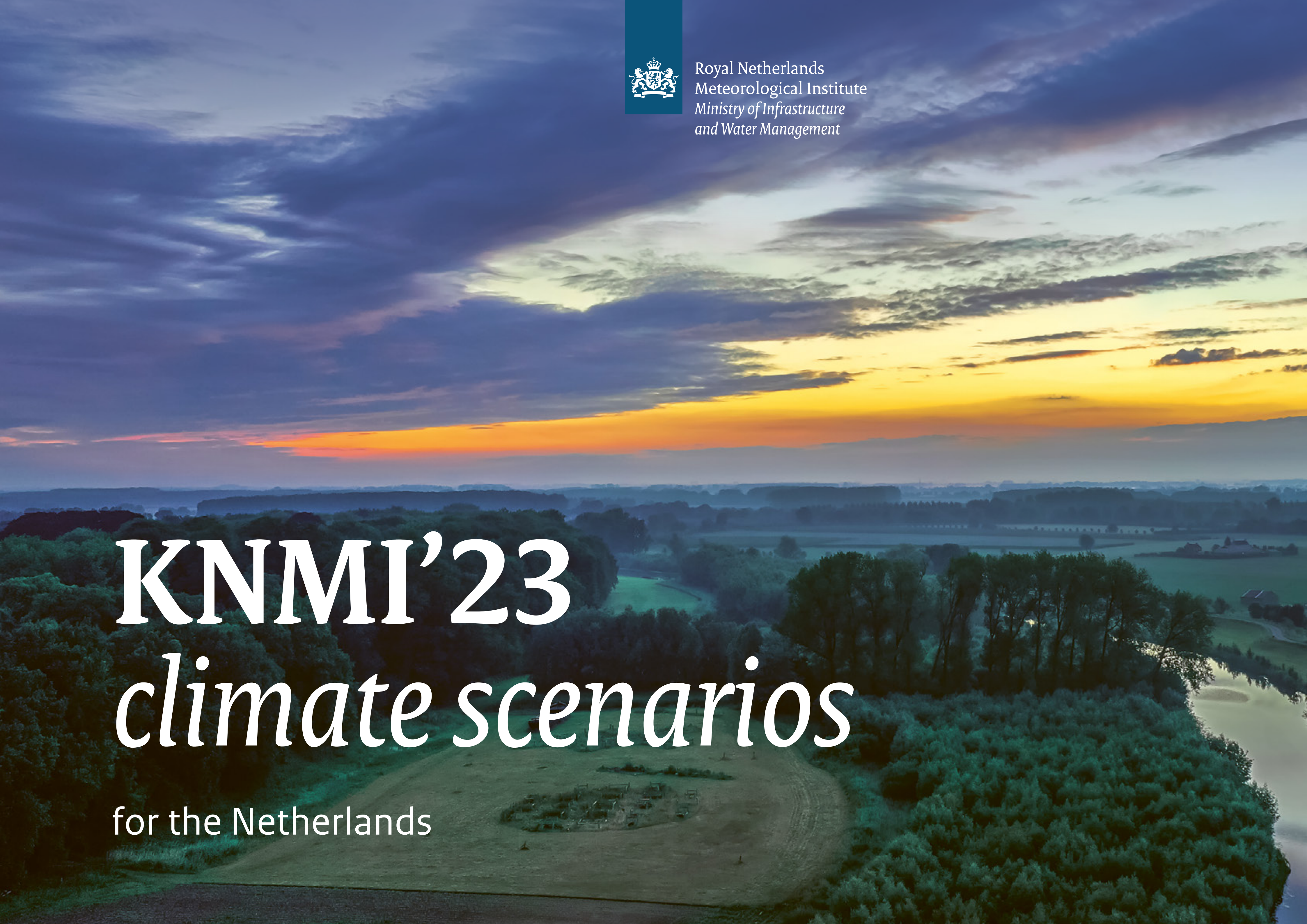
Royal Netherlands Meteorological Institute
Ministry of Infrastructure and Water Management

KNMI'23 *climate scenarios*

for the Netherlands



Chris Biesheuvel

About KNMI

The Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut - KNMI) is the national knowledge institute for weather, climate and seismology. We are one of the Dutch government's key knowledge partners for climate change. As a scientific institute, we conduct research into climate change in the Netherlands, and represent the Netherlands on the Intergovernmental Panel on Climate Change (IPCC).

KNMI advises the Dutch government on climate change and warns the Dutch society about dangerous weather conditions and the impacts of climate change. We continuously develop high-quality knowledge and deploy it to reduce safety risks and to contribute to a sustainable society. Our knowledge and our models form the basis for the latest national climate scenarios, which we use to translate global findings on the impacts of climate change to the Dutch situation.

With these new climate scenarios, KNMI offers a guideline for policy advisers and other professionals so they can make adequate decisions to ensure a safe, liveable and prosperous Netherlands in a changing climate.

Key figures in KNMI’23

Season	Variable	Indicator	Climate in 1991-2020 = reference period	**2050** (2036-2065)				**2100** (2086-2115)			
				Ld	Ln	Hd	Hn	Ld	Ln	Hd	Hn
	Global temperature rise compared to 1991-2020			+0.8°C	+0.8°C	+1.5°C	+1.5°C	+0.8°C	+0.8°C	+4.0°C	+4.0°C
	Global temperature rise compared to 1850-1900			+1.7°C	+1.7°C	+2.4°C	+2.4°C	+1.7°C	+1.7°C	+4.9°C	+4.9°C
Year	Sea level along the Dutch coastline	average level	0 cm [1]	+24 (16-34) cm	+24 (16-34) cm	+27 (19-38) cm	+27 (19-38) cm	+44 (26-73) cm	+44 (26-73) cm	+82 (59-124) cm	+82 (59-124) cm
		rate of change	3 mm/year [1]	+3 (1-6) mm/year	+3 (1-6) mm/year	+5 (4-8) mm/year	+5 (4-8) mm/year	-1 (-4-4) mm/year	-1 (-4-4) mm/year	+11 (6-23) mm/year	+11 (6-23) mm/year
	Temperature	average	10.5°C	+0.9°C	+0.9°C	+1.6°C	+1.5°C	+0.9°C	+0.9°C	+4.4°C	+4.1°C
	Precipitation	amount	851 mm	0%	+3%	-2%	+3%	0%	+3%	-3%	+8%
	Solar radiation	average	120 W/m²	+5.8 W/m²	+4.8 W/m²	+5.4 W/m²	+2.5 W/m²	+5.8 W/m²	+4.8 W/m²	+7.1 W/m²	+1.3 W/m²
	Humidity	average relative humidity [2]	82%	-1%	-1%	-1%	0%	-1%	-1%	-1%	+1%
	Evaporation	potential evaporation (Makkink)	603 mm	+7%	+6%	+9%	+6%	+7%	+6%	+17%	+11%
	Wind	average wind speed	4.8 m/s	-0.1 m/s	-0.1 m/s	0.0 m/s	0.0 m/s	-0.1 m/s	-0.1 m/s	-0.1 m/s	-0.1 m/s
Winter	Temperature	average	3.9°C	+0.7°C	+0.7°C	+1.2°C	+1.3°C	+0.7°C	+0.7°C	+3.7°C	+3.9°C
		average daily maximum	6.3°C	+0.7°C	+0.7°C	+1.1°C	+1.2°C	+0.7°C	+0.7°C	+3.5°C	+3.6°C
		average daily minimum	1.4°C	+0.7°C	+0.7°C	+1.2°C	+1.4°C	+0.7°C	+0.7°C	+4.0°C	+4.2°C
	Precipitation	amount	218 mm	+4%	+5%	+4%	+7%	+4%	+5%	+14%	+24%
		number of wet days (0.1 mm)	57 days	0.0 days	0.0 days	0.0 days	+0.6 days	0.0 days	0.0 days	0.0 days	+1.1 days
		days with >= 10 mm	5.4 days	+0.4 days	+0.5 days	+0.5 days	+0.8 days	+0.4 days	+0.5 days	+1.6 days	+2.5 days
		10-day total precipitation exceeded once every 10 years	109 mm [3]	-2%	+2%	0%	+2%	-2%	+2%	+8%	+15%
	Solar radiation	average	34 W/m²	+1.2 W/m²	+1.5 W/m²	+0.8 W/m²	+0.4 W/m²	+1.2 W/m²	+1.5 W/m²	-0.7 W/m²	-1.5 W/m²
	Humidity	average relative humidity [2]	87%	0%	0%	+1%	+1%	0%	0%	+1%	+2%
	Wind	average wind speed	5.6 m/s	-0.1 m/s	-0.1 m/s	0.0 m/s	+0.1 m/s	-0.1 m/s	-0.1 m/s	+0.1 m/s	+0.2 m/s
		days with wind direction between north and west	13 days	+0.1 days	-0.8 days	0.0 days	+0.1 days	+0.1 days	-0.8 days	-1.7 days	-1.0 days

Table 1: KNMI’23 scenario table with country averages.

Season	Variable	Indicator	Climate in 1991-2020 = reference period	**2050** (2036-2065)				**2100** (2086-2115)			
				Ld	Ln	Hd	Hn	Ld	Ln	Hd	Hn
Spring	Temperature	average	9.6°C	+0.8°C	+0.7°C	+1.3°C	+1.1°C	+0.8°C	+0.7°C	+3.6°C	+3.3°C
		average daily maximum	13.7°C	+0.9°C	+0.8°C	+1.2°C	+1.0°C	+0.9°C	+0.8°C	+3.3°C	+2.9°C
		average daily minimum	5.5°C	+0.7°C	+0.7°C	+1.4°C	+1.3°C	+0.7°C	+0.7°C	+3.9°C	+3.7°C
	Precipitation	amount	153 mm	+1%	+3%	0%	+4%	+1%	+3%	+4%	+10%
	Solar radiation	average	161 W/m^2	+6.6 W/m^2	+5.2 W/m^2	+3.2 W/m^2	+0.8 W/m^2	+6.6 W/m^2	+5.2 W/m^2	-0.2 W/m^2	-4.8 W/m^2
	Humidity	average relative humidity [2]	78%	-1%	-1%	0%	0%	-1%	-1%	+1%	+2%
	Evaporation	potential evaporation (Makkink)	190 mm	+6%	+5%	+6%	+4%	+6%	+5%	+10%	+6%
	Drought	maximum precipitation deficit April and May	76 mm	+11%	+6%	+15%	+5%	+11%	+6%	+21%	+8%
	Wind	average wind speed	4.7 m/s	-0.1 m/s	-0.1 m/s	0.0 m/s	0.0 m/s	-0.1 m/s	-0.1 m/s	+0.1 m/s	0.0 m/s
Summer	Temperature	average	17.3°C	+1.2°C	+1.1°C	+2.1°C	+1.7°C	+1.2°C	+1.1°C	+5.1°C	+4.7°C
		average daily maximum	21.7°C	+1.4°C	+1.2°C	+2.2°C	+1.7°C	+1.4°C	+1.2°C	+5.4°C	+4.7°C
		average daily minimum	12.9°C	+1.0°C	+1.0°C	+1.9°C	+1.8°C	+1.0°C	+1.0°C	+5.0°C	+4.9°C
	Precipitation	amount	235 mm	-8%	-2%	-13%	-5%	-8%	-2%	-29%	-12%
		1-day total precipitation exceeded once every 10 years [4]	63 mm [3]	+4 (1-6)%	+5 (2-7)%	+6 (2-9)%	+9 (5-14)%	+4 (1-6)%	+5 (2-7)%	+15 (5-26)%	+26 (12-41)%
		hourly precipitation exceeded once per year [4]	16 mm [3]	+4 (2-6)%	+6 (3-8)%	+6 (2-9)%	+11 (6-16)%	+4 (2-6)%	+6 (3-8)%	+15 (5-26)%	+31 (17-46)%
	Solar radiation	average	206 W/m^2	+12 W/m^2	+9.1 W/m^2	+14 W/m^2	+7.4 W/m^2	+12 W/m^2	+9.1 W/m^2	+24 W/m^2	+11 W/m^2
	Humidity	average relative humidity [2]	77%	-2%	-1%	-2%	-1%	-2%	-1%	-4%	-1%
	Evaporation	potential evaporation (Makkink)	286 mm	+8%	+6%	+11%	+7%	+8%	+6%	+22%	+14%
	Drought	maximum precipitation deficit for April-September	160 mm	+22%	+13%	+35%	+15%	+22%	+13%	+79%	+37%
		maximum precipitation deficit for April-September exceeded once every 10 years	265 mm	+16%	+9%	+30%	+16%	+16%	+9%	+63%	+30%
	Wind	average wind speed	4.2 m/s	-0.1 m/s	-0.1 m/s	-0.1 m/s	-0.1 m/s	-0.1 m/s	-0.1 m/s	-0.2 m/s	-0.2 m/s
Autumn	Temperature	average	11.2°C	+1.0°C	+0.9°C	+1.8°C	+1.6°C	+1.0°C	+0.9°C	+5.0°C	+4.8°C
		average daily maximum	14.5°C	+1.1°C	+1.1°C	+1.9°C	+1.6°C	+1.1°C	+1.1°C	+5.1°C	+4.6°C
		average daily minimum	7.8°C	+0.9°C	+0.9°C	+1.8°C	+1.7°C	+0.9°C	+0.9°C	+5.1°C	+5.1°C
	Precipitation	amount	245 mm	+4%	+5%	+1%	+4%	+4%	+5%	+1%	+13%
	Solar radiation	average	77 W/m^2	+3.7 W/m^2	+3.5 W/m^2	+3.7 W/m^2	+1.4 W/m^2	+3.7 W/m^2	+3.5 W/m^2	+5.4 W/m^2	+1.0 W/m^2
	Humidity	average relative humidity [2]	85%	-1%	0%	-1%	0%	-1%	0%	-1%	0%
	Wind	average wind speed	4.7 m/s	-0.1 m/s	-0.1 m/s	-0.1 m/s	0.0 m/s	-0.1 m/s	-0.1 m/s	-0.2 m/s	-0.1 m/s

↵ Key figures in KNMI'23

Explanation of table 1

The figures for climate change are rounded to 0.1°C for temperature, to 0.1 for all other variables below ten (mm, days, %, m/s, W/m^2) and to whole numbers for all figures above ten. Ranges are rounded to whole numbers.

The national averages were calculated based on:

- Temperature, solar radiation, evaporation, humidity and wind averages of five weather stations: De Bilt, De Kooy, Eelde, Vlissingen and Maastricht
- Precipitation: averages were based on 13 precipitation stations (P13).
- Drought: the P13 stations + the evaporation measured at the closest KNMI weather stations.

See www.knmi.nl/klimaatscenarios for a comprehensive table with climate change figures based on the KNMI'23 climate scenarios. This website includes additional variables, seasons, time horizons (2150), locations, calculations for moderate emission scenarios, additional impact cases and possible corrections. The final page of this report displays key figures for the KNMI's five main weather stations (p. 65).

1 The reference period for sea-level change is 1995-2014. Sea level is measured relative to the average sea level for this period.

2 The relative humidity is given in percentage points (for example: the relative humidity in the reference period is 80%, so an increase of 1% leads to 81%).

3 The amount of precipitation in the reference period is the amount that occurs on average once a year at a location, as described in STOWA 2019-19, *Neerslagstatistiek en -reeksen voor het waterbeheer 2019* ('Precipitation statistics and time series for water management in 2019'). An updated version is planned for 2024. These data are rounded to whole numbers.

4 Based on an alternative methodology and models, and includes an uncertainty range due to fluctuations of small-scale processes during showers (see 'Summer showers, hailstorms and thunderstorms').

Instructions for using the scenario table

The climate change figures in the scenario table (Table 1) for 2100 give the changes in the variables for 2086-2115 compared to the average during the reference period (1991-2020). Both averages concern 30-year periods. Due to natural variability these values will fluctuate from year to year. The light grey band represents 90% of these year-to-year variations (see example below).

Every ten years KNMI calculates long-term averages of measurements for a large number of KNMI weather stations. The most recent long-term averages cover the 1991-2020 period. This is the reference period for 'today's climate'. The climate change figures were calculated relative to this period.

Example calculation

In order to find out how much the maximum precipitation deficit (a measure of drought) has changed in the Netherlands around the year 2100:

1) In the scenario table, find the variable under 'summer' and read the information in the light blue column: the current (1991-2020) average maximum precipitation deficit is 160 mm.

2) Now find the figures for 2100 in the last four columns: the average maximum precipitation deficit increases in all four scenarios for around 2100 compared to the current situation (1991-2020), but increases the most in the 'High emission, dry' (Hd) scenario (by +79%). The smallest increase occurs in the 'Low emission, wet' (Ln) scenario (+13%).

3) This gives the following range for the average maximum precipitation deficit in the four scenarios (averaged over 2086-2115): between 181 and 286 mm.

- Hd, 'High emission, dry' scenario: 160 x 1.79 = 286 mm
- Ln, 'Low emission, wet' scenario: 160 x 1.13 = 181 mm

4) Notice that drought conditions vary greatly from year to year. This can be seen in the observed maximum annual precipitation deficit (1906-2022) in Figure 1: the black dots fall both (well) above and (well) below the blue trend line.

The light grey band indicates where 90% of the annual values for maximum precipitation deficit fall, i.e., on average, 9 in 10 years fall within the band and 1 in 10 fall outside it. The extremely dry years of the past, such as 1976 (362 mm), 2018 (308 mm) and 2022 (318 mm), fall outside the band. Around 2100, the upper limit of the 90% range of the driest scenario, Hd, is 445 mm. The most extreme droughts in the Hd scenario could get considerably drier than that. Wet years will also continue to occur, as the lower limit of the 90% range indicates.

Maximum precipitation deficit for April-September

Increasing drought

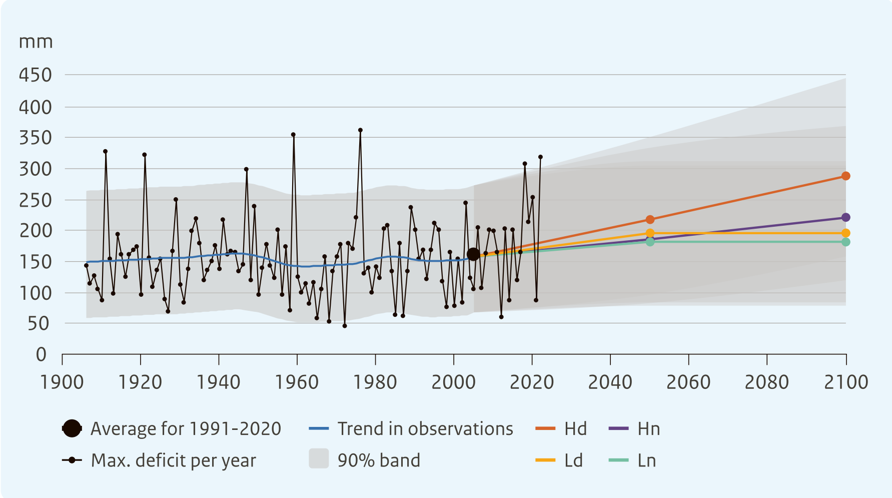


Figure 1: Maximum precipitation deficit for April-September in mm (national average): observations (black) and the four KNMI'23 climate scenarios (2050 and 2100, in four colours).

5) The conclusion is, that by around 2100 (2086-2115) the maximum precipitation deficit will have increased in all four scenarios compared to the current situation (1991-2020). There is a particularly sharp increase in the incidence of drought in the 'High emission, dry' (Hd) scenario.

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The KNMI'23 climate scenarios for the Netherlands: *summary*

KNMI has presented four new scenarios for climate change in the Netherlands (including the Caribbean Netherlands) around the years 2050 and 2100 (Figure 2). The KNMI'23 climate scenarios are based on the latest insights and replace the KNMI'14 climate scenarios. The data for sea-level rise are based on new insights from the IPCC concerning the potentially accelerated disintegration of the Antarctic ice sheet. In KNMI'23, the drought problem in the Netherlands and surrounding regions has been mapped out better, and the changes in precipitation extremes during summer showers have been better substantiated. There are also more accurate estimates of the global temperature rise caused by given increases in greenhouse gases. Just as with the KNMI'14 scenarios, the new climate scenarios can be used to evaluate the possible impacts of climate change on various sectors, and so supplement and update the risk assessments of the 'national adaptation strategy'. The Delta Programme's 'delta scenarios' will be based on the KNMI'23 climate scenarios in combination with PBL's socio-economic scenarios for the Netherlands (the 'WLO scenarios').
The climate scenarios for the Caribbean Netherlands serve as a starting point for adaptation policies for Bonaire, Sint Eustatius and Saba (the BES islands).

The extent to which our climate will change depends on the amount of greenhouse gases that will be emitted in the future and on the sensitivity of the climate system. Therefore we have adopted two scenarios:

- The first is a high emission scenario (denoted by a capital 'H') in which emissions will continue to increase at the same rate until 2080 and then level off. Around 2100, this will result in global warming of 4.9°C[1] (based on the best estimate for climate sensitivity).
- In the low emission scenario (denoted by a capital 'L'), emissions are rapidly reduced and greenhouse gases are removed from the atmosphere, in line with the Paris Agreement to limit global warming to well below 2°C. Around 2100, this will have resulted in global warming of 1.7°C.

We have decided to work with a wide range of emission scenarios to make the consequences of international climate policy choices as clear as possible, and to allow for a reliable risk assessment of the potential consequences of climate change for the Netherlands. The changes in the Dutch climate will likely take place within this bandwidth. We also conducted additional calculations to consider the effects of a scenario with moderate emissions on specific applications. These can be found at www.knmi.nl/klimaatscenarios.

In all scenarios, as the climate heats up, the Netherlands will experience drier summers and wetter winters. The climate models give different results for the extent of these changes. We selected two variants for each emission scenario to depict these different extents:

- a 'wet' scenario (denoted by a lower case 'n', from 'nat' in Dutch), in which the winters are much wetter and the summers slightly drier, and
- a 'dry' scenario (denoted by a lower case 'd'), in which the winters are slightly wetter and the summers much drier.

In the Caribbean Netherlands, temperatures will rise and precipitation will decrease. This decrease is the strongest in the dry scenarios for the dry season (December-April).

