ≥ 80 fraction is much bigger for precipitation events than for all events. This is a consequence of a large number of non precipitation hours which have a weather code < 80. The top 10% precipitation hours has a bigger ≥ 80 ratio which indicates that extreme precipitation events are more likely to be convective. Another interesting feature is the strong increase of the ≥ 80 fraction for the precipitation hours as function of temperature starting from the temperature range between 10 and $15°C$.

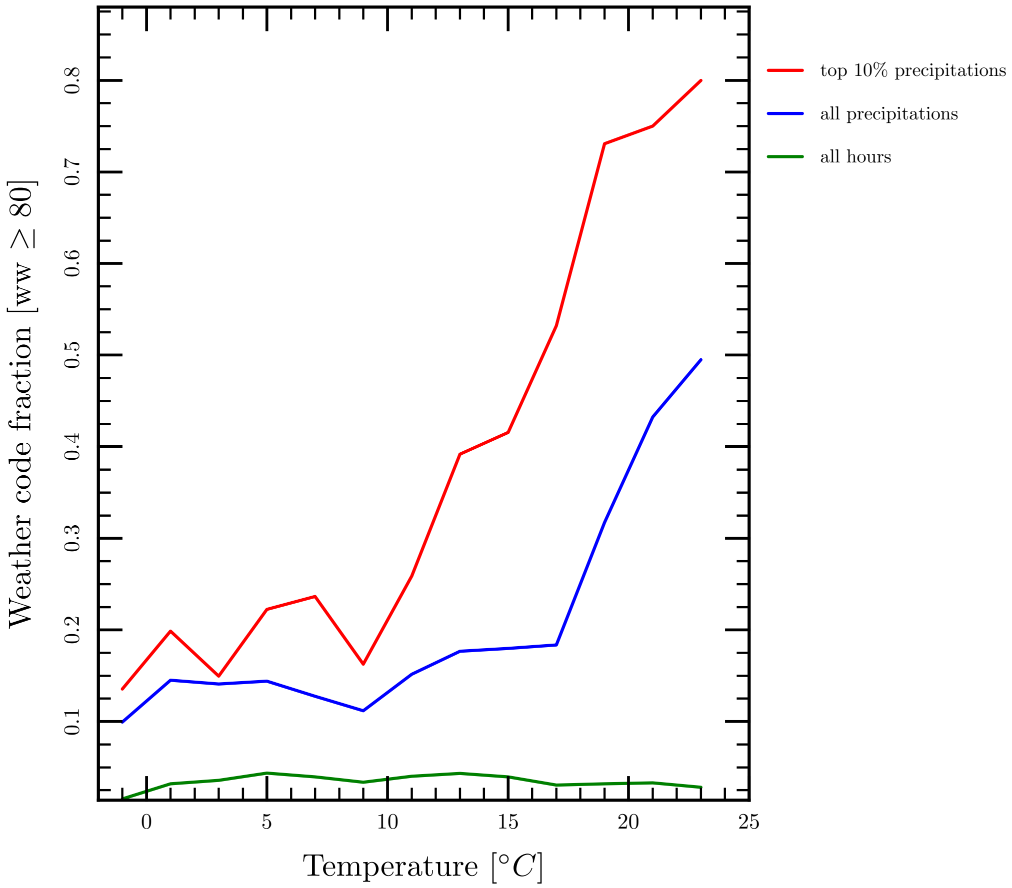


Figure 2.2: Weather code fraction ≥ 80 as function of temperature taken for temperature bins of $2°C$. The weather codes 13, 17, 18 and 19 are taken as weather codes bigger than 80

As seen from figure 2.2 the weather code is a variable that may be able to distinguish convective and large scale precipitation events. To see the influence of the weather code on the extreme precipitation events, a similar plot as figure 2.1 is created but with a selection for weather codes ≥ 80 and weather codes < 80 (Note again that weather codes 13, 17, 18 and 19 account as ≥ 80). From this figure (figure 2.3) it clearly can be seen that the slope bigger than the Clausius-Clapeyron scaling is present for weather codes ≥ 80 and not for the other case. This is a strong argument that the convective precipitation events are responsible for the increase of slope of the precipitation percentiles as function of temperature. Since weather code data is only present after 1951 the selections on these contain less data. More research should be performed to analyze the slope of figure 2.3. It might be interpreted as a linear line for the full temperature region, which would suggest a super Clausius-Clapeyron scaling for convective precipitation events.

