

Effects of Climate Change on Weather-Induced Loads on Buildings

Implications for Characteristic Values of Precipitation,
Snow, and Wind Loads in the Netherlands

Master Thesis
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Precipitation, Snow, and Wind Loads in the
Netherlands

by

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Preface

You are about to read the thesis *Effects of Climate Change on Weather-Induced Loads on Buildings – Implications for Characteristic Values of Precipitation, Snow, and Wind Loads in the Netherlands*. This thesis marks the completion of my Master's programme of Civil Engineering at the Delft University of Technology.

I chose this topic because I have always been interested by extreme weather events and the influence of climate change on them. Together with my education and passion for structural engineering, it was a perfect opportunity to combine both interests. In this thesis, I investigate how climate change may affect weather-induced loads from precipitation, snow, and wind on buildings in the Netherlands. Central to this research are the KNMI'23 Climate Scenarios for the future climate projections.

I would like to thank my graduation committee: Ir. Sander Pasterkamp, Dr. Elisa Ragno, and Dr.ir. Paul Korswagen Eguren for their guidance, feedback, and support throughout this project. Their different areas of expertise helped me to approach this research from both a structural engineering perspective and a climate science perspective. Special thanks go to my daily supervisor Sander Pasterkamp, who helped to shape this project from the beginning. His experience as a building engineer and his constructive feedback were of great value during the project. I would also like to thank Elisa Ragno for her advice on extreme value analysis and climate models, which greatly improved this research. Finally, I would like to thank Paul Korswagen Eguren for identifying the limitations of my work and for providing extensive feedback during the progress meetings.

Furthermore, I would like to thank the KNMI for providing additional information that was not publicly available. This greatly helped me to identify inhomogeneities in the historical observations. I also appreciated their explanations regarding historical short-duration precipitation measurements and trends.

Finally, I would like to thank my parents and brother for their continuous moral support throughout my studies. Furthermore, many of my close friends have recently completed their theses. I am grateful to them for sharing their experiences, advice, and encouragement during my own journey.

Enjoy reading this thesis.

Tim Verhulst
Delft, July 2026

Summary

Structural design in the Netherlands is based on characteristic weather-induced load values prescribed in the Dutch National Annexes of the Eurocode. These values are derived from historical meteorological observations and generally correspond to a return period of 50 years. As climate change is expected to affect the frequency and intensity of extreme weather events, the current design values may not longer be representative in future climatic conditions.

This research investigated how climate change may affect characteristic values for precipitation, snow, and wind loads on structures in the Netherlands and assessed the implications for structural design. Historical observations from KNMI weather stations were analysed and compared with the current characteristic values prescribed in the Dutch National Annexes. Future changes were assessed using the KNMI'23 Climate Scenarios.

For precipitation, recent Dutch depth–duration–frequency studies indicate that the current 50-year return level for 5-minute precipitation is already approximately 20 % higher than the value prescribed in the Dutch National Annex. The climate projections indicate a further increase in extreme precipitation, resulting in an estimated factor of change of approximately 1.06 for a 50-year return level under 1.1 °C global warming relative to the 1991–2020 reference period. Combined, these findings imply that emergency drainage widths may need to increase by approximately 27 % compared with current practice.

Historical snow depth observations showed decreasing trends in annual maximum snow depth, while estimated 50-year return levels were generally lower than the current characteristic ground snow load. Although quantitative snow projections are unavailable, multiple climate indicators consistently suggest that conditions favourable for snowfall and persistent snow cover will become less frequent under future climate change.

For wind, estimated 50-year return levels of the 10-minute mean wind velocity were generally comparable to or lower than the values prescribed in the Dutch National Annex. Furthermore, the KNMI'23 Climate Scenarios project only minor changes in extreme wind velocities relative to the associated model uncertainty, indicating no clear need to revise the current characteristic wind loads.

Overall, the results indicate that climate change is expected to have the largest impact on precipitation-related loads. Snow loads are likely to decrease, while characteristic wind loads are expected to remain relatively unchanged. Consequently, future revisions of the Dutch National Annex are most likely to require adaptations of the prescribed precipitation intensities, whereas the current evidence does not indicate a comparable need for snow or wind loads.

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Part I

General

Introduction

This chapter introduces the subject of the research. It starts by defining the contextual background, followed by a description of the research problem. The research objectives and scope are then defined, after which the research questions are presented. The chapter concludes with the research method and an outline of the thesis structure.

1.1. Research context

Structures such as buildings, bridges, and towers must be designed to withstand various types of loads throughout their design life. In Eurocode 0: NEN-EN 1990 (NEN, 2019b), these loads are categorised into three groups: permanent loads, variable loads, and accidental loads. Permanent loads are present throughout the entire design life of a structure and exhibit negligible variation in magnitude. Typical examples include the self-weight of structural components and fixed installations. In contrast, variable loads vary in magnitude over time and cannot be neglected. These actions often arise from the environment or human activity, such as imposed loads, wind, or snow. Accidental loads are defined by their short duration but significant intensity. Although their occurrence is rare, their potential impact on structural integrity is substantial. Examples of accidental loads include explosions or impacts.

As specific weather phenomena differ for each country, the weather induced variable loads also differ between countries. Therefore, their characteristic values are defined in the National Annexes of the Eurocode. Their magnitudes are based on historical observations.

Extreme weather events sometimes contribute to the partial or complete collapse of buildings in the Netherlands. For example, in 2018, when a combination of high temperatures and atmospheric instability resulted locally in intense precipitation events of 40 mm to 70 mm. Since it was accompanied by strong wind gusts, it resulted in near-horizontal rainfall. This contributed to the collapse of the roof of an industrial building (NOS, 2018). During another period of heavy rainfall in the summer of 2025, the roof of an industrial building also collapsed. Strong winds have likewise caused structural damage, including failures of façades (NOS, 2024) and the partial collapse of the roof of a football stadium in 2022 (NOS, 2022). Snow loads have also led to structural failures. A recent example occurred in January 2026, when the roof of a sports facility partially collapsed after heavy snowfall (NOS, 2026).

Structural failures associated with extreme weather are not limited to recent decades. During the winter of 2005, several roofs collapsed under heavy snow loads (Kool & Schmidt, 2006). Longer ago, the severe storm of 1674 damaged numerous buildings throughout the Netherlands, also resulting in the partial collapse of the Dom Church in Utrecht (KNMI, n.d.-aa).

Human-induced climate change influences the frequency and intensity of several types of extreme weather events. These changes have already been observed and are projected to continue in the future (Arias et al., 2021). As weather-induced loads on structures are directly related to these extreme events, changes in their intensity and frequency may affect the characteristic values currently prescribed in the Dutch National Annexes. Consequently, characteristic values derived from historical observations may

no longer satisfy the intended level of structural reliability throughout the design life of future structures.

1.2. Research problem

Climate change and its effects have been studied within the field of climatology, including changes in global temperature, sea level rise, and the intensity and frequency of certain weather events. In the Netherlands, the Royal Netherlands Meteorological Institute (KNMI) has published several climate scenarios describing possible future effects of climate change on weather phenomena.

However, the implications of these climate scenarios for structural design, and in particular for the characteristic values of weather induced loads, have not yet been systematically assessed for the Netherlands (Özer et al., 2022).

1.3. Research objectives and scope

The objective of this research is to assess the effects of climate change on the characteristic values of precipitation, snow, and wind loads on buildings in the Netherlands. This is achieved by analysing both historical observations and projected changes under KNMI'23 climate scenarios.

The research considers only the effects of climate change on structural loads in the Netherlands. The analysis is limited to weather induced loads from precipitation, snow, and wind. Other climate induced loads such as thermal loads are not included.

1.4. Research questions

Based on the research context, problem, objectives, and scope, the research questions are set up.

The main research question is:

How do climate change scenarios affect characteristic values for precipitation, snow and wind loads on buildings in the Netherlands, and what are their implications for structural design?

Several subquestions should answer this research question:

- To what extent do current characteristic values for precipitation, snow, and wind loads in the Dutch National Annex reflect recent observations and trends?
- How are precipitation, snow, and wind loads expected to change under different climate scenarios in the Netherlands?
- What changes in characteristic values for precipitation, snow, and wind loads can be derived from climate change scenarios, and how do these compare to current values in the Dutch National Annex.

The second and third subquestion seem to be similar. However, the third subquestion combines the findings of subquestion one and three.

1.5. Research method

This research combines a literature review, statistical analysis of historical meteorological observations, and analysis of climate model projections to assess the implications of climate change for characteristic weather-induced loads on structures in the Netherlands.

To answer the first subquestion, the current characteristic values prescribed in the Dutch National Annexes of Eurocode 1 are analysed together with the methodology for precipitation, snow, and wind loads in structural design. Recent Dutch studies on weather extremes should then be analysed together with historical observations from the KNMI. Weather stations need to be selected to capture the main spatial differences in weather extremes across the Netherlands. The homogeneity of the measurements should be examined by evaluating changes in instrumentation and station location. Finally, trend analyses and extreme value analyses need to be performed to estimate characteristic values, which can be compared with those prescribed in the Dutch National Annexes.

The second subquestion addresses the projected effects of climate change on precipitation, snow, and wind extremes. First, climate change background and the development of climate scenarios should

be examined. Then the underlying methodology of the KNMI'23 climate scenarios should be reviewed. Subsequently, the available climate model output can be analysed using extreme value analysis to quantify the projected changes in 50-year return levels for different time horizons and global warming levels. When projections of specific weather events and/or the temporal resolution are unavailable, assumptions should be made to translate the available model output to the weather variables of interest for structural design.

The third subquestion combines the findings of the historical analyses and the climate projections to assess the implications for the characteristic values prescribed in the Dutch National Annexes.

1.6. Thesis structure

This research covers three main weather related loads: precipitation, snow, and wind. This report is therefore divided into five parts. The first part consists of a general literature study which covers the KNMI'23 climate projections. The second part covers precipitation, the third snow, and the fourth covers wind, finally the fifth covers a general discussion, conclusion, and recommendations section.

For each of these parts, an individual literature study is conducted and in each part the methodology of the analysis is discussed. Each part also covers its own discussion, conclusion, and recommendations.

2

Literature study

This chapter reviews the literature that forms the basis for the analyses presented in this thesis. First, the physical background of climate change and climate scenarios are discussed. Subsequently, the Dutch meteorological observation network is described, which provides for the selection of weather stations used in the historical analyses. The development and methodology of the KNMI'23 climate scenarios are then reviewed, as these scenarios are the basis of the climate projections considered in this research. Followed by recent studies to climate change. Subsequently, some terminology in Eurocode 0 is presented. Finally, statistical concepts and methodologies required for the trend analyses and extreme value analyses are introduced.

2.1. Climate change

This section introduces the physical background of climate change and the natural variability of Earth's climate. It subsequently discusses the development of global climate scenarios, recent research on the Atlantic Meridional Overturning Circulation (AMOC), and the development of CMIP7 as the successor to CMIP6.

2.1.1. History of Earth's climate

The Earth is estimated to be approximately 4.54 billion years old (U.S. Geological Survey, 1997). The climate has undergone substantial changes during all these years. In its early history, the Earth's surface temperature reached around 2000°C and had decreased to temperatures above 200°C after several tens of millions of years. Between 2.5 and 4 billion years ago, the global temperatures on earth are estimated to have ranged between 0°C (resulting in occasional glaciations in some regions) (Catling & Zahnle, 2020) and 85°C (Choi, 2017). Periods of glaciation interspersed with non-glacial periods between 2.4 and 2.1 billion years ago and were potentially driven by changes in microscopic life. Later, between roughly 750 to 600 million years ago, global temperatures again declined, leading to at least two glaciations (Scott, 2021). In contrast, the Jurassic period (between 200 to 146 million years ago) marked a period with significantly higher temperatures and much larger CO_2 concentrations compared to those of the present day, with global temperatures between 5°C to 10°C higher than today. (Sellwood & Valdes, 2008). Finally, more recently, the Last Glacial Cycle occurred between 115 to 11.7 thousand years ago (Wilmes et al., 2023).

These examples show that Earth's climate has always been dynamic, with fluctuations occurring over tens of thousands to millions or even billions of years. In Figure 2.1 these fluctuations over the last 60 million years are visible.

The current temperatures on Earth are comparable to those observed millions of years ago. However, focussing on the past few centuries shows a gradual rise in both global temperature and atmospheric CO_2 concentration. Callendar (1938) was among the first to show that this temperature increase resulted from CO_2 emissions produced by fuel combustion. Later, Plass (1956) concluded that increasing CO_2 concentrations as a result of human influence, would raise the global mean temperatures by ap-

proximately 1.1°C per century. Subsequently, Sawyer (1972) predicted that an expected increase of 25 % in CO_2 concentrations would lead to a global temperature raise of 0.6°C by the end of the 20th century. The author also highlighted that since the end of the last Ice Age, global temperatures had only slightly changed. Furthermore, the total energy emitted by industries was negligible compared to the total kinetic energy of the atmosphere. Thus, the author concluded that there was no immediate cause for concern, but recommended further study.

In 1988, the oil and gas multinational Shell conducted confidential internal research on greenhouse effects (Shell Environmental Conservation Committee, 1988). The report acknowledged that the CO_2 concentration had already risen by 15 % over the previous century and projected that a doubling of pre-industrial levels could occur by the third quarter of the 21st century. This was projected to lead to an increase in global temperatures of 1.3°C to 3.3°C . In addition, fossil fuel combustion was found to be the main driver of rising CO_2 concentrations. Warning was given that global warming as a likely consequence of increasing greenhouse gas levels, would have major environmental, social, and economic consequences.

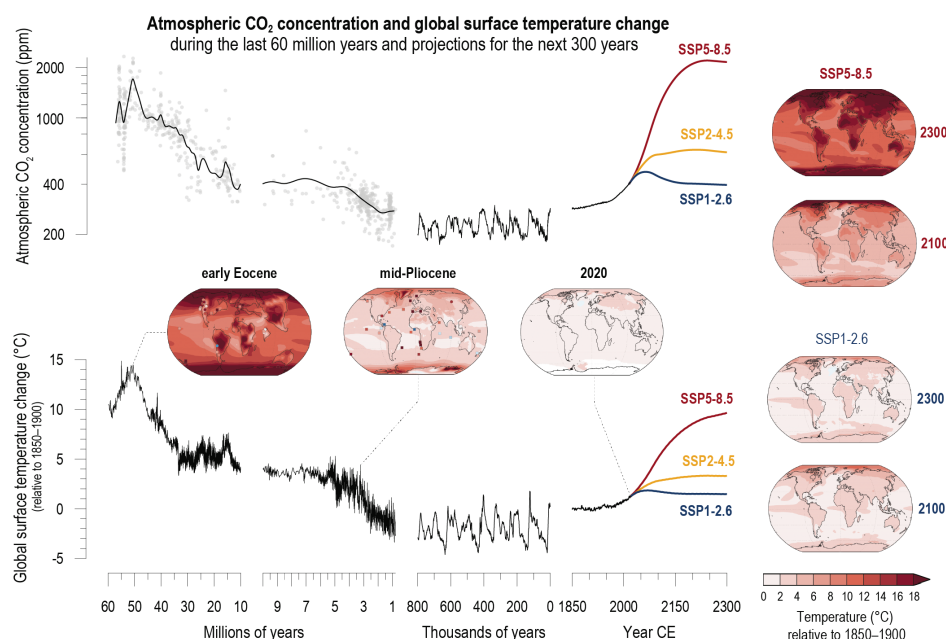


Figure 2.1: Historic changes in atmospheric CO_2 and global surface temperature, including projections for the next 300 years. From *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Technical Summary, Figure TS.1, p. 44), by Intergovernmental Panel on Climate Change, 2021. Reprinted under the IPCC's non-commercial use policy.

According to Arias et al. (2021), numerous scientific studies have demonstrated that the current change of climate is primarily driven by human activities. In addition, human influence has contributed to an increase in intensity and/or frequency of various weather events.

The examples discussed above illustrate that, since the last century, the understanding of experts on the climate effects of fuel combustion has grown significantly. Even the major energy company Shell secretly recognised the adverse consequences of fuel combustion. The resulting increase in global temperatures is now clearly notable.

Hawkins (n.d.) helped to communicate these changes to the general public by developing 'warming stripes'. This is a visual representation of the global temperature change over time. Each stripe represents one year, with a certain reference period selected to calculate the mean temperature. The years warmer than the mean of the reference period are shown in red, while cooler years appear in blue.

Selten, F. (2025) made these stripes visible since the beginning of the Common Era, using the period 1850–1900 as the baseline reference. Global temperatures before 1900 have been reconstructed using

information stored in nature, such as tree rings or glaciers. As shown in Figure 2.2, global temperatures between approximately 1 and 1100 CE were slightly higher than the average of the 1850–1900 period. Earth experienced a gradual cooling trend before the Industrial Revolution, being caused by several factors. Such as Earth's axis tilt variations and active volcanos, both leading to less received sunlight (Selten, F., 2025). Around 1900, this slow cooling trend reversed sharply to a rapid increase in global temperatures relative to the 1850–1900 mean. In 2024, this rise was 1.54°C above pre-industrial levels. Similarly to this rise in temperature, atmospheric CO_2 concentrations increased drastically since the invention of the steam engine. Between 1 and 1800 CE, the carbon dioxide levels remained nearly constant at 280 ppm, but began to climb steeply after 1800 as visible in Figure 2.2.

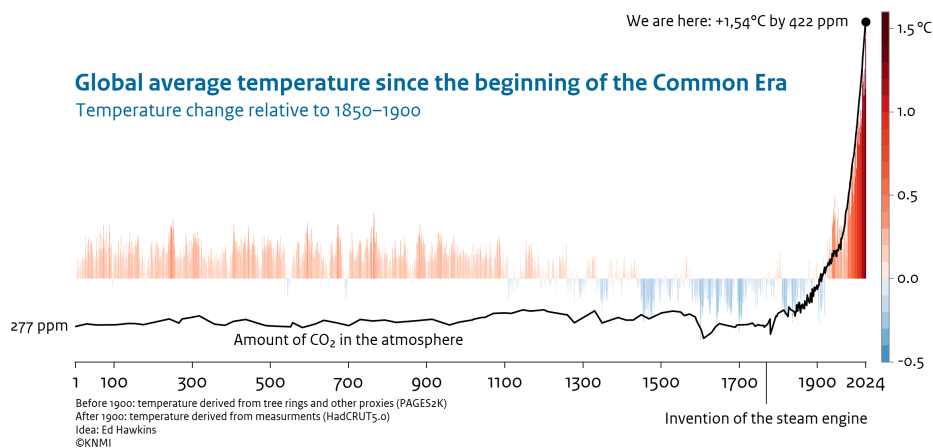


Figure 2.2: Warming stripes since the beginning of the Common Era. Adapted from "*Koninklijk Nederland Meteorologisch Instituut*", by F. Selten, 2025 (<https://www.knmi.nl/over-het-knmi/nieuws/klimaatstrepen-vanaf-het-begin-van-de-jaartelling>). Licensed under KNMI's CC0 copyright. Note: in Figure text has been translated from Dutch to English.

On average, the global surface temperature increased by approximately 1.09°C during the period 2011–2020 compared to 1850–1900. The central estimate of human-induced warming is 1.07°C from 1850–1900 to 2010–2019, while the likely contribution from natural forcing alone ranges from -0.1°C to $+0.1^{\circ}\text{C}$ (Arias et al., 2021).

2.1.2. Climate scenarios

As mentioned above, projections of future climate change were already being made during the 20th century. In the second half of the last century, scientists started developing projections for a range of possible climate scenarios. For example, in the IPCC's IS92 scenarios, six potential future pathways were used. Where each was based on different assumptions regarding population, economic growth, energy supplies, and other related factors (Leggett et al., 1992).

In 2010, Representative Concentration Pathways (RCP) were developed to provide a new basis for climate modelling. These scenarios are defined by their radiative forcing, which is the difference between incoming and outgoing radiation in the atmosphere. The pathways are named according to their projected radiative forcing levels in the year 2100. The four main pathways are RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Each pathway represents possible trajectories of greenhouse gas concentrations over time that would lead to the corresponding radiative forcing level (Moss et al., 2010). The RCPs were not designed for socio-economic comparability. Instead, each model includes its own assumptions about socio-economic factors such as population or energy use (van Vuuren et al., 2011).

Shared Socioeconomic Pathways (SSPs) were developed in parallel to RCPs to enable integrated climate change assessments. The SSPs describe a set of plausible narratives for future global development, including factors as demographics, human progress, economics, policies, natural resources, and the environment. However, SSPs themselves do not account for the impacts of climate change, but rather give a framework in which different global development trajectories affect challenges of mitigation and adaptation. Five SSPs represent five different worlds with varying levels of difficulty in addressing

climate change. In SSPs 1-3, the challenges for mitigation and adaption vary together, while in SSPs 4 and 5, either the challenge for mitigation or adaptation dominates over the other. Below, the five pathways are summarised (O'Neill et al., 2017):

- *SSP1: Sustainability ('Taking the green road'): Low challenges to mitigation and low challenges to adaptation*
The world moves toward sustainable development, with decreasing inequality both between and within countries. Strong commitments to global development goals result in solved environmental issues in the long term. The energy and resource use decreases, since resource efficiency is improved, and awareness leads to more sustainable consumption habits. In addition, investment in education is high and population growth is relatively low.
- *SSP2: 'Middle of the road': Moderate challenges to mitigation and moderate challenges to adaptation*
Global development follows historical patterns, with uneven economic growth between countries. Technological innovation continues without major breakthroughs. While the demand on fossil fuels gradually declines, environment degradation still continues. Finally, investments in education are moderate, and population growth stabilizes at an intermediate level.
- *SSP3: Regional rivalry ('A rocky road'): High challenges to mitigation and high challenges to adaptation*
In this world, national and regional interests dominates, leading to low international cooperation and growing inequality. Environmental and global issues are not solved because most countries are unwilling to cooperate and address these issues. Several countries are shifting toward more authoritarian governance. The demand for energy and resources is high and investments in education and technology decrease. Finally, population growth is high in developing countries and low in wealthier regions.
- *SSP4: Inequality ('A road divided'): Low challenges to mitigation and high challenges to adaptation*
Global inequality increases and power lies in the hands of a small group of people, even within democratic nations. Economic growth varies between low to moderate between countries and technology development occurs primarily in wealthy economies. Environmental policies are implemented mainly in regions with middle to high wealth. In addition, investments in education and technology are uneven within countries. Finally, population growth is low in rich countries and relatively high in the rest of the world.
- *SSP5: Fossil-fuelled development ('Taking the highway'): High challenges to mitigation and low challenges to adaptation*
The global economy grows rapidly, and is driven by a dependency on fossil fuels. Awareness of global environmental issues is low, although technological and educational investments are high. Investments in education and technology are high. The demand for resources and energy grows substantially. Finally, population growth is relatively low worldwide.

The RCPs describe trajectories of radiative forcing levels based on different concentrations of greenhouse gases in the atmosphere. In contrast, the SSPs outline potential pathways of socioeconomic development. According to van Vuuren and Carter (2013), these two frameworks can be combined into an RCP-SSP matrix. In such a matrix, each cell represents a specific radiative forcing level and greenhouse gas emissions in 2100, together with a socioeconomic pathway. O'Neill et al. (2016) proposed plausible RCP-SSP combinations that can be used in the Scenario Model Intercomparison Project (ScenarioMIP) within Phase 6 of the Coupled Model Intercomparison Project (CMIP6). ScenarioMIP provides coordinated climate model simulations based on alternative future scenarios, which facilitates integrated research on climate change. Eight radiative forcing pathways were considered, and for each, one SSP was selected to generate the corresponding emissions and land-use trajectories that would produce the radiative forcing level by 2100.

It is important to note that different SSPs may lead to the same global average forcing level in 2100, but can still result in different climate outcomes due to varying socioeconomic assumptions. Therefore, several criteria were considered for the selection of possible SSPs. They were chosen to be both representative and relevant for climate research. In total, eight RCP-SSP scenarios were selected by

O'Neill et al. (2016) and grouped into two tiers of priority, each containing four scenarios. All scenarios from tier one are elaborated here (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) along with scenario SSP1-1.9 (given as SSPa-b) from tier two, because all these scenarios are considered in the report from the IPCC. Table 2.1 summarises the tier one scenarios.

Table 2.1: Overview of scenarios from tier one (O'Neill et al., 2016)

Scenario name	Forcing in 2100 [W^2/m]	Description
SSP5-8.5	8.5	Higher end of the forcing range, SSP5 was chosen since it was the only pathway with sufficient emissions to produce a radiative forcing of $8.5 \text{ W}^2/\text{m}$ in 2100.
SSP3-7.0	7.0	Medium to high end of the forcing range, SSP3 was chosen since its high land use and its high forcing in combination with a vulnerable society are important for several climate studies.
SSP2-4.5	4.5	Medium part of the forcing range, SSP2 was chosen since the land use and aerosol projections are not as intense as other pathways.
SSP1-2.6	2.6	Low end of the forcing range, SSP1 was chosen since it projects a major land use change, visible in increased forest cover.
SSPa-b	$\pm$ or < 2.0	Low end of the forcing range. In this scenario, global warming is limited by 1.5°C based on the Paris agreement. SSP1 was chosen as a primary candidate, since SSP1-1.9 has a likely probability to remain below 1.5°C in 2100. However, it has a lower probability of staying below 1.5°C at the middle of the century.

In the SSP1-1.9 and SSP1-2.6 scenarios, CO_2 emissions are projected to become negative in the second half of the century. In SSP2-4.5, the emissions remain approximately at current levels until the middle of the century, afterwards it gradually declines. In contrast under SSP3-7.0 and SSP5-8.5, emissions are projected to roughly double by 2050 and 2100, respectively (Arias et al., 2021).

The plausibility of some of these scenarios has been debated by researchers. Hausfather and Peters (2020) argued that RCP8.5 and SSP5-8.5 are often incorrectly portrayed as 'business as usual' scenarios, whereas they actually represent unlikely worst-case scenarios. Similarly, Hausfather (2025) concluded that high-emission scenarios are becoming increasingly unlikely and that the central estimate of global warming by 2100 is likely below 3°C . Nevertheless, Riahi et al. (2022) emphasised that high-end scenarios such as RCP8.5 and SSP5-8.5 are relevant for the assessment of risks associated with these scenarios. Since IPCC's Fifth Assessment Report on climate change in 2014, these scenarios are less likely, although they cannot entirely be dismissed, particularly given uncertainties in feedback in the carbon cycle (Arias et al., 2021). Finally, van Dorland et al. (2024) stated that climate models tend to underestimate the intensity of temperature and precipitation extremes across Europe.

At the lower end of the emission pathways, the plausibility of SSP1-1.9 could also be debated. In this scenario, the global warming is likely limited by 1.5°C by 2100, which is in line with the objectives of the Paris Agreement. However, achieving such an outcome would require extremely strong mitigation efforts. Therefore, SSP1-1.9 can be seen as a scenario demonstrating the requirements to meet the Paris targets (O'Neill et al., 2016).

2.2. Meteorological observations in the Netherlands

This section describes the meteorological observation network of the Royal Netherlands Meteorological Institute (KNMI). It then explains the selection of the five weather stations considered in the historical analyses of precipitation, snow, and wind.

In the Netherlands, 51 automatic weather stations are operational, of which 37 are located on land. The locations of the stations have been determined following the guidelines of the World Meteorological Organization. Because the coastal climate differs from the more continental climate of the eastern part of the country, the selected stations in this study should capture these regional variations. Automatic weather stations continuously record measurements and send them every few seconds to the KNMI.

Observations are updated every ten minutes on the KNMI website. Measured variables include air temperature, humidity, precipitation amount, wind speed and its direction, and solar radiation (KNMI, n.d.-b). In addition, approximately 322 KNMI volunteers manually measure precipitation in their rain gauge every morning around nine o'clock. In case of snowfall, the snow cover is measured with a ruler (KNMI, n.d.-x).

As noted above, it is important to consider multiple weather stations in order to capture regional differences in Dutch weather. Analysing all available stations would provide the most complete picture, but this would be highly time consuming. Therefore, a representative subset of stations is selected that still capture variations across the country.

Since the Netherlands is divided into three different wind zones in the Dutch National Annex of NEN-EN 1991-1-4 for wind loads (NEN, 2023), at least one station from each zone should be included. For precipitation intensity and characteristic snow load, regional differences are neglected, and only a single value is given for the entire country. Nevertheless, regional extremes can therefore be directive on a country scale. The precipitation rate is, for example, higher in the western part of the country and in the southern part of the province of Limburg (KNMI, n.d.-h). While drought extremes during summer are more intense in the inland areas of the country compared to the coastal region (Philip et al., 2020). Finally, wind velocities are typically higher in coastal regions than inland regions (KNMI, 2022).

To represent these regional patterns, weather stations are selected from each corner of the country and one from the centre. In the south-west part of the country the weather station in Vlissingen is chosen, and for the north-west part De Kooy near Den Helder is considered. Beek near Maastricht in the south of Limburg is chosen for the south-east corner, and Eelde near Groningen is chosen for the north-east corner. Finally, De Bilt is selected for the middle of the country. De Bilt is located centrally in the country and it does not have a full sea or continental climate, making it representative for the rest of the Netherlands (KNMI, n.d.-b). Figure 2.3 presents the exact locations of the five weather stations in the Netherlands.

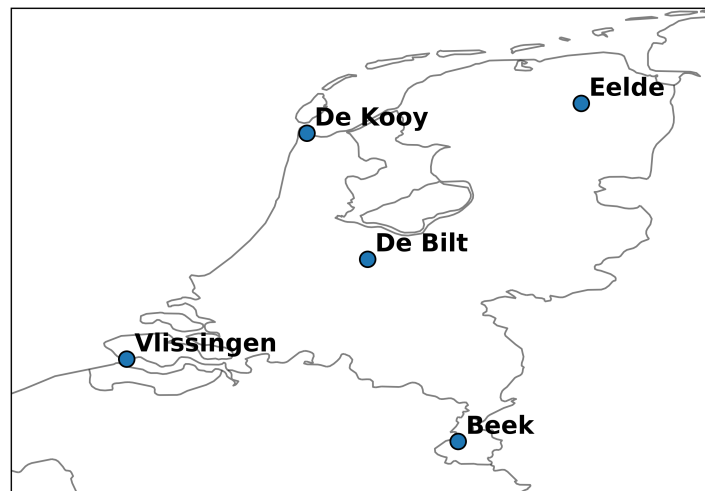


Figure 2.3: Selected locations of five weather stations

An advantage of the selected stations is that, for all of them, temperature and manual precipitation measurements have been homogenised (KNMI, n.d.-i)(Brandsma & van der Schrier, 2020), making them directly suitable for trend analysis. For the five stations, several changes in location, instrumentation and/or changes in surroundings have occurred. It is important to identify these changes, as the hourly wind and precipitation observations have not been homogenised, making them unsuitable for trend analysis. This issue can be addressed by considering only time periods during which the measurements are homogeneous. Major changes in location or instrumentation for the five stations are listed below (KNMI, n.d.-i):

- Station *Vlissingen* was temporary relocated to another location approximately 1.8 km north of

Vlissingen between 1947 and 1958.

- Station *De Kooy* was originally located in Den Helder, but was relocated to De Kooy on 1 August 1972.
- Station *De Bilt* was moved approximately 300 m to a more open location on the 27 August 1951. In addition, the measurement instruments were changed in 1950.
- Station *Beek* was originally located in the centre of Maastricht, but was relocated to Maastricht Aachen Airport in Beek in 1951. The new location is located approximately 9 km from the original location and is situated 65 m higher in elevation.
- Station *Eelde* continued the measurements of station Groningen. Station Eelde is located 10 km south of Groningen and has been in operation since 1951.

Another advantage of the five selected weather stations is that the key indicators used in the KNMI national climate projections are provided either for the national mean or for specific locations, including De Bilt, De Kooy, Groningen, Maastricht (near Beek), and Vlissingen (KNMI, n.d.-m), which corresponds to or are located near the selected stations.

2.3. KNMI'23 Climate Scenarios for the Netherlands

This section reviews the KNMI'23 climate scenarios for the Netherlands developed by van Dorland et al. (2024), which form the basis for the climate projection analyses in this thesis. The underlying methodology, climate models, and projected changes in relevant meteorological phenomena are discussed.

The KNMI'23 climate scenarios provide projections of future climate change in the Netherlands for four time horizons: 2033, 2050, 2100, and 2150. The projections are based on three greenhouse gas emission pathways from the SSPs: SSP1-2.6 (low), SSP2-4.5 (moderate), SSP5-8.5 (high). The 2033 horizon was included because global warming is expected to reach roughly 1.5 °C above pre-industrial levels around that time. All projected changes are considered relative to the reference period of 1991–2020, which is approximately 0.85 °C warmer than the pre-industrial reference period of 1850–1900. Table 2.2 presents the different scenarios considered by the KNMI.

The KNMI'23 scenarios provide projections for a wide range of climate variables, such as temperature, precipitation, and wind velocity. In addition, specific attention was given to extreme weather phenomena such as intense summer precipitation. Projections of the extremes are more uncertain than projections of mean climate conditions due to limitations in current climate models.

The scientific basis of the KNMI'23 scenarios is formed by the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). KNMI adopted the assessed range of Global Surface Air Temperature (GSAT) change, which constrains the climate sensitivity of the Coupled Model Intercomparison Project (CMIP6) climate models using multiple lines of evidence. The KNMI scenarios are linked to the median of the assessed GSAT range. This approach reduced uncertainty associated with climate sensitivity. The remaining uncertainty can afterwards be represented through shifts in the timing at which specific warming levels are reached.

SSP scenario	Scenario name	2033	2050	2100	2150
SSP1-2.6	L	0.6 (0.4–0.9)	0.9 (0.5–1.3)	0.8 (0.4–1.5)	0.7 (0.3–1.4)
SSP2-4.5	M		1.1 (0.8–1.6)	1.9 (1.3–2.9)	2.1 (1.4–3.3)
SSP5-8.5	H		1.5 (1.0–2.0)	4.0 (2.8–5.6)	5.5 (3.9–8.0)

Table 2.2: KNMI'23 climate scenarios with global warming levels according to the median values of the IPCC GSAT assessed range relative to the 1996–2015, given in °C. In brackets the 90 % confidence interval.

Regional climate projections are significantly more uncertain than global temperature projections. KNMI therefore based its regional climate scenarios on the CMIP6 ensemble and also addressed the large spread in precipitation changes for the Netherlands and the Rhine-Meuse basin. The CMIP6 models project both increasing and decreasing annual precipitation trends. This wide range is primarily caused

by uncertainties in future atmospheric circulation patterns, which results in a general increase in winter precipitation and a decrease in summer precipitation with varying magnitude across the models.

To overcome the issue of these uncertainties propagating into the projections, KNMI considered a storyline approach. Rather than focusing on emission scenarios alone, the CMIP6 models were divided into three groups with each 11 models, each representing different circulation responses and precipitation patterns. The two main groups are the "Wet" and "Dry" storylines. The Wet storyline is particularly relevant for water safety assessments and expresses a strong increase in winter precipitation and a limited summer drying, which results in an overall increase of annual precipitation. The Dry storyline is especially relevant for water availability assessments and expresses a strong summer drying and a much smaller increase in winter precipitation. This results into lower annual precipitation sums and an increase risk of drought.

The Wet and Dry variants were derived from projections around 2100 under the SSP5-8.5 scenario, since the climate change signal is strongest relative to the natural variability for this combination of scenario and time horizon. The resulting differences between the storylines were then translated into other scenarios and time periods. One major assumption of this methodology is that regional responses scale approximately linearly with cumulative greenhouse gas emissions and global warming levels.

The climate projections of CMIP6 are based on Global Climate Models (GCMs), which works on large spatial resolutions. These resolutions are insufficient for local projections in the Netherlands. Although regional climate models could be used to dynamically downscale GCM simulations, it was not possible to downscale the complete CMIP6 ensemble since necessary boundary condition data were not available. To overcome this limitation, KNMI considered a retuned version of the EC-Earth v3 climate model, for which a 16-member initial-condition ensemble was available. All ensemble members were run under identical forcing levels, but started from slightly different initial conditions. As a result, the ensemble presents a range of plausible climate realisations and provides a large sample of natural variability. This large ensemble is the basis of the KNMI'23 resampling methodology.

Each EC-Earth ensemble member was dynamically downscaled with the Regional Atmospheric Climate Model (RACMO). RACMO works at a much higher spatial resolution of around $12\text{ km} \times 12\text{ km}$ and it provides a more realistic representation of regional climate processes. Since each RACMO simulation is linked to a corresponding EC-Earth ensemble member, the years selected during the resampling procedure can be replaced by their RACMO years.

Future land-use changes are included in the RACMO simulations and therefore influence part of the projected climate response. Vegetation types are considered in an underlying land-use dataset in RACMO. An issue in the land-use dataset was observed, since there was a large drop in high vegetation in some parts of the country between 2004 and 2005. This discontinuity affected several model variables, such as near-surface wind velocities. This was addressed by a bias-correction procedure. However, the influence of future land-use changes remains present in the final climate projections.

van Dorland et al. (2024) states that in the RACMO simulations, a steady expansion of urban areas during this century is assumed. A limitation of the model is that urban areas are represented as *bare soil*, which corresponds to surface roughness length of approximately 0.013 m. While for urbanised areas the surface roughness is actually around 0.5 m. Consequently, projected wind velocities over urbanised areas may be biased and the effects of urbanisation on local atmospheric processes are likely not fully represented. In contrast, the SSP1-2.6 simulations include substantial afforestation in northern parts of the Netherlands. Particularly, in a region of roughly $50\text{ km} \times 50\text{ km}$ covering parts of the provinces of Groningen and Drenthe. The increased forest cover raises the surface roughness and therefore decreases local wind velocities. Therefore, the projected changes in wind velocity in KNMI'23 are a combination of climate change and land-use change. The assumptions regarding future land use are therefore an important source of uncertainty in the RACMO simulations. Since sea points are not affected by the land-use change, these can provide insights in wind trends based on climate change alone.

The changes in surface roughness may also affect precipitation projections. For example, the large projected afforestation in specific parts of the country lead to higher surface roughness, which decreases local wind velocities. While it increases momentum exchange and boundary-layer mixing, which can result in an increase of precipitation.

van Dorland et al. (2024) have compared the change in mean precipitation for the winter (DJF) and summer (JJA) seasons for a specific ensemble member between the reference period and the future period of 2070–2100 for the SSP1-2.6 scenario. They considered the land-use change according to the RACMO for the future period. And also considered the mean precipitation change for the future period with land-use fixed at its 2016 state. As visible in Figure 2.4, for the changing land-use, the changes for both seasons are largest around the Groningen-Drenthe region. While for the fixed land-use, the changes are much more consistent around the country. The spatial differences between the two variants are showing that the changing land-use has substantial influence on precipitation in the eastern and northeastern provinces.

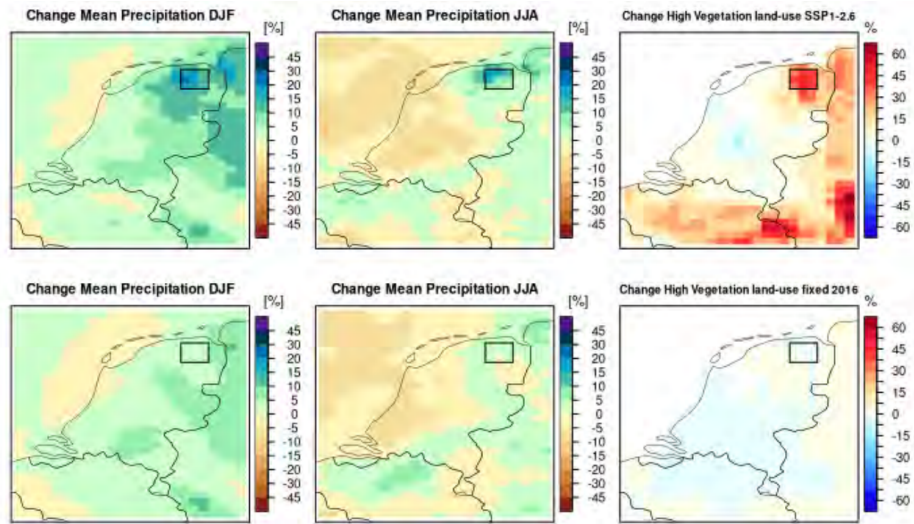


Figure 2.4: Changes in mean precipitation for winter (DJF) and summer (JJA) seasons between reference period and 2070–2100 period for SSP1-2.6. For the land-use of the future period (top row) and fixed land-use to the 2016 state (bottom row). Figure cropped from *KNMI National Climate Scenarios 2023 for the Netherlands* (fig 2.69, p. 97), by Koninkrijk Nederlands Meteorologisch Instituut, 2024. Licensed under KNMI's CC0 copyright.

For each climate scenario and time horizon, the 16 member EC-Earth3 ensemble provides a total of 480 years (16 members times 30 years). KNMI applied a resampling procedure in which multiple years were selected and recombined based on several climate constraints. These constraints were chosen, such that the resulting climate series reproduce the wet and dry climate responses derived from a wider CMIP6 ensemble. In this way, the high-resolution EC-Earth3 output aligned with the CMIP6 projections. This procedure eventually produced eight resampled ensemble members, which reduced the influence of internal climate variability while preserving the targeted climate signal.

After this resampling procedure the EC-Earth3 ensemble members were dynamically downscaled with RACMO. Consequently bias correction of the resampling output was conducted. The RACMO outputs differ from real observations due to various reasons. Such as due to natural variability, differences in resolution. Observations are local, while the RACMO outputs cover averaged values over a $12\text{ km} \times 12\text{ km}$ grid cell. Also important is the roughness map of RACMO which may differ with reality. Biases in the RACMO data were corrected for each variable, month and location separately. The KNMI considered Quantile Delta Mapping. For temperature the differences of the quantiles of the observations and of the RACMO output are preserved, while for wind and precipitation the ratios are preserved (van Dorland et al., 2024).

Finally, RACMO does not provide its output directly on a grid of geographical coordinates. To simplify the selection of locations within the Netherlands, the KNMI interpolated the model output to a grid defined by geographical longitude and latitude coordinates. The original spatial resolution of approximately $12\text{ km} \times 12\text{ km}$ is preserved in the resulting dataset. The projections are given on a daily resolution and include mean, maximum, and minimum temperature, precipitation, wind velocity, relative humidity, potential evapotranspiration, and solar radiation (KNMI, n.d.-f, n.d.-q). As noted previously, the projections for 2150 are based on an extrapolation of the CMIP6 model band-

widths beyond 2100, since the CMIP6 simulations do not extend beyond that year. The projected changes were scaled according to the estimated global warming levels around 2150.

For the low forcing scenarios, KNMI only provides a single future time horizon between 2050 and 2150. This is because the projected global warming levels for these periods are very similar (see Table 2.2), resulting in only minor differences in the projected climate conditions. Furthermore, the reference period is considered from the reference period of the dry variant of the moderate forcing scenario around 2050. The reference period of this specific scenario was found to reproduce historical climate extremes most accurately (KNMI, n.d.-q).

In total, the dataset contains 15 climate scenarios, each consisting of 30 years of projections centred around a specific time horizon. For the moderate and high forcing pathways, projections are available for both wet and dry variants around the horizons of 2050, 2100, and 2150, resulting in 12 scenarios. Furthermore, wet and dry variants are provided for the low forcing pathway, together with a separate low forcing reference scenario representing the climate around 2033 (KNMI, n.d.-f).

2.4. Recent climate change studies

2.4.1. Shutdown of Atlantic meridional overturning circulation

The Atlantic meridional overturning circulation (AMOC) is a large system of water currents in the Atlantic Ocean. An important part of this circulation is the Gulf Stream, which transports warm surface water from the Gulf of Mexico towards western Europe. The AMOC is primarily driven by differences in water density. This depends on temperature and salinity, while wind also influences the circulation. As the warm surface water flows northwards, it cools and becomes denser. In addition, in the north of the North Atlantic Ocean, sea-ice formation increases the salinity of the water further. These processes increase the density of seawater, causing it to sink to depths of roughly 2 km to 3 km and then flow southwards as deep water. This circulation is the major reason of the relatively mild climate of western Europe compared with regions in North America at similar latitudes (Mokkenstorm & Verheggen, 2024).

Climate change is expected to weaken the AMOC. Increased melting of ice on Greenland adds a large amount of freshwater into the North Atlantic Ocean, reducing the salinity and density of the surface water. Furthermore, increasing ocean temperatures decrease the water density even further. Therefore, deep water formation reduces, leading to a reduction in AMOC strength. Research suggests that the AMOC has already weakened by approximately 15 % since the middle of the twentieth century (Mokkenstorm & Verheggen, 2024).

The study of Drijfhout et al. (2025) focused on the period after 2100 and projected a complete shutdown of the northern AMOC by 2300 in 70 % of the simulations for SSP5-8.5, 37 % for SSP2-4.5, and 25 % for SSP1-2.6. In contrast, van Westen, Vanderborght, et al. (2025) suggested that an AMOC collapse could already be started around 2063 under SSP2-4.5 and around 2055 under SSP 5-8.5 scenario. These different findings illustrate that the moment and probability of an AMOC collapse remain highly uncertain.

A strong weakening or collapse of the AMOC would have major consequences for the climate of the Netherlands and Europe. Simulations show that summer heat extremes would reduce, whereas winter cold extremes would intensify significantly (van Westen & Baatsen, 2025). Furthermore, annual precipitation amounts in Europe are expected to decrease under an AMOC collapse. Leading to more intense summer drying (van Westen, van der Wiel, et al., 2025). This impacts for example agriculture and freshwater availability. Consequently, changes in the AMOC could have major societal and environmental impacts.

2.4.2. Recent development of CMIP7

Recently, Van Vuuren et al. (2026) developed the ScenarioMIP framework for CMIP7, the successor of the CMIP6 scenario framework. The new framework was developed as several lessons were learned from CMIP6. In particular, the very high-emission SSP5-8.5 scenario and the strong mitigation SSP1-1.9 scenario are now considered less plausible, based on current expectations regarding future socio-economic development. Therefore, the highest forcing scenario in CMIP7 is lower than that considered in CMIP6. Another important change is that the scenarios are no longer directly linked to the Shared

Socioeconomic Pathways (SSPs). Instead, they are designed to cover a wide range of plausible future greenhouse gas emission pathways, but still remaining to be compatible with different socio-economic developments. This provides greater flexibility for climate impact assessments and allows comparison with evolving socio-economic projections, which was not possible for CMIP6.

Van Vuuren et al. (2026) proposed seven scenarios, including some pathways in which emissions change drastically during the twenty-first century. Ordered from the highest to the lowest emissions, these scenarios are:

- *High*: a high-emission pathway representing the upper bound of plausible future emissions, with radiative forcing lower than that of SSP5-8.5.
- *High-to-low*: initially follows the *High* pathway, followed by rapid emission reductions towards net-zero CO_2 emissions by 2100.
- *Medium*: represents emission trajectories that are consistent with current climate policies.
- *Medium-to-low*: follows intermediate emissions that gradually decline towards net-zero CO_2 emissions by 2100.
- *Low*: limits global warming to approximately $1.5^\circ C$ by the end of the century.
- *Very low*: also limits warming to around $1.5^\circ C$, but with a smaller temperature overshoot during the century.
- *Low-to-negative*: initially exceeds the warming of the *Very low* scenario, followed by negative CO_2 emissions later in the century.

2.5. Eurocode 0

Some terminology and design methodology from Eurocode 0 (EN 1990) need to be introduced to clarify the definitions used throughout this thesis.

For weather-induced variable loads, the characteristic values prescribed in the Eurocodes generally correspond to an annual probability of exceedance of 0.02, equivalent to a return period of 50 years. To determine the design load acting on a structural element, permanent and variable loads are combined according to the load combination rules of EN 1990 and its Dutch National Annex (NEN, 2019b, 2019c). These combinations include partial safety factors and combination factors. Combination factors account for the fact that it is unlikely that several variable loads simultaneously reach their characteristic values. For example, the Dutch National Annexes prescribe that rainwater loads are not considered together with snow and wind loads when verifying the ultimate limit state (state for which a structure (partially) collapses). Consequently, rainwater, snow, and wind loads are not combined with one another in the ULS load combinations but are each considered individually in combination with the relevant permanent and variable loads. The design load is therefore determined by the most unfavourable load combination.

This shows that a characteristic value is not the same as a design value. A characteristic value represents a representative magnitude of an individual load, whereas a design value is obtained after applying the prescribed load combinations and partial safety factors.

2.6. Statistical methods

This section introduces the statistical methods used to analyse historical observations and climate projections. These methods are subsequently applied to detect trends and to estimate return levels of weather-induced loads.

2.6.1. Mann-Kendall trend test

The Mann-Kendall (MK) trend test (Kendal, 1975; Mann, 1945) is a non-parametric statistical test used to detect monotonic trends. As it is a non-parametric test, it does not require the data to follow a specific distribution. However, the observations are assumed to be independent. Since the underlying distribution of environmental data is often unknown, the MK test is widely used for trend detection.

For this research, the Mann-Kendall trend test is used to determine whether there is evidence of a monotonic trend in the historical observations.

Given a time series $\mathbf{X} = \{x_1, x_2, \dots, x_n\}$, Kendall's S statistic is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (2.1)$$

where n is the number of observations and $j > i$. The sign function is defined as:

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if } x_j > x_i, \\ 0 & \text{if } x_j = x_i, \\ -1 & \text{if } x_j < x_i. \end{cases} \quad (2.2)$$

The statistic S represents the difference between the number of increasing and decreasing pairs in the time series. For sample sizes larger than approximately ten observations, S is approximately normally distributed and can be standardised to a Z -statistic (Kamal et al., 2018):

$$Z = \begin{cases} \frac{S - 1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \frac{S + 1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0. \end{cases} \quad (2.3)$$

A positive value of Z indicates an increasing monotonic trend, while a negative value indicates a decreasing trend. The variance $\text{Var}(S)$, accounting for tied values, is given by:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^g t_p(t_p-1)(2t_p+5)}{18} \quad (2.4)$$

where g is the number of tied groups and t_p is the number of observations in the p^{th} group.

The null hypothesis (H_0) states that no monotonic trend is present in the time series. This hypothesis is rejected when $|Z| > Z_{1-\alpha/2}$, where α is the chosen significance level. For $\alpha = 0.05$, there is a 5% probability of a Type I error, i.e. incorrectly rejecting the null hypothesis.

2.6.2. Extreme value analysis

Extreme value analysis (EVA) is a central part of this thesis, as structural design is concerned with rare weather events. The characteristic values prescribed in the Eurocodes generally correspond to an annual probability of exceedance of 0.02, equivalent to a return period of 50 years. Estimating these characteristic values from historical observations and climate projections therefore requires extreme value analysis.

A series observations cannot directly be used in extreme value analysis, as samples should be taken from the series. Two main sampling approaches are commonly used: the Block Maxima (BM) method and the Peak Over Threshold (POT) method. In the BM method, the time series is divided into equal time blocks (e.g. years), and the maximum value within each block is selected. In the POT method, all observations exceeding a predefined threshold are selected.

The BM method generally leads to approximately independent observations, provided that the block size is sufficiently large. However, it has the disadvantage that information is lost, as only one observation per block is considered. In addition, it may be less suitable for short time series. The POT method makes more use of the available data, but requires careful selection of the threshold and additional steps (such as declustering) to ensure approximate independence of the exceedances.

In this study, the block maxima method is adopted by considering annual maxima, as this was likely the approach used to derive the current characteristic values for precipitation, snow, and wind loads prescribed in the Dutch National Annexes. Furthermore, all analysed data series exceed 15 years in length, which is assumed to be sufficient for the application of the block maxima method.

For the BM method, the annual maxima are commonly modelled using the Generalized Extreme Value (GEV) distribution. The cumulative distribution function (CDF) of the stationary GEV distribution is given by (Coles, 2001):

$$\Psi_{GEV}(x) = \exp \left\{ - \left[1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right]^{-1/\xi} \right\}, \quad \text{for } 1 + \xi \left(\frac{x - \mu}{\sigma} \right) > 0 \quad (2.5)$$

where μ is the location parameter, $\sigma > 0$ is the scale parameter, and ξ is the shape parameter, which controls the tail behaviour of the distribution.

In the case of non-stationary conditions, the GEV parameters may vary as a function of a covariate x_c (e.g. time):

$$\Psi_{GEV}(x | x_c) = \exp \left\{ - \left[1 + \xi(x_c) \left(\frac{x - \mu(x_c)}{\sigma(x_c)} \right) \right]^{-1/\xi(x_c)} \right\} \quad (2.6)$$

The parameters of the GEV distribution can be estimated using methods such as maximum likelihood estimation.

2.7. ProNEVA

This section introduces the ProNEVA framework developed by Ragno et al. (2019), which is used to perform the extreme value analyses of the historical precipitation, snow, and wind observations.

Ragno et al. (2019) developed a Process-informed Nonstationary Extreme Value Analysis (ProNEVA) framework in MATLAB. This framework combines extreme value theory with process-based covariates and applies a Bayesian inference approach to estimate the parameters of the Generalized Extreme Value (GEV) distribution. The parameter estimation is performed using a Hybrid Evolution Markov Chain Monte Carlo (HE-MCMC) algorithm. Although ProNEVA is primarily designed for non-stationary extreme value analysis, it can also be applied in a stationary setting by excluding covariates and assuming constant GEV parameters.

The ProNEVA framework consists of several steps that lead to the estimation of the GEV parameters and the assessment of model performance. First, the user must specify whether a stationary or non-stationary GEV model is considered. In the case of a non-stationary model, one or more covariates must be selected. These covariates represent drivers of variability, such as time or temperature. Subsequently, the functional dependence of the GEV parameters on the selected covariates must be defined. The location parameter μ , scale parameter σ , and shape parameter ξ can be modelled as functions of the covariate. This includes linear, quadratic, and exponential relationships. The scale parameter must remain positive. This is achieved by modelling the scale parameter in logarithmic space. The shape parameter ξ is more difficult to estimate due to its strong influence on the tail behaviour.

After defining the model structure, prior distributions for the GEV parameters must be specified. ProNEVA supports several types of prior distributions, including uniform, normal, and gamma distributions. For example, a normal prior is defined by its mean and standard deviation. The choice of priors reflects prior knowledge or assumptions about the parameter values and plays an important role in Bayesian inference, particularly for small datasets. Once the model structure and priors are defined, the Bayesian inference procedure is performed using the HE-MCMC algorithm. This algorithm combines elements of evolutionary computation and Markov Chain Monte Carlo sampling. Multiple chains are run in parallel to assess convergence and improve robustness.

The output of ProNEVA consists of the GEV parameters. In addition, the framework provides several diagnostic tools to evaluate model performance and goodness-of-fit. These include quantile–quantile (QQ) plots, probability–probability (PP) plots, and residual analyses. Furthermore, ProNEVA generates return level plots, which relate the magnitude of extreme events to their associated return periods.

These plots are particularly relevant for structural design, as they allow direct comparison with characteristic values used in design codes.

Part II

Precipitation

Literature study for precipitation

This chapter reviews the literature relevant for the precipitation analysis. First, some theoretical background of precipitation is given. Subsequently, the methodology for calculating rainwater loads in structural design according to Eurocode 1 and the Dutch National Annex is discussed. Subsequently, the Dutch precipitation measuring network and observed precipitation trends are described. Finally, the precipitation part of the KNMI'23 climate scenarios is explained, including the underlying climate models and their projected changes in precipitation extremes.

3.1. Theoretical background of precipitation and global trends

This section first introduces the physical processes behind precipitation and the factors influencing its intensity and occurrence. It then presents observed global trends and projections in precipitation.

According to National Geographic Society (2023), *"Precipitation is any liquid or frozen water that forms in the atmosphere and falls to Earth"*. Precipitation therefore includes phenomena such as rain, hail, or snow.

Rainfall occurs when water droplets reach the surface in liquid form. This often results from the melting of snowflakes that fall through a sufficiently warm layer of air (KNMI, n.d.-s). Hail forms when strong vertical air currents in convective clouds transport ice particles over and over through regions with temperatures just below and above freezing. This allows the ice particles to grow through melting and freezing cycles (KNMI, n.d.-k). Snow occurs when atmospheric conditions are sufficiently cold for snowflakes to reach the surface without melting (KNMI, n.d.-t).

A distinction can be made between convective precipitation and large-scale precipitation. The first generally occurs during summer when solar radiation heats the land surface, causing warm air to rise. Convective precipitation is often characterised by local short-duration intense precipitation. In contrast, large-scale precipitation develops when broad air masses are forced to rise by large scale atmospheric processes. This upward movement may occur along frontal zones, where warm air rises above cold air, or when the air is forced over elevated terrain. Large-scale precipitation generally covers larger areas and often include longer-duration events (van Dorland et al., 2024).

Temperature plays an important role in determining the amount of moisture that can be stored in the atmosphere. According to the Clausius–Clapeyron (CC) relation, the atmospheric saturation water vapour content increases by approximately 6 % to 7 % per degree Celsius of warming, assuming constant relative humidity (KNMI, n.d.-c; Lenderink & Attema, 2015). However, this assumption is not always valid in practice. To account for variations in relative humidity, dew point temperature should be considered instead according to Lenderink et al. (2017). *"The dew point is the temperature the air needs to be cooled to (at constant pressure) in order to achieve a relative humidity of 100 %."* (NOAA's National Weather Service, n.d.).

Using observations from the Netherlands and Hong Kong, Lenderink et al. (2011) found that extreme precipitation intensities can increase at roughly twice the Clausius–Clapeyron rate when analysed as a

function of dew-point temperature. This is so-called super-Clausius-Clapeyron scaling corresponds to an increase of roughly 12 % to 14 % per degree Celsius. According to Lenderink et al. (2017), this scaling behaviour is mostly related to convective precipitation. Increasing near-surface humidity leads to more intense convective storms, while other atmospheric properties remain relatively unchanged. These findings indicate that climate change may result in a stronger increase in extreme rainfall than would be expected from the increase in atmospheric moisture alone. However, uncertainties remain about how future changes in atmospheric stability and large-scale circulation may influence this relationship.