The KNMI'23 climate scenarios for the Netherlands in summary
Accelerated sea-level rise
Increase in average and extreme temperatures
More sunshine
More droughts
Wetter winters
More extreme summer showers
Potentially stronger wind gusts and downbursts during heavy showers
Little change in wind speed and direction

Table 2: How the climate will change this century in all scenarios compared to the reference period (1991-2020). The extent of change varies per scenario.

1 Global warming relative to the pre-industrial era (1850-1900). This figure will be 0.9°C lower if compared to the reference period (1991-2020) used for the KNMI'23 climate scenarios.

Four scenarios for climate change in the Netherlands

Figure 2: Four scenarios for climate change in the Netherlands. The number of small blocks represents the extent of climate change around 2100 compared to 1991-2020.

More extremes in the future climate of the Netherlands

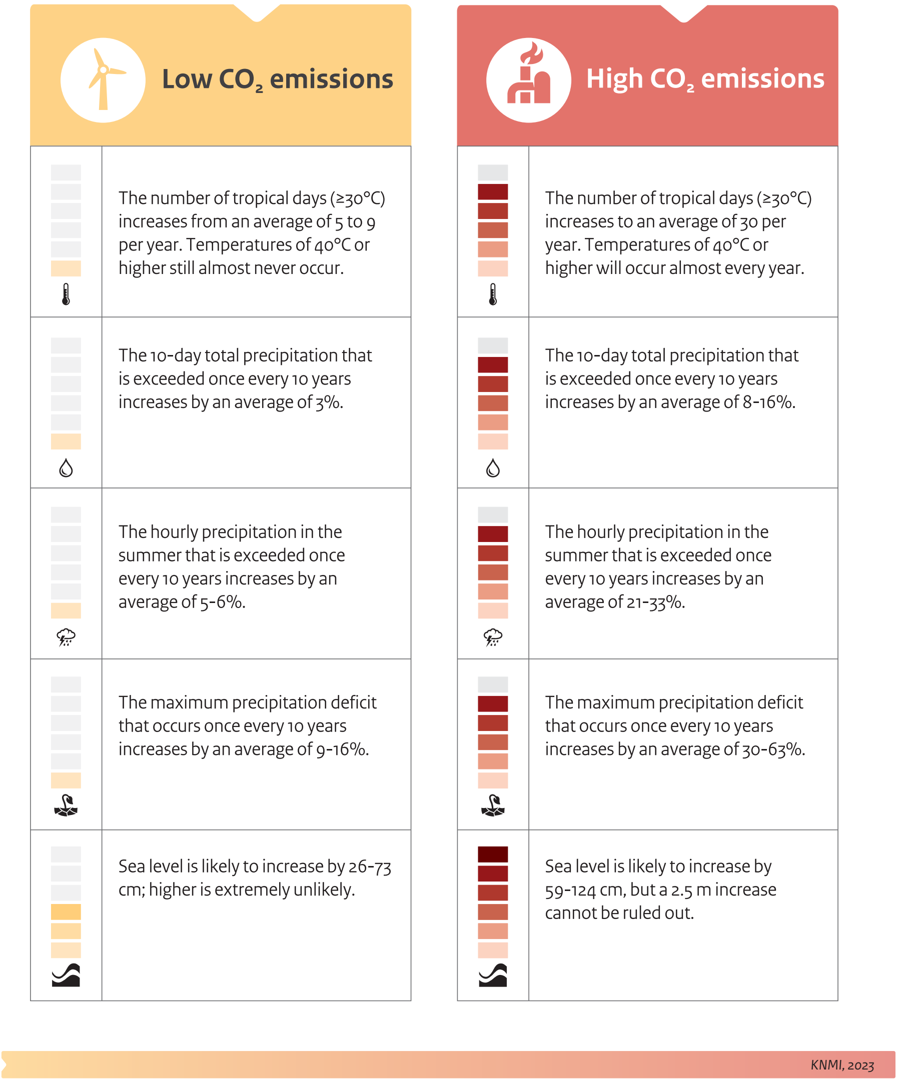

Figure 3: More extremes in the climate of the Netherlands around 2100 compared to 1991-2020.

Combining the two emission scenarios (H and L) with the two 'wet' (n) and 'dry' (d) variants results in the climate scenarios Hn, Hd, Ln and Ld. These are the new KNMI'23 climate scenarios, which replace the KNMI'14 climate scenarios (ref. 3). Climate change in the Netherlands is likely to occur within the boundaries of these climate scenarios and so they are suitable for assessing the effects of climate change on most applications.

The climate is already changing, and we are noticing this in the increase in extremes of heat, drought and precipitation. The science of 'climate attribution' has demonstrated that the frequency of extreme weather events has already increased as a result of human-induced climate change. The KNMI'23 climate scenarios reveal what else awaits the Netherlands if greenhouse gas emissions continue to increase at the current rate until 2080. They also reveal that the extent of climate change will be much less severe if the world would abide by the Paris Agreement (low emissions, see Figure 3). All four scenarios show that the Netherlands in any case faces sea level and temperature rises, drier summers and wetter winters (Table 2). The extent of the change varies per scenario. Climate scenarios enable users to consider the possible consequences of climate change and the resulting extreme weather conditions and make the necessary decisions to ensure the Netherlands remains a safe, sustainable and habitable country to live in.

Introduction

There is no question that humans are changing the climate. Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years. This was the conclusion reached by the IPCC's sixth climate report, which was published in August 2021 (ref. 1). The average global temperature in 2022 was 1.2°C higher than in the pre-industrial era (1850-1900). With further warming of the climate, the frequency and intensity of heatwaves, extreme precipitation and droughts will continue to increase globally. Some processes, such as warming oceans, melting ice caps and rising sea levels, will continue for centuries or even millennia.

Climate change is already evident in the Netherlands

The Netherlands has already become over 2°C warmer since monitoring started in 1901. Precipitation has increased by over 20%. This precipitation occurs in the form of more extreme showers. The likelihood of extreme heatwaves has increased. In the Caribbean Netherlands, temperatures have been increasing by about 0.2°C per decade since the 1980s. Techniques that were developed relatively recently make it possible to calculate what the human contribution has been to these changes. These 'attribution' techniques involve combining observations and calculations of climate models with and without human influence. One such climate attribution study concluded that the July 2019 heatwave (ref. 2), which saw temperatures in the Netherlands rise above 40°C for the first time ever, would have been virtually impossible without human-induced climate change.

The KNMI'23 climate scenarios: future climate change in the Netherlands

The KNMI'23 climate scenarios translate the insights and research results from the most recent IPCC report (2021) to the situation in the Netherlands, including the Caribbean Netherlands. These scenarios were calculated using the latest climate models, which describe a range of possible changes in the climate of the Netherlands based on a given level of greenhouse gas emissions.

A selection was made from this range. Climate scenarios were subsequently selected (in consultation with stakeholders) that together represent a wide range of possible outcomes. Human-induced climate change in the Netherlands is likely to fall within this range. The scenarios were developed to provide a broad group of stakeholders with an idea of how the climate will change between now and the end of this century. New is an outlook for 2150 and a sketch of how warm it will become in the Netherlands if global warming is limited to 1.5°C, as agreed in Paris. This 1.5°C increase is likely to be reached around the year 2033.

Two reference periods: current situation and the pre-industrial era

The climate scenarios reveal how the Dutch climate might continue to change in the future. We calculated averages and extremes (temperature, precipitation, solar radiation and wind speed) for 30-year periods centred on specific years in the future (e.g. 2050 and 2100). We compared this future climate with the most recent reference period, 1991-2020. The average global temperature during this reference period was 0.9°C higher than in the pre-industrial era (1850-1900), the reference used by IPCC. The 1.5 to 2°C warming set down in the Paris Agreement is relative to the pre-industrial era and corresponds to 0.6 to 1.1°C warming relative to 1991-2020.

Natural variability and gradual trends

The climate varies naturally. These variations are caused by interactions between the atmosphere, the oceans, the land masses and the ice sheets. Examples of this so-called natural variability that affect the global average temperature and precipitation patterns are the irregular El Niño and La Niña events. Natural variability at the regional scale is often larger than that at the global scale and is strongly related to variations in wind direction. These in turn are linked to the widely varying distribution of high and low pressure areas. That some Dutch winters are colder than others is connected to natural variability.

The longer the period that is averaged, the smaller the natural variability around this average will be (Figure 4). Even 30-year averages still reveal natural variability, but it is much smaller than the year-to-year variations. Precipitation and wind patterns in the winter show the largest natural variability. For this reason, we have provided the year-to-year variability. This gives an impression of how individual years may deviate from the average.

Natural temperature variability in De Bilt at various time scales

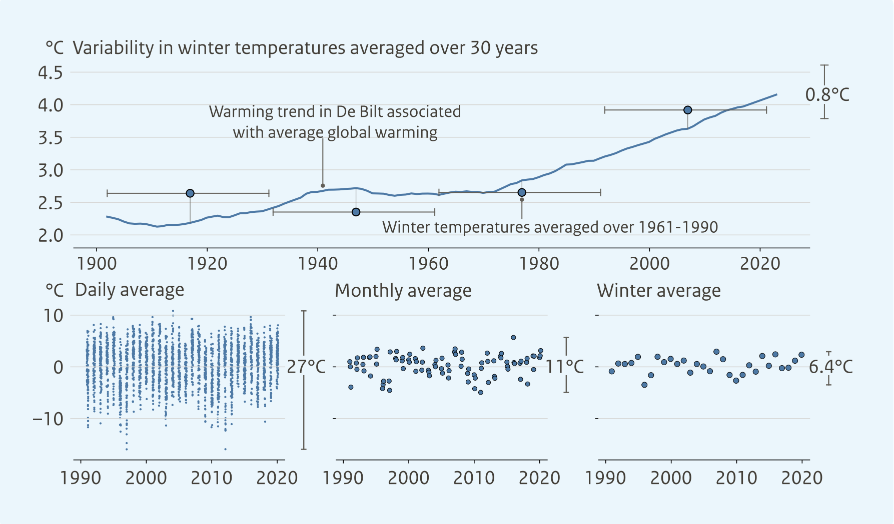

Figure 4: Natural variability in winter temperatures in De Bilt. Averaged over 30-year periods (top) and averaged per day, month and season (bottom). The variations were calculated relative to the warming trend (above, blue line).

Scenarios with low emissions (L) and high emissions (H)

The IPCC uses various scenarios. These are based on combinations of socio-economic developments and climate policies and known as Shared Socioeconomic Pathways (SSPs). These SSPs result in varying concentrations of greenhouse gases. There are scenarios in which the emissions remain to increase and scenarios in which these emissions are rapidly reduced, eventually to zero. Each scenario involves a specific timing and geographical distribution of greenhouse gas emissions. Climate models calculate how much the climate will change in each scenario based on the concentrations of greenhouse gases in the atmosphere. Higher concentrations of greenhouse gases result in higher temperatures and more precipitation worldwide.

In 2015, almost all the countries in the world signed the Paris Agreement to keep average global warming well below 2°C, and preferably at 1.5°C, compared to the pre-industrial era. Taken together, the pledges that countries made to reduce their greenhouse gas emissions are still insufficient to meet this target. Nevertheless, the low emission scenario (L) of the Paris Agreement is still achievable. This scenario is based on SSP1-2.6 and will result in about 1.7°C of global warming by around the years 2050 and 2100 (Figure 5). Because the warming in this scenario more or less stabilises after 2050, the scenario data for 2100 are the same as the data for 2050. The SSP scenario with the highest emissions (SSP5-8.5) was taken for the high emission scenario (H). This scenario will result in 2.4 and 4.9°C of global warming by 2050 and 2100 respectively (black dots in Figure 5). Figure 5 also gives the global warming for the five SSPs around the year 2100. The distribution in the coloured bands represents the uncertainty in climate sensitivity. If climate sensitivity turns out to be high, the most probable global warming of 4.9°C around 2100 in SSP5-8.5 could also be reached in a lower-emission scenario (SSP3-7.0).

Global temperature rise compared to 1850-1900

Black dots: temperature rise used in the KNMI'23 climate scenarios

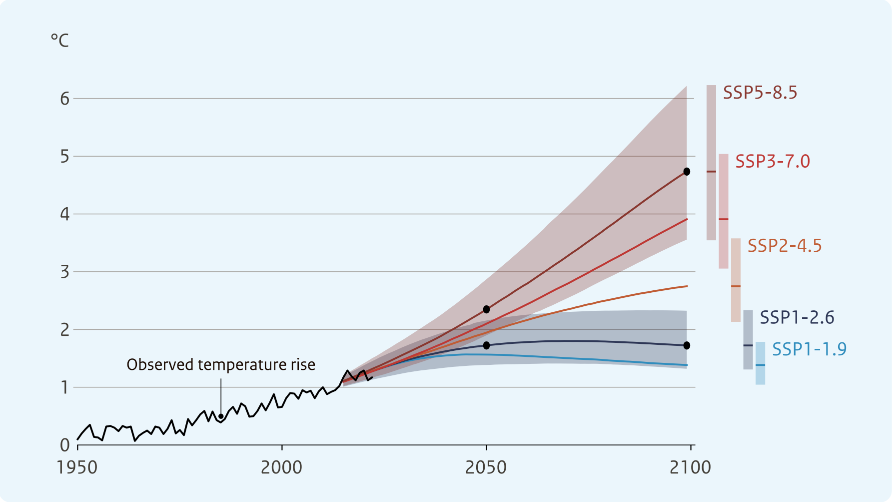

Figure 5: Global temperature rise as observed (black line) and projected per SSP (median (coloured lines) and 90% range). Vertical bars: global warming for five SSPs around the year 2100. Source: IPCC.

Scenarios with much wetter winters (n) or much drier summers (d)

Besides a global temperature rise based on the emission scenarios in the SSPs, climate models give different results for regional climate change for the same SSP. These regional differences are partly due to the unpredictability of areas of low and high pressure, which have a major impact on precipitation in particular (Figure 6). Partly in light of the recent severe droughts, it was decided to calculate two variants (d and n) for each emission scenario (L and H): one for very dry summers (Ld and Hd), and one for very wet winters (Ln and Hn). The dry variants show a decrease in annual precipitation, which makes it more difficult to recover from a dry summer in the following winter.

Averages and extremes

Besides sea-level rise and average changes in temperature, precipitation and other climate variables for the four seasons, a large number of other climate indicators were also included per climate scenario. These were precipitation and temperature extremes, solar radiation, evaporation, humidity, drought and wind. The averages and extremes in the reference period for the Netherlands are given in the table at the front of this report. Some of the variables revealed clear differences within the Netherlands (such as the number of 'summer days'). The calculated values of these variables for various weather stations are provided at the back of this report.

Air pressure and precipitation patterns over Europe

Dry summers in the south, wet winters in the north

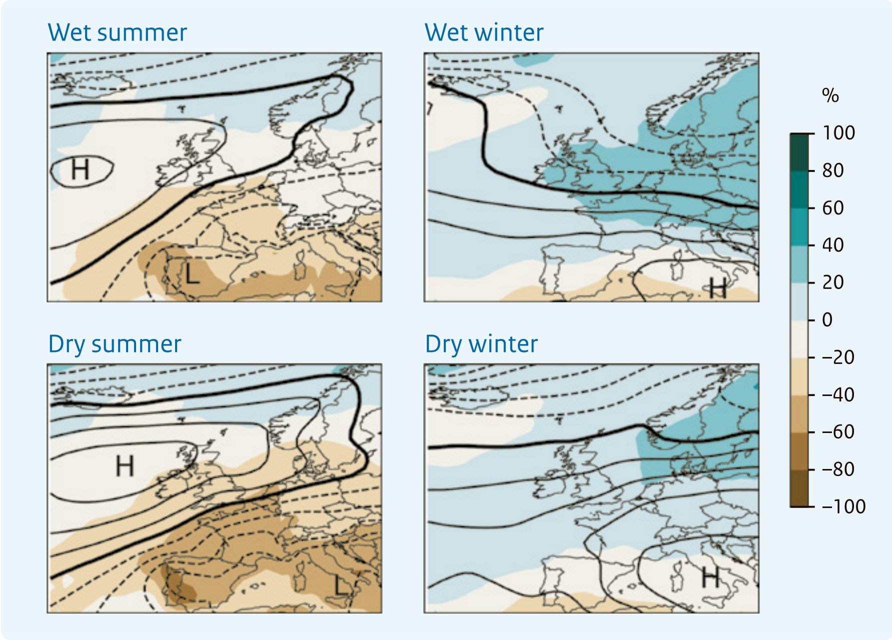

Figure 6: Air pressure and precipitation patterns over Europe for dry and wet global climate models with high emissions around the year 2100. Precipitation changes are shown as percentages.

Trend in observations and projections per variable

Temperature

Developments to date

The annual mean temperature in the Netherlands has increased by more than two degrees since monitoring started in 1906 (Figure 7). This is almost twice as much as the 1.2°C (in 2022) increase in global mean temperature since the pre-industrial period (1850-1900). In the winter, this is partly due to the wind blowing more often from the west. Increasing solar radiation due to decreasing cloud cover and decreasing air pollution leads to an extra warming in spring and summer. Half of the temperature rise in the Netherlands since the beginning of the last century took place in the last 30 years.

Developments in the future

According to all KNMI'23 climate scenarios the temperature in the Netherlands is rising (Figures 7 and 8). Around both 2050 and 2100, the effects of global warming will be felt most intensely in summer, and the least in winter and spring. The stronger warming in the summer will partly be caused by the drier soils. The wind will also blow more often from the east (Figure 6), bringing warm, dry air. These effects are strongest in the dry scenarios, hence the summer warming in the dry scenarios will also be stronger than in the wet scenarios. In most scenarios, the annual-mean warming in the Netherlands in 2050 and 2100 will be slightly larger than the average global warming.

There are large differences in warming between the high and low emission scenarios. This means that global climate policies aiming at reducing emissions can lead to a reduction of the warming.

> Global climate policies will have a strong influence on the future climate of the Netherlands

Regional temperature differences

The temperature rise in the Netherlands will be smaller in the north-west than in the south-west (Figure 9). In Western Europe, temperatures will rise more in summer than in winter.

Extreme temperatures

In the Netherlands the temperature rise is affecting the hottest summer days and the coldest winter days most. On the coldest winter days, the air usually flows in from northern Europe, where winter temperatures will rise the most. On the hottest summer days, the wind often blows in from the south, where summer temperatures will rise the most. For the winter, this will result in a significant decrease in the number of days with maximum temperatures below zero (ice days). In the H scenarios, the number of ice days in De Bilt decreases from 6 days in the current climate to 3 days around 2050, and to less than 1 day around 2100. In the L scenarios, around 4 ice days per year still occur around 2050 and around 2100.

The number of tropical nights (with a minimum temperature of 20°C or higher) will increase. In the H scenarios, the number of tropical nights in De Bilt will increase from 0.3 in the current climate, to 3 around 2050, and to 19 around 2100.
In the L scenarios, about 1 tropical night will occur per summer. The number of summer days (with a maximum temperature of 25°C or higher) will also increase. In the H scenarios, the number of summer days in De Bilt will increase from 28 in the current climate to 49 around 2050, and to 89 around 2100. In the L scenarios, 40 summer days will occur per year.

Annual mean temperature
The temperature continues to rise

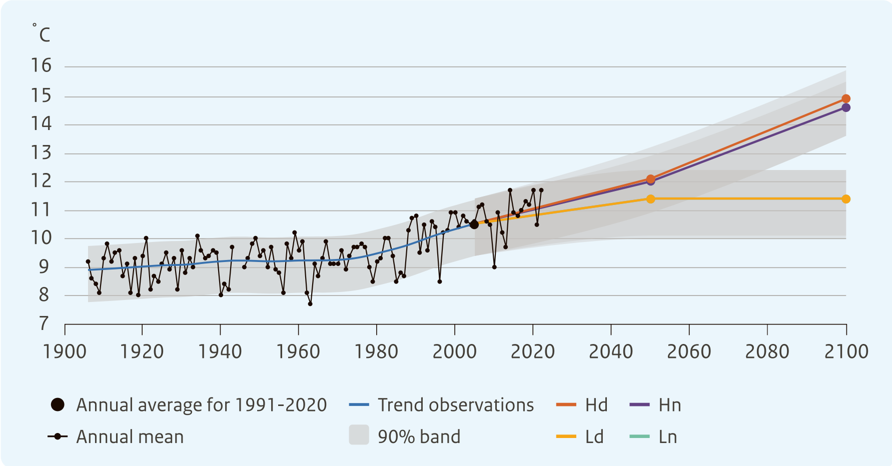

Figure 7: Annual mean temperature (national average): observations (black) and the four KNMI'23 climate scenarios (2050 and 2100, in three colours; Ln and Ld coincide).