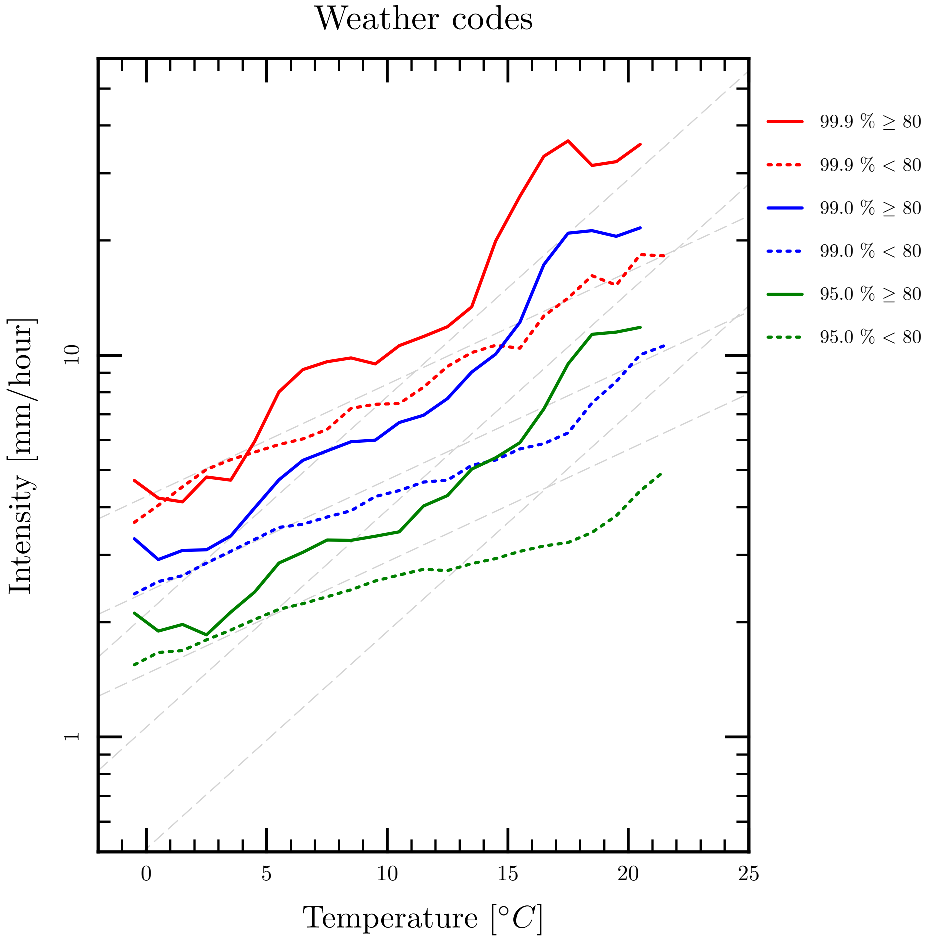


Figure 2.3: Precipitation percentiles as function of temperature. The 99.9 (red), 99.0 (blue) and 95 (green) percentiles are compared. Both for case1: weather codes 13, 17, 18, 19 and ≥ 80 (solid ≥ 80) and case2: other weather codes (dotted < 80).

Since the Netherlands is a country next to the sea, it can be expected that different wind directions might result in different precipitation mechanisms. To be able to see the effects of different wind directions, first a study is done on the fraction of precipitation events for three different directions. The result of this is shown in figure 2.4. Wind coming from the East is chosen between 30° and 150°. This direction is associated with wind coming from continental Europe. Wind from the sea (West) is selected between 230°and 310°. Wind from the South is chosen to be between 130° and 210°. This to include wind from the South and exclude wind from the sea as much as possible. It can be seen that the West wind is dominant for the temperature range between $2°C$ and $17°C$ and is rapidly decreasing for temperatures less than $5°C$ and bigger than $15°C$. This results makes it possible that the results from figure 2.3 are not purely temperature effects, but may be due to a shift in dominant precipitation wind direction which is a function of temperature as seen from figure 2.4. The wind coming from the land (East) becomes more dominant for higher temperatures. This can be a reason for the increase in slope of the precipitation percentiles as function of temperature as well. For higher temperatures the slope of precipitation percentile as function of daily average temperature decreases as seen in figure 2.5. This might indicate that the tendency towards Clausius-Clapeyron is restored. But the same figure as function of the dew point temperature T_{dew} (figure 2.6) does not show this behavior. This makes it more likely that the decrease of precipitation percentiles at higher temperature is due to dehydration effects.

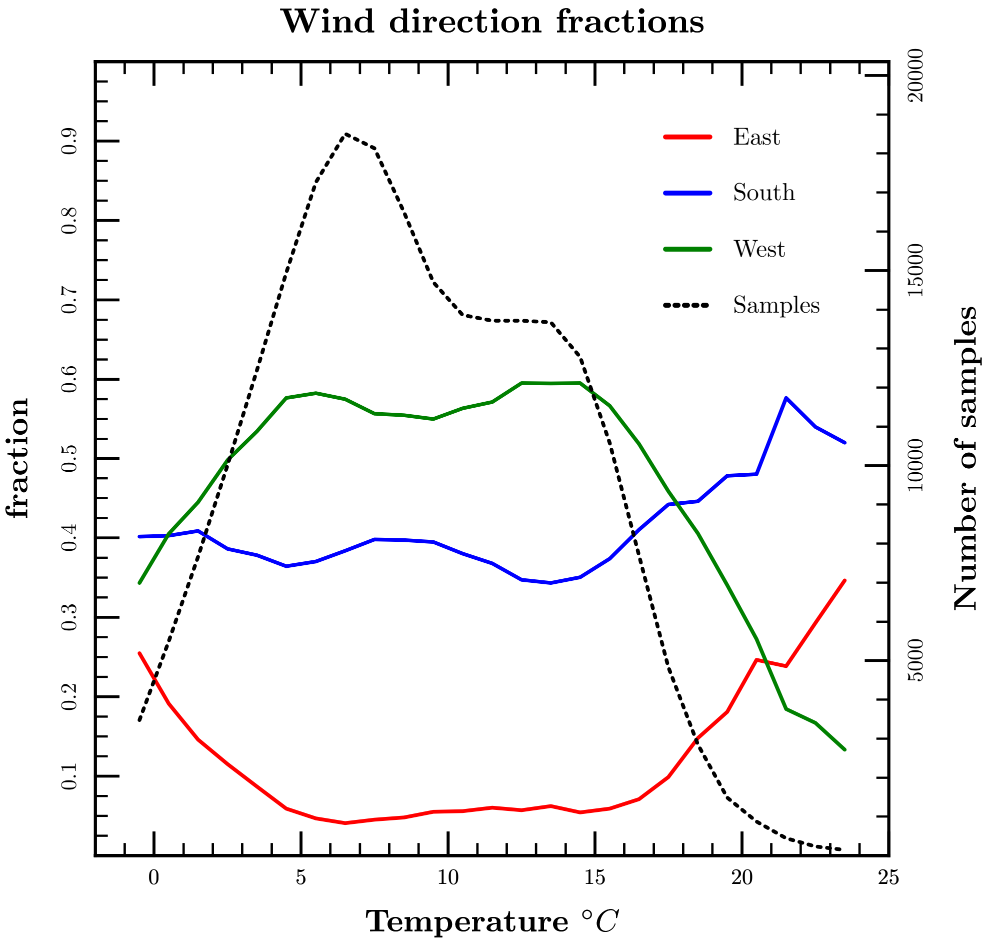


Figure 2.4: The fractions of the wind directions 30-150° (East, red), between 130-210° (South, blue) and between 230-320°(West, green) for precipitation hours. The number of available samples per temperature bin is indicated with the black dotted line (right axis).

