How to incorporate climate change projections in the probabilistic assessment of civil structures

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Civil structures such as buildings, bridges, and flood defences, need to be designed to withstand extreme climatic actions during their entire design lifetime. Due to climate change, more extreme conditions are expected for those events that are relevant to civil structures (*e.g.* an increase in sea level or precipitation). Projecting the future climate is however an extremely challenging task which is highly subjected to uncertainties. This study investigates how these uncertainties can be included in the probabilistic design and assessment of civil structures. This is done by evaluating the uncertainties in global (IPCC, AR5) and regional (KNMI'14, the Netherlands) climate change projections. We identified that there is currently a discrepancy between the expectations of structural engineers with respect to uncertainty quantification on the one hand, and the limitations of climate science on the other hand. This leads to the following engineering challenges on (1) how to include or quantify uncertainties related to the climate change scenarios; (2) how to translate the available information about modelling uncertainties in climate models into the required quantitative information for traditional risk and reliability assessments; and (3) how to employ the provided climate change projections for the 30-year mean-values for the estimation of the required 50, 1000, or even 10.000 year extreme values. We discussed how these challenges lead to pragmatic modelling choices of engineers, and how this potentially leads to reduced structural safety. However, we believe that with a close collaboration between climate experts and engineers, many of these challenges can be addressed within the current limitations of science.

Key words: Climate change, structural reliability, modelling uncertainties, AR5, KNMI'14

1 Introduction

Civil structures, such as buildings, bridges, or flood defences, need to be designed to withstand extreme climatic actions during their entire design lifetime, which typically lies between 50 to 100 years [1]. Due to climate change, however, more extreme weather conditions are expected for those events that are relevant to civil structures. The latest study from the Intergovernmental Panel on Climate Change (IPCC) states that an increase in global mean sea level, or an increase in precipitation, are likely events to happen in the near future [2]. From a structural safety point of view, these climate changes need to be considered in both the design of new structures and the assessment of existing ones [3].

Traditionally, the statistical properties of extreme weather events are determined from historical data, see *e.g.* [4] for the statistical evaluation of extreme wind speeds, or [5] for the statistical evaluation of extreme sea water levels. In this approach, it is implicitly assumed that the weather conditions are stationary, *i.e.*, do not change in time. Due to climate change, however, the actual climate conditions are not stationary and are expected to change significantly in the future. As such, the traditional approach for the determination of extreme climatic actions should be updated to include climate change projections as well.

To include climate change projections in the assessment of structures, several steps should be taken as visualized in Figure 1. First, a set of plausible IPCC scenarios are constructed based on various assumptions about the anthropogenic driving forces [6]. Then, global climate models project the future changes for a variety of so-called climate variables (*e.g.* global mean temperature rise, global mean sea level rise, atmospheric circulation, *etc.*) both for the near and distant future [2]. The results from the global climate models are then used as input for regional climate models considering regional scenarios. The last step, which is the responsibility of the engineers, is to incorporate the regional projections into the design and assessment of civil structures.

It is acknowledged that each step in Figure 1 is an extremely challenging task. Firstly, each of the chosen climate scenarios is subjected to uncertainties due to the unpredictability of human behaviour [7]. Furthermore, the climate varies temporally and spatially due to complex interactions between different factors, such as solar radiance, emission from volcanoes, changes in the Earth’s orbit, physical and biogeochemical interactions of the climate system, oceanic changes, and anthropogenic impacts [8]. Predictability of the future climate conditions at a time scale of 30 to 100 years ahead and a relatively small spatial scale (*e.g.* the Netherlands) is therefore bounded by uncertainties.

From a structural reliability point of view, all uncertainties relevant to the design of the structure need to be taken into account probabilistically, *i.e.*, by modelling them as stochastic random variables [9]. This includes uncertainties in (a) the loading parameters (such as the wind speed or sea water level), (b) the resistance parameters (such as the material properties), (c) the adopted strength or loading models (often referred to as modelling uncertainties), and (d) the different climate scenarios. At this stage, however, it is not entirely understood how to include (uncertainties in) climate change projections in the probabilistic design and assessment of civil structures. This study investigates this by performing a literature review on the global (from IPCC) and regional (the Netherlands) climate change projections, with a special focus on uncertainty modelling, see Section 2 and 3 respectively. Based on the literature review, a discussion is provided in Section 4 about the challenges that engineers may face whilst trying to incorporate the climate change projections in the design and assessment of civil structures. Conclusions and recommendations are given in Section 5.