Winter and summer temperatures

Warming is highest in the summer

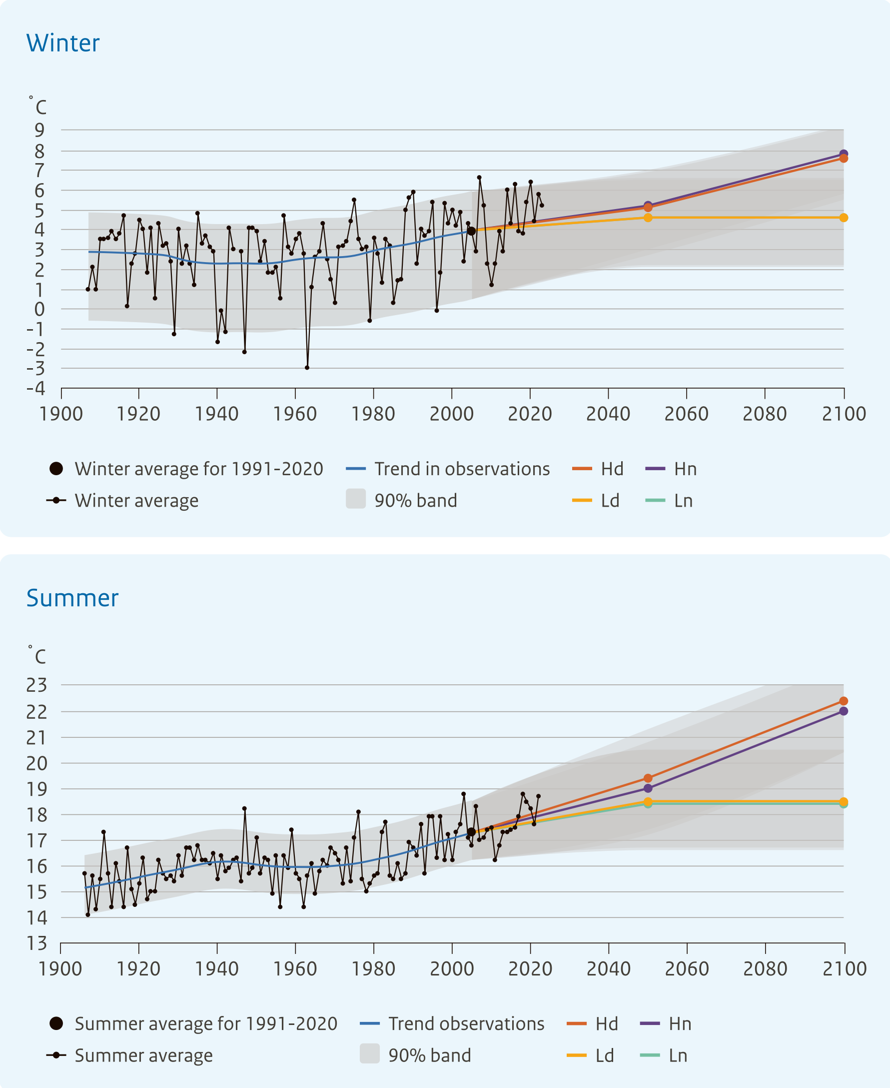

Figure 8: Winter and summer temperatures (national average): observations (black) and the four KNMI'23 climate scenarios (2050 and 2100, in four colours).

Temperature in Western Europe

Warming increases towards the south-east

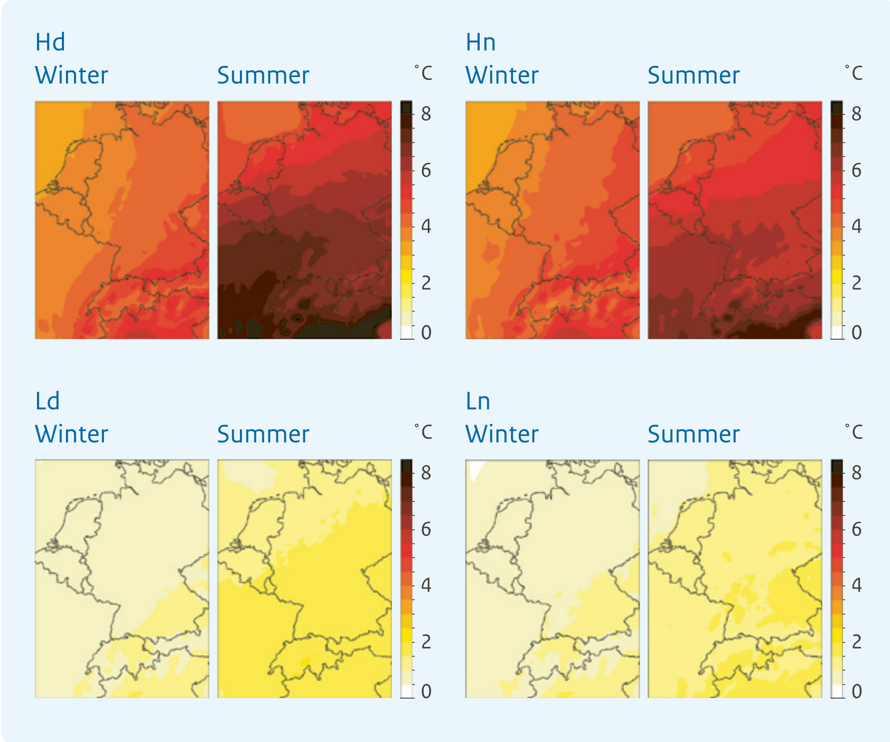

Figure 9: Temperature change in Western Europe in winter and summer around 2100 according to the four KNMI'23 climate scenarios.

Urban climate issues

The vast majority of Dutch people live and work in urban areas. Cities contribute significantly to the emissions that affect the climate. At the same time, climate change will have a stronger effect on the health and economy of cities. This is due to the 'urban heat island effect': urban areas are warmer than the countryside. Cities therefore urgently need to adapt to climate change.

Mounting effects

Dutch cities face mounting effects due to climate change. Global warming and more and longer periods of drought will lead to more extreme temperatures during heatwaves, resulting in more excess mortality. The nearby North Sea, which is also warming up, will contribute to more and heavier showers and flooding.

The urban heat island effect is largely caused by the way most cities develop, with lots of buildings and pavement and less space for greenery. As a result, more solar radiation reaching the ground during the day is absorbed, while there is less evaporation by plants. Human activities in urban areas also generate more heat than those in the countryside. As much of the heat is absorbed, the main impact of the urban heat island effect is that cities cool less after the sun sets. During extreme heat waves, this negatively affects people's sleep and health.

Cities also have an influence on the formation and distribution of precipitation. The air above cities is not only warmer, but also more polluted. Water droplets easily form around these fine dust particles. Furthermore, the buildings in urban areas slow down the wind. Big cities such as Amsterdam, The Hague and Rotterdam have relatively high precipitation as a result. Because many cities in the Netherlands lie close together, it is difficult to determine the precise extent of this effect on an individual city. The nearby North Sea also influences the wind and precipitation.

Climate-adaptive design

The temperature differences between the city and countryside will not further increase by global warming. The negative effects of global warming will first be felt in the cities because temperatures are already closer to the human thresholds due to the urban heat island effect. This leads to a stronger increase in the number of tropical nights in the city than in the countryside. Due to regional differences in summer temperatures, the highest values are reached in cities in the south-eastern Netherlands. Part of the urban heat island effect can be reduced by planting more greenery in cities. With more plants, the solar radiation causes more water to evaporate, instead of heating the air.

Early warning

Redesigning cities is not the only way to adapt to the increasing likelihood of extreme weather such as heatwaves; a system of timely and clear warnings will also help. Providing such early warnings makes it possible to take timely measures against an approaching heatwave. When hot weather is likely to form a health risk (based on a KNMI weather forecast), the National Institute for Public Health and the Environment (RIVM) activates the 'National Heat Plan'. This heat plan contains guidelines and advice for the general public and healthcare professionals such as GPs, nurses and other medical staff. The aim is to reduce the risk of heat-related health problems, especially for vulnerable groups such as elderly people, young children, the chronically ill, and people with limited mobility.

Future weather

The heatwave of July 2019 in a warmer climate

Heatwaves have a large impact on society. Intense heat during the day is often followed by tropical nights. Urban environments can be more than 5°C warmer than the surrounding countryside. Heatwaves already occur much more often. This increase will continue as the climate warms. As a result, summers like 2018 and 2019, which were considered 'extreme' in the current climate, will become normal. The impact of a heatwave is determined by its intensity, duration and spatial area. As the climate warms, all three factors will increase, while the number of relatively cool days (with temperatures below 25°C) will decrease. We used a regional climate model to show how the warmest heatwave ever recorded in the Netherlands would look like in a warmer climate. On 25 July 2019, a temperature of 40.7°C was recorded in Gilze-Rijen, breaking the national record by over 2°C. This was an extreme heatwave, even for the current warmer climate. Around 1900, such high temperatures were nearly impossible in the Netherlands (ref. 2). Today, the probability of such a heatwave occurring in the Netherlands is once every 50 to 100 years.

If the July 2019 heatwave were to occur in a global climate that was 2°C warmer than today (figures 10 and 11), the likely consequences would be:

- Temperature maxima reach values between 42.5 and 45°C in many places in the Netherlands.
- The 'heatwave index' (sum of degrees Celsius above 30°C) will double.
- The area of the country with temperatures above 40°C will significantly increase.
- Higher temperatures will lead to longer heatwaves, particularly in scenarios with severe droughts.

In a 4°C warmer climate, urban temperatures as high as 50°C could become possible. In that scenario, the summer of 2019 would have virtually been one continuous heatwave.

Code orange for heat

KNMI issues weather warnings for extreme weather. At least one of the following criteria must apply for a code orange to be declared for heat: a maximum temperature of 34°C or higher for 3 days in a row, a maximum temperature of 36°C or higher for 2 days in a row, or 1 day with a maximum temperature of 38°C or higher. This situation occurred once in De Bilt during the 1991-2020 reference period, from 24-26 July 2019. Around 2050, such events will occur in De Bilt in the Ln, Ld, Hn and Hd scenarios respectively 2, 4, 5 and 8 times every 30 years, and around 2100 respectively 2, 4, 25 and 66 times every 30 years.

Maximum temperature in the south-eastern Netherlands

Heatwaves are warmer and last longer

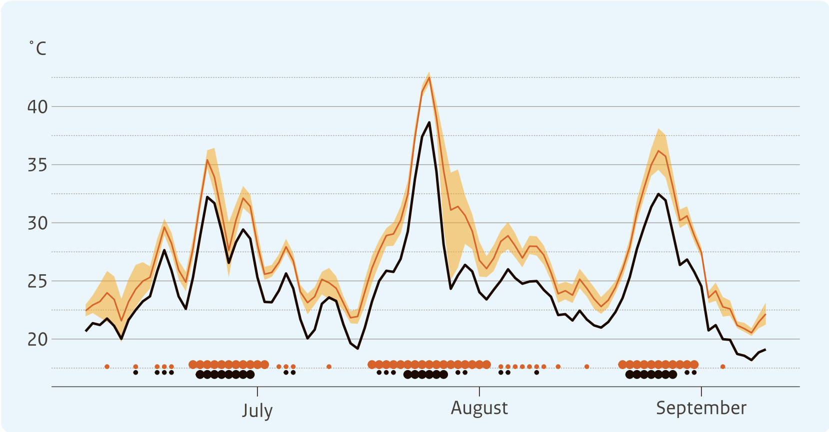

Figure 10: Three-day average maximum temperature in the south-eastern Netherlands in the summer of 2019 (black), and in case of 2°C of global warming (orange). The large dots represent days with heatwaves.

Extreme heat: today (2019) and in a warmer climate
Several days of temperatures well above 40°C in many places

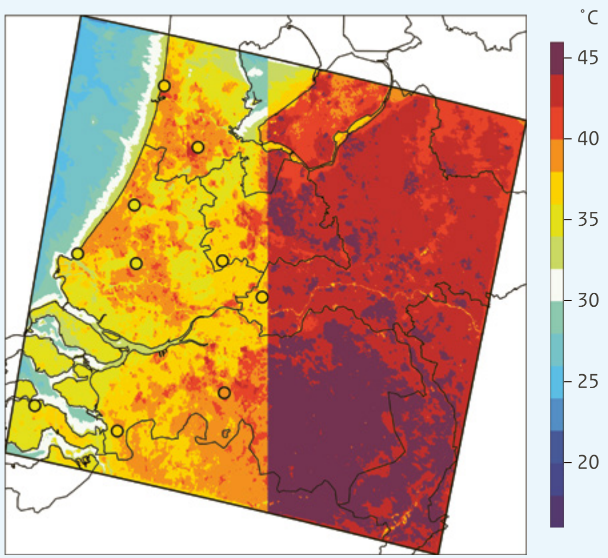

Figure 11: Average maximum temperature from 24-26 July 2019, based on observations (dots), regional climate simulations for the current climate (left half) and simulations for 2°C of global warming (right half).

Precipitation

Large-scale precipitation occurs when warm and cold air masses meet. The warm, light air rises above the cold, heavy air, cools and rains out. Small scale precipitation, such as a summer shower, follows the same pattern. However, the reason the air rises in the summer is different: the sun heats the air close to the ground.

The amount of water vapour in the air increases by about 7% per degree of warming, if there is enough water available to evaporate. This is not always the case in summer, when the soil is much drier than in winter. An increase in precipitation often follows an increase in the amount of moisture in the atmosphere. If the prevailing wind direction changes, and hence also the supply of dry or moist air, precipitation will either decrease or increase accordingly.

Winter precipitation increases in all climate scenarios

Developments to date

Annual precipitation in the Netherlands has increased by about 20% since 1906 (Figure 12, dark blue trend line). All seasons have grown wetter, but especially the winter. The annual precipitation increased particularly in the 1980s and 1990s. There are always large natural variations in precipitation.

Developments in the future

Winter precipitation will continue to increase in all four climate scenarios (Figure 13). In both L scenarios, precipitation around 2100 will be the same as that around 2050, because both scenarios project the same level of warming. In 2100, the increase in winter precipitation compared to 1991-2020 is smallest in the Ld scenario (+4%) and largest in the Hn scenario (+24%). In future winters, winds will blow from the west more often on average than today, especially in the Hn scenario, bringing in more humid air from the North Atlantic Ocean (Figure 6).

Summer precipitation has increased in recent decades. However, in all four climate scenarios precipitation will decrease, the most in the Hd scenario (-29%). Summer precipitation decreases as more dry, continental air is brought in from the east. There are two reasons why more easterly winds will occur: changes in sea water temperatures west of Ireland, and a strong warming in southern Europe.

Annual precipitation

Annual precipitation changes little

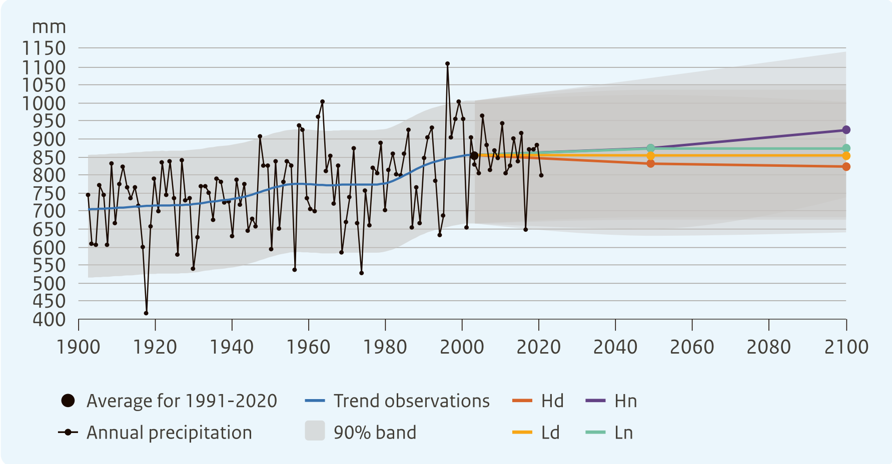

Figure 12: Annual precipitation (national average): observations (black) and the four KNMI’23 climate scenarios (2050 and 2100, in four colours).

Precipitation will increase in spring and autumn, but less than in winter. It increases most in the Hn scenario. So, winter, spring and autumn will be wetter, while summers will be drier, especially in the H scenarios. The change in annual precipitation ranges from -3% in the Hd scenario to +8% in the Hn scenario (for 2100).

In the H scenarios, winter precipitation will increase in most of Western Europe, while summer precipitation will decrease (Figure 14). Winter precipitation will increase by the same amount almost everywhere. The decrease in summer precipitation will vary more widely across the continent, with the largest decrease in the south and west.

Summer precipitation decreases in all climate scenarios

Winter and summer precipitation

More precipitation in winter, less in summer

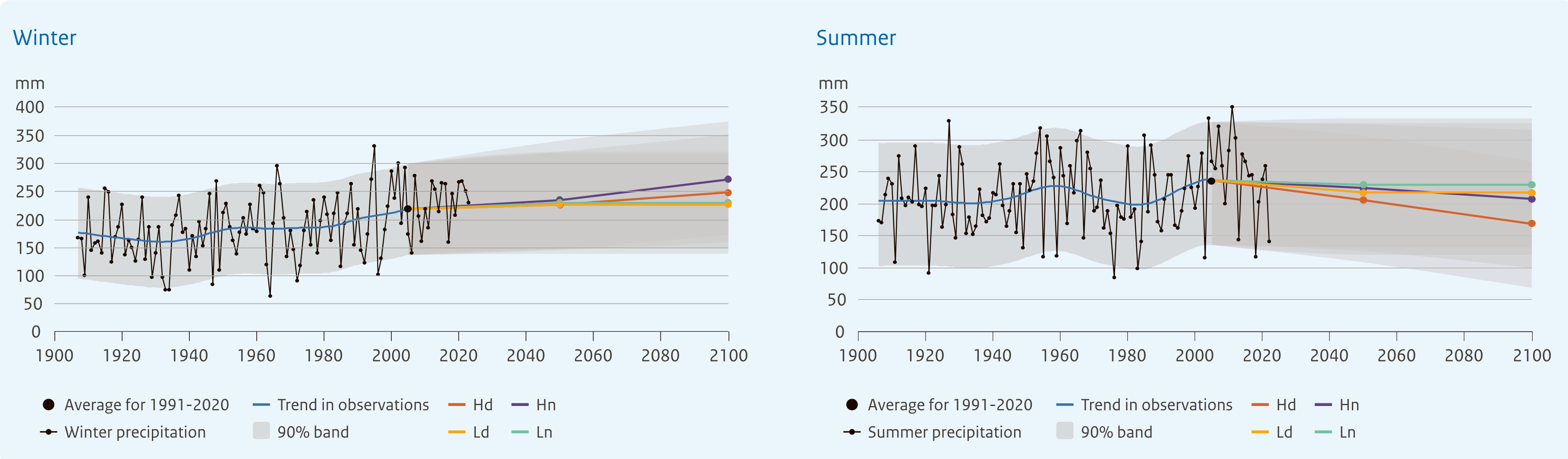

Figure 13: Precipitation in the Netherlands (national average) in winter (left) and summer (right): observations (black) and the four KNMI'23 climate scenarios (2050 and 2100, in four colours).

Change in precipitation in Western Europe

More precipitation in winter, less in summer

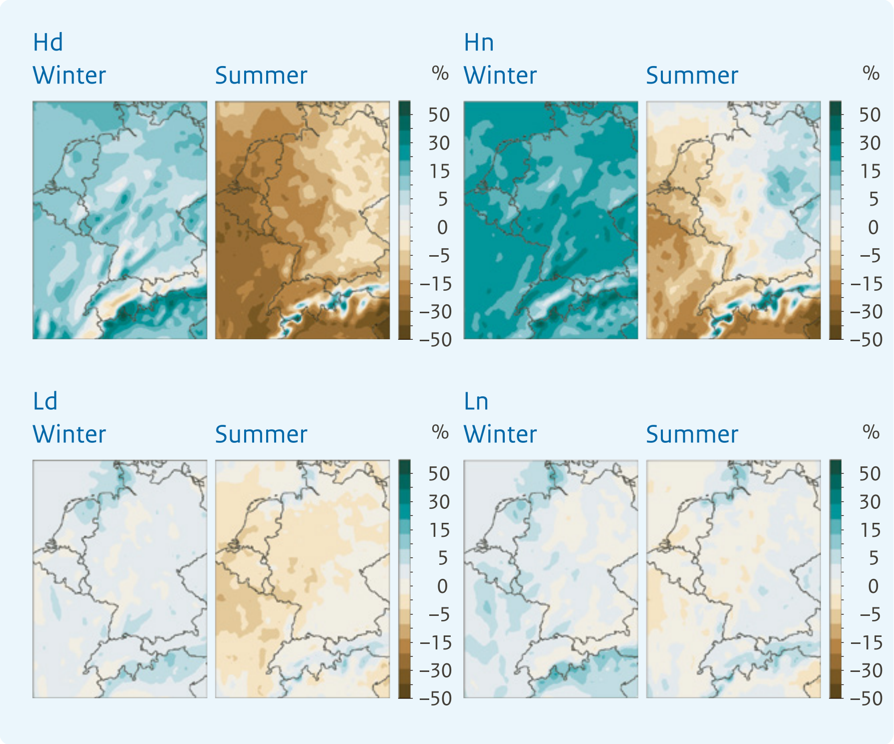

Figure 14: Changing precipitation in Western Europe in winter and summer around 2100 (according to the four KNMI'23 climate scenarios).

Summer showers, hail and thunderstorms

Showers occur when there is a large temperature difference between the Earth's surface and the air above (Figure 15). The atmosphere is then 'unstable'. After a hot summer day, when the lower layers of the air have warmed up considerably, this warm air will rise and cool. If there is enough water vapour in the rising air, some of it will condense into water droplets. A cloud consists of a vast quantity of such water droplets. In a cumulonimbus cloud, the top of the cloud is so high that it is made of ice particles instead of water droplets. Heavy showers are often accompanied by wind gusts, hail and thunderstorms.

Summer showers

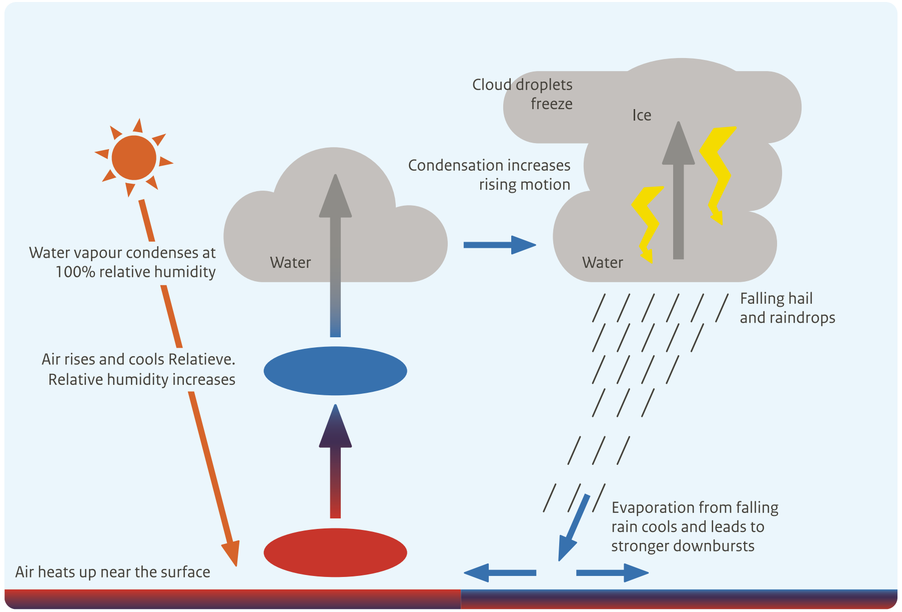

Figure 15: Formation and development of summer showers.