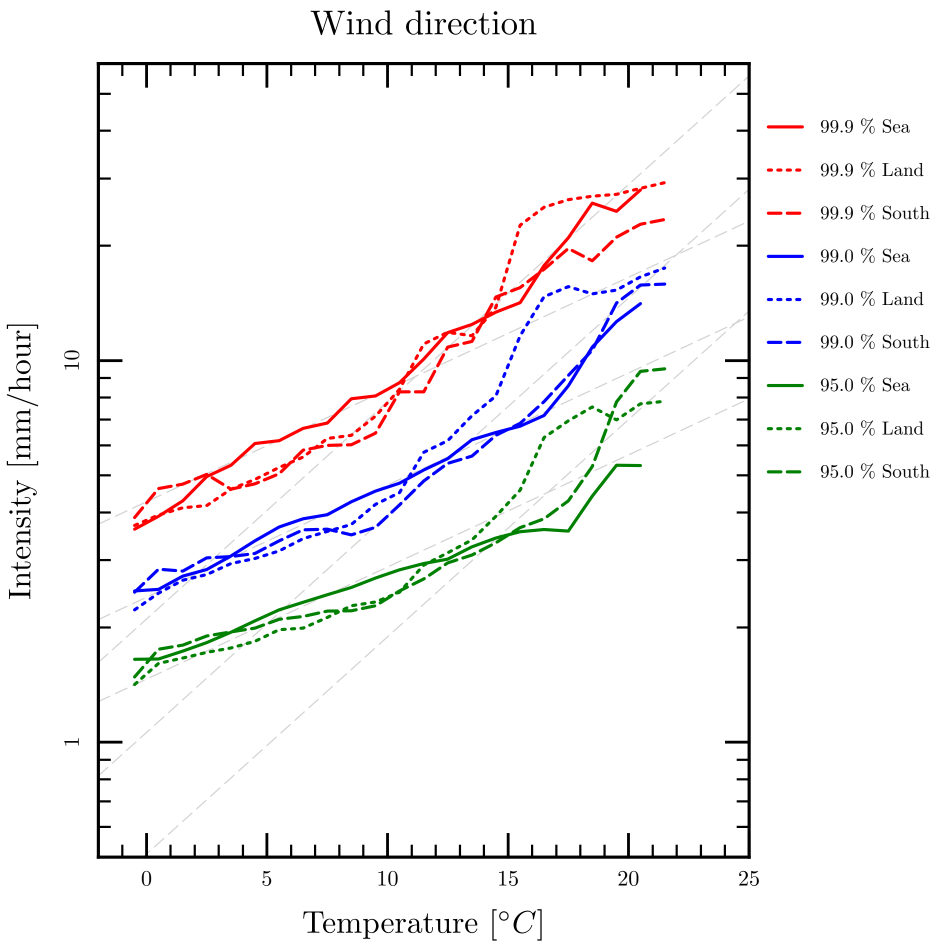


Figure 2.5: Precipitation percentiles as function of temperature. The 99.9 (red), 99.0 (blue) and 95 (green) percentiles are compared for wind directions 30-150° (East, Land, dotted), 150-200° (South, dashed) and 210-330° (West, Sea, solid).

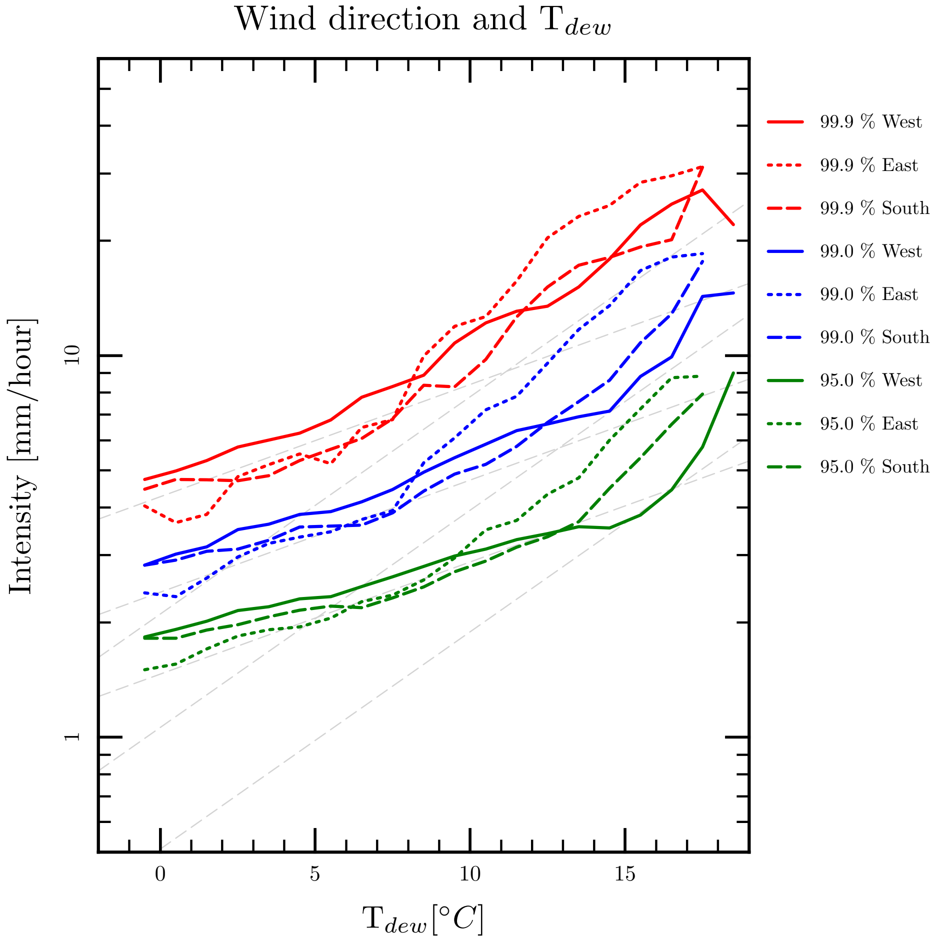


Figure 2.6: Precipitation percentiles as function of the temperature T_{dew}. The 99.9 (red), 99.0 (blue) and 95 (green) percentiles are compared for wind directions 30-150° (East, Land, dotted), 150-210° (South, dashed) and 210-330° (West, Sea, solid).