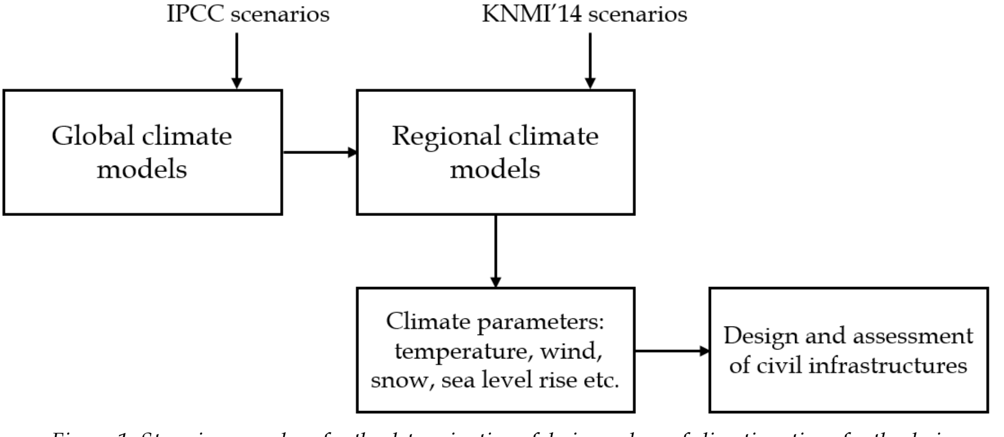


Figure 1. Stepwise procedure for the determination of design values of climatic actions for the design and assessment of civil structures

2 Global climate change assessments from IPCC

The science of climate change, its natural, political, and economic impacts, and possible response strategies are assessed by the intergovernmental body of the United Nations, called the IPCC. This section summarizes the climate change projections as presented in the IPCC's Fifth Assessment Report [2], from here on referred to as AR5. It is however noted that at the moment of writing, the IPCC has already launched AR6, which is not yet taken into account in the current paper. In the following sections, we start with providing an overview on the IPCC scenarios and Representative Concentration Pathways (Section 2.1), followed by presenting the results IPCC climate projections (Section 2.2). Next, we discuss the uncertainties involved in the IPCC climate projections (Section 2.3) and provide an example for the projected global mean sea level rise (Section 2.4).

2.1 IPCC scenarios and Representative Concentrative Pathways (RCPs)

In order to assess the future climate, the AR5 uses a set of plausible climate scenarios that are constructed based on various assumptions about the anthropogenic driving forces, such as demographic and socio-economic developments, land use, technological changes, and their relationships [6]. The scenarios are represented by so-called the Representative Concentration Pathways (RCPs), each providing a trajectory for a possible time evolution of the emission concentrations of greenhouse gases and aerosols, and land use up to the year 2100 and further. Four RCPs, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, are employed, which are labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 Watt/m^2, respectively). Figure 2 shows the CO_2-equivalent concentrations for each RCP.

The process of selecting the representative RCPs is carefully done by a group of experienced (climate) experts [6]. It is hereby important to remark that the chosen RCPs merely represent conditional foresights for future climate change, and that the real climate change might evolve outside of these scenarios [8]. After all, it is difficult to predict the future behaviour of a single human being, let alone of the entire Earth's population. One of the reasons for this, is so-called reflective human behaviour (*i.e.* actions that are influenced by information) which is highly intractable in the context of prediction [10]. As such, the scenarios represented by the RCPs are highly subjected to uncertainties. How engineers currently deal with these uncertainties is further discussed in Section 4.1.

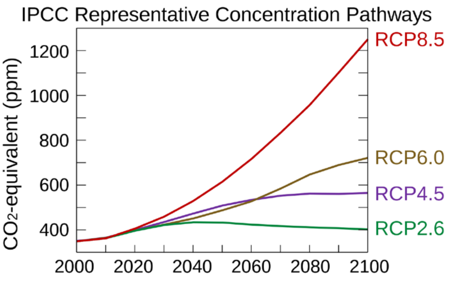


Figure 2. CO_2-equivalent concentrations according to the four RCPs as employed in AR5 (source: Wikipedia, adapted from [11])

2.2 *IPCC climate projections, models, and variables*

The AR5 defines the term "climate projection" as a potential future situation under assumption of a scenario, whilst a "climate prediction" or "climate forecast" is an estimate of the actual evolution of the climate in the future. Stated differently, climate projections can be seen as a tool to explore the "space of options" which may or may not occur in the future [12].

In order to obtain the future projections, climate change models are used to simulate the response of the climate system. On a global scale, this occurs within the so-called Coupled Model Intercomparison Project Phase 5 (CMIP5)[1], which combines a large amount of climate models worldwide [13]. These climate models range from simple energy balance models to complex and computationally demanding systems, see Table 1. Within the CMIP5, the climate change model results are generated over four RCPs using: (1) Atmosphere–Ocean General Circulation Models (AOGCMs), which are also called General Circulation Models (GCMs); (2) Earth System Models (ESMs); and (3) Earth System Models of Intermediate Complexity (EMICs). Each model focuses on different components of the climate system and is developed and employed by various organizations around the world. Historical observations of changes in the climate system, such as temperature, energy budget, heat content, water cycle and cryosphere, carbon, and other biogeochemical cycles, but also the IPCC scenarios, serve as input for the models.

[1] CMIP5 provides a framework for coordinated assessments of the coupled atmosphere-ocean general circulation models (GCMs) in the IPCC 5th assessment report (AR5).