Climate change affects not only precipitation extremes, but also the global hydrological cycle. Rising temperatures increase evaporation from the oceans and evapotranspiration over land. Globally, evaporation and precipitation must remain approximately balanced. Consequently, global mean precipitation is projected to increase by approximately 2 % per degree global warming (KNMI, n.d.-h).

Although global mean precipitation is expected to increase, regional responses may differ significantly. Anthropogenic aerosols to some extent counterbalance warming by cooling the Earth's surface, as a result reducing precipitation. Furthermore, differences in warming rates between land and ocean influence atmospheric circulation patterns and moisture transport. Furthermore, changes in land use can affect evapotranspiration, run-off, and regional precipitation patterns (Arias et al., 2021). As a result, some regions are projected to become wetter, while others may experience drying. In general, wet regions tend to become wetter and dry regions tend to become drier under global warming (KNMI, n.d.-h).

Observations already indicate changes in the global hydrological cycle. Since around 1950, both the intensity and frequency of heavy precipitation events over land have increased. Atmospheric water vapour concentrations have risen since at least the 1980s. According to the IPCC, it is extremely likely that these trends will continue as global temperatures increases further (Arias et al., 2021).

Table 3.1 presents projected changes in global mean annual land precipitation for five SSP scenarios. These changes are relative to the 1995–2014 reference period. During this reference period, the global mean daily land precipitation was roughly 2.27 mm, with a 90 % confidence interval ranging from 1.98 mm to 2.58 mm. For the mid-century period of 2041–2060, projected increases range from approximately 2.6 % to 4.0 %. Towards the end of the century (2081–2100), these increases become larger and start to depend more on the scenario. Values are ranging from approximately 2.6 % under SSP1-9 to 8.8 % under SSP5-8.5. expressed relative to the 1995–2014 reference period. During this reference period, the mean daily precipitation was 2.27 mm with a 90 % confidence interval ranging from 1.98 mm to 2.58 mm. The projected increase in mean global land precipitation ranges from 2.6 % to 4.0 % for the mid-term period, while for the long-term period this range widens to between 2.6 % to 8.8 % (Douville et al., 2021).

Table 3.1: Projected mean global land annual precipitation increase for the 2041–2060 and the 2081–2100 period relative to the 1995–2014 reference period. Ranges show 90 % confidence. Adapted from Douville et al. (2021).

Annual precipitation increase	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
Mid-term (2041–2060) relative to the reference period					
Absolute [mm/d]	0.07 [0.02–0.11]	0.07 [0.00–0.13]	0.06 [0.01–0.13]	0.06 [0.02–0.12]	0.09 [0.01–0.16]
Relative [%]	3.1	3.1	2.6	2.6	4.0
Long-term (2081–2100) relative to the reference period					
Absolute [mm/d]	0.06 [0.01–0.10]	0.08 [0.02–0.16]	0.11 [0.02–0.19]	0.14 [0.03–0.22]	0.20 [0.07–0.32]
Relative [%]	2.6	3.5	4.8	6.2	8.8

While the projections in Table 3.1 describe changes in global mean precipitation, several studies have investigated changes in precipitation at regional and local scales, as well as changes in precipitation extremes.

Aalbers et al. (2017) examined the local changes in mean and extreme precipitation in Western Europe and to what extent these changes can be attributed to climate change or internal variability. They considered a 16-member ensemble covering the 1850–2100 period, with for each member slightly different starting conditions. Historical emissions up to 2005 were applied, after which the RCP8.5 scenario was used. The different starting conditions allowed to distinguish the climate change signal from internal climate variability.

The results show a clear increase in heavy precipitation across most parts of Western Europe, especially during winter. During summer, the mean precipitation tends to decrease in most regions, while heavy precipitation often increases. Meaning that future summers generally become drier with more extreme precipitation. The local precipitation projections are strongly affected by internal climate variability, making regional estimates uncertain. Still, the increase in heavy precipitation emerges as a relatively robust climate change signal.

Gründemann et al. (2022) investigated rainfall extremes under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios for the future period of 2071–2100, relative to the historical 1971–2000 period. Daily precipitation data from 25 CMIP6 models were analysed, showing that rarer rainfall events are likely to increase more in magnitude in the future than common rainfall events. This means that the tails of extreme value distributions for rainfall are expected to become heavier in the future. For daily land rainfall, the projected global increase in magnitude ranges from 10.5 % to 28.2 % for annual events and from 13.5 % to 38.3 % for centennial events, with the lowest and highest values corresponding to lower and higher emission scenarios, respectively. An increase in the global median magnitude of extreme precipitation events was predicted for all SSPs for all models. Particular around the subtropics the magnitude of rare rainfall events is expected to increase much more than the common ones. However, for some oceanic regions the magnitudes of the common ones are expected to increase more than the rare ones.

3.2. Rainwater loads in the Eurocode

This section describes the methodology prescribed in the Dutch National Annex of NEN-EN 1991-1-3 for determining rainwater loads on structures.

In NEN-EN 1991-1-3 (NEN, 2019a) the snow loads on structures are discussed, whereas rainwater loads are not included in this part of the Eurocode. However, the Dutch National Annex of NEN-EN 1991-1-3 provides rules for rainwater loads originating from precipitation (NEN, 2019d). These loads are particularly relevant for roof structures and especially for industrial buildings, which are often relatively lightweight structures.

In the annex of snow load the terms *rain intensity* and *precipitation intensity* are used interchangeably, although these refer to different phenomena. The term precipitation intensity is used when design intensities are specified in the annex. Implicitly it seems to be assumed that precipitation reaching the roof surface will eventually become liquid water. This explains why the resulting load is referred to as *rainwater* load.

In this thesis the terminology of rainwater load and precipitation load are used simultaneously, however they both refer to rainwater loads on buildings as a result of precipitation.

Rainwater loads are classified as climatic free actions, meaning that they originate from the climatic system and may have different spatial distributions over a structure. Therefore, the effects of water accumulation on the structure must be evaluated.

Several assumptions are made when considering rainwater loads:

- Water cannot be discharged by the regular drainage system.
- Water can be discharged by the roof edge or by emergency drainage.
- The least favourable case of water accumulation must be considered. The deformation of the structure prior to the occurrence of rainwater loads strongly influences the accumulation of water.

Figure 3.1 shows a flow diagram of the variables influencing rainwater loads on a structure according to the Dutch National Annex of NEN-EN 1991-1-3. The grey part indicates the aspects investigated in this thesis. The different variables are discussed below.

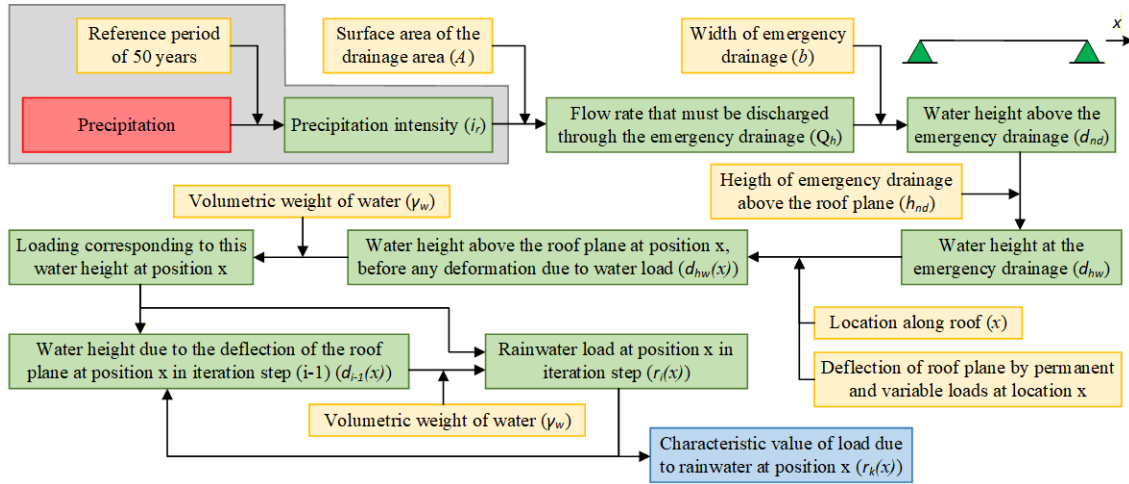


Figure 3.1: Rainwater loads on structures according to the Dutch National Annex of NEN-EN 1991-1-3

The reference period of a structure is the period used as the basis for the statistical assessment of variable actions. For most structures a reference period of 50 years is considered.

For a reference period of 50 years the corresponding precipitation intensity for rainwater loads is $0.0500 \times 10^{-3} \text{ m/s}$. The annex does not specify the duration of the precipitation event related with this intensity. However, the KNMI study by A. Buishand and Wijngaard (2007) shows that a precipitation event with a duration of 5 minutes and a return period of 50 years corresponds to a precipitation amount of 15 mm, which equals to an intensity of $0.0500 \times 10^{-3} \text{ m/s}$. Therefore, it is assumed that the Dutch National Annex implicitly refers to a precipitation duration of 5 minutes.

The National Annex also provides precipitation intensities for reference periods of 1, 15 and 100 years. For intermediate values, linear interpolation may be applied. For a reference period of 100 years, an intensity of $0.0561 \times 10^{-3} \text{ m/s}$ is prescribed, which is nearly identical to the value reported by A. Buishand and Wijngaard (2007) for 5-minute precipitation events with a 100-year return period. For a reference period of 1 year, the Annex gives an intensity of $0.0215 \times 10^{-3} \text{ m/s}$. In contrast, A. Buishand and Wijngaard (2007) reported a value of approximately $0.017 \times 10^{-3} \text{ m/s}$ for a 1-year return period. This suggests that the value specified in the Annex corresponds more closely to a return period of roughly 2 years. The reason behind this choice is not given. It may have been considered to obtain conservative interpolated values for intermediate return periods or to keep a conservative lower limit.

After selecting the reference period, the surface area of the drainage area must be determined. The size and shape of the drainage area depend on the slope of the roof. The emergency drainage system for each drainage area must be able to discharge a flow rate Q_a , which is defined as the drainage area A multiplied by the precipitation intensity i_r :

$$Q_a = A \times i_r \quad (3.1)$$

The relationship between the discharge of the drainage area and the individual emergency drains is given by:

$$Q_a = \sum_{i=1}^n Q_{h,i} \quad (3.2)$$

where $Q_{h,i}$ is the required discharge capacity of emergency drain i in m^3/s and n is the number of emergency drains.

The water height above the emergency drainage is determined based on the discharge and width of the drainage opening. For a rectangular drainage opening this relation is given by:

$$d_{nd} = 0.70 \left(\frac{Q_h}{b} \right)^{2/3} \quad (3.3)$$

Where d_{nd} is the water height above the drainage (in m), Q_h is the required discharge capacity of the emergency drainage (in m³/s, and b is the width of the drainage opening (in m).

The water height at the emergency drainage (d_{hw}) equals the water height above the drainage (d_{nd}) plus the height of the emergency drainage above the roof plane (h_{nd}).

The deformation of the structure may be determined analytically or iteratively. When an iterative procedure is executed (as shown in Figure 3.1), the rainwater load at position x is calculated as:

$$r_i(x) = (d_{hw}(x) + d_{i-1}(x)) \times \gamma_w \quad (3.4)$$

where:

- $r_i(x)$ is the load in iteration i at position x , in kN/m²
- $d_{i-1}(x)$ is the water height caused by deformation of the roof plane at position x in the $(i - 1)^{\text{th}}$ iteration, in m
- $d_{hw}(x)$ is the water height above the roof plane before deformation due to rainwater loads at position x , in m
- γ_w is the volumetric weight of water (10 kN³/m)

The iteration may be stopped when the load increase between iterations becomes smaller than 1 % of the load. At that point, the load in iteration i is taken as the characteristic value of rainwater load. For the calculation of the deformation of the roof structure due to rainwater loads, the stiffness of the structure should be reduced by dividing it by a factor of 1.3. For the determination of the deformation caused by the rainwater load, only the load resulting from the initial water height $d_{hw}(x)$ should be considered. The total water height above the roof structure at position x is equal to the water height minus the elevation of the roof structure at that location.

The elevation of the roof structure at position x must include the deformation caused by the characteristic values of the permanent loads and the combination values of all variable loads, with the exception of rainwater loads. In this way, the rainwater load is applied on the already deformed roof structure, which influences the accumulation of water and the resulting load distribution.

Finally, Section 7.3 of the Dutch National Annex of NEN-EN 1991-1-3 provides rules and recommendations for the detailing of emergency drainage systems. For example, when no roof slope is present, it is recommended to limit the distance between emergency drains to 30 m.

As indicated in Figure 3.1, this research focuses only on the potential effects of climate change on precipitation intensity. If precipitation intensity changes, several design parameters may be adjusted to maintain the same characteristic (annual probability of exceedance of 0.02) rainwater load:

- Modifying the drainage area by adapting roof slopes
- Changing the width of emergency drainage openings
- Adjusting the height of emergency drainage above the roof plane
- Modifying the stiffness of the roof structure

Consequently, a change in precipitation intensity does not necessarily imply that the strength or stiffness of roof structures must be adapted. Various design parameters can be adjusted to accommodate changes in precipitation intensity.

3.3. National precipitation measurements and trends

This section describes the Dutch precipitation observation network and discusses observed trends in precipitation.

3.3.1. Measuring network

Precipitation in the Netherlands on land is recorded either by the 37 automatic or the approximately 322 manual precipitation stations. The volunteers of the manual observations only measure the precipitation

and if present the snow depth over the previous day each morning. While the automatic weather stations measure precipitation intensities every 12 seconds (Wauben, 2004). Still, since daily manual precipitation dates back to 1850, the manual measurements are better able in showing trends and since the network has become dense since the 1950, it allows to make local differences within the country visible (Brandsma & van der Schrier, 2020). Below the manual precipitation and automatic set-ups are discussed in more detail. Furthermore changes in instrumentation have introduced inhomogeneities in the recorded data, and this will also be elaborated.

Manual precipitation measurements are conducted by a wide network of volunteers across the Netherlands. Each morning, at around 10:00 during summer and 09:00 during winter, volunteers measure the precipitation collected over the last 24 hours in their rain gauge. A heating element melts solid precipitation, such as snow. One millimetre of melted snow corresponds roughly to one centimetre of snow (KNMI, n.d.-x).

For mean temperatures in the Netherlands observations of station De Bilt are considered, since it neither represents a full maritime or continental climate and is therefore considered to be representative for the entire country. However, specifically for precipitation, local differences within the country are relatively large, therefore the national mean precipitation is based on 13 manual precipitation stations. These are called "P13" and consists of the following stations: De Bilt, De Kooy, Groningen, Heerde, Hoofddorp, Hoorn, Kerkwerpe, Oudenbosch, Roermond, Ter-Apel, West-Terschelling, Westdorpe, and Winterswijk (KNMI, 2023).

Earlier manual precipitation measurement configurations were prone to wind-induced errors, which led to a reduction of the gauge height from 1.5 m to 0.4 m above ground level around 1946. This modification improved measurement accuracy and increased recorded precipitation amounts by approximately 2.5 % compared to the earlier set-up. Within about one year, around 65 % of the rain gauges were lowered (Brandsma & van der Schrier, 2020). The homogenised series does not include a correction for precipitation undercatch before this height adjustment (KNMI Climate Explorer, 2026b).

Between 2012 and 2014, KNMI introduced a new rain gauge for manual measurements. Apart from a larger reservoir capacity, the gauges were identical to the previous design. However, a loosely connected ring on the funnel caused leaks in some gauges, allowing rain falling on the outside of the funnel to enter the reservoir. Consequently, this led to an overestimation of precipitation. The leaks were sealed in June-July 2017 and later the affected gauges were replaced with non-faulty ones. In the (homogenised) manual precipitation dataset, the precipitation measurements of 65 out of 320 stations were corrected using correction factors derived from comparisons with nearby non-leaking gauges and several statistical models (Brandsma et al., 2020; KNMI Climate Explorer, 2026b).

Some stations (including De Bilt) were identified as potentially affected by leakage, but no correction was applied because the suspected leakage period coincided with a gauge relocation. The rain gauges at the manual precipitation stations in Beek and Eelde were confirmed to be not leaking, while the series for Vlissingen and De Kooy were corrected for leakage effects (Brandsma et al., 2020).

From 2026 onwards, volunteers will start using a new rain gauge, as the existing instruments have reached the end of their service life. Furthermore, the new gauges simplify the measurement procedure (KNMI, 2025).

The KNMI uses electronic precipitation gauges for their automatic measurements. These have a catch area of 400 cm² and measure the precipitation intensity in 0.006 mm/h levels by the change of height (in 0.001 mm resolution) of a floating part in the reservoir every 12 seconds. The reservoir is automatically emptied when it is almost full (Wauben, 2004).

Several changes in instrumentation have occurred for the five considered automatic precipitation stations over the past decades, while homogenised series are not available. Originally, the automatic rain gauges in the Netherlands were placed in the so-called English set-up. In this configuration, wind-induced measurement errors are reduced compared with gauges placed directly at ground level, as demonstrated by Kuik (2001). In the English set-up, the rain gauge is placed in the centre of a circular pit with a diameter of 3 m. The pit is filled with gravel and surrounded by a brick wall with a height of 0.4 m. The rim of the rain gauge is positioned at the same height as the pit surface, while the surrounding soil gently slopes upward toward the wall. This configuration stimulates a more horizontal airflow

over the gauge opening, in that way reducing wind-induced undercatch. However, the English set-up has several drawbacks, such as high construction and maintenance costs and increased sensitivity of the gauge to debris (Wauben, 2004).

For this reason, a new configuration was introduced in which the rain gauge is installed within an Ott windscreen. This windscreen has a circular arrangement of stainless-steel flaps, with the rim of the gauge positioned at the same height as the windscreen. Experiments comparing the English set-up and the Ott windscreen, using the same rain gauge, showed that the windscreen configuration results in an average annual precipitation loss of about 1.5 % compared to the English set-up. During windy seasons, this difference can increase to approximately 6 % (Wauben, 2004).

At four of the five stations, the English set-up was replaced by the Ott windscreen configuration: in 2007 at De Kooy, 2008 at De Bilt, 2005 at Beek, and 2009 at Eelde. At Vlissingen, the most recent change in instrumentation occurred in 1993. In both configurations the same rain gauge type is used (Brandsma, 2014). Appendix A.2 summarises the instrumentation changes for the automatic precipitation measurements.

Since 1993, electronic precipitation gauges were used. Before the electronic precipitation gauges, the KNMI used so called pluviographs, which continuously measured the precipitation on a strip. An advantage of this system was that precipitation sums for each arbitrary interval could be determined. A disadvantage, especially at airports was the daily replacement of the precipitation strips. In De Bilt continuous measurements were available since 1897 and for Vlissingen, De Kooy, Beek, and Eelde since 1957 (T. A. Buishand & Velds, 1980).

3.3.2. Historical observations and trends

Focusing on trends in annual precipitation sums over the period 1951–2009 for 240 manual stations, T. A. Buishand et al. (2011) found an average increase in precipitation of approximately 118 mm across the Netherlands. The monotonic increase was statistically significant for half of the stations. Locally, the largest increases occurred in the coastal regions, which the author attributed to increasing North Sea temperatures. In contrast, the smallest increases were found in the eastern part of the country, particularly in the south-east. For precipitation sums between April and September, the coastal regions again showed the largest increases, whereas decreases were observed in the southeastern part of the Netherlands (T. A. Buishand et al., 2011).

The differences in annual sums between two climatological periods of 1961–1990 and 1991–2020 were also found to be substantial. For the P13 stations the mean annual precipitation sum between the two periods increased by 779 mm to 851 mm or by 9 %. In contrast, for both periods the number of days per year with more than 0.3 mm precipitation remained roughly constant at 192 days. This indicated that the number of wet days had changed little, whereas the precipitation amount on wet days had increased. The number of days with more than 10 mm and 20 mm of precipitation increased by approximately 14 % and 24 %, respectively (Selten & Siegmund, 2022; Siegmund, 2022).

Focussing on seasonal mean precipitation trends in the Netherlands between the two climatological periods of 1901–1930 and 1991–2020, (van Dorland et al., 2024) reported the strongest increase of 30 % observed in winter, followed by 20 % for autumn, 10 % for summer, and lowest for spring (5 % to 10 %). Overall, the annual mean precipitation increased by approximately 20 %.

For the period of 1991–2020 and the P13 stations Siegmund (2024) showed that days with around 5 mm of precipitation contributed the most to the annual sum of 851 mm. On average 12 days with around 4 mm to 5 mm precipitation resulted in 54 mm of the total sum. Days with more precipitation contributed less to the annual sums, because fewer days with those amounts of precipitation occurred. In contrast, days with 0 mm to 1 mm precipitation occurred the most, but contributed even less than days with around 10 mm of precipitation. Finally, roughly half of the annual precipitation sums could be attributed to the 25 wettest days (Siegmund, 2022).

As stated above, over the period of 1991–2020 the mean annual precipitation over the P13 stations was 851 mm. This value, however differed locally. KNMI provides interpolated maps with 30-year mean annual precipitation sums in the Netherlands for the periods 1981–2010 and 1991–2020. Figure 3.2 shows the interpolated map of mean annual precipitation sums for the 1991–2020 period. The map

shows that the highest precipitation sums occurred in the provinces of North Holland and South Holland. High sums are also observed east of Utrecht, particularly in the forested Veluwe region. Within South Holland the highest annual precipitation sums are found in an area encompassing Delft, Zoetermeer, and parts of The Hague, Rotterdam and Leiden. In North Holland, highest precipitation amounts occur around Zaandam and Purmerend, as well as in the rural areas in-between. The lowest mean annual precipitation sums (700 mm/yr to 725 mm/yr) are observed in the central part of the province of Limburg.

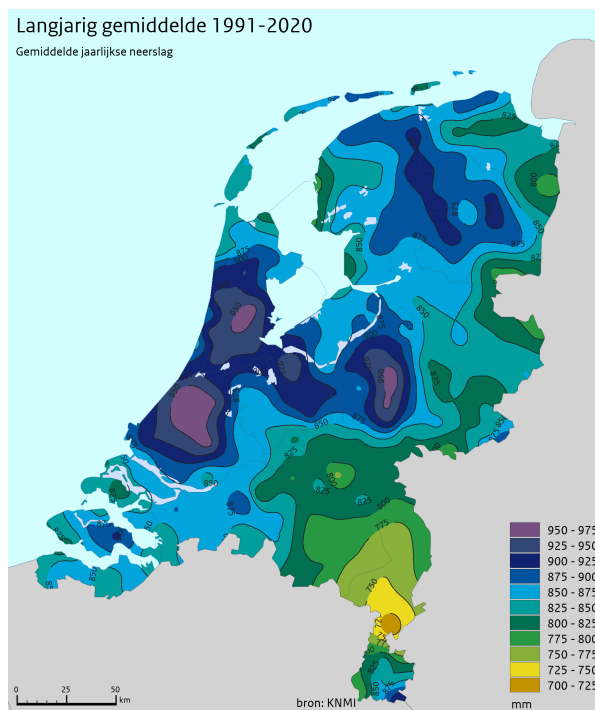


Figure 3.2: Interpolated map of 30-year mean of annual precipitation sums in 1991–2020 based on manual precipitation measurements. From "Koninklijk Nederlands Meteorologisch Instituut", by KNMI, n.d.-n. (https://www.knmi.nl/klimaat-viewer/kaarten/neerslag-verdamping/gemiddelde-hoeveelheid-neerslag/jaar/Periode_1991-2020). Licensed under KNMI's CC0 copyright.

Above is focussed more on daily and annual precipitation sums. But as elaborated in Section 3.2, for rainwater loads on roof structures the intensity for 5-minute precipitation events with a return period of 50 years is considered. Which corresponds to an intensity of $0.0500 \times 10^{-3} \text{ m/s}$. This value corresponds with the 50-year return level of 5-minute precipitation events as investigated by A. Buishand and Wijngaard (2007).

A. Buishand and Wijngaard (2007) investigated short duration precipitation extremes for precipitation durations between 5 and 120 minutes for station De Bilt. The methodology of their research is elaborated below.

Data with annual maxima were considered between 1906–1990. These values were based on the set-up before the electronic precipitation gauges, where precipitation was recorded continuously on precipitation strips. The 5 and 10 minute values up to 1983 were hard to read and therefore likely resulted in an error of 10 % to 20 %. A GEV distribution was fitted by applying maximum likelihood. The shape parameter was kept constant at -0.090 for all precipitation durations. This was based on research on precipitation in Belgium, which showed a minor change in shape parameters for durations between 10 minutes and 24 hours. Therefore the author assumed that the shape parameter of 5-minute events is similar to longer durations. With a maximum likelihood estimation it resulted in a location and scale parameter of respectively 5.30 mm and 2.02 mm. With a 50-year return level of 14.7 mm. However to keep a consistency between the different durations, a regression line was fitted for the two parameters, with as variable the natural logarithm of the duration. This resulted in a GEV distribution for 5-minute precipitation events with a location parameter of 5.32 mm, a scale parameter of 2.05 mm and

a shape parameter of -0.090 . For the 50-year return level of 5-minute events, this resulted in 14.9 mm or an intensity of 0.05 mm/s which is slightly higher than the value where consistency of the durations is not considered.

The data used by A. Buishand and Wijngaard (2007) is not publicly available, however the KNMI has provided this data after a request. This allowed a comparison to be made with the fixed shape parameter of -0.09 and a shape parameter fitted on the available data.

The data showed no monotonic trend, which justifies the choice of a stationary extreme value analysis. Using a maximum likelihood fit, this resulted in the following parameters shape, location, and scale parameters: 0.043 , 5.44 , and 2.09 . This means that the tail is much less heavy, compared to the fit in A. Buishand and Wijngaard (2007). This results in a much lower 50-year return level of 12.9 mm for 5-minute events. This is presented in Figure 3.3, together with the GEV distributions for the fixed shape and the fixed shape where consistency is kept between the durations.

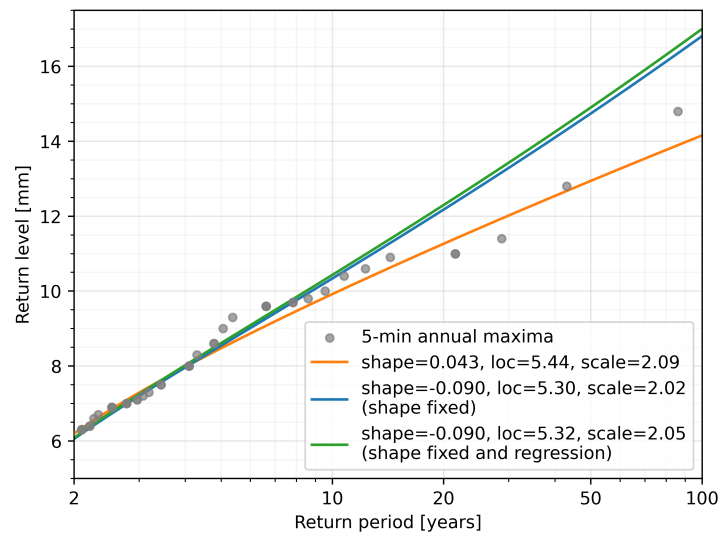


Figure 3.3: Return level plots for 5-minute precipitation events for different GEV-fits

Beersma et al. (2018) investigated extreme precipitation events in the Netherlands for event durations ranging from 10 to 720 minutes. Additional details of this study, together with studies on longer precipitation durations, are provided in Appendix A.1. Using a reference period of 2003–2016 and observations from several weather stations across the Netherlands, the authors obtained a dataset of 436 annual maxima for each event duration. Extreme value analysis was then applied to derive equations for estimating precipitation amounts corresponding to different event durations (between 10 and 720 minutes) and return periods. For a 10-minute event, the estimated 50-year return level was 24.7 mm . By extrapolating the depth–duration relationship to a duration of 5 minutes, the corresponding 50-year return level was estimated to be 18.1 mm , equivalent to a precipitation intensity of 0.06 mm/s (217 mm/h).

These results suggest that the estimated 5-minute precipitation intensity for the period 2003–2016 is higher than that reported for the period 1906–1990 (A. Buishand & Wijngaard, 2007). However, this comparison should be interpreted with caution, as it is based on extrapolated values and differences in data sources and methodologies. Also, the research of A. Buishand and Wijngaard (2007) is based only on station De Bilt, while Nicolai et al. (2024) considered 31 weather stations across the country. Also, several adjustments in gauge set-up took place for De Bilt between 1906–1990, likely resulting in inhomogeneous precipitation series.

Furthermore, the extrapolated 5-minute intensity is approximately 20 % higher than the value specified in the National Annex of NEN-EN 1991-1-3, indicating that the Annex may underestimate short-duration precipitation extremes. However, part of this inconsistency may be attributed to differences in the underlying data and methodology. The Annex is likely based on observed 5-minute precipitation data in De Bilt, whereas the estimate in this study is derived by extrapolation from 10-minute statistics for 31

stations. Still, the research of A. Buishand and Wijngaard (2007) only considered De Bilt up to 1990, while this research considers 31 stations around the country for a more recent period of time. Making a research on De Bilt solely, underestimating the intensities of short duration events around the country. Furthermore, extreme precipitation events are occurring now more often than earlier and are likely to become more frequent for climate change. Therefore, a revision of the Annex might be justified.

3.4. KNMI'23 climate scenarios methodology and projections

As stated in Section 3.1, a distinction can be made between large-scale precipitation and convective precipitation. In the KNMI'23 climate scenarios this distinction is also made for precipitation projections.

3.4.1. Large-scale precipitation

Large-scale precipitation projections are mostly driven by thermodynamic and dynamic changes in the atmosphere (van Dorland et al., 2024). A major thermodynamic mechanism is the increase in atmospheric moisture content with rising temperatures. As stated earlier, according to the Clausius-Clapeyron relationship, the water holding capacity of the atmosphere increases by approximately 7 % per °C of warming. This provides more moisture for precipitation and generally contributes to increasing precipitation. However, precipitation changes are not only determined by moisture availability. Dynamic processes, such as changes in atmospheric circulation, wind direction, and vertical air motions, also play an important role. For the Netherlands, these circulations changes are particularly relevant because air coming from the direction of the North Sea contains substantially more moisture than air masses from the continental directions. Changes in the frequency and duration of certain circulation patterns can therefore either increase or decrease the thermodynamic increase in atmospheric moisture. According to the KNMI, uncertainties in these circulation changes are one of the main causes of the large spread in projected precipitation changes across the CMIP6 models (van Dorland et al., 2024).

In the large-scale precipitation projections by van Dorland et al. (2024), several general trends can be observed. Across all scenarios and both dry and wet variants, the magnitude of change increases with time and is more pronounced in higher emission scenarios. As expected, the Wet scenarios show a more positive change in precipitation and a less negative change in precipitation compared to the Dry scenarios. While for the Dry scenarios a more negative and less positive change in precipitation is projected compared to the Wet scenarios. The strongest precipitation increases occur during winter in the Wet scenarios, while the largest decreases occur during summer in the Dry scenarios, which is consistent with the way these scenarios are defined by the KNMI.

A more detailed assessment of the precipitation projections by the KNMI over the Netherlands reveals some regional differences. In the low-emission scenarios (Ld and Ln), precipitation responses are weaker and exhibit greater noise compared to higher emission scenarios. In both Ld and Ln, the summer precipitation is projected to decrease in the entire country, except for the top north. During winter, precipitation is projected to slightly increase in the entire country, with largest increases in the north-east. The slight increase in precipitation during summer in the northern regions, in contrast to the decrease in the rest of the country, is caused by strong afforestation under the SSP1-2.6 scenario. Overall, northern regions are projected to become wetter, while the southern regions become drier. Regional variations in the direction of change were likely caused by random noise in the climate models. Therefore, these small differences should be considered statistically meaningless (van Dorland et al., 2024).

In Table 3.2 the mean annual precipitation changes for the Netherlands for the 2100 time horizon for different forcing scenarios and wet and dry variants are presented. The values are based on the grid cells of the P13 manual precipitation stations (KNMI, n.d.-m).

Table 3.2: Mean precipitation increases around 2100 in the Netherlands with respect to the 1991–2020 reference period. For each scenario, the first column provides the projected precipitation (mm) and the second column the relative change (%) with respect to the 1991–2020 reference period. Adapted from van Dorland et al. (2024).

	1991–2020	Ld		Ln		Md		Mn		Hd		Hn	
Annual	851	851	0	868	+3	834	−1	894	+5	817	−3	919	+8
Winter	218	225	+4	227	+5	229	+5	240	+10	249	+14	270	+24
Spring	153	155	+1	158	+3	158	+4	162	+7	159	+4	168	+10
Summer	235	216	−8	228	−2	200	−15	228	−3	167	−29	204	−12
Autumn	245	255	+4	257	+5	252	+3	262	+7	247	+1	277	+13

3.4.2. Convective precipitation

Convective precipitation extremes often occur during the warm season (May to September). Under a warming climate, the frequency of these extremes are expected to occur more frequently and over a longer part of the year. Since convective rainfall depends on different processes on different scales, KNMI employed a combination of models for the modelling of convective rainfall. Such as global climate models (GCMs), regional climate models (RCMs), and convection permitting climate models (CPMs), all had different strengths and limitations. GCMs were capable of modelling large-scale climate processes and circulation changes. However, their spatial resolution was too coarse to resolve convective circulations. RCMs (such as RACMO) provided more detailed regional representation of the climate. However, they still operated at grid sizes that are too large to simulate the vertical motions and cloud dynamics associated with convective precipitation. Instead, convection was considered by parametrisation schemes that estimated the net effect of unresolved convective processes. The parametrisations were a major source of uncertainty, that often led to an underestimation of short duration precipitation extremes (van Dorland et al., 2024).

van Dorland et al. (2024) used CPMs to overcome these limitations for convective precipitation representation. CPMs operate at $2.5 \text{ km} \times 2.5 \text{ km}$ resolutions and resolve deep convective motions. As a result, the formation and development of convective storms can be simulated more realistically. KNMI compared the CPM simulations with hourly precipitation observations from 30 to 35 Dutch weather stations for the period 1991–2020. Furthermore, observations from France were considered, as the current French climate may resemble future summer conditions in the Netherlands. The comparison showed that CPMs reproduce hourly precipitation extremes significantly better than RCMs. The RCM simulations significantly underestimated the intensity of extreme hourly precipitation events.

A major assumption in the methodology was that future changes in extreme convective precipitation can be related to changes in atmospheric moisture availability. Dew point temperature was used as a key indicator, since it reflects the amount of water vapour in the atmosphere. Observations showed a strong relationship between extreme hourly precipitation and dew point temperature (as stated in Section 3.1). Rising dew point temperatures generally increase precipitation intensities. The projected changes in dew point temperature from climate models were therefore used by the KNMI to estimate future convective precipitation extremes. However, considerable uncertainty remained because the relationship between dew point temperature and extreme precipitation was not constant under all atmospheric conditions. It might be influenced by factors such as atmospheric stability and large-scale circulation patterns (van Dorland et al., 2024).

Still CPMs also have important limitations. They demand high computational costs and the simulations are therefore considered for small domains and short time periods. Consequently, CPMs cannot fully represent large-scale climate circulation changes that are captured by GCMs and RCMs. Therefore, the projected changes in hourly and daily precipitation extremes were given for the wet and dry variants for 4°C global warming. These were given for each season and for specific return periods. The return level changes were derived using a Generalized Pareto Distribution (GDP). The reported lower and upper values should not be interpreted as confidence, but rather as plausible bounds according to van Dorland et al. (2024).

A key assumption of the KNMI methodology is that both the projected changes in dew point temperature and precipitation frequency scale roughly linearly with global temperature change. Furthermore, it

was assumed that the relationship between extreme precipitation intensity and dew point temperature, derived from observations and CPM simulations, remains valid in the future. These assumptions allow the CPM projections to be scaled to different warming levels. The projected changes in hourly precipitation at a global warming level of 4°C are shown in Figure 3.4, while the corresponding changes for daily precipitation extremes are presented in Figure 3.5. The solid black line represent the median projections and the dashed line indicate the uncertainty range.

As shown in Tables 5.5 till 5.8 in van Dorland et al. (2024), both hourly and daily precipitation extremes are currently highest during summer. Future projections indicate increasing precipitation extremes for all seasons. The wet variant exhibits substantially larger increases than the dry variant. For both hourly and daily precipitation extremes, the strongest increases are generally projected for autumn. The differences between the wet and dry variants arise from different projected changes in atmospheric moisture availability and precipitation frequency. Furthermore, hourly precipitation extremes show a larger sensitivity to climate change than daily extremes. This emphasises the stronger influence of convective processes on short-duration precipitation events. Overall, the results indicate that the extreme precipitation events are likely to become more intense in all seasons. Although the magnitude between seasons differs and is highly uncertain.

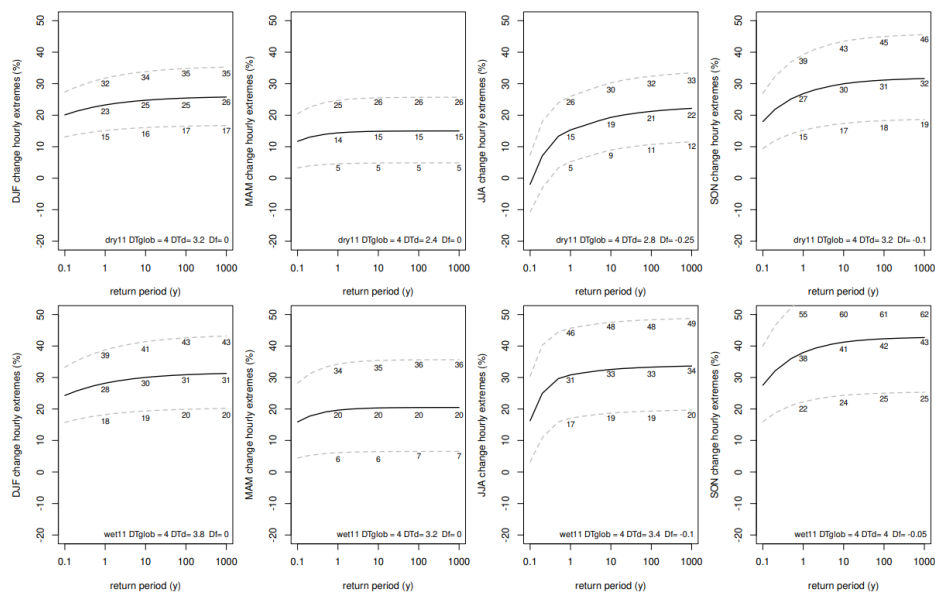
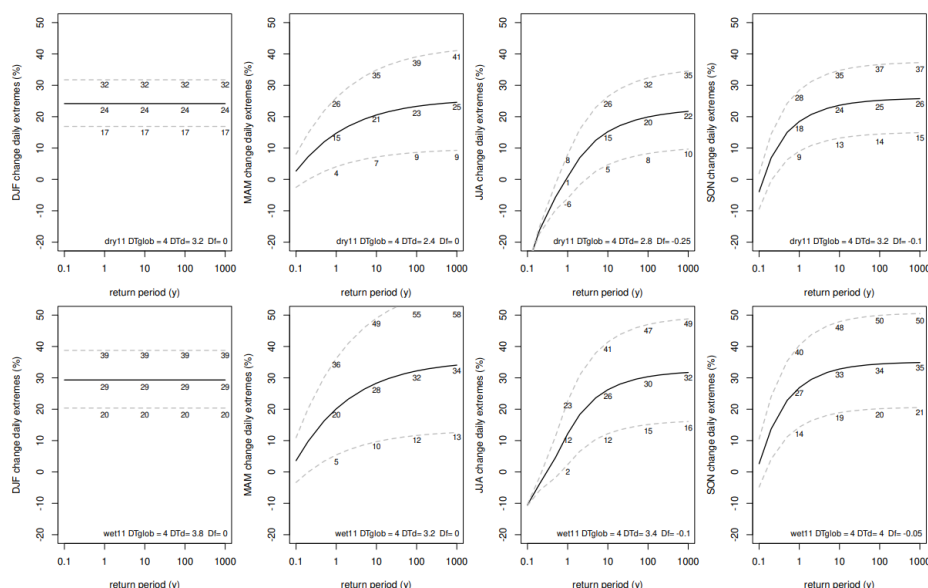


Figure 3.4: Projected changes in return levels of hourly precipitation extremes for a global temperature rise of 4°C for all seasons. Dry scenarios are visible on top and Wet scenarios below. From left to right: winter (DJF), spring (MAM), summer (JJA), and autumn (SON). From *KNMI National Climate Scenarios 2023 for the Netherlands* (fig 5.33, p. 216), by Koninkrijk Nederlands Meteorologisch Instituut, 2024. Licensed under KNMI's CC0 copyright.



Based on the KNMI'23 climate projections, Nicolai et al. (2024) derived scaling factors for precipitation amounts for event durations ranging from 10 minutes to 8 days. Separate scaling factors were developed for annual precipitation extremes and winter precipitation extremes. The derived relationships were expressed as a function of global warming level. In this literature review, the methodology and results of the annual precipitation extremes are considered, as these are most relevant for the assessment of rainwater loads on structures (Section 3.2).

The methodology of Nicolai et al. (2024) consisted of several steps. First, RACMO output from the KNMI'23 climate projections was analysed for the grid cell containing De Bilt. It is not explicitly stated whether the original ensemble resamples or the user-friendly processed KNMI output was used. For each climate scenario, variant, and time horizon, eight ensemble members are available, resulting in 240 years of daily precipitation projections per scenario. For each scenario, annual maxima were extracted for precipitation durations between 1 and 10 days, with steps of one day. Subsequently, stationary GEV distributions were fitted to these annual maxima. The uncertainty of the fitted distributions was estimated through bootstrapping, from which the 95 % confidence interval was derived.

An important methodological choice concerns the shape parameter of the GEV distribution. The shape parameter was kept fixed for all scenarios. This choice was motivated by the relatively limited sample sizes and by earlier findings suggesting that the shape parameter may vary only little between climates (van den Brink, 2023). However, more recent studies indicate that climate change may affect the upper tail behaviour of precipitation extremes. For example, Gründemann et al. (2022) found that rare rainfall events are projected to increase more strongly than common events, suggesting possible changes in the tail of the distribution. Similarly, Jayaweera et al. (2025) showed that the largest increases occur for the rarest rainfall events and suggested that such behaviour may require a non-stationary shape parameter. Consequently, fixing the shape parameter may underestimate changes in the most extreme precipitation events.

Based on the fitted GEV distributions, depth-duration-frequency (DDF) curves were constructed for all climate scenarios. To obtain physically realistic curves, several constraints were considered. For example, precipitation depth was required to increase with increasing event duration. Spline smoothing was later applied while ensuring that the resulting curves remained within the confidence intervals of the fitted return levels. Factors of change were then derived by dividing the precipitation amounts of the future climate scenarios by those of the reference climate. Additional smoothing was applied to

remove non-monotonic behaviour in the factors of change as a function of precipitation duration.

The resulting RACMO-based factors of change for the high forcing scenarios around 2100 (roughly 4 °C global warming) were subsequently compared with factors derived from the CPMs. Since the CPM projections were only available per season rather than for annual extremes, the summer season (JJA) was used for the comparison. This choice was considered since the largest short-duration precipitation extremes in the Netherlands generally occur during summer.

For a duration of one day and return periods exceeding approximately one year, the RACMO factors of change were generally higher than the CPM-derived summer factors. The wet RACMO variant remained within the range. Furthermore, the CPM projections suggested larger changes for the wet variant, while the RACMO results indicated larger changes for the dry variant for return periods larger than five years. Because the CPM comparison did not show a clear difference between the wet and dry variant, Nicolai et al. (2024) concluded that no clear distinction could be made between these variants for precipitation extremes. Since the wet variant showed a better correspondence between CPM and RACMO results, it was considered as the representative scenario for the next analysis.

The RACMO analysis provided factors of change only for durations between 24 and 240 hours. However, the research of Nicolai et al. (2024) also required factors for durations between 10 minutes and 24 hours. The CPM results could be considered for hourly and daily durations. Although the CPM projections indicated slightly larger changes for hourly precipitation than for daily precipitation, these differences were small compared with the overall uncertainty. Therefore, it was assumed that sub-daily precipitation durations exhibit approximately the same relative changes as the 24 hour precipitation durations derived from RACMO.

To obtain factors of change for intermediate durations, a logarithmic quadratic polynomial was fitted through the mean factors of change for durations of 24, 48, 72, 96 and 120 hours. For durations exceeding 120 hours, the factor corresponding to 120 hours was considered. This resulted in the following factors of change for a global warming level of 4 °C (Nicolai et al., 2024):

- 1.234 for durations between 10 minutes and 24 hours
- 1.109 for durations between 120 and 240 hours

For durations between 24 and 120 hours, the factor of change is given by:

$$0.009134 \cdot (\ln D)^2 - 0.1508 \cdot \ln(D) + 1.621 \quad (3.5)$$

where D is the event duration in hours.

Nicolai et al. (2024) extended these factors to other levels of global warming, by applying a linear interpolation. At the time of the study, the global warming level relative to the centre of the 1991–2020 reference period was approximately 0.4 °C. For this warming level, the factor of change was equal to one. The authors assumed a linear relationship between global warming and the factor of change, which resulted in:

$$1 + (V_{2100Hn}(D) - 1) \times (Ts - 0.4) / (4 - 0.4) \quad (3.6)$$

where $V_{2100Hn}(D)$ is the factor of change for duration D under the wet high forcing scenario around 2100 and Ts is the global warming level of interest.

The resulting scaling factors for annual precipitation extremes are presented in Figure 3.6. It should be noted that the final factors did not include the uncertainties that were associated with the climate projections, the GEV fitting, the fixed shape parameter, the comparison between RACMO and CPM, or the extrapolation from daily to sub-daily durations. Consequently according to Nicolai et al. (2024), the presented factors should be interpreted as best estimates.

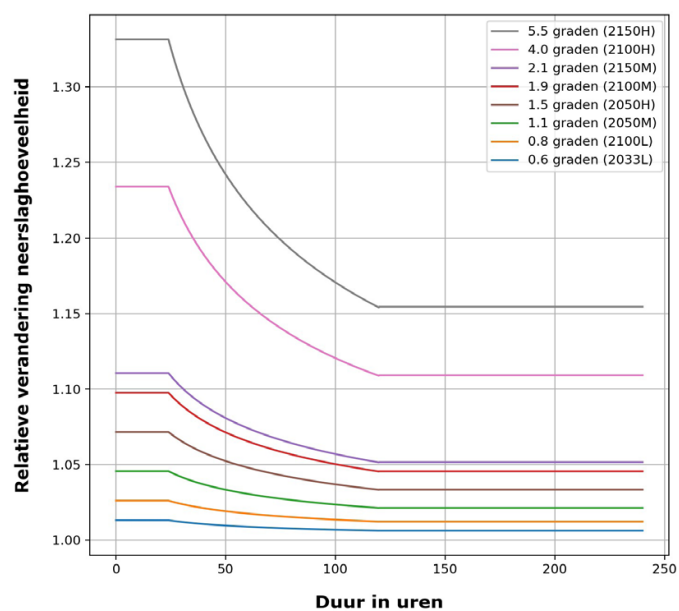


Figure 3.6: Factors of change for annual precipitation extremes for different global warming levels and event durations. From *Neerslagstatistiek KNMI'23* (fig. 18, p. 26), by Stichting Toegepast Onderzoek Waterbeheer, 2024.

Methodology precipitation analysis

The methodology used to answer the precipitation-related research questions consists of two main components: a historical observation analysis and an analysis of future climate projections.

4.1. Historic analysis

The methodology for the historical precipitation analysis is presented in this section.

The advantages and limitations of both manual precipitation stations and automatic weather stations are discussed in Section 3.3.1. For the historical analysis, precipitation observations from stations Vlissingen, De Kooy, De Bilt, Beek, and Eelde were considered. These stations were selected to represent the different climates within the Netherlands.

4.1.1. Annual and daily precipitation sums

For the analysis of annual and seasonal precipitation sums and annual maxima of daily precipitation, the daily observations from the manual precipitation stations were used. These observations are considered to be more suitable for long trend analyses, because they provide the longest and most homogeneous observations.

For stations Vlissingen, De Bilt, Beek, and Eelde, homogenised daily precipitation series were obtained from KNMI Climate Explorer (2026a). Although homogenised observations were available from approximately 1910 onwards, these observations were not corrected for changes in gauge height (KNMI Climate Explorer, 2026b). To ensure consistency, only observations from the homogenised series of 1951 onwards were therefore considered. For De Kooy, no homogenised precipitation series were available. Therefore, the regular daily precipitation observations from KNMI (2026b) were used. These observations have been corrected for the known faulty precipitation gauge and do not show unusual discontinuities. The series was therefore considered sufficiently homogeneous for this study.

The first complete year of observations is 1951 for Vlissingen, De Bilt, Beek, and Eelde, and 1959 for De Kooy. For all stations, observations up to 31 December 2025 were included. This results in record lengths of 75 years for four stations and 67 years for De Kooy.

The annual and seasonal precipitation sums of the five stations were first compared with sums of the P13 stations, to assess whether the selected stations are representative for the precipitation variability in the Netherlands. Subsequently, long-term trends in annual and seasonal precipitation sums were analysed.

For the analysis of precipitation extremes, the annual maxima of daily precipitation were derived for each station. Potential monotonic trends in these annual maxima were investigated with the Mann-Kendall trend test. Depending on the presence or absence of a statistically significant monotonic trend, either a stationary or a non-stationary extreme value analysis was performed using the ProNEVA toolbox. GEV distributions were fitted to the annual maxima series. For stations showing a significant

trend, a non-stationary GEV model was considered, in which the location parameter varies with time. Finally, the goodness of fit of the fitted distributions was evaluated.

4.1.2. Approximation of 5-minute precipitation intensities

As discussed in Section 3.3.1, the KNMI changed its precipitation measurement methodology in 1993, after which precipitation was recorded in discrete intervals rather than a continuous measurement. Since then, hourly precipitation totals and durations have been available from the automatic weather stations. Also 10-minute precipitation observations are available.

For this study, the hourly precipitation dataset was selected because it provides both the total precipitation amount per hour (in 0.1 mm resolution) and the duration of precipitation within that hour (in 0.1 h steps). A precipitation duration of 0.1 hour corresponds to approximately 6 minutes and therefore provides the closest available approximation of the 5-minute precipitation intensities considered in the Eurocode (KNMI, n.d.-u).

For all hours with a recorded precipitation duration of 0.1 hour, a corresponding 6-minute precipitation intensity was calculated by dividing the hourly precipitation amount by 0.1 hour. The resulting intensities were then used to derive annual maxima. The available 10-minute precipitation observations were not considered. Although these data provide a more direct estimate of short-duration precipitation intensities, they are only available from 2012 onwards. The resulting record length was considered too short for a reliable annual maxima analysis. In addition, the size and complexity of these datasets were beyond the scope of this research.

An important limitation of the hourly precipitation dataset is that multiple precipitation events occurring within a single hour are stored into one hourly precipitation amount and one total precipitation duration. Consequently, individual short-duration precipitation events may not be resolved, potentially leading to an underestimation of the extreme short-duration intensities.

As discussed in Section 3.3.1, several changes in instrumentation have occurred over time, introducing potential inhomogeneities into the observations. To minimise these effects, only data recorded in the year after the most recent major instrumentation change at each station were considered. The most relevant changes were the introduction of the electronic precipitation gauge and the installation of the Ott screen.

For all stations, observations up to 31 December 2025 were included. The starting years of the analysed series were as follows:

- Vlissingen: 1994;
- De Kooy: 2008;
- De Bilt: 2009;
- Beek: 2006;
- Eelde: 2010.

Still, the lengths of these time series are only slightly longer than those of the available 10-minute precipitation observations. Although the selected dataset provides more observations, the sample sizes remain relatively small for extreme value analysis. As a result, the fitted GEV distributions and derived return levels may be associated with considerable uncertainty.

Annual maxima of the derived 6-minute precipitation intensities were extracted for each station. Potential monotonic trends were then assessed. Depending on the outcome of the trend analysis, either stationary or non-stationary GEV distributions were fitted using the ProNEVA toolbox. Finally, the goodness of fit of the fitted distributions was evaluated and the resulting 50-year return levels were compared with the precipitation intensities prescribed for rainwater loads in the Eurocode.

4.2. Future climate projections analysis

This section shows the methodology for the projected precipitation analysis.

For the analysis of the future 5-minute precipitation intensities, a methodology similar to the approach

of Nicolai et al. (2024) was applied (See Subsection 3.4.2 for further details). The user-friendly RACMO outputs from the KNMI'23 climate scenarios were considered for the low, moderate, and high radiative forcing scenarios, including both wet and dry variants and the available time horizons of 2050, 2100, and 2150. The daily precipitation outputs were used. The grid cell containing De Bilt was selected, allowing direct comparison with the historical observations.

As discussed in Section 2.3, projected land-use changes influence future precipitation projections. These effects are especially noticeable in the eastern and northeastern parts of the Netherlands. Around De Bilt, however, the influence of land-use changes on projected precipitation intensities is relatively limited. The selected grid cell was therefore considered to be representative for analysing the climate change signal in precipitation extremes.

For each scenario, variant, and time horizon, the annual maxima of daily precipitation were taken for all eight ensemble members. The same procedure was applied for the model reference period (1991–2020). The modelled annual maxima of the reference period were subsequently compared with the observed annual maxima at De Bilt to assess the performance of the model output. In addition, monotonic trends within the annual maxima series of each ensemble member were evaluated. If no significant monotonic trends were detected, the annual maxima of the eight ensemble members were combined into a single series. This resulted in 240 annual maxima values per scenario (8 ensemble members of 30 years), increasing the sample size available for the extreme value analysis.

Because this study focuses on short-duration precipitation events relevant for rainwater loads and emergency drainage design for building, only annual maxima of daily precipitation were considered. Annual maxima of multi-day precipitation totals were not analysed.

GEV distributions were fitted to the annual maxima using the `scipy.stats.genextreme` implementation in Python. The distribution parameters were estimated using the maximum likelihood method. In contrast to Nicolai et al. (2024), the shape parameter was not fixed but estimated separately for each scenario. This choice was motivated by recent studies suggesting that climate change may affect the tail behaviour of precipitation extremes and that a constant shape parameter may therefore not be suitable under changing climatic conditions (see Section 3.4.2).

The fitted GEV distributions were subsequently used to estimate 50-year and 100-year return levels. Factors of change were determined by dividing the return levels of the future scenarios by those of the reference period. The 100-year return levels were used to compare the RACMO derived projections with the available CPM projections for 4 °C global warming. The CPM projections are reported for return periods of 0.1, 1, 10, 100 and 1000 years, making a direct comparison at a return period of 100 years possible. Furthermore, the 100-year return period lies sufficiently far in the upper tail of the distribution to assess projected changes in extreme precipitation. However, avoiding the larger uncertainties linked to the 1000-year return period.

4.3. Emergency drainage design under climate change

This section describes the methodology used to assess the effects of climate change for the design of emergency drainage systems.

To assess the implications of climate change for emergency drainage design, the moderate radiative forcing scenario (SSP2-4.5) and the 2050 time horizon were considered. SSP2-4.5 was selected because it represents a pathway in which global greenhouse gas emissions remain approximately at current levels until the middle of the century before gradually declining. This scenario was considered to represent a likely future under current climate policies. The 2050 time horizon was chosen assuming that a building is designed and constructed today with a design life of approximately 50 years. The corresponding KNMI'23 projections, representing the period 2036–2065 and a global warming level of approximately 1.1 °C relative to 1991–2020, were therefore assumed to be representative for most of the building's design life.

As discussed in Section 3.2, increases in precipitation intensity can be adjusted for by modifying several aspects of the roof design, such as increasing the structural stiffness to reduce roof deformations. In this analysis, only the emergency drainage design was considered. The width of the emergency drainage opening was taken as the design parameter to account for changes in precipitation intensity. The

projected 50-year return level of the 5-minute precipitation intensity was divided by the characteristic intensity prescribed in the Dutch National Annex of NEN-EN 1991-1-3 to obtain a factor of change. Subsequently, the emergency drainage equations provided in the National Annex were used to translate this factor into the corresponding increase in the required drainage width.

5

Results precipitation analysis

This chapter presents the results of the precipitation analysis based on the methodology described in Chapter 4. The analysis focuses on both historical observations and projected changes under the KNMI'23 Climate Scenarios. To keep this chapter concise, additional figures, tables, and information are provided in Appendices A and D. Section 5.1 discusses the historical daily precipitation observations. Including the identified trends in annual maxima and the extreme value analysis of daily precipitation sums. Section 5.2 presents the extreme value analysis of historical 6-minute precipitation events. Section 5.3 presents the results of the analysis of projected short-duration precipitation extremes. Finally, Section 5.4 discusses the implications of the projected changes for the design of emergency drainage systems on buildings in the future under climate change.

5.1. Historical daily precipitation

This section first presents trends in historical annual precipitation sums. Subsequently, trends in the annual maxima of daily precipitation sums are analysed, followed by an extreme value analysis of these annual maxima.

5.1.1. Trends in annual and seasonal precipitation sums and wet days

Precipitation sums are analysed on annual, winter, spring, summer, and autumn bases. Here, "winter" refers to the months December, January, and February (DJF), "spring" to March, April, May (MAM), "summer" to June, July, August (JJA) and "autumn" to September, October, November (SON). This seasonal classification allowed trends to be compared across the year and later enables comparison with the KNMI'23 climate scenarios.

Figure 5.1 shows the mean precipitation sums for the five selected manual stations from 1959 onwards. The sums are presented for the calendar year and for each season. A first-order polynomial trend line was fitted to the mean precipitation sums. The mean precipitation sums of the five stations for specific years and climatological periods were compared with the P13 station results.