The wind speed as function of the temperature is also investigated for some precipitation cases. The result is shown in figure 2.7. This graph is created using temperature bins of $2°C$ incremented by $2°C$ every step. For every bin all hours having that temperature are selected (Green in graph). On this data two subsets are created. One containing all the precipitation hours (Blue) and one containing the 10% most heavy precipitation events (Red). These three cases are compared with each other by means of the average value (solid line) surrounded by a band indicating the 25 and the 75 percentiles of that set. These percentiles are obtained by the standard percentile method described in the technical report [5]. From this graph (figure 2.7) some interesting features appear. At first the peak of wind speeds for the temperature range between 2 and $12°C$. In this peak there is a clear difference between the three cases. The precipitation cases have higher winds speeds here indicating more extreme weather. Considering the temperature region this peak of wind speed is dominated by large scale weather situations. For higher temperatures the difference between the three cases almost disappears. There is no significant wind speed increase for precipitation events. This can be explained by the more convective character of the precipitation events which have no significant influence on the daily mean wind speed.

The scale plot for wind speeds is given in figure 2.8. In this plot the distinction is made for wind speeds equal or bigger than the temperature bin average and the hours where the wind speed is below this average. In the super Clausius-Clapeyron region the days with below average wind speeds have slightly higher precipitation extremes.

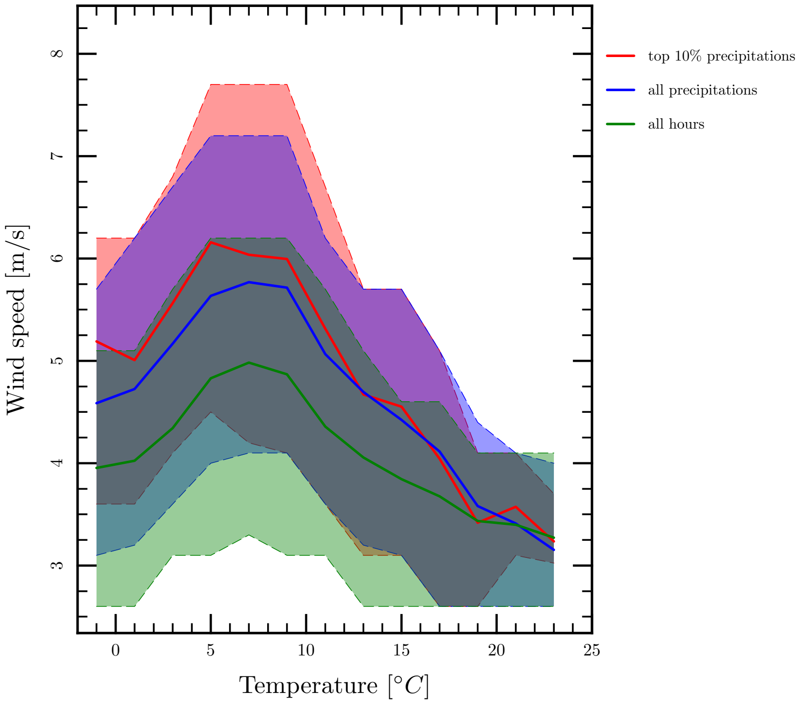


Figure 2.7: Wind speed as function of temperature. The lines are averaged values of temperature bins of $2°C$ with a band around it bounded by the 25 and 75 percentiles of the temperature bin. The results for the 10% most extreme precipitations (red), all precipitations (blue) and all hours (green) are shown