More or fewer showers in the future?
Several factors will determine whether the number of showers will increase if the climate of the Netherlands becomes warmer. Some of these factors will lead to more showers, others to less.

The atmosphere in warmer climates contains more water vapour. As a result, showers produce more precipitation. More water vapour in the atmosphere also means more condensation heat is released, so that the air rises faster and also rains out faster. On the other hand, climate models indicate that the air in the top layer of the atmosphere is warming faster than the air at the Earth's surface. The atmosphere will grow more stable, and this will slow down the rising air. The increasing condensation heat will have a larger effect, so that extreme showers will occur more frequently in the future.

> Extreme showers will occur more frequently in the future

If the relative humidity of the air is low, cloud droplets can only form at higher altitudes. So, in periods of low relative humidity (which will occur more often in summer due to climate change), showers are less likely to occur.

When the relative humidity is low, a relatively large proportion of the precipitation will evaporate before reaching the earth's surface. Evaporation cools the air, which becomes heavier and descends. This increases the likelihood of downbursts. The descending cold air disperses when it reaches the earth's surface, thus lifting the air that is already present there. This leads to new showers.

Extreme precipitation

Until recently, climate models provided too little detail to be able to simulate individual showers. A new generation of climate models can do this, and these models also provide a much better representation of observed extreme precipitation events. However, since these models have a very high resolution they require a lot of computing power, so the results are limited to the Netherlands and a small area around it. Moreover, relatively few scenarios have so far been calculated. The scenarios for changes in extreme precipitation (Figure 16) were therefore calculated by combining the results of these high-resolution models with the results of lower resolution models. This was done for two scenarios representing wetter and drier average climate conditions in the Netherlands. Each scenario has a range based on the distribution given in the high-resolution climate models. New in these scenarios (compared to the KNMI'14 climate scenarios) is that changes in rare, very extreme precipitation (with return periods of up to 1000 years) have also been calculated.

Extreme precipitation

More extreme precipitation per day and hour

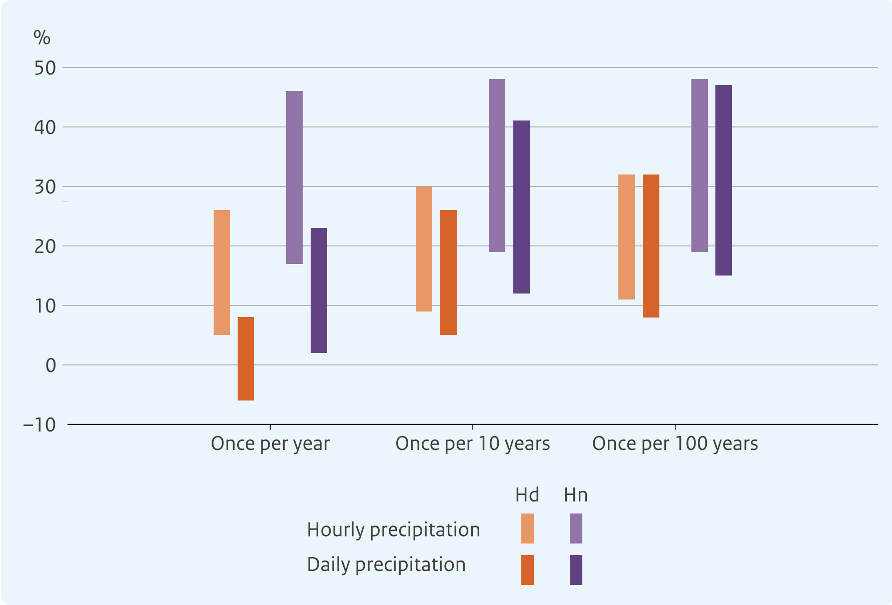

Figure 16: Range of percentage changes of extreme daily and hourly precipitation in summer (according to the high KNMI'23 climate scenarios for around 2100).

Largest hailstones likely to get even bigger

The number of light summer showers will decrease in the future. The number of heavy showers will increase. Hence, there will be a shift from lighter to heavier showers (with more precipitation per shower) and more intense showers (with more rain in a given period of time).

Hail, wind gusts and thunderstorms

There is very little information available on which to build scenarios for thunderstorms, hail and wind gusts in the future. Recent research has led to more uncertainty about how the intensity of these weather conditions will change. As there will be more water vapour in the atmosphere, the rising motion of the air will increase, so presumably the largest hailstones will get even bigger. As more precipitation evaporates, the wind gusts and downbursts that occur during showers may also become stronger. It is uncertain whether lightning will also occur more often in the Netherlands.

Drought and evaporation

Drought occurs when there is less precipitation than normal, when more water evaporates than normal, or both. This can lead to a water shortage, with associated problems for safety (weaker flood defences due to drier embankments), agriculture, inland shipping, residential areas, water quality and the environment. Prolonged or multi-year droughts in particular cause such effects, as in 2018, 2019, 2020 and 2022 (Figure 17, left).

In autumn and winter, precipitation exceeds evaporation. In summer, this is the other way round, causing a precipitation deficit. Precipitation and evaporation fluctuate widely from year to year, making it difficult to identify systematic trends. April and May in particular have been drier in recent decades, especially inland. This is partly due to higher temperatures (due to climate change) and partly due to more sunshine (due to a decrease in air pollution).

Extreme drought

In the Netherlands, the likelihood of drought and extreme drought will increase, particularly in the 'High emission scenario, dry' (Hd) (Figure 17, right). In this driest scenario, an average summer in the future will be about as dry as an extremely dry summer today.

> According to the warm, dry scenario, an average summer around 2100 will be about as dry as an extremely dry summer today

The Netherlands lies in an area of decreasing summer precipitation, while higher temperatures will increase evaporation. Precipitation and evaporation are affected by changes in air circulation. Westerly winds typically carry in moist air, leading to more precipitation. Easterly winds typically carry in dry air, leading to more evaporation, particularly in the summer. The precipitation deficit in the Netherlands is expected to increase sharply, especially in the south (Figure 18).

Precipitation deficit today and around 2100

Precipitation deficit increases

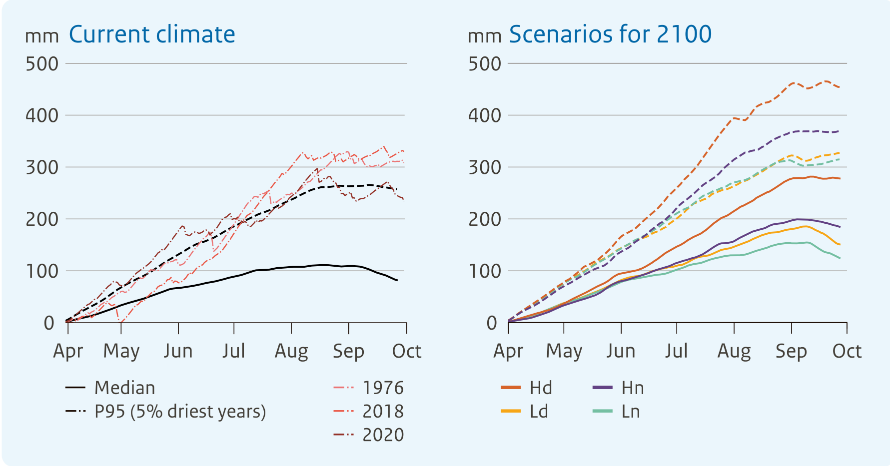

Figure 17: Precipitation deficit in De Bilt in the current climate (1991-2020, left) and around 2100 for the four KNMI'23 climate scenarios (right). Dotted lines give the 5% driest years.

Maximum precipitation deficit today and around 2100

Precipitation deficit increases

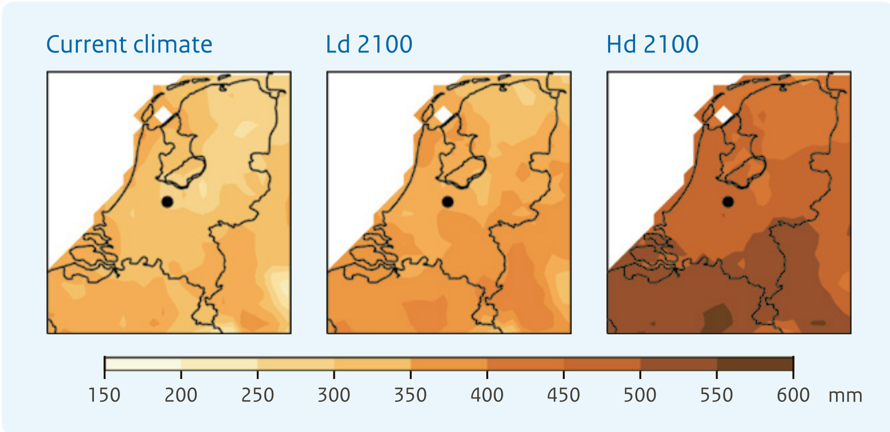

Figure 18: The maximum precipitation deficit in the 5% driest years in the current climate and in the two dry KNMI'23 climate scenarios for around 2100. Black dot: De Bilt (Figure 17).

Solar radiation and cloud cover

Clouds block solar radiation and thereby determine how much radiation reaches the earth. In general, the thicker the cloud, the more solar radiation it reflects. In the Netherlands, it is –on a yearly basis– sunnier near the coast than inland. This is because fewer clouds form above the relatively cool sea water in spring and summer.

Solar radiation is also reflected by aerosols: suspended particles in the atmosphere, such as air pollution, which in addition influence cloud formation. Aerosol loads have decreased as the air in Europe has become cleaner since the 1980s. During this same period, cloud cover also decreased and clouds became thinner. This has increased the amount of solar radiation by about 4 W/m^2 (4%) per decade (Figure 19), and so contributed to the warming of the Netherlands.

Annual mean solar radiation

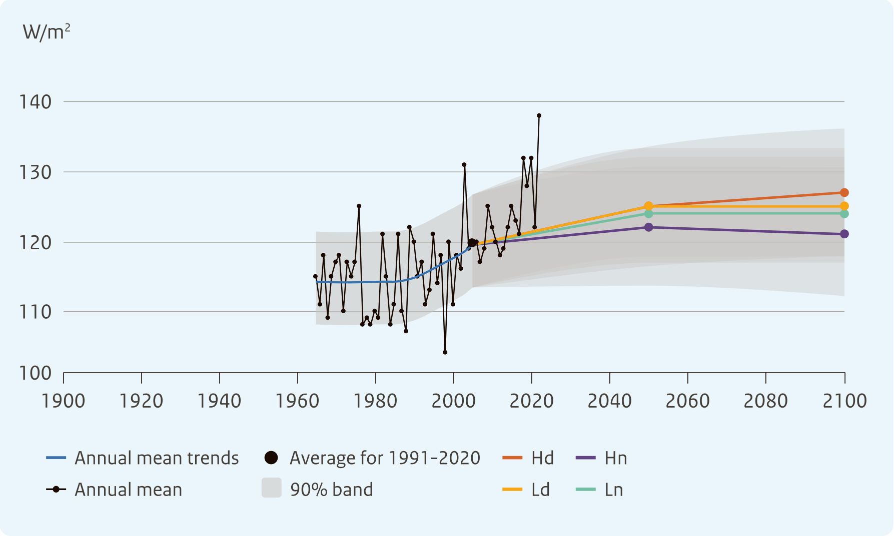

Figure 19: Annual mean solar radiation in the Netherlands since 1965 (national average): observations (black) and the four KNMI'23 climate scenarios (2050 and 2100, in four colours).

Solar radiation increases slightly

The air is expected to become slightly cleaner in the future, especially in the low emission scenario, in which aerosols continue to slowly decrease. As a result, average solar radiation will still increase slightly compared to the 1991-2020 period (Figure 19), although the natural year-to-year variations remain large (recent years in particular have been sunnier than average).

There is a clear difference between dry and wet in the high emission scenarios: solar radiation shows the largest increase in the dry scenario (Hd), particularly in the south of the country (Figure 20) and in the summer. This is due to more cloudless days, as a result of an increase in relatively dry easterly winds. In winter, solar radiation will in fact decrease, due to more westerly winds and an increase in cloud cover. Differences between summer and winter are smaller in the low scenarios.

Solar radiation

More sun in summer

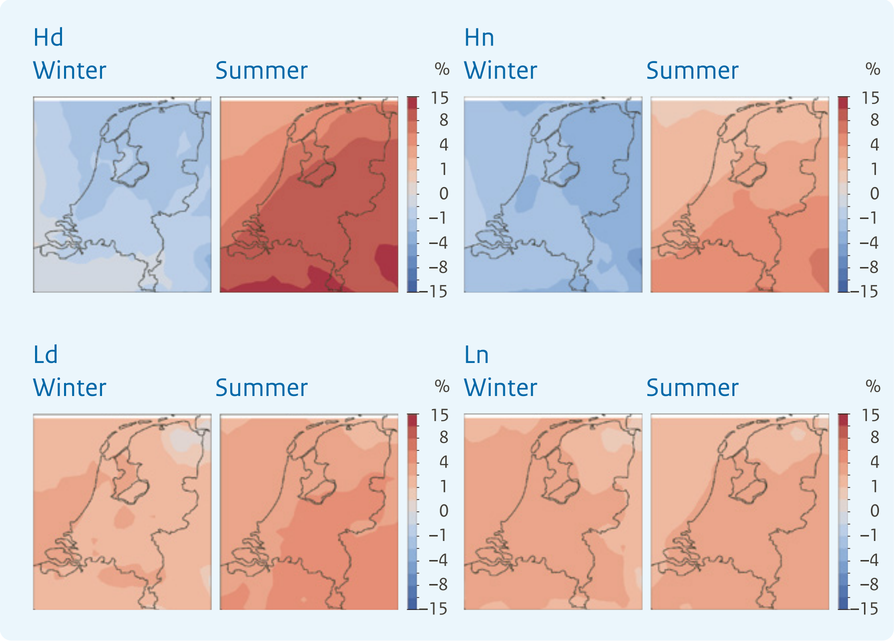

Figure 20: Changing solar radiation in winter and summer around 2100 according to the four KNMI'23 climate scenarios.

Wind, storms and wind gusts

Low wind speeds can lead to reduced air quality and the development of fog. Wind turbines generate less energy at low wind speeds. High wind speeds can involve risks for public safety, such as falling trees or floods. The latter occur when strong north-west winds prevail above the North Sea for prolonged periods. Wind speeds are never constant, and certainly not during strong winds. While wind gusts last only a few seconds, they can reach speeds of more than twice the average wind speed. In addition, heavy showers may give rise to wind gusts and downbursts. This will not change in future.

Wind speeds observed over land in the Netherlands have been slightly decreasing since about 1990 (Figure 21). This trend is not visible for the North Sea. It is likely that the decrease over land has been caused by an increased roughness of the surface, a consequence of urbanisation.

Dangerous winds

The main risk of strong winds is that they can cause storm surges. The duration and direction of the wind also plays an important role. Gale-force north-westerly winds pose the highest risk to the Netherlands. The expected number of days with north-westerly winds with an average speed of at least 14 m/s (wind force 7 or more) will decrease slightly (Figure 22). Little or no change is expected for the wind speed itself. So, future storms will not push the water level up any higher above the average sea level than today, but the average sea level itself will be higher.

> Wind-driven water surge will be no higher than today. The threat to coastal safety only comes from sea-level rise

Wind speeds in winter and summer

The mean wind speed barely changes

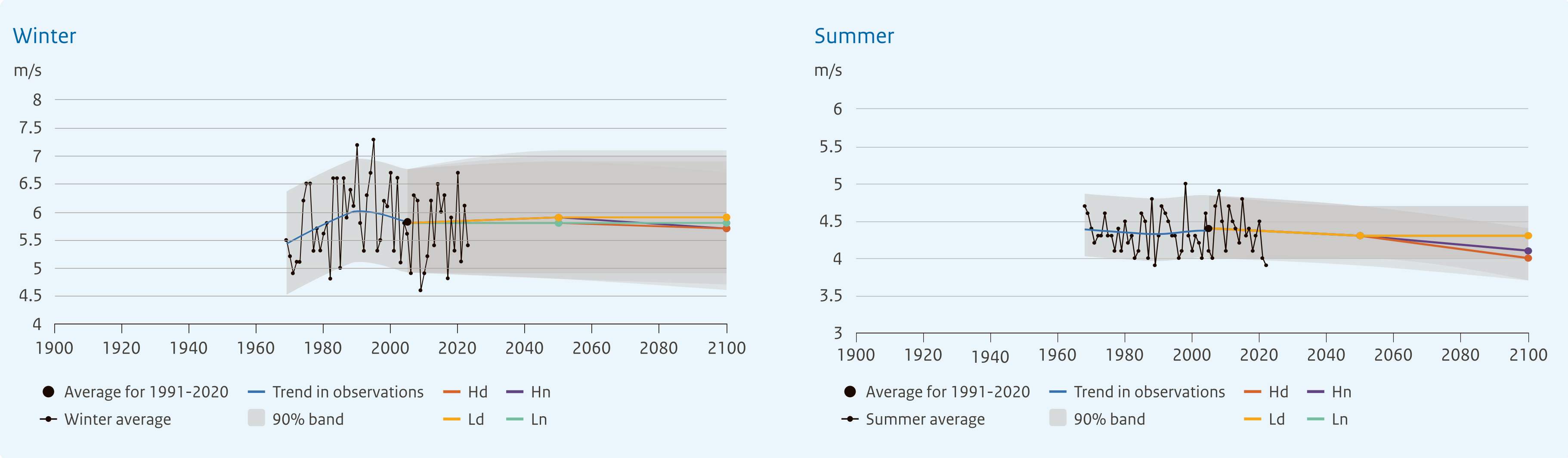

Figure 21: Mean wind speeds in winter (left) and summer (right) at the Schiphol weather station: observations (black) and the four KNMI'23 climate scenarios (2050 and 2100).

Wind direction today and around 2100

Fewer days with strong north-westerly winds

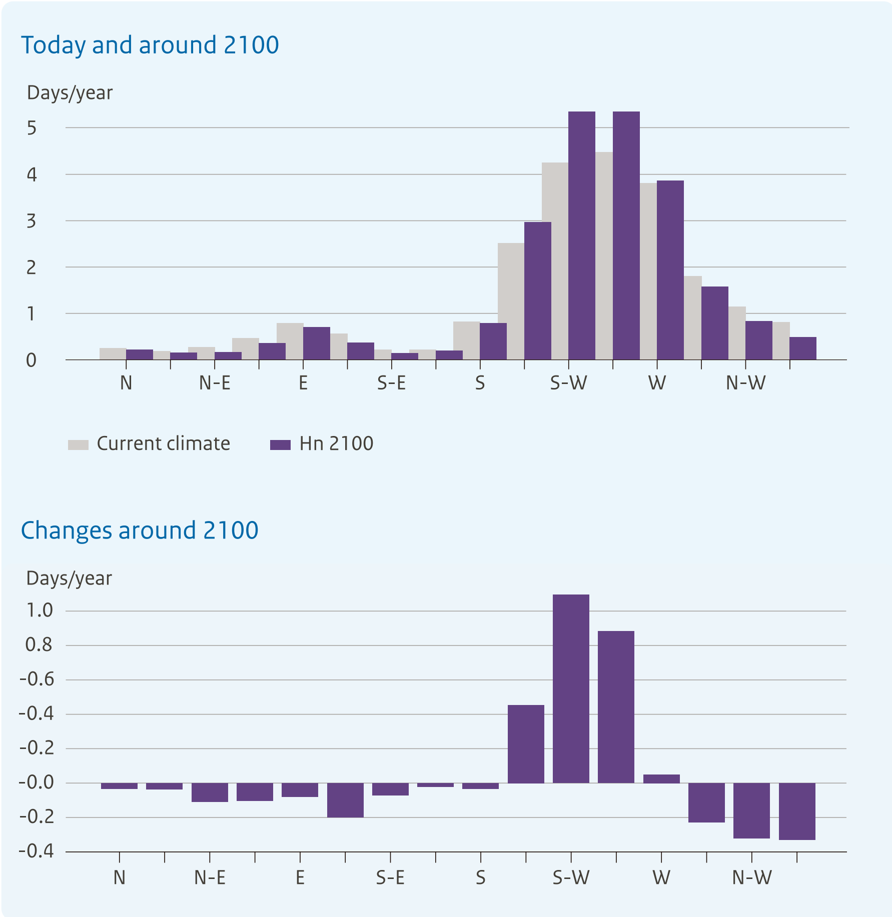

Figure 22: Days per year with wind speed at K13 (North Sea, 53.2°N, 3.2°E) exceeding 14 m/s, for various wind directions in 1991-2020, and in the Hn scenario around 2100 (top), and the differences between the two (bottom).

Visibility and fog

Fog consists of tiny water droplets that float in the air just above the ground. These droplets form around aerosols. Meteorologists speak of 'fog' when visibility is less than 1000 metres. Fog can hamper road, shipping and air traffic.

Various types of fog are distinguished in the Netherlands. The most common type is radiation fog, where infrared radiation causes the lower air layers to cool rapidly, saturating the air with moisture. Sometimes fog is caused by the horizontal movement of air, particularly near the coast when warm, moist air flows in from the North Sea over the colder surface of the land. Finally, ground fog occurs regularly above relatively cold water surfaces and wet fields in the summer. Fog occurs more often inland than near the coast.

In recent decades, the number of hours of fog has decreased sharply everywhere in the Netherlands (about 50% less over 40 years). This is because the air has become cleaner. With fewer dust particles, water droplets do not form as easily. Air pollution is expected to decrease slightly further this century. This reduces the likelihood of fog, but changing weather conditions will likely also play a role. Estimates of the occurrence of fog in the future[1] are based on the formation of radiation fog during periods with little wind and high moisture levels near the Earth's surface.