Table 1. Main features of the AOGCMs, ESMs and EMICs participating in CMIP5 including components and resolution of the atmosphere and the ocean models [2]. Model complexity for the components is indicated by colour shading (darker colours indicate higher complexity)

			AOGCM					ESM			
	Model name		Atmos	Land Surface	Ocean	Sea-Ice	FC	Aerosol	Atmos Chem	Land Carbon	Ocean BGC
	ACCESS1.0, ACCESS1.3	Australia									
	BCC-CSM1.1, BCC-CSM1.1(m)	China									
	BNU-ESM	China									
	CanCM4	Canada									
	CanESM2										
	CCSM4										
	CESM1 (BGC)										
	CESM1 (WACCM)	USA	HT								
	CESM1 (FASTCHEM)										
	CESM1 (CAM5)										
	CESM1 (CAM5.1-FV2)	USA									
	CMCC-CM, CMCC-CMS	Italy	HT								
	CMCC-CESM		HT								
	CNRM-CM5	France									
	CSIRO-Mk3.6.0	Australia									
	EC-EARTH	Europe									
CMIP5	FGOALS-g2	China									
	FGOALS-s2										
	FIO-ESM v1.0	China									
	GFDL-ESM2M, GFDL-ESM2G										
	GFDL-CM2.1	USA									
	GFDL-CM3		HT								
	GISS-E2-R, GISS-E2-H	USA	HT					p2,p3*	p2, p3*		
	GISS-E2-R-CC, GISS-E2-H-CC		HT					p2,p3*	p2, p3*		
	HadGEM2-ES										
	HadGEM2-CC	UK	HT								
	HadCM3										
	HadGEM2-AO	Korea									
	INM-CM4	Russia									
	IPSL-CM5A-LR / -CM5A-MR / -CM5B-LR	France	HT								
	MIROC4h, MIROC5		HT								
	MIROC-ESM	Japan	HT								
	MIROC-ESM-CHEM		HT								
	MPI-ESM-LR / -ESM-MR / -ESM-P	Germany	HT								
	MRI-ESM1	Japan	HT								
	MRI-CGCM3		HT								
	NCEP-CFSv2	USA									
	NorESM1-M	Norway									
	NorESM1-ME										
AMIP	GFDL-HIRAM C180 / -HIRAM C360	USA									
	MRI-AGCM3.2S / -AGCM3.2H	Japan									

EMIC

Model name		Atmos	Ocean	Land Surface	Sea Ice	Coupling	Biosphere	Ice Sheets	Sediment & Weathering
Bern3D	Switzerland								
CLIMBER2	Germany								
CLIMBER3	Germany								
DCESS	Denmark								
FAMOUS	UK								
GENIE	UK								
IAP RAS CM	Russia								
IGSM2	USA								
LOVECLIM1.2	Netherlands								
MESMO	USA								
MIROC-lite	Japan								
MIROC-lite-LCM	Japan								
SPEEDO	Netherlands								
UMD	USA								
Uvic	Canada								

For each RCP, the AR5 projects the future climate for several (global) climate variables, such as the Global Mean Surface Temperature (GMST) change, the Global Mean Sea Level (GMSL) rise, the changes in atmospheric circulation, *etc*. Many of these variables are presented as 30-year mean values for the time periods of 2046-2065 and 2081-2100, whereby the changes are provided with respect to the reference period 1986-2005. Additionally, the AR5 provides an assessment on climate extremes such as droughts, floods, heat waves, *etc.* However, the assessment of climate extremes is particularly challenging considering the intrinsically rare nature of these events and their complex physical nature. Therefore, the AR5 provides only qualitative information on the extremes. From an engineering point of view, however, quantitative information on extreme weather events is of utmost importance. How engineers currently deal with this challenge is further discussed in Section 4.3.

2.3 ***Uncertainties in the global climate projections***

Any model generation is guided by a balance between the ability to represent reality, and the pragmatic need for simplicity and generality such that a large variety of problems can be analysed [14]. As a result, any model prediction, including those for climate change assessments, will deviate from reality and is subjected to modelling uncertainties. In the context of the AR5, these modelling uncertainties are referred to as "structural uncertainties" [15]. The AR5 employs several approaches to quantify and communicate these modelling uncertainties, which range from a fully quantitative approach (*i.e.*, model ensembles) to a semi-quantitative approach (*i.e.*, the quantitative likelihood language), to a fully qualitative approach (*i.e.*, qualitative confidence level). These approaches will briefly be discussed below and in Section 4.2.1.