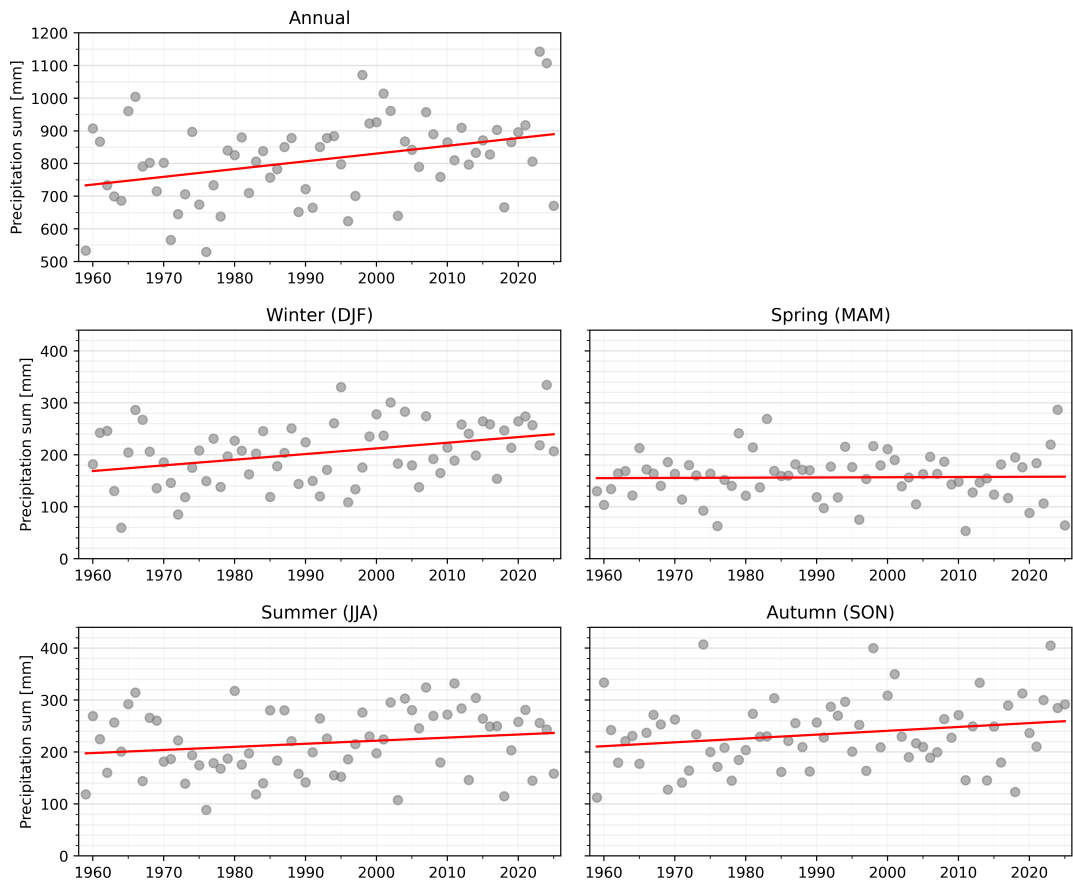


Figure 5.1: Mean precipitation sums of five stations

Figure 5.1 shows that the fitted trend lines for both annual and seasonal precipitation are positive. The estimated trends are 2.37 mm/yr for annual precipitation, 1.09 mm/yr for winter, 0.04 mm/yr for spring, 0.59 mm/yr for summer, and 0.74 mm/yr for autumn. A Mann-Kendall trend test with a significance level of 0.05 indicates a statistically significant monotonic upward trend for annual and winter precipitation, whereas no significant monotonic trends were detected for the other seasons.

For the annual precipitation sums, 1959 and 1976 stand out as very dry years, with totals of respectively 534 mm and 529 mm. In contrast, 2023 and 2024 were very wet, with annual precipitation sums of respectively 1143 mm and 1107 mm at the five selected stations. For the KNMI P13 stations, the corresponding sums were respectively 1155 mm and 1143 mm. (Huiskamp, 2024)(Huiskamp, 2025). Seasonal precipitation sums show that the largest amounts of precipitation occurred during autumn, followed by summer and winter, with the lowest amounts recorded in spring. A notable year is 2011, during which spring precipitation was exceptionally low (53 mm), while summer precipitation was extremely high (332 mm). As a result, 2011 had simultaneously the driest spring and the wettest summer in at least a century (KNMI, n.d.-l).

Table 5.1 presents the 30-year mean precipitation sums and the number of wet days for the periods 1961–1990 and 1991–2020, together with the corresponding percentage differences. Increases in 30-year mean precipitation were observed for the annual, winter, summer, and autumn seasons, whereas spring showed a small decrease of 4.8 %

The annual 30-year mean precipitation sums of the five stations closely approximate the KNMI P13 national means, which was 779 mm for 1961–1990 and 851 mm for 1991–2020 (Siegmund, 2022). Nevertheless, the average of the five stations underestimates the national mean by approximately 10 mm. In contrast to the increase in mean annual precipitation sums between the two climatological periods, no corresponding increase was observed in the mean annual number of wet days. A clear decrease in wet days was only evident for spring, while differences in the other seasons were negligible. Over-

all, these results indicate that although the annual precipitation sum has increased, the number of wet days has remained nearly constant. This suggests that precipitation events have become more intense rather than more frequent. These findings are similar to the KNMI findings, which also concluded that increases in total precipitation were primarily driven by higher precipitation intensities rather than by an increase in the frequency of wet days (Siegmond, 2022).

Table 5.1: 30-year mean precipitation sums and wet days for the periods 1961–1990 and 1991–2020 for all seasons.

Season	Mean precipitation			Wet days		
	1961–1990 [mm]	1991–2020 [mm]	Difference [%]	1961–1990 [d]	1991–2020 [d]	Difference [%]
Year	767	843	+10.0	202	201	−0.5
Winter	186	214	+15.1	56	59	+4.7
Spring	160	153	−4.8	49	43	−12.1
Summer	202	234	+15.8	44	45	+1.9
Autumn	219	241	+10.1	53	55	+2.2

Focusing on the individual trends of the annual and seasonal precipitation sums for the five stations shows consistent results with the trends derived from the mean of the five stations. For both annual and winter precipitation sums, a statistically significant monotonic upward trend was detected at all stations. In spring and autumn, a monotonic upward trend was observed only at De Bilt. In summer such a trend was identified only at Vlissingen and De Kooy.

Figure 5.2 presents the distributions of the annual precipitation sums for the five selected stations. For all stations, the mean annual precipitation sum increases across the three periods. Between 1961–1990 and 1991–2020, the lower bound increases for all stations except De Kooy. In the 1991–2020 period, the mean precipitation sums at Vlissingen, De Kooy, and De Bilt are lower than their medians, indicating left-skewed distributions.

Across all periods, the highest annual precipitation sums are observed at De Bilt, followed by Eelde, De Kooy, and Vlissingen, with the lowest sums at Beek. No immediate clear spatial pattern is evident from this ordering.

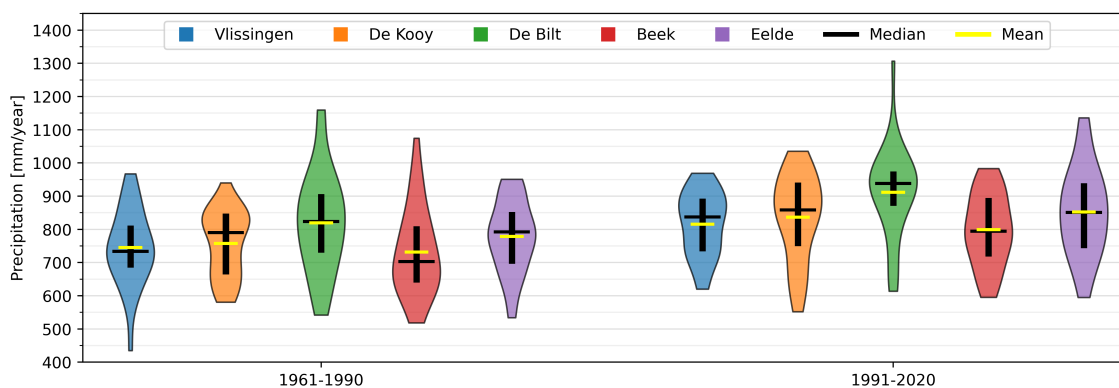


Figure 5.2: Violin plots for 30-year precipitation sum for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Maastricht*, and *Eelde*

5.1.2. Trends in daily precipitation sums

Figure 5.3 shows the time series of daily precipitation sums for the five stations. All individual observations are displayed, together with the annual maxima and a first-order polynomial trend line fitted to the annual maxima.

For Eelde, the fitted trend line has a zero slope. For De Kooy, De Bilt, and Beek, the estimated slopes are small and close to zero. In contrast, Vlissingen exhibits a clear positive slope, suggesting an increase in annual maximum daily precipitation over time. The Mann-Kendall trend test confirms that

a statistically significant upward trend in annual maxima is present only at Vlissingen. A seasonal analysis reveals that, during winter, significant upward trends are observed at Vlissingen and De Bilt. In spring, only for De Bilt is a monotonic upward trend identified. During summer, significant upward trends are found at Vlissingen and De Kooy. Finally, no significant trends are observed during autumn.

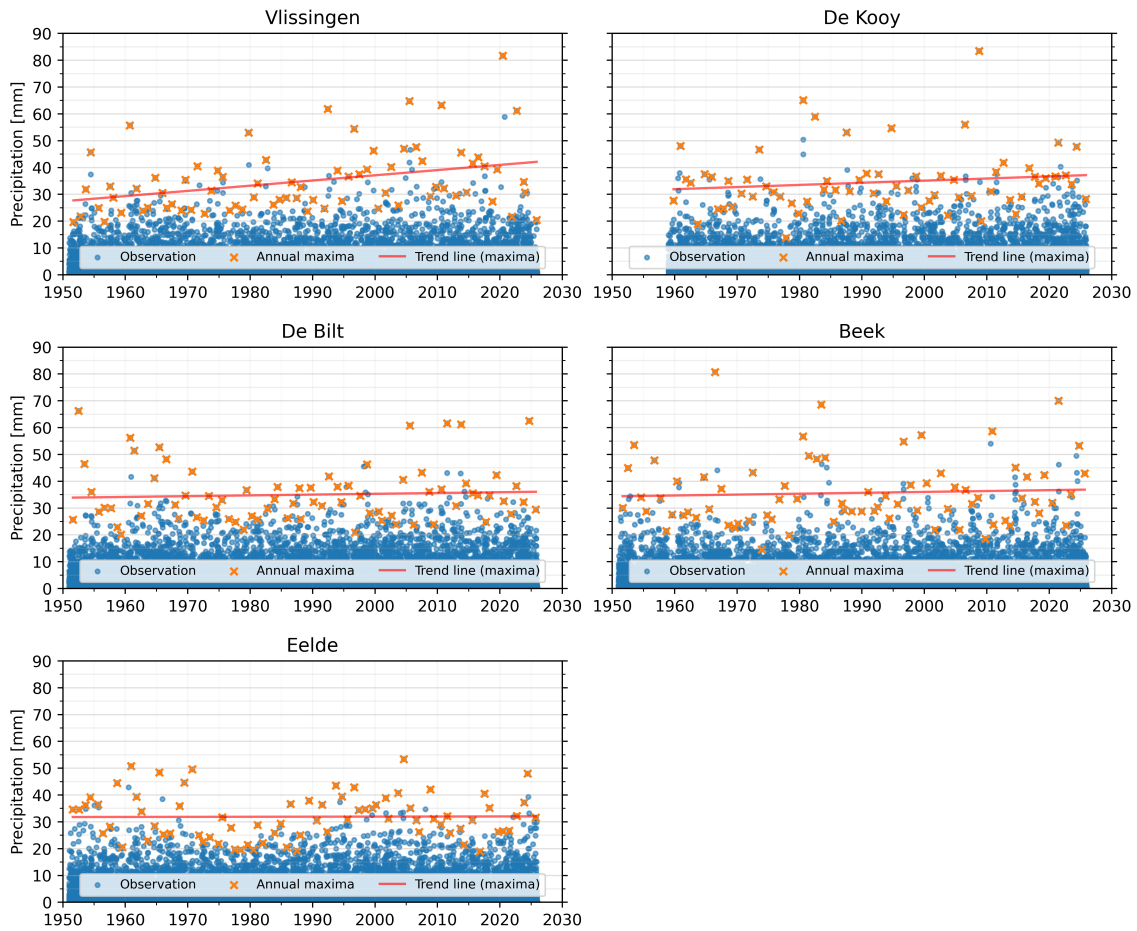


Figure 5.3: Daily precipitation, annual maxima of daily precipitation and a first-order polynomial trend line fitted to the annual maxima for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

Figure 5.4 presents the distributions of the annual maxima of daily precipitation for the climatological periods 1961–1990 and 1991–2020. For both periods, the distributions are right-skewed. For all stations except Beek, the mean and upper bounds of the annual maximum daily precipitation are higher in 1991–2020 than in 1961–1990. In contrast, Beek experiences a slight decrease in the mean annual maximum. Moreover, the range of annual maximum precipitation has increased between the two periods at all stations except De Bilt, where the range shows little change. Between 1961–1990 and 1991–2020, the largest increase in mean annual maximum daily precipitation was observed at Vlissingen: 34.0 %, corresponding to 10.4 mm/d. And the smallest increase occurs at De Kooy, with a rise of 4.5 % (1.48 mm/d increase). In contrast, Beek shows a decrease of 2.1 %, corresponding to an absolute change of -0.7 mm/d.

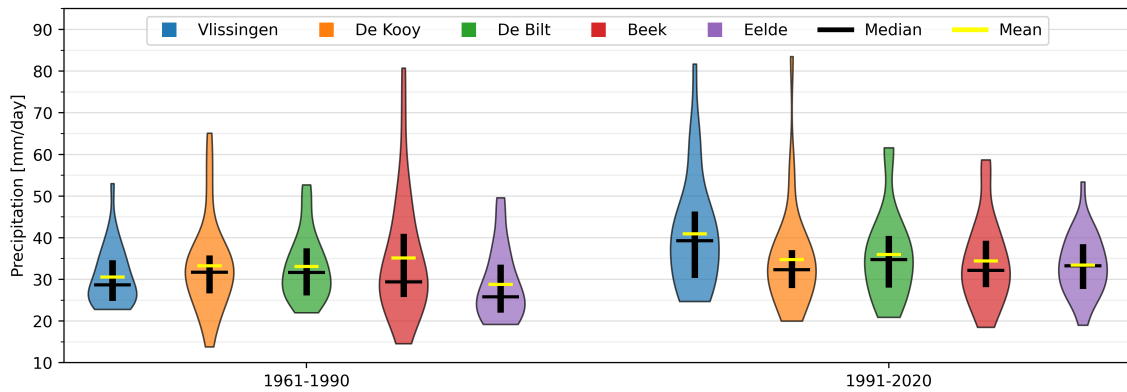


Figure 5.4: Violin plots for 30-year annual maxima of daily precipitation for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

5.1.3. Extreme value analysis of daily precipitation sums

For the extreme value analysis performed using the ProNEVA toolbox, a stationary generalized extreme value distribution was fitted to the annual maxima at all stations, with the exception of Vlissingen. The Mann-Kendall trend analysis indicates no statistically significant monotonic trends in the annual maxima at De Kooy, De Bilt, Beek, and Eelde. The chosen priors and model settings are provided in Appendix A.3.1. The rejection rates of the KS tests for the fitted extreme value distributions were all below 4%. This indicates that in fewer than 4% of the 10 000 simulated posterior samples, the null hypothesis that the modelled and observed distributions are identical was rejected at the 5% significance level. The RMSE of the fitted distributions was below 3.5% of the observational range for all stations, which indicates a satisfactory fit.

The PP and QQ plots (Appendix A.3.1) further demonstrate good agreement between the fitted distributions and the observations. However, for De Kooy and De Bilt, several upper quantiles in the QQ plots fall below the 1:1 line, indicating that the fitted model slightly underestimates the highest observed extremes. This suggests that the upper tail of the fitted distribution may be somewhat lighter than the tail of the observed data. This could lead to a small underestimation of very long return period precipitation extremes.

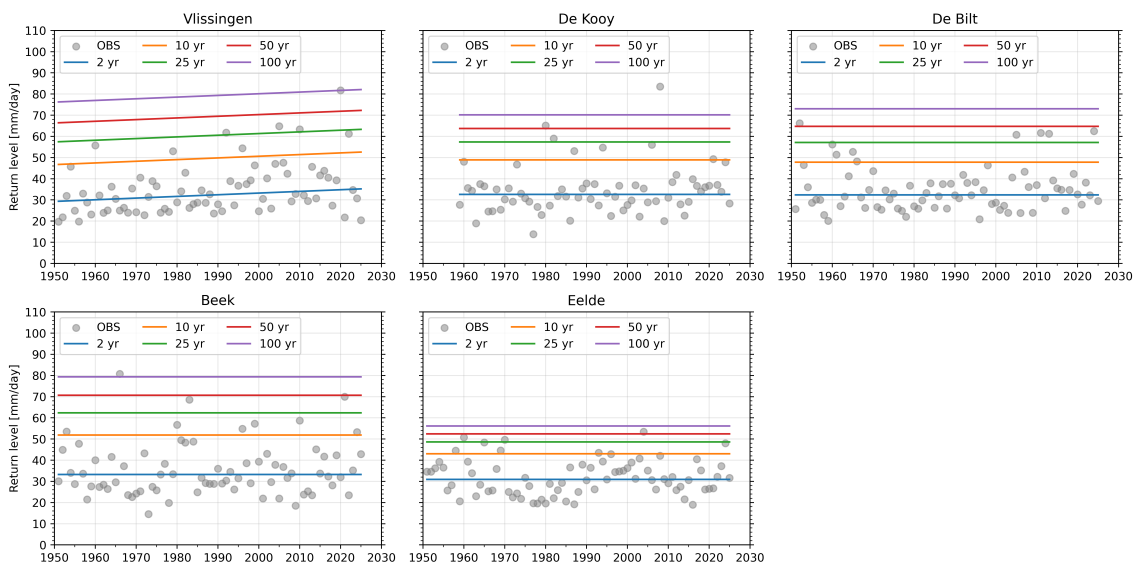


Figure 5.5: Return level plot of daily precipitation between 1951 (1959 for *De Kooy*) and 2025 for stations *Vlissingen*, *De Bilt*, *Beek*, and *Eelde* with return periods between 2 and 100 years

Figure 5.5 presents the estimated return level plots together with the observed annual maximum daily

precipitation for all stations. For Vlissingen, the estimated return levels increase over time, which is in line with the non-stationary extreme value model fitted to the data and the statistically significant upward monotonic trend in the annual maxima at this station. The estimated 50-year return level is lowest at Eelde (52.5 mm/d), followed by De Kooy (63.7 mm/d), De Bilt (64.8 mm/d), and Beek (70.7 mm/d). For Vlissingen, the estimated 50-year return level increased from 66.4 mm/d in 1951 to 72.3 mm/d in 2025.

5.2. Historical 6-minute precipitation intensities

This section presents the results of the historical 6-minute precipitation events. First, trends in the annual maxima are examined, followed by an extreme value analysis to estimate the corresponding return levels. Finally, the estimated return levels are compared with the values prescribed in the Dutch National Annex of NEN-EN 1991-1-3 and with recent studies, as discussed in Section 3.3.2.

5.2.1. Changes in the intensity of 6-minute precipitation events

Figure 5.6 presents the time series of precipitation intensity for events with a duration of 6 minutes at all stations. The annual maxima are highlighted, and a first-order polynomial trend line is fitted to these annual maxima. Vlissingen and De Kooy exhibit slightly positive slopes in the fitted trend lines, whereas De Bilt and Eelde show slightly negative slopes. Beek displays a relatively strong positive slope. Although the fitted trend lines differ between stations, the MK test applied to the annual maxima indicates that none of the stations exhibits a statistically significant monotonic trend in 6-minute precipitation intensity.

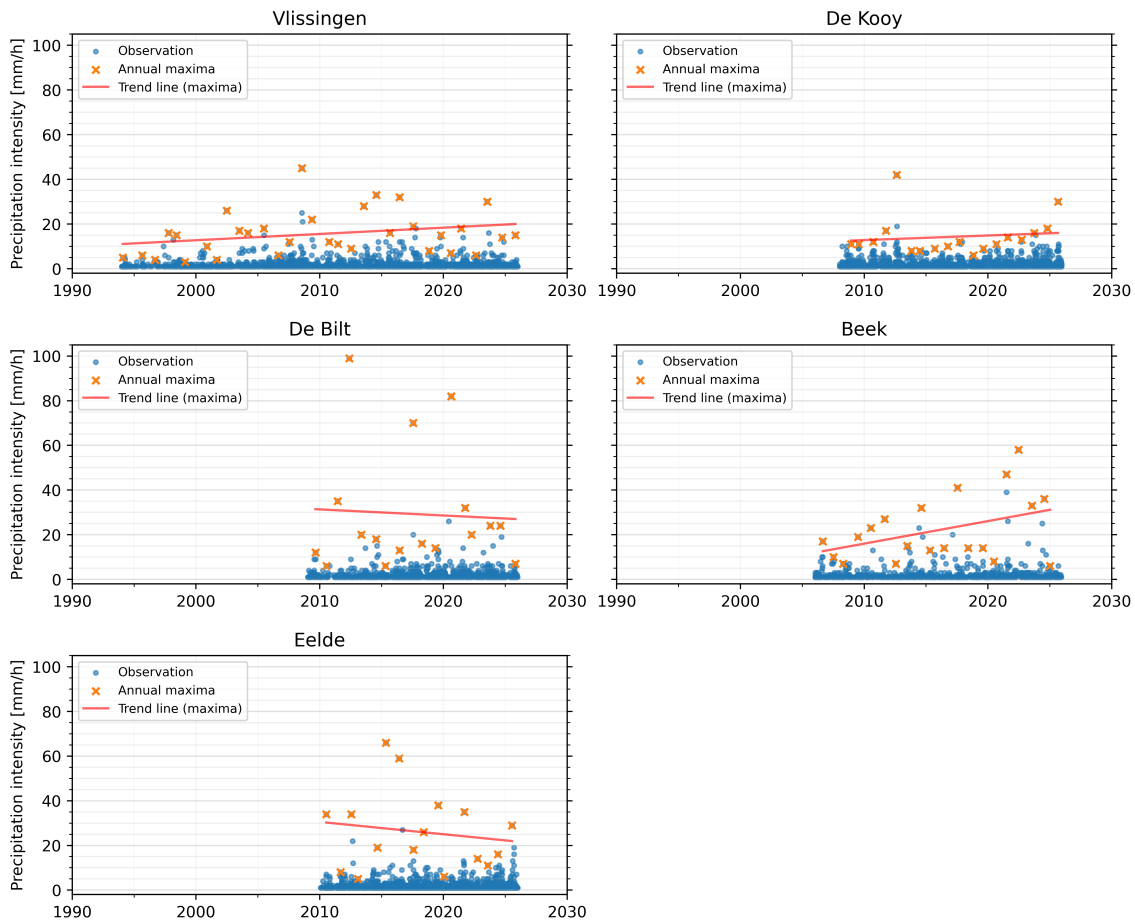


Figure 5.6: Precipitation intensity of events with a 6-minute duration, annual maxima highlighted, and a first-order polynomial trend line fitted to the annual maxima for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

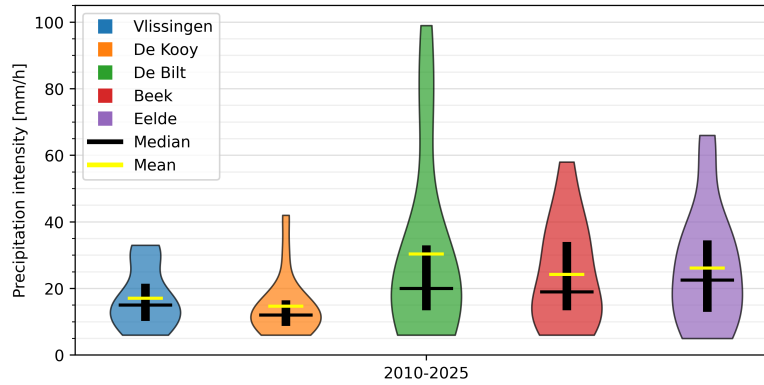


Figure 5.7: Violin plot with annual maxima distribution of precipitation intensity of events with a 6-minute duration between 2010 and 2025 for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

Figure 5.7 shows violin plots of the distributions of annual maximum precipitation intensity for 6-minute events. The highest mean annual maximum intensity is observed at De Bilt (30.4 mm/h), followed by Eelde, Beek, Vlissingen, and finally De Kooy (14.7 mm/h). The upper bound was likewise highest at De Bilt (99 mm/h) and lowest at Vlissingen (33 mm/h). The highest intensity at De Bilt occurred on 23 May 2012 during the afternoon, when thunderstorm activity was observed by the station. Finally, at all stations, the mean exceeds the median, indicating right-skewed distributions.

5.2.2. Extreme value analysis of intensity of 6-minute precipitation events

As none of the stations exhibited a statistically significant monotonic trend in the annual maxima, a stationary generalized extreme value distribution was fitted to the annual maxima at all stations using the ProNEVA toolbox. The selected priors and model settings are provided in Appendix A.3.2.

For all stations, the KS test applied to the fitted extreme value distributions resulted in rejection rates below 1 %. This indicates that fewer than 1 % of the 10 000 simulated samples were rejected at the 5 % significance level when compared to the observed data. The RMSE corresponded to approximately 2.5 % of the range of observations for most stations and 6.3 % for De Kooy, which remains within an acceptable range.

The PP and QQ plots (Appendix A.3.2) indicate a generally good correspondence between the fitted distributions and the observations. However, for De Kooy and De Bilt, the upper quantiles in the QQ plots fall below the 1:1 line, suggesting that the fitted distribution has a slightly lighter upper tail than the observed data and therefore underestimates the most extreme values.

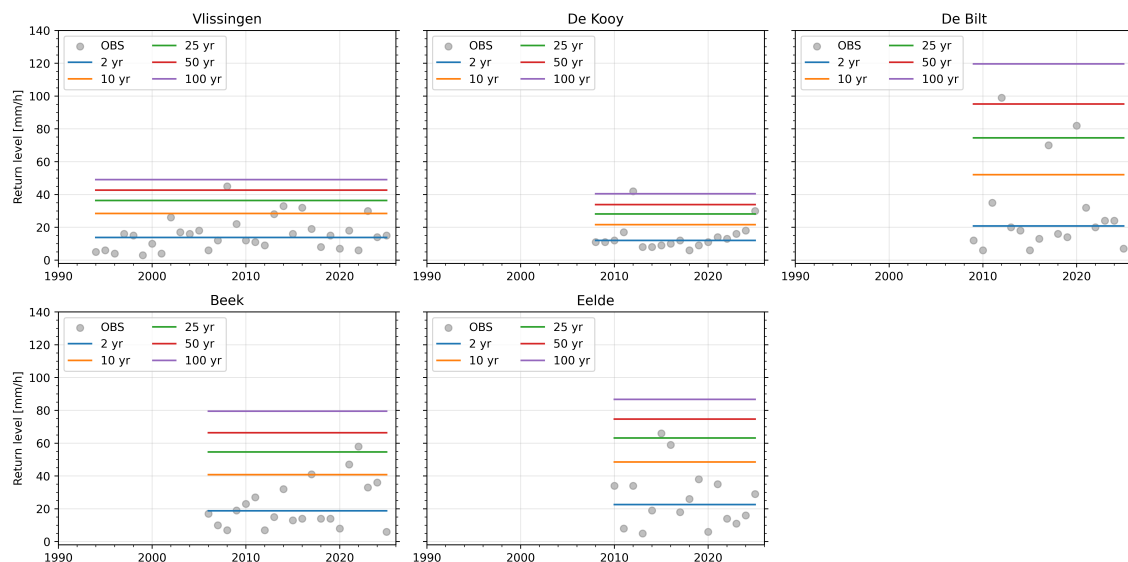


Figure 5.8: Estimated return level plot of precipitation intensity of events with a 6-minute duration between 2010 and 2025 for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde* with return periods between 2 and 100 years

Figure 5.8 presents the estimated return levels for the five stations. The 50-year return level is highest at De Bilt (95 mm/h), followed by Eelde, Beek, Vlissingen, and De Kooy (43 mm/h).

It should be noted that the available length of observations series for the hourly precipitation data is relatively short. Consequently, return level estimates for long return periods, such as 50 years, are subject to substantial uncertainty.

As multiple short-duration precipitation events may be stored into a single longer event in the hourly precipitation data, a second extreme value analysis was performed to assess the potential influence of the recording methodology. For each hour, precipitation events with a reported duration of 0.2 hour were selected and were assumed to consist of two consecutive precipitation events of equal duration (0.1 hour) and equal intensity. Subsequently, for each station and each year, annual maxima were determined by taking the maximum value of either the recorded 0.1 hour intensities or the reconstructed 0.1 hour intensities derived from the 0.2 hour events. For none of the stations was evidence found for a monotonic trend in the annual maxima series. Therefore, stationary GEV distributions were fitted using the ProNEVA toolbox (see Appendix A.3.3 for more details). The estimated 50-year return levels are presented as *Version 2* and compared with the original analysis based only on the recorded 0.1 hour events (*Version 1*).

Table 5.2: Comparison between estimated 50-year return level of precipitation intensity for recorded 6-minute precipitation events (*Version 1*) and for the combination of recorded and reconstructed 6-minute precipitation events (*Version 2*)

	50-year RL Version 1 [mm/h]	50-year RL Version 2 [mm/h]	Difference [%]
Vlissingen	43	55	28.3
De Kooy	34	63	86.0
De Bilt	95	93	−2.4
Beek	66	70	5.9
Eelde	75	87	17.0

Table 5.2 shows that the estimated 50-year return levels of the second analysis resulted in equal or higher values for all stations, except for De Bilt. Relative to Version 1, the increases range from 5.9 % for Beek to 86.0 % for De Kooy. For De Bilt, the second analysis resulted in slightly lower estimated

50-year return level of 95 mm/h, which may be caused by the estimation of the parameters of the GEV distribution or because the most extreme events were better captured in *Version 1*.

These findings suggest that the hourly precipitation storage methodology of the KNMI may significantly influence the estimation of short-duration precipitation extremes. And the results indicate that annual maxima values derived solely from recorded 0.1 hour events may underestimate the true extremes, when multiple short and intense events are stored into a single longer event. However, the magnitude of this effect remains uncertain. This is caused by the assumption that a 0.2 hour event consists of two precipitation events with equal duration and intensity. This assumption is highly simplified and may not represent the actual duration and intensity of the precipitation events.

5.2.3. Comparison with Eurocode precipitation intensity

The estimated 50-year return level for De Bilt was approximately half of the design intensity specified in the Dutch National Annex of NEN-EN 1991-1-3 (0.05 mm/s, equivalent to 180 mm/h). This design intensity likely originates from the study by A. Buishand and Wijngaard (2007), which reported the same 50-year return level for 5-minute precipitation intensities at De Bilt.

A comparison with the annual maxima presented by A. Buishand and Wijngaard (2007) shows a significant difference. After converting the considered annual maxima of 5-minute precipitation amounts of that study into intensities, approximately eight annual maxima exceed 120 mm/h. In contrast, all annual maxima derived from the 6-minute intensities in the present study remain below 100 mm/h. Part of this difference may be explained by the fact that shorter-duration precipitation events generally exhibit higher extreme intensities than longer-duration events. Consequently, a 5-minute return level would be expected to exceed the corresponding 6-minute return level.

However, a direct conversion from the derived 6-minute intensities to 5-minute intensities is not considered appropriate. The hourly precipitation datasets store the precipitation durations in discrete steps of 0.1 hour. This makes it likely that some rounding has occurred in the reported durations. For example, an actual duration of 0.12 hours may be stored as 0.1 hour. This introduces uncertainty in the reconstructed intensities and also limits the reliability of any conversion to a 5-minute duration.

A more important limitation is related to the way the hourly precipitation data are stored. Multiple short precipitation events occurring within the same hour were combined into a single precipitation sum and duration. As a result, short-duration intensity peaks may be smoothed out or completely lost. This was demonstrated with an additional EVA analysis, referred to as *Version 2*. Together with the differences in methodology, this is one of the reasons why the annual maxima obtained for the five stations are substantially lower than those reported in earlier Dutch studies.

The precipitation depth-duration-frequency scaling functions presented by Nicolai et al. (2024), resulted in an extrapolated 50-year return level of 18.1 mm for a 5-minute precipitation event. This corresponds to an intensity of approximately 217 mm/h. The methodological differences between this study and A. Buishand and Wijngaard (2007) have already been discussed in the literature review.

Overall, the short length of the available 6-minute precipitation series, combined with a somewhat different methodology and the limitations of the stored hourly precipitation observations, resulted in estimated return levels that are significantly lower than those reported in previous Dutch studies. For this reason, the 50-year return level considered in the remainder of this thesis is based on the extrapolated 50-year return level of Nicolai et al. (2024), corresponding to a 5-minute precipitation amount of 18.1 mm and therefore an intensity of 217 mm/h.

5.3. Projected precipitation

This section presents the results of the analysis of the projected short-duration precipitation extremes derived from the KNMI'23 Climate Scenarios. First, the extreme value analysis of the RACMO output of daily precipitation is presented. Then, the projected changes are compared with the CPM projections given by van Dorland et al. (2024). This analysis is based on a single RACMO grid cell at the location of De Bilt.

5.3.1. Extreme value analysis of daily precipitation of RACMO outputs

Figure 5.9 shows violin plots of the annual maxima of daily precipitation sums for the reference period for both observations and the eight model ensembles for De Bilt.

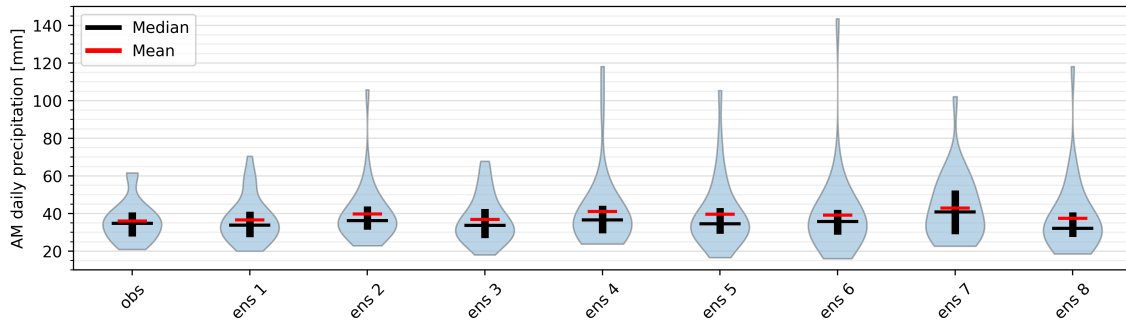


Figure 5.9: Violin plot of annual maxima of daily precipitation sums for the reference period 1991–2020 for observations and model output ensemble members

Figure 5.9 shows that the annual maxima from the RACMO output are generally higher than the observed annual maxima. The observed mean annual maximum was 36.0 mm, while the ensemble means ranged between 36.6 mm to 43.0 mm. A similar behaviour was observed for the 95th percentile values, which was 61.0 mm for the observations and ranged between 59.0 mm to 80.4 mm for the ensembles. This overestimation may partly result from spatial averaging within the 12 km × 12 km RACMO grid cell, while the observations represent precipitation at a single location within that grid cell. Local precipitation extremes may therefore differ from the grid-cell average. Nevertheless, annual precipitation sums generally showed a better agreement between observations and model output. This suggests that the RACMO model specifically tends to overestimate the most extreme daily precipitation events.

For the observed annual maxima of daily precipitation in De Bilt during 1991–2020, no statistically significant monotonic trend was detected using a Mann-Kendall trend test. Applying the same test to the eight RACMO ensembles of the reference period showed that only one ensemble showed an increasing trend. Therefore, the majority of ensembles displayed consistent behaviour in annual trends with the observations.

For the future scenarios, only a limited number of ensembles showed statistically significant monotonic trends. For the scenarios Hn2050, Hn2100, Mn2150, Md2050, and Md2150, only one ensemble indicated an increasing trend, while all remaining ensembles showed no significant trend. All other scenarios showed no statistically significant trends in any ensemble. Since the annual maxima within the 30-year periods were therefore generally stationary, the annual maxima of all eight ensembles for each scenario were combined into a single dataset of 240 annual maxima. This substantially increased the sample size and improved the robustness of the extreme value analysis. Consequently, a stationary GEV distribution was fitted for each scenario.

The uncertainty of the fitted GEV distributions was estimated using bootstrap resampling. For each scenario, 1000 bootstrap samples were generated and the 90% confidence interval was determined using the 5th and 95th percentiles. The GEV parameters were estimated using maximum likelihood estimation.

Focussing on the upper tails of the fitted distributions in Figure 5.10 reveals several inconsistencies. According to the KNMI CPM results, daily precipitation intensities are expected to increase with increasing global warming. However, the scenarios Mn2100 and Md2100 showed larger upper-tail values than the corresponding high radiative forcing scenarios Hn2100 and Hd2100. In contrast, the Mn2150 and Md2150 scenarios showed lower upper-tail values again. This behaviour was likely caused by a limited number of exceptionally high annual maxima within the Hn2100 and Hd2100 datasets, which highly influenced the fitted shape parameter and therefore the extrapolated return levels.

The PP and QQ plots presented in Appendix D confirm that especially for Mn2100 and Md2100 the upper tails were difficult to fit accurately. The fitted GEV distributions underestimated the most extreme

modelled annual maxima for these scenarios. In contrast, the PP plots indicate that the GEV distributions generally provide a good fit to the central parts of the distributions well. Furthermore, generally for all scenarios (including the reference scenario) the extremes were underestimated by the fitted distributions. One exception is for the low radiative forcing scenarios, where the extreme values were overestimated by the fitted distributions.

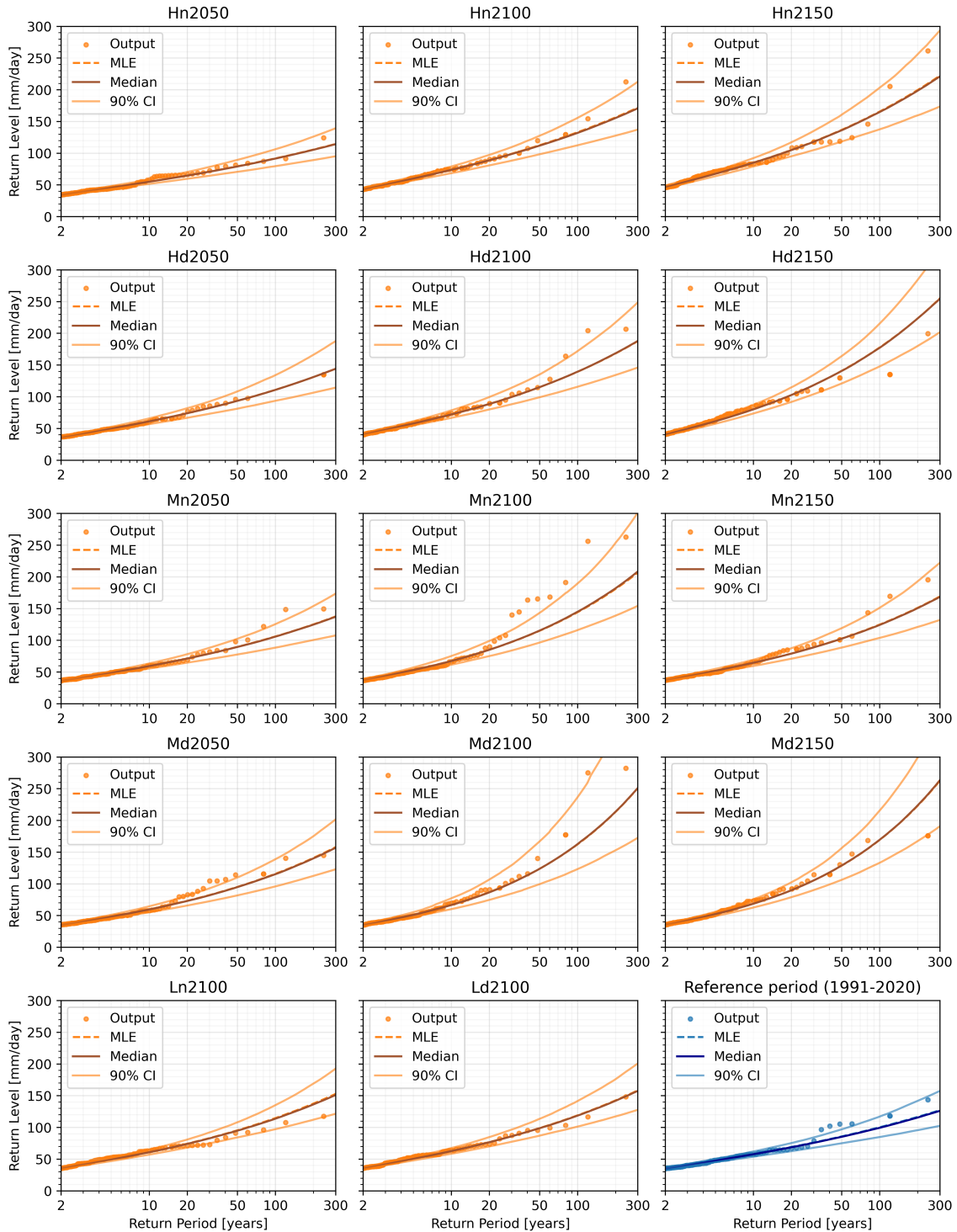


Figure 5.10: Annual maxima values of 24-hour precipitation amounts with fitted GEV distributions for different climate scenarios in grid cell of De Bilt. Median values and 90 % confidence interval are determined by bootstrapping

The 50-year return level of daily precipitation was determined for each scenario based on the median of bootstrap estimates. By comparing these values with the 50-year return level of the reference scenario, factors of change were obtained. The uncertainty range was determined by comparing all bootstrap realisations of the future scenarios with those of the reference scenario. This resulted in a 5–95 percentile range for the factor of change. The results are presented in Table 5.3.

In general, the 50-year return levels increased with increasing global warming. The largest increase occurred for the high radiative forcing scenarios around 2150, where factors of change of approximately 1.6 were obtained. However, several inconsistencies are also visible. For example, the Mn2100 scenario shows higher return levels than Mn2150, despite the latter corresponding to a larger global warming level. This behaviour is consistent with the earlier observation that a limited number of extreme outliers strongly affect the fitted distributions for Mn2100. In addition, the dry variants generally showed slightly larger return levels than the corresponding wet variants. This may indicate that although total precipitation increases more strongly in the wet scenarios, the dry scenarios may contain fewer but more intense precipitation events. Still, these differences remain relatively small compared with the overall uncertainty ranges. The Hn2050 scenario showed another exception, since its 50-year return level was lower than that of the reference period. No physical explanation could be found for this behaviour. It is therefore likely that this result is caused by internal climate variability or uncertainties in the fitted GEV distribution.

The uncertainty ranges generally increase for scenarios with larger factors of change. This behaviour is expected, since stronger climate change scenarios show a larger spread in extreme precipitation values and therefore larger uncertainty in the fitted upper tail behaviour. While, the Md2100 showed the largest uncertainty range, which is likely caused by the poor fit of the GEV distribution.

Comparing the estimated 50-year return level daily precipitation amounts of the reference model output for the grid cell of De Bilt, with the estimated 50-year return level precipitation amount for the historical observations in De Bilt, shows somewhat higher values for the model output of 85.9 mm and 64.8 mm for the observations. The reference periods do not fully match, as the model output holds for 1991–2020 and the observations for 1951–2025. However, the model output has in total 240 annual maxima and the observations only 75. This allows more extremes to be captured for the model output and could explain the higher value for the model reference period.

Comparing the estimated 50-year return levels of daily precipitation for the reference RACMO simulation and the historical observations at De Bilt shows that the model has a higher return level. The estimated 50-year return level is equal to 85.9 mm for the RACMO reference simulation, compared with 64.8 mm for the observations. This comparison should be interpreted with caution, as the reference periods differ: the RACMO reference output spans the period 1991–2020, whereas the observational analysis covers 1951–2025. Furthermore, the RACMO reference output consists of 240 annual maxima, obtained from the eight ensemble members, whereas the observational dataset contains only 75 annual maxima. The larger sample size results in a more robust estimation of the GEV parameters and the corresponding return level, but does not directly explain the higher value. As discussed previously, the RACMO model also tends to overestimate the most extreme daily precipitation events relative to the observations, which is likely the main reason for the higher estimated return level.

Although the RACMO reference model output overestimates the 50-year return level relative to the observations, this does not directly mean that the derived factors of change are biased. Since the factors of change are obtained by comparing future scenarios with the RACMO reference output, part of the bias is expected to cancel out. This assumes that this bias remains approximately constant under future climate scenarios. This assumption results in a source of uncertainty.

Table 5.3: Statistical properties of the estimated 50-year return levels of 24-hour precipitation amounts for different climate scenarios around De Bilt

Scenario	50-year return level [mm]	Factor of change [-]	5–95 percentile range factor of change [-]	Global warming [°C]
Ref	85.9	-	-	0.0
Ln2100	95.5	1.12	0.93–1.33	0.8
Ld2100	99.0	1.16	0.96–1.38	0.8
Mn2050	89.7	1.05	0.87–1.26	1.1
Mn2100	115.0	1.35	1.08–1.76	1.9
Mn2150	102.9	1.21	0.99–1.48	2.1
Md2050	95.3	1.12	0.92–1.35	1.1
Md2100	123.9	1.45	1.12–2.01	1.9
Md2150	128.8	1.52	1.20–1.91	2.1
Hn2050	79.5	0.93	0.79–1.11	1.5
Hn2100	112.6	1.31	1.09–1.58	4.0
Hn2150	136.9	1.60	1.30–1.99	5.5
Hd2050	93.7	1.10	0.91–1.33	1.5
Hd2100	115.2	1.34	1.10–1.67	4.0
Hd2150	141.0	1.65	1.35–2.01	5.5

Since each scenario corresponds to a certain global warming level, the factors of change can be plotted against global warming to investigate whether a trend is visible. Figure 5.11 shows the factors of change for both wet and dry variants as a function of global warming level. In general, the factors increase with increasing global warming, which is physically consistent with the expected intensification of precipitation extremes in a warmer climate. However, the increase is not perfectly monotonic. For both variants, a decrease in the factor of change is visible between the L2100 scenarios (0.8 °C global warming) and the M2050 and H2050 scenarios (1.1 °C to 1.5 °C global warming).

The fitted GEV distributions shown in Figure 5.10 indicate that for the L2100 scenarios the upper tail is slightly overestimated, while for both M2050 scenarios the upper tail is underestimated. Furthermore, the annual maxima of the H2050 scenarios contain limited upper extremes compared to other scenarios. Since the estimation of return levels strongly depends on a limited number of extreme values, these differences affect the fitted shape parameter and therefore the resulting factors of change.

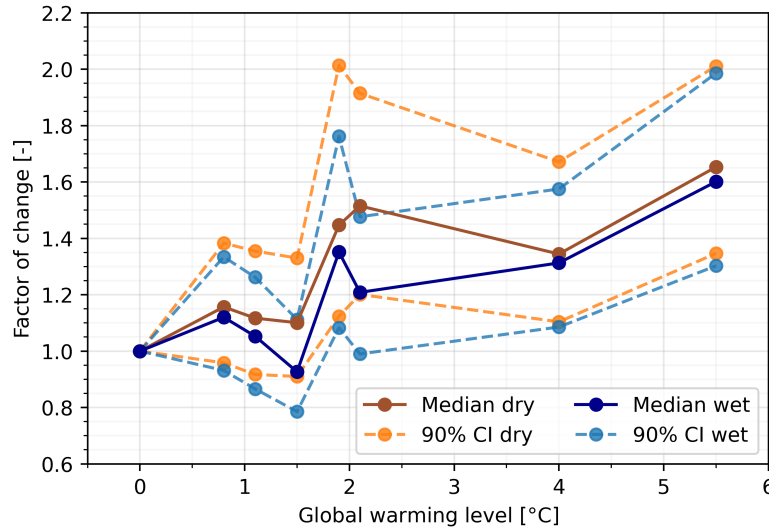


Figure 5.11: Factor of change for 50 year return levels for daily precipitation for dry and wet variants for different global warming levels

5.3.2. Comparison with Convection-Permitting Model outputs

The CPM-based scaling factors for daily and hourly precipitation for the Hn2100 and Hd2100 scenarios are compared with the RACMO-based factors of change. The factor of change for 100-year return levels for Hn2100 and Hd2100 for daily precipitation are respectively 1.32 and 1.39. The 100-year return level scaling factors for the wet variant of 4° global warming of the CPM presents values between 1.29 and 1.34 between the different seasons, showing a good correspondence with the RACMO factor of change. While for the dry variant, the CPM 100-year return level scaling factors are showing values between 1.20 and 1.25, being much lower than the value of the RACMO factor of change. This already shows a better correspondence for the wet variant, compared to the dry variant.

Next the hourly and daily CPM scaling factors were compared. For the wet variant, the projected 100-year return level scaling factors for daily precipitation are 1.29, 1.32, 1.30 and 1.34 for winter, spring, summer, and autumn, respectively. For hourly precipitation, the corresponding values are 1.31, 1.20, 1.33 and 1.42. Although some seasonal differences are visible, the annual average scaling factors are approximately equal.

Based on the currently available KNMI projections, it is therefore assumed that sub-hourly precipitation extremes scale approximately similarly to hourly and daily precipitation extremes. Consequently, the factor of change derived for daily precipitation is also considered for 5-minute precipitation events.

Following the methodology of Nicolai et al. (2024), only the wet variant is used to derive the final scaling relation. Since the factors of change do not increase perfectly monotonically with global warming, the factor for Hn2100 (4°C global warming) is used as the reference point of interpolation. To relate the derived scaling factors to present-day precipitation statistics, the reference period of the current precipitation depth-duration-frequency curves must be considered. According to Nicolai et al. (2024) in 2023 was concluded that no update of these curves from Beersma et al. (2019) was required. Therefore, the curves can be taken to be representative for the year of 2023. And the factor of change is assumed to be equal to 1.0 for this year. The centre of the reference period of the KNMI is the year 2005. Relative to the 1850–1900 baseline, global warming levels were approximately 0.83 °C in 2005 and 1.23 °C in 2023 (Copernicus, 2026). This corresponds to an increase of roughly 0.4 °C between the reference period and the year 2023.

Assuming a linear relationship between global warming and the factor of change, this results in the following expression (similar as in Nicolai et al. (2024)):

$$FC(GW) = 1 + (F_{Hn2100} - 1) \times (GW - 0.4) / (4 - 0.4) \quad (5.1)$$

where FC is the factor of change for 5-minute precipitation events, GW is the global warming level in $^{\circ}\text{C}$ relative to the 1991–2020 reference period, and F_{Hn2100} equals 1.31. This results to the following equation:

$$FC(GW) = 0.0869 \times GW + 0.9652 \quad (5.2)$$

Figure 5.12 shows the resulting scaling function together with the 90 % uncertainty interval. The uncertainty bounds are derived by linearly interpolating between zero uncertainty at the global warming level of 2023 and the uncertainty range of the Hn2100 scenario.

$$FC_{low} = 0.0238GW + 0.9905 \quad (5.3)$$

$$FC_{up} = 0.1598GW + 0.9361 \quad (5.4)$$

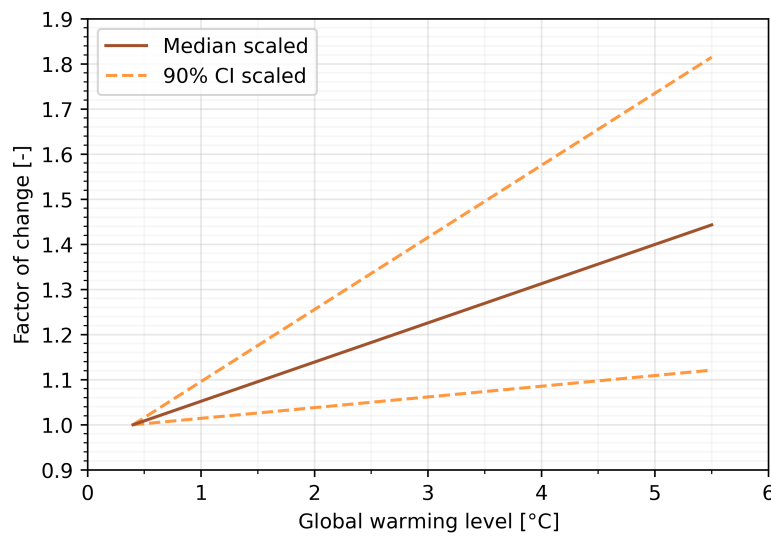


Figure 5.12: Factor of change function together with the 90 % uncertainty range

5.3.3. Conclusion

By applying a similar method as Nicolai et al. (2024), factors of change were derived for the 50-year return levels of daily precipitation amounts. The results are based on RACMO outputs for the grid cell around De Bilt. The analysis showed that the annual maxima of daily precipitation generally increase under increasing global warming, although variability exists between scenarios and ensembles. Comparison with KNMI CPM results showed that the wet variant of the high radiative forcing scenario around 2100 shows good agreement between RACMO and CPM projections. Furthermore, the CPM projections indicate that hourly precipitation extremes increase roughly at the same rate as daily precipitation extremes. Due to the absence of KNMI projections for sub-hourly precipitation durations, it was therefore assumed that 5-minute precipitation extremes scale equally to daily and hourly precipitation extremes.

The final factor of change function indicates a linear increase in extreme precipitation intensities with increasing global warming. For a global warming level of 1.9°C , equation 3.6 gives a factor of change of roughly 1.13. Applying this factor to the 50-year return level of a 5-minute precipitation event of 18.1 mm (Beersma et al., 2019) results in a projected precipitation amount of approximately 20.8 mm. Including the uncertainty interval results in values between roughly 18.8 mm and 23.0 mm.

The analysis also showed that considerable uncertainty exists in the estimation of future extreme precipitation. It was assumed that bias in the 50-year return levels remains approximately constant under

future climate scenarios. Furthermore, the fitted GEV distributions are sensitive to a limited number of extreme annual maxima, especially in the moderate radiative forcing scenarios around 2100. In addition, several assumptions were required, such as the assumption that sub-hourly precipitation changes similarly to daily precipitation.

It is therefore recommended that future KNMI climate scenarios include projections for sub-hourly precipitation extremes. This would substantially improve the reliability of structural engineering applications where short-duration precipitation events are involved, such as rainwater loads and emergency drainage design.

5.4. Changes in emergency drainage design under climate change

In this section, the 2050 time horizon under the moderate radiative forcing scenario is considered, corresponding to approximately 1.1 °C global warming relative to the 1991–2020 reference period. It is assumed that a building is designed and constructed today with a design life of 50 years. The projected precipitation changes associated with 1.1 °C warming are therefore taken as representative for the design period.

Recent studies on short-duration precipitation extremes indicate that estimated 5-minute precipitation intensities have increased compared with earlier assessments. This increase can likely be attributed to the availability of longer observational records and a larger number of stations, while climate change may also contribute to the observed changes. The Dutch National Annex to NEN-EN 1991-1-3 currently prescribes a characteristic 50-year return level precipitation intensity of 0.05 mm/s (0.05×10^{-3} m/s). However, the most recent analysis by Beersma et al. (2019) reported an extrapolated 50-year return level intensity of approximately 0.06 mm/s. Consequently the precipitation intensity is already 20 % higher, independent of the considered global warming level.

Applying the precipitation scaling relation of Equation 5.2 for 1.1 °C global warming results in a factor of change of 1.061. This results in a projected design intensity of approximately 0.064 mm/s. Consequently, the projected intensity is about 27 % higher than the value currently prescribed in the Dutch National Annex.

Assuming that the emergency drainage system is designed such that the resulting rainwater load on the roof remains unchanged compared the current intensity of 0.05 mm/s, the following relation from the National Annex can be considered:

$$d_{nd} = 0.70 \left(\frac{Q_h}{b} \right)^{2/3} \quad (5.5)$$

where d_{nd} is the water depth above the emergency drainage opening (m), Q_h is the required discharge capacity (m^3/s), and b is the width of the drainage opening (m).

Rearranging the equation gives:

$$b = Q_h \left(\frac{0.70}{d_{nd}} \right)^{3/2} \quad (5.6)$$

For a constant allowable water depth d_{nd} , the required width of the emergency drainage is directly proportional to the design discharge capacity. Since the discharge capacity is proportional to the design rainfall intensity, the required drainage width scales with the projected increase in precipitation intensity.

Based on the projected design intensity of 0.064 mm/s, the required drainage width would therefore increase by a factor of approximately 1.27 relative to the value obtained using the current Annex intensity. In other words, emergency drainage openings would need to be approximately 27 % wider to maintain the same rainwater load on the roof.

Based on Figure 5.12, a similar figure was derived, with the global warming on the x-axis, but now with the percentage of width change of the emergency drainage. Figure 5.13 shows that the width change reaches roughly 73 % for 5.5 °C global warming.

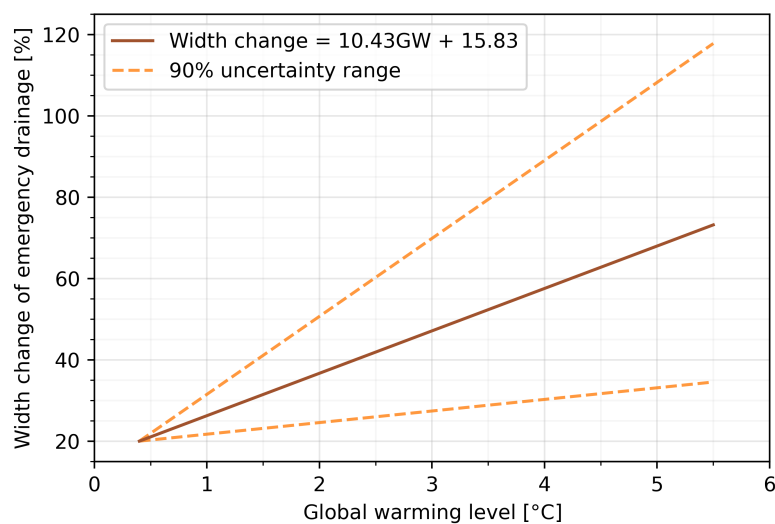


Figure 5.13: Width change function for emergency drainage together with the 90 % uncertainty range

It should be noted that substantial uncertainty remains associated with the projected increase in precipitation extremes. Nevertheless, even the lower bound of the projected change indicates an increase in 50-year return levels of precipitation intensity, suggesting that larger emergency drainage capacities may be required in the future.