Models reveal that the number of weather types in which fog occurs will be largely unaffected by global warming, regardless of the season. There may be slightly less fog due to further improvements in air quality, but this decrease will be much smaller than that during the past 40 years (Figure 23).

Fog

Fog will barely decrease further

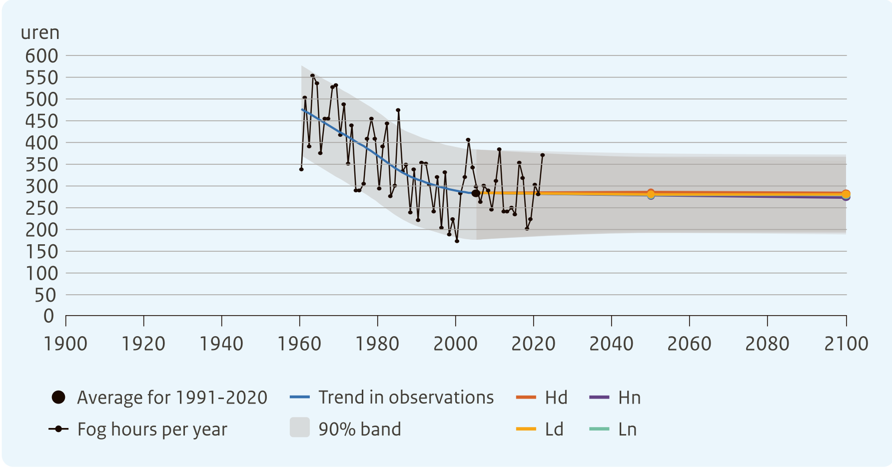

Figure 23: Hours with fog (visibility less than 1 km) per year in De Bilt: observations (black) and the four KNMI'23 climate scenarios (2050 and 2100).

1 See www.knmi.nl/klimaatscenarios for the comprehensive table of changes for the KNMI'23 climate scenarios, including the figures for fog.

Sea-level rise

Global sea level had hardly changed since the beginning of the Common Era but started rising during the 19th century. Since 1900, sea level has risen about 20 cm (1.7 mm/year). sea-level rise has accelerated during the past 50 years and reached a rate of about 2.3 mm/year from 1971 to 2018, and 3.7 mm/year from 2006 to 2018. Sea-level rise is still accelerating.

Sea-level rise along the Dutch coast

Since 1890, sea level has risen by 25 cm compared to the Dutch reference level (NAP). Averaged over 130 years, sea-level rise was ~1.9 mm/year (Figure 24). This number takes into account the effect of land subsidence, which is responsible for about a quarter of the relative sea-level rise (gas extraction has led to considerably more land subsidence near the monitoring station in Delfzijl). Changes in regional sea level are also influenced by natural variations in wind speed and direction, which determine surge levels off the coast. .

If we correct for wind variations, an acceleration is visible: 2.9 mm/year from 1993 to 2021, compared to 1.8 mm/year from 1890 to 1993. Compared with the KNMI'14 climate scenarios (ref. 3), and the 2021 Climate Signal (ref. 4), the current scenarios correspond better with the observations of the past 30 years. This is because we now have a better understanding of the processes that cause regional sea level differences (Figure 24).

> Due to improved sea level scenarios, the model outcomes of today match the observations more closely

Future sea-level rise

For the Dutch coast, around 2050, a further sea-level rise of 16-34 cm is expected in the low emission scenario, and 19-38 cm in the high emission scenario. Around 2100, an increase of 26-73 cm is expected in the low emission scenario, and 59-124 cm in the high emission scenario (Figure 25). The upper limit of sea-level rise around 2100 could reach 2.5 m if poorly understood processes that are neglected in the standard scenarios, mainly associated with the increasing instability of the Antarctic ice sheet, do make a substantial contribution.

> In the low emission scenario, sea-level rise until 2100 is substantial (26-73 cm), in the high emission scenario a lot more (59-124 cm)

Even if greenhouse gas emissions were to be halted today, sea level would continue to increase, not only during this century, but for many hundreds of years to come. This is because the ice sheets are no longer in equilibrium with the present (and future warmer) climate. Even if the temperature remains stable, they will continue to shrink. The rate and extent of sea-level rise will thus depend on the extent by which climate and land ice are brought further out of balance during the following years. The total amount of greenhouse gases emitted plays an all-important role here.

As a result, even in the low emission scenario, sea level along the Dutch coast will likely have risen by more than a metre in 2150. In the high emission scenario, exceedance of 1 metre sea-level rise will occur much earlier.

Rate of sea-level rise in the North Sea

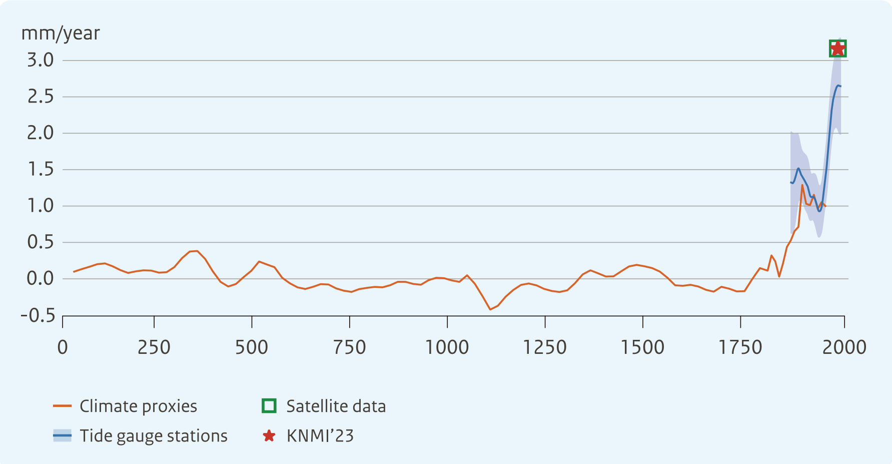

Figure 24: Rate of sea-level rise off the European coastline over the past 2000 years according to different methods. Climate proxies are estimates based on coral growth and archaeological information, for example.

The ice sheets of Greenland and Antarctica are shrinking at an increasing rate (Figure 26). Between 2009 and 2018, these ice sheets lost respectively 7 and 4 times as much of their mass than between 1992 and 2001. If the world heats up by more than 2°C, the future of Antarctica will become very uncertain. In such a scenario, the floating ice shelves surrounding Antarctica's land ice will largely disappear by the end of this century. Without the push-back effect of these floating ice shelves, the land ice will flow faster towards the sea, accelerating the disintegration of the ice sheet.

> Even if emissions are greatly reduced, the sea level along the Dutch coast will eventually rise by more than a metre

Because the melting of the Greenland ice sheet contributes little to sea-level rise along the Dutch coast, the rate of sea-level rise in our region will almost entirely be determined by the rate at which the Antarctic ice sheet loses mass. According to the high emission scenario, sea level will have risen around 2 to 6 metres by 2300. If the potential effects of less well understood processes in Antarctica are also taken into account, this number could become more than 17 metres (Figure 25).

Mass loss of Greenland and Antarctic ice sheets since 1990

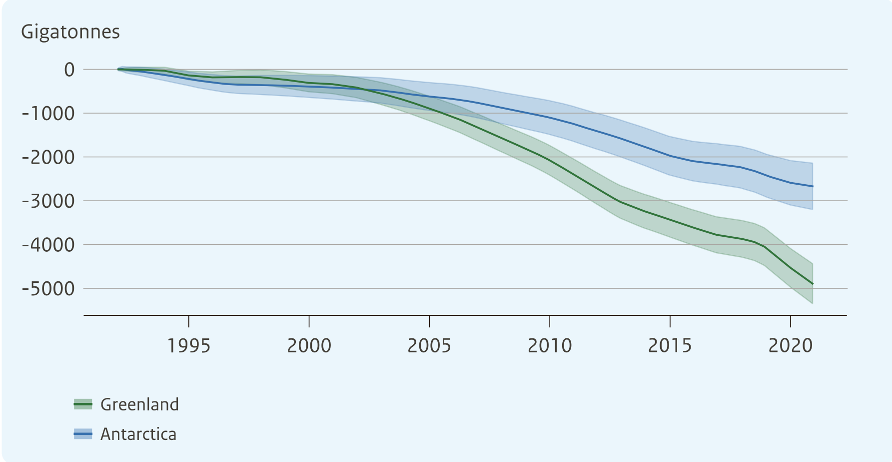

Figure 26: Mass change of Greenland and Antarctic ice sheets over the past three decades.

Sea level along the Dutch coast

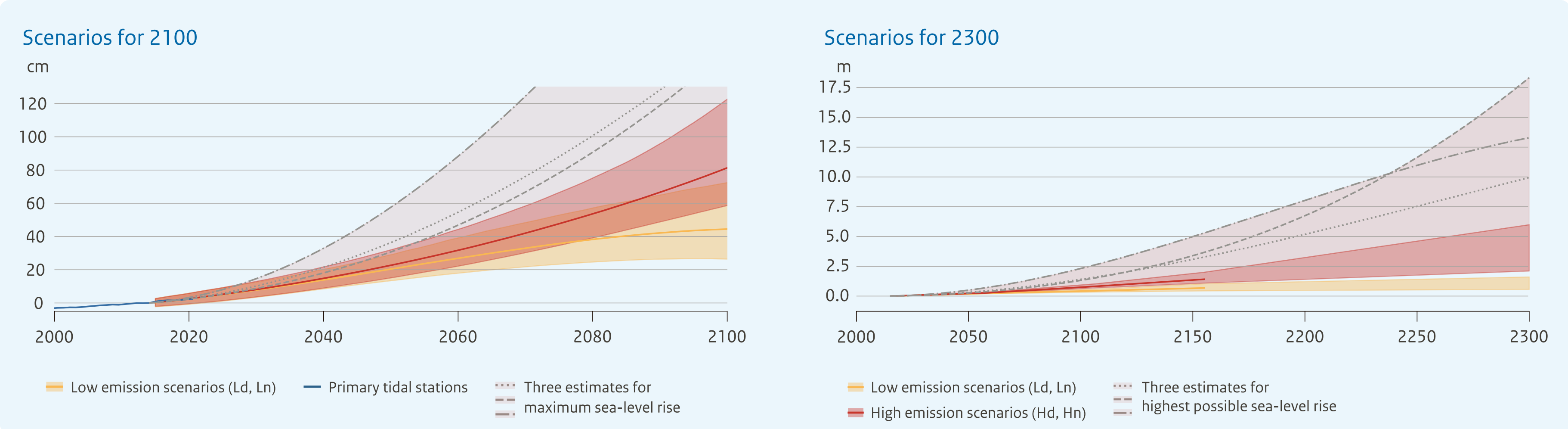

Figure 25: Sea level scenarios for the Dutch coast around 2100 and 2300 relative to current levels (median and 90% band), including three estimates of the highest possible sea-level rise (dashed lines in light pink band).

How warm will it get in the Netherlands if the world warms by 1.5°C?

The Paris Agreement sets a limit on global warming of well below 2°C compared to pre-industrial levels (1850-1900), and preferably no more than 1.5°C. These figures are averaged over a 20-year period. There is a high likelihood that 1.5°C warming will be exceeded during a single year within the next 5 years. Based on climate models, the IPCC expects that the 1.5°C warming (20-year average) may be reached as early as around 2033. A sharp reduction in emissions and large-scale removal of CO_2 from the atmosphere will be needed to reverse this warming and bring it down to 1.5°C by 2100.

The KNMI'23 climate scenarios describe climate change relative to the most recent reference period (1991-2020). In this period, global warming was 0.9°C with respect to the period 1850-1900. We therefore expect an additional global warming of 0.6°C between the most recent climate normal and 2033, of which 0.3°C has already happened.

Warming of the Netherlands around 2033

11.2°C in De Bilt if planet warms by 1.5°C

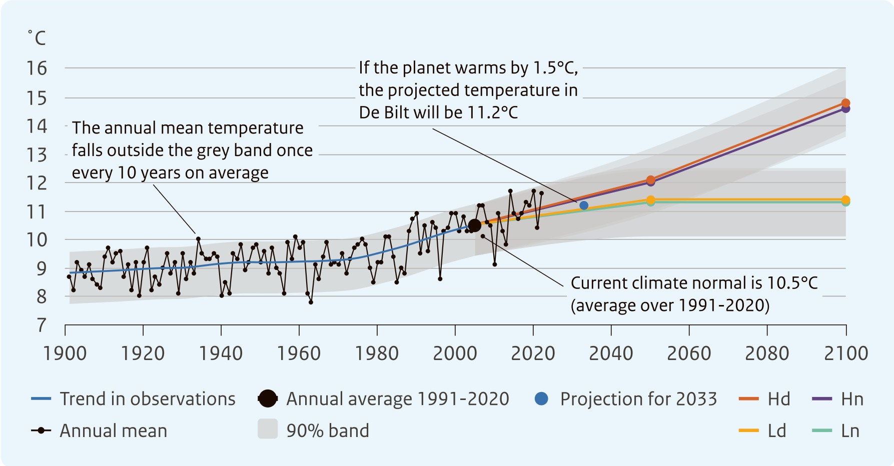

Figure 27: Annual mean temperature in De Bilt: observations (black) and the four KNMI'23 climate scenarios (2050 and 2100, in four colours), including the expected temperature around 2033 (blue dot).

Around 2033, 25% more summer days will be recorded in De Bilt on average

We calculated what the Dutch climate will look like in 2033, using the same method we used for 2050 and 2100. The annual mean temperature in the Netherlands around 2033 will be 0.7°C higher than during the reference period: 11.2 ± 0.2°C (Figure 27, blue dot). On average, 25% more summer days will be recorded in De Bilt, and 20% less ice days.

Climate scenarios for the BES islands

Bonaire, Sint Eustatius and Saba are municipalities of the Netherlands with a special status, and collectively known as the BES islands. We produced climate scenarios for temperature, precipitation, wind and sea-level rise for these islands in the Caribbean. Because hurricanes have a high impact, we also looked at how these will change. The climate change observed in the BES islands to date has been described in other publications (ref. 4 and 5).

Developments in the future

As for the Netherlands, we also developed four climate scenarios for the BES islands: high emission, dry (Hd) and wet (Hn) and low emission, dry (Ld) and wet (Ln). We used the same method as for the Netherlands, but focused on the wet and dry seasons instead of the summer and winter.

Precipitation and temperature

In all four climate scenarios for the BES islands, the temperature and wind speed increase, while precipitation decreases. In the low emission scenario, temperatures rise until 2050 and then stabilise. Precipitation decreases slightly. In the high emission scenario, temperatures continue to increase and precipitation continues to decrease (Figure 28). Around 2100, more warming is expected in the wet scenarios and in the wet season, while increased drying is expected in the dry scenarios and in the dry season. Around 2050, these differences will be smaller (Table 3). For Bonaire, we see a stronger increase in wind speed in the dry scenarios and in the wet season. For Sint Eustatius and Saba, this increase is smaller. The future climate of the Caribbean will be more similar to that under El Niño conditions today, with less precipitation and higher wind speeds.

> In the low emission scenario, Bonaire can expect a reasonably strong sea-level rise of 31-78 cm around 2100, in the high emission scenario 55-127 cm

However, there is a difference between the weather observations and the model calculations. While the models describe El Niño conditions, the actual observations in the field rather suggest a La Niña scenario, with more precipitation and less wind. It is not yet fully understood why the observations differ from the calculations, but it may partly be due to natural variability. The difference may in any case affect the climate scenarios for the Caribbean. So, precipitation may decrease less in the coming decades than the models suggest. Just as for the Netherlands, on the BES islands, the differences in warming between the high and low emission scenarios are determined by the level of global emissions. This means that climate policies aimed at reducing emissions can have an important influence on the future climate of the BES islands.

Precipitation and temperature on the BES islands

The BES islands are getting warmer and drier

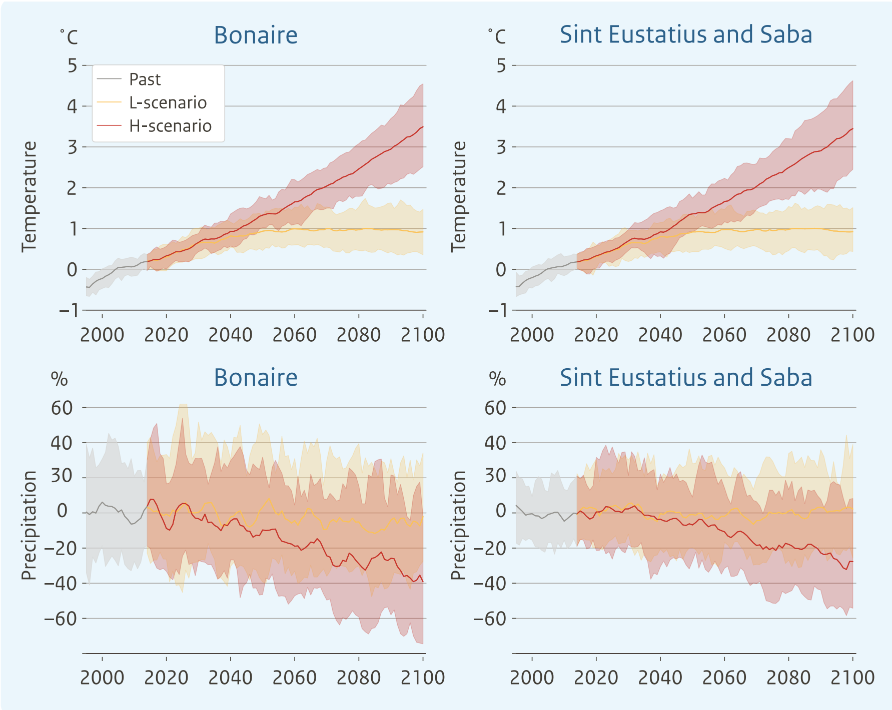

Figure 28: Projected changes (relative to 1991-2014) in the annual mean temperature and precipitation on Bonaire, Sint Eustatius and Saba for the low (yellow) and high (red) emission scenarios (median and 90% band).

Key figures for the BES islands

Bonaire

Season	Variable	Indicator	Climate in 1991-2020 = reference period	**2050** (2036-2065)				**2100** (2086-2115)			
				Ld	**Ln**	**Hd**	**Hn**	**Ld**	**Ln**	**Hd**	**Hn**
Year	Sea level	Average level	0 cm [1]	+23 (14-34) cm	+23 (14-34) cm	+25 (16-37) cm	+25 (16-37) cm	+48 (31-78) cm	+48 (31-78) cm	+81 (55-127) cm	+81 (55-127) cm
	Sea level	Rate of change	4 mm/year [1]	+2 (1-6) mm/year	+2 (1-6) mm/year	+4 (2-8) mm/year	+4 (2-8) mm/year	-1 (-1-4) mm/year	-1 (-1-4) mm/year	+11 (5-24) mm/year	+11 (5-24) mm/year
	Temperature	Average	28.5°C	+0.8°C	+0.8°C	+1.2°C	+1.3°C	+0.7°C	+0.7°C	+3.0°C	+3.3°C
	Precipitation	Amount	514 mm	-8%	0%	-15%	-2%	-7%	0%	-48%	-11%
	Wind	Average wind speed [2]	7.8 m/s	+2%	+1%	+3%	+1%	+2%	0%	+11%	+4%
Wet season	Temperature	Average	28.9°C	+0.8°C	+0.8°C	+1.3°C	+1.3°C	+0.7°C	+0.7°C	+3.1°C	+3.4°C
	Precipitation	Amount	346 mm	-6%	2%	-13%	0%	-5%	+2%	-48%	-12%
	Wind	Average wind speed [2]	7.6 m/s	+3%	+1%	+5%	+1%	+2%	+1%	+14%	+5%
Dry season	Temperature	Average	27.8°C	+0.8°C	+0.8°C	+1.2°C	+1.3°C	+0.7°C	+0.7°C	+2.9°C	+3.2°C
	Precipitation	Amount	169 mm	-12%	-3%	-20%	-5%	-11%	-3%	-48%	-7%
	Wind	Average wind speed [2]	8.0 m/s	+1%	0%	+2%	+1%	+1%	0%	+7%	+3%

Sint Eustatius and Saba

Season	Variable	Indicator	Climate in 1991-2020 = reference period	**2050** (2036-2065)				**2100** (2086-2115)			
				Ld	**Ln**	**Hd**	**Hn**	**Ld**	**Ln**	**Hd**	**Hn**
Year	Sea level	Average level	0 cm [1]	+21 (13-32) cm	+21 (13-32) cm	+23 (14-34) cm	+23 (14-34) cm	+46 (29-76) cm	+46 (29-76) cm	+78 (50-126) cm	+78 (50-126) cm
	Sea level	Rate of change	3 mm/year [1]	+3 (1 tot 7) mm/year	+3 (1-7) mm/year	+4 (2-8) mm/year	+4 (2-8) mm/year	0 (-1-6) mm/year	0 (-1-6) mm/year	+12 (6-26) mm/year	+12 (6-26) mm/year
	Temperature	Average	27.8°C	+0.8°C	+0.8°C	+1.2°C	+1.3°C	+0.7°C	+0.7°C	+3.0°C	+3.2°C
	Precipitation	Amount	1034 mm	-6%	+3%	-12%	+2%	-5%	+3%	-44%	-8%
	Wind	Average wind speed [2]	7.0 m/s	0%	0%	+1%	0%	0%	0%	+4%	+2%
Wet season	Temperature	Average	28.5°C	+0.8°C	+0.8°C	+1.3°C	+1.3°C	+0.7°C	+0.7°C	+3.0°C	+3.3°C
	Precipitation	Amount	730 mm	-7%	+5%	-14%	+4%	-6%	+4%	-48%	-7%
	Wind	Average wind speed [2]	6.9 m/s	0%	+1%	+1%	+1%	0%	+1%	+4%	+2%
Dry season	Temperature	Average	26.8°C	+0.8°C	+0.8°C	+1.2°C	+1.2°C	+0.7°C	+0.7°C	+3.0°C	+3.1°C
	Precipitation	Amount	304 mm	-3%	-3%	-8%	-5%	-3%	-3%	-34%	-9%
	Wind	Average wind speed [2]	7.1 m/s	0%	-1%	+1%	-1%	0%	-1%	+5%	+2%

Table 3: Climate change figures for sea level, temperature, precipitation and wind on Bonaire (p. 37) and Sint Eustatius and Saba (p. 38). Wet season: May-November; dry season: December-April.