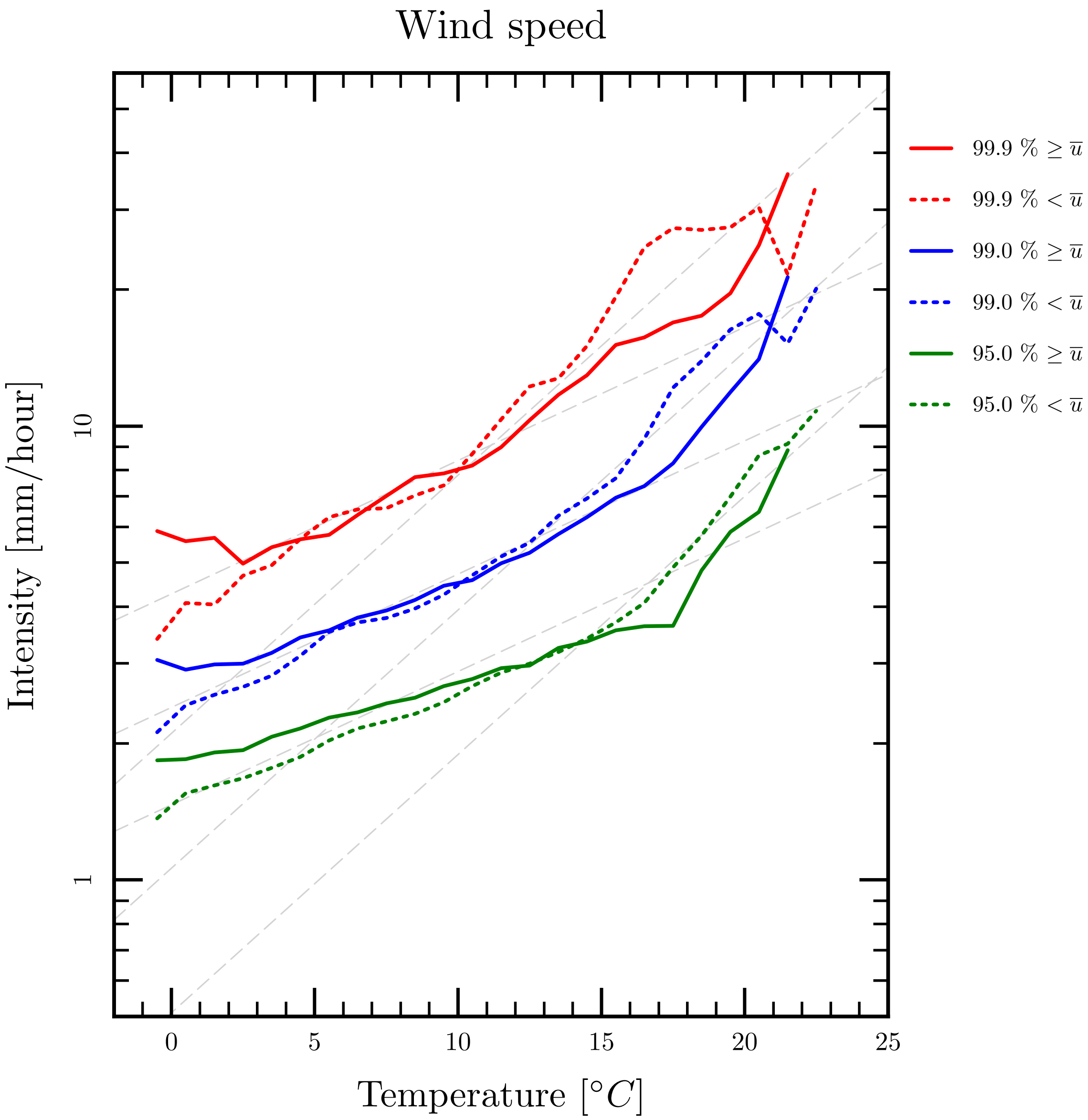


Figure 2.8: Precipitation percentiles as function of temperature. The 99.9 (red), 99.0 (blue) and 95 (green) percentiles are compared. Both for case1: wind speeds ≥ temperature bin average (solid) and case2: wind speeds below temperature bin average (dotted).

CHAPTER 3

Multiple weather stations

Until now, only measurement data from the KNMI site in De Bilt was used. Since this is one location, mostly convective precipitation events in the Netherlands may not have been measured by this measurement station. To obtain a more global insight of precipitation in the Netherlands, measurement data of multiple measurement stations is combined to compare some results for all of these stations with the results obtained from the De Bilt measurements. Data from the past 15 year is taken for 28 measurement stations. This corresponds with about 420 years of measurement data of which 27% (112 years) has a weather code specification. This is significantly more than the amount of De Bilt measurement data used (100 year for precipitation, 57 for weather code selections).

Table 3.1: Overview of all weather stations

Name	**Station id**
VALKENBURG	210
IJMUIDEN	225
DE KOOY	235
SCHIPHOL	240
HOORN (TERSCHELLING)	251
DE BILT	260
STAVOREN	267
LELYSTAD	269
LEEUWARDEN	270
MARKNESSE	273
DEELEN	275
LAUWERSOOG	277
HEINO	278
HOOGEVEEN	279
EELDE	280
HUPSEL	283
NIEUW BEERTA	286
TWENTHE	290
VLISSINGEN	310
WESTDORPE	319
WILHELMINADORP	323
ROTTERDAM	344
CABAUW	348
GILZE-RIJEN	350
EINDHOVEN	370
VOLKEL	375
MAASTRICHT	380
ARCEN	391

3.1 Scale plots

To be able to say something about how specific the De Bilt measurements are, some graphs from the previous chapter are reproduced using data from the weather stations listed in table 3.1. In this case not the previous 100 years but the previous 15 years is taken into account. These stations are also selected on completeness of data in this period. The plots for all precipitation events and the distinction between weather codes are reproduced using multiple measurement station data. The result of all precipitation events is shown in figure 3.1. Figure 3.1 shows a similar trend as figure 2.1. This indicates that it is not likely that the increased slope between 10 and 15° is due to the fact that the data is from one location. The temperature axis represents the daily average calculated using temperature

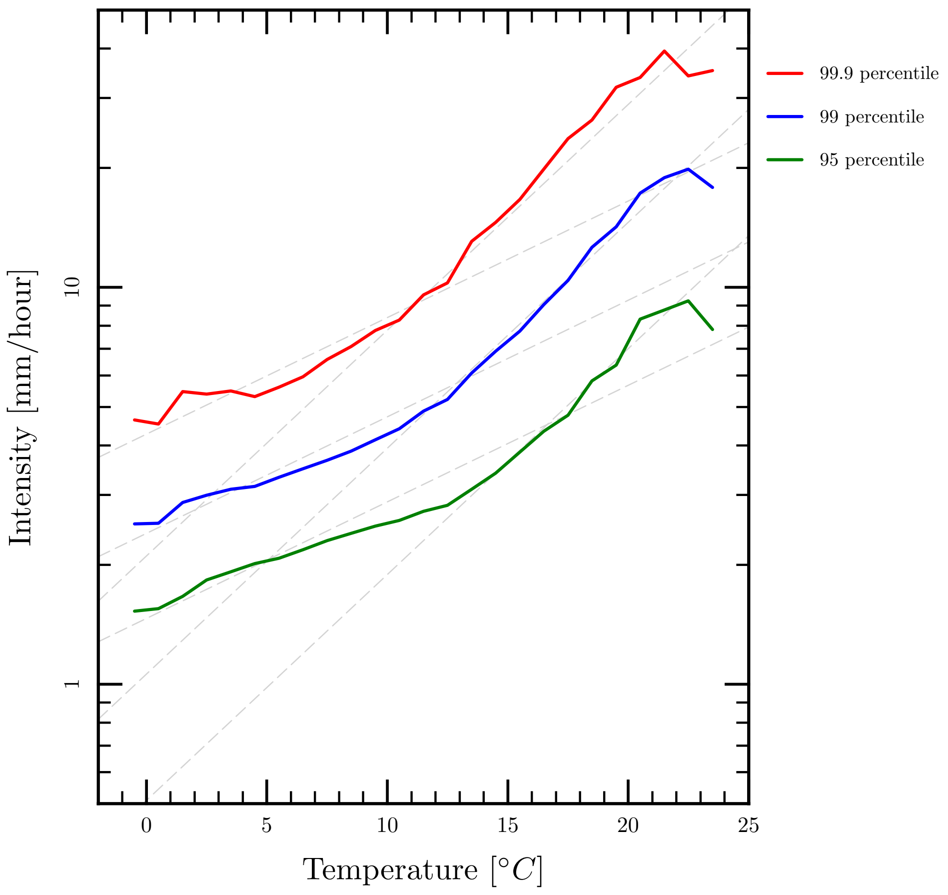


Figure 3.1: 95, 99 and 99.9 percentiles for all precipitation hours of the stations listed in table 3.1 created using a gpd fit on the last 5% of the data. The fit is done on temperature bins of 3°C which are incremented by 1°C