6

Discussion, conclusion, and recommendations precipitation

This chapter discusses the methodology and results of the precipitation analysis. It then answers the research questions related to precipitation loads and concludes with recommendations for future research on the effects of climate change on precipitation loads.

6.1. Discussion

Historical observations of approximately 6-minute precipitation events were used as an estimation for the 5-minute precipitation intensity considered in the Dutch National Annex of NEN-EN 1991-1-3. Because of changes in the automatic precipitation measurement instrumentations between 1993 and 2010, only relatively short homogeneous observation series were available. As a result, the fitted GEV distributions are associated with considerable uncertainty. In addition, the hourly precipitation datasets provide only the total precipitation amount and total precipitation duration within each hour. Consequently, multiple short precipitation events occurring within the same hour are combined into a single event, which may lead to an underestimation of short-duration precipitation intensities.

To estimate future changes in short-duration precipitation extremes, it was assumed that the scaling behaviour of the 50-year return level of daily precipitation sums is similar to the scaling behaviour of 5-minute precipitation events. Furthermore, it was assumed that the model bias in 50-year return level values remains constant for the different climate scenarios. The derived factors of change for daily precipitation extremes generally increased with increasing global warming levels, although some fluctuations between scenarios were observed. A comparison with the available CPM projections for hourly and daily precipitation extremes under approximately 4 °C global warming showed that the RACMO-derived factors of change for the wet scenarios correspond reasonably well with the CPM results. Since no projections are currently available for sub-hourly precipitation durations, the same scaling behaviour was assumed for 5-minute precipitation events. This assumption represents one of the main sources of uncertainty in the projected characteristic values.

The 50-year return level of 0.06 mm/s reported in recent Dutch studies was combined with the projected factor of change for 50-year return levels of 5-minute precipitation intensities to estimate the future intensities. Compared with the current Annex value of 0.05 mm/s, the estimate for the current situation is already approximately 20 % higher. Consequently, even before accounting for future climate change, maintaining the same rainwater loads as today, would require emergency drainage widths of approximately 20 % larger than those based on the current Dutch National Annex.

The analysis focused only on rainwater ponding loads on roofs as described in the Eurocode framework. Potential interactions between extreme precipitation and wind were not considered. Nevertheless, severe precipitation events are sometimes accompanied by strong winds. Such combined events may influence the distribution of ponding water along a roof surface. For example, during the severe thun-

derstorms of 29 May 2018, heavy precipitation was accompanied by strong wind gusts, resulting in rainfall occurring at nearly horizontal angles (NOS, 2018). The possible contribution of combined wind and precipitation events to roof ponding therefore deserves further investigation.

6.2. Conclusion

The precipitation-related research questions can be answered as follows.

To what extent do current characteristic values for precipitation loads in the Dutch National Annex reflect recent observations and trends?

Recent analyses of precipitation extremes in the Netherlands indicate that the characteristic 50-year return level of 5-minute precipitation intensity is higher than the value currently prescribed in the Dutch National Annex. The study of Beersma et al. (2019), based on a different methodology, on observations from a large number of stations, and multiple precipitation durations, reported an extrapolated intensity of approximately 0.06 mm/s, compared with the Annex value of 0.05 mm/s.

How are precipitation loads expected to change under different climate scenarios in the Netherlands?

The derived scaling relation for the 50-year return level of the intensity of short-duration precipitation events indicates an increase with increasing global warming:

$$FC(GW) = 0.0869 \times GW + 0.9652 \quad (6.1)$$

where FC is the factor of change and GW is the global warming level in °C relative to the 1991–2020 reference period. This relationship suggests that short-duration precipitation extremes are expected to become more intense under future climate conditions.

What changes in characteristic values for precipitation loads can be derived from climate change scenarios, and how do these compare to current values in the Dutch National Annex?

The projected increase in precipitation intensity implies that larger rainwater volumes must be discharged from roofs during extreme events. For a building designed today and exposed to approximately 1.1 °C additional warming during its design life, the projected design precipitation intensity increases by approximately 27 % relative to the value currently prescribed in the National Annex. However, already 20 % can be attributed to recent studies, providing a higher intensity as in the Annex. In order to maintain similar rainwater loads on the roof, the required emergency drainage capacity would need to increase accordingly, which for a constant water depth translates into emergency drainage openings that are approximately 27 % wider.

The main research question can therefore be answered as follows.

How do climate change scenarios affect characteristic values for precipitation loads on buildings in the Netherlands, and what are their implications for structural design?

Based on the available observations and KNMI'23 climate projections, climate change is expected to increase the magnitude of short-duration precipitation extremes in the Netherlands. Consequently, larger rainwater volumes may need to be drained by roof drainage systems during extreme events. It can be account for these changes by increasing drainage capacities, adapting roof geometries, or incorporating higher rainwater loads in structural design calculations.

6.3. Recommendations

Future research should investigate the combined effects of extreme precipitation and wind on rainwater ponding and the implications for (structural) design. These combined events may result in loading conditions that are currently not well represented by current design approaches.

It is further recommended that future KNMI climate scenario products include projections for sub-hourly precipitation durations. This would significantly reduce the uncertainty associated with translating daily-scale climate projections to the short-duration precipitation events relevant for structural engineering applications. In addition, the development of future climate projections for hourly wind velocities and wind gusts would enable a more comprehensive assessment of rainwater ponding.

Part III

snow

Literature study for snow

This chapter reviews the literature relevant for the snow analysis. First, the physical processes behind snowfall are presented. Subsequently, the methodology for determining snow loads in structural design according to Eurocode 1 and the Dutch National Annex is discussed. Subsequently, the Dutch automatic temperature and manual snow measurement networks are displayed, together with observed temperature and snow depth trends. Finally, the snow related indicators in the KNMI'23 climate scenarios are presented.

7.1. Theoretical background of snowfall and European trends

This section first introduces the physical processes behind snowfall together with factors that influence snow density and melting processes.

Snow occurs when atmospheric conditions are sufficiently cold for snowflakes to reach the surface without melting. In the Netherlands, snowfall often develops when cold air from the polar regions is transported to the country. An increase in snowfall intensity can be caused by the relative hot air around the North Sea (KNMI, n.d.-t).

For the background information on snowfall, the ensemble forecast of snow cover used by the KNMI are considered. The KNMI presents forecasts for several weather variables based on the ECMWF Ensemble Prediction System (EPS). Snow cover is reported as the expected accumulation in cm per 6-hour period and is based on the median of 51 ensemble members (KNMI, n.d.-a).

To understand how snow cover is simulated, the snow scheme described by (Dutra et al., 2010) is considered. This model does not determine whether precipitation falls as rain or snow, it rather simulates the changes of snowpack once snowfall has occurred. The accumulation of snow is determined by the snow water equivalent (SWE), which represents the amount of liquid water contained in the snowpack. SWE is commonly expressed in kg^2/m , and can be calculated as (Dutra et al., 2010):

$$SWE = \rho_w \cdot h_w \quad (7.1)$$

where ρ_w is the density of water and h_w is the equivalent depth of liquid water.

The resulting snow depth depends on both the SWE and the density of snow. In the HTESSEL snow scheme, the density of newly fallen snow is considered as a function of near-air surface temperature and wind velocity. Higher temperatures generally result in denser, wetter snow, while stronger winds increase snow density through packing. Snow density is constrained between 50 and 450 kg/m^3 (Dutra et al., 2010). Snow depth can be estimated as:

$$h_{\text{snow}} = \frac{SWE}{\rho_{\text{snow}}} \quad (7.2)$$

where ρ_{snow} is the snow density.

The snowpack undergoes compaction, which reduces snow depth while conserving mass. In the HT-ESSEL scheme, compaction depends primarily on the load exerted by the overlying snow, the viscosity of the snowpack (dependent on temperature) and the amount of liquid water retained within the snow. Liquid water accelerates the compaction process and also reduces snow depth without changing the SWE (Dutra et al., 2010). This study does not provide information for the probability of snowfall occurrence.

Melting of snow depends on the surface energy balance. Important contributors are incoming and reflected shortwave radiation, longwave radiation, heat exchange with the atmosphere, and heat transfer from the underlying ground. Consequently, factors such as cloud cover, snow albedo, air temperature, ground temperature, and rainfall influence the melting rate of the snowpack. Rainfall can fasten the melting both through the addition of liquid water and through the transfer of heat from warm rainwater to the snowpack. The compaction of snow depends on various aspects, such as the pressure of the overlying snow and the snow viscosity. Furthermore, melted snow water retained in the snow deck decreases the depth, but keeps the SWE constant. The melting of a snow cover depends on processes such as incoming and reflected solar radiation, which in return depend on cloudiness, and the albedo of snow. Furthermore air temperature is a major contributor. Furthermore the amount and temperature also affects the melting. Furthermore, the temperature of the ground and snow cover are of importance (ECMWF, n.d.).

According to O’Gorman (2015), the effect of climate change on extreme snowfall at higher latitudes differs from its effect on extreme rainfall and therefore requires further research. The author highlights that snowfall extremes in a changing climate are influenced by two opposing influences: an increasing saturation vapour pressure and a frequency change of temperatures that are below the rain-snow transition temperature.

The impacts of climate change of the SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenario on snowfall in the Northern Hemisphere are examined by Quante et al. (2021) using CMIP6 data, with a reference period of 1851–1920. The mean daily snowfall across most of the Northern Hemisphere is projected to decrease in the future for all three scenarios. However, at high latitudes, the mean daily snowfall is projected to increase in the future, even for higher emission scenarios. Moreover, for larger areas of the Northern Hemisphere, the 99.9th percentile of daily snowfall is expected to increase for high latitudes in all climate scenarios. In contrast, Western Europe exhibits a decreasing trend in the 99.9th percentile of daily snowfall.

Also, the *expected extreme magnitude (EEM)* was determined for future snowfall by Quante et al. (2021). This is defined as the mean of all events exceeding a specified percentile of the historical reference period. So, this is a measure for the change of the tail of the distribution and therefore shows possible changes in the intensity of snowfall events. For Western Europe the 99.9th percentile EEM is projected to slightly increase for all scenarios, although these projections are highly uncertain.

In summary extreme snowfall events are expected to become rarer in Western Europe in the future under strong climate change, but the intensity of EEM may increase slightly. Furthermore, the SSP3-7.0 warming scenario shows similar trends to the more intense SSP5-8.5 scenario with regard to the future intensity of extreme snowfall events. Table 7.1 presents the projected changes in the mean and 99.9th percentile daily snowfall for Western Europe relative to the historical baseline (1851–1920) by the end of the century for the three scenarios.

Table 7.1: Model ensemble median of approximate changes in daily snowfall at the end of the century in Western Europe under three different climate scenarios. Adapted from Quante et al. (2021)

	SSP1-2.6	SSP3-7.0	SSP5-8.5
Change in mean [% baseline]	−60	−90	−90
Change in 99.9th percentile [% baseline]	−45	−70	−80

O’Gorman (2014) found that the optimal temperature for extreme snowfall is around -2°C . At much

lower temperatures, nearly all precipitation falls as snow, but the reduced moisture capacity of the air limits snowfall intensity. Conversely, at temperatures near or above zero, a large fraction of precipitation falls as rain. Around -2°C , a substantial portion of precipitation falls as snow, while the air can still hold relatively high amounts of moisture, resulting in the greatest snowfall intensity.

7.2. Snow loads in the Eurocode

In NEN-EN 1991-1-3 the snow loads on structures are described, and its Dutch National Annex provides specific rules for applications in the Netherlands (NEN, 2019a, 2019d). Similar to precipitation loads, snow loads particularly relevant for roof structures, especially for industrial buildings, which are often relatively lightweight structures.

This section elaborates on the determination of snow loads on structures according to NEN-EN 1991-1-3 and its Dutch National Annex.

When determining snow loads on roofs, it should be considered that snow may accumulate in different patterns and in varying quantities. These patterns are influenced by factors such as the shape, thermal properties, and roughness of the roof, heat under the roof, neighbouring buildings or surrounding terrain, and the local climate. Furthermore the snow load on roofs should be evaluated for both the distributed snow load and the redistributed snow load. This distinction is particularly relevant for roofs with more than one span, where snow may accumulate unevenly due to drifting or sliding.

The procedure used to determine the characteristic snow load on structures is shown in Figure 7.1. The grey part indicates the aspects that are investigated in this research.

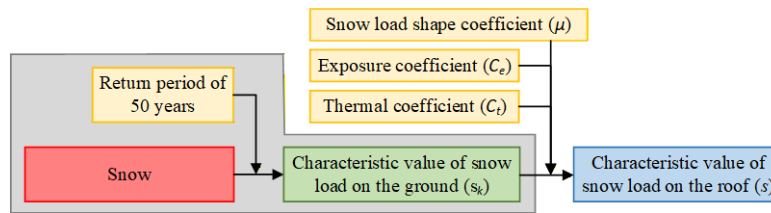


Figure 7.1: Characteristic snow load on structures according to NEN-EN 1991-1-3 and its Dutch National Annex

The characteristic value of the snow load on the ground at the relevant location s_k is based on a return period of 50 years. Or in other words: the snow load on the ground based on an annual probability of exceedance of 0.02. The Dutch National Annex specifies a value of $0.7 \text{ kN}^2/\text{m}$ for the entire country, based on compact snow with a volumetric weight of $2.0 \text{ kN}/\text{m}^3$. However, the snow map provided in the main code indicates that for most parts of the Netherlands a ground snow load at sea level of $0.2 \text{ kN}^2/\text{m}$ would be sufficient, while a value of $0.7 \text{ kN}^2/\text{m}$ only occurs in a small area in the far north of the country.

The ground snow load should be adjusted for return periods other than 50 years. Appendix D of NEN-EN 1991-1-3 provides a conversion formula for this purpose. The formula should not be used for return periods shorter than 5 years.

$$s_n = s_k \left[\frac{1 - V \frac{\sqrt{6}}{\pi} [\ln(-\ln(1 - P_n)) + 0.57222]}{(1 + 2.5923V)} \right] \quad (7.3)$$

where s_n is the ground snow load corresponding to a return period of n years, s_k is the characteristic ground snow load for a return period of 50 years, P_n is the annual probability of exceedance (approximately equal to $1/n$), and V is the coefficient of variation of the annual maximum snow load. The Dutch National Annex reports a value of $V = 0.8$ for the Netherlands.

For a return period of 100 years, the prescribed characteristic ground snow load of $0.7 \text{ kN}^2/\text{m}$ should be multiplied by a factor of 1.143. This results in characteristic ground snow load of $0.8 \text{ kN}^2/\text{m}$.

Subsequently, The characteristic snow load on a roof can be determined, which is given by:

$$s = \mu_i C_e C_t s_k \quad (7.4)$$

Where μ_i is the snow load shape coefficient, C_e is the exposure coefficient, and C_t is the thermal coefficient. In the Netherlands, the exposure coefficient and the thermal coefficient are taken equal to 1.0. The snow load shape coefficient may differ between the distributed and redistributed situations and depends on the shape and slope of the roof. These values are provided in the main code or, when applicable, in the National Annex.

Furthermore, the Dutch National Annex states that in the Netherlands loads due to rainfall on snow, melting and refreezing, exceptional snow loads, and snow drifting do not need to be considered.

As indicated in Figure 7.1, this research focuses only on the potential effects of climate change on the characteristic value of the ground snow load. A change in this value would directly lead to a change in the characteristic snow load on roofs, as long as the roof geometry remains unchanged. In contrast to rainwater loads, a change in the ground snow load directly affects the required strength and stiffness of the structure.

7.3. National temperature measurements

Relevant for snowfall is temperature, therefore the temperature measurements at the automatic weather stations are shortly discussed.

KNMI measures the mean daily temperature (TG), the minimum daily temperature (TN), and the maximum daily temperature (TX).

The temperature observations for the five main automatic weather stations of the KNMI have been homogenised (Brandsma & van der Schrier, 2020; KNMI, n.d.-i), making them directly suitable for trend analysis. Currently, two versions of homogenised temperature series are available for these five main stations. The first version, released in 2016, was constructed by continuing measurements at both the original and relocated station sites. Differences between the parallel measurements were used to derive correction factors, which were subsequently applied to the earlier observations (KNMI, n.d.-i).

Based on further research, KNMI released a second version of the homogenised temperature series in January 2026 using an improved homogenisation methodology. Unlike the first version, this approach includes additional meteorological variables (wind, cloud cover, humidity) to account for differences in weather conditions at four of the five stations. Homogenisation adjustments were applied mainly to the first half of the twentieth century and for stations up to 1970. After this period, the raw measurements did not require homogenisation (KNMI, 2026a). Although the overall climate trends in the second version are similar to those in the first, derived indicators such as the number of ice days and tropical days differ slightly. These differences occur because such indicators are defined using strict thresholds and are therefore sensitive to small changes in homogenised temperature values (KNMI, 2026a).

7.4. National snow measurements and trends

This section describes the Dutch snow observation network and discusses observed trends in precipitation.

7.4.1. Measuring network

Snow depth measurements are conducted simultaneously with the manual precipitation measurements by the wide network of more than 300 volunteers across the Netherlands. Each morning, at around 10:00 during summer and 09:00 during winter, volunteers measure the precipitation collected over the last 24 hours in their rain gauge. A heating element melts solid precipitation, such as snow. One millimetre of melted snow corresponds roughly to one centimetre of snow. And they measure snow depth in centimetres with a ruler. (KNMI, n.d.-x).

Furthermore, the KNMI uses specific codes to describe snow conditions. Code 997 indicates a closed snow cover thinner than 1 cm, 998 denotes a broken snow cover, and 999 refers to snowdrifts. When calculating the annual number of snow cover days (days with a snow cover), days with a measured snow depth above 1 cm as well as days coded 997, 998, or 999 are classified as snow cover days. Snow

cover days therefore include not only days with snowfall, but also days on which an existing snow cover persists.

7.4.2. Historical observations and trends

T. A. Buishand (1986) analysed snow cover depths at 13 stations in the Netherlands for the winters between 1956 and 1983. Annual maxima were fitted using a Gumbel distribution, from which 50-year return levels of snow depth were derived. The results clearly demonstrate a spatial variability in the Netherlands. The 50-year return levels range from roughly 18 cm in Vlissingen to 37 cm in Leeuwarden, with the highest values generally occurring in the eastern and northeastern parts of the country. In contrast, the lowest values are observed in the coastal regions.

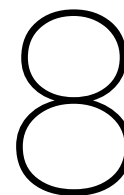
A more recent analysis by de Vries and Selten (2026) indicate that snowfall and persistent snow cover have become increasingly rare in the Netherlands. Using snow cover observations for De Bilt since 1961, they show a strong decline in closed snow cover days. Around 1961, roughly 23 snow cover days per winter were observed, this has decreased to approximately 3 days present day. In addition, the observed snow cover depths have decreased substantially over time.

7.5. KNMI'23 climate scenarios limitations

In the KNMI'23 projections, changes in snowfall are not explicitly discussed. However, the projections do include estimates of the number of frost days and freezing days, providing potential indirect changes in snowfall. During a frost day, the daily minimum temperature measured at 1.5 m above ground level falls below 0 °C (KNMI, n.d.-w)(KNMI, n.d.-z). In contrast, during an ice day, the daily maximum temperature remains below 0 °C throughout the entire day (Selten, 2025). Table 7.2 presents the projected number of frost and ice days for the different scenarios around 2050, 2100, and 2150 for station De Bilt.

Table 7.2: Projected frost and ice days at De Bilt around 2100 with respect to the 1991–2020 reference period. Adapted from KNMI (n.d.-m)

	1991–2020	Horizon	Ld	Ln	Md	Mn	Hd	Hn
Frost days (TX < 0°C)	53	2050	39	40	37	38	33	30
		2100	39	40	27	28	11	11
		2150	39	40	25	25	5.3	5.3
Ice days (TN < 0°C)	6.4	2050	3.6	3.8	3.3	3.3	3.1	3.1
		2100	3.6	3.8	2.0	2.4	0.3	0.4
		2150	3.6	3.8	2.2	1.8	0.0	0.1



Methodology snow analysis

The methodology used to answer the snow-related research questions consists of two main components: a historical analysis and an analysis of future climate projections.

For the temperature and snow related indicators, winter years were considered instead of calendar years. This approach ensures that each winter season is represented by a single observation and avoids splitting extremes of one winter across two calendar years. For example, annual minimum temperatures may originate from two different winters, whereas winter year minima represent one minimum per winter season.

KNMI defines winter as the period December–February, with the winter year assigned to January and February (KNMI, n.d.-z). KNMI also uses a winter half year covering October–March (Siegmund, 2024). Restricting the analysis to these periods could exclude extreme events occurring in September or April. Therefore, a winter year was considered here as the period from 1 July to 30 June of the following year. This definition ensures that all cold-season events belong to a single analysis year while minimising the risk of excluding relevant temperature or snow events.

8.1. Historic analysis

The historical analysis consisted of two parts. The first focused on temperature related indicators, including winter year minimum temperatures, frost days, and ice days. The second focused on snow cover characteristics, such as the number of snow cover days and annual maximum snow depths.

The five stations Vlissingen, De Kooy, De Bilt, Beek, and Eelde were considered throughout the analysis.

8.1.1. Temperature, frost days, and ice days

For the analysis of temperature related indicators, version 2 of the homogenised daily temperature series was used. Temperature observations are available from 1901 for De Bilt and from 1907 onwards for the remaining four stations. Winter years between 1911 and 2020 were analysed for all stations using the homogenised dataset of KNMI Data Platform (2026). The analysis focused on changes between climatological reference periods of 30 years.

Winter year minimum temperatures, numbers of frost days, and numbers of ice days were analysed for the periods 1931–1960, 1961–1990, and 1991–2020. An additional period of 1911–1940 was included to provide a longer-term historical perspective, although this period overlaps by 10 years with the 1931–1960 interval. Violin plots were used to visualise the distributions within each 30-year period and to assess potential shifts in variability and central tendency over time.

8.1.2. Snow cover days and snow cover depth

Historical snow cover observations from the five manual precipitation stations were analysed. Data were obtained from KNMI (2026b) and cover the winter years 1957–2025 for all stations except De

Kooy, where observations start in 1959. The snow depth series were not homogenised. However, snow depth observations are based on visual measurements and the measurement methodology was assumed to be unchanged throughout the observation period. Furthermore, station relocations were considered limited relative to the spatial scale of snowfall events. The series were therefore assumed to be sufficiently homogeneous for the purposes of this analysis.

First, the number of snow cover days per winter year was analysed for the climatological periods 1961–1990 and 1991–2020. Days with a measured snow depth exceeding 1 cm, as well as days coded as 997, 998, or 999, were classified as snow cover days. Consequently, snow cover days include both days with active snowfall and days on which an existing snow cover remained present.

Subsequently, annual maximum snow depths were analysed. For this purpose, codes 997 and 998 were replaced by a snow depth of 0.5 cm, representing a thin snow cover. Assigning a value of zero would artificially increase the number of winters without snow cover. Code 999 was replaced by 1 cm, which was assumed to represent the minimum snow depth required for snow drift formation. Although significantly higher drift heights may occur, snow drifts cannot form without the presence of snow cover. For example, snow drift heights approaching 1 m may occur when the surrounding snow cover is only roughly 10 cm high (KNMI, 2013).

Violin plots were made for both climatological periods and all stations to compare changes in annual maximum snow depths. In addition, the distribution of all snow depth observations was analysed and Mann-Kendall trend tests were applied to the winter year maxima to assess the presence of monotonic trends.

Depending on the outcome of the trend analysis, either stationary or non-stationary GEV distributions were fitted using the ProNEVA toolbox. Finally, the goodness of fit of the fitted distributions was evaluated and the resulting 50-year and 100-year return levels were compared with the characteristic ground snow loads prescribed in the NEN-EN 1991-1-3 and its Dutch National Annex.

8.2. Future climate projection analysis

This section displays the methodology for the projected wind velocity analysis.

As discussed in the literature review, the KNMI'23 Climate Scenarios do not provide explicit projections for snowfall occurrence or snow cover depth. Although snow models exist, these generally require meteorological variables that are not available within the KNMI'23 climate projections. Therefore, an empirical model was developed to estimate future snow cover characteristics from projected temperature and precipitation data.

The model was based on historical observations of daily snow depth, precipitation, and temperature. A key component is the conversion of precipitation amounts (mm) into snow depth increases (cm). KNMI states that 1 mm of precipitation approximately corresponds to 1 cm of snow cover (KNMI, n.d.-r). However, this ratio varies substantially with temperature and meteorological conditions. In addition, snow cover evolves through compaction and melting processes that reduce snow depth over time, although the total water equivalent is largely conserved during compaction.

The model was therefore required to account for the following processes:

- The relation between precipitation amount and snow cover increase (snow density) as a function of temperature.
- Accumulation of snow cover through newly fallen snow.
- Melting and compaction processes affecting the persistence of snow cover.

To develop the model, historical observations of snow cover, precipitation, and temperature were analysed. Snow depth observations were only available from the manual precipitation stations, whereas the automatic stations only record the occurrence of snowfall within hourly intervals. To ensure consistency in both location and observation time, manually observed precipitation data from the same stations were therefore used. Temperature observations were obtained from nearby automatic weather stations. All the observations were combined in one dataset.

The timing of the observations required additional processing. Snow depth and precipitation are measured manually around 09:00 local time, whereas standard daily temperature observations are based on a 00:00–00:00 interval. To improve consistency between the variables, daily temperatures were recalculated over a 09:00–09:00 period, corresponding more closely to the observation window of the snow and precipitation measurements.

Results snow analysis

This chapter displays the results of the snow analysis based on the methodology described in Chapter 8. The analysis focuses on both historical observations and projected changes of snow indicators under the KNMI'23 Climate Scenarios. To keep this chapter concise, additional figures, tables, and information are provided in Appendices B and E.

Section 9.1 discusses the historical snowfall indicators as frost and ice days. Section 9.2 presents the extreme value analysis of historical snow depths. Section 9.3 presents the snow indicator projections.

9.1. Historical snowfall indicators

This section presents the analysed historical snowfall indicators for the five stations.

9.1.1. Minimum temperature, frost days, and ice days

Figure 9.1 present violin plots for the three 30-year periods. The horizontal black lines indicate the median values. Vertical black lines extend from the first to the third quartile of the annual values within each 30-year period. Finally, the horizontal yellow line denote the mean values.

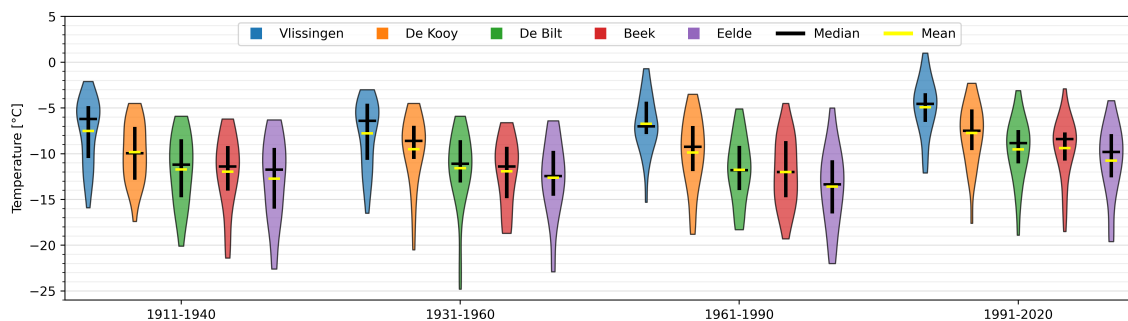


Figure 9.1: Distribution of winter year minima of daily minimum temperature

Figure 9.1 shows the distributions of the winter minima of the daily minimum temperatures. For all stations, both the mean values and the lower and upper bounds of the winter minimum temperature distribution increased for all stations between 1911–1940 and 1991–2020. The mean values of the winter minima are similar for the 1931–1960 and 1961–1990 periods. For nearly all stations and periods, the mean winter minimum temperature is lower than the median, indicating a left-skewed distribution. Across all periods, the mean winter minimum temperature is lowest at Eelde, slightly higher at Beek and De Bilt, followed by De Kooy, and highest for Vlissingen. This spatial pattern highlights the influence of regional differences, with higher winter temperatures near the coast and colder temperatures in inland regions. Between the 1911–1940 and 1991–2020 periods, the mean winter minimum temperature

increased by between 15.5 % at Eelde and 34.7 % at Vlissingen. In absolute terms, the increases range from 2.0 °C at Eelde to 2.6 °C at Vlissingen, with a mean absolute increase of 2.3 °C across the five stations. Overall, the absolute increases at Beek and Vlissingen are comparable and higher than those observed at the other three stations. De Bilt exhibits a smaller absolute increase than both De Kooy and Eelde. These patterns indicate a stronger rise in mean winter minimum temperatures in the southern part of the Netherlands compared with the northern regions.

Although the mean values of the minimum temperatures increased between the 1911–1940 and 1991–2020 period, the corresponding 30-year means for the 1911–1940 and the 1961–1990 periods are relatively similar and show only a slight increase. This limited warming may be partially attributed to the cooling influence of air pollution.

While aerosols can cause health problems, they also contribute to the reflection of incoming solar radiation. Resulting in a reduction of sunlight reaching the Earth's surface and exerting a cooling effect. Furthermore, CO_2 concentrations amplify climate warming, whereas SO_2 contribute to cooling. After the Second World War, industrialisation led to increased air pollution, which temporarily moderated global warming. However, from the 1970s onwards, the warming effect of CO_2 became dominant, as CO_2 persists much longer in the atmosphere than aerosols. In addition, air quality regulations introduced in Europe during the 1970s substantially reduced aerosol emissions. This resulted in cleaner air and a stronger warming effect in Europe compared to the rest of the world. Warm south-western winds in Europe also contribute to this enhanced warming. Globally, mean earth surface temperatures would have been approximately 0.5 °C higher relative to pre-industrial levels if aerosols effects did not exist (Sterl & Verheggen, 2025).

Figures 9.2 and 9.3 show the distributions of frost days and ice days per winter year for the three climatological periods and the five stations.

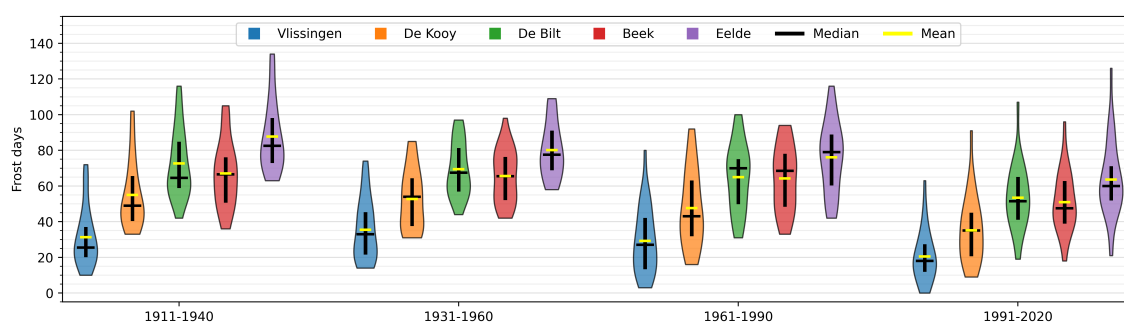


Figure 9.2: Distribution frost days per winter year

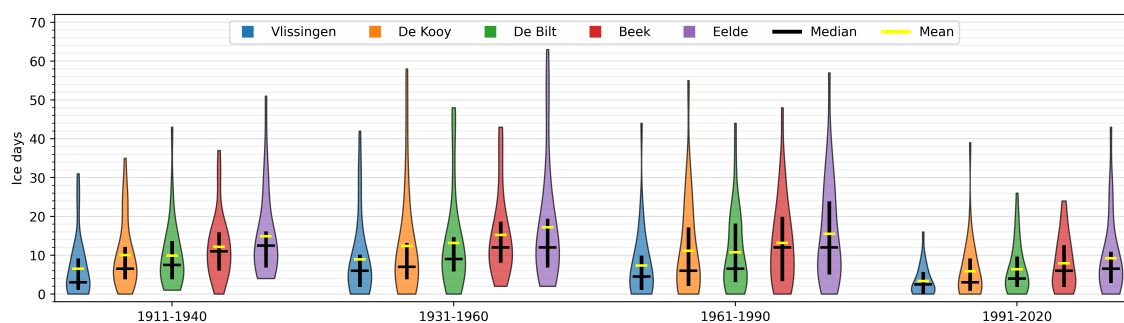


Figure 9.3: Distribution of ice days per winter year

The distributions of winter-year number of frost day in Figure 9.2 shows a clear decrease in mean frost day occurrence for all stations in 1991–2020 compared to 1911–1940. The downward shift in the median of frost days indicates a reduced likelihood of winters with as many frost days as observed during 1911–1940. In contrast, the upper bounds of the frost day distributions are similar to, or even

higher than, those in 1911–1940 for all stations except Vlissingen. Furthermore, across the four periods, the range of the distribution of frost days has widened for nearly all stations, indicating an increase in interannual variability.

Between the 1911–1940 and 1991–2020 periods, the mean number of frost days decreased by between 19.2 % at De Bilt and 36.1 % at De Kooy. A clear spatial pattern is noticeable, with coastal stations exhibiting larger relative decreases than inland stations. In contrast, a different spatial pattern is observed in the absolute changes. The mean number of frost days declined by between 10.7 days at Vlissingen and 24.1 days at Eelde, with an average reduction of 18.0 days across the five stations. In absolute terms, the decreases are generally larger at stations located in the eastern part of the country.

Similarly, Figure 9.3 shows the distributions of the number of ice days per winter-year. It reveals an even more pronounced decrease in the mean number of ice days for all stations in the 1991–2020 period compared to 1911–1940. For all stations, both the median and the upper and lower bounds have decreased, with the exception of the upper bound at De Kooy. This indicates a reduced likelihood of both individual ice days and winters characterised by a high number of ice days. In addition, the ranges of the ice day distributions are narrower in 1991–2020 than in 1911–1940 for all stations except De Kooy, suggesting a reduction in interannual variability.

Notably, the mean values and upper bounds for the 1931–1960 and 1961–1990 periods are comparable and higher than those observed for 1911–1940. Between the 1931–1960 and 1991–2020 periods, the mean number of ice days decreased by between 63 % at Vlissingen and 47 % at Eelde. Just as for frost days, a clear spatial pattern is visible, with coastal stations exhibiting larger relative decreases than inland stations. In absolute terms, the reduction ranges from 5.6 days at Vlissingen to 8.0 days at Beek, indicating slightly larger absolute decreases at inland stations compared with coastal stations.

For both frost and ice days, the highest mean values and the upper bounds occurred at Eelde and the lowest at Vlissingen. This pattern is consistent with the spatial distribution of mean daily temperatures, which are highest at Vlissingen and lowest at Eelde.

9.1.2. Snow cover days

Figure 9.4 shows the distributions of the number of snow cover days per winter for the climatological periods 1961–1990 and 1991–2020. For all stations, both the mean and upper bound are lower in 1991–2020, and the interquartile ranges have narrowed, indicating reduced interannual variability. The lowest mean number of snow days occurs at Vlissingen, followed by De Kooy and De Bilt, while Beek and Eelde record the highest values. The relative decrease in mean snow days ranges from 42.3 % (Beek) to 53.9 % (Eelde), corresponding to absolute reductions between 6.4 days (Vlissingen) and 16.1 days (Eelde). No clear spatial pattern is observed in the magnitude of these changes. The frequency of winters without any snow further illustrates this decline. During 1961–1990, only one snow-free winter occurred at Vlissingen, De Bilt, and Eelde, two at De Kooy, and none at Beek. In 1991–2020, snow free winters increased at all stations except Eelde, reaching six at De Kooy.

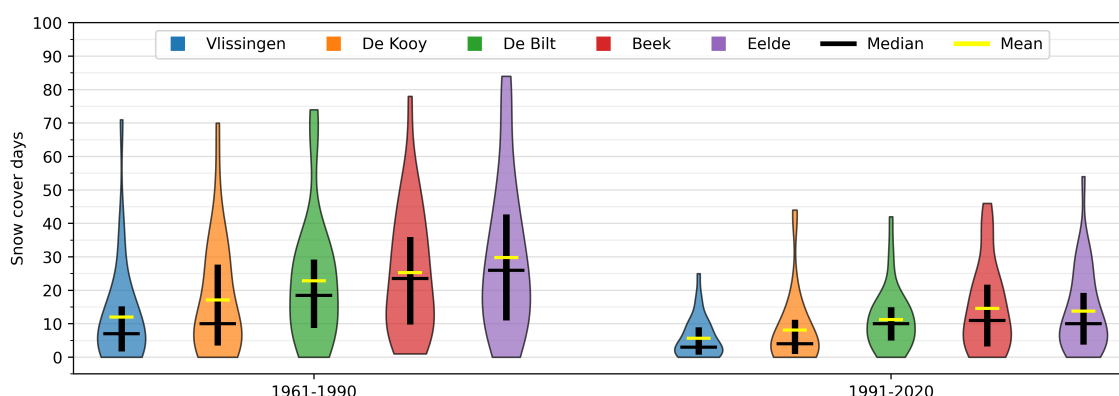


Figure 9.4: Violin plots for 30-year winter year of snow cover days for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

9.2. Historical snow cover depth

This section presents the observed snow cover depths for the five selected weather stations, followed by an extreme value analysis. The estimated return levels are then compared with the characteristic values prescribed in the Dutch National Annex of NEN-EN 1991-1-3.

9.2.1. Changes in winter year maxima of snow cover depth

Figure 9.4 presents the winter maximum snow depth time series. Winters without snow were assigned a value of 0 cm. All fitted linear trend lines show negative slopes, strongest at De Bilt and Eelde and weakest at the coastal stations. The Mann-Kendall trend test confirms statistically significant downward monotonic trends at De Kooy, De Bilt, Beek, and Eelde, but not at Vlissingen.

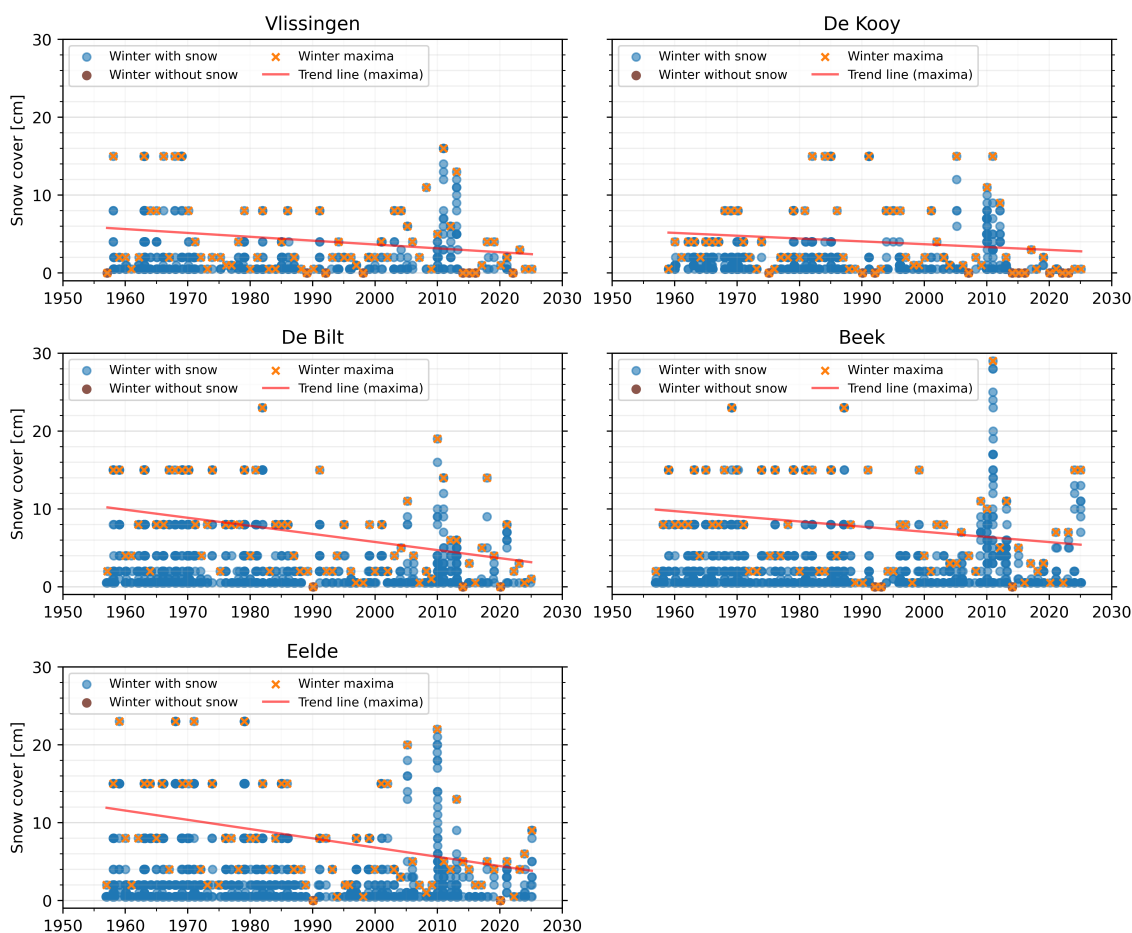


Figure 9.5: Snow cover for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

Figure 9.6 presents the distributions of winter maximum snow depth for both climatological periods. Mean values are lowest for coastal stations and highest for inland stations. Furthermore, coastal stations exhibit only minor changes in mean and upper bound between the two periods. At De Bilt, both decrease and at Beek and Eelde, the mean decreases while upper bounds remain similar or slightly increase. The interquartile range narrows substantially at De Bilt, Beek, and Eelde, indicating reduced interannual variability. Nevertheless, at Beek snow depths above 25 cm still occurred in 1991–2020. Relative reductions in mean winter maximum snow depth range from 12.2 % (De Kooy) to 40.5 % (De Bilt). Inland stations show the largest decreases of approximately 39 %, while coastal stations exhibit decreases of approximately 14 %. Absolute reductions follow the same pattern, ranging from -0.57 cm (De Kooy) to -3.80 cm (Eelde).

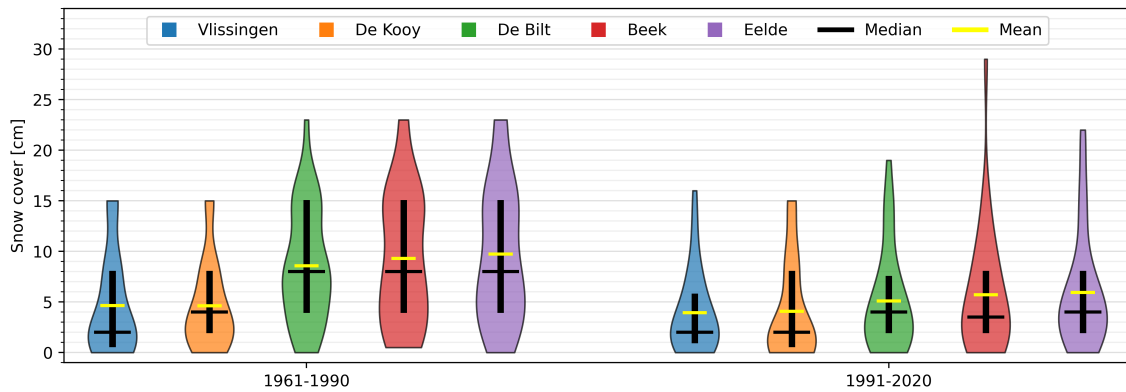


Figure 9.6: Winter maxima of snow depth for manual stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

Figure 9.7 presents the relative frequency distribution of observed snow depths. Most snowfall events result in depth smaller than 2 cm. An unusually low frequency occurs in the 6–8 cm bin compared to adjacent bins. Also, fewer than 1 % of events produce depths between 16 cm and 22 cm. For this no clear explanation was found. Clear spatial differences are visible: at Vlissingen and De Kooy approximately 80 % of events remain below 4 cm, whereas deeper snow is more frequent at Eelde and Beek.

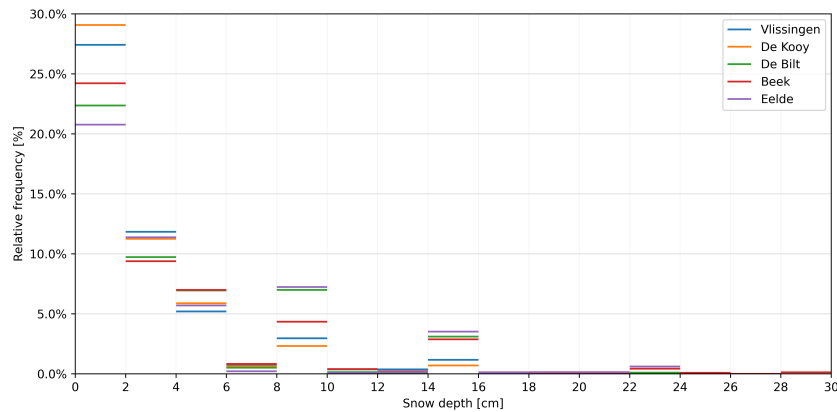


Figure 9.7: Snow depth distribution of 1959–2025 for manual stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

9.2.2. Extreme value analysis of snow cover depth

Because no significant trend is detected at Vlissingen, a stationary generalized extreme value distribution was fitted for this station, while non-stationary models were applied at the remaining stations. Due to the highly discrete behaviour of snow depth measurements (as in Figure 9.7) and the large resolution of 1 cm, a small uniform jitter (-0.5 cm to $+0.5$ cm) was added to winter maxima prior to fitting the model. Model settings are provided in Appendix B.1.

KS rejection rates 4.5 % or smaller for all stations. RMSE values correspond to approximately 15 % of the range of observations at Vlissingen and De Kooy and roughly 8 % at the other stations. This indicates a moderate fit. The discrete structure of the data limits further improvement. The PP plots show acceptable agreement, although QQ plots reveal deviations in the upper tail due to repeated identical maximum values (e.g. six identical 15 cm maxima at De Kooy).

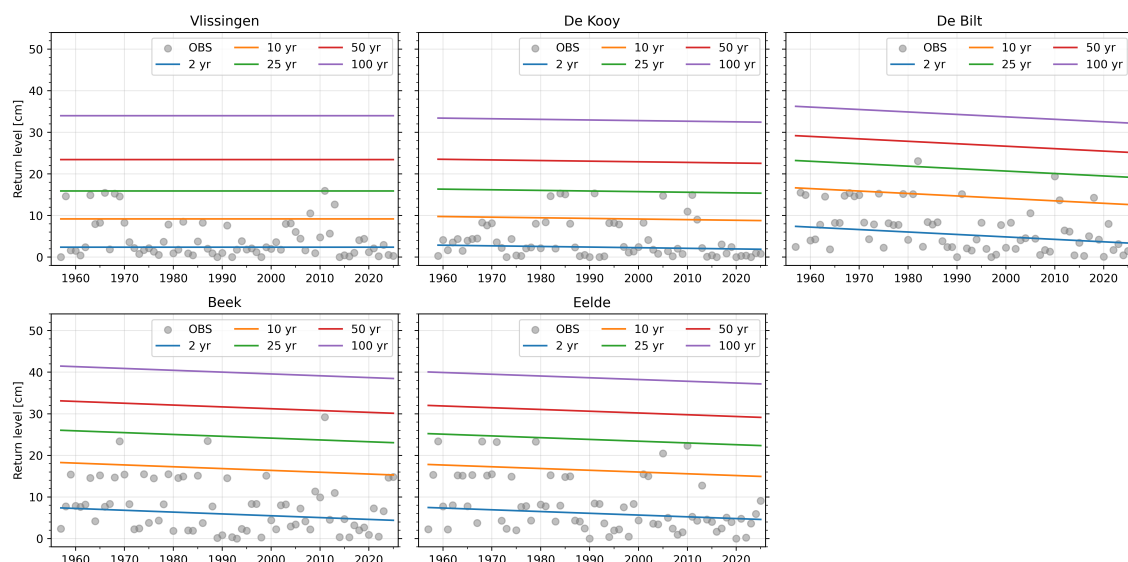


Figure 9.8: Estimated return levels for snow cover for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

Figure 9.8 presents the estimated snow depth return levels. In line with the non-stationarity models, return levels decrease over time at all stations except Vlissingen. The highest 50-year return levels occur at the start of the series, 33.1 cm at Beek and 32.0 cm at Eelde, and decrease to 30.1 cm and 29.7 cm in 2025. Coastal stations show lower values with the lowest at De Kooy in 2025 with 22.8 cm.

9.2.3. Comparison with Eurocode snow load

As stated in Section 7.2, the Dutch National Annex of NEN-EN 1991-1-3 prescribes a uniform characteristic ground snow load of 0.7 kN/m^2 for the entire Netherlands. This value is based on compacted snow with a volumetric weight of 2.0 kN/m^3 , corresponding to a snow depth of 35 cm. Table 9.1 compares this prescribed value with the estimated 50-year return level snow loads for each station, where the 50-year return level is taken as the characteristic ground snow load. The conversion from snow depth to snow load is based on the same volumetric weight as adopted in the National Annex.

For all stations except Vlissingen, the annual maxima are described by a non-stationary GEV distribution with a decreasing trend over time. Consequently, the estimated 50-year return level depends on the year for which it is evaluated. Using the return level around 2025 would implicitly assume that the current decreasing trend continues throughout the design life of a structure. Therefore, evaluating the return level at the start of the observation period would result in a substantially more conservative estimate that is unlikely to be representative of future conditions. Also, the snow indicator projections presented in Section 9.3.1, indicates a further reduction in climatic conditions favourable for substantial snow accumulation.

Therefore, to obtain a representative estimate of the historical snow climate while avoiding both of these extremes, the 50-year return levels are evaluated at the centre of the observation period, as this also represents the average climatic conditions over the analysed period. The resulting values are presented in Table 9.1.

Table 9.1: Comparison between estimated 50-year return level and given characteristic value of ground snow load based on Dutch National Annex of NEN-EN 1991-1-3

	Snow load Annex [kN ² /m]	Snow cover estimated [cm]	Snow load estimated [kN ² /m]	Estimated < Annex	Difference [%]
Vlissingen	0.7	23.4	0.47	yes	33.1
De Kooy	0.7	23.0	0.46	yes	34.2
De Bilt	0.7	27.2	0.54	yes	22.3
Beek	0.7	31.6	0.63	yes	9.7
Eelde	0.7	30.6	0.61	yes	12.6

All estimated characteristic snow loads are lower than the value prescribed in the National Annex (0.7 kN²/m). The largest relative difference is observed at De Kooy (34.2 %), while the smallest occurs at Beek (9.7 %). Even when considering the modelled return level snow loads around 1960, all values remain below the annex value. At Beek, the estimated snow load in 1960 is approximately 0.66 kN²/m, which is still 6 % lower than the prescribed characteristic value of 0.7 kN²/m.

Additionally, as noted in Section 7.2, the main part of NEN-EN 1991-1-3 provides a map of characteristic ground snow loads for the Netherlands at sea level, with values ranging 0.2 kN²/m over the largest part of the country to 0.7 kN²/m in some specific regions. Based on the location of the five stations, it can be concluded that all values shown on this map are lower than the estimated characteristic ground snow load. Consequently, structures designed using these values may not withstand the actual snow load levels. This disagreement is most pronounced for Beek, where the estimated snow load is 0.63 kN²/m, while the map indicates a value of 0.2 kN²/m. Therefore, it is appropriate that the Dutch National Annex recommends a uniform value of 0.7 kN²/m for the entire country.

Furthermore, the estimated 100-year return levels of snow cover depth and the corresponding characteristic ground snow loads are prescribed Appendix B. For all stations, the estimated values at the centre of the time series remain below the characteristic ground snow load of 0.8 kN²/m, which is obtained from NEN-EN 1991-1-3 and its National Annex. The relative differences are smaller than those found for the 50-year return period. For station Beek, the estimated 100-year return level ground snow load is only 0.1 % lower than the characteristic value.

It should be noted that the above comparisons assumes that the annual maximum snow depths, to which the GEV distributions are fitted, can be converted to snow loads using the volumetric weight of 2.0 kN/m³ prescribed in the Dutch National Annex. However, the analysis of precipitation and snow cover observations at the five stations, presented in Figure 9.9 (Section 9.3), suggests an average volumetric weight of approximately 1.5 kN/m³. This value was derived from daily observations of precipitation and changes in snow cover depth and is therefore representative of freshly fallen snow with a maximum age of approximately 24 hours.

The difference between the observed value and the value prescribed in the Eurocode is not unexpected. NEN-EN 1991-1-3 indicates that freshly fallen snow has a volumetric weight of approximately 1.0 kN/m³, while a value of 2.0 kN/m³ is considered for compacted snow several hours to days after snowfall. The average value of 1.5 kN/m³ derived from the observations therefore lies between these two characteristic values and appears physically plausible.

This comparison should still be interpreted with caution. The available observations only allow the relation between precipitation and snow cover increase to be analysed over daily observations. Processes such as compaction and melting and a snowpack could not be considered. Consequently, the derived volumetric weight is representative of newly accumulated snow rather than the denser snowpacks that may develop after prolonged accumulation and compaction. Therefore, the volumetric weight of 2.0 kN/m³ prescribed in the Dutch National Annex remains the most appropriate value for converting the estimated return levels of snow depth into characteristic ground snow loads.

9.3. Projected snow analysis results

During the model development it became obvious that snowfall occurrence and snow cover change depend on too many processes to be represented accurately by a simple model based only on daily temperature and precipitation. Analysis of historical days with increases in snow cover showed that the relation between precipitation and snow cover change is highly variable and likely influenced by additional meteorological factors.

Figure 9.9 presents the relation between daily precipitation and snow cover change for historical observations at the same five stations as considered in the historical snow cover analysis. Only days with more than 1 cm increase in snow cover and more than 1 mm of precipitation were included to reduce the influence of very small values and outliers. Daily mean temperatures were again considered over the 09:00–09:00 interval.

The term “*snowfall*” is intentionally avoided here, since measured snow cover change does not necessarily correspond directly to snowfall amount due to simultaneous melting and compaction processes. Figure 9.9 shows that no clear relation exists between precipitation amount and snow cover increase, based on different mean daily temperatures. In general, lower temperatures tend to produce larger snow cover increases for a given precipitation amount. However, large variability remains visible over the full temperature range. For temperatures between roughly -5°C and $+3^{\circ}\text{C}$, the ratio between precipitation and snow cover change varies between approximately 0.016 and 0.85. This corresponds to snow cover increases ranging from roughly 0.12 cm to 6.3 cm for 1 mm of precipitation. The mean ratio is approximately 0.15, suggesting that on average 1 mm of precipitation corresponds to approximately 0.7 cm of snow cover increase. This is roughly 33 % less than the KNMI rule of thumb.

Since the y-axis of Figure 9.9 represents the ratio between precipitation amount and snow depth, multiplying these values by 1000 converts the ratio to the density of freshly fallen snow. The mean density is approximately 150 kg/m^3 , corresponding to approximately 1.5 kN/m^3 .

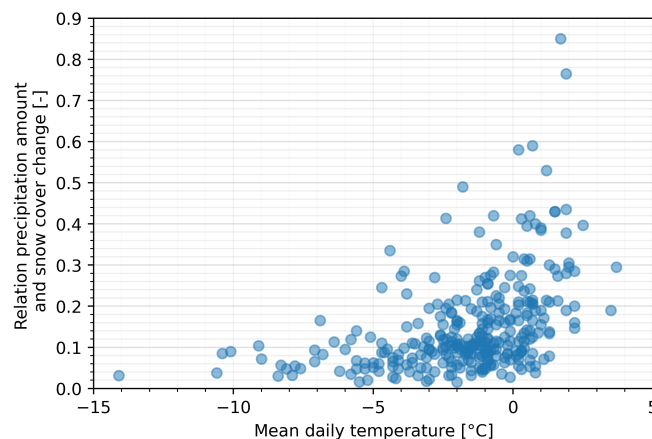


Figure 9.9: Relation between daily precipitation and snow cover change based on the mean daily temperature between 09:00 and 09:00 for five stations in the Netherlands. Multiplication of the y-axis values yields into density of newly fallen snow

In addition, no fixed threshold temperature could be found above which snowfall and snow accumulation no longer occur. Snow cover increases of more than 1 cm were still observed for daily minimum temperatures up to $+2.2^{\circ}\text{C}$, daily mean temperatures up to $+4.4^{\circ}\text{C}$, and daily maximum temperatures up to $+10.8^{\circ}\text{C}$. These observations are shown in Figure 9.10. This highlights that the occurrence of snowfall and snow accumulation cannot be described by using a single daily temperature threshold.

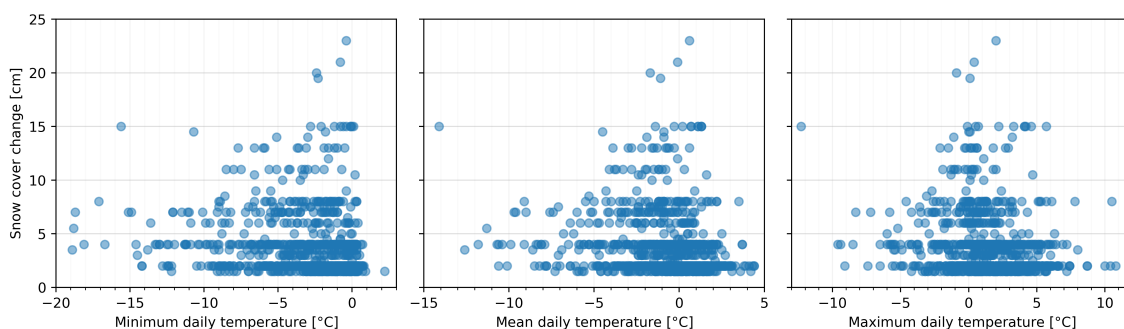


Figure 9.10: Snow cover change for different daily temperatures between 09:00 and 09:00 for five stations in the Netherlands

Modelling snow melting processes also showed to be difficult using the available observations. The manually measured snow depth observations only provide a single daily measurement around 09:00. Consequently, when multiple consecutive days show similar snow depths, it cannot be determined whether melting occurred together with new snowfall or whether temperatures remained sufficiently low to prevent melting. Precipitation observations alone are also insufficient to distinguish between snowfall accumulation and melting processes. As a result, no reliable temperature dependent melting coefficient could be derived from the available data.