1 The reference period for sea-level change is 1995-2014. The average sea level for this period has been set at 0.

2 Pressure level 925hPa, about 800m above sea level.

Sea-level rise

Sea-level rise poses a particular threat to low-lying Bonaire. At Bonaire, the sea level is rising by 3.7 mm per year (about the world average), and in Sint Eustatius and Saba by 3.0 mm per year. Around 2050, the sea level around Bonaire is expected to have increased by 14-34 cm in the low emission scenario, and by 16-37 cm in the high emission scenario. Around 2100, an increase of 31-78 cm is expected in the low emission scenario, and 55-127 cm in the high emission scenario (Figure 29). The upper limit of sea-level rise could reach 3.4 m before 2100 under the influence of as yet little understood processes, such as increasing instability of the Antarctic ice sheet. Sint Eustatius and Saba are expected to experience slightly less sea-level rise than Bonaire.

Sea level at Bonaire until 2100

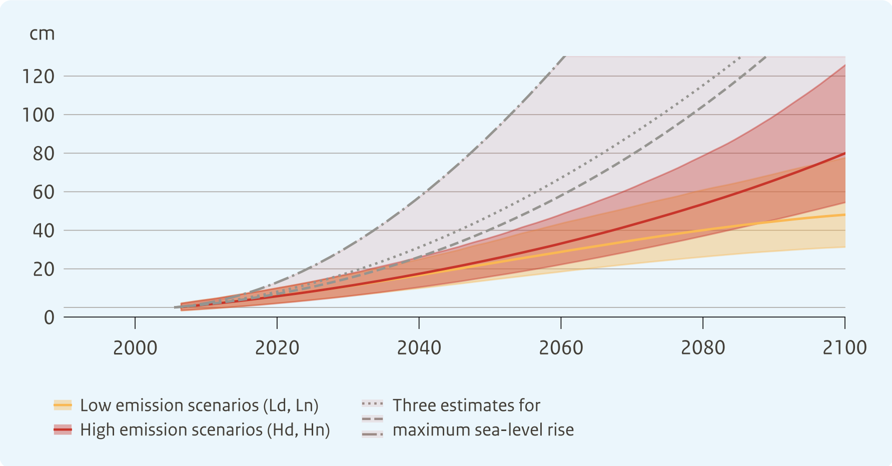

Figure 29: Sea level scenarios for Bonaire around 2100 relative to current levels (median and 90% band), including three estimates for the maximum sea-level rise (dashed lines in light pink band).

Hurricane frequency

Hurricanes are amongst the most dangerous weather phenomena in the region. Hurricanes involve extremely strong winds and heavy rainfall and may also cause high waves, storm surges and landslides. We calculated the return periods of various wind speeds in the BES islands region for the period 2015-2050 (Figure 30). We did this using a statistical model that calculates hurricane data based on the expected characteristics of future hurricanes. The return periods for Bonaire are about twice as long as those for Sint Eustatius and Saba. This is because many hurricanes pass to the north of Bonaire, while Sint Eustatius and Saba are more often on the direct path of hurricanes. There will be only minor changes in the return periods in the coming decades. Only hurricanes of the most severe category are expected to occur more frequently on Sint Eustatius and Saba: once every 20 to 34 years from 2015 to 2050, compared to once every 39 years from 1980 to 2017.

> There will be a higher likelihood of severe hurricanes with high rainfall on Sint Eustatius and Saba

Return periods of hurricanes

More frequent strongest-category hurricanes expected in the future

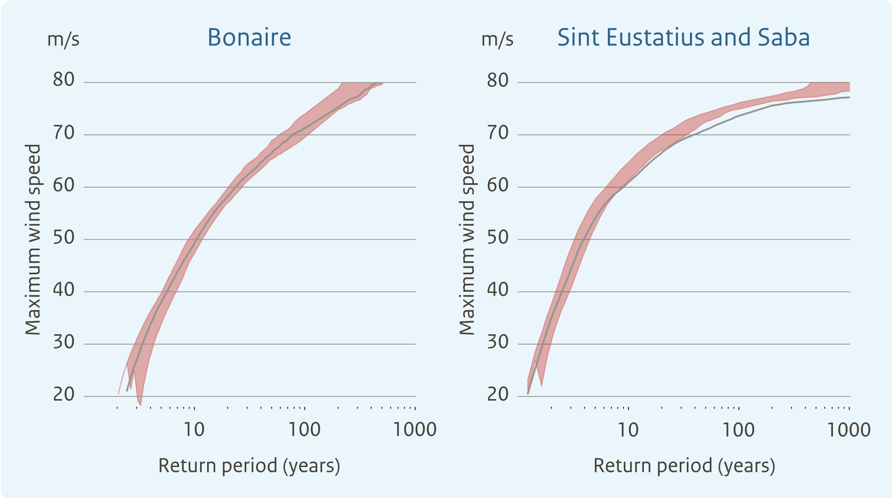

Figure 30: Return periods wind speeds within 250 km of the BES islands, today (1980-2017, grey) and in the future (2015-2050, red) in the high emission scenario.

Future weather

Hurricanes like Irma (2017) in a warmer climate

In September 2017, Sint Maarten and the other Windward Islands were hit by Hurricane Irma. As far as we know, this was the first time a hurricane of the highest category (wind speeds ≥70 m/s) reached these islands. In the climate of the future, as seawater temperatures increase, hurricanes may become stronger.

Global climate models are usually not detailed enough to simulate individual hurricanes. However, by using the results of a low-resolution (global) climate model as boundary conditions for a high-resolution (regional) climate model, it is still possible to simulate hurricanes in the current and future climate in detail.

Historical hurricanes such as Irma can also be simulated with this regional climate model by using the observed atmospheric and oceanic conditions as boundary conditions. Hurricane Irma simulated in this manner reveals a clear eye where almost no precipitation and little wind occurs (Figure 31). Around the eye (between the two red circles) is an area with hurricane-force winds and intense rainfall. The simulated wind speed and precipitation intensity in the model are very similar to those recorded by weather stations.

The same regional model was used to describe future changes in wind speed and precipitation during hurricanes. The model reveals that the most severe hurricanes in the future are likely to be associated with higher maximum wind speeds and higher maximum precipitation intensities (Figure 32). This will increase the impact of the most severe hurricanes, but it is not clear whether hurricanes will occur more frequently.

Hurricane Irma (2017)

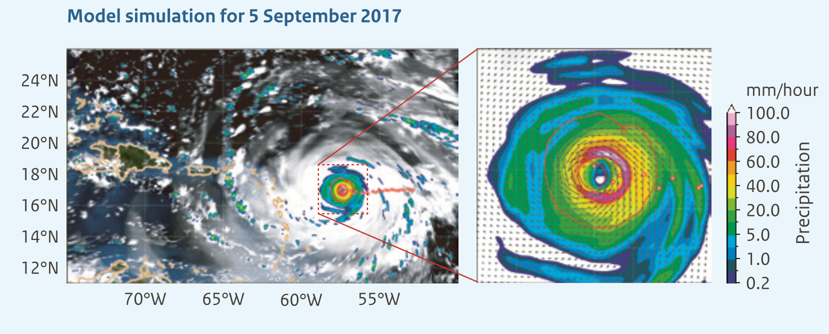

Figure 31: Hurricane Irma approaches the Caribbean: overview and detail. The white shading in the left image depicts cloud cover, the other colours represent the amount of precipitation per hour, and the arrows give the wind speed. The red dotted line shows the trajectory of the hurricane.

Wind speed and precipitation in hurricanes

More wind and precipitation in the strongest hurricanes

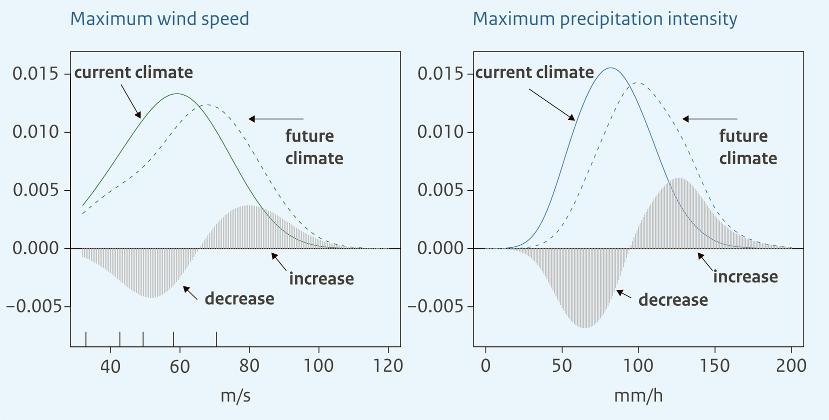

Figure 32: Probability distribution of maximum wind speed and maximum precipitation intensity during hurricanes in the current climate (solid line) and in a 3.4°C warmer climate (dashed line), and the difference.

KNMI'23 climate scenarios in practice: *11 impact case studies*

The following pages give the results of 11 impact case studies. Several institutes have used the KNMI'23 climate scenarios to consider the potential consequences of climate change. More information about how the scenarios can be applied in practice is available at www.knmi.nl/klimaatscenarios.

The Netherlands Environmental Assessment Agency is cooperating with several knowledge institutes to publish an updated review of the climate risks for the Netherlands. Table 4 provides an overview of the main risks for the Netherlands based on the previous review, but in line with the KNMI'23 climate scenarios.

Climate change risks for the Netherlands

Sectors	Risks
Coastal effects	The rising sea levels have implications for flood protection and water management policies. The latter includes, for example: an increasing need for sand supplementation, and an increasing water demand to prevent salt intrusion. Sea-level rise will increase the likelihood of floods and hence the risks for people, the environment and the economy.
Flooding	Increased precipitation in the winter will lead to higher river discharges and so a greater risk of the Rhine, Meuse and other smaller rivers over-flowing their dikes. As heavy rain will occur more frequently, the risk of flooding will increase.
Water supply	The increase of drought events will lead to more regular water shortages. When water availability is limited, people will have to decide how to distribute the scarce water available between the various functions it needs to meet: drinking water, nature management, agriculture and inland shipping.
Water quality	As surface water temperatures rise, the ecology of the water will also change. Surface water will become less suitable as a source of drinking water. Blue-green algae will occur more frequently in ponds and lakes, making these waters unsuitable for swimming.
Health	As temperatures rise, winter mortality will decrease, but heat and smog will cause more problems and higher mortality in the summer. More exposure to UV radiation will mean an increased risk of skin cancer. The longer pollen season will also mean more 'allergy days'. More cases of infectious diseases transmitted by vectors such as ticks and mosquitoes are also expected.
Mobility	An increase in extreme precipitation events will lead to more traffic disruptions in the summer. While less frequent frosts will mean a lower risk of slippery roads and frost damage, there will be an increased risk of surface rutting during heatwaves. Higher discharges of the major rivers in the winter and lower discharges in the summer will restrict shipping on inland waterways.
Energy	Less energy will be needed for heating, but more will likely be used for cooling. Warmer water in the rivers will mean less cooling water is available for power plants.
Agriculture	Agricultural yields may be reduced by an increase in extreme weather. Droughts in particular are a major risk for crop yields. Salinisation will affect sensitive crops such as bulbs and fruit trees in the lower-lying Netherlands.
Nature	The risks are greatest for ecosystems that depend on precipitation, such as heathlands, grasslands and bogs. Heat-loving plant and animal species will increase, cold-loving species will decline. This may lead to mismatches in the food chain. Global warming also increases the risk of wildfires.
Recreation	Higher temperatures will mean more 'recreation days', but the number of days cold enough for skating will decrease. Major recreational events are more likely to be disrupted by extreme weather.

Table 4: Climate change risks for the Netherlands this century. Courtesy of the Netherlands Environmental Assessment Agency. Based on ref. 6 and 7: klimaatadaptatienederland.nl/overheden/nas/adaptatietool/.

Changes in temperature-related mortality

Lisbeth Hall, Danny Houthuijs and Maciek Strak (RIVM)

Persistent hot weather and heat waves will lead to an increase in health issues, sleeping problems and premature deaths, particularly amongst the elderly and chronically ill. Mortality is always highest during extremely hot and extremely cold weather, but even small deviations from the 'optimal' temperature lead to an increase in deaths. In the Netherlands, mortality is lowest when the average daily temperature is around 17°C.

Global warming will lead to higher heat-related mortality and lower cold-related mortality (Figure 33). The population will increase, and because the proportion of elderly people is also increasing, the number of people vulnerable to extreme temperatures will continue to grow. Cold-related mortality is higher today (5800) than heat-related mortality (660). In the high emission scenario (Hd), this may have reversed by around 2100, with more heat-related mortality (11,000) than cold-related mortality (6600). Around 2100, over 8000 more people will die prematurely from the effects of heat in the high emission scenario (Hd) than in the low emission scenario (Ld). About half of the growth in temperature related mortality can be attributed to population growth and ageing.

The calculations do not take account of people becoming accustomed to heat, or climate adaptation measures such as more trees and more shading.

Temperature-related mortality

More heat-related mortality and less cold-related mortality

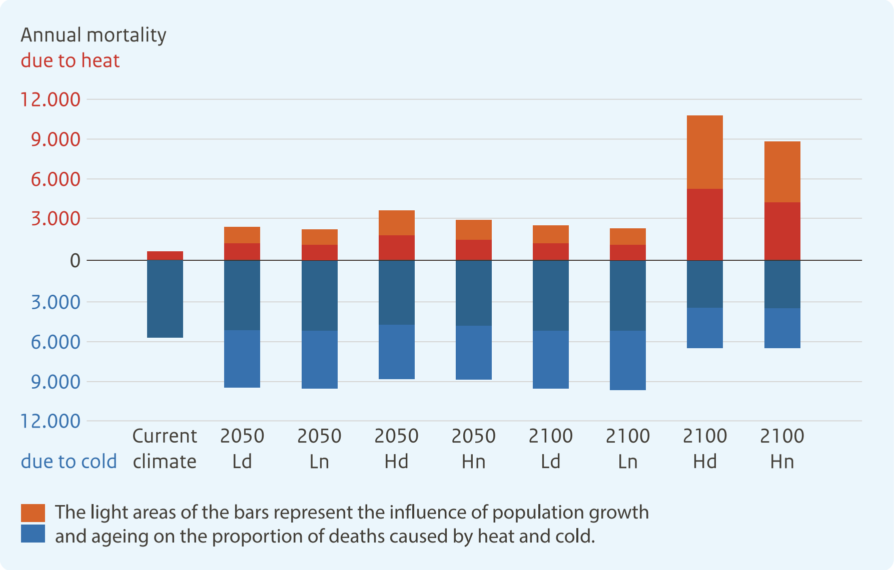

Figure 33: Average annual mortality in the Netherlands related to heat and cold in the current climate (1991-2020), and potentially for the climate of around 2050 and 2100 (based on the KNMI'23 climate scenarios).

Heat stress in Amsterdam

Nabil Tanouti and Pam Geven (City of Amsterdam)

Greening Osdorp Noord


Sanne Couprie (City of Amsterdam)

Urban heat stress is unhealthy and can even cause excess mortality, particularly in vulnerable groups such as the elderly and young children. The effects of high temperatures on urban health will not only be determined by the changing climate, but also by the design of public spaces and the degree of vulnerability and adaptability of the urban population.

People living in the Amsterdam district of Osdorp Noord face a relatively high risk of heat stress because of the density of high-rise buildings and roads in this area. Residents often do not own their homes and so are not directly responsible for taking measures to improve the homes.

The KNMI'23 climate scenarios reveal that, around 2100, the number of tropical nights per year in Osdorp Noord will increase from 1 in the current climate to 2 in the low emission scenario (Ln), and 26 in the high emission scenario (Hd) (Figure 34). Due to the urban heat island effect there are more tropical nights in urban areas than in the countryside. To combat the heat in Amsterdam, the municipality is greening the city, including on roofs and facades, along walkways and around squares. The plants provide natural cooling. It is important to cooperate with, for example, housing associations, schools, daycare centres and other affected institutions to help keep houses and schools cool and healthy during hot periods.

Tropical nights in Amsterdam and environs

Many more tropical nights in the high emission scenario

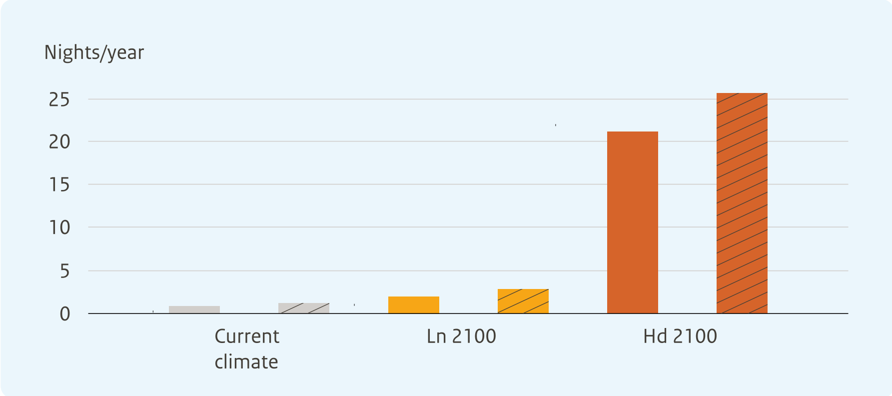

Figure 34: Tropical nights (minimum temperature at least 20°C) in the summer around 2100 in Osdorp Noord (hatched) and outside Amsterdam (not hatched), calculated for the Ln and Hd climate scenarios. The urban heat island effect (ref. 8) has been taken into account.

Risk of wildfires also increasing in the Netherlands

Cathelijne Stoof and Hugo Lambrechts
(Wageningen University & Research)[1]

Wildfires are more likely to be associated with southern Europe than the Netherlands, but in fact some 550 fires are already recorded each year in this country, burning off a total of some 440 hectares (ref. 9). Although these fires are usually relatively small, they do involve major challenges. Wildfires often occur at the same time, they require different methods to fight than fires in buildings, and the Dutch are insufficiently aware of the risks they pose. Moreover, the Netherlands does not have a uniform national policy for preventing and fighting wildfires. The risk of wildfires is not only influenced by the weather (e.g. drought and wind), but also by vegetation cover and nature management measures. Their impact on the environment varies (Figure 35).

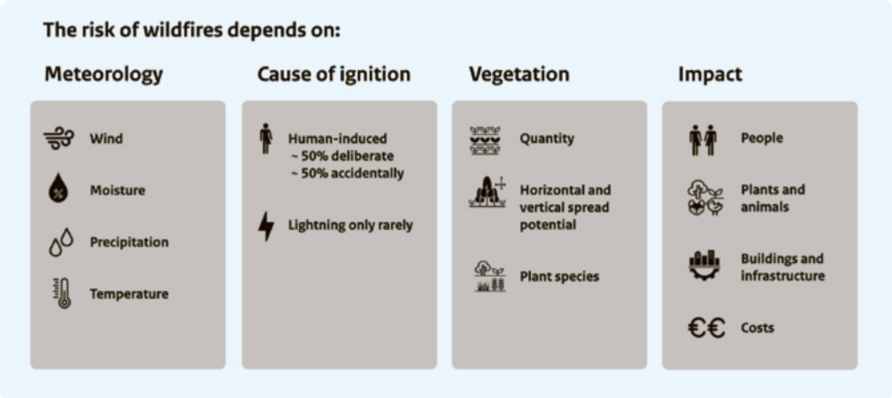

Figure 35: Factors affecting wildfire risk.

Figure 36 shows the potential change in the number of days with favourable weather conditions for wildfires. Whether and by how much the fire danger days will decrease or increase depends on the climate scenario: in the Ln scenario, the number of days decreases by 25% until 2100; in the Hd scenario, it increases by 300%. The south and south-eastern parts of the Netherlands have the most fire danger days, both in the current climate and in all the climate scenarios. The wildfire season is expected to last longer, with longer lasting and more intense fires.

Fire danger days per year

Strongest increase in the 'High emission, dry' scenario

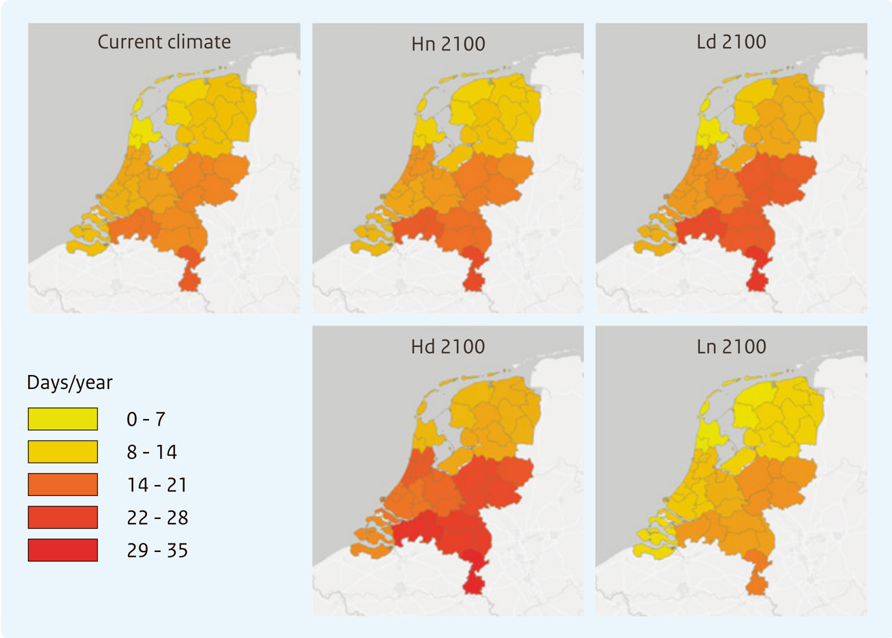

Figure 36: Fire danger days per year (favourable weather conditions for wildfires), in the current climate and around 2100, according to the four KNMI'23 climate scenarios (calculated by Wageningen University & Research, see ref. 10).