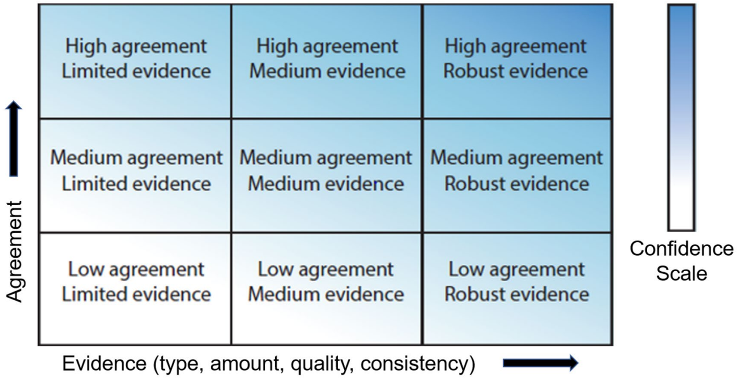
2.3.1 Model ensembles

The AR5 uses results from model ensembles to provide quantitative information on the modelling uncertainties in the climate change projections. As discussed in the previous section, climate projections are generated from the CMIP5 model framework. Hereby different CMIP5 models will result in different model outcomes, even though these models are projecting the same climate variable for the same RCP [16]. These differences are caused by a difference in complexity of the models, different combinations of input-parameters, different discretization of the land-soil conditions, *etc.* To account for these differences, the AR5 presents the climate projections as the mean of these model ensembles. It is hereby expected that the ensemble mean leads to a better overall projection the individual models [16]. For some climate variables, the AR5 additionally provides the 90% range over these model ensembles. It should however be noted that this 90% range does not necessarily coincide with the 90% confidence bound in the traditional statistical sense, which will be further explained in the next section.

2.3.2 Calibrated likelihood language

Another metric used by the AR5 is the calibrated likelihood language, which connects the quantitative likelihood of a finding with a representative term from the daily language, see Figure 3. The quantitative likelihood can be based on statistical analysis of observations, results from model ensembles, or expert judgement. The likelihood language is sometimes used to supplement the information obtained from the model ensemble. This is

Qualitative confidence level



Calibrated likelihood language

Term	Likelihood of outcome
Virtually certain	99-100%
Very likely	90-100%
Likely	66-100%
About as likely as not	33-66%
Unlikely	0-33%
Very unlikely	0-10%
Exceptionally unlikely	0-1%

Figure 3. Two metrics for communicating the degree of certainty in an outcome from AR5 [2]

exemplified in Section 2.4 for the GMSL rise. This means that even though the ensemble range is given as 90%, the corresponding likelihood term may be "likely" (66-100%) instead of "very likely" (90-100%) after consideration of additional modelling uncertainties which were not captured by the model ensemble.

2.3.3 Qualitative confidence level

The last metric employed in the AR5 is the qualitative confidence level, which expresses the validity of a finding, based on the evidence (*e.g.* understanding, theory, data, models, expert judgement), and so-called, the degree of author team's agreement, see Figure 3. The confidence increases towards the top right corner. Although not explicitly mentioned in the figure, five confidence levels are distinguished as very low, low, medium, high, and very high. The qualitative confidence level serves as a clear and transparent metric for the communication of modelling uncertainties in the climate change projections. The metric is however fully qualitative, which makes it difficult for engineers to use the information in quantitative reliability calculations. The confidence level will therefore not be discussed further in this study.

*2.4 **Example: IPCC projections on the Global Mean Sea Level rise (GMSL rise)***

The AR5 projection of the GMSL rise is given in Table 2. As discussed, both the ensemble mean, and the 90% ensemble range are given. After including additional uncertainties and accounting for different levels of confidence in the (sub-)models, the AR5 evaluates the provided ranges as "*likely*" (*i.e.*, likelihood between 66% and 100%). For both time horizons, the confidence level is defined as *medium*.

Table 2. The AR5 projection of the GMSL rise and likely range for 2046-2065 and 2081-2100 [2]

		2046-2065		2081-2100	
	Scenario	Mean (m)	*Likely* range (m)	Mean (m)	*Likely* range (m)
Global sea level rise (m)	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

3 Regional climate change assessment for the Netherlands

Since the IPCC (AR5) does not provide climate projections for individual countries, the Dutch Meteorological Institute, KNMI[2], [8] translates the global projections from the AR5 to the regional projections for the Netherlands. This section summarizes these projections, which are from here on referred to as KNMI'14. Firstly, we provide an overview on the KNMI'14 climate scenarios and their connection with the global RCPs. Then, we discuss the climate models used for the KNMI'14 projections and the uncertainties related to these projections. Lastly, we present the climate projections, variables, and indicators, and provide some examples.

3.1 KNMI'14 climate scenarios and their connection with the RCPs

Considering the RCPs, KNMI developed four climate scenarios which apply to the Netherlands specifically. They are used to provide projections for the time periods of 2036-2065 (around the year 2050) and 2071-2100 (around the year 2085), with respect to the reference period of 1981-2010 (around the year 1995). The scenarios are constructed based on *plausibility* (complied with theory and observation, internally consisted models, and results), *relevance* (fitted in the need and interest of the stakeholders) and *legitimacy* (transparently constructed, different views embedded) (for more information, see [8]). Extreme scenarios with low chance and climate transitions are not considered. Historical observations, expert judgement, and the input from the IPCC were taken into account while constructing the scenarios.