An extra limitation originates from the daily measurement procedure itself. Since snow depth is only measured once each morning, short-lived snow covers may not be recorded in the observations. This is illustrated by the snowfall event of 15 February 2026 shown in Figure 9.11. During the late afternoon and evening, snowfall in parts of the Netherlands resulted in temporary snow cover depths of roughly 5 cm near Gilze-Rijen in North Brabant. However, rising temperatures during the night caused most of the snow cover to melt before the following morning. Consequently, many stations reported either no snow cover or only a broken snow cover on 16 February 2026 at 09:00.

This example demonstrates that brief snow cover events may be overlooked in the KNMI snow cover observations. It also helps explain why relating daily precipitation amounts to observed snow cover using daily temperatures alone is difficult, since important sub-daily processes are not recorded in the available measurements.

For structural engineering applications, snow weight rather than snow depth is generally the primary quantity of interest, since loads are directly related to the water equivalent of snow. In principle, this reduces the importance of relating precipitation amounts to snow depth. However, the analysis showed that it remains difficult to determine when precipitation falls as snow, how much snow accumulates, and how fast melting processes occur based on daily temperature and precipitation observations.

Given this findings, it is recommended that future versions of the KNMI Climate Scenarios include projections of snow cover. In addition further research into the relation between precipitation, snow cover, and additional meteorological variables may improve the modelling of snowfall and snow accumulation processes.

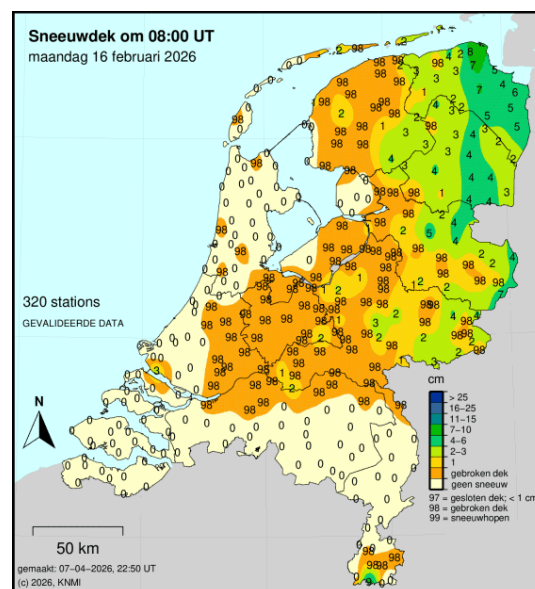
Finally, measuring snow depth more frequently than once per day could improve the representation of short duration snow cover events. Furthermore, based on the observations discussed in Section 9.2.1, where certain snow depths appear to occur considerably less frequently than neighbouring values, it may be valuable for the KNMI to further investigate potential measurement flaws and the accuracy of the current depth measurement procedure.

9.3.1. Snow indicators

Since development of a reliable model for estimating future snow cover under different climate scenarios was not successful, several climate indicators related to snowfall occurrence and snow cover persistence are analysed instead. These indicators provide insight into whether climatic conditions which are favourable for snowfall and snow accumulation are expected to increase or decrease under different climate scenarios.



(a) Snowfall at Efteling, Kaatsheuvel in North Brabant on 15 Februari 2026 around 18:30. By R. Verhulst, 2026. Reprinted with permission.



(b) Snow cover map of 16 February. From "Koninklijk Nederlands Meteorologisch Instituut", by KNMI, n.d.-j (<https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten>). Licensed under KNMI's CC0 copyright.

Figure 9.11: Example of snow cover persisting for less than one day

For this analysis, the grid cell corresponding to De Bilt in the KNMI'23 climate scenarios model output is considered. As discussed in Section 2.2, due to its central location in the Netherlands, it is representative of neither a full maritime nor a fully continental climate. KNMI also provides key figures for De Bilt for indicators such as precipitation, frost days and ice days for all climate scenarios. These values may differ slightly (not more than 2%) from the values derived from the gridded model output. The key figures are based on the original model samples rather than the user friendly model output (KNMI, n.d.-q). The user friendly model output is used here because it provides more detailed information regarding statistical properties and ensemble spread of the projections.

The analysis focuses on the KNMI'23 scenarios for the time horizons around 2050 and 2100. Each scenario and ensemble contains 30 years of projections. However, since winter years rather than calendar years are considered, only 29 complete winter years are available for each period. Consequently, the reference period consists of the winter years 1992–2020 and the future periods correspond to 2037–2065 and 2087–2115 for the 2050 and 2100 horizons, respectively.

In the analysis the following indicators are considered:

- Winter precipitation sum: changes may affect the potential amount of snowfall.
- Number of frost and ice days: related to conditions under which precipitation fall as snow and snow cover may persist.
- Precipitation sum during days with a daily mean temperature below 0 °C: provides a proxy indicator for climatic conditions favourable for snowfall accumulation.
- Maximum number of consecutive days with a daily mean temperature below 0 °C: provides information on the persistence and potential built-up of snow cover.

For all indicators, winter years are defined from July until June, where the months July–December are corresponding to the following calendar year (e.g. December 2019 corresponds to winter year 2020). For the winter precipitation sum, only the meteorological winter months December, January, and February (DJF) are considered. For each indicator, the model output for the reference period is compared with observations over the same period. This allows the performance of the model to reproduce historical conditions to be assessed.

The figures in this section present the ensemble mean values over the 29 winter years. In Appendix E,

violin plots are provided which illustrate the distributions within the ensembles and between individual years. Furthermore, since upper tail values are of particular relevance in structural engineering, tables in Appendix E also present the 5–95 percentile intervals for all indicators.

In Figure 9.12, the mean winter precipitation sums for De Bilt grid cell are shown for the different climate scenarios. As stated above, the precipitation sums are calculated over the winter months December, January, and February. The reference period shows good agreement between the observations (239 mm) and the model output (235 mm), indicating that the model reproduces the historical mean winter precipitation reasonably well. Consistent with the definitions of the wet and dry KNMI'23 scenarios, the wet variants show higher winter precipitation sums than the corresponding dry variants within the same radiative forcing level. In addition, higher radiative forcing levels generally result in larger increases in winter precipitation.

For the low radiative forcing scenarios, the projected mean winter precipitation sums remain close to the reference period values, with only minor increases for the wet variants and small decreases for the dry variants. For the moderate forcing scenarios, the wet variants show comparable increases for both future time horizons, while the dry variants show only limited changes between 2037–2065 and 2087–2115. This limited difference may result from internal climate variability and the relatively short analysed periods. The largest increases occur for the wet variant of the high radiative forcing scenario, which is consistent with the physical expectation that a warmer atmosphere can contain more moisture and therefore produce higher precipitation amounts.

The 95th percentile values for the reference period are 343 mm for the model output and 332 mm for the observations, again indicating good agreement between the model and observations. For the future projections, the 95th percentile increases to 334 mm for Ln2100, 356 mm for Mn2100, and 402 mm for Hn2100. This suggests that for moderate to high global warming in combination with regional wetting effects may lead to more extreme winter precipitation sums.

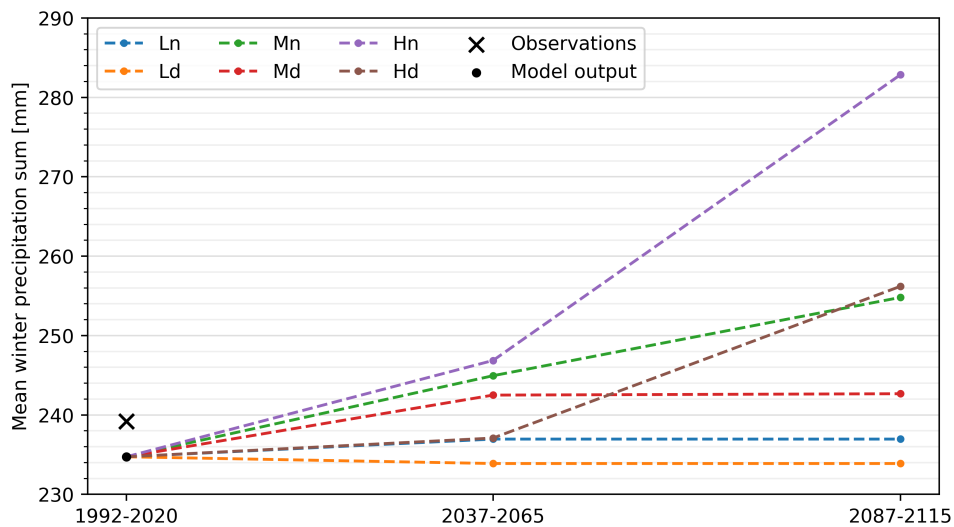


Figure 9.12: Mean winter precipitation sum around De Bilt

Figure 9.13 shows the mean number of frost days per winter year. The observations and model output for the reference period show very good agreement, indicating that the model reproduces the historical mean numbers of the frost days accurately. Since frost days are primarily temperature-driven, relatively small differences are observed between the wet and dry variants within each radiative forcing level. However, minor differences remain visible. According to the KNMI'23 scenarios (van Dorland et al., 2024), the wet and dry variants are associated with differences in large-scale atmospheric circulation, which may also influence local temperatures and therefore the number of frost days.

For the reference period, both the observations and the model output show a mean of 53 frost days per winter year. For the low radiative forcing scenarios, this decreases to approximately 39 days for both

future periods. For the moderate forcing scenarios, the mean decreases further to approximately 28 days in 2087–2115. Under high radiative forcing, the mean number of frost days decreases to approximately 10.5 days per winter year around 2100, which corresponds to a reduction of approximately 80 % relative to the reference period.

The 95th percentile values for the reference period are 83 frost days for the model output and 77 frost days for the observations, again indicating good correspondence between model and observations. For 2087–2115, these values decrease to approximately 68 days for the low forcing scenarios, 55 days for the moderate forcing scenarios, and 29 days for the high forcing scenarios. This indicates that winters with a substantial number of frost days may still occur under moderate warming. However, values comparable to those observed during the reference period become increasingly unlikely.

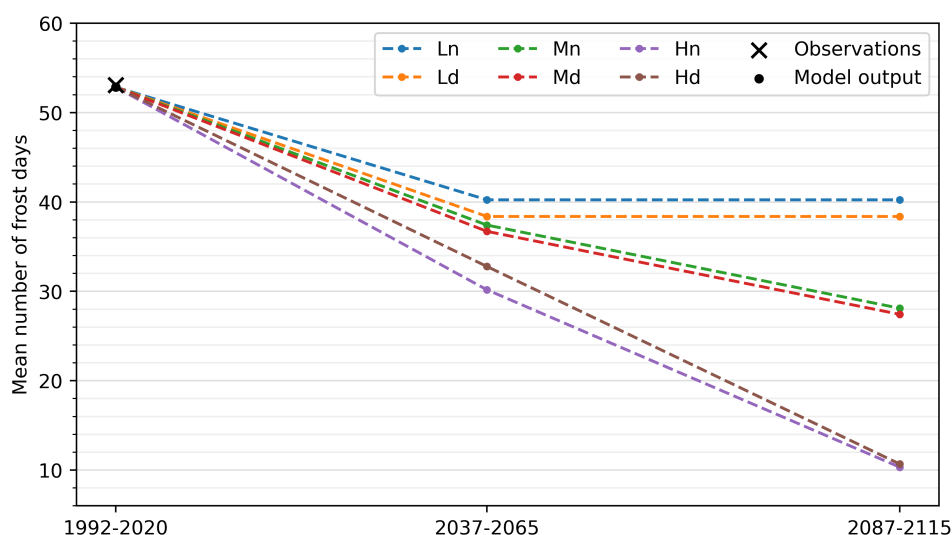


Figure 9.13: Mean winter year number of frost days around De Bilt

Similar trends are observed for the number of ice days, shown in figure 9.14. All scenarios project a decrease in the number of ice days, while only limited differences are observed between the wet and dry variants within each forcing level. These small differences are likely related to the same circulation related effects discussed for frost days.

The model output and observations for the reference period shows good agreement, with mean values of 6.2 and 6.3 ice days per winter year, respectively. For the period 2087–2115, the projected mean decreases to approximately 3.5 days for the low forcing scenarios, 2.2 days for the moderate forcing scenarios, and only 0.3 days for the high forcing scenarios. This corresponds to a reduction of approximately 95 % relative to the reference period.

The 95th percentile values for the reference period are 18.4 and 19.6 ice days for the model output and observations respectively. Around 2100, these values decrease to approximately 13.0 days for Ln2100 and to only 2.0 days for the high forcing scenarios. For the moderate forcing scenarios, the projected 95th percentile values is approximately 9.5 days around 2100. This indicates that winters with several ice days may still occur around De Bilt under moderate warming, although such winter become less frequent.

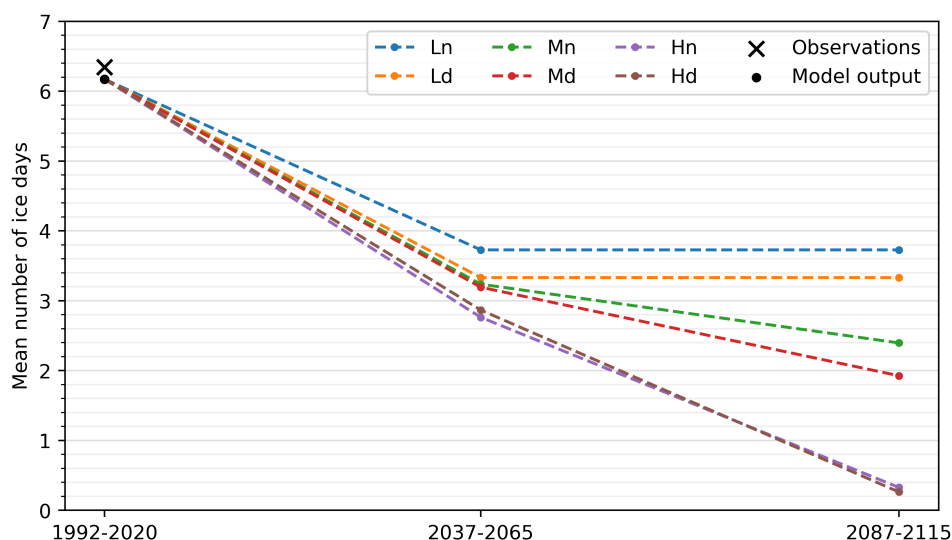


Figure 9.14: Mean winter year number of ice days around De Bilt

Figure 9.15 shows the mean winter precipitation sum during days with a daily mean temperature below 0°C . The agreement between the model output and observations for the reference period is moderate. The model output gives a mean value of 10.4 mm, which is approximately 21 % higher than the observed value of 8.6 mm. This indicates that the model overestimates precipitation occurring during freezing conditions.

For the low and moderate forcing scenarios, the wet variants show higher values than the dry variants. For the high forcing scenarios, the wet and dry variants show similar values, since freezing conditions become increasingly rare in both cases. For the period 2087–2115, the projected mean values decrease to between 0.8 mm and 6.1 mm, depending on the scenario.

The 95th percentile values also show a moderate model overestimation. For the reference period, the model output gives a value of 34.4 mm, while the observations give 28.0 mm, corresponding to an overestimation of approximately 23 %. For the future scenarios, the 95th percentile ranges from 4.5 mm for Hd2100 to 29.2 mm for Ln2100. For the moderate forcing scenarios around 2100, the average 95th percentile is approximately 17.2 mm.

This indicator should be interpreted with caution. It does not directly represent snowfall or snow depth, since processes such as snow density variations and melting are not considered. In addition, precipitation occurring during these days with a mean temperature below freezing does not necessarily fall entirely as snow. Still, the indicator provides a useful proxy for climate conditions which are favourable for snowfall accumulation.

Finally, both the mean values and the 95th percentile values differ by approximately 22 % between the model output and the observations, with the model overestimating precipitation during days with the mean daily temperature below zero. If this bias remains approximately constant under future climate conditions, the projected values may overestimate the actual precipitation sums for days with a mean temperature below zero. Consequently, the projected potential for snowfall accumulation may also be overestimated.

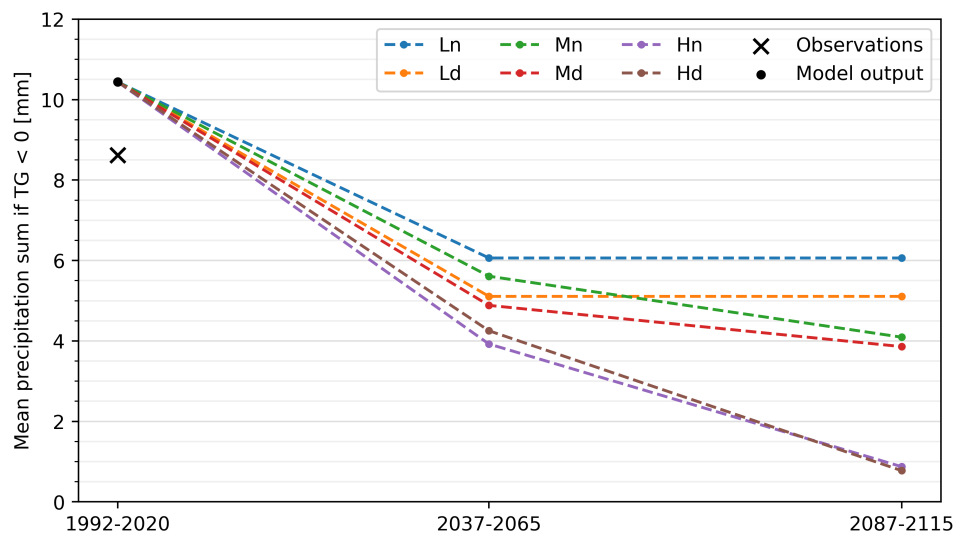


Figure 9.15: Mean winter year precipitation sum if daily mean temperature is below zero degrees Celsius around De Bilt

Figure 9.16 presents the mean maximum winter year number of consecutive days with a daily mean temperature below 0 °C. The model output and observations for the reference period show good agreement, with mean values of 7.8 and 7.4 days, respectively. For the future scenarios, the projected mean decreases to between 1.6 and 6.0 days for the period 2087–2115, depending on the radiative forcing level. Although this indicator primarily depends on temperature, small differences remain visible between the wet and dry variants. These differences are likely associated with the circulation related effects discussed previously for frost days.

For the reference period, the 95th percentile values are 16.0 days for the model output and 19.8 days for the observations. For the moderate forcing scenarios around 2100, the projected mean values decrease to approximately 4.6 days, while the 95th percentile decreases to approximately 11.4 days. This corresponds to a reduction of approximately 28 % relative to the model reference period and indicates that longer freezing periods become less common under future warming.

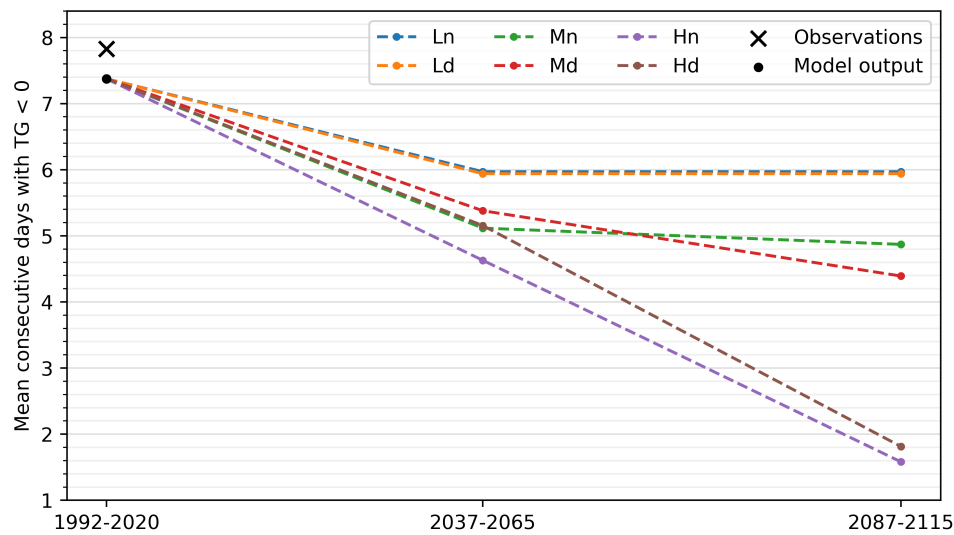


Figure 9.16: Mean winter year number of maximum consecutive days with daily temperature below zero degrees Celsius around De Bilt

9.3.2. Conclusion

Based on the five snow indicators considered for the reference period and the 2050 and 2100 time horizons of the KNMI'23 climate scenarios, all scenarios indicate a reduction in climatic conditions which are favourable for snowfall and persistent snow cover around De Bilt. Although winter precipitation sums are generally projected to increase, particularly for the wetter and higher radiative forcing scenarios, the number of frost days, ice days, and prolonged freezing periods decreases substantially. Consequently, winter precipitation is increasingly expected to occur as rainfall rather than snowfall.

The strongest reductions are observed for indicators that are directly related to freezing conditions. For the high radiative forcing scenarios in the 2087–2115 period, the mean number of frost days are projected to decrease by approximately 80 % relative to the reference period, while the mean number of ice days decreases by approximately 95 %. Furthermore, the number of consecutive days with daily mean temperatures below zero degrees Celsius decreases considerably. This reduces the likelihood that snow cover can persist or accumulate over multiple days.

The indicator based on the winter precipitation sum during days with a daily mean temperature below 0 °C also shows a significant decrease for all future scenarios. However, this indicator should be interpreted with caution. It does not directly represent snowfall or snow depth since it neglects processes such as snow density variations, melting or compaction. Furthermore, precipitation occurring during days with mean temperature below freezing does not necessarily fall entirely as snow. Nevertheless, the indicator provides a useful proxy for climatic conditions associated with snowfall occurrence and snow accumulation.

For the reference period, the model overestimates this indicator relative to observations by approximately 21 % for the mean and 23 % for the 95th percentile. Assuming that this relative model bias remains constant under future climate conditions, a simplified scaling correction can be applied to the projected values by also assuming 1 mm of precipitation being equal to 1 cm of snowfall. After correction, the 95th percentile values decrease from approximately 28 cm in the observed reference period to values between 15 cm and 22 cm for the 2050 scenarios, and to approximately 14 cm for the moderate forcing scenarios around 2100. For the high forcing scenarios around 2100, the corrected value decreases to approximately 4 cm.

These values should not be interpreted as characteristic snow loads or estimates of future ground snow loads. Instead, they provide an indication of the decreasing potential for substantial snowfall accumulation around De Bilt.

Overall, all indicators suggest that winters with significant snow accumulation become substantially less frequent under increasing radiative forcing. Finally, it should be noted that the projected changes in the snow indicators may vary locally within the Netherlands, since the analysis is limited to the grid cell of De Bilt. Local differences in climatic conditions, such as the influence of maritime and continental effects, may result in slightly different trends in snowfall related indicators for other locations.

9.4. Changes in characteristic snow load values under climate change

For the moderate forcing scenarios around 2050, the snow indicators suggest that substantial snow accumulations become less likely than during the reference period. The projected decrease in the number of consecutive freezing days further reduces the probability that snow covers can persist and accumulate over multiple days. Similar but more pronounced changes are projected for the 2100 time horizon, particularly under the high radiative forcing scenarios.

Although no quantitative characteristic values can be derived, the results provide no indication that characteristic snow loads in the Netherlands will increase under future climate conditions. On the contrary, all analysed indicators point towards a decreasing likelihood of substantial snow accumulation. This likely decreases the characteristic ground snow loads in the Netherlands.

Furthermore, the historical observations of snow depth for the five stations, generally shows a decreasing trend in extremes.

10

Discussion, conclusion, and recommendations snow

This chapter discusses the methodology and results of the snow analysis. It then answers the research questions related to snow loads and concludes with recommendations for future research on the effects of climate change on snow loads.

10.1. Discussion

The historical snow depth observations of the five stations were assumed to be sufficiently homogeneous for the analysis. Since snow depth was recorded in steps of 1 cm, the observations showed strong discrete behaviour. In addition, some snow depths occurred considerably more frequently than others, indicating potential rounding effects. These characteristics introduced uncertainty into the fitted extreme value distributions.

An important assumption in the comparison between the estimated 50-year return levels of snow depth and the characteristic ground snow load prescribed in the Dutch National Annex concerns snow density. The conversion from snow depth to snow load was based on the density of compact snow prescribed in the National Annex (2.0 kN/m^3). According to NEN-EN 1991-1-3, this density is representative of snow covers several hours to days after snowfall. However, the analysis of observed snowfall events indicated an average density of approximately 1.5 kN/m^3 . It should be noted that this analysis was based on newly fallen snow with a maximum age of approximately 24 hours, as snow depth observations were performed once per day. Processes such as compaction which increase snow density over time, could not be quantified from the available observations.

Furthermore, for the non-stationary extreme value analysis, all stations except Vlissingen show decreasing return levels over time. The estimated return level at the centre of the observation period was considered for comparison with the Dutch National Annex, as this represents the average climatic conditions over the analysed period. Furthermore, since annual maximum snow depths showed a decreasing trend and future climate projections indicate increasingly unfavourable conditions for snowfall and persistent snow cover, the characteristic snow load is expected to decrease further under climate change. In addition to the estimated 50-year return levels of the ground snow load, 100-year return levels were also derived. For all stations, the estimated 100-year values remained below the corresponding characteristic values derived from NEN-EN 1991-1-3 and its Dutch National Annex.

A simplified snow cover model based on temperature and precipitation was explored to derive future snow load projections. However, snowfall occurrence and snow accumulation depend on additional meteorological processes that were not available in the climate scenario outputs. Furthermore, snow depth observations were only available once per day, limiting the possibility of relating snow accumulation and melt processes to short-term temperature variations. As a result, no sufficiently robust model could be developed to derive quantitative projections of future snow depth or snow loads.

10.2. Conclusion

The snow-related research questions can be answered as follows.

To what extent do current characteristic values for snow loads in the Dutch National Annex reflect recent observations and trends?

The historical analysis showed that the estimated 50-year return levels of snow depth generally correspond to snow loads that are lower than the characteristic ground snow load prescribed in the Dutch National Annex when the same snow density is assumed. In addition, decreasing trends in snow cover indicators were observed at most stations.

How are snow loads expected to change under different climate scenarios in the Netherlands?

The KNMI'23 climate scenarios do not provide direct projections of snowfall or snow cover depth. Nevertheless, all analysed snow-related indicators show a substantial reduction in climatic conditions favourable for snowfall and persistence of snow covers. In particular, the projected decreases in frost days, ice days, and prolonged freezing periods suggest that snowfall occurrence and snow accumulation will become less frequent under future climate conditions.

What changes in characteristic values for snow loads can be derived from climate change scenarios, and how do these compare to current values in the Dutch National Annex?

No quantitative changes in characteristic snow loads could be derived, since reliable projections of future snow depth or snowfall amounts were not available.

The main research question can therefore be answered as follows:

How do climate change scenarios affect characteristic values for snow loads on buildings in the Netherlands, and what are their implications for structural design?

Although quantitative projections of future characteristic snow loads could not be obtained, all analysed indicators point towards a decreasing likelihood of substantial snowfall and persistence of snow covers. Consequently, there is no evidence that climate change will increase snow loads on buildings in the Netherlands.

10.3. Recommendations

Future climate scenario products should include projections of snowfall, snow water equivalent, and snow cover depth. Such information would allow direct assessment of future snow loads and would improve the applicability of climate scenarios for structural engineering purposes.

In addition, future snow observations should provide information on snow density and snow water content. This would allow more reliable conversions between snow depth and snow load and improve understanding of how snow properties may change under future climate conditions.

Part IV

wind

Literature study for wind

This chapter reviews the literature relevant for the wind analysis. First, global wind trends are discussed. Subsequently, the methodology for calculating wind loads in structural design according to Eurocode 1 and the Dutch National Annex is discussed. Then, the Dutch wind measuring network and observed wind trends are described. Finally, the wind component of the KNMI'23 Climate Scenarios is explained, including the projected changes in wind velocities.

11.1. Global wind trends and projections

In the the IPCC Working Group 1 report, only limited information is provided on global wind projections. The expected level of change of mean wind speed and severe wind storms is given for regions on all continents. For Western and Central Europe, there is a low confidence that the mean wind speed will decrease and a medium confidence that severe wind storms will increase (Arias et al., 2021).

Other studies have provided more quantitative projections for wind speeds in specific regions and under different global warming levels.

Vautard et al. (2010) analysed data from 822 surface weather stations worldwide and found that near-surface wind speeds (NSWS) across most mid-latitude continental areas of the Northern Hemisphere declined by 5 % to 15 % between 1979 and 2008. A stronger slowdown was observed in strong winds compared with weak winds. These declines were attributed for 10 % to 50 % to changes in atmospheric circulation and for 25 % to 60 % to increased surface roughness.

Under climate change as global temperature rises by 1.5 °C to 4.0 °C, the NSWS is expected to continue decreasing over the mid to high latitudes of the Northern Hemisphere, while increasing over the Southern Hemisphere. These contrasting trends could be caused primarily by changes in temperature gradients induced by global warming (Zha et al., 2021).

Shen et al. (2022) examined CMIP6 climate scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5) for the period 2021–2100 and found that global NSWS is projected to decrease overall. A decline was projected for the Northern Hemisphere, north of 20°N and an increase for the Southern Hemisphere, south of 20°N, likely driven by shifts of temperature gradient under global warming. For the near-term (2021–2040) and mid-term (2041–2060) periods, the differences between emission scenarios appear minor. While in the long-term (2081–2100), a more substantial global decrease in NSWS is projected with stronger declines under higher emission scenarios.

For Europe, a similar trend is visible. Regional emissions appear to have limited correlation with local NSWS changes. Under the highest emission scenario, the NSWS will decrease by –1.29 %, –1.89 %, and –3.03 % for the near-term, mid-term, and long-term periods in the mid to high attitudes of the Northern Hemisphere. South of 20°N, the increases in NSWS for the three periods are +0.03 %, +0.22 %, and +1.63 % (Shen et al., 2022).

11.2. Wind loads in the Eurocode

This section elaborates on the determination of wind loads on structures according to NEN-EN 1991-1-4 and its Dutch National Annex (NEN, 2011, 2023). Wind loads fluctuate over time and generally act as pressures on the external surfaces of buildings. For open structures, wind may also act on the internal surfaces. In structural design, wind loads are therefore simplified as sets of pressures or forces acting on structures. Wind loads are classified as variable fixed loads.

In NEN-EN 1991-1-4 a distinction is made between wind pressures and wind forces. Wind pressures mainly refer to pressures acting on building facades, whereas wind forces are considered for individual structural elements such as advertising boards or truss structures. Since the focus of this thesis is on buildings rather than individual structural elements, the discussion in this section is limited to wind pressures.

The procedure used to determine the characteristic (based on an annual probability of exceedance of 0.02) wind pressure on structures is shown in Figure 7.1. The figure presents the various factors that influence wind pressure on structures. The grey part indicates the aspects investigated in this research.

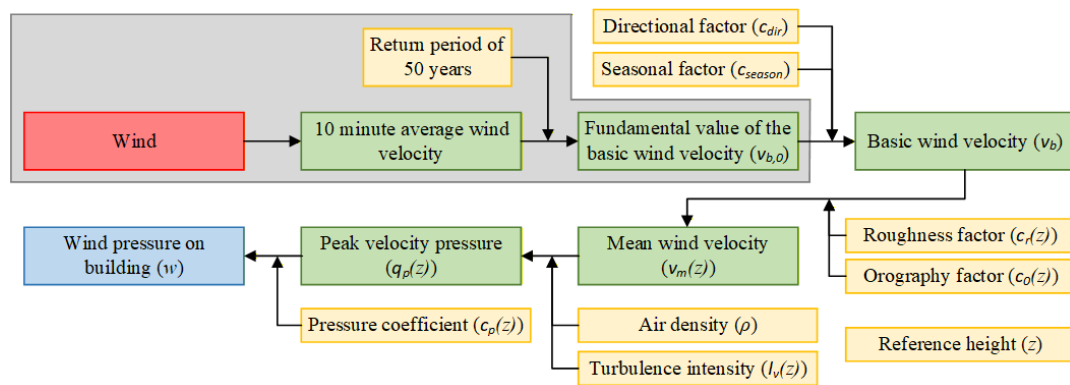


Figure 11.1: Characteristic wind pressure load on structures according to NEN-EN 1991-1-4 and its Dutch National Annex

The fundamental value of the basic wind velocity ($v_{b,0}$) is defined as the 10-minute mean wind velocity with an annual probability of exceedance of 0.02. In this definition, wind direction and seasonal effects are not considered. The wind velocity must be measured at a height of 10 m above a flat terrain with low vegetation.

The Dutch National Annex divides the Netherlands into three wind regions with different fundamental wind velocities. Wind region 1 has the highest basic wind velocity and covers the northern part of the province of North Holland (north of 52.5° latitude) and all Wadden Islands. Wind region 2 includes the remainder of North Holland and the provinces of South Holland, Zeeland, Flevoland, Friesland, and Groningen. Wind region 3 has the lowest wind velocities and covers the remaining part of the country. Table 11.1 presents the fundamental values of the basic wind velocity for these regions.

Table 11.1: Fundamental values of basic wind velocity according to the Dutch National Annex of NEN-EN 1991-1-4

Wind region	1	2	3
$v_{b,0}$ m/s	29.5	27.0	24.5

The basic wind velocity (v_b) is then determined by:

$$v_b = c_{dir} \cdot c_{season} \cdot v_{b,0} \quad (11.1)$$

where c_{dir} is the directional factor and c_{season} the seasonal factor. According to the Dutch National Annex, both factors must be taken equal to 1.0.

The mean wind velocity at reference height z is determined by:

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b \quad (11.2)$$

Where $c_r(z)$ is the roughness factor and $c_o(z)$ is the orography factor at the reference height z .

The roughness factor accounts for the terrain roughness and height above ground level at the windward side of the structure. The method to determine this factor is provided in the main code and the National Annex and it depends strongly on the terrain category of the location. A detailed explanation of this procedure is beyond the scope of this research. The orography factor accounts for the influence of terrain characteristics such as hills or cliffs if they increase the wind velocity by more than 5 %. Appendix A.3 of the main code describes how this factor must be determined. If the terrain slope is smaller than 3°, the orography factor may be taken equal to 1.0.

The peak velocity pressure $q_p(z)$ can then be determined as:

$$q_p(z) = (1 + 7 \cdot l_v(z)) \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) \quad (11.3)$$

where $l_v(z)$ is the turbulence intensity at height z , which depends on the terrain category and the mean wind velocity. The density of air, given by ρ is taken equal to 1.25 kg/m³.

Since several calculation steps are required to determine the peak velocity pressure at height z , the Dutch National Annex provides Table NB.5. This table gives peak velocity pressures for various heights, wind regions, and terrain categories, assuming an orography factor equal to 1.0.

The external wind pressure on buildings can then be determined by:

$$w_e = q_p(z_e) \cdot c_{pe} \quad (11.4)$$

where c_{pe} is the external pressure coefficient, which depends on the geometry, dimensions of the structure, and the considered wind direction. These coefficients are provided in the main code and the National Annex. Similarly, the internal wind pressure can be determined using internal pressure coefficients.

As indicated in Figure 11.1, this research focuses only on the potential effects of climate change on the fundamental value of the basic wind velocity. A change in this value directly affects the wind pressure acting on structures, provided that the geometry of the structure remains unchanged. Consequently, changes in the basic wind velocity may influence the required strength and stiffness of structural elements or the stability of an entire structure.

11.3. National wind measurements and trends

This section elaborates on the Dutch wind measurement network and observed trends in the past years.

11.3.1. Measuring network

Wind is generally measured at a height of 10 m above open terrain at the automatic weathers stations throughout the Netherlands (KNMI, n.d.-y). Wind observations are available at hourly, daily, and 10-minute temporal resolutions. In this study, the hourly datasets are used, as they provide the longest continuous observations records. The hourly datasets include the hourly mean wind velocity, the 10-minute mean wind velocity over the last 10 minutes of the hour, the maximum wind gust, and the corresponding dominant wind direction. All wind velocities are reported with a resolution of 0.1 m/s KNMI (n.d.-u).

The historic wind measurements of the five stations are available since 1951 onwards. Next to the changes in location given in Section 2.2, the data shows jumps at some instances, possibly caused by other adjustments in the measurement set-up or location. Since these changes are not publicly documented, KNMI was contacted to provide additional information on modifications to the wind measurement set-up. Appendix C.1 presents these documented changes since 1951 together with the

resampled hourly mean wind velocity for the five stations. Vertical bars indicate changes in measurement height, instrumentation, location, or recorder.

The documented modifications provided important insights. Since 1993 and 1997, wind measurements at stations De Bilt and Vlissingen have been performed at a height of 20 m instead of the usual 10 m. At De Bilt, this choice was made because high trees and the KNMI building obstruct winds from the southwestern to northwestern directions. Measuring at 20 m approximates the wind velocity that would be observed at 10 m in the absence of these obstacles. However, for the remaining wind directions with fewer obstacles the measured wind velocities may be slightly higher than those at 10 m. As winds in the Netherlands originate mainly from the western half direction, where wind velocities are typically highest, no corrections were applied to the Bilt wind series (KNMI, n.d.-o).

Station Vlissingen is located on a dike near the coastline, with land to the north and water to the south. The reason for measuring at 20 m at this station is unclear. According to KNMI, when wind originates from land (225° – 360° and 0° – 45°), the measured wind velocity should be reduced by roughly 11 % to represent wind at 10 m above open terrain. For the remaining directions, wind originating from the sea and measured wind velocities are higher due to the smoother surface and the greater measurement height (approximately 28 m above mean sea level). In these cases, wind velocities are roughly 17 % higher than at 10 m above open terrain and should therefore be reduced by approximately 14.5 %. These corrections can be easily applied in Python, as hourly major wind directions are recorded over each hour.

The main documented changes in wind measurements since 1951 are summarised below:

- At station *Vlissingen*, numerous modifications occurred between 1958 and 1997. Measurement height and location changed six times, with heights ranging from 9 m to 20 m. The recorder changed four times and the instrumentation twice. In 1997 the instrumentation was relocated by 14.5 m and the measurement height increased from 15 m to 20 m.
- At station *De Kooy*, the wind instrumentation was changed in 1972 and the measurement height lowered from 13.9 m to 10 m. Small relocations occurred in 1972 and 1980. The recorder changed in 1984 and 1993, and the set-up was relocated by 120 m in 2001.
- At station *De Bilt*, the instrumentation was changed in 1953 and 1961. Over the past 75 years, the measurement height varied between 10.0 m and 38.3 m. The recorder was changed 3 times.
- At station *Beek*, the instrumentation was changed in 1961 and the measurement height was lowered from 12.5 m to 10 m. The set-up was relocated by 200 m in 1988 and by 1100 m in 2005. The recorder changed in 1988 and 1991.
- At station *Eelde*, the measurement height was lowered from 12 m to 10 m in 1966. A small relocation occurred in 1973. The recorder changed in 1988 and 1990, and the set-up was relocated by 257 m in 1995.

11.3.2. Historical observations and trends

Wever (2012) analysed long-term changes in near-surface wind velocities and surface roughness across stations in the Netherlands and seven other European countries. The study combined observations of wind velocity series with an inverse modelling approach to derive changes in surface roughness over time.

The estimation of surface roughness was based on the relationship between observed wind velocity at standard measurement height and the logarithmic wind profile. By assuming neutral atmospheric stability conditions, the author applied a boundary-layer formulation in which wind velocity depends on friction velocity and surface roughness length. This allowed them to invert the wind profile equation and derive effective roughness lengths from long-term wind observations.

Using this method, time series of roughness length were reconstructed by Wever (2012) for the period 1962–2009. The results show a general upward trend in roughness length across most stations, which is interpreted as an increase in effective surface roughness due to changes in land use, vegetation, and urbanisation effects in the surrounding area. On average, the roughness length roughly doubled over the full analysis period.

In addition, trends in observed wind velocities were analysed for the period 1981–2009. A statistically significant decrease in mean wind speed of approximately 0.13 m/s per decade was found across most of the stations. By comparing the reconstructed roughness trends with the observed wind speed trends, the authors attributed roughly 70 % of the long-term decline in wind velocities to increasing surface roughness. The remaining 30 % could not be explained by roughness changes alone and was therefore attributed to other factors such as large-scale circulation variability or changes in atmospheric conditions.

Selten (2022) concluded particularly for the Netherlands that the wind velocities have decreased over the past 30 years. The author concluded similar to the research of Wever (2012) that this decrease is probably mainly the consequence of an increasing in surface roughness. It is noted that global warming still does not have substantial effects on the wind velocities in the Netherlands.

The study by Selten (2022) further notes that changes in local roughness affect measured wind velocities more strongly compared to the climate change effects on wind velocities that can currently be detected in the Dutch wind observations. Although climate change is expected to influence atmospheric circulation patterns, no clear long-term trend in Dutch wind velocity can currently be attributed to global warming. Consequently, observed decreases in measured wind velocity should not automatically be interpreted as evidence for decreasing large-scale wind conditions over the Netherlands.

11.4. KNMI'23 Climate scenarios methodology and projections

For wind projections, the available RACMO output includes daily mean wind velocity. Changes in wind gusts are addressed more qualitatively, since projections of future gust extremes remain uncertain. Nevertheless, KNMI'23 indicates that stronger wind gusts may occur under future climate conditions, although the available evidence is still limited.

Projected changes in mean wind velocity are influenced not only by climate change but also by assumptions regarding future land use. The effect of land-use change is particularly present in the provinces of Groningen and Drenthe. An important limitation of the current RACMO implementation is that urban areas in the future land-use projections are represented as bare soil. As a consequence, surface roughness is underestimated in urban environments, which may lead to an overestimation of projected wind velocities in these areas.

van Dorland et al. (2024) note that grid cells at sea are unaffected by projected land-use changes. Therefore, sea locations positioned close to the Dutch coast provide a useful reference when the objective is to assess the influence of climate change on wind velocities without the additional effects of changing surface roughness.

For the five main stations in the Netherlands, the projected changes in annual mean wind velocity remain relatively small. Around the 2100 time horizon, the different KNMI'23 scenarios generally show slightly lower mean wind velocities than during the reference period. With changes not exceeding -0.2 m/s (KNMI, n.d.-m).

According to van Dorland et al. (2024), a major conclusion of KNMI'23 is that the projected changes in mean wind velocity are small compared with the spread between climate models. The inter-model variability within the CMIP6 ensemble has a similar or even larger order of magnitudes, than the projected mean changes. Consequently, the direction and magnitude of future wind velocity changes over the Netherlands remains uncertain, and projected changes should therefore be interpreted with caution.

12

Methodology wind analysis

12.1. Historic analysis

As discussed in Section 11.2, the Eurocode is based on the 10-minute mean wind velocity. The KNMI does not provide long continuous records of arbitrary 10-minute intervals, but hourly observations contain the mean wind velocity over the final 10 minutes of each hour (KNMI, n.d.-u). These observations were therefore considered in the present study. Throughout this chapter, the term *10-minute mean wind velocity* is used to refer to these hourly recorded 10-minute averages. Potential inhomogeneities in the wind observations were assessed based on documented station relocations, changes in instrumentation, and modifications in measurement height. The most recent station relocations and instrument changes generally appeared to have a limited influence on the observed wind velocities (Appendix C.1). Restricting the analysis to periods after the most recent relocation would substantially shorten several records and reduce the number of annual maxima available for the extreme value analysis. Therefore, small potential inhomogeneities associated with the most recent relocations at De Kooy, Beek, and Eelde were accepted in favour of longer observation series.

Changes in measurement height were considered more critical, since wind velocity strongly depends on height above ground level. To minimise the influence of these changes, only observations after the most recent height modification were considered. Using complete years only, the analysed periods start in 1998 for Vlissingen, 1973 for De Kooy, 1994 for De Bilt, 1962 for Beek, and 1967 for Eelde. All series extend until the end of 2025.

Annual maxima of the 10-minute mean wind velocity were considered for each station. Subsequently, Mann-Kendall trend tests were performed to assess the presence of monotonic trends in the annual maxima series. Depending on the outcome of the trend analysis, either stationary or non-stationary GEV distributions were fitted using the ProNEVA toolbox. For the non-stationary analyses, the location parameter was allowed to vary with time. Finally, the goodness of fit of the fitted distributions was evaluated and the resulting 50-year and 100-year return levels were compared with the fundamental basic wind velocities prescribed in the NEN-EN 1991-1-4 and its National Annex.

12.2. Future climate projections analysis

The KNMI'23 climate scenarios do not provide hourly or sub-hourly wind projections. Therefore, projected changes in daily mean wind velocity were used as a proxy for changes in the 10-minute mean wind velocity. This approach is based on the assumption that relative changes in daily mean wind velocity are similar to changes in 10-minute mean wind velocity. Although this assumption cannot be verified directly with the available climate model output, no more detailed wind projections are currently available.

The user-friendly RACMO output of the KNMI'23 Climate Scenarios was considered for the low, moderate, and high radiative forcing scenarios, including both wet and dry variants and the available time horizons of 2050, 2100, and 2150. Only daily mean wind velocity was analysed.

As discussed in the literature review, projected changes in land use substantially influence the simulated wind velocities over land. To minimise this effect, sea grid cells located close to the Dutch coast were selected, following the recommendations of van Dorland et al. (2024). These grid cells are largely unaffected by projected land-use changes and therefore better represent the climatic wind signal. The selected locations are shown in Figure 12.1.

For comparison with observations, stations De Kooy and Eelde were selected. These stations combine relatively long homogeneous series of 10-minute mean wind velocity with locations close to the coast, where the highest wind velocities in the Netherlands generally occur. Consequently, these stations are most relevant for assessing characteristic wind velocities used in structural design.

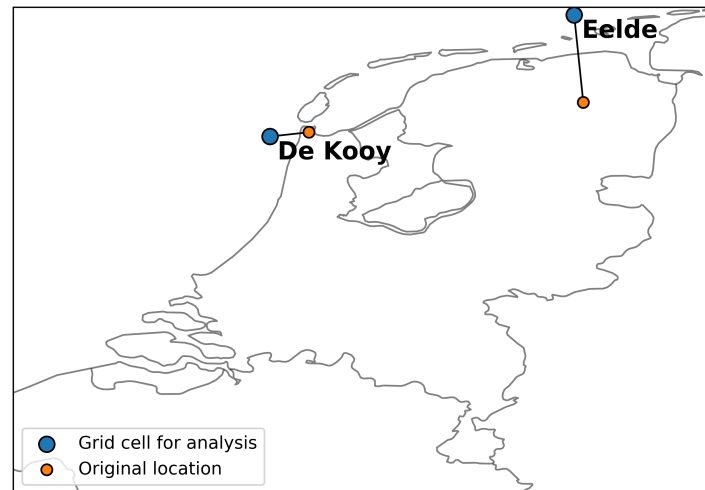


Figure 12.1: Selected locations of wind projections

The reference period of the RACMO output is 1991–2020. To ensure consistency between observations and model output, annual maxima of the observed 10-minute mean wind velocity were taken for the period 1986–2025. The centre of this period coincides with the centre of the RACMO reference period. Using the longer observational period increases the number of annual maxima available for the extreme value analysis while maintaining consistency with the model reference climate.

For each station, annual maxima of the observed 10-minute mean wind velocity were analysed using a GEV distribution fitted using the `scipy.stats.genextreme` implementation in Python. Distribution parameters were estimated by maximum likelihood estimation. The corresponding 50-year return levels were estimated together with their 90% confidence intervals. Confidence intervals were determined through bootstrapping. Because wind velocities are recorded in discrete steps of 1 m/s since 1995, small noise was added during the bootstrap procedure.

For each climate scenario, variant, and time horizon, annual maxima of daily mean wind velocity were extracted from all eight ensemble members. The same procedure was applied to the RACMO reference period (1991–2020). The annual maxima from the eight ensemble members were subsequently combined into a single sample, resulting in 240 annual maxima values per scenario (8 ensemble members of 30 years). This substantially increases the sample size available for the extreme value analysis.

GEV distributions were fitted to the annual maxima in Python. The fitted distributions were subsequently used to estimate 50-year return levels of daily mean wind velocity. Factors of change were obtained by dividing the 50-year return level of each future scenario by the corresponding return level of the RACMO reference period.

Finally, these factors of change were applied to the observed 50-year return levels of the 10-minute mean wind velocity. In this way, projected 50-year return levels for the 10-minute mean wind velocity were obtained while propagating the uncertainty of the observational GEV fits into the final projections. The 50-year return level was selected because it corresponds to the fundamental basic wind velocity used in the Eurocode and therefore forms the most relevant return level for structural design.

12.3. Wind loads under climate change

To assess the implications of climate change for wind loads, the moderate radiative forcing scenario (SSP2-4.5) and the 2050 time horizon were considered for similar reasons as described in Section 4.3.

13

Results wind analysis

This chapter shows the results of the wind analysis based on the methodology elaborated in Chapter 12. The analysis focuses on both historical observations and projected changes under the KNMI'23 Climate Scenarios. To keep this chapter concise, additional figures, tables, and information are provided in Appendices C and F.

Section 13.1 discusses the historical wind velocities and presents an extreme value analysis. Section 13.2 presents the results of the analysis of projected short-duration wind extremes. Finally, Section 13.3 discusses the implications of the projected changes for the wind loads on buildings.

13.1. Historic wind analysis results

This section first presents trends in historical wind velocities. Subsequently, trends in the annual maxima of the 10-minute mean wind velocities are analysed, followed by an extreme value analysis of these annual maxima. Finally, these estimated return level values are compared with the values specified in the National Annex of NEN-EN 1991-1-4

Figure 13.1 presents the considered time series of 10-minute mean wind velocity for the five stations. The annual maxima are highlighted, and a first-order polynomial trend line is fitted to these maxima. The highest maxima occur at the coastal stations Vlissingen and De Kooy, while the lowest values are observed at the inland station De Bilt. For both De Bilt and Beek, the fitted trend lines have only minor negative slopes, indicating no clear trend over time. Vlissingen is the only station showing a positive slope, whereas De Kooy and Eelde exhibit negative slopes. The Mann-Kendall trend test applied to the annual maxima indicates statistically significant monotonic upward trends only at De Kooy and Eelde. However, no significant trend is identified for the other stations.

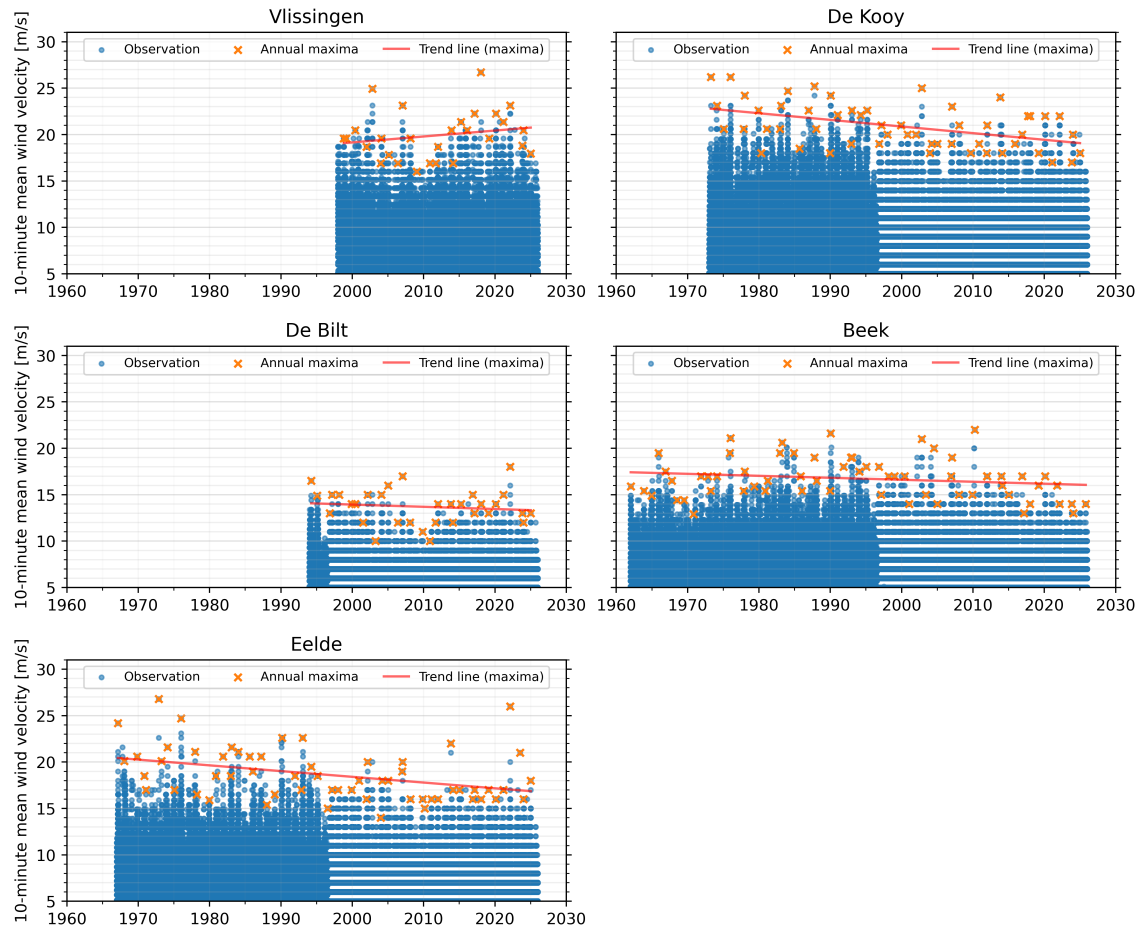


Figure 13.1: 10-minute mean wind velocity of the last 10 minutes of an hour, annual maxima highlighted, and a first-order polynomial trend line fitted to the annual maxima for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

Figure 13.2 presents violin plots of the annual maxima of 10-minute mean wind velocity for all stations for the period 1998–2025, with 1998 being the first full year of observations at all stations. During this period, the mean annual maxima are similar for Vlissingen and De Kooy at approximately 20 m/s. Although Vlissingen shows a higher upper bound and a lower lower bound, indicating larger interannual variability than De Kooy. The mean annual maxima are 17.6 m/s for Eelde, 16.2 m/s for Beek, and lowest at De Bilt with 13.5 m/s. Interannual variability is highest at Eelde and lowest at De Kooy and De Bilt. As expected, coastal stations experience higher mean annual maxima than inland stations. Regarding the distribution shape, Vlissingen, Beek, and Eelde show right-skewed distributions, while De Kooy displays a symmetric distribution, and De Bilt exhibit a left-skewed distribution.

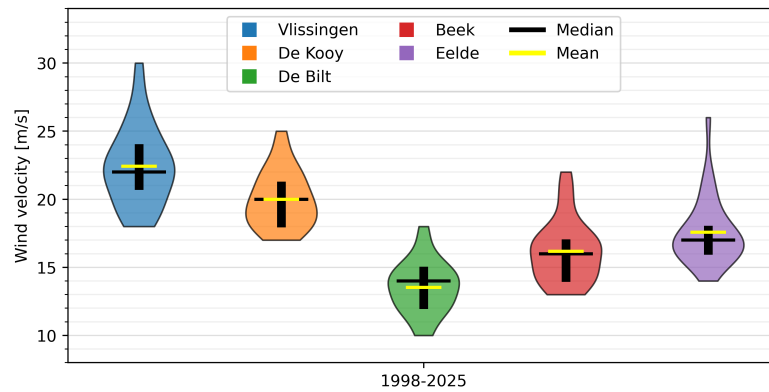


Figure 13.2: Violin plot with annual maxima of 10-minute mean wind velocity between 1998 and 2025 for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

13.1.1. Extreme value analysis of wind velocity

Because De Kooy and Eelde show statistically significant monotonic trends, non-stationary generalized extreme value distributions were fitted for these stations using the ProNEVA toolbox. For the remaining stations, stationary distributions were applied. The model settings as selected priors are provided in Appendix C.2.

The KS test rejection rates were below 5 % for all stations. The RMSE was approximately 16 % of the range of observations for De Kooy, De Bilt, and Beek, and about 9 % for Vlissingen and Eelde. These values indicate a moderate fit, that is likely influenced by the discrete behaviour of the wind data. Nevertheless, the PP and QQ plots (Appendix C.2) show good overall agreement, including for the upper quantiles.