1 This study was funded by: the European Union Horizon 2020 research and innovation programme (grant agreements 860787 and 101037419).

Impact of increased solar radiation on electricity generation

Martien Visser (Energieopwek.nl)

The number of solar panels in the Netherlands is growing. In 2022, 15% of all electricity consumed in the Netherlands was generated by solar panels (source: Statistics Netherlands, CBS). This growth is badly needed since electricity use will increase, amongst other things, to power electric vehicles and electric heating and to make the planned transition from fossil fuels to renewable electricity generation. Because solar panels produce more electricity when there is more solar radiation, an increasing amount of sunshine will benefit the production of renewable electricity.

An individual solar panel currently has a capacity of about 0.4 kWp. If annual solar production is 880 kWh/kWp, as it was on average over the past 30 years (Figure 37), then an individual panel will produce 352 kWh (0.4 x 880) per year. Eight panels will produce as much electricity as an average Dutch household consumes annually. Solar radiation levels have gradually increased over the past 30 years, and the last few years have been even sunnier than average. This led to new solar production records, such as in 2022, when a standard panel produced 408 kWh (0.4 x 1020).

According to the KNMI’23 climate scenarios, solar radiation is expected to stay high compared to the levels of late last century, so solar energy production will remain high too. Records like that of 2022 will continue to be exceptional.

Solar energy

Production stays comparable with the level around 2000

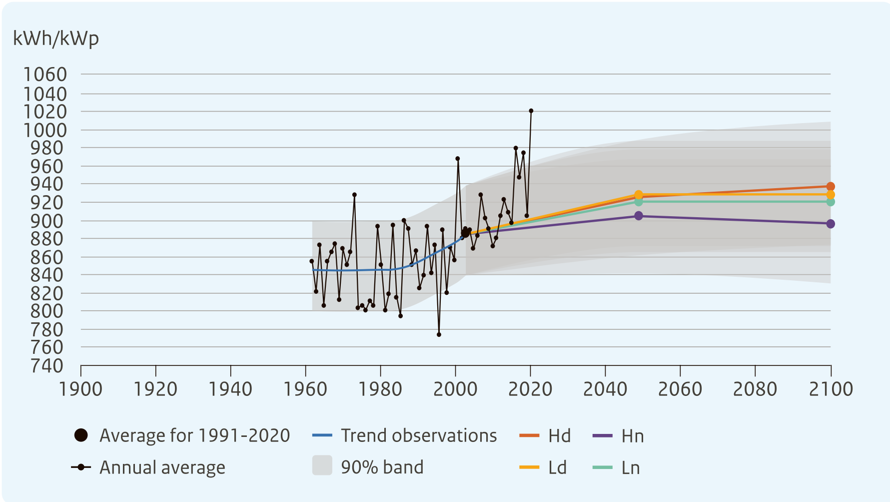

Figure 37: Annual energy production in the Netherlands of a standard solar panel system, from 1965 to 2022 and in the four KNMI’23 climate scenarios.

Impact of extreme weather on crop yields

Puck Mulders (TU Eindhoven) and Pytrik Reidsma (Wageningen University & Research)

Extreme weather conditions have a severe impact on potato yields. Detailed data of farms on sandy soils reveal that extreme rainfall reduces yields by 36% (because the potatoes rot). Extreme rainfall is defined as more than 45 mm during a single day, or more than 60 mm during 3 days, combined with precipitation on more than 75% of the days during a 3 week period (see ref. 11). In drought conditions (less than 10 mm of rainfall during 30 days), yields are reduced by 13%. During the 1991-2020 period, such extreme weather conditions occurred in 37% of the years, with extreme precipitation occurring in 17% and drought in 20% of the years (Figure 38).

These percentages will increase in the future. In 2100, the number of weather extremes will remain about the same under the L scenarios. Under the H scenarios, however, extreme weather will occur in about half of the years, with extreme precipitation in 23-27% and drought in 23-33% of the years. Years with both extremes will also occur more frequently. Adaptation strategies will be required to limit yield losses, such as developing varieties that are more resistant to drought and extreme rainfall. Alternative crop rotation systems and the targeted application of organic matter will also be required to improve infiltration and groundwater retention.

Extreme weather today and around 2100

More frequent extreme weather in the high emission scenarios

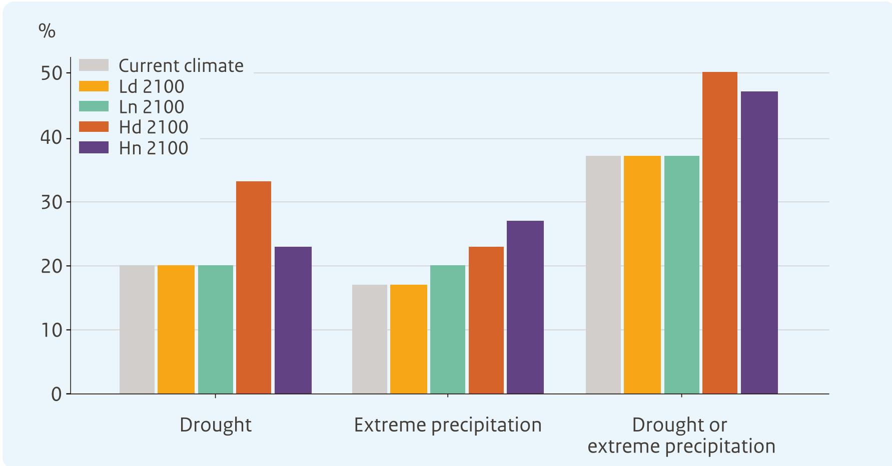

Figure 38: Percentage of years with extreme weather in the current climate and in the four KNMI'23 climate scenarios for around 2100.

Will more Dutch people spend their holidays at Dutch beaches?

Bas Amelung (Wageningen University & Research)
and Valentina Zelada (University of Chile)

Over the past 30 years, Vlissingen has experienced about 71 days of good beach weather each year (Figure 39). During this period, the number of good beach days increased from 60 to over 80 per year. The sunny days will continue to increase in all climate scenarios, but the extent varies. In the low emission scenarios, the number of good beach days per year will increase by about 15 until 2050 and then stabilise. In the high emission scenarios, the number of good beach days will increase to almost 120 by 2100. The rise in temperature is the main reason for this, followed by the increase in solar radiation.

More good beach days could lead to more Dutch people choosing to spend their holidays in the Netherlands, which will benefit the beachfront bars and restaurants. But climate change will also have negative impacts on beach tourism, such as narrower beaches due to rising sea levels. Whatever the form of tourism, warmer weather increases the risk of water shortages. Moreover, as cloud cover decreases and people go about more dressed for summer, the risk of skin cancer will increase.

Beach weather

More days of good beach weather

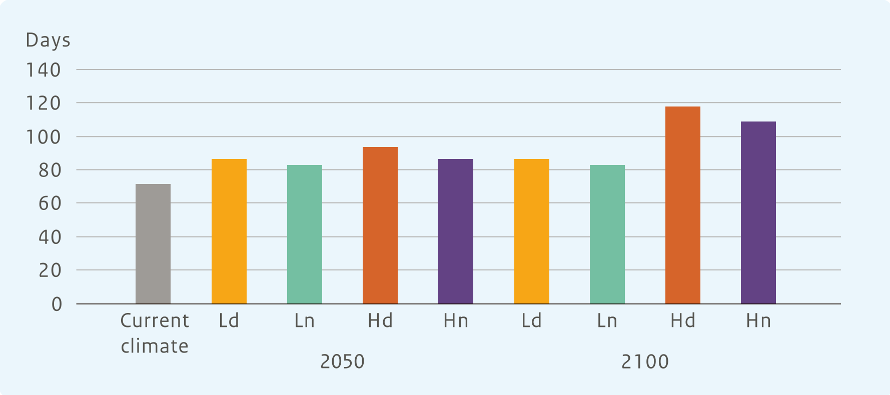

Figure 39: Number of days per year with good weather conditions for beach tourism in Vlissingen in the current situation and according to the four KNMI'23 climate scenarios (HCI-B score at least 80; ref. 12).

Freshwater supply from the Dutch ‘blue heart’

Herbert Bos (representing platform IJsselmeergebied)

Rijkswaterstaat en bouwconsortium Levvel – Topview Luchtfotografie

The IJsselmeer lake region (‘the blue heart of the Netherlands’) plays a crucial role in the lives of millions of people in the northern Netherlands. It has three main functions: it is used to store excess water and so protects against floods, it serves as a freshwater buffer in times of drought, and it is an important ecological system for regional biodiversity. The region is also important for shipping, the drinking water supply, recreation, agriculture and fisheries, sand extraction, energy production, and it has significant historical value. These functions and values are sometimes at odds with each other.

According to the KNMI’23 climate scenarios, the three main functions of the IJsselmeer lake region will come under pressure. Earlier research revealed that, around 2050 and under the most extreme climate scenario, the current fresh-water buffer (Lake IJsselmeer itself) will fail to meet the demand once every 5 years (ref. 13). However, the latest climate scenarios suggest this will occur even more frequently.

In all scenarios, the precipitation deficit will increase in spring and summer. This means less water will flow into the IJsselmeer lake region, while the demand for water for both ecological and economic values will only increase. Climate change is causing freshwater shortages –faster than previously thought– for nature, agriculture, industry and other water-dependent processes in the region (Figure 40). Various changes will be needed to ensure the IJsselmeer lake region can continue to function as a freshwater buffer. The supply will have to be increased, the demand reduced, and the buffer function will need to be optimised.

Lake IJsselmeer water supply

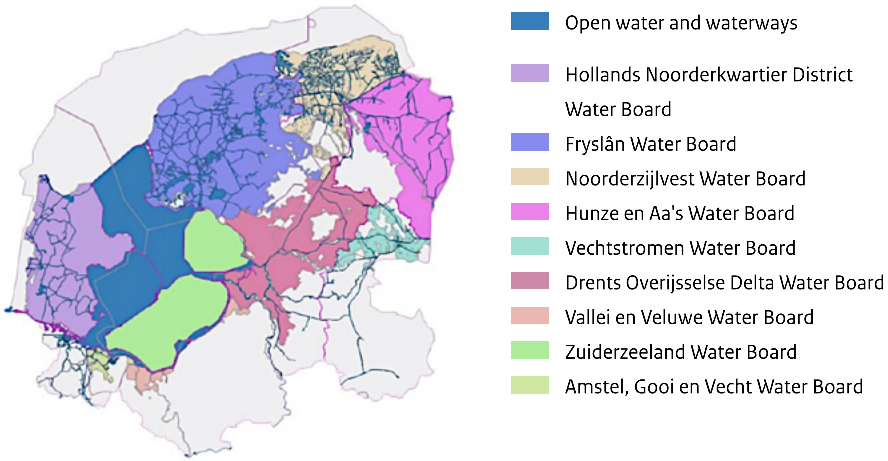

Figure 40: IJsselmeer water supply region; supply of fresh water from the IJsselmeer lake region to the catchments of the nine surrounding water boards. Source: Bestuursovereenkomst waterverdeling regio IJsselmeergebied.

Climate-proof construction

Dana Huibers (municipality of Dordrecht)

Climate adaptation in Dordrecht

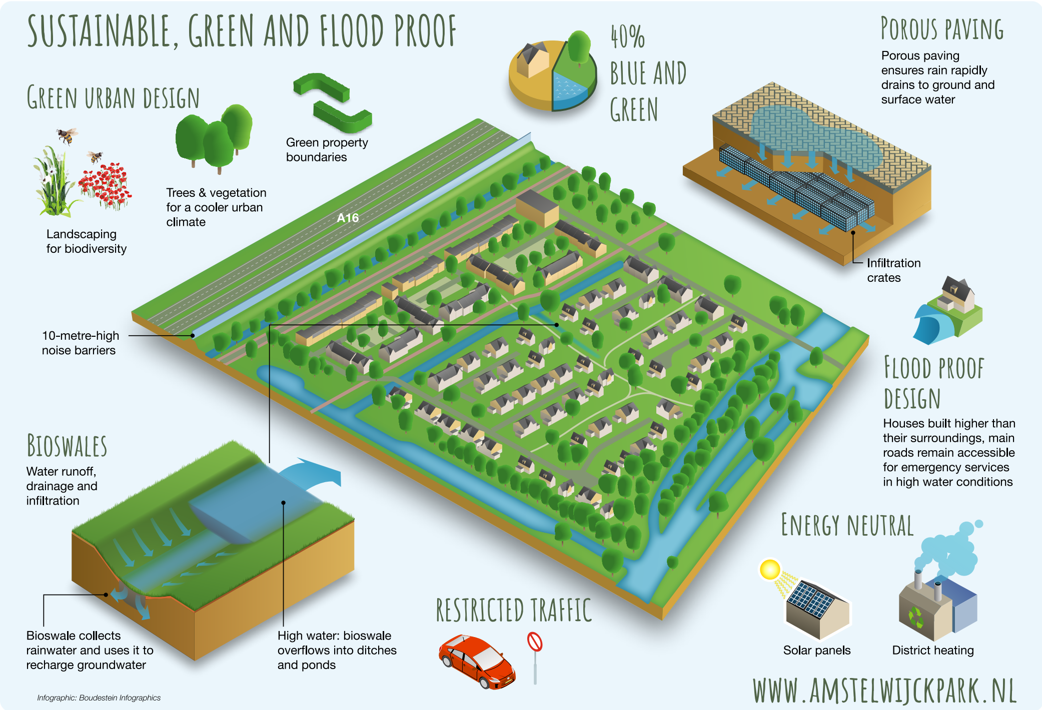

Figure 41: Climate adaptive development plan for the Amstelwijck district in Dordrecht.

Dordrecht wants to be a green and healthy city, but it is also building 11,000 new homes. In Dordrecht's Amstelwijck district, around 800 houses are being built with special attention for nature and climate (Figure 41). Forty per cent of the new housing project will be covered by vegetation and water. The construction companies, property developers, government agencies and funding bodies involved jointly signed the Climate-adaptive construction Covenant of the province of Zuid-Holland The requirements in the covenant will ensure that heavy rainfall and heat will have less impact than on regular areas. Residents will also play an active and important role: they have to keep their front garden partly green and will get tips on how to create nature-friendly gardens. So, all the stakeholders will work together to create a future-proof vegetation and water-rich living environment.

Also interested in Climate-adaptive building?

Since March 2023, developers and other stakeholders can download a guide to get an idea of the climate-adaptive measures they can take to prepare for the future. See www.klimaatadaptatienederland.nl (in Dutch).

Less risk of damage to blossoms due to fewer late spring frosts

Lucas Hulsman and Oscar Hartogensis
(Wageningen University & Research)

As the climate warms, spring temperatures will also rise and so plants and trees will blossom earlier. However, blossoms are vulnerable to frosts, which can occur quite late into spring. It is uncertain whether the arrival of the last frosts will undergo the same acceleration as the blossoming.

When plants blossom before the last spring frost, this is known as a ‘false spring’. Research has indeed revealed that cherry trees are blossoming earlier than they used to. Although the last spring frosts are also falling earlier, the number of false springs has increased slightly since 1980.

According to the KNMI’23 climate scenarios, there will be less and shorter false springs in the Netherlands in the future. This is because the likelihood of frosts will decrease sharply in late spring, due to higher temperatures in north-eastern Europe (the source of the cold weather during that period). The average duration of a false spring in Wageningen is currently 38 days per year (Figure 42). The high emission scenarios in particular describe a substantial decrease to 6 to 10 days around 2100.

The average duration of a false spring will vary throughout Europe. For example, it will increase significantly in southern Scandinavia and the Baltic states, because there the arrival of the last night frosts is accelerating more slowly.

Duration of a false spring
Decreases most in the high emission scenarios

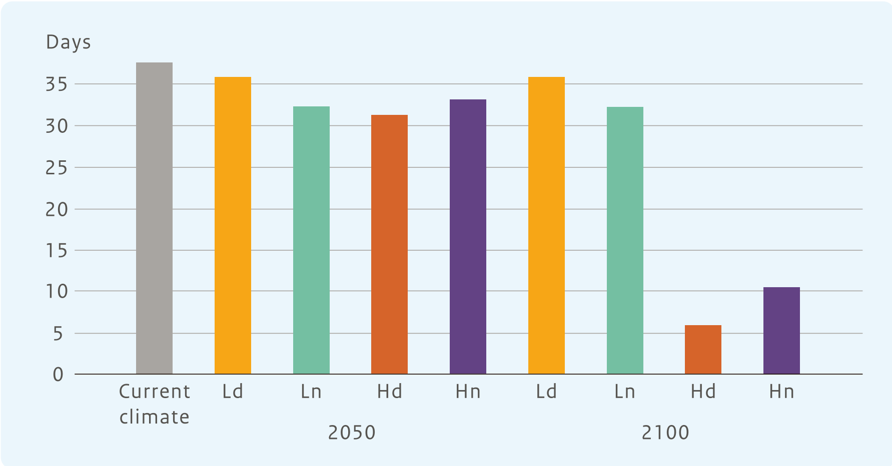

Figure 42: Average period between the first cherry blossoms and the last night frost in the current situation and according to the four KNMI’23 climate scenarios (ref. 14).

Farmers preparing for droughts and extreme precipitation with water and soil management measures

Marco Arts and Bas Worm (Water Board Vechtstromen)

The hamlet of Breklenkamp is situated in the north-eastern tip of the province of Twente. This sandy agrarian landscape with incised stream valleys has suffered a lot from drought in the past years. The streams and fens were dry for long periods, irrigation was impossible and giant trees died off. Heavy precipitation also caused problems, with the lowest lying fields flooding several times a year. The Vechtstromen Water Board closely consults with residents on how to retain as much water as possible. The farmers and general public are aware that drought is already a problem today, and will remain so in the future. The residents learn how to contribute to a more climate resilient region, with the help of the water board. Various measures have been put in place already, such as installing weirs and adjusted water level management (aimed at water retention), improving the water storage capacity of the soil (sustainable soil management) and adapting cultivation with deep-rooted grassland and rich in herbs. The water board also continuously monitors water and soil moisture levels to support adaptive water management.

The new climate scenarios reveal that both the likelihood of droughts (Figure 43) and the likelihood of extreme precipitation will increase. This will make it all the more important to carefully manage the land in cooperation with stakeholders.

Maximum precipitation deficit for April-September

Increasing drought

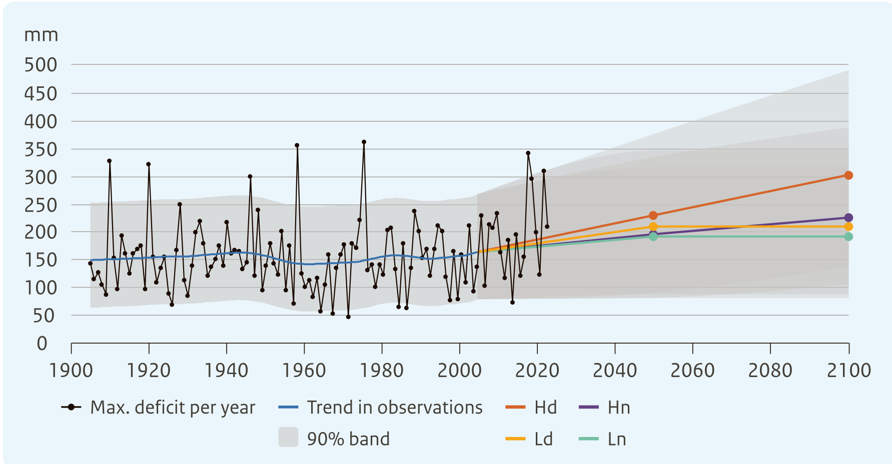

Figure 43: Maximum precipitation deficit in Twente: observations (black) and the four KNMI'23 climate scenarios (2050 and 2100, in four colours).

Oosterschelde flood barrier will need to be closed more often

Robert Vos and Wilbert Huibregtse (Rijkswaterstaat)

Eric van der Weegen

As sea levels rise, the Oosterschelde flood barrier will have to close more often. Since it was constructed 35 years ago, the barrier has closed about 30 times, or around once per year. The KNMI'23 climate scenarios reveal that the sea level will continue to increase in the coming decades, and so the barrier will have to be closed more often: from 3 times per year in the low emission scenarios up to 20 times per year in the high emission scenarios (Figure 44).

Every time it closes, the flood barrier is subject to high wave loads, so parts of the barrier will wear out faster and need to be replaced sooner. While maintenance will have to be carried out more often, there will be less opportunity to do so, because maintenance work cannot be done during periods with high water levels and waves.

So, sea-level rise is shortening the maintenance season, which currently runs from April to October. In order to carry out maintenance as soon as the weather permits, more accurate prediction models for weather, water levels and waves are being developed. However, the chance that the maintenance work will still have to be aborted due to high water levels and waves will increase.

As a result, the storm surge is then temporarily not operational and must remain partially or fully closed.

More closures will not only be problematic for maintenance, but will also harm the fragile Oosterschelde ecosystem.

Oosterschelde flood barrier closures

Number of closures per year will increase this century

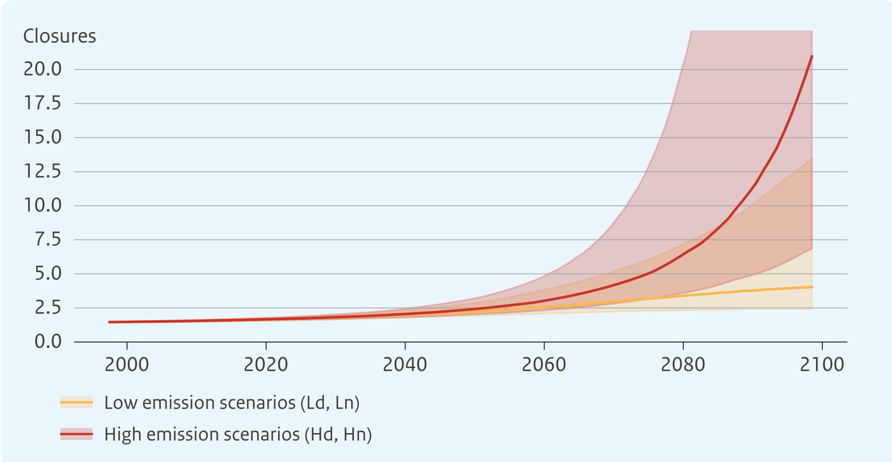

Figure 44: Number of closures of the Oosterschelde flood barrier, based on sea level calculations in two KNMI'23 climate scenarios, and assuming that the barrier closes when sea level reaches three metres above NAP (current closure conditions).