In total four scenarios are considered, which are referred to as G_H, W_H, G_L, and W_L, see Figure 4. The scenarios are derived from the global mean surface temperature rise (GMST rise) and the changes in atmospheric circulation as described below.

- It is distinguished between moderate GMST rise (G) and higher GMST rise (W). The moderate scenarios (G) present an increase of 1°C for 2050 and 1.5°C for 2085. The warm scenarios (W) show a higher increase in the GMST rise, with 2°C for 2050 and 3.5°C for 2085. The chosen temperature rises based on the range of values generated by CMIP5 for the RCP4.5 and RCP8.5, as is illustrated in Figure 4.
- Change in air circulation is considered as a main driver of the regional conditions which strongly deviate from the global estimations. Variations in regional air conditions are

[2] Koninklijk Nederlands Meteorologisch Instituut

distinguished between two different groups: “L” for low air circulation (*i.e.*, drier winters and summers) and “H” for high air circulation (*i.e.*, wetter winters, drier summers). Also here, the choices for the atmospheric circulations are connected to the scenario choices for the increase in GMST rise.

KNMI emphasizes that the regional scenarios cannot be linked one-to-one to the global RCPs. Furthermore, since the KNMI’14 scenarios, as for similar to the IPCC scenarios, are developed based on a number of assumptions, KNMI points out that the provided scenarios only represent conditional foresights for future climate change, and that the real climate change may evolve outside the range of the four scenarios. This especially holds when considering smaller areas and shorter time periods. As in the case of the global RCP scenarios, therefore, the regional KNMI’14 scenarios are highly subjected to uncertainties. Considering this, KNMI states that the quantitative estimate of the likelihood of any scenario is not the scope of their assessment, and that assigning probabilities to different scenarios is discouraged. The challenges that engineers face whilst dealing with these uncertainties are further discussed in Section 4.1.

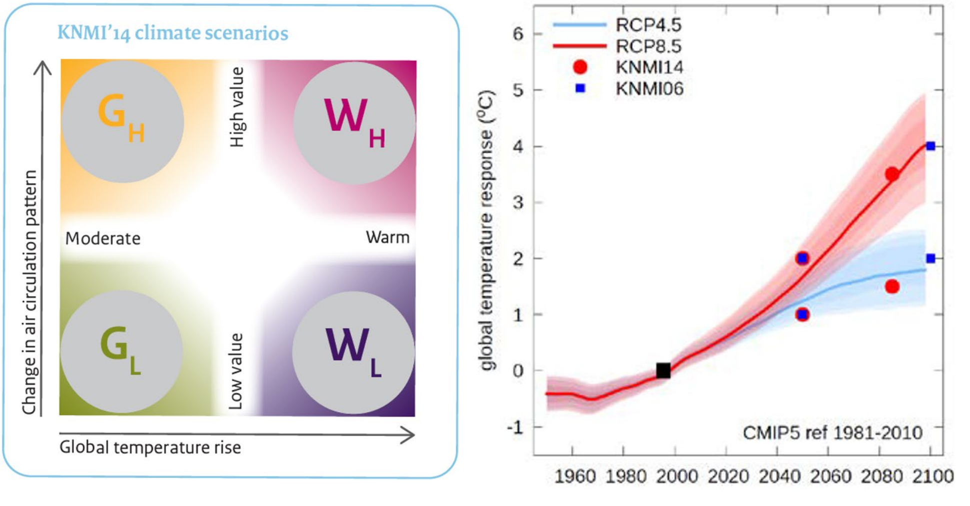


Figure 4. Left: KNMI'14 climate scenarios. Right: GMST rise according to CMIP5 climate projections for two RCPs including the starting points for the KNMI’14 scenarios [8]. The solid-coloured lines represent the CMIP5 ensemble mean, and the lighter shading indicates the 50%, 80% and 90% ensemble ranges. The dots and squares indicate the global temperature rise selected for the KNMI’14 climate scenarios.

3.2 Climate models for KNMI'14 climate projections

The global IPCC climate models from CMIP5 are downscaled using regional climate models (RCMs) derived for the Netherlands. Each RCM is forced by specified lateral and ocean conditions from an AOGCM, and simulates atmospheric and land surface processes, while accounting for high-resolution topographical data, land-sea contrasts, surface characteristics, and other components of the Earth-system [8]. A large amount of input for the KNMI'14 projections are obtained from CMIP5. The analyses have been performed using two climate models, namely EC-Earth (KNMI global model) and RACMO2 (KNMI regional model for Europe). Hereby, the projected changes from 245 AOGCM projections (covering the period 1950-2100) for Western Europe serve as an input. A group of EC-Earth simulations is downscaled with the RACMO2 regional climate model. KNMI states that since the RCMs cannot resolve systematic discrepancies in the trends of the large-scale projections, the KNMI'14 scenarios are not based on a direct utilization of the available AOGCM model output. Besides, it is also noted in the report that not all aspects (including the correlation between variables) of the model configuration can be validated or corrected which may have an influence on the climate projections.