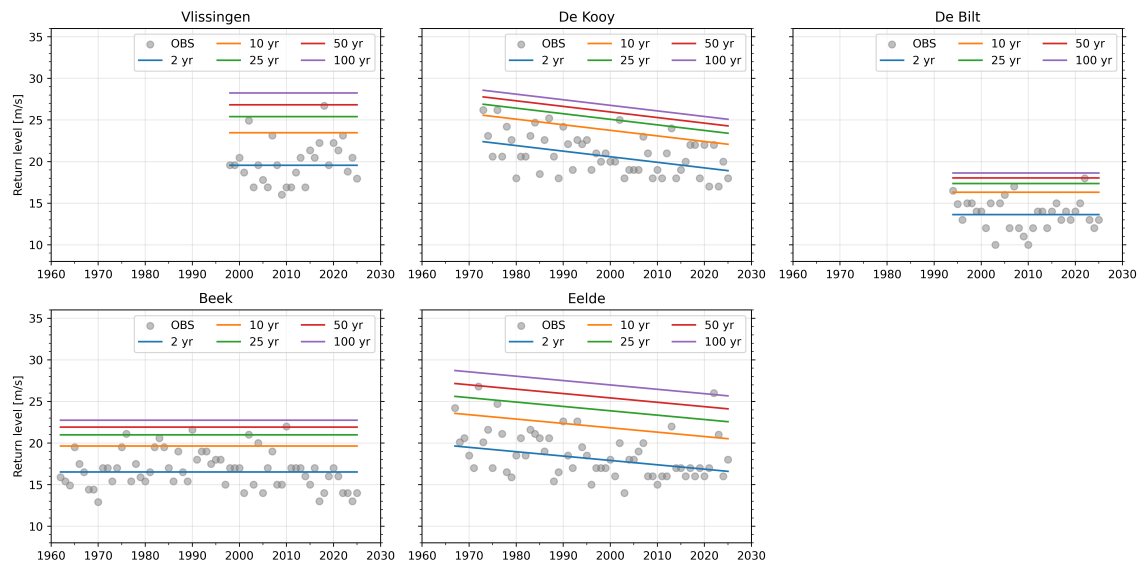


Figure 13.3: Estimated return level plot of 10-minute mean wind velocity for stations *Vlissingen*, *De Kooy*, *De Bilt*, *Beek*, and *Eelde*

The estimated return levels of the fitted annual maxima are shown in Figure 13.3. For De Kooy and Eelde, the non-stationary 50-year return levels decrease from 27.8 m/s and 27.2 m/s at the start of the series to 24.3 m/s and 24.1 m/s in 2025, respectively. In 2011, when the current version of NEN-EN 1991-1-4 was released, these values were 25.2 m/s and 24.9 m/s. For the stationary stations, the estimated 50-year return levels are constant over time. With values of 26.8 m/s (Vlissingen), 21.9 m/s (Beek), and 18 m/s (De Bilt).

13.1.2. Comparison with Eurocode wind velocities

The estimated 50-year return levels for the 10-minute mean wind velocity are compared with the fundamental basic wind velocities provided in the Dutch National Annex of NEN-EN 1991-1-4 (section 11.2). As described earlier, the Netherlands is divided into three wind regions, each with a certain fundamental value of basic wind velocity. Table 13.1 compares these prescribed values with the estimated 50-year return levels. These can be interpreted as a station estimate of the fundamental basic wind velocity. For the stations of De Kooy and Eelde, where the 50-year return level is non-stationary, the 50-year return values at the start of the series are considered. Although, both are showing a decreasing trend over time, it cannot be guaranteed that this trend will continue to decline over the coming 50 years. Furthermore, as stated in the literature review a major part of the decreasing wind velocity trends can be attributed by an increasing surface roughness. The decreasing trend in annual maxima may therefore generally be caused by surface roughness effects.

For all stations except Eelde, the estimated values are lower than those given in the National Annex. The relative difference is smallest for Eelde and largest for De Bilt. For De Bilt, the estimated fundamental wind velocity is substantially lower than the value corresponding to wind region 3. This suggests that if stations near De Bilt also exhibit very low fundamental wind velocities, an introduction of an additional lower wind region could be considered.

Although the five selected stations capture the main spatial variations in Dutch wind climate, particularly the higher wind velocities along the coast. It cannot be excluded that other locations may experience slightly higher extremes, potentially leading to higher estimated 50-year return levels.

Table 13.1: Comparison between estimated and given fundamental value of basic wind velocity the Dutch National Annex of NEN-EN 1991-1-4

	Wind Region	Annex $v_{b,0}$ [m/s]	Estimated $v_{b,0}$ [m/s]	Estimated < Annex	Difference [%]
Vlissingen	2	27.0	26.8	yes	0.6
De Kooy	1	29.5	27.8	yes	7.8
De Bilt	3	24.5	18.0	yes	26.4
Beek	3	24.5	21.9	yes	10.6
Eelde	2	27.0	27.2	no	0.1

Finally, the estimated 100-year return levels are compared with the corresponding fundamental values of the basic wind velocity derived according to NEN-EN 1991-1-4 and its Dutch National Annex. The full analysis is presented in Appendix C.2.1. In general, the estimated 100-year return levels are lower than the prescribed values. However, for stations Vlissingen and Eelde, the estimated values slightly exceed those of the National Annex.

13.2. Projected wind analysis results

This section presents the results of the analysis of the projected daily mean wind velocities of the KNMI'23 climate scenarios. The methodology applied in this section is The projections are analysed for stations De Kooy and Eelde. To keep the main text concise, the figures corresponding to De Kooy are presented in Appendix F.2.

13.2.1. Extreme value analysis of RACMO wind projections

Figure 13.4 presents the fitted GEV distribution for the annual maxima of the observed 10-minute mean wind velocity at station Eelde for the period of 1986–2025. The uncertainty in the fitted return levels was quantified through 3000 bootstrap resamples, from which the median estimates and 90 % confidence intervals were derived. The confidence interval is relatively wide, which is likely related to the limited sample size and the discrete behaviour of the recorded wind velocities. The median 50-year return level is approximately 24.6 m/s.

Comparable results were obtained for station De Kooy. However, the associated confidence interval

is approximately half the width of that found for Eelde, indicating a more robust estimate of the return level. The median 50-year return level for De Kooy is approximately 25.4 m/s.

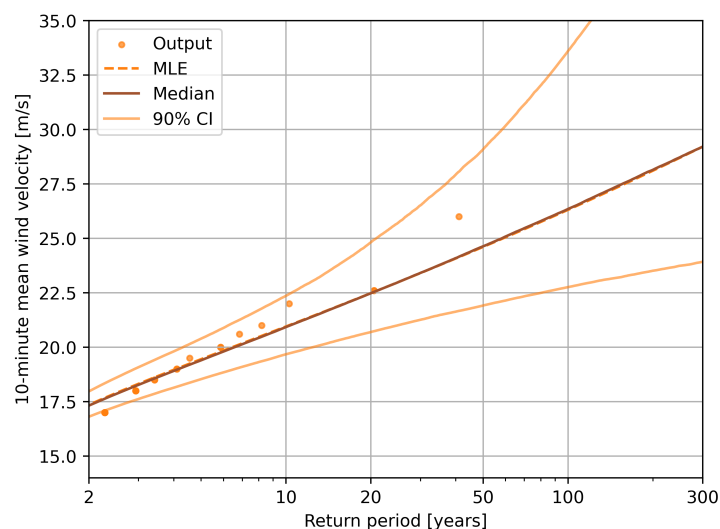


Figure 13.4: Fitted GEV distributions for 10-minute mean wind velocities over 1986–2025 for Eelde. Median values and 90 % confidence interval are determined by bootstrapping

Figures 13.5 and F.1 present the fitted GEV distributions of the annual maxima of daily mean wind velocity derived from the RACMO projections for Eelde. For each scenario and variant, the annual maxima of the eight ensemble members were combined, resulting in samples of 240 years. The fitted distributions show very similar 50-year return levels across the different climate scenarios and time horizons. Similar results were obtained for De Kooy.

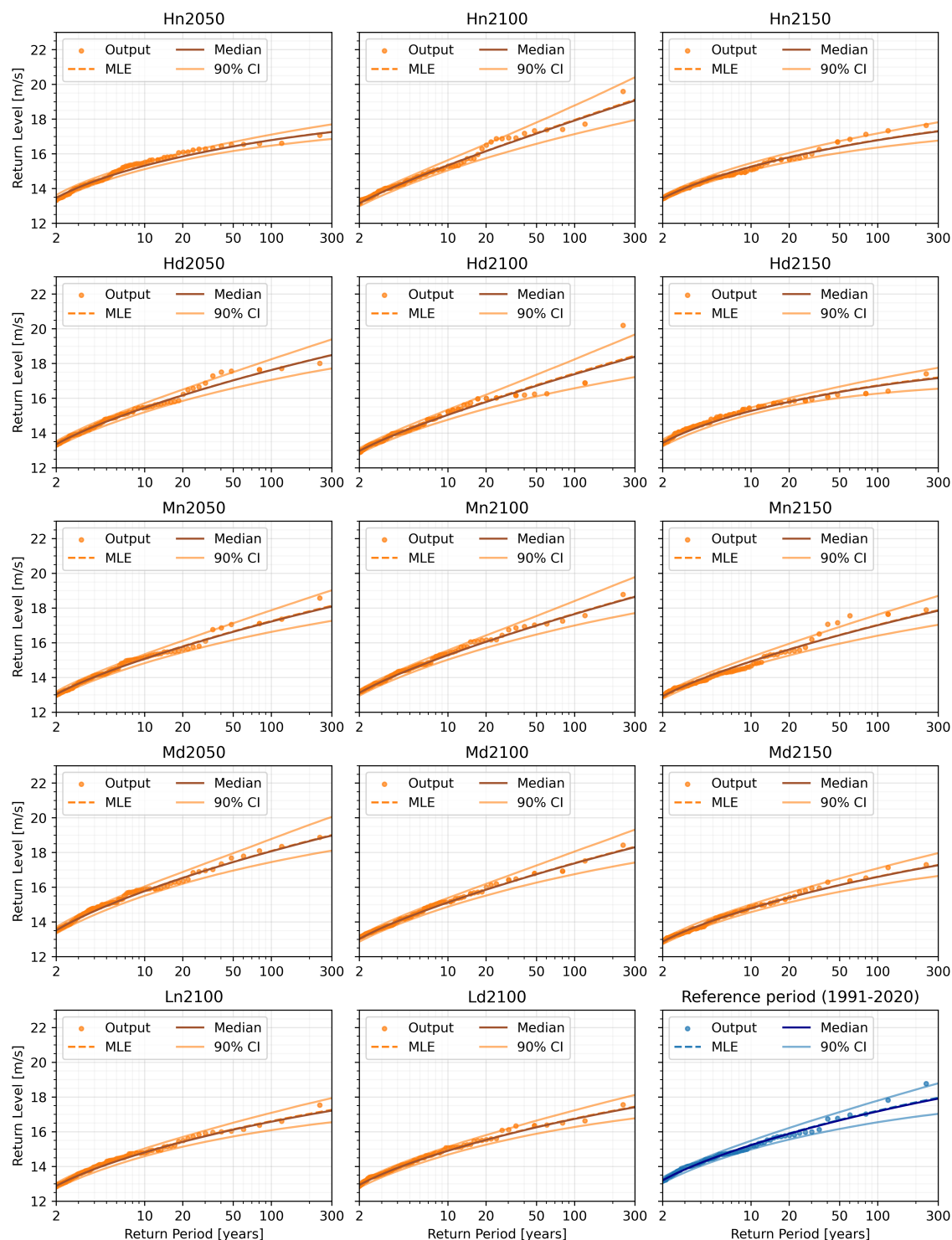


Figure 13.5: Annual maxima values of daily mean wind velocities with fitted GEV distributions for different climate scenarios in sea grid cell near Eelde. Median values and 90 % confidence interval are determined by bootstrapping

The projected 50-year return levels of the 10-minute mean wind velocity were estimated by combining the bootstrap distributions of the observed return levels with the factors of change derived from the RACMO projections. This procedure allows the uncertainty in the observed return levels to be propagated into the future projections.

Figure 13.6 presents the resulting projections for Eelde as a function of global warming level. Differ-

ences between the wet and dry variants are small, while the projected changes in the 50-year return level are negligible compared with the width of the confidence interval.

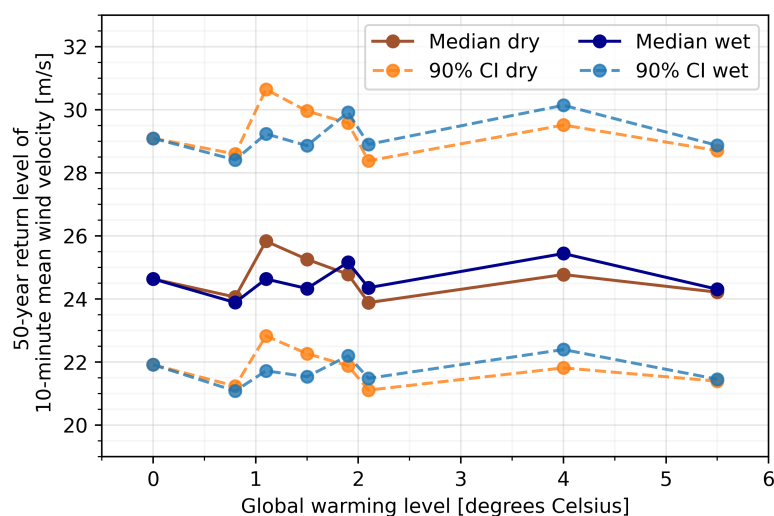


Figure 13.6: Projected 50-year return level of 10-minute mean wind velocity for dry and wet variants for different global warming levels for De Kooy

For De Kooy, a similar pattern is observed. The projected return levels for the wet and dry variants remain close to each other throughout the considered warming range. Up to approximately 2.1 °C global warming, only minor changes are projected. For the highest warming levels (4.0 °C and 5.5 °C), a small increase in the 50-year return level is projected.

Figure 13.7 presents the projected 50-year return levels separately for the high, moderate, and low radiative forcing scenarios for Eelde. Also in this representation, the projected changes remain small relative to the uncertainty bounds. For De Kooy, slight increases are projected for the low and high radiative forcing scenarios, whereas the moderate forcing scenario shows little change or a small decrease relative to the reference period.

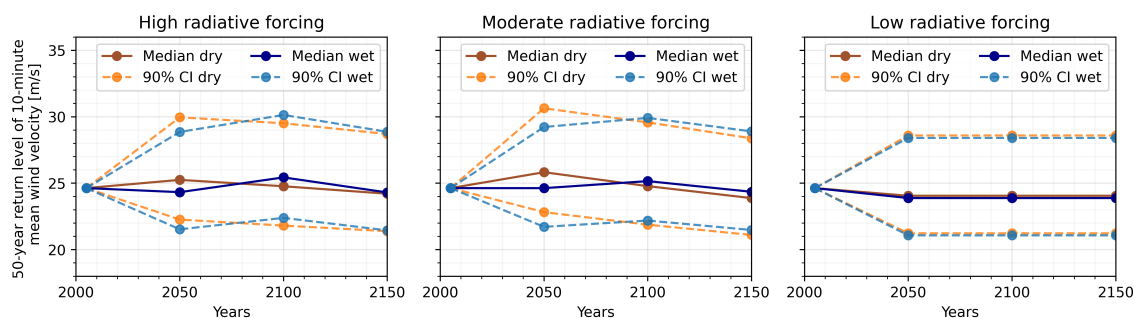


Figure 13.7: Projected 50-year return level of 10-minute mean wind velocity for dry and wet variants for different radiative forcing scenarios for De Kooy

13.2.2. Conclusion

The analysis indicates that the projected changes in the 50-year return level of the 10-minute mean wind velocity are small compared with the uncertainty associated with both the observational extreme value analysis and the climate model projections. Furthermore, the methodology relies on the major assumption that relative changes in extreme daily mean wind velocity change comparably with extreme 10-minute mean wind velocity. The results therefore suggest that future changes in design wind velocities in the Netherlands remain uncertain and are likely small relative to the current uncertainty range. This finding is consistent with the KNMI'23 Climate Scenarios, which indicate only limited changes in mean wind velocities.

It is recommended that future climate scenario products provide projections for hourly or sub-hourly wind velocities. Such projections would make the climate projections much more suitable for structural engineering purposes.

In addition, it would be valuable if future climate projections distinguished between changes caused by climate change and changes resulting from projected land-use. This would facilitate a clearer interpretation of the physical drivers behind projected wind velocity changes.

13.3. Changes in characteristic wind load values under climate change

This section discusses the expected changes in characteristic wind values for the moderate radiative forcing scenario around the 2050 time horizon. The analysis focuses on the results obtained for stations De Kooy and Eelde.

As described in Section 11.2, De Kooy and Eelde are located in wind regions 1 and 2 of the Dutch National Annex of NEN-EN 1991-1-4. These regions correspond with fundamental basic wind velocities of 29.5 m/s and 27.0 m/s, respectively. The historical analysis based on the longest available homogeneous series of 10-minute mean wind velocity resulted in estimated 50-year return levels of 27.8 m/s for De Kooy and 27.2 m/s for Eelde. For Eelde this value is slightly higher than the prescribed value in the National Annex.

To ensure consistency with the KNMI'23 reference climate, additional GEV analyses were performed for the period 1986–2025, which has the same central year as the RACMO reference period. These analyses resulted in median 50-year return levels of approximately 25.4 m/s for De Kooy and 24.6 m/s for Eelde. The corresponding 90 % confidence intervals are relatively wide. The lower return levels compared with the longer observational series are likely related to the shorter series length and the absence of some of the most extreme historical wind events.

For the moderate forcing scenarios around 2050 (Mn2050 and Md2050), the projected changes in the 50-year return level of the 10-minute mean wind velocity are small for both stations. For De Kooy, both the wet and dry variants show only a marginal increase relative to the reference period. For Eelde, the projected changes are close to zero, with slight increases or decreases depending on the variant. In all cases, the projected changes are substantially smaller than the uncertainty associated with the estimated return levels. Furthermore, the projected 50-year return levels remain close to the present-day values and do not differ significantly from the characteristic wind velocities currently described in the Dutch National Annex. The differences between the wet and dry variants are also negligible compared with the uncertainty range.

Based on these findings, it can be concluded that the characteristic wind loads used for structural design are not expected to change substantially over the coming decades. For a building designed today with a design life of approximately 50 years, the projected changes in extreme values of 10-minute mean wind velocities appear negligible compared with the uncertainty in both the observational extreme value analysis and the climate model projections.

Discussion, conclusion, and recommendations wind

This chapter discusses the methodology and results of the wind analysis. It then answers the research questions related to wind loads and concludes with recommendations for future research on the effects of climate change on wind loads.

14.1. Discussion

Several limitations should be considered when interpreting the results of the wind analysis.

For the historical analysis, the Eurocode design wind load is based on the 10-minute mean wind velocity. Long homogeneous observations series of this variable are limited in the Netherlands. Therefore, hourly datasets containing the 10-minute mean wind velocity measured over the final 10 minutes of each hour were used. Although these observations provide the longest available records, the strongest 10-minute mean wind velocities may occur outside the recorded interval, possibly resulting in a slight underestimation of annual maxima.

The analysed time series were assumed to be sufficiently homogeneous. Earlier observations showed that changes in measurement height introduced substantial inhomogeneities and were therefore excluded from the analysis. Station relocations generally produced much smaller effects and were accepted in order to retain sufficiently long series for the extreme value analysis. Nevertheless, some influence of these relocations on the estimated return levels cannot be excluded.

The wind observations were recorded with a resolution of approximately 1 m/s, resulting in relatively discrete annual maxima. This contributes to uncertainty in the fitted GEV distributions and the associated return levels. A block maxima approach with a GEV distribution was applied because it provides a straightforward method for wind extremes. However, this approach uses only one observation per year, therefore reducing the available sample size. Alternative approaches such as Peak-Over-Threshold methods may provide more efficient use of the available data.

The estimated 50-year return levels of the 10-minute mean wind velocity were generally comparable to or lower than the fundamental basic wind velocities prescribed in the Dutch National Annex. Only for Eelde was a slightly higher value obtained. The origin of these differences remains uncertain, partly because the reference period and methodology used to derive the characteristic values in the National Annex are not documented. For the 100-year return level, the estimated velocity values exceeded those derived from the Dutch National Annex for stations Vlissingen and Eelde. These differences may be attributed to uncertainties in the fitted GEV distributions, the limited length of the series of observations, or differences between the reference period considered in this study and that underlying the National Annex.

For the climate projections, an important limitation is that the KNMI'23 scenarios only provide daily mean

wind velocities. Consequently, it was assumed that changes in extreme 10-minute mean wind velocities scale similar with changes in daily mean wind velocities. Although this assumption was necessary due to the absence of sub-daily projections, it introduces additional uncertainty into the results.

Furthermore, projected wind velocity changes in RACMO are strongly influenced by projected land-use changes. Previous studies have shown that increasing surface roughness has already contributed substantially to observed decreases in wind velocity in the Netherlands. In addition, KNMI notes that urban areas are not fully represented in the land-use model, which may affect projected wind velocities locally. To minimise these effects, sea grid cells near De Kooy and Eelde were selected, since wind projections over sea are largely unaffected by land-use changes. Even for these locations, the projected changes remained small compared with both observational and model uncertainty.

Finally, only two locations were considered in the projection analysis and five stations in the historical analysis. Although these stations capture important regional differences within the Netherlands, local wind conditions may differ from the values presented here.

14.2. Conclusion

The wind-related research questions can be answered as follows.

To what extent do current characteristic values for wind loads in the Dutch National Annex reflect recent observations and trends?

The historical analysis showed that the estimated 50-year return levels of the 10-minute mean wind velocity are generally comparable to, or lower than, the fundamental basic wind velocities prescribed in the Dutch National Annex. Only for Eelde was a slightly higher value obtained. No clear evidence was found that the current Annex values substantially underestimate present-day wind extremes.

How are wind loads expected to change under different climate scenarios in the Netherlands?

The analysed KNMI'23 climate projections indicate only minor changes in extreme wind velocities for both coastal and inland locations. The projected changes are small compared with the associated uncertainty and do not show a consistent increase or decrease across all scenarios.

What changes in characteristic values for wind loads can be derived from climate change scenarios, and how do these compare to current values in the Dutch National Annex?

The projected changes in characteristic wind velocities are negligible relative to both the uncertainty in the extreme value analysis and the uncertainty in the climate projections. Consequently, the resulting characteristic wind loads remain close to the values currently prescribed in the Dutch National Annex.

The main research question can therefore be answered as follows:

How do climate change scenarios affect characteristic values for wind loads on buildings in the Netherlands, and what are their implications for structural design?

Based on the currently available observations and KNMI'23 climate projections, climate change is not expected to substantially affect characteristic wind loads on buildings in the Netherlands during this century. The projected changes are small compared with the associated uncertainties and are therefore currently unlikely to require modifications for structural design.

14.3. Recommendations

Several recommendations can be made for future research.

First, future studies could investigate longer homogeneous wind observations to improve the estimation of extreme wind velocities. Furthermore, the application of Peak-Over-Threshold methods may provide a more robust representation of wind extremes than the annual maxima approach adopted here. Second, future climate scenario products should provide projections for hourly and sub-hourly wind characteristics, including 10-minute mean wind velocities and wind gusts if possible. Such information would be directly applicable to structural engineering design and would reduce the need for scaling assumptions. Third, future climate model products should distinguish between changes caused by climate change and changes resulting from projected land-use differences. This would improve the interpretation of projected wind velocity changes and allow the individual contributions of both mechanisms to be assessed. Finally, the uncertainty associated with future wind projections remains

relatively large compared with the projected changes themselves. The development of regional climate models and larger climate model ensembles is therefore recommended to reduce uncertainty in future projections of wind extremes relevant for structural design.

Part V

Discussion, conclusion, and recommendations

15

Discussion

This chapter discusses the assumptions and limitations of the methodology and results regarding the effects of climate change on precipitation, snow, and wind loads on structures in the Netherlands.

15.1. Assumptions

For all extreme value analyses, the block maxima method was applied to derive samples from the observational and climate model datasets. Compared with the peak-over-threshold method, the block maxima approach does not require declustering of observations or the selection of a threshold value. It was therefore considered the most straightforward approach within the scope of this research. A disadvantage is that only a limited number of annual maxima are obtained. This was particularly relevant for the analyses of short-duration precipitation and wind velocities, where some homogeneous series consisted of only a few decades of observations. Consequently, estimation of the GEV shape parameter, which controls the behaviour of the upper tail, remains uncertain.

As the Eurocode describes for ultimate limit states load cases that precipitation or snow do not occur together with wind, the same is considered in this research. Nevertheless, simultaneous occurrence of precipitation and strong winds may influence roof ponding behaviour. Several recent extreme summer precipitation events in the Netherlands were accompanied by strong wind gusts, indicating that combined effects could be relevant for structural applications.

15.1.1. Analysis of historical observations

For the historical analyses, it was assumed that the five selected KNMI stations (Vlissingen, De Kooy, De Bilt, Beek, and Eelde) represent the main spatial variations in weather extremes across the Netherlands.

For the hourly precipitation and wind datasets, instrumentation changes and station relocations introduced inhomogeneities. To minimise their influence, only observations taken after major instrumentation changes were considered. Minor station relocations, in some cases up to approximately 1.8 km, were assumed not to substantially affect the homogeneity of the series.

The reference periods underlying the characteristic values in the Dutch National Annexes are not explicitly documented. Therefore, the return levels derived from the available historical observations were directly compared with the current characteristic values. Since the National Annex values were derived from earlier observational periods, part of the differences may originate from the use of different reference periods.

For precipitation, the focus was on 5-minute precipitation events because the characteristic rainwater load in the Dutch National Annex is likely based on a 5-minute precipitation intensity with a 50-year return period. As suitable recent long-term 5-minute observations were unavailable, 6-minute precipitation intensities derived from hourly precipitation duration records were considered. Because intensity

generally increases for shorter durations, this approximation may slightly underestimate the actual 5-minute return levels.

For wind, the Eurocode is based on 10-minute mean wind velocities measured at 10 m height. Long homogeneous records of continuous 10-minute observations were unavailable. Therefore, hourly datasets containing the mean wind velocity over the final 10 minutes of each hour were used. This approach may underestimate actual annual maxima because extreme 10-minute periods occurring earlier within the hour are not captured.

For snow, winter-year maxima between 1957 and 2025 were analysed. Since no clear discontinuities were observed in the snow depth series, the records were assumed to be sufficiently homogeneous. Several assumptions were required when processing the historical snow observations. Snow cover codes representing a closed snow cover of less than 1 cm and a broken snow cover were assigned a depth of 0.5 cm. This value represents the mean of the measurement interval and provides a realistic estimate for broken snow covers. Snow drift observations were assigned a depth of 1 cm. Although considerably larger local snow accumulations can occur due to drifting, insufficient information was available to estimate drift depths. This assumption may therefore have resulted in an underestimation of some annual maxima and associated return levels. To convert snow depth return levels into characteristic ground snow loads, the density of compact snow prescribed in the Dutch National Annex (2.0 kN/m³) was adopted. According to NEN-EN 1991-1-3, this density is representative for snow several hours to several days after snowfall and was therefore considered appropriate for comparison with observed maximum snow depths.

15.1.2. Analysis of climate change projections

Several additional assumptions were required because the KNMI'23 climate scenarios do not provide projections at the sub-hourly scales relevant for structural design.

For precipitation, it was assumed that changes in the return levels of 5-minute precipitation intensities scale similarly to changes in daily precipitation extremes. This assumption was supported by the CPM projections presented in KNMI'23, which indicate comparable relative changes for hourly and daily precipitation extremes at high return periods. Nevertheless, the lack of sub-hourly climate projections remains a significant source of uncertainty. For this analysis, only the grid cell corresponding to De Bilt was considered. It was assumed that the projected trends for De Bilt are representative for the entire country.

A comparable assumption was made for wind. Changes in the return levels of 10-minute mean wind velocities were assumed to scale similarly to changes in daily mean wind velocities, as no hourly or sub-hourly wind projections were available. For wind projections, grid cells located over the North Sea were selected instead of the grid cells directly corresponding to the weather stations. KNMI'23 indicates that projected wind changes over land are strongly influenced by assumed future land-use developments. By considering nearby sea grid cells, the analysis focused on the influence of climate change rather than land-use change.

15.2. Limitations

Although the selected stations capture the main climatological differences within the Netherlands, only five locations were analysed. Consequently, local variations in weather extremes may not be fully represented.

The available homogeneous observation periods for hourly precipitation and wind were relatively short because of instrumentation changes and modifications in measurement procedures. Combined with the use of the block maxima method, this reduced the number of samples available for extreme value analysis and increased uncertainty in the fitted GEV distributions.

A major limitation of the hourly precipitation dataset is the storage methodology used by KNMI. For each hour, only the total precipitation amount and total precipitation duration are recorded. As a result, multiple short precipitation events occurring within the same hour are merged into a single observation. This likely leads to an underestimation of short-duration precipitation extremes and may explain part of the inconsistency between the return levels obtained in this study and those reported in literature.

An important limitation of the climate projection analysis is the lack of sub-hourly precipitation and wind projections in KNMI'23. In addition, explicit projections of snowfall and snow cover are currently unavailable. Consequently, several assumptions were required to translate available climate projections into quantities relevant for structural engineering.

Finally, this study focused on climate conditions represented by 30-year periods surrounding the KNMI'23 time horizons of 2050, 2100, and 2150. Although indicative changes in characteristic loads around 2050 were derived, a full reliability based assessment of structures throughout their design life was found to be beyond the scope of this research. Such an assessment would require incorporation of both structural uncertainties and climate projection uncertainties. Moreover, the KNMI'23 scenarios represent different socio-economic pathways and radiative forcing trajectories, which introduces substantial uncertainty regarding future climate developments. Therefore, this research eventually focused on identifying the potential magnitude and direction of climate induced changes in structural loads rather than developing a complete reliability framework for structural design adaptive to climate change.

Conclusion and recommendations

In this chapter, the main findings of the research are summarised and recommendations for future research are provided.

16.1. Conclusion

This research investigated the implications of climate change for characteristic values of precipitation, snow, and wind loads on structures in the Netherlands. Historical observations, extreme value analyses, and KNMI'23 climate projections were considered to assess whether current characteristic values in the Dutch National Annex remain representative under changing climatic conditions.

For precipitation, the analysis of recent Dutch depth–duration–frequency studies showed that current estimates of 50-year return levels for 5-minute precipitation events are approximately 20% higher than the value prescribed in the Dutch National Annex. This difference is likely explained by the use of a larger number of stations and possible climate change effects that have occurred since the development of the current characteristic values.

For snow, all five analysed stations showed a statistically significant decreasing trend in annual maximum snow depth. Non-stationary GEV analyses indicated that the corresponding 50-year return levels are lower than the characteristic ground snow load of 0.7 kN/m^2 prescribed in the Dutch National Annex when the same compact snow density of 2.0 kN/m^3 is assumed. These findings suggest that the current characteristic value satisfies recent observations.

For wind, decreasing trends in annual maxima of 10-minute mean wind velocity were found at De Kooy and Eelde, while no significant trends were detected at the other stations. The estimated 50-year return levels were generally lower than the fundamental basic wind velocities prescribed in the Dutch National Annex, although the value for Eelde was found to be a bit higher to the prescribed characteristic value.

The KNMI'23 climate projections indicate that precipitation extremes are expected to increase under future climate change. Based on the considered methodology, a factor of change of approximately 1.31 was derived for the 50-year return level of 5-minute precipitation intensity under 4°C global warming relative to the 1991–2020 reference period. This suggests that short-duration precipitation events may become significantly more severe during the coming century.

For snow, quantitative projections of snow depth and snowfall are currently unavailable within KNMI'23. Nevertheless, all analysed snow related indicators, including frost days, ice days, and consecutive freezing days, show a strong decrease under future warming. These indicators suggest that the occurrence and persistence of substantial snow covers will become less likely in the future.

For wind, projected changes in daily mean wind velocity were generally small compared with the associated model uncertainty. Based on the currently available climate projections, no clear evidence exists for either a substantial increase or decrease in characteristic wind loads in the Netherlands.

The main research question:

"How do climate change scenarios affect characteristic values for precipitation, snow and wind loads on buildings in the Netherlands, and what are their implications for structural design?"

can therefore be answered as follows.

Climate change is expected to have the largest impact on rainwater loads. Increasing precipitation extremes require adaptations in emergency drainage capacity and roof design in order to maintain current safety levels. For snow, the available projections indicate a decreasing likelihood of substantial snow accumulation, suggesting that future characteristic snow loads may decrease. However, quantitative projections remain unavailable. For wind, projected changes remain small relative to their uncertainty and current evidence does not support modification of the characteristic wind loads in the near future.

Overall, the results suggest that precipitation is the weather-induced load most likely to require adaptation of characteristic values under future climate change conditions in the Netherlands.

16.2. Recommendations

For future analyses of historical weather extremes, it is recommended to consider stations with the longest homogeneous observation series in addition to ensuring spatial coverage across the Netherlands. Furthermore, peak-over-threshold methods could be considered as an alternative to block maxima approaches, particularly for relatively short datasets, as they make more efficient use of the available observations.

For precipitation, future KNMI climate scenario products should include projections at hourly and sub-hourly timescales. This would significantly reduce the uncertainty associated with translating daily climate projections into the short duration precipitation extremes that are relevant for structural engineering applications. In addition, future research should investigate whether wind driven rainwater ponding effects should be incorporated into structural design methodologies.

For snow, future climate scenario products should provide projections of snowfall, snow water equivalent, snow cover depth, and snow density. Such information would enable direct assessment of future snow loads and substantially improve the applicability of climate scenarios for structural engineering. Furthermore, future observations should include more detailed measurements of snow density and snow water content to improve understanding of the relationship between snow depth and snow load.

For wind, future climate scenario products should provide projections of hourly and sub-hourly wind velocities, including 10-minute mean wind velocities. Such information would be directly applicable to structural design and would remove the need for scaling assumptions based on daily mean wind velocities. In addition, future climate model products should distinguish more clearly between changes caused by climate change and those resulting from projected land-use changes. This would improve the interpretation of projected wind changes and their relevance for structural engineering applications.

In general, future research should focus on methods for incorporating climate projection uncertainty and socio-economic scenario uncertainty into characteristic values of weather induced loads and design values for load combinations. In the end, structural design standards may need to evolve from fixed characteristic values towards approaches that account for changing climatic conditions throughout the design life of a structure.

Finally, climate change may also affect other weather induced loads on structures, including thermal loads. This is especially relevant for bridges.

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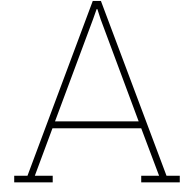
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Appendices



Precipitation observations

In this appendix, additional information, figures or tables are given that support the sections about precipitation observations.

A.1. Literature study precipitation

In this section additional details are provided of research to precipitation extremes in the Netherlands.

In Beersma et al. (2018), extreme precipitation was analysed for event durations ranging from 10 minutes to 12 hours. Generalized Extreme Value (GEV) and Generalized Logistic (GLO) distributions were fitted to annual maxima of precipitation for durations of 10, 20, 30, 40, 50, 60, 120, 180, 240, 480 and 720 minutes. The analysis was based on data from 31 weather stations, with typical record lengths of 12 to 14 years (2003–2016), resulting in 436 annual maxima for each precipitation duration. Due to the relatively short record lengths, trends in the annual maxima could not be detected. Consequently, the extreme value analysis was carried out under the assumption of stationarity.

All details and formulas provided below are presented in the report of Beersma et al. (2018).

The cumulative distribution function of the GLO distribution was given by:

$$F_{GLO}(x) = \left[1 + \left(1 - \xi \frac{x - \mu}{\sigma} \right)^{1/\xi} \right]^{-1}, \quad \xi \neq 0 \quad (\text{A.1})$$

$$F_{GLO}(x) = \left[1 + \exp \left(-\frac{x - \mu}{\sigma} \right) \right]^{-1}, \quad \xi = 0 \quad (\text{A.2})$$

Where μ is the location parameter, σ is the scale parameter, and ξ is the shape parameter.

Compared to the GEV distribution, the GLO distribution generally assigns a higher probability to extreme precipitation values, resulting in more conservative estimates for high return periods.

The 10-minute precipitation data were recorded at fixed time intervals. As a result, an event spanning, for example, 12:05–12:15 was split across two observation intervals. Consequently, annual maxima based on fixed 10-minute intervals tend to underestimate the true maxima over arbitrary 10-minute intervals. To account for this effect, Beersma et al. (2018) derived estimates of random 10-minute maxima by combining fixed 10-minute and 20-minute annual maxima. The true 10-minute maximum was assumed to lie between these values, effectively defining a lower bound (10-minute maxima) and an upper bound (20-minute maxima).

The annual maxima for the different durations were fitted to both GEV and GLO distributions. The GLO distribution was found to provide a better fit to the observed data. Subsequently, regression models were developed to express the GLO parameters as functions of the event duration D (in minutes). These relationships were formulated as second-order polynomials in $\log_{10}(D)$:

$$\mu = 1.02 \left[7.339 + 0.848 \log_{10}(D) + 2.844 (\log_{10}(D))^2 \right] \quad \text{for } 10 \leq D \leq 720 \text{ min} \quad (\text{A.3})$$

$$\gamma = \frac{\sigma}{\mu} = 0.04704 + 0.1978 \log_{10}(D) - 0.05729 (\log_{10}(D))^2 \quad \text{for } 10 \leq D \leq 104 \text{ min} \quad (\text{A.4})$$

$$\xi = -0.0336 - 0.264 \log_{10}(D) + 0.0636 (\log_{10}(D))^2 \quad \text{for } 10 \leq D \leq 90 \text{ min} \quad (\text{A.5})$$

Here, the scale parameter σ was indirectly modelled with the dispersion coefficient γ .

For longer durations, alternative formulations were provided in Beersma et al. (2018), but these are not considered here. The factor 1.02 applied to the location parameter accounts for the systematic undercatch of precipitation by automatic gauges.

The precipitation amount x (in mm) corresponding to a return period T and duration D was given by:

$$x(T) = \mu \left(1 + \frac{\gamma}{\xi} \left[1 - \left\{ \frac{1 - \exp[-1/T]}{\exp[-1/T]} \right\}^{\xi} \right] \right), \quad \xi \neq 0 \quad (\text{A.6})$$

$$x(T) = \mu \left(1 - \gamma \ln \left\{ \frac{1 - \exp[-1/T]}{\exp[-1/T]} \right\} \right), \quad \xi = 0 \quad (\text{A.7})$$

In a later report (Beersma et al., 2019), the analysis was extended to event durations up to 10 days. For durations shorter than 90 minutes, the methodology and parameters remain unchanged. For longer durations, additional data sources were considered, including radar data (approximately 19 years) and long-term observations from 219 manual precipitation stations (up to 66 years of data), resulting in more robust estimates for long duration precipitation events. Despite these improvements, the minimum event duration considered remains 10 minutes.

Contacting KNMI confirmed that extrapolation is currently the only feasible approach to derive precipitation estimates at 5-minute duration level. Otherwise a rule of thumb should be applied that states that return levels of 5-minute precipitation amounts are roughly 0.7 of the 10-minute events.

The 50-year return level for precipitation events with a duration of 10 minutes, according to Eq. A.1, is 24.7 mm. For the extrapolated 5-minute duration, the corresponding return level is 18.1 mm, which is equivalent to an intensity of 0.06 mm/s (217 mm/h).

A.2. Inhomogeneities in historical observations

This section focuses on changes in the automatic precipitation measurement set-up that may have introduced inhomogeneities into the hourly precipitation data.

Tables A.1, A.2, A.3, A.4, A.5 present the instrumentation changes for the five automatic precipitation stations considered in this study. The information was retrieved from documentation provided by the KNMI, archived webpages (with station changes up to 2015) (KNMI, n.d.-d, n.d.-e, n.d.-g, n.d.-p, n.d.-v), and the studies of Wauben (2004) and Brandsma (2014).

According to documentation provided by the KNMI and the archived webpages, the current precipitation gauges have a catch area of 2 dm². However, Wauben (2004) reported that the automatic precipitation gauges used by the KNMI have a catch area of 4 dm². The KNMI confirmed that the catch area is indeed 4 dm². Furthermore, the documentation of the KNMI did not specify the rim height of the precipitation gauge in the Ott screen set-up. However, based on the information provided by Brandsma (2014), the rim height is likely 1.0 m.

Table A.1: Precipitation measurement changes for station Vlissingen since 1951 onwards

Period	Instrumentation	Catch area [dm ²]	Rim height above ground level [m]
1957-01-01 – 1962-04-09	Pluviograph	4	0.40
1962-04-10 – 1993-04-30	Pluviograph	2	0.40
1993-05-01 – today	Electric measurement	4	1.00

Table A.2: Precipitation measurement changes for station De Kooy since 1951 onwards

Period	Instrumentation	Catch area [dm ²]	Rim height above ground level [m]
1957-01-01 - 1972-07-31	Pluviograph	4	0.40
1972-08-01 - 1992-12-31	Pluviograph	2	0.40
1993-01-01 - 2007-04-26	Electric measurement	4	0.40
2007-04-26 - today	Likewise, in Ott screen	4	1.00

Table A.3: Precipitation measurement changes for station De Bilt since 1951 onwards

Period	Instrumentation	Catch area [dm ²]	Rim height above ground level [m]	Additional details
1981-04-01 – 1993-02-28	Pluviograph	2	0.40	
1993-03-01 – today	Electric measurement	4	0.40	
2008-09-25	Likewise	4	0.40	Relocated 200 m
2008-09-25 – today	Likewise, in Ott Screen	4	1.00	

Table A.4: Precipitation measurement changes for station Beek since 1951 onwards

Period	Instrumentation	Catch area [dm ²]	Rim height above ground level [m]	Additional details
1957-01-01 – 1966-06-30	Pluviograph	4	0.40	
1976-07-01 – 1991-02-28	Pluviograph	2	0.40	
1991-03-01 – 2005-10-06	Electric measurement	4	0.40	
2005-10-07 – today	Likewise, in Ott screen	4	1.00	
2005-11-01	Likewise	4	1.00	Relocated 1770 m

Table A.5: Precipitation measurement changes for station Eelde since 1951 onwards

Period	Instrumentation	Catch area [dm ²]	Rim height above ground level [m]	Additional details
1957-01-01 - 1973-05-01	Pluviograph	4	0.40	
1973-05-01	Likewise	4	0.40	Relocated 750 m
1973-05-02 - 1991-03-15	Pluviograph	2	0.40	
1991-03-16 - 2009-05-18	Electric measurement	4	0.40	
2009-05-18 – today	Likewise, in Ott Screen	4	1.00	

A.3. Extreme value analysis of historical observations

A.3.1. Daily precipitation

Table A.6 presents the prior distributions used as input for ProNEVA for the five stations, based on daily historical precipitation data. For all stations, the prior distribution is assumed to be normal, defined by a prior mean and prior standard deviation. The prior location mean is set equal to the mean of the annual maxima series and the standard deviation is set to two times the standard deviation of series of annual maxima. The mean of the prior scale is set to the logarithm of the standard deviation of the series of annual maxima and the standard deviation of the prior scale is set to 2. The prior shape mean and standard deviation are set to 0 and 0.2, respectively. For nonstationary analyses, the location parameter is selected to be linearly changing in time. The number of chains is set to three, the maximum number of iterations to 10 000, and the burn-in period to 9000.

Table A.7 presents selected ProNEVA outputs related to statistical trend detection and model performance.

Table A.6: Prior parameters per station

Station	Type	Prior location		Prior scale		Prior shape	
		Mean	Std	Mean	Std	Mean	Std
Vlissingen	Nonstationary	35	24	2.5	2	0	0.2
De Kooy	Stationary	35	23	2.5	2	0	0.2
De Bilt	Stationary	35	21	2.5	2	0	0.2
Beek	Stationary	36	25	2.5	2	0	0.2
Eelde	Stationary	32	17	2.0	2	0	0.2

Table A.7: Statistical test results and model performance per station

Station	Mann-Kendall	White test	KS rejection rate	RMSE [mm/h]
Vlissingen	1	1	0.37	1.30
De Kooy	0	0	3.58	2.43
De Bilt	0	0	0.26	1.59
Beek	0	0	0.61	1.08
Eelde	0	0	0.45	1.10

Figure A.1 shows the predictive probability density function (PDF) of daily precipitation. Figure A.2 presents the PP and QQ plots, while Figure A.3 shows the estimated return level plots with a 90 % confidence interval for the five stations.

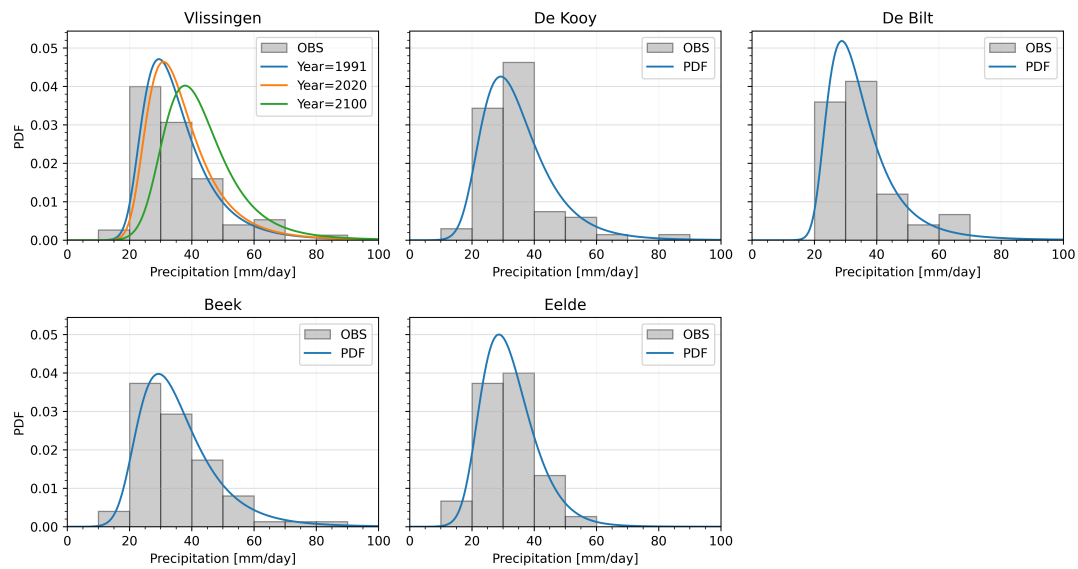


Figure A.1: Predictive distribution for daily precipitation for the five stations

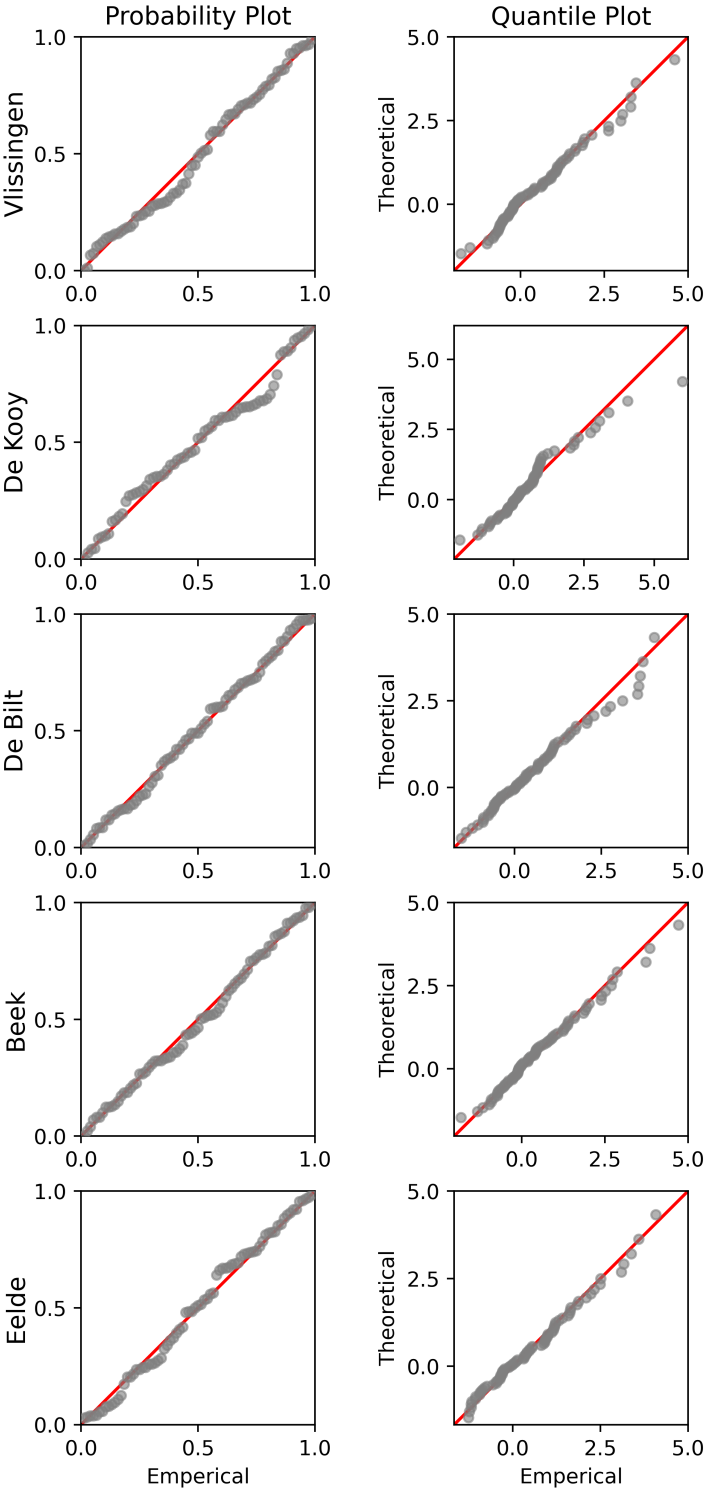


Figure A.2: PP and QQ plots for daily precipitation

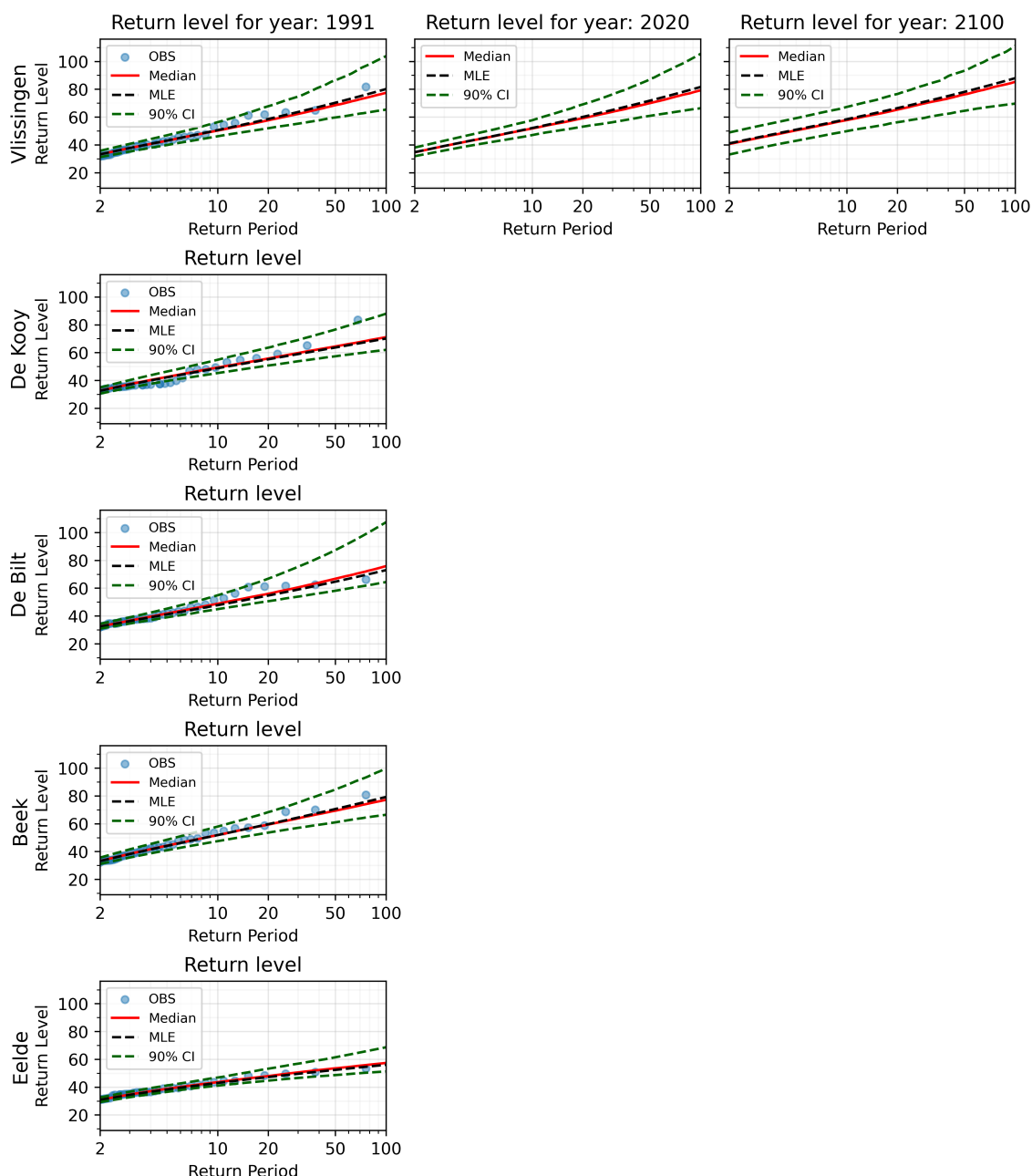


Figure A.3: Return level plots for daily precipitation

A.3.2. 6-minute precipitation events

Table A.8 presents the prior distributions used as input for ProNEVA for the five stations, based on 6-minute precipitation event data. For all stations, the prior distribution is assumed to be normal, defined by a prior mean and prior standard deviation. The prior location mean is set equal to the mean of the annual maxima series and the standard deviation is set to two times the standard deviation of series of annual maxima. The mean of the prior scale is set to the logarithm of the standard deviation of the series of annual maxima and the standard deviation of the prior scale is set to 2. The prior shape mean and standard deviation are set to 0 and 0.2, respectively. The number of chains is set to three, the maximum number of iterations to 10 000, and the burn-in period to 9000.

Table A.9 presents selected ProNEVA outputs related to statistical trend detection and model performance.

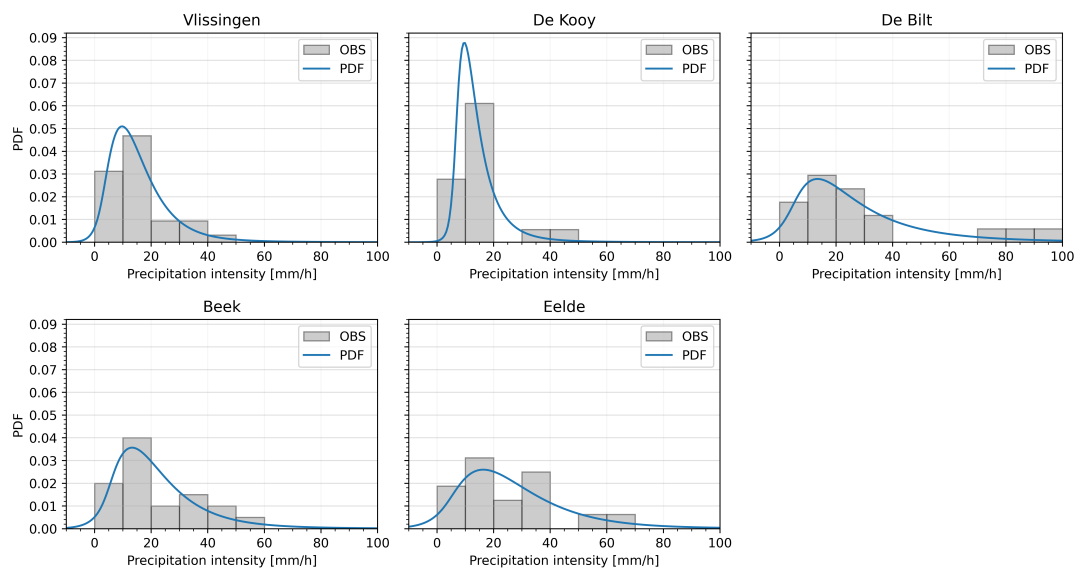
Table A.8: Prior parameters per station

Station	Type	Prior location		Prior scale		Prior shape	
		Mean	Std	Mean	Std	Mean	Std
Vlissingen	Stationary	16	20	2.5	2	0	0.2
De Kooy	Stationary	14	18	2.0	2	0	0.2
De Bilt	Stationary	29	56	3.5	2	0	0.2
Beek	Stationary	26	36	3.0	2	0	0.2
Eelde	Stationary	26	60	3.5	2	0	0.2

Table A.9: Statistical test results and model performance per station

Station	Mann-Kendall	White test	KS rejection rate	RMSE [mm/h]
Vlissingen	0	0	0.56	1.25
De Kooy	0	0	0.77	2.28
De Bilt	0	0	0.70	2.27
Beek	0	0	0.11	1.26
Eelde	0	0	1.71	2.74

Figure A.4 shows the predictive probability density function (PDF) of 6-minute precipitation events. Figure A.5 presents the PP and QQ plots, while Figure A.6 shows the estimated return level plots with a 90 % confidence interval for the five stations.