data from all measurement stations. The case for convective precipitation events weather codes is shown in figure 3.2. For non convective weather codes the result is shown in figure 3.3. Comparing these plots with figure 2.3 no substantial differences can be found. This indicates that measurement data from one station can be used for analysis given that there is enough data. The region above $20°C$ still does not give a clear indication of what mechanism is responsible for the drop in the slope. It can be a result of lesser data in that temperature region but can indicate a recovery of the Clausius-Clapeyron relation as well. It can also be the case that this temperature range is dominated by atmospheric conditions (high pressure and relatively low atmospheric moisture amounts) which suppress the most extreme precipitation events.

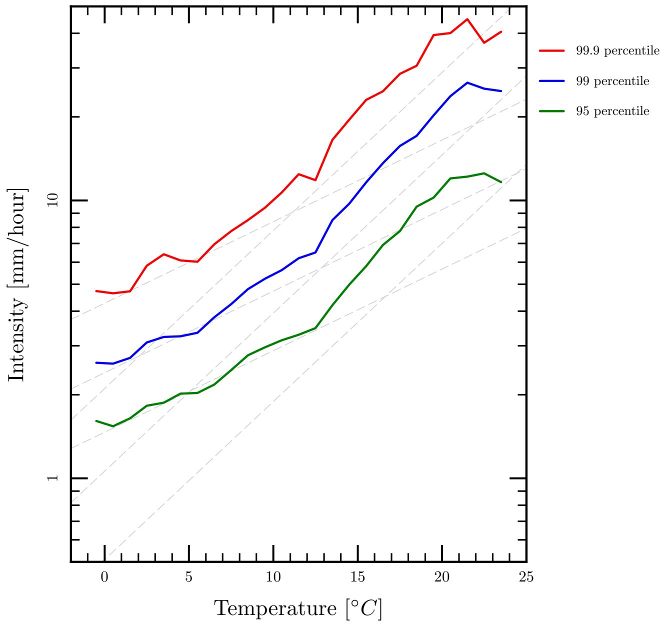


Figure 3.2: 95, 99 and 99.9 percentiles for all precipitation hours with weather codes ≥ 80 and $13, 17, 18, 19$ of the stations listed in table 3.1 created using a gpd fit on the last 5% of the data. The fit is done on temperature bins of $3°C$ which are incremented by $1°C$

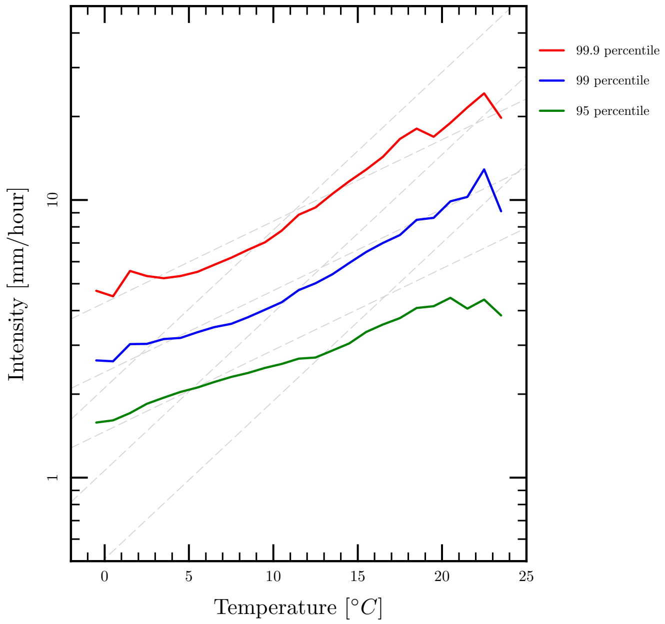


Figure 3.3: 95, 99 and 99.9 percentiles for all precipitation hours with weather codes not equal to ≥ 80 or $13, 17, 18, 19$ of the stations listed in table 3.1 created using a gpd fit on the last 5% of the data. The fit is done on temperature bins of $3°C$ which are incremented by $1°C$

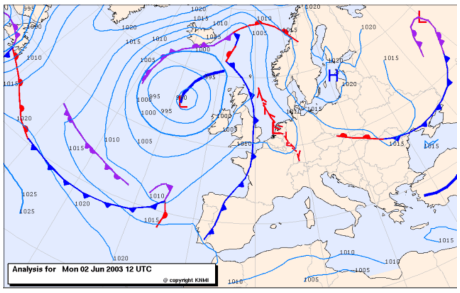
CHAPTER 4

Extreme events

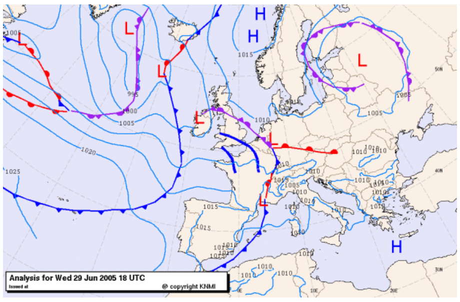
The most extreme precipitation events will determine many boundaries and limitations for water systems in the Netherlands. In order to get a better understanding of these events the most extreme precipitation events in the past are listed together with some meteorological parameters. The result of this for the De Bilt measurement data is listed in table 4.1. This is also done for data of multiple measurement stations (table 3.1). The result of the maximal precipitation events of multiple station is given in table 4.2. Here three temperatures are given. The hourly temperature, the station day average temperature and the daily average temperature based on data from all the stations. To get a better national view of the meteorological situation for events after 2003, the weather maps for these events are listed in figure 4.1. There is not one typical weather situation, which is a confirmation of the unpredictable nature of weather outliers. Most of the extreme events are in the afternoon or evening which is an indication of the convective contribution to these extreme precipitation events. This is confirmed by the weather codes which are mostly convective for these events. The wind speed is an important parameter since this indicates the nature of the rain. Slow wind speeds might indicate a local event that stays on one place.