3.3 Uncertainties in the KNMI'14 projections

3.3.1 Climate change versus natural variability

Before addressing the uncertainties related to the KNMI'14 projections, it is important to understand how the projections are envisioned. For each climate variable, KNMI'14 provides information on both the *natural variability* of the climate variable on the one hand, and the projected *climate change* on the other hand. It is hereby implicitly assumed that the natural variability at present is representative for the natural variability in the future as well (further explained in Section 3.4). As such, KNMI'14 models the climate process as a superposition of a slowly varying trend-signal (related to climate change) and a faster fluctuating random component (related to natural variability). This is exemplified in Figure 5, which shows the KNMI'14 projections of the 30-year mean summer precipitation relative to 1981-2010 for a given scenario. Several independent model runs are conducted which include random components. The results of each individual model run are represented as blue lines, and show natural variability from one model run to the other. The mean value of the model ensemble is given as a grey line, which represents the climate change (that is steadily decreasing).

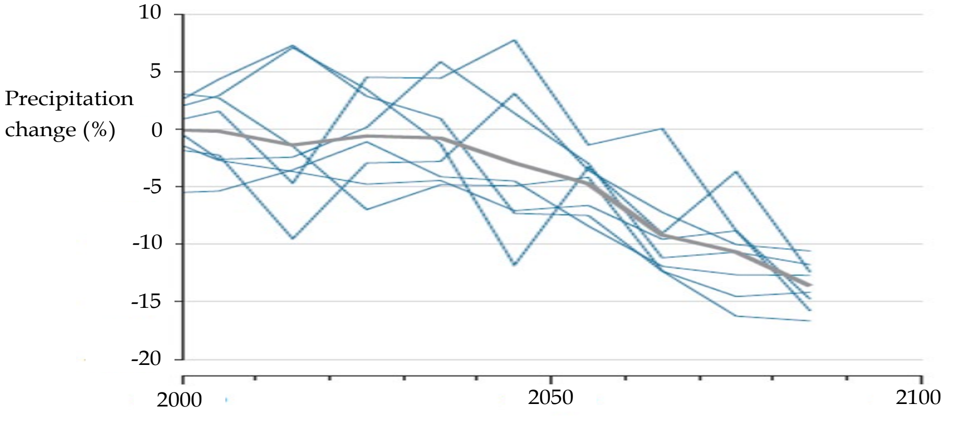


Figure 4. KNMI'14 projections for summer precipitation (30-year averages, relative to 1981-2010) in the Netherlands according to the eight independent calculations using the same model and same scenario. The grey line represents the mean of all model-runs.

3.3.2 Modelling uncertainties

Like global climate models, regional climate models (RCMs) are highly subjected to modelling uncertainties (see Section 2.3). The main sources of model uncertainties which are mentioned in the KNMI'14 report are:

- Limited model capability and configurations,
- Complex model-specific formulation and model-specific systematic biases,
- Large differences in spatial response patterns due to the inherent uncertainty in climate response and the role of natural variability at decadal time scales,
- Shortcomings in historical observations,
- Limitations on the available set of regional climate model projections that are necessary to improve the temporal and spatial structure of the GCM projections,
- Limited ability to generate realistic initial states,
- Uncertainty originated by the expert judgement.

To communicate these modelling uncertainties, KNMI'14 provides 90% ranges from model ensembles for some selected climate variables and indicators. This is further explained in the next section.

3.4 *Climate variables, indicators, and projections*

3.4.1 Climate variables and indicators

For each climate scenario, KNMI provides projections of climate variables (*e.g.* temperature, precipitation, wind, sea level rise, *etc.*) and corresponding climate indicators (*e.g.* climate indicators for 'wind' are the 'highest daily mean wind speed', or the '30-year mean wind speed', see also Table 3), see Appendix-A for an overview of all variables and indicators. The climate variables and indicators were carefully chosen such that they serve different stakeholders (*e.g.* for engineering purposes, politics/governmental decisions *etc.*). At this stage, however, most of the provided climate variables and indicators focus on 30-year mean values rather than extremes. Even though these mean values are extremely relevant from a climatological point of view, their application in engineering calculations is somewhat more limited. How this leads to challenges in engineering design is further discussed in Section 4.3.

3.4.2 Climate projections

For each climate variable and corresponding climate indicator, the KNMI'14 report [8] provides the following information (see also Table 3):

- The (previous) *climate normal*, which presents the values of the climate variables and indicators for the period 1951-1980.
- The *climate normal*, which presents the values of the climate variables and indicators for the reference period 1981-2010 (around the year 1995). The climate normal is derived by a statistical analysis of detrended (meteorological) station observations. Typically, a single meteorological station is chosen for this purpose. In reality, however, climate normals are expected to vary all over the country.
- The *climate projection*, which is given for different time horizons (2036-2065 and 2071-2100) and with respect to the climate normal. As discussed before, the climate projection either presents a single value, or a range of values, typically given as the 90% range.
- The *natural variability*, which is determined from the same (detrended) observations as the climate normal and provided as the 90% confidence bound. KNMI hereby assumes that the natural variability in the future is (to the first order) identical to the historical climate until 2100.