**Figure A.4:** Predictive distribution for 6-minute precipitation events for the five stations

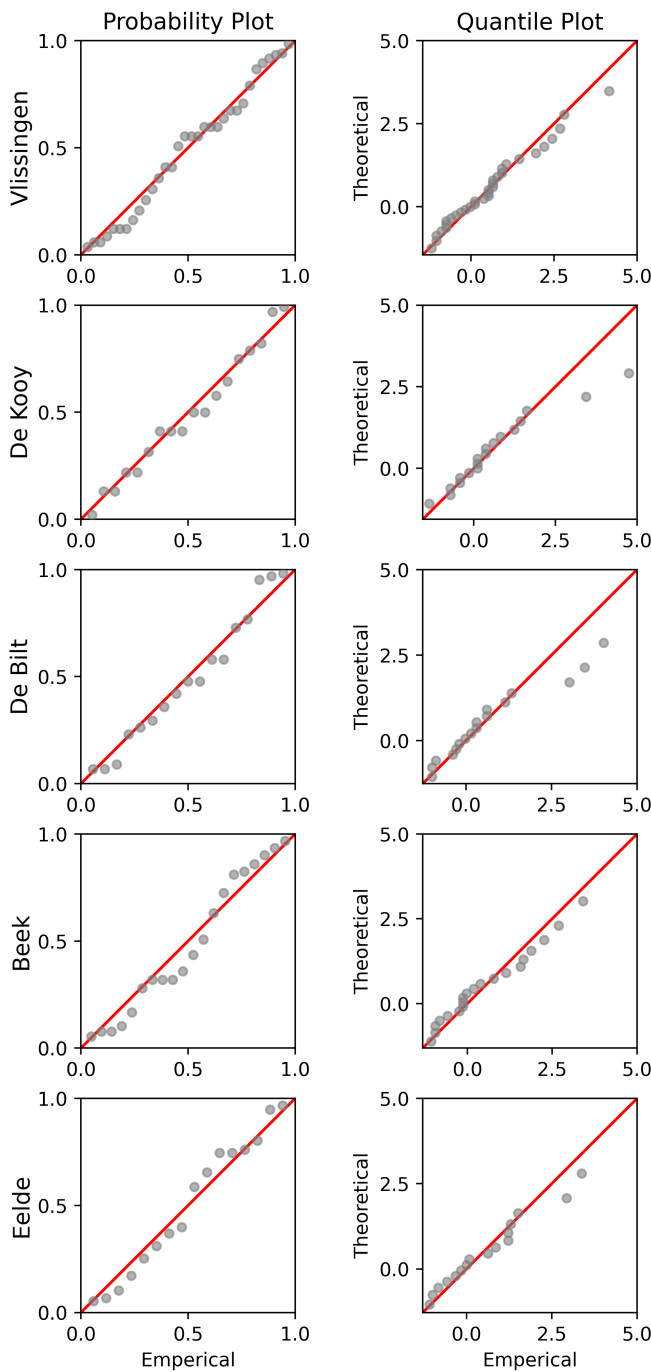


Figure A.5: PP and QQ plots for 6-minute precipitation events

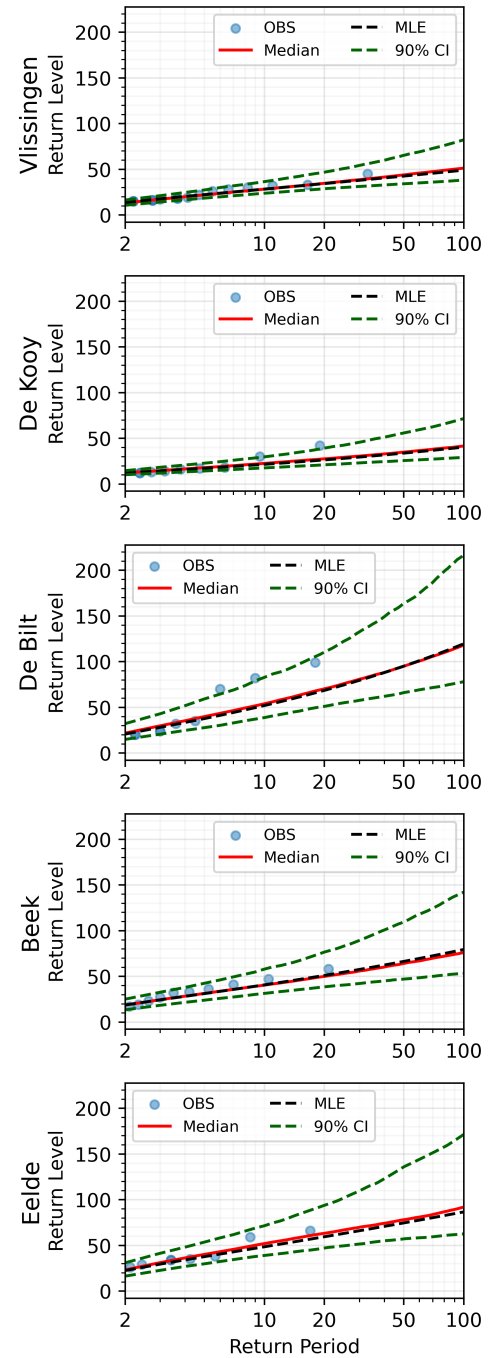


Figure A.6: Return level plots for 6-minute precipitation events

A.3.3. 6-minute precipitation events (Version 2)

In this section additional information and figures are provided for *Version 2* of the EVA of 6-minute precipitation events. For each hour, precipitation events with a reported duration of 0.2 hour were selected and were assumed to consist of two consecutive precipitation events of equal duration (0.1 hour) and equal intensity. Subsequently, for each station and each year, annual maxima were determined by taking the maximum value of either the recorded 0.1 hour intensities or the reconstructed 0.1 hour intensities derived from the 0.2 hour events.

Table A.10 presents the prior distributions used as input for ProNEVA for the five stations, based on the retrieved series of annual maxima. For all stations, the prior distribution is assumed to be normal,

defined by a prior mean and prior standard deviation. The prior location mean is set equal to the mean of the annual maxima series and the standard deviation is set to two times the standard deviation of series of annual maxima. The mean of the prior scale is set to the logarithm of the standard deviation of the series of annual maxima and the standard deviation of the prior scale is set to 2. The prior shape mean and standard deviation are set to 0 and 0.2, respectively. The number of chains is set to three, the maximum number of iterations to 10 000, and the burn-in period to 9000.

Table A.11 presents selected ProNEVA outputs related to statistical trend detection and model performance.

Table A.10: Prior parameters per station (version 2)

Station	Type	Prior location		Prior scale		Prior shape	
		Mean	Std	Mean	Std	Mean	Std
Vlissingen	Stationary	22	24	2.5	2	0	0.2
De Kooy	Stationary	25	61	3.5	2	0	0.2
De Bilt	Stationary	32	53	3.5	2	0	0.2
Beek	Stationary	29	29	2.5	2	0	0.2
Eelde	Stationary	33	38	3.0	2	0	0.2

Table A.11: Statistical test results and model performance per station (version 2)

Station	Mann-Kendall	White test	KS rejection rate	RMSE [mm/h]
Vlissingen	0	0	0.22	1.04
De Kooy	0	0	3.37	3.59
De Bilt	0	0	0.46	2.35
Beek	0	0	0.12	1.44
Eelde	0	0	0.33	1.10

Figure A.7 shows the predictive probability density function (PDF) of 6-minute precipitation events. Figure A.8 presents the PP and QQ plots, while Figure A.9 shows the estimated return level plots with a 90 % confidence interval for the five stations.

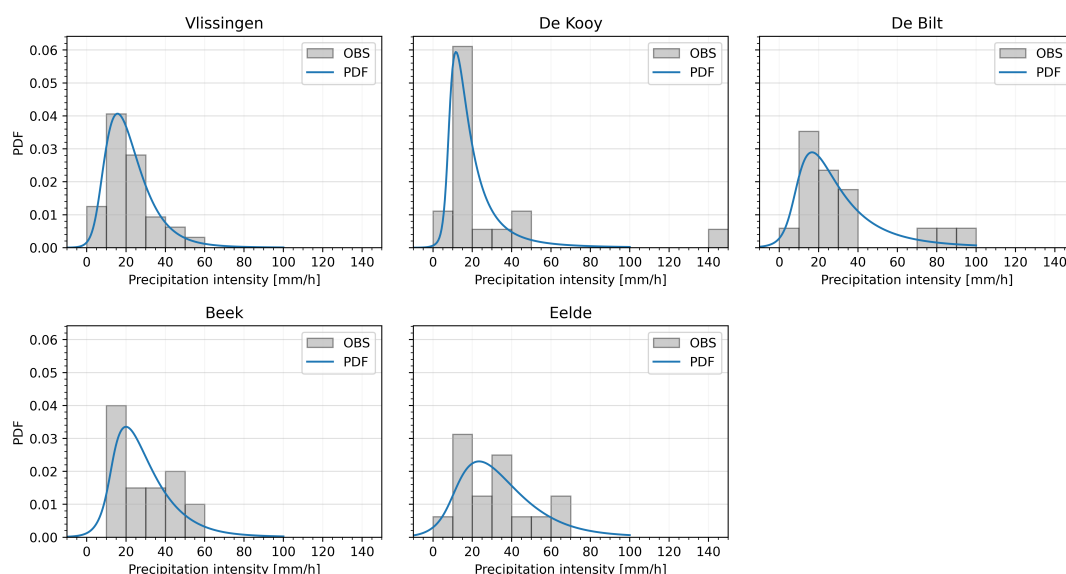


Figure A.7: Predictive distribution for 6-minute precipitation events for the five stations (version 2)

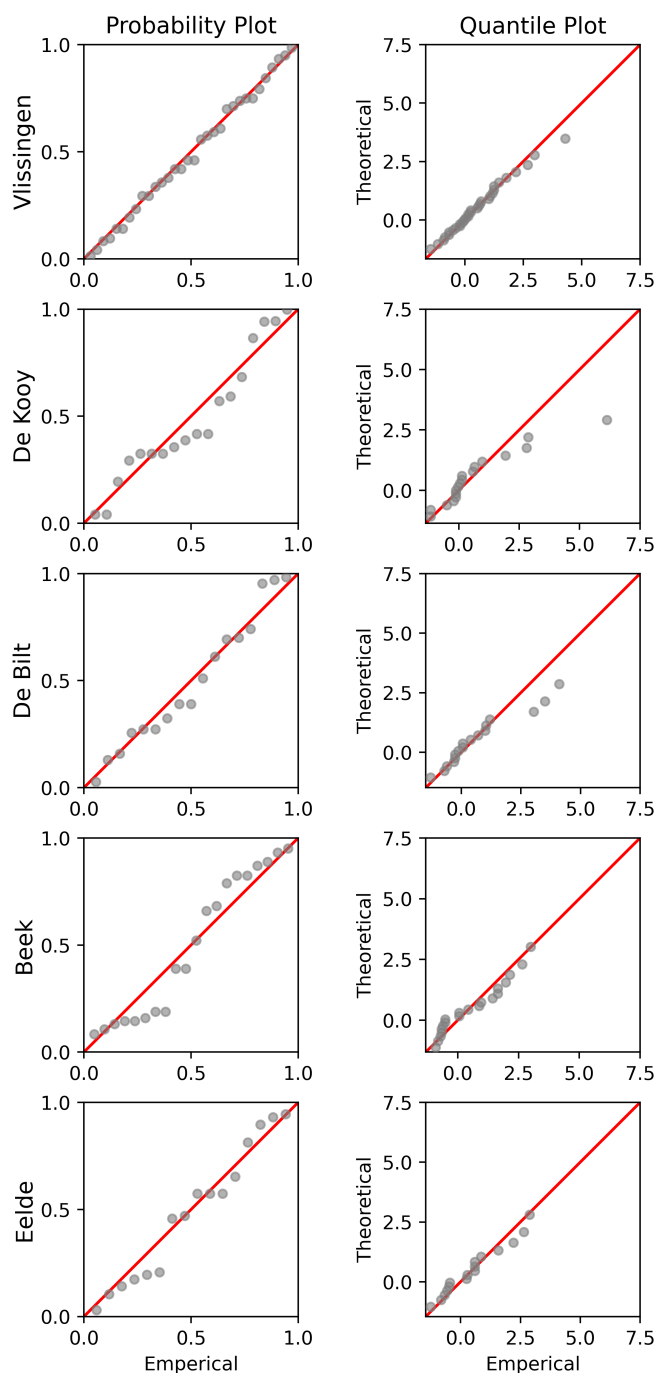


Figure A.8: PP and QQ plots for 6-minute precipitation events (version 2)

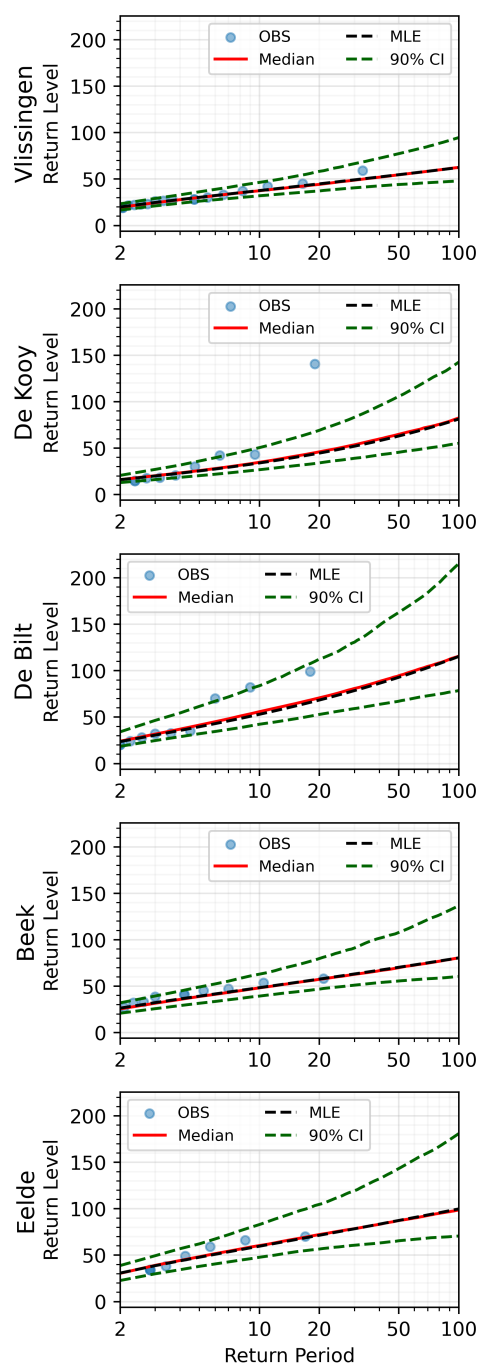


Figure A.9: Return level plots for 6-minute precipitation events (version 2)

Figure A.10 presents the estimated return level plots for the five stations.

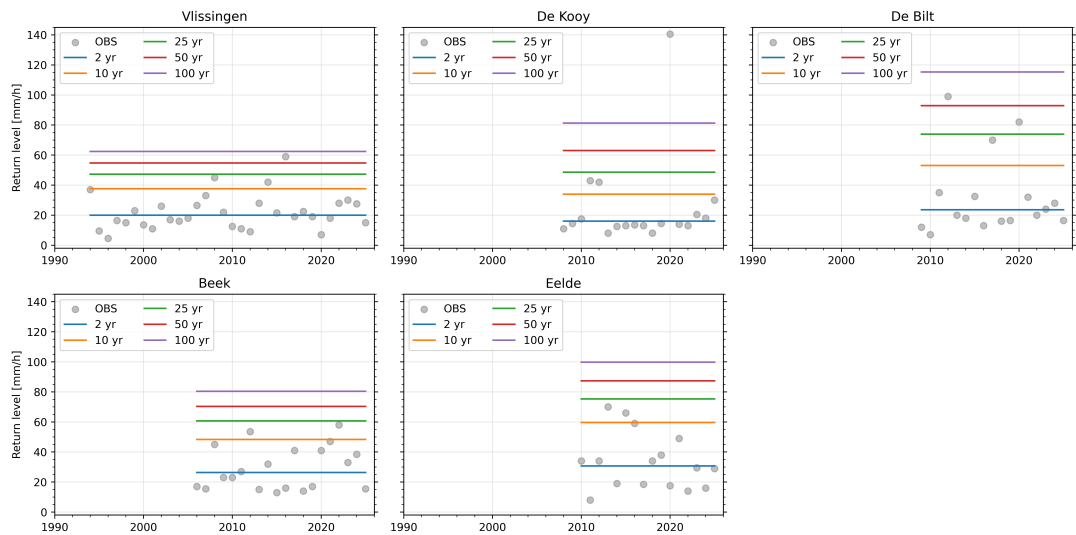


Figure A.10: Return level plots for 6-minute precipitation events (version 2)

B

Snow observations

In this appendix, additional figures or tables are given that support the sections about snow observations.

B.1. Extreme value analysis of historical observations

Table B.1 presents the prior distributions used as input for ProNEVA for the five stations, based on daily historical snow data. For all stations, the prior distribution is assumed to be normal, defined by a prior mean and prior standard deviation. The prior location mean is set equal to the mean of the annual maxima series and the standard deviation is set to two times the standard deviation of series of annual maxima. The mean of the prior scale is set to the logarithm of the standard deviation of the series of annual maxima and the standard deviation of the prior scale is set to 2. The prior shape mean and standard deviation are set to 0.3 and 0.2, respectively. For nonstationary analyses, the location parameter is selected to be linearly changing in time. The number of chains is set to three, the maximum number of iterations to 10 000, and the burn-in period to 9000.

Table B.2 presents selected ProNEVA outputs related to statistical trend detection and model performance.

Table B.1: Prior parameters per station

Station	Type	Prior location		Prior scale		Prior shape	
		Mean	Std	Mean	Std	Mean	Std
Vlissingen	Stationary	4	9	1	2	0.3	0.2
De Kooy	Nonstationary	4	9	1	2	0.3	0.2
De Bilt	Nonstationary	7	11	1	2	0.3	0.2
Beek	Nonstationary	8	13	1	2	0.3	0.2
Eelde	Nonstationary	8	13	1	2	0.3	0.2

Table B.2: Statistical test results and model performance per station

Station	Mann-Kendall	White test	KS rejection rate	RMSE [mm/h]
Vlissingen	0	0	1.41	2.34
De Kooy	1	0	1.18	2.29
De Bilt	1	0	4.50	1.94
Beek	0	0	3.60	1.91
Eelde	1	0	3.00	2.10

B.1.1. 100-year return level

Table B.3 presents the estimated 100-year return level of ground snow load and compares it with the derived characteristic value from NEN-EN 1991-1-3 and its National Annex.

Table B.3: Comparison between estimated 100-year return level and given characteristic value of ground snow load based on Dutch National Annex of NEN-EN 1991-1-3

	Snow load Annex [kN ² /m]	Snow cover estimated [cm]	Snow load estimated [kN ² /m]	Estimated < Annex	Difference [%]
Vlissingen	0.8	34.0	0.68	yes	15.0
De Kooy	0.8	32.9	0.66	yes	17.7
De Bilt	0.8	34.2	0.68	yes	14.4
Beek	0.8	40.0	0.80	yes	0.1
Eelde	0.8	38.6	0.77	yes	3.5

Figure B.1 shows the predictive probability density function (PDF) of daily snow. Figure B.2 presents the PP and QQ plots, while Figure B.3 shows the estimated return level plots with a 90 % confidence interval for the five stations.

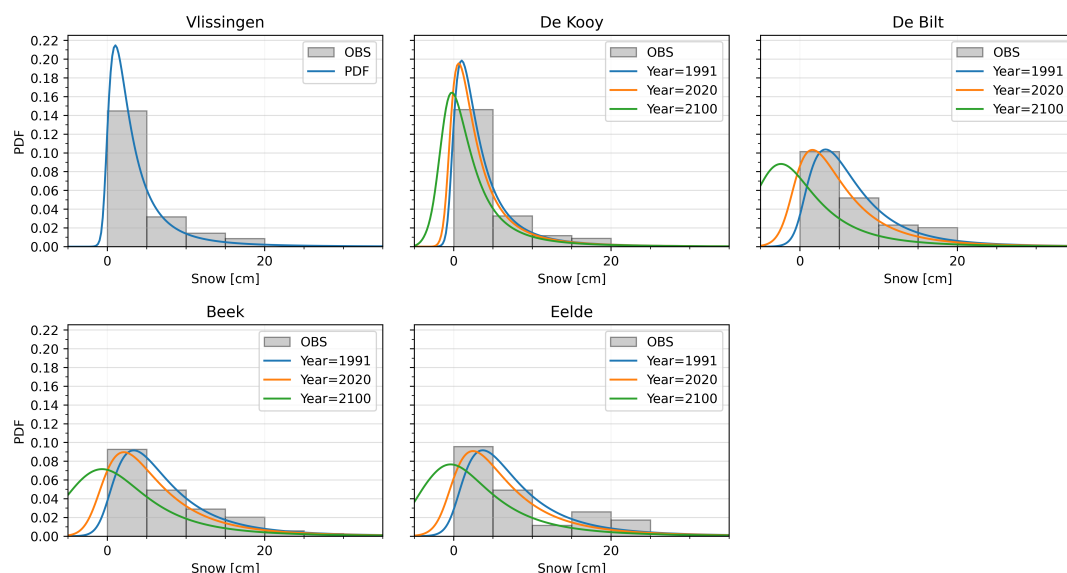
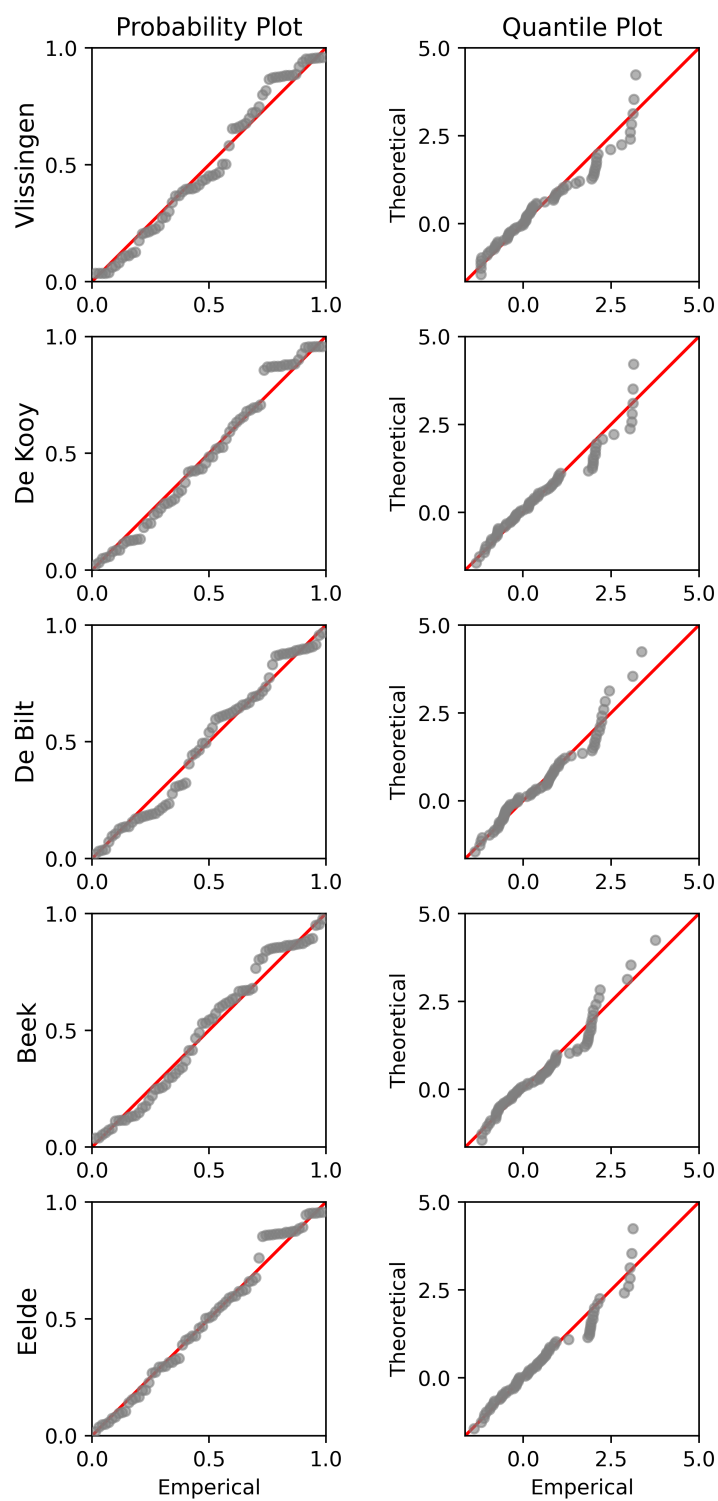


Figure B.1: Predictive distribution for daily snow for the five stations

**Figure B.2:** PP and QQ plots for daily snow

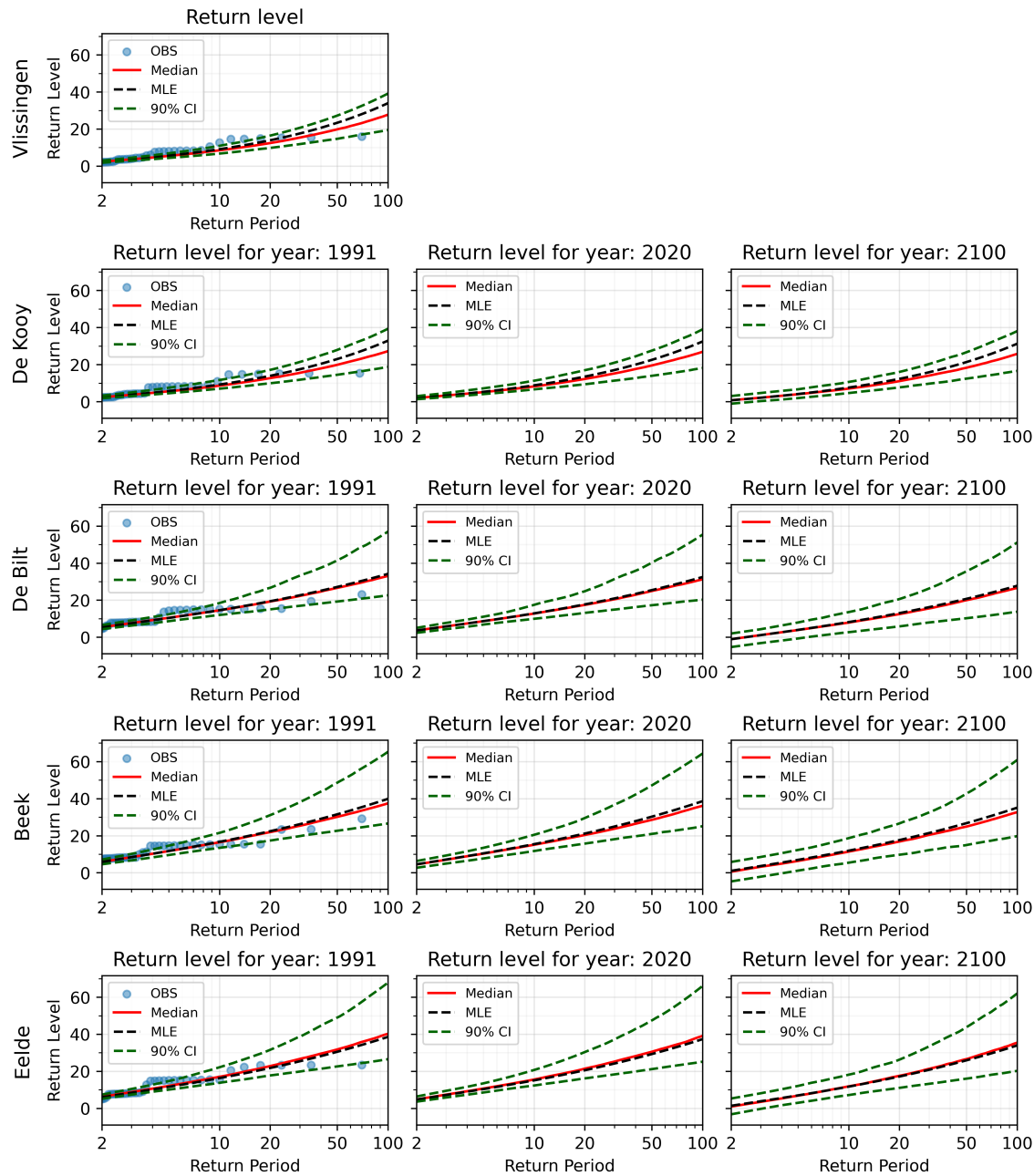
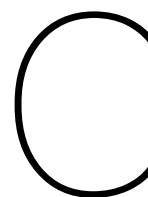


Figure B.3: Return level plots for daily snow



Wind observations

In this appendix, additional figures or tables are given that support the sections about wind observations.

C.1. Inhomogeneities in historical observations

Tables C.1, C.2, C.3, C.4, and C.5 present the different changes in wind measurement height, instrumentation, location, and recorder since 1951 onwards for the five stations. The information was retrieved from documentation provided by the KNMI and archived webpages (with station changes up to 2015) (KNMI, n.d.-d, n.d.-e, n.d.-g, n.d.-p, n.d.-v).

Table C.1: Wind measurement changes for station Vlissingen since 1951 onwards

Period	Measurement height [m]	Instrumentation, location, and recorder
1958-04-30 – 1959-11-20	16.4	Dines at meteo building.
1959-11-21 – 1967-03-08	10.0	Cup anemometer with frequency meter and electric wind vane. Metrawatt recorder. Located at port dam.
1967-03-10 – 1968-07-02	15.0	Likewise. Located at service building.
1968-07-03 – 1972-01-30	10.0	Likewise. Wind met mast at port dam.
1972-01-31 – 1982-10-01	15.0	Likewise. Located at service building with Nieaf recorder.
1982-10-02 – 1993-04-31	15.0	Likewise. Camille Bauer recorder.
1993-05-01 – today	15.0	Likewise. Digital registration.
1997-10-03	20.0	Relocation of instruments by 14.5 m.

Table C.2: Wind measurement changes for station De Kooy since 1951 onwards

Period	Measurement height [m]	Instrumentation, location, and recorder
1954-11-22 – 1972-07-31	13.9	New type of Dines with direction registration.
1972-08-01 – 1984-12-11	10.0	Cup anemometer with frequency meter and electric wind vane. Heath recorder. Small relocations at 1972-09-25 and 1980-08-26.
1984-12-12 – 1992-12-31	10.0	Likewise. Camille Bauer recorder.
1993-01-01 – today	10.0	Likewise. Digital registration.
2001-10-11	10.0	Relocation of instruments by 120 m.

Table C.3: Wind measurement changes for station De Bilt since 1951 onwards

Period	Measurement height [m]	Instrumentation, location, and recorder
1953-02-17 – 1960-12-31	38.3	Met mast <i>De Spijker</i> . Several different wind gauges.
1961-01-01 – 1982-07-31	10.0	Cup anemometer with frequency meter and electric wind vane. Nieaf recorder.
1982-08-01 – 1993-05-24	10.0	Likewise. Camille Bauer recorder.
1993-05-25 – 1993-06-25	10.0	Likewise. Digital registration.
1993-06-26 – today	20.0	Likewise.

Table C.4: Wind measurement changes for station Beek since 1951 onwards

Period	Measurement height [m]	Instrumentation, location, and recorder
1961-08-01 – 1988-07-15	10.0	Cup anemometer with frequency meter and electric wind vane. Nieaf recorder. Small relocation at 1985-05-29.
1988-04-20	10.0	Relocation of instruments by 200 m
1988-07-16 – 1991-11-07	10.0	Likewise. Camille Bauer recorder.
1991-11-07 – today	10.0	Likewise. Digital registration.
2005-11-01	10.0	Relocation of instruments by 1100 m

Table C.5: Wind measurement changes for station Eelde since 1951 onwards

Period	Measurement height [m]	Instrumentation, location, and recorder
1954-09-21 – 1954-12-28	14.8	Cup anemometer with frequency meter and electric wind vane. Metrawatt recorder.
1954-12-29 – 1956-07-12	10.7	Likewise. Wind met mast was tilted one degree in NNW direction.
1956-07-13 – 1960-08-29	10.0	Likewise. Wind met mast.
1960-08-30 – 1966-05-26	12.0	Likewise. Antenna mast.
1966-05-27 – 1988-06-28	10.0	Likewise. Wind met mast. Small relocation at 1973-03-23.
1988-06-29 – 1990-10-09	10.0	Likewise. Camille Bauer recorder.
1990-10-10 – today	10.0	Likewise. Digital registration.
1995-09-25	10.0	Relocation of instruments by 257 m

Figure C.1 presents monthly and annual resampled hourly mean wind velocity for the five stations. The vertical bars indicate a change in measurement height, instrumentation, location, or recorder. These changes resulted in possible inhomogeneities.

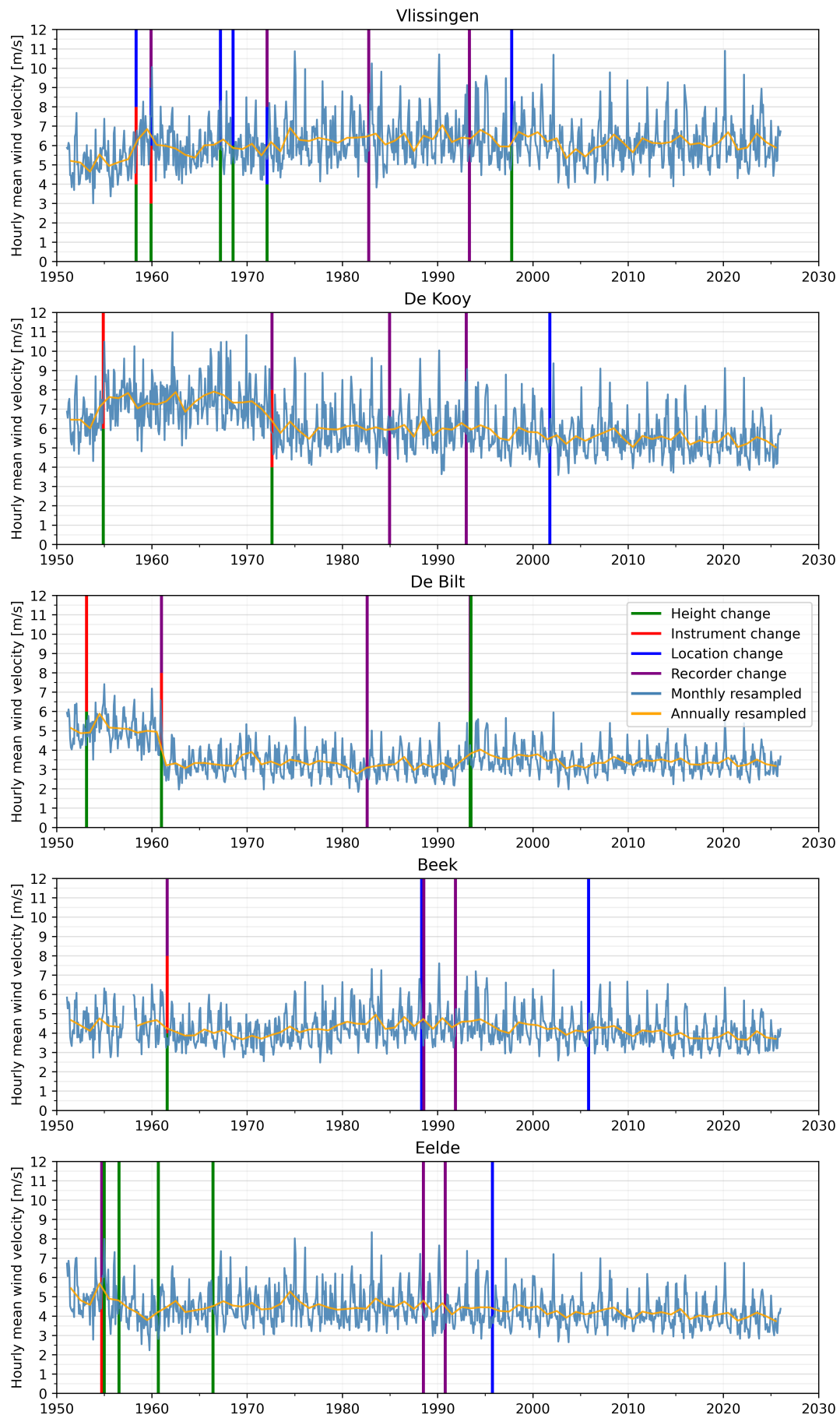


Figure C.1: Resampled hourly wind velocity together with changes in measurement set-up indicated as vertical bars for the five stations

C.2. Extreme value analysis of historical observations

Table C.6 presents the prior distributions used as input for ProNEVA for the five stations, based on daily historical wind data. For all stations, the prior distribution is assumed to be normal, defined by a prior mean and prior standard deviation. The prior location mean is set equal to the mean of the annual maxima series and the standard deviation is set to two times the standard deviation of series of annual maxima. The mean of the prior scale is set to the logarithm of the standard deviation of the series of annual maxima and the standard deviation of the prior scale is set to 2. The prior shape mean and standard deviation are set to 0 and 0.2, respectively. For nonstationary analyses, the location parameter is selected to be linearly changing in time. The number of chains is set to three, the maximum number of iterations to 10 000, and the burn-in period to 9000.

Table C.7 presents selected ProNEVA outputs related to statistical trend detection and model performance.

Table C.6: Prior parameters per station

Station	Type	Prior location		Prior scale		Prior shape	
		Mean	Std	Mean	Std	Mean	Std
Vlissingen	Stationary	20	5	1.0	2	0	0.2
De Kooy	Nonstationary	21	5	1.0	2	0	0.2
De Bilt	Stationary	14	4	0.5	2	0	0.2
Beek	Stationary	17	4	1.0	2	0	0.2
Eelde	Nonstationary	19	6	1.0	2	0	0.2

Table C.7: Statistical test results and model performance per station

Station	Mann-Kendall	White test	KS rejection rate	RMSE [mm/h]
Vlissingen	0	0	1.01	1.02
De Kooy	1	0	0.76	1.47
De Bilt	0	0	2.02	1.24
Beek	0	0	4.79	1.39
Eelde	1	0	5.01	1.11

Figure C.2 shows the predictive probability density function (PDF) of 10-minute mean wind velocity. Figure C.3 presents the PP and QQ plots, while Figure C.4 shows the estimated return level plots with a 90 % confidence interval for the five stations.

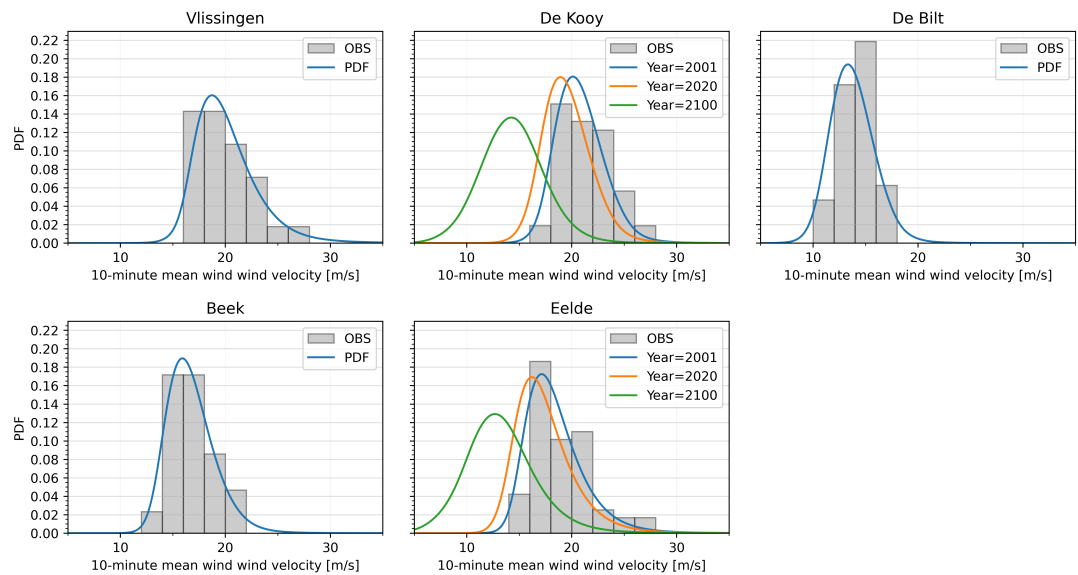


Figure C.2: Predictive distribution for 10-minute mean wind velocity for the five stations

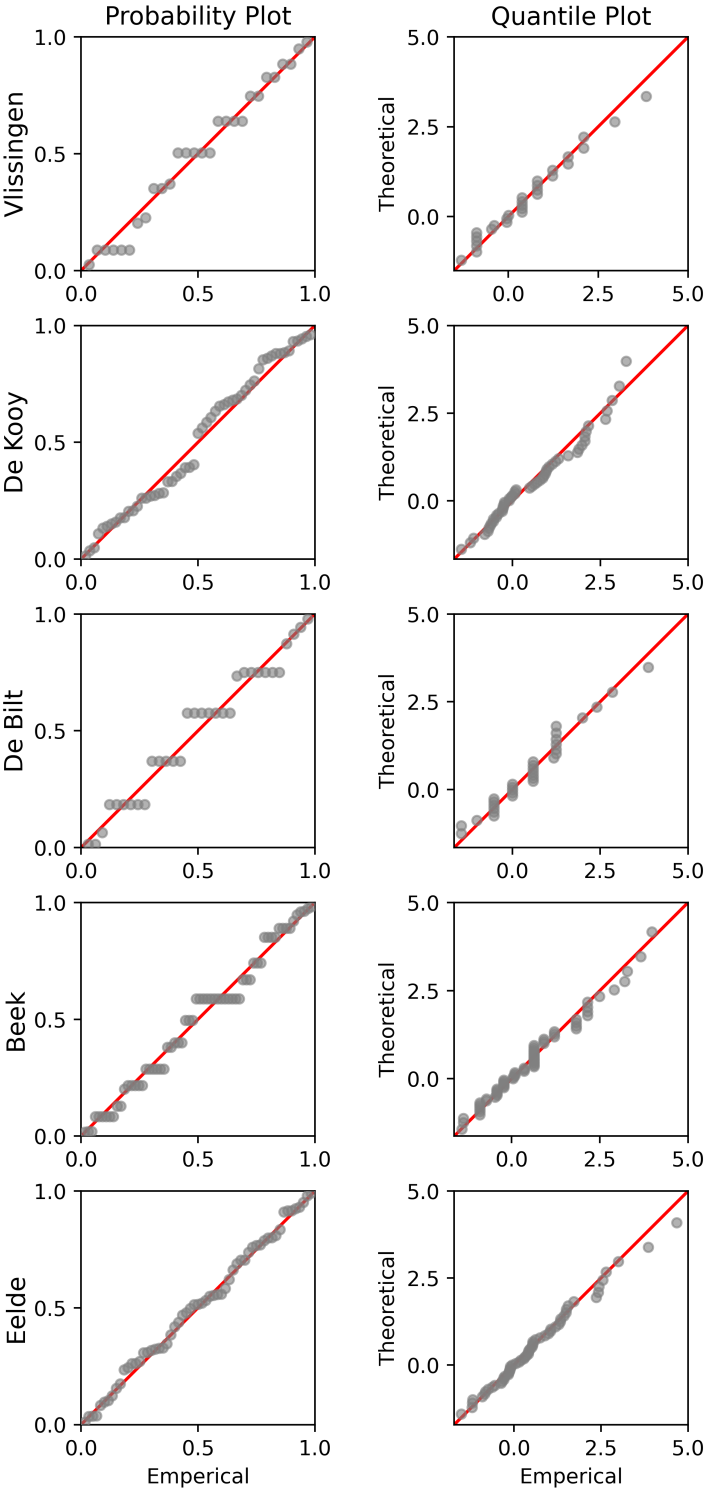


Figure C.3: PP and QQ plots for 10-minute mean wind velocity

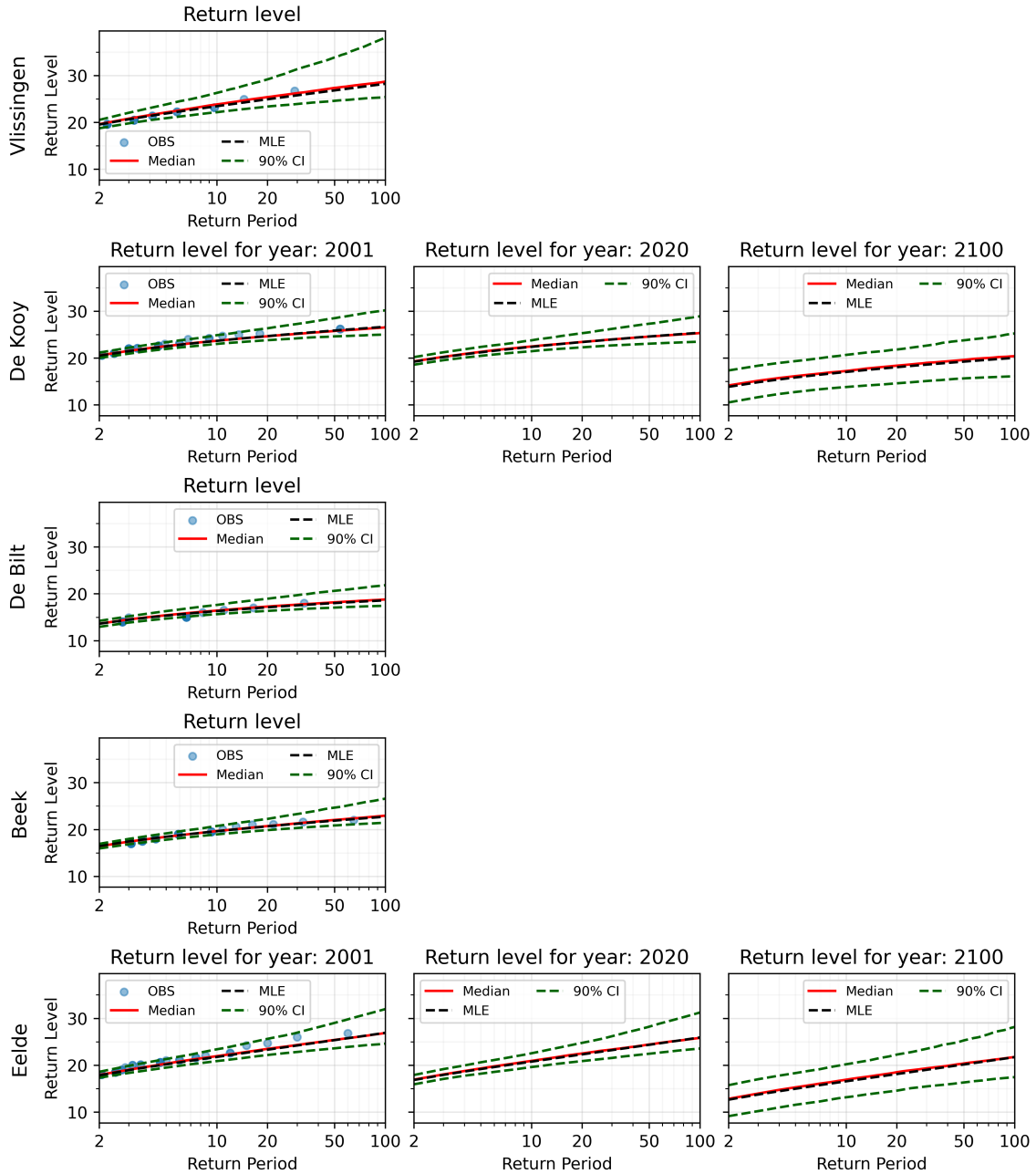


Figure C.4: Return level plots for 10-minute mean wind velocity

C.2.1. 100-year return level

The fundamental values of the basic wind velocity in the Dutch National Annex of NEN-EN 1991-1-4 are given for an annual probability of exceedance of 0.02, corresponding to a return period of 50 years. The Annex also provides a conversion formula for other return periods. Here, a return period of 100 years is considered.

The conversion factor for the fundamental basic wind velocity correspond to an annual probability of exceedance p is given by (NEN, 2011):

$$c_{prob} = \left(\frac{1 - K \cdot \ln(-\ln(1-p))}{1 - K \cdot \ln(-\ln(0.98))} \right)^n \quad (C.1)$$

where K is the shape parameter and n is the exponent. The values of these parameters are provided

in Table NB.2 of the Dutch National Annex (NEN, 2023).

Table C.8: Values of K and n for three wind regions according to the Dutch National Annex of NEN-EN 1991-1-4 (NEN, 2023)

Wind region	1	2	3
K	0.2	0.234	0.281
n	0.5	0.5	0.5

Furthermore, the National Annex states that:

$$(1 - p) = e^{(-\frac{1}{R})} \quad (\text{C.2})$$

where R is the reference period. For R larger than 25, p can be approximated by: $p = 1/R$.

Using the exact expression for p and a return period of 100 years, the conversion factors for the three wind regions were calculated.

Table C.9: Values of c_{prob} and fundamental value of basic wind velocity for a return period of 100 years according to the Dutch National Annex of NEN-EN 1991-1-4 (NEN, 2023)

Wind region	1	2	3
c_{prob}	1.0387	1.0421	1.0461
$v_{b,0}$ [m/s]	30.64	28.14	25.63

Table C.10: Comparison between estimated and given fundamental value of basic wind velocity the Dutch National Annex of NEN-EN 1991-1-4

	Wind Region	Annex $v_{b,0}$ [m/s]	Estimated $v_{b,0}$ [m/s]	Estimated < Annex	Difference [%]
Vlissingen	2	28.14	28.24	no	0.4
De Kooy	1	30.64	28.57	yes	6.8
De Bilt	3	25.63	18.62	yes	27.4
Beek	3	25.63	22.75	yes	11.2
Eelde	2	28.14	28.72	no	2.1

Table C.10 shows that the estimated 100-year return levels for stations Vlissingen and Eelde are slightly higher than the values prescribed by the Annex. Both stations are located in wind region 2. In contrast, the estimated values for De Kooy, De Bilt, and Beek remain below the prescribed values.

These results indicate that the conversion factor prescribed for a 100-year return period generally results into values that are higher than the estimated return levels. However, for stations Vlissingen and Eelde, the estimated values slightly exceed those of the National Annex. For station Eelde, the estimated value already exceeded the given value for the 50-year return period, indicating that this behaviour is not only caused by the conversion from a 50-year to a 100-year return period. The observed differences may instead be related to uncertainties in the fitted GEV distributions, the length of considered annual maxima, or differences between the reference period in this study and that of the National Annex.

D

Precipitation projections

This appendix presents additional figures corresponding to Section 5.3, about the precipitation projections.

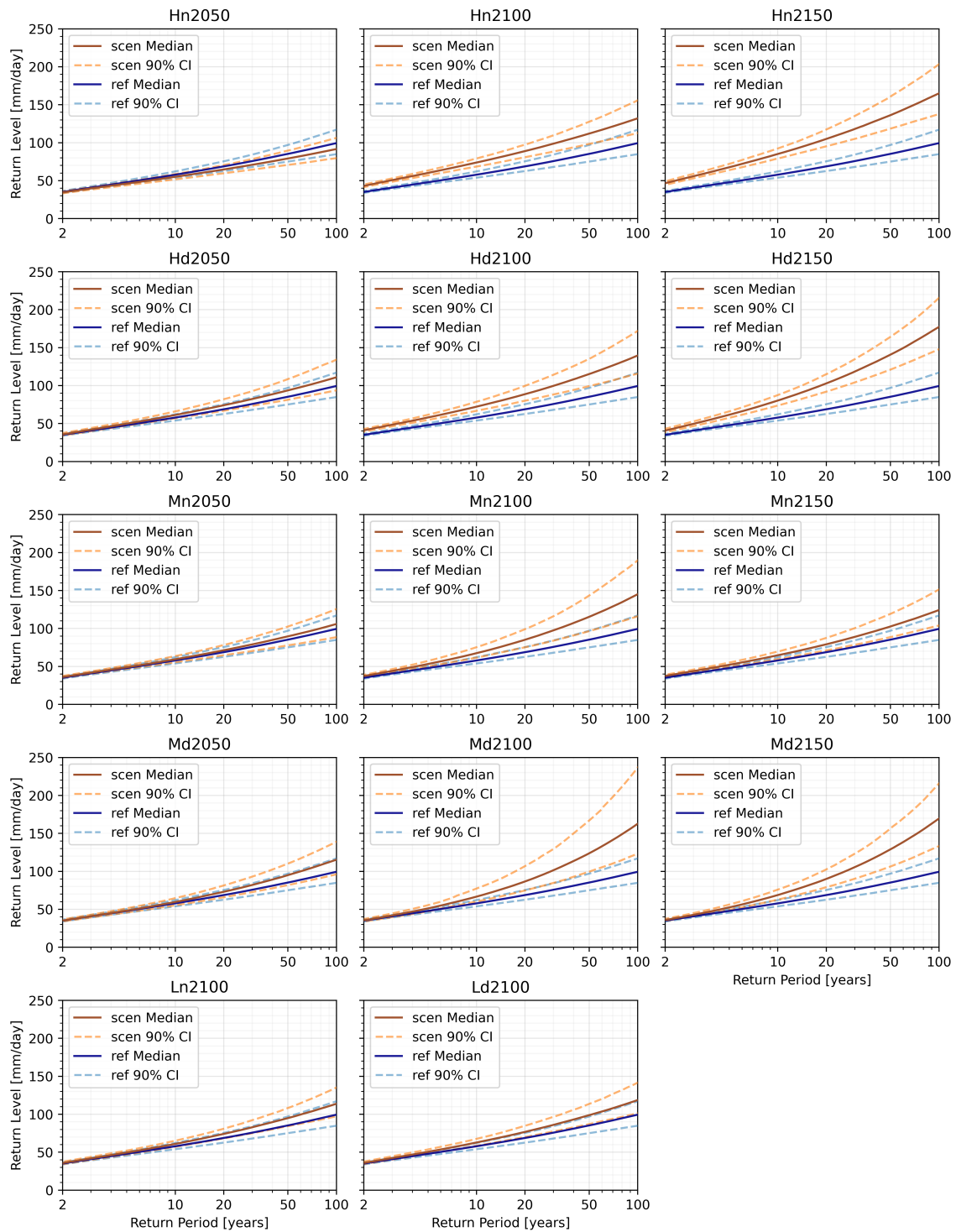


Figure D.1: Fitted GEV distribution of 24-hour precipitation amounts for different climate scenarios together with the reference scenario. Median values and 90 % confidence interval are determined by bootstrapping

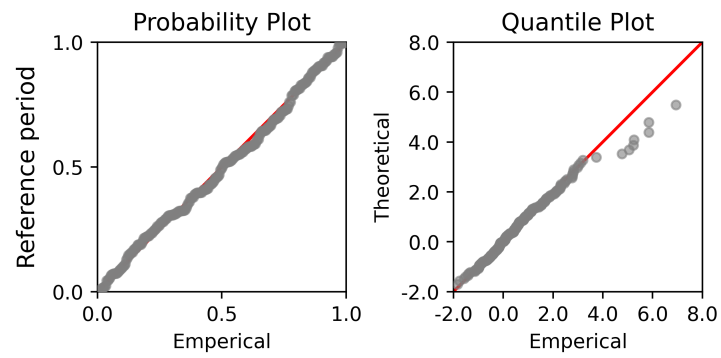


Figure D.2: PP and QQ plots for 24 hour precipitation amounts for reference period

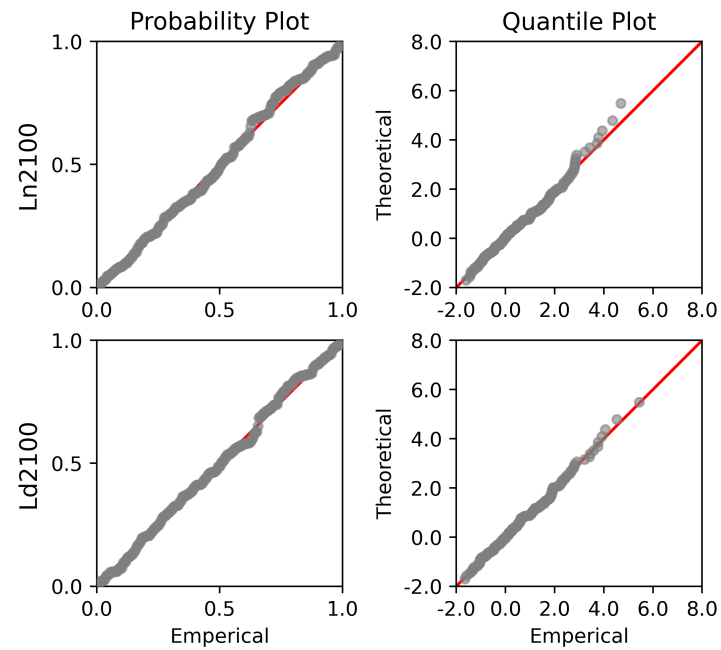


Figure D.3: PP and QQ plots for 24 hour precipitation amounts for low radiative forcing scenarios

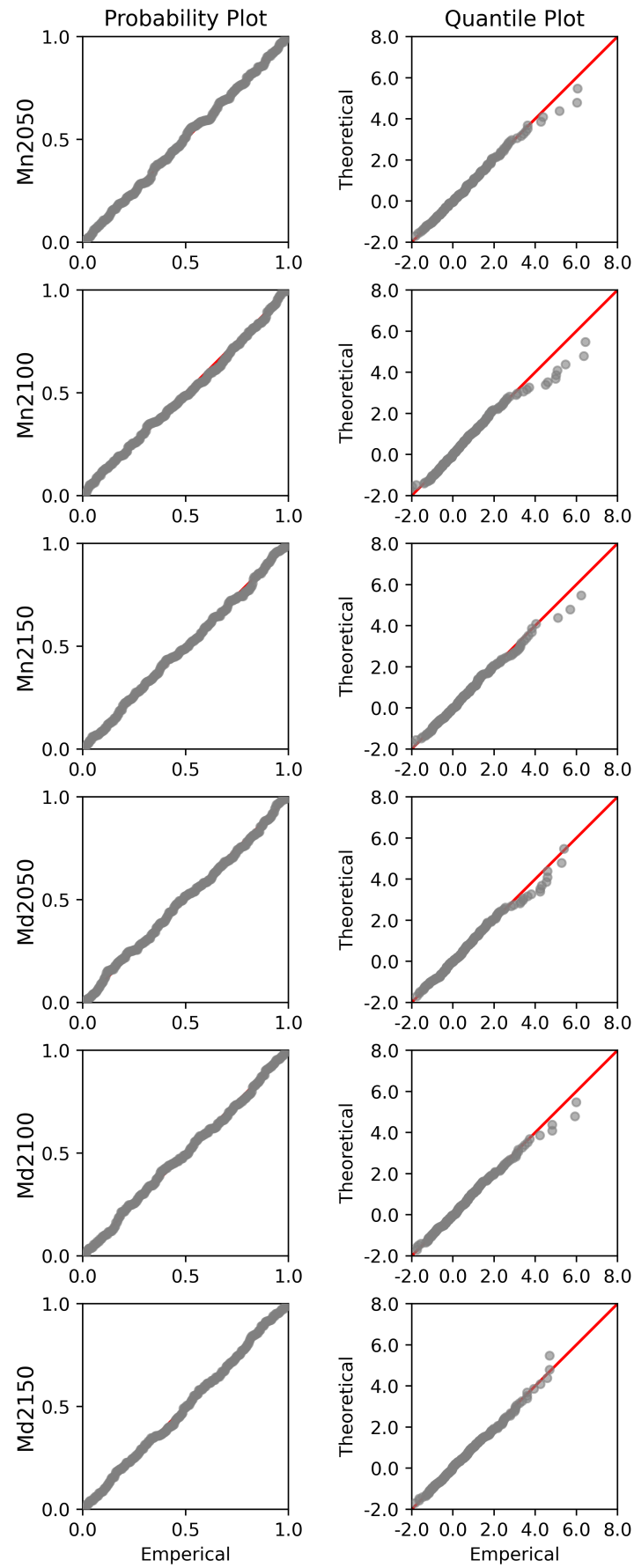


Figure D.4: PP and QQ plots for 24 hour precipitation amounts for moderate forcing scenarios

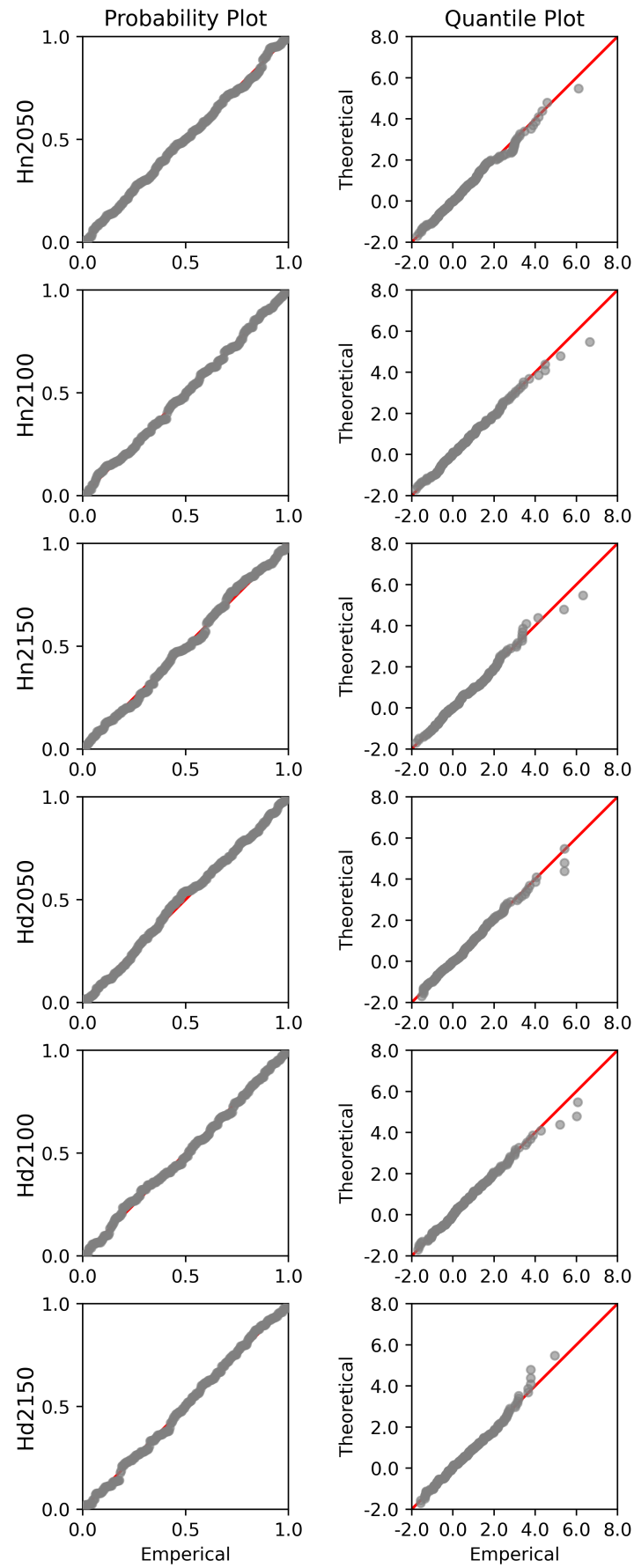


Figure D.5: PP and QQ plots for 24 hour precipitation amounts for high forcing scenarios

Snow indicator projections

In this appendix, additional figures or tables are given that support the sections about snow indicator projections.