Table 4.1: The 20 most extreme precipitation events of the last 100 years from De Bilt measurement data sorted by precipitation. The amount of precipitation is in mm, the wind speed is in m/s and the temperature is in $°C$. WW is the weather code.

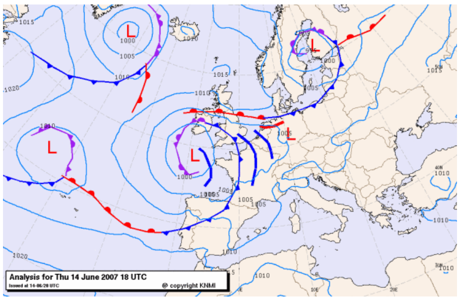
date	**precipitation**	**temperature**	**wind_direction**	**wind speed**	**sunshine_fraction**	**WW**	T_{dew}
1953-06-13 20:00:00	44.1	16.0	171.0	3.1	0.11	91.0	13.3
1997-08-24 23:00:00	34.3	23.8	197.0	2.3	0.59	95.0	20.54
1961-06-06 21:00:00	31.7	19.5	255.0	2.6	0.71	95.0	16.53
1994-07-31 20:00:00	30.7	24.3	198.0	3.1	0.58	97.0	18.7
2005-07-30 00:00:00	29.6	17.5	234.0	3.5	0.48	63.0	16.6
1995-05-25 18:00:00	28.4	16.1	336.0	2.1	0.13	92.0	13.21
1909-08-09 20:00:00	28.2	21.4	24.0	3.6	0.67	-999.0	18.0
1979-05-30 21:00:00	27.0	19.7	93.0	2.6	0.38	97.0	16.34
1952-07-03 19:00:00	26.9	16.8	7.0	7.2	0.0	95.0	15.49
1917-06-18 18:00:00	26.5	22.8	218.0	4.1	0.47	-999.0	15.63
1974-06-17 16:00:00	24.4	17.7	230.0	2.1	0.37	92.0	14.4
1910-06-07 21:00:00	23.4	22.3	82.0	4.1	0.54	-999.0	16.56
1945-05-20 19:00:00	23.2	16.7	105.0	4.6	0.57	-999.0	12.24
1930-06-27 15:00:00	22.9	16.1	299.0	3.1	0.05	-999.0	15.13
1998-06-06 16:00:00	22.8	17.9	142.0	2.5	0.18	91.0	16.58
1992-07-03 22:00:00	22.8	18.3	79.0	2.1	0.19	92.0	13.16
2000-07-29 15:00:00	22.5	15.9	238.0	2.0	0.13	91.0	14.77
1966-07-19 18:00:00	22.4	17.4	27.0	3.1	0.07	95.0	16.25
1973-05-21 16:00:00	21.9	15.3	185.0	2.1	0.4	95.0	12.24
2002-08-07 10:00:00	21.7	18.1	298.0	1.3	0.25	83.0	16.61