KNMI'23 and KNMI'14 compared

The scientific insights in the 2021 IPCC report (ref. 1), on which the KNMI’23 climate scenarios are based, build on those of the previous IPCC report, which in turn formed the basis for the KNMI’14 climate scenarios (ref. 3). The KNMI’23 climate scenarios are based on the latest, high-resolution climate models and data.

The main changes in the KNMI’23 scenarios compared to the 2014 scenarios are as follows:

- The scenarios are directly linked to the emission scenarios, and thus to climate policy.
- The scenarios look further ahead, to 2150. For sea-level rise to 2300.
- The changes are compared to the most recent reference period for the Dutch climate, 1991-2020.
- The scenarios indicate a stronger increase of drought.
- The sea-level rise scenarios are based on improved understanding of the influence of Antarctica, and include estimates of the highest possible future sea level.
- Better substantiation of the increase in extreme summer precipitation. The increase in the most extreme precipitation remains unchanged high; the increase in less extreme showers (occurring a few times a year) is lower than described in the KNMI’14 scenarios.
- The scenarios include additional information about high temperatures.
- The scenarios also describe the future climate change on the- BES Islands.

See Table 5 for an overview of the differences between the two sets of climate scenarios.

Users of the climate scenarios indicated that water scarcity is one of the main challenges for the future, especially after the recent dry years. In response to this, the KNMI’23 climate scenarios do not only distinguish two high emission (H) and low emission (L) scenarios, but also distinguish two variants (d and n) that differ in the degree of decrease of summer precipitation and the increase in winter precipitation

The KNMI’14 climate scenarios used two other variants (based on changes in air circulation patterns), but these were not directly linked to drought and were not correlated between the seasons, as has been done for the KNMI’23 scenarios. Consequently, annual precipitation increases in all the KNMI’14 climate scenarios, while in KNMI’23 some scenarios show a decrease and some show an increase in annual precipitation. The use of dry and wet variants resulted in a narrower range in temperature change in the low and high emission scenarios than in the 2014 scenarios.

Differences between the KNMI’14 and KNMI’23 climate scenarios

Theme	KNMI’14	KNMI’23
Greenhouse gas emissions (socio-economic scenarios)	Based on moderate and high emissions: RCP4.5 and RCP8.5	Direct link with low and high emissions: SSP1-2.6 (in line with the Paris Agreement) and SSP5-8.5
Annual mean temperature	Wider range around 2050	Implementing the Paris Agreement leads to less warming in the low emission scenario for 2100
Annual precipitation	Increase in all scenarios	Increase or decrease
Extreme precipitation per hour/day	Initial estimates based on observations and climate models	High-resolution climate models provide better substantiation
Sea level	Possible extreme sea-level rise is not taken into account	Additional estimates for the highest possible sea-level rise (low probability, high impact)
BES islands	-	First scenarios for these territories
Reference period	1981-2010	1991-2020
Time horizons	2030 - 2050 - 2085	2033 (1.5°C) - 2050 - 2100 - 2150 2300 (sea-level rise)
Basic information for impact studies	Transformed time series only	Transformed and bias-corrected time series

Table 5: Differences between the KNMI’14 and KNMI’23 climate scenarios

See www.knmi.nl/klimaatscenarios for a Table with the calculations of these differences.

Background information

Definition of a climate scenario

A climate scenario is a plausible and consistent representation of future climate conditions, which is used to consider the possible consequences of human-induced climate change (IPCC). Such a scenario is not a prediction of a future climate, nor can a degree of probability be assigned to it.

Current state of science

The KNMI'23 climate scenarios reflect the current scientific knowledge of the climate. The scenarios are primarily based on the most recent IPCC report (2021) and KNMI research on the climate of the Netherlands. In addition to the latest knowledge about climate processes and the observed trends, model calculations were also essential for building the climate scenarios. KNMI chose to work with a set of four climate scenarios.

This selection was based on the following criteria: *credibility* (are the effects of climate change in the Netherlands likely to fall within the boundaries of the four climate scenarios, and are the scenarios all coherent?), *relevance* (do the scenarios answer a need?) and *clarity* (are the scenarios clearly described?). An international advisory committee supervised the development of the KNMI'23 climate scenarios. The choices were made in consultation with a sounding board of stakeholders and users of climate scenarios.

Shared Socioeconomic Pathways (SSPs)

Climate researchers use Shared Socioeconomic Pathways (SSPs) to compare the outcomes of various climate models. These SSPs describe demographic, socio-economic and technological developments in the future based on different levels of greenhouse gas and aerosol emissions and land use patterns. In the first section of the sixth assessment report on the physical basis of the climate system, the IPCC describes outcomes based on five SSPs, showing a wide range of potential outcomes. They range from a scenario with ambitious climate policies in line with the Paris Agreement (1.5°C, SSP1-1.9) to a scenario in which emissions continue to increase (SSP5-8.5). Since global warming is mainly caused by the amount of greenhouse gases in the atmosphere, a low emission scenario results in less warming than a high emission scenario. So, global climate policy will determine which emission scenario will come about, and what this will mean for global warming. The differences in warming between these SSPs will play a major role, especially in the long term (after 2050).

Scientific uncertainty

Besides uncertainty about the future global climate policy, there is also scientific uncertainty about the extent to which the climate system will respond to a change in atmospheric greenhouse gas levels. At the global level, this means there is also uncertainty about average global warming in the future. Climate sensitivity (the increase in the global mean temperature associated with doubling the amount of CO_2 in the air) is now estimated to be between +2.5 and +4.0°C, a more precise estimate than in the previous 2013 IPCC report.

Uncertainties about climate processes play an even bigger role at the regional level. For example, summer levels of precipitation, soil moisture, cloud cover and radiation are uncertain. These processes can give rise to a 'positive feedback loop'. For example, dry soils lead to less cloud cover and precipitation and more solar radiation, and so to higher temperatures that dry out the soil even more. In turn, these processes influence the occurrence of high and low pressure areas. These areas, and the associated atmospheric circulations, also fluctuate in the longer term.

In principle, such uncertainties about the climate of the future can be reduced by more study into how the climate system works, and by developing more reliable climate models. However, the climate also includes an unpredictable component. This natural variability is caused by interaction between the atmosphere, the oceans, the land masses and the ice sheets. This means that considerable differences can occur, even over 30 year periods. We can estimate the influence of this natural variability by running various model simulations, the only difference being a small disturbance in the initial situation. In the course of time these simulations start showing differences in the results. Temperature changes due to climate change (the trend) will exceed that of the natural temperature variability (the noise) within decades. But this does not apply to the general patterns of precipitation and wind. For example, the natural variation in average winter precipitation over 30 years is about 10%. This means that any given 30-year period could be 10% wetter or drier than another.

The observed changes are the result of a combination of climate change and natural variability, but it is very difficult to distinguish between the two. This makes it difficult to accurately evaluate the models based on the observed trends. A model that correctly represents climate processes does not necessarily also accurately reflect trends, while a model that accurately represents an observed trend is not necessarily a reliable model.

Model calculations

The climate scenarios are based on analyses of 33 different climate models. Additional calculations were also carried out using the EC-Earth3 and RACMO2 KNMI climate models. This resulted in more than 8000 years of climate data for the Netherlands, with a spatial resolution of about 10 kilometres. Eight model calculations representing periods of 30 years were selected for each of the four KNMI'23 climate scenarios. The scenarios were distinguished by global greenhouse gas emissions and the change in annual precipitation. The RACMO2 calculations were selected based on the distribution of annual precipitation in the global model calculations (these models were also evaluated by the IPCC). The availability of multiple calculations for each scenario also made it possible to distinguish the trend (climate change) from the noise (natural variability). Besides these model calculations, additional data obtained from observations and ultra-high resolution models was used to simulate a number of indicators, including precipitation extremes. Please refer to the scientific report (ref. 15) for more detailed information about the methodology used.

Fluctuations, spikes and coincidental weather extremes

In addition to global warming that is clearly human-induced, the observations also reveal fluctuations in the climate due to natural variability on all time scales. Due to a coincidental combination of events, various human-induced and natural climate effects can reinforce each other and lead to 'spikes' in the observed extremes. This was the case on 25 July 2019, when the old heat record of 38.6°C (recorded in Warnsveld on 23 August 1944) was exceeded by more than 2°C (40.7°C in Gilze-Rijen). Due to a combination of extreme drought and a powerful high-pressure area with very sunny weather, all the solar energy that day was converted into warming the earth's surface and the air above it.

Climate models take account of such extremes caused by natural variability. For example, we see significant outliers in the 16 simulations for winter precipitation in the Netherlands during the reference period (1991-2020, Figure 45). This means the observed precipitation in a given year can deviate significantly from the long-term trend.

Natural variability

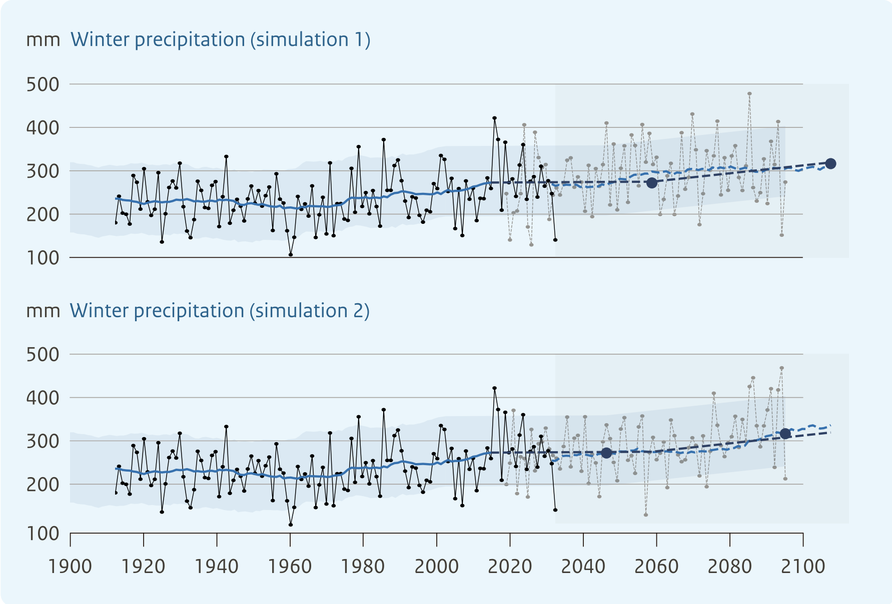

Figure 45: Calculated variability in winter precipitation. Winter precipitation was calculated based on two simulations for the same climate scenario (light blue dotted line). Dark blue: average of all simulations used for this scenario.

Processes that are not taken into account in climate models

Climate models are getting increasingly better at describing the physical, chemical and biological processes that influence the climate, and are based on increasingly higher spatial resolutions. However, there are a number of processes that remain difficult to simulate. This is due to a lack of sufficiently accurate measurements, poor spatial resolution and because some natural events (such as a major volcanic eruption) are impossible to predict. For instance, the accelerated disintegration of the Antarctic ice sheet cannot yet be accurately modelled. This also applies to changes in major ocean current systems, which are influenced by the volume of North Atlantic ocean water that sinks to greater depths. This only takes place at a relatively small scale and affects the strength of the Gulf Stream. According to climate models, the Gulf Stream will weaken during this century, but the extent to which is very uncertain. There is also uncertainty about the rate of permafrost thawing, which involves the release of CO_2 and methane. While these processes and events can be described, quantification of the release is uncertain. Furthermore, some climate models assume that volcanic eruptions will continue to occur as frequently in the future as in the 20th century. But this cannot be predicted, while an increase in the frequency of eruptions could slow the rate of climate warming, because major volcanic eruptions can lead to several years of climate cooling.

Climate sensitivity and feedback loops in the climate system

The low emission scenario assumes the world's governments will implement ambitious climate policies (as set down in the Paris Agreement). The high emission scenario assumes an increase in emissions at the current rate until 2080 and only then a levelling off. This scenario probably overestimates global CO_2 emissions, as many measures to reduce greenhouse gases are already being implemented. However, there is still the possibility that the temperature changes calculated for the high emission scenario (H) using the best estimate of climate sensitivity could become reality. In case of a high climate sensitivity the most likely warming of 4.9°C around 2100 (SSP5-8.5) could also be reached in the moderate emissions scenario (SSP3-7.0). Moreover, feedback loops in the climate system can cause additional natural emissions, for example through deforestation, oceans absorbing less greenhouse gases, or greenhouse gases being released with permafrost thawing. Climate models cannot yet sufficiently take account of these feedback loops in the calculations of CO_2 concentrations in the various SSPs. Climate change in the Netherlands is therefore very likely to fall somewhere between the L and H scenarios.

Three estimates of the maximum sea-level rise

There is as yet no scientific consensus about the maximum possible rate of sea-level rise under a high emission scenario. Three methods have been used to estimate that rate:

1) *Physical evidence discussion*. This method involves organising an open discussion between climate scientists and sea level experts about the maximum sea-level rise that is physically plausible (ref. 16).

2) *Marine Ice Cliff Instability*. For this method, we used the result of a numerical model that simulates the physical mechanisms of Marine Ice Cliff Instability in Antarctica (ref. 17).

3) *Structured Expert Judgement*. This method uses a questionnaire that was sent to the world's leading glaciologists. They were not required to explain their views, or justify their estimates of the contributions of Antarctica and Greenland to sea-level rise based on physical mechanisms (ref. 18), so this method produced less conservative estimates than the 'Physical evidence discussion'.

Each method resulted in an estimate of the maximum sea-level rise. We cannot calculate the probability that these estimates will be exceeded. However, based on the characteristics of these methods and a comparison with the reference scenarios, we assume a probability of 0 to 5% under the high emission scenario. This probability decreases with moderate emissions.

Background to the climate scenarios for the BES islands

The same global climate models and methods were used for the climate scenarios for the BES islands as for the Netherlands. However there were some differences. While a regional climate model was used to translate the data of the global models to the Netherlands situation, for the BES islands, this translation was made using a statistical model. We selected a group of 10 'wet' and 10 'dry' models from the results of the 29 models available for the Caribbean Netherlands. These groups of models represented the maximum increase and decrease in precipitation by 2100. The relatively low resolution models, based on past temperature and precipitation records, were extrapolated with the help of measurements carried out in the region of the BES islands. This is because there are no good data available for the BES islands themselves. Instead, we conducted a 're-analysis' of a weather model for the temperature, and we used rainfall data from Curacao (80 km from Bonaire) and Sint Maarten (50 km from Sint Eustatius and Saba) for precipitation.

Just as for the Netherlands, we have presented the climate scenarios for the BES islands separately by season. While in the Netherlands the temperature largely determines the season, on the BES islands this is precipitation. So, for the Caribbean Netherlands, we distinguish between the wet season (May-November) and the dry season (December-April).

El Niño and La Niña are climate patterns that occur around the equator in the Pacific Ocean. They affect global air circulation, which is driven by fluctuations in seawater temperatures in the tropical Pacific Ocean. La Niña causes lower seawater temperatures in the eastern Pacific Ocean than normal. Air rises above the western Pacific and above the Caribbean, and falls above the central Pacific (Figure 46). Easterly or westerly winds blow in the lower and upper air layers. This is called the Walker circulation, and it shifts to the west during a La Niña event. Where the air rises, as in the Caribbean, there is more precipitation, and where the air descends, there is less. During El Niño, the eastern Pacific warms up, shifting the Walker circulation eastwards. Air rises above the central Pacific and falls above the Caribbean. So, the BES islands experience less precipitation during El Niño than during La Niña.

Walker circulation and seawater temperature

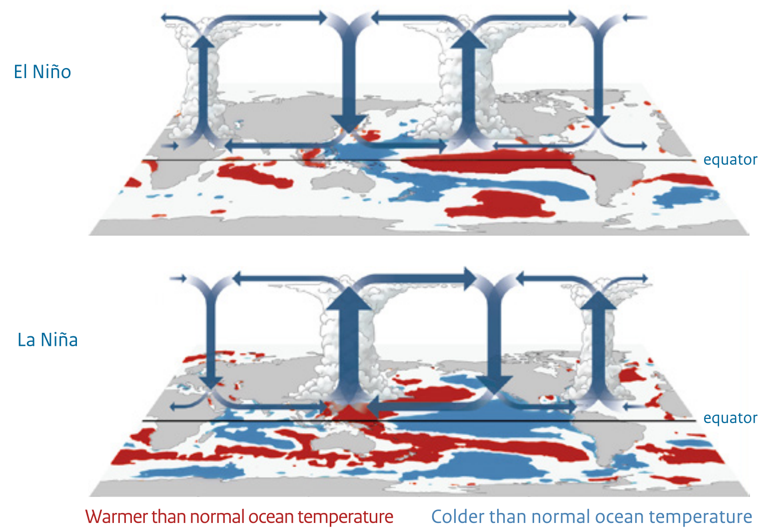

Figure 46: Changes in air circulation at the equator (Walker circulation) and ocean temperatures during El Niño (top) and La Niña (bottom). Source: KNMI/NOAA.

Glossary

Growing season: April to September.

Return period: the average time between two events where a certain value is exceeded (e.g. 50 mm of precipitation during one day). The return period can be calculated for a large region (e.g. the Netherlands) or a specific location. Local return periods are generally much longer than regional return periods.

Urban heat island effect: the phenomenon that average temperatures in cities are higher than in the surrounding countryside due to more warming during the day and less cooling at night.

Heatwave: at least five consecutive summer days (maximum temperature 25.0°C or higher) in De Bilt, of which at least three with tropical temperatures (30.0°C or higher).

IPCC: Intergovernmental Panel on Climate Change.

Paris Agreement: international treaty concluded at the end of the Paris climate conference in 2015, in which it was agreed to limit global warming to well below 2°C and preferably no more than 1.5°C.

Climate sensitivity: the global temperature rise if CO_2 levels double.

Climate scenario: plausible and coherent overview of possible future climate conditions based on historical data and assumptions about greenhouse gas emissions. Used to conduct exploratory studies into the potential effects of climate change.

Natural climate variability: climate variations around the long-term average, caused by the many complex processes and interactions in the climate system.

Precipitation deficit: the sum of the potential evaporation minus precipitation between 1 April to 30 September.

Reference period: period used to compare current or future data, usually a period of 30 years. The reference period for the KNMI'23 climate scenarios is 1991-2020.

SSP: Shared Socioeconomic Pathway. SSPs each have a scenario number followed by a number for the approximate radiative forcing (in W/m^2) in 2100. The scenarios increase from 1 for the most sustainable path, to 5 for the highest emissions path. In this report, SSP1-2.6 is the low emission scenario, and SSP5-8.5 is the high emission scenario.

Time horizon: year or period in the future to which a scenario applies.

Emission scenario: plausible future emissions of greenhouse gases and aerosols, based on a coherent and internally consistent set of demographic, socio-economic and technological developments, including climate policies.

Vector: an organism, for example a tick or mosquito, which can transmit pathogens or parasites from one host (animal or plant) to another.

Winter: December, January and February.

Winter half-year: October to March.

Summer: June, July and August.

Summer half-year: April to September.

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Key figures for five locations

Locations	Indicator (number of)	Climate in 1991-2020 = reference period	**2050** (2036-2065)				**2100** (2086-2115)			
				Ln	Hd	Hn	Ld	Ln	Hd	Hn
De Bilt	Summer days (max. temp. ≥25°C) per year	28 days	41	39	52	45	41	39	93	84
	Tropical days (max. temp. ≥30°C) per year	5.0 days	9.4	8.5	13	10	9.4	8.5	35	25
	Frost days (min. temp. <0°C) per year	53 days	39	40	33	30	39	40	11	10
	Ice days (min. temp. <0°C) per year	6.4 days	3.7	3.9	3.1	3.2	3.7	3.9	0.4	0.4
De Kooy	Summer days (max. temp. ≥25°C) per year	11 days	15	15	20	18	15	15	48	44
	Tropical days (max. temp. ≥30°C) per year	1.3 days	2.1	2.1	2.9	2.4	2.1	2.1	8.4	6.9
	Frost days (min. temp. <0°C) per year	35 days	25	26	22	20	25	26	7.0	7.0
	Ice days (min. temp. <0°C) per year	5.9 days	3.8	3.6	3.0	2.8	3.8	3.6	0.6	0.4
Eelde	Summer days (max. temp. ≥25°C) per year	24 days	38	37	43	39	38	37	80	72
	Tropical days (max. temp. ≥30°C) per year	5.1 days	9.6	9.4	12	9.4	9.6	9.4	28	21
	Frost days (min. temp. <0°C) per year	63 days	48	49	42	40	48	49	16	15
	Ice days (min. temp. <0°C) per year	9.2 days	5.2	5.1	5.0	4.4	5.2	5.1	0.8	0.4
Vlissingen	Summer days (max. temp. ≥25°C) per year	17 days	26	24	34	30	26	24	74	67
	Tropical days (max. temp. ≥30°C) per year	2.3 days	4.4	3.9	7.0	5.3	4.4	3.9	19	15
	Frost days (min. temp. <0°C) per year	20 days	12	13	11	9.0	12	13	1.0	1.0
	Ice days (min. temp. <0°C) per year	3.3 days	1.5	1.7	1.1	1.4	1.5	1.7	0.0	0.0
Maastricht	Summer days (max. temp. ≥25°C) per year	36 days	55	52	64	56	55	52	108	99
	Tropical days (max. temp. ≥30°C) per year	7.7 days	16	14	20	16	16	14	52	41
	Frost days (min. temp. <0°C) per year	51 days	41	41	32	30	41	41	13	12
	Ice days (min. temp. <0°C) per year	7.8 days	4.3	4.0	3.9	3.3	4.3	4.0	0.2	0.4

Table 6: KNMI'23 scenario table for five locations. The scenario figures represent the average number of days per year around 2050 and around 2100.

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