Figures E.1 and E.2 present violin plots of the winter (DJF) precipitation sums around De Bilt for all climate scenarios for the periods 2037–2065 (referred to as 2050) and 2087–2115 (referred to as 2100). In addition, Table E.1 summarises the corresponding statistical properties of the precipitation sums.

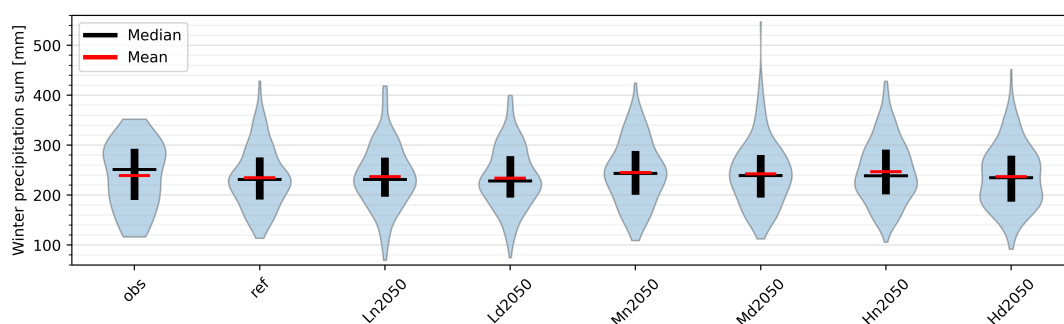


Figure E.1: Winter (DJF) precipitation sums for all climate scenarios during the period 2037–2065 around De Bilt

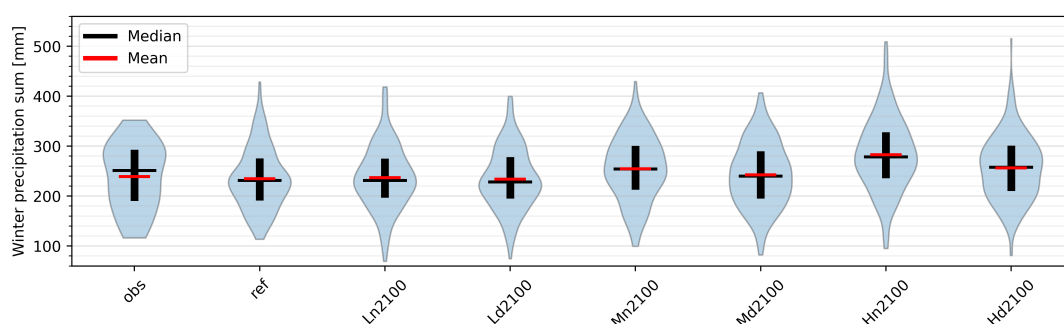


Figure E.2: Winter (DJF) precipitation sums for all climate scenarios during the period 2087–2115 around De Bilt

Table E.1: Statistical properties of winter (DJF) precipitation sums for different climate scenarios around De Bilt

Scenario	Mean [mm]	Median [mm]	5–95 percentile range [mm]
Ref (obs)	239	251	138–332
Ref (model)	235	231	142–343
Ln2050	237	231	132–334
Ld2050	234	228	133–334
Mn2050	245	243	145–358
Md2050	242	239	147–357
Hn2050	247	238	154–353
Hd2050	237	235	147–348
Ln2100	237	231	132–334
Ld2100	234	228	133–334
Mn2100	255	254	150–356
Md2100	243	240	146–349
Hn2100	283	278	177–402
Hd2100	256	258	156–357

Figures E.3 and E.4 present violin plots of the winter year frost days around De Bilt for all climate scenarios for the periods 2037–2065 (referred to as 2050) and 2087–2115 (referred to as 2100). In addition, Table E.2 summarises the corresponding statistical properties of the frost days.

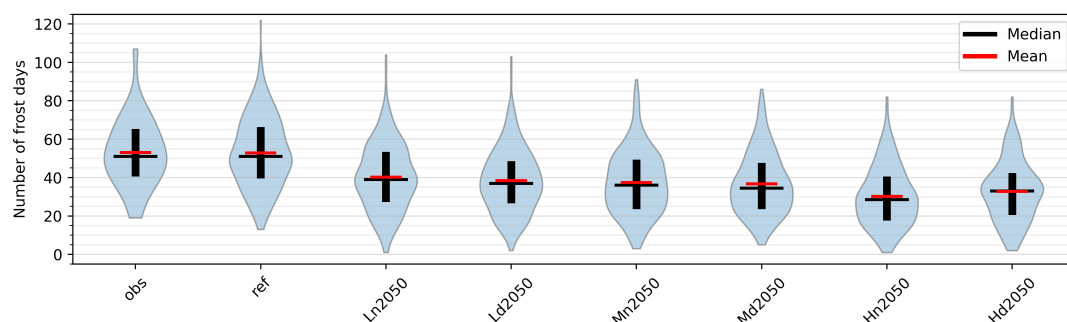
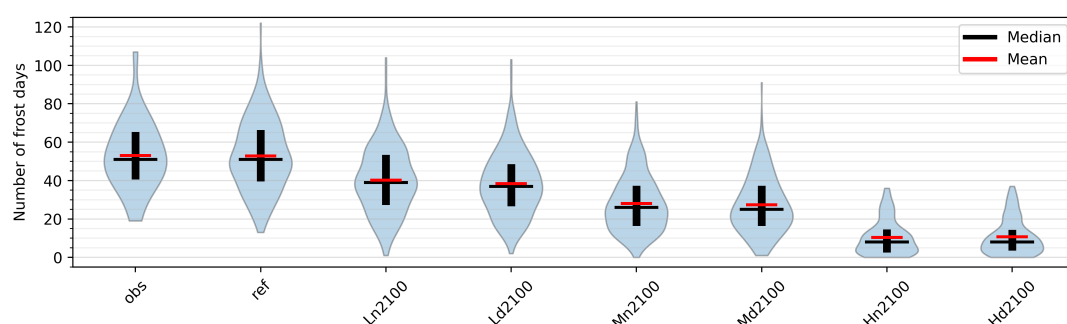
**Figure E.3:** Winter year frost days for all climate scenarios during the period 2037–2065 around De Bilt**Figure E.4:** Winter year frost days for all climate scenarios during the period 2087–2115 around De Bilt

Table E.2: Statistical properties of winter year frost days for different climate scenarios around De Bilt

Scenario	Mean [days]	Median [days]	5–95 percentile range [days]
Ref (obs)	53	51	27–77
Ref (model)	53	51	24–83
Ln2050	40	39	14–69
Ld2050	38	37	14–66
Mn2050	37	36	12–65
Md2050	37	34	14–64
Hn2050	30	28	8–57
Hd2050	33	33	8–61
Ln2100	40	39	14–69
Ld2100	38	37	14–66
Mn2100	28	26	10–54
Md2100	27	25	6–55
Hn2100	10	8	0–28
Hd2100	11	8	0–30

Figures E.5 and E.6 present violin plots of the winter year ice days around De Bilt for all climate scenarios for the periods 2037–2065 (referred to as 2050) and 2087–2115 (referred to as 2100). In addition, Table E.3 summarises the corresponding statistical properties of the ice days.

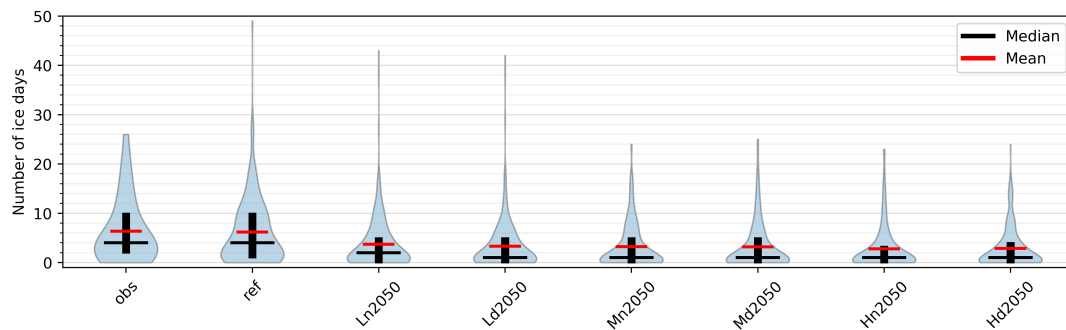
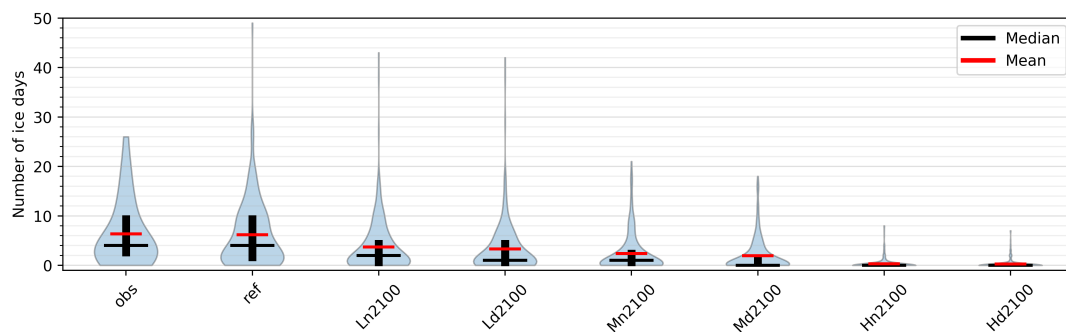
**Figure E.5:** Winter year ice days for all climate scenarios during the period 2037–2065 around De Bilt**Figure E.6:** Winter year ice days for all climate scenarios during the period 2087–2115 around De Bilt

Table E.3: Statistical properties of winter year ice days for different climate scenarios around De Bilt

Scenario	Mean [days]	Median [days]	5–95 percentile range [days]
Ref (obs)	6.3	4.0	0.0–19.6
Ref (model)	6.2	4.0	0.0–18.4
Ln2050	3.7	2.0	0.0–13.0
Ld2050	3.3	1.0	0.0–12.0
Mn2050	3.2	1.0	0.0–13.0
Md2050	3.2	1.0	0.0–13.4
Hn2050	2.8	1.0	0.0–12.4
Hd2050	2.9	1.0	0.0–13.0
Ln2100	3.7	2.0	0.0–13.0
Ld2100	3.3	1.0	0.0–12.0
Mn2100	2.4	1.0	0.0–10.0
Md2100	1.9	0.0	0.0–9.0
Hn2100	0.3	0.0	0.0–2.0
Hd2100	0.3	0.0	0.0–2.0

Figures E.7 and E.8 present violin plots of the winter year precipitation sum if the daily mean temperature is below 0°C for all climate scenarios around De Bilt for all climate scenarios for the periods 2037–2065 (referred to as 2050) and 2087–2115 (referred to as 2100). In addition, Table E.4 summarises the corresponding statistical properties of the winter year precipitation sums if the daily mean temperature is below 0°C .

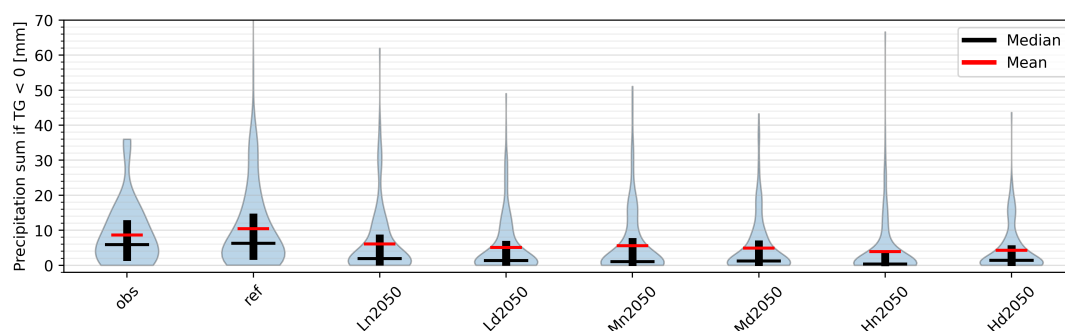
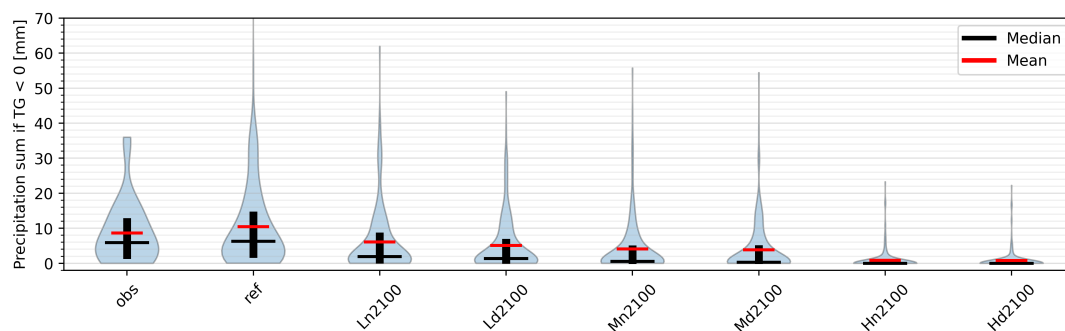
**Figure E.7:** Winter year precipitation sum if the daily mean temperature is below 0°C for all climate scenarios during the period 2037–2065 around De Bilt**Figure E.8:** Winter year precipitation sum if the daily mean temperature is below 0°C for all climate scenarios during the period 2087–2115 around De Bilt

Table E.4: Statistical properties of winter year precipitation sum if the daily mean temperature is below 0 °C for different climate scenarios around De Bilt

Scenario	Mean [mm]	Median [mm]	5–95 percentile range [mm]
Ref (obs)	8.6	5.9	0.1–28.0
Ref (model)	10.4	6.3	0.0–34.4
Ln2050	6.1	1.9	0.0–29.2
Ld2050	5.1	1.4	0.0–23.5
Mn2050	5.6	1.1	0.0–23.6
Md2050	4.9	1.2	0.0–20.2
Hn2050	3.9	0.3	0.0–19.3
Hd2050	4.3	1.4	0.0–17.8
Ln2100	6.1	1.9	0.0–29.2
Ld2100	5.1	1.4	0.0–23.5
Mn2100	4.1	0.5	0.0–17.9
Md2100	3.9	0.3	0.0–16.6
Hn2100	0.9	0.0	0.0–5.4
Hd2100	0.8	0.0	0.0–4.5

Figures E.9 and E.10 present violin plots of the winter year maximum number of consecutive days with daily mean temperature below 0 °C for all climate scenarios around De Bilt for all climate scenarios for the periods 2037–2065 (referred to as 2050) and 2087–2115 (referred to as 2100). In addition, Table E.5 summarises the corresponding statistical properties of the winter year maximum number of consecutive days with daily mean temperature below 0 °C.

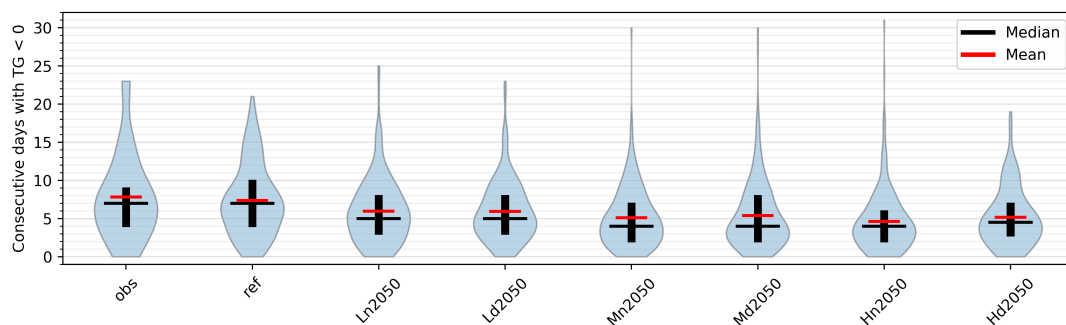


Figure E.9: Winter year maximum number of consecutive days with daily mean temperature below 0 °C for all climate scenarios during the period 2037–2065 around De Bilt

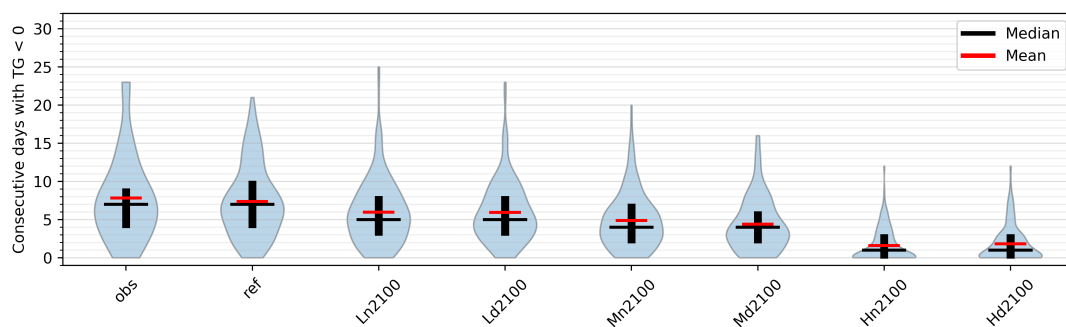
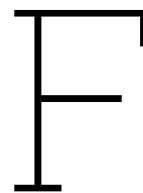


Figure E.10: Winter year maximum number of consecutive days with daily mean temperature below 0 °C for all climate scenarios during the period 2087–2115 around De Bilt

Table E.5: Statistical properties of winter year maximum number of consecutive days with daily mean temperature below 0 °C for different climate scenarios around De Bilt

Scenario	Mean [days]	Median [days]	5–95 percentile range [days]
Ref (obs)	7.8	7.0	1.0–19.8
Ref (model)	7.4	7.0	1.0–16.0
Ln2050	6.0	5.0	0.0–14.0
Ld2050	5.9	5.0	1.0–13.0
Mn2050	5.1	4.0	0.6–12.0
Md2050	5.4	4.0	1.0–13.4
Hn2050	4.6	4.0	0.0–12.4
Hd2050	5.2	4.5	0.0–12.0
Ln2100	6.0	5.0	0.0–14.0
Ld2100	5.9	5.0	1.0–13.0
Mn2100	4.9	4.0	0.0–11.4
Md2100	4.4	4.0	0.0–11.4
Hn2100	1.6	1.0	0.0–6.0
Hd2100	1.8	1.0	0.0–7.0



Wind projections

This appendix presents additional figures corresponding to Section 13.2, about the wind projections.

F.1. Eelde

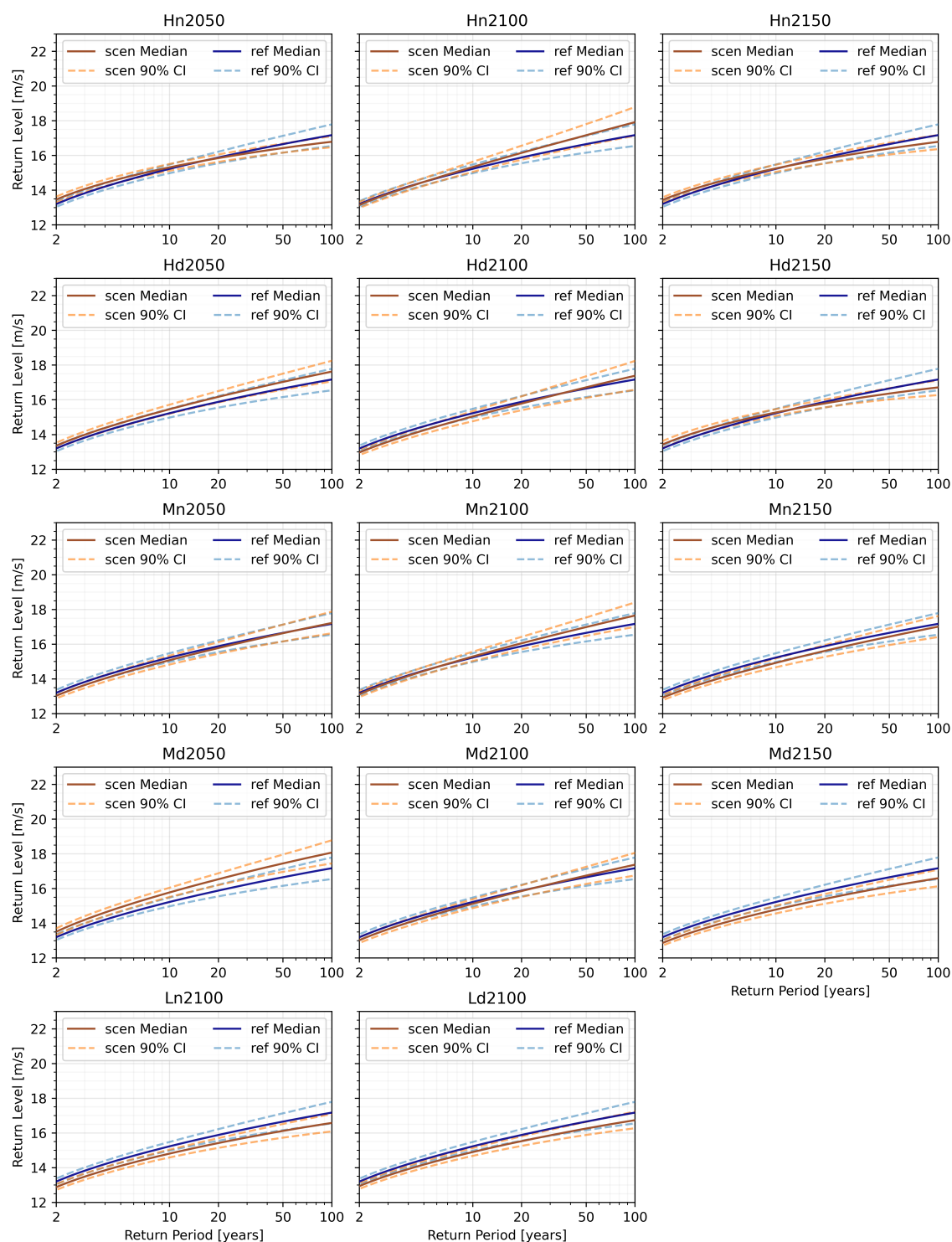


Figure F.1: Fitted GEV distribution of daily mean wind velocities for different climate scenarios together with the reference scenario in sea grid cell near Eelde. Median values and 90 % confidence interval are determined by bootstrapping

The figures below present PP and QQ plots of the fitted GEV-distribution for 24 hour mean wind velocity for Eelde.

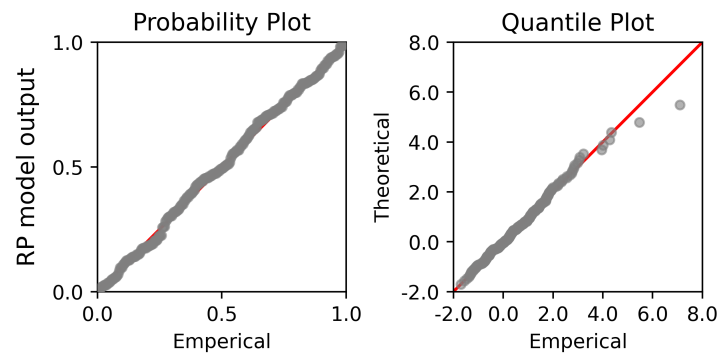


Figure F.2: PP and QQ plots for 24 hour mean wind velocity for reference period of model output for Eelde

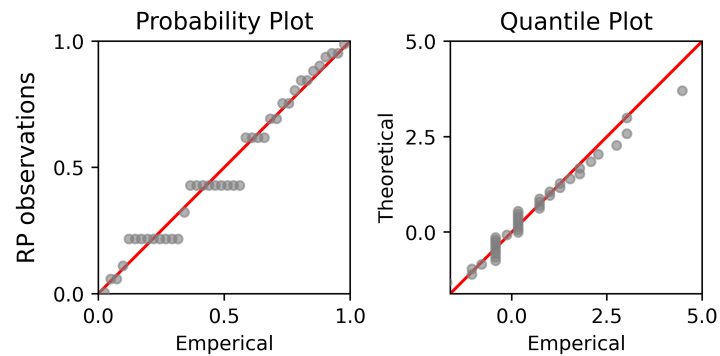


Figure F.3: PP and QQ plots for 24 hour mean wind velocity for reference period of observations for Eelde

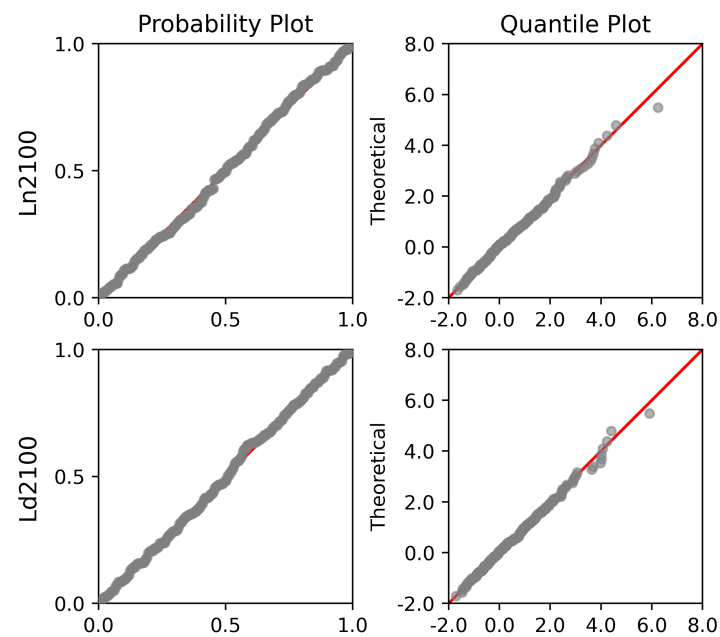


Figure F.4: PP and QQ plots for 24 hour mean wind velocity for low radiative forcing scenarios for Eelde

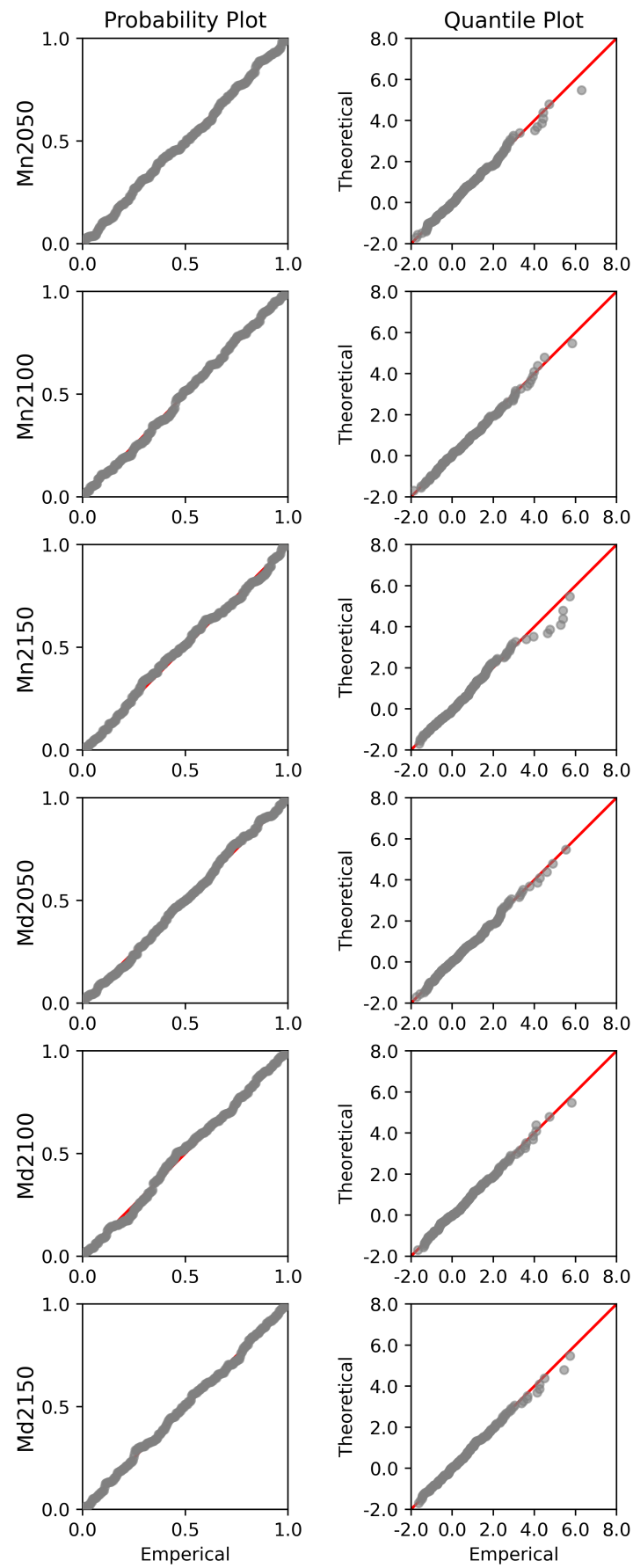


Figure F.5: PP and QQ plots for 24 hour mean wind velocity for moderate forcing scenarios for Eelde

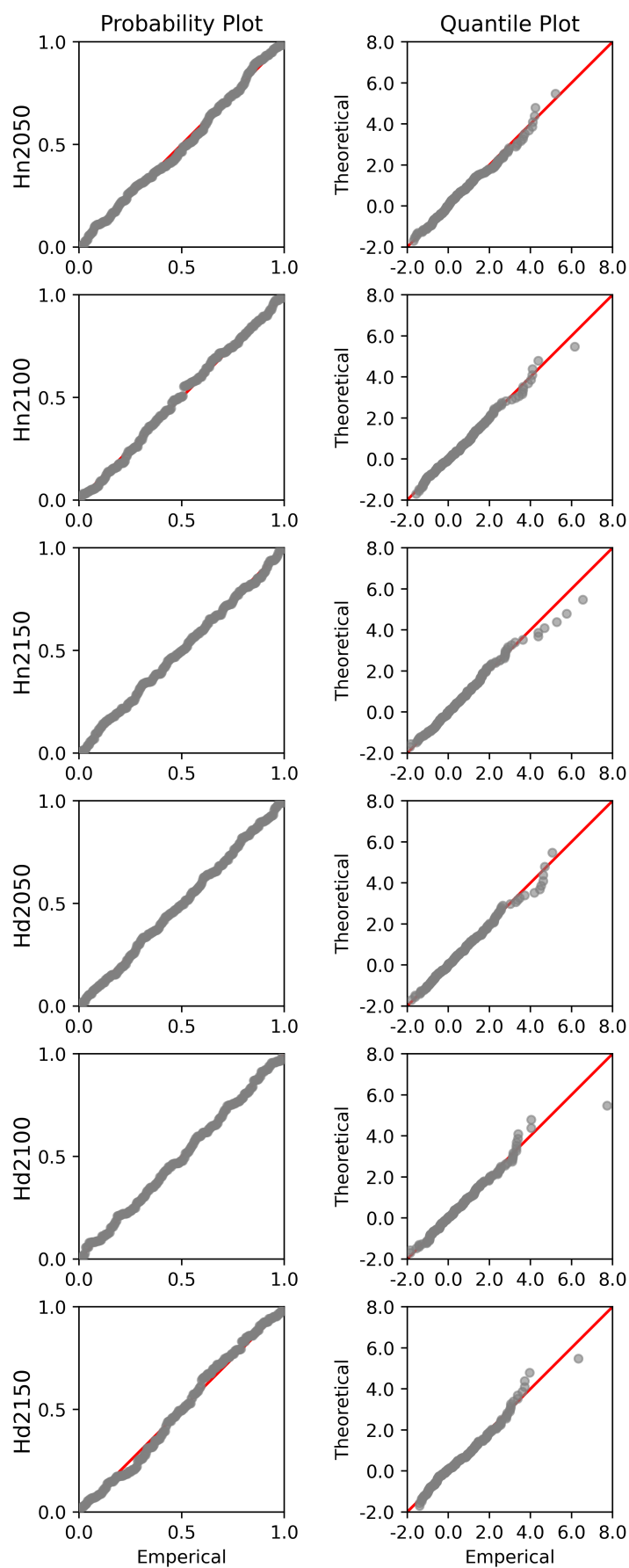


Figure F.6: PP and QQ plots for 24 hour mean wind velocity for high forcing scenarios for Eelde

F.2. De Kooy

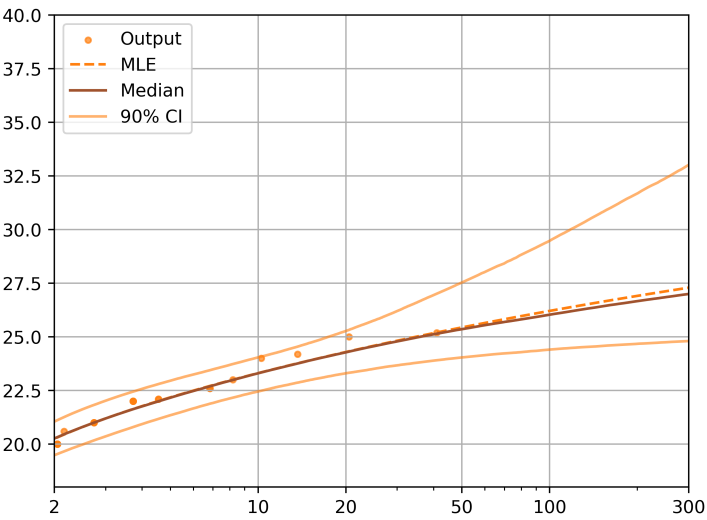


Figure F.7: Fitted GEV distributions for 10-minute mean wind velocities over 1986–2025 for De Kooy. Median values and 90% confidence interval are determined by bootstrapping

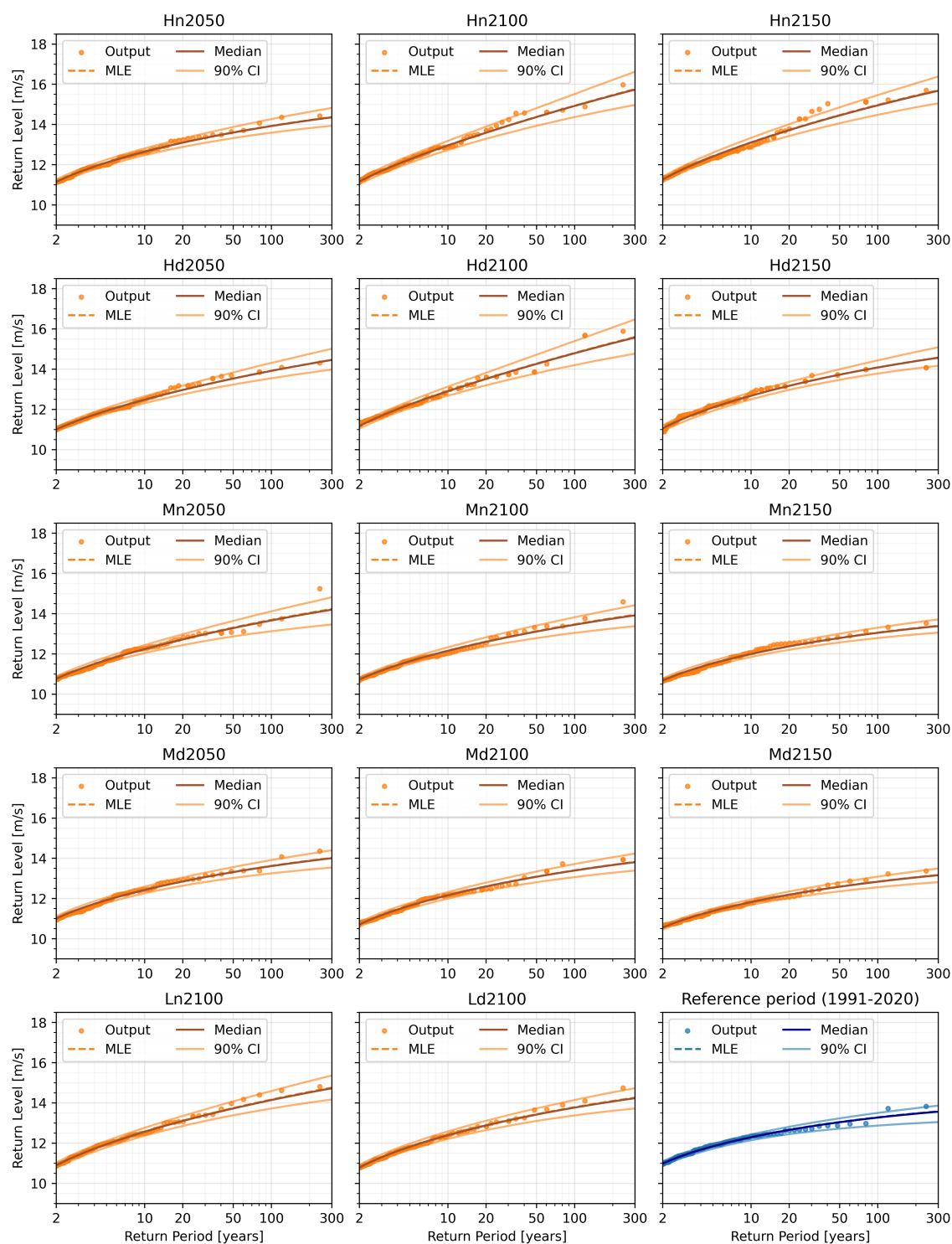


Figure F.8: Annual maxima values of daily mean wind velocities with fitted GEV distributions for different climate scenarios in sea grid cell near De Kooy. Median values and 90% confidence interval are determined by bootstrapping

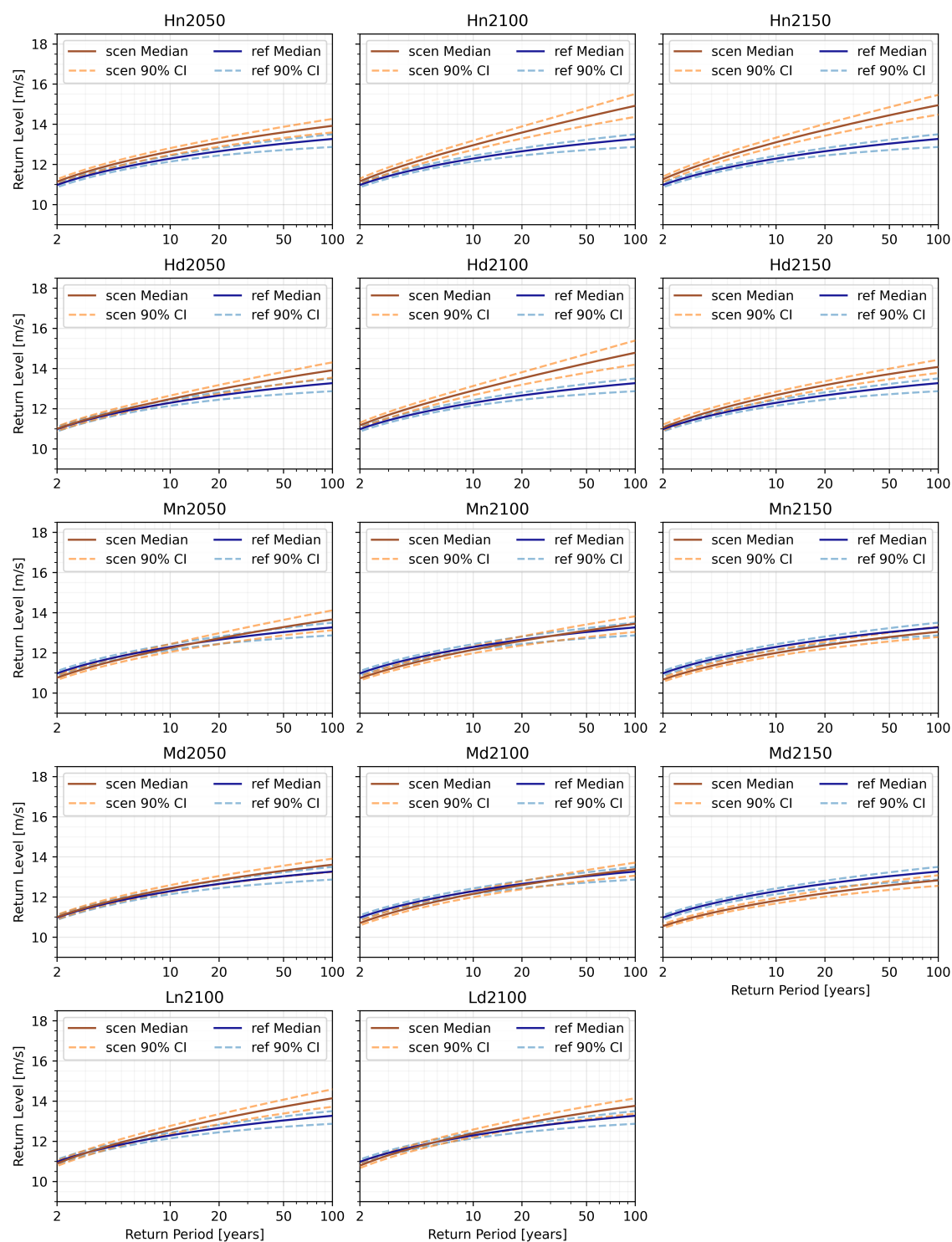


Figure F.9: Fitted GEV distribution of daily mean wind velocities for different climate scenarios together with the reference scenario in sea grid cell near De Kooy. Median values and 90% confidence interval are determined by bootstrapping

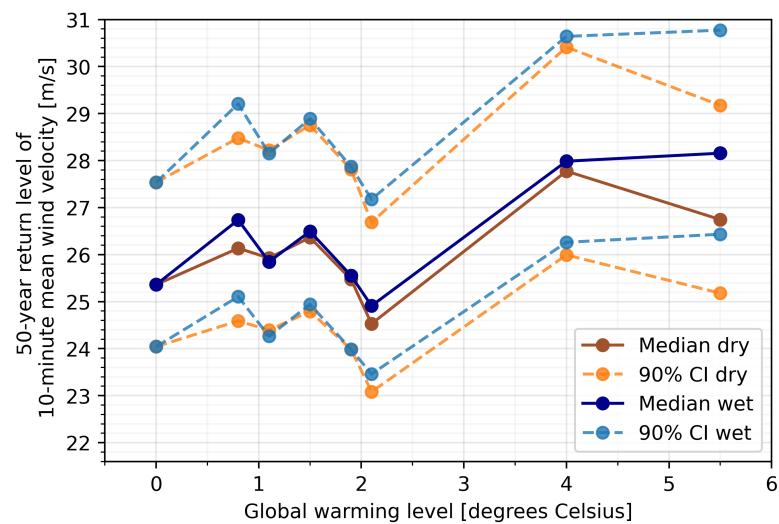


Figure F.10: Projected 50-year return level of 10-minute mean wind velocity for dry and wet variants for different global warming levels for De Kooy

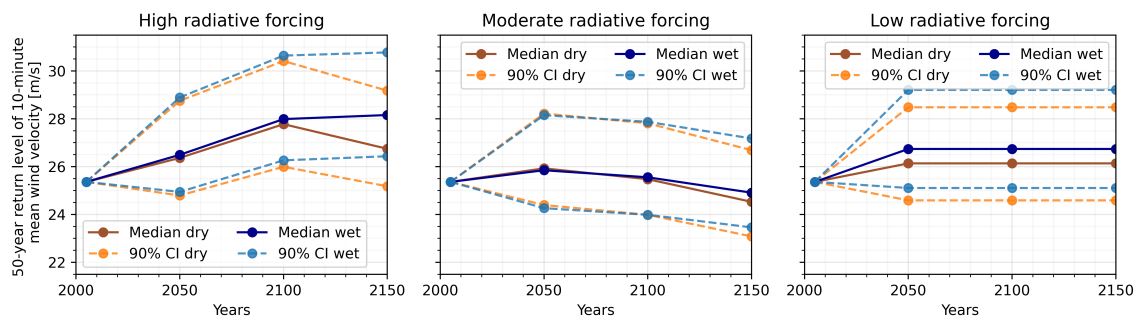


Figure F.11: Projected 50-year return level of 10-minute mean wind velocity for dry and wet variants for different radiative forcing scenarios for De Kooy

The figures below present PP and QQ plots of the fitted GEV-distribution for 24 hour mean wind velocity for De Kooy.

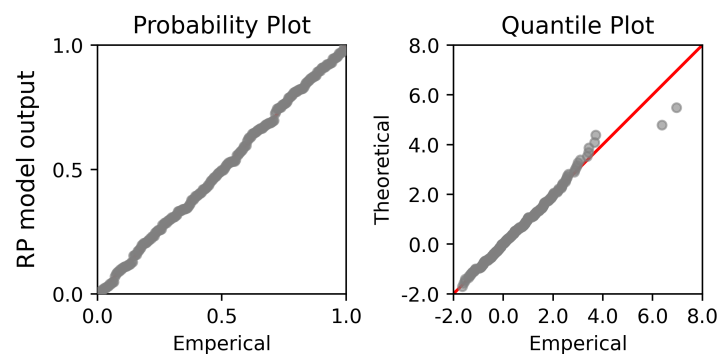


Figure F.12: PP and QQ plots for 24 hour mean wind velocity for reference period of model output for De Kooy

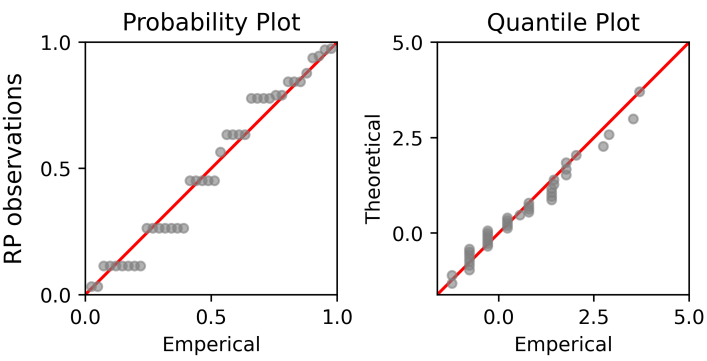


Figure F.13: PP and QQ plots for 24 hour mean wind velocity for reference period of observations for De Kooy

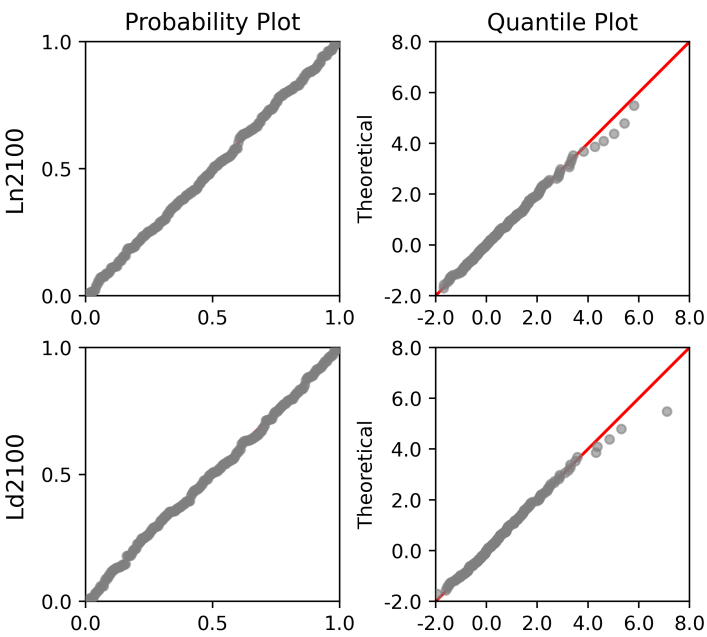


Figure F.14: PP and QQ plots for 24 hour mean wind velocity for low radiative forcing scenarios for De Kooy

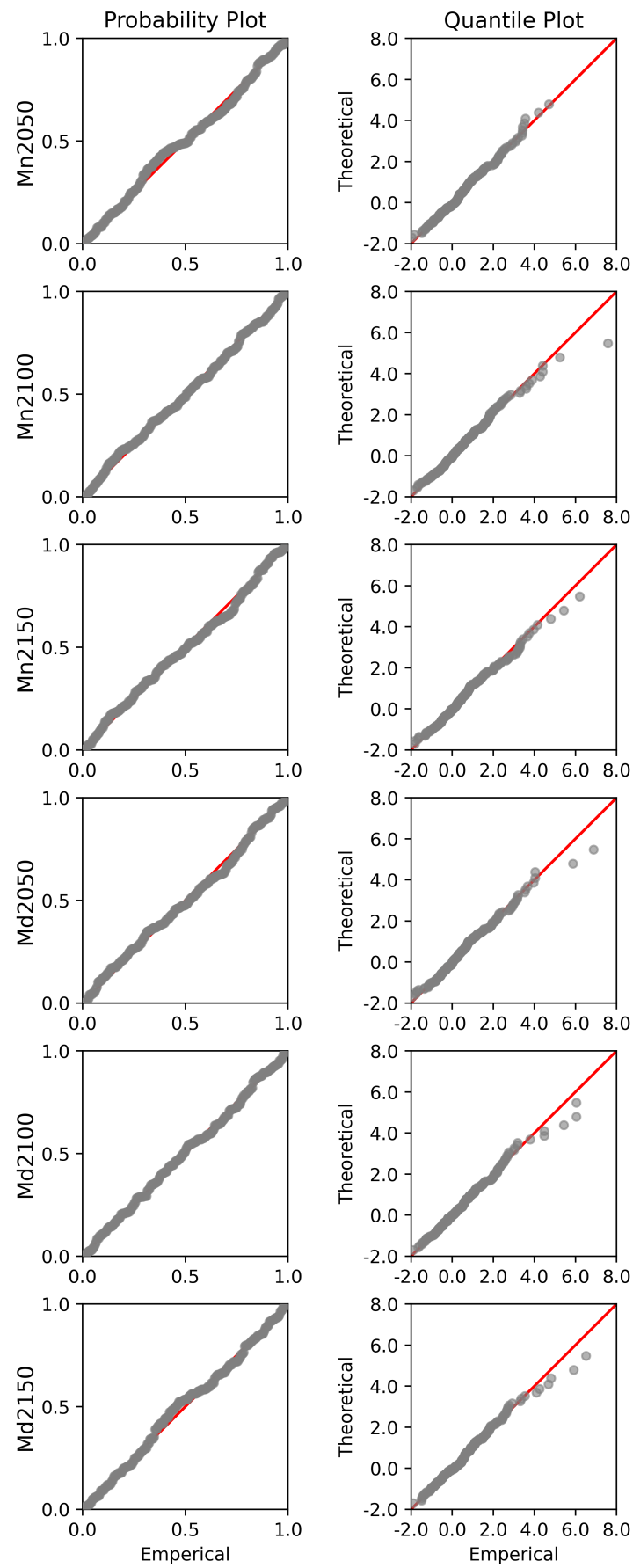


Figure F.15: PP and QQ plots for 24 hour mean wind velocity for moderate forcing scenarios for De Kooy

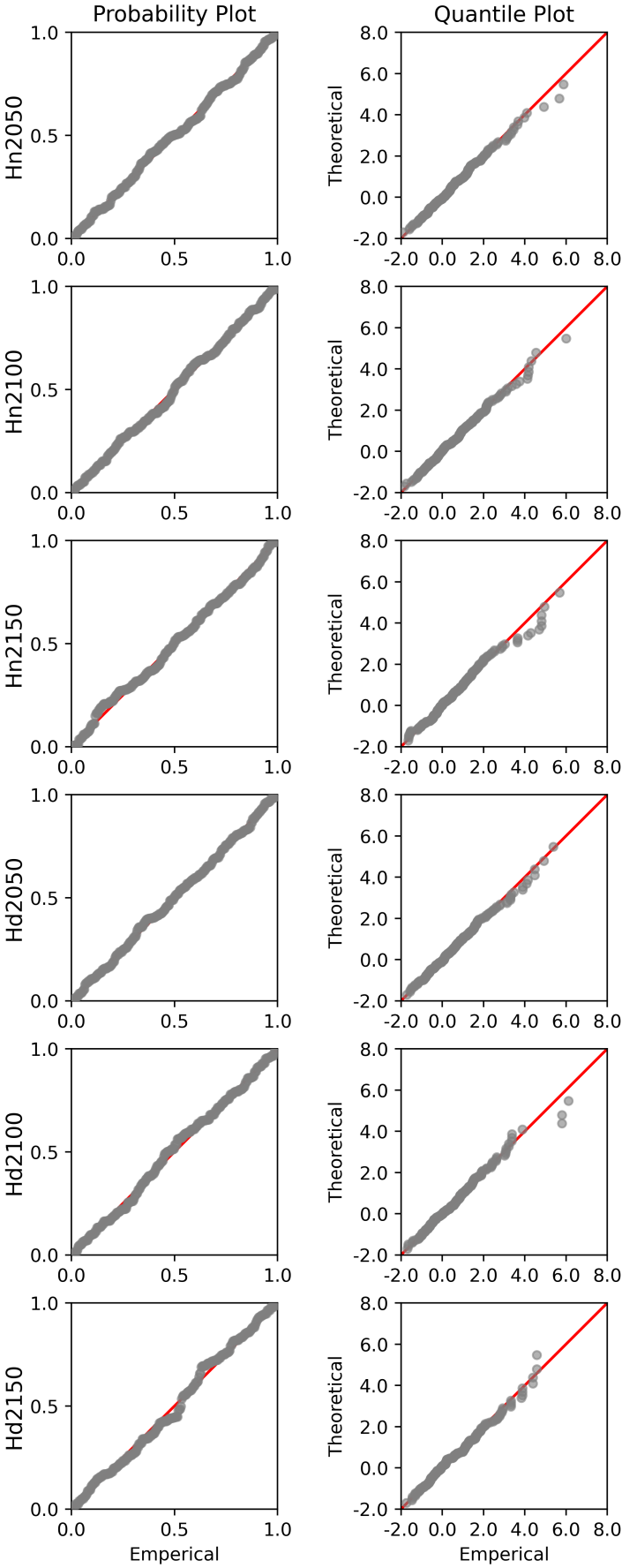


Figure F.16: PP and QQ plots for 24 hour mean wind velocity for high forcing scenarios for De Kooy