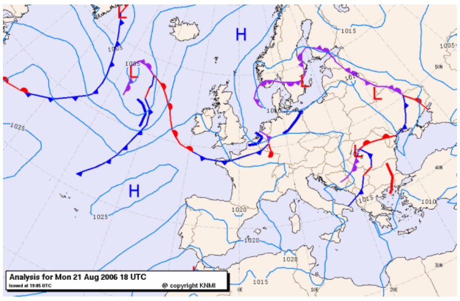
(a) 2003-06-02 12am 72.8mm



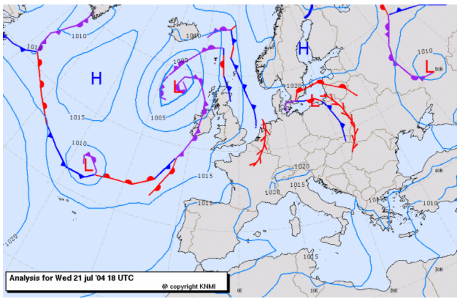
(b) 2005-06-29 18pm 64.4mm



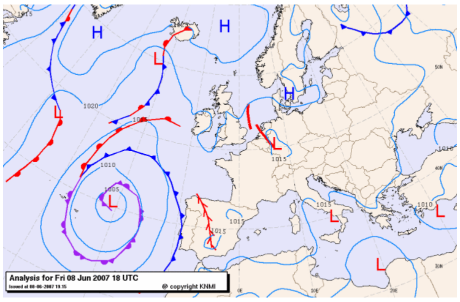
(c) 2007-06-14 18pm 49.5mm



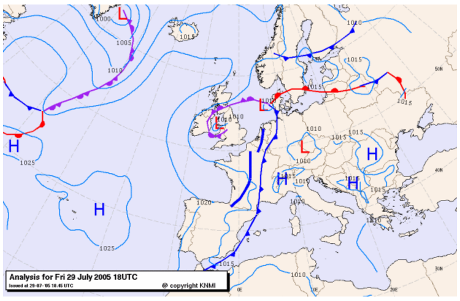
(d) 2006-08-21 18pm 42.2mm



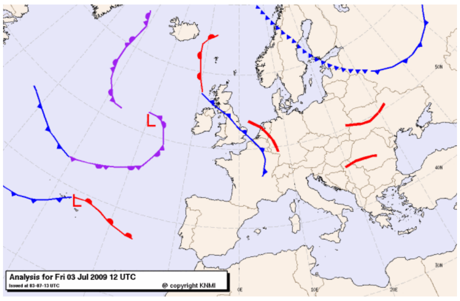
(e) 2004-07-21 18pm 41.9mm



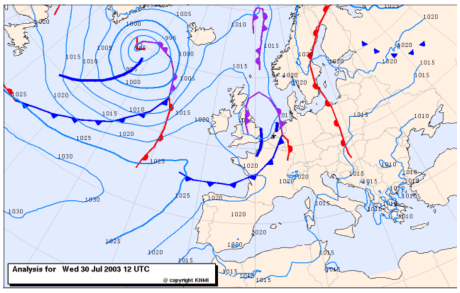
(f) 2007-06-08 18pm 38.7mm



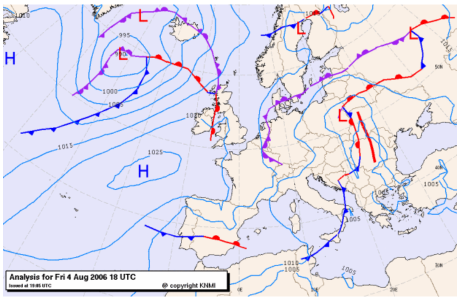
(g) 2005-07-29 18pm 38.0mm



(h) 2009-07-03 12pm 37.2mm



(i) 2003-07-30 12pm 36.8mm



(j) 2006-08-04 18pm 36.1mm

Figure 4.1: Weather maps for the most extreme precipitation events after 2003

Table 4.2: List of most extreme precipitation events of the past 15 year in the Netherlands. For temperature and T_{dew}, subscript 1 is the hour value, subscript 2 is the average temperature value measured by the specific weather station and subscript 3 indicates the average temperature of that day calculated using measurements of all weather stations. Temperature values are in degrees Celsius, precipitation in *mm*. The wind speed is in m/s.

Date	**Station**	**Precipitation**	T_1	T_2	T_2	$T_{dew,1}$	$T_{dew,2}$	$T_{dew,3}$	W_{angle}	W_{speed}	**WW**
2003-06-02 14:00:00 UTC	MARKNESSE	72.8	15.6	20.3	20.0	15.5	16.3	16.1	260.0	6.0	-999
2002-08-05 13:00:00 UTC	WESTDORPE	68.5	14.5	15.8	16.9	13.7	14.9	15.3	220.0	4.0	-999
2005-06-29 21:00:00 UTC	CABAUW	64.4	15.6	19.4	18.4	15.0	15.5	14.2	240.0	5.0	-999
1996-06-08 13:00:00 UTC	VOLKEL	53.7	18.5	22.1	20.8	18.0	18.0	16.9	270.0	9.3	95
2007-06-14 16:00:00 UTC	HOOGEVEEN	49.5	15.6	17.1	18.3	15.5	15.2	15.8	60.0	10.0	92
1997-06-29 18:00:00 UTC	LEEUWARDEN	47.7	15.0	16.5	15.7	15.0	14.1	13.9	40.0	12.0	95
2006-08-21 16:00:00 UTC	CABAUW	42.2	14.1	16.3	16.6	13.4	14.5	14.2	290.0	4.0	-999
2004-07-21 17:00:00 UTC	VOLKEL	41.9	18.2	18.3	18.3	17.7	16.7	16.0	990.0	3.0	-999
1998-08-23 21:00:00 UTC	STAVOREN	38.8	14.0	15.4	14.5	14.0	11.8	11.8	90.0	5.0	-999
2007-06-08 16:00:00 UTC	CABAUW	38.7	19.9	21.8	21.9	19.8	18.8	17.6	240.0	7.0	-999
2005-07-29 22:00:00 UTC	ARCEN	38.0	16.9	22.1	20.9	16.3	18.5	18.0	990.0	3.0	-999
2009-07-03 14:00:00 UTC	ARCEN	37.2	18.3	22.3	21.5	18.0	18.3	17.1	340.0	5.0	-999
2003-07-30 15:00:00 UTC	MARKNESSE	36.8	17.4	18.4	18.8	17.0	15.7	15.8	140.0	4.0	-999
2002-07-30 18:00:00 UTC	HOEK VAN HOLLAND	36.6	20.2	21.8	23.6	19.0	19.1	18.5	80.0	7.0	97
1994-07-07 05:00:00 UTC	LAUWERSOOG	36.5	15.6	15.9	15.0	15.1	13.3	12.4	230.0	6.7	-999
1995-07-09 03:00:00 UTC	HOORN (TERSCHELLING)	36.4	14.6	16.4	21.9	13.8	14.8	18.4	50.0	8.2	-999
2006-08-04 16:00:00 UTC	HUPSEL	36.1	16.5	16.9	18.2	16.2	15.0	15.8	360.0	3.0	-999
2008-06-02 22:00:00 UTC	DEELEN	35.3	17.9	23.1	20.6	17.8	16.6	16.3	10.0	4.0	92
1997-07-22 22:00:00 UTC	NIEUW BEERTA	35.0	16.5	20.0	18.4	16.4	16.9	16.5	0.0	4.0	-999
2000-07-02 19:00:00 UTC	ELL	34.3	17.8	20.1	18.1	17.0	16.4	14.9	350.0	3.0	-999

CHAPTER 5

Conclusions and recommendations

This internship was a good learning experience. Both in learning about the way a company functions and scientifically. The fact that the KNMI is a government institute is also a factor determining the company culture. Because during the period of the internship some employment changes were made contributed to the insight in how the company functions. It seems to be a governmental top down organized institute where research is performed on project basis (AK, MK, RK). There are more departments at the KNMI then experienced in this internship, so this classification might not be valid for these.

From this internship some important conclusions can be made. No exclusive insights are found, but important ones for future research. The already available research is reproduced [2] and some meteorological parameters are studied. The two most important ones selected for this report are the weather codes and the wind direction. Selecting data based on weather code proved to be able to separate the super Clausius-Clapeyron relation from the expected precipitation increase with temperature. Since the selection based on weather code is done in such a way that convective precipitation events are separated from large scale precipitation events, this is a strong argument that convective systems are responsible for the super Clausius-Clapeyron findings. For temperatures bigger than $20°C$ no exclusive result is found. Since this region might be crucial for determining the real mechanism of the relation between precipitation and temperature, it should be studied in more detail. One of the reasons that no hard conclusions can be made in this region is the fact that there is little data available in this region. The Dutch climate is the limiting factor for this. Studies of Mediterranean or even tropical data can solve this, but goes beyond the scope of this internship project. The rapid decrease of the number of West wind ‘days‘ above $18°C$ can be important as well. For higher temperatures more wind is coming from the sea than from continental Europe. The different nature of these winds can also be responsible for the different precipitation temperature relations. The fact that when when the dew point temperature is taken in stead of the daily average temperature and the drop in precipitation increase is not found for all wind directions might indicate dehydration effects as well for this region.

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