For engineering purposes, the main interest goes to the *climate projections*, rather than the *climate normals* or *natural variability*. This is because in many structural reliability calculations, engineers already perform statistical analysis on location-specific historical data, and therefore already possess information regarding the (location-specific) *climate normals* and *natural variability* (*i.e.*, in the shape of distribution functions).
The climate variables of 'wind', and 'sea level rise at North Sea coast', which deem the most relevant in the field of structural engineering, are further discussed below.

*Table 3. KNMI'14 projections for the climate variables 'wind' and 'Sea level at North Sea coast' as obtained from [8]. *Values rounded to 5 cm precision.*

		Wind (December, January, February)			Sea level at North Sea coast	
Period		30-yearly momentary mean wind speed (i.e. mean wind speed)	highest daily mean wind speed per year	no. of days between south and west wind	absolute level w.r.t. NAP*	rate of change*
1951-1980		N.A.	N.A.	44 days	- 4 cm	1.2 mm/year
1981-2010		6.9 m/s	15 m/s	49 days	+ 3 cm	2.0 mm/year
2036-2065	G_L	-1.1%	-3.0%	-1.4%	+15 to +30 cm	+1 to +5.5 mm/year
	G_H	0.5%	-1.4%	3.0%		
	W_L	-2.5%	-3.0%	-1.7%	+20 to +40 cm	+3.5 to +7.5 mm/year
	W_H	0.9%	0.0%	4.5%		
2071-2100	G_L	-2.0%	-2.0%	-1.6%	+25 to + 60 cm	+1 to +7.5 mm/year
	G_H	0.5%	-0.9%	6.5%		
	W_L	-2.5%	-1.8%	-6.5%	+45 to + 80 cm	+4 to +10.5 mm/year
	W_H	2.2%	2.0%	4.0%		
natural variability (averaged over 30 years)		±0.36%	±3.9%	±6.4%	±1.4 cm	±1.5 mm/year

3.4.3 KNMI'14 projections for the climate variable 'wind'

The KNMI'14 projections for the climate variable 'wind' are presented in Table 3 - green columns. Three indicators are distinguished: the mean wind speed, the highest daily mean wind speed per year, and the number of days between south and west wind. The projections correspond to the winter season (December, January, February) and synoptic storms only. The climate normals and natural variations are derived from the Den Helder station and represent potential wind speeds for the period between 1981-2012. The choice for the Den Helder station may seem as a remarkable choice, given the fact that wind climate in Den Helder can hardly be seen as 'average' for the whole Netherlands. However, KNMI states that the results are representative for everywhere in the Netherlands, because the changes in wind speeds are generated by large scale pressure systems which are much larger than the Netherlands. It is therefore expected that changes do not necessarily vary over the country. This argumentation was backed by model results.

3.4.4 KNMI'14 projections for the climate variable 'Sea level at North Sea coast'

The KNMI'14 projections for the sea level at North Sea coast are presented in Table 3 - blue columns. Two indicators are distinguished: the absolute level (which represents the 30-year mean value) and the rate of change (also with respect to the 30-year mean value). In the projections, no distinction was made between the scenarios with high (H) and low (L) atmospheric circulation. This because the changes in air circulation over Europe are expected to have minor impact on long-term sea level rise. Therefore, two scenarios are distinguished for sea level rise, namely scenario G ($G_L = G_H$) and scenario W ($W_L = W_H$). The climate normals and natural variations are derived from six measurement stations along the Dutch coast. The data spanned period between 1901 – 2012 and were filtered from tidal effects. Land subsidence is not included in the projections since it varies widely along the Dutch coastline and reliable estimates are not available. For both indicators, both the mean value and 90% range of the model ensemble is provided.

4 Discussion

The previous sections summarize the global (IPCC) and regional (KNMI) climate change projections, with a focus on their uncertainties. This section discusses how the provided information can be used in the probabilistic design and assessment of civil structures. First, we discuss how to deal with the uncertainties in the climate change scenarios. Next, we discuss how we can quantify modelling uncertainties from climate change projections. Last, we discuss the uncertainties related to the projection of extreme climate events.

*4.1 **Uncertainties in global and regional climate scenarios***

As discussed in Section 2.1 and 3.1, both global and regional climate change scenarios are highly uncertain due to the unpredictability of human behaviour. In order to account for these uncertainties, ideally, one would want to investigate *all possible* climate change scenarios and assign probabilities (or likelihoods) to every single one of them [17]. For a variety of reasons, however, this approach is currently not operational. Not only the resources are limited to investigate all possible scenarios, but also the act of assigning probabilities to different scenarios is highly debated. An important argument in this matter is that some type of uncertainties (*i.e.*, those related to climate change scenarios) cannot be captured by traditional probabilistic methods, as discussed in *e.g.* [7, 10, 18]. Dessai and Hulme [10] for example argue that "in the case of climate change, unknowable knowledge does not translate solely into stochastic uncertainty." Hall [7] discusses that not only the climate scenarios (RCPs) are uncertain, but also the scientific community does not agree on *how* uncertain they are. As such, he states that "to reduce this uncertainty to a single probability distribution in order to generate probabilistic scenarios would seem to misrepresent the state of current scientific knowledge." [7].

Currently, neither IPCC (the AR5 report) nor KNMI'14 projections assign likelihoods to any given climate scenarios. Although this is understandable, the lack of quantitative information about the uncertain scenarios severely challenges the risk-based decision-making, see [7, 19-21]. This especially holds for engineers, whose core task is to design *safe* structures – hereby the safety being expressed as some maximum allowed probability of failure which is referred to as the 'failure criterion'. The only way to assess the safety of a structure, is to calculate the probability that the structure may fail and to compare this value with a failure criterion. This calculation, however, indisputably requires the incorporation of uncertainties of all kinds – including those related to the different climate scenarios.

At this stage, to the best of our knowledge, there is no consensus amongst scientists on how to include uncertainties from climate change scenarios into risk-based calculations. Nevertheless, the design and assessment of civil structures continues, and engineers are deemed to make decisions in one way or the other. This often leads to either one of the following pragmatic decisions:

- engineers choose the most conservative climate scenario to be on the 'safe' side;
- engineers assign their own probability to each scenario;
- engineers exclude climate change in the design of civil structures because it requires too many assumptions and responsibilities from their side.

Neither of these options are desirable. The first option directly leads to stronger structures with more material use, which is undesirable from an economic and environmental point of view. The second option is also not desirable since it requires engineers to make (uniformed) guesses about the probabilities of different scenarios, even though they have little to no experience about climate change. The last option is the least preferable because neglecting the climate change projections possibly leads to an underestimation of the true climatic loads on the structure, hence endangering the structural safety. It is hereby believed that a close collaboration between climate experts and engineers is strongly needed to address this issue.

4.2 Modelling uncertainties in global and regional climate models

Modelling uncertainties play an important role in the probabilistic design and assessment of civil structures. They account for the possibility that according to the models' prediction the structure lies in the 'safe' domain, whereas in reality it may not [14]. Both IPCC (AR5) and KNMI'14 explicitly address the modelling uncertainties related to climate change projections (see Section 2.3 and 3.3.2, respectively). From a traditional risk and reliability point of view, we ideally want to quantify these modelling uncertainties as stochastic random variables representing the difference between the models' prediction and reality [14]. For simple models, this difference can be quantified by (laboratory) experiments. This approach is however not possible in case of climate projections since we cannot perform experiments in the future. Ditlevsen [14] emphasizes that the quantification of model uncertainties does not necessarily need to come from experimental data, and that "the evaluation of model uncertainty primarily must be based on professional insight and understanding arising from accumulated experience and only seldomly in situations involving direct experimental data". In line with these thoughts, both the IPCC and KNMI address the modelling uncertainties by (a combination of) the following approaches.

- Comparison of model results with historical observations.
- Presenting ranges from model ensembles.
- Providing expert opinions on the modelling uncertainties.

Although both IPCC (AR5) and KNMI'14 use all these options, neither quantifies the modelling uncertainties in terms of stochastic random variables. However, we believe that with some adaptations, the provided information could be adjusted for this purpose as well. This is further discussed in the following sections.

4.2.1 *Modelling uncertainties in global climate projections*

The IPCC developed a clear framework for the communication of modelling uncertainties in the climate change projections. They compare the model results with historical observations, present the projected ranges from model ensembles (Section 2.3.1) and provide expert opinions in terms of a likelihood language (Section 2.3.2) and qualitative confidence level (Section 2.3.3). For probabilistic implementation, the combination of the ensemble ranges and the likelihood language is particularly interesting, since both communicate the uncertainties in a quantitative way. At this stage, however, the authors of this study do not fully understand how this quantitative information can be interpreted from a probabilistic point of view. This is explained as follows. Considering the GMSL rise for RCP2.6, the AR5 projects a mean increase of 0.24m with a '*likely*' range of 0.17-0.32 m for the period of 2046-2065. The provided range represents the 90% range from the model ensemble, and the '*likely*' term indicates that the likelihood of the range lies somewhere between 66-100%. The following questions rise on what this information exactly means from a probabilistic point of view.

- Does it mean that the provided range 0.17-0.32 m corresponds to a confidence bound somewhere between 66% and 100%? In other words, the most conservative estimate of the confidence bound is 66% and the least conservative estimate of the confidence bound is 100%? If this is the case, it should be noted that there is a significant difference between a confidence bound of 66% and 100% from a probabilistic point of view, leading to significantly different outcomes. Furthermore, the application of a confidence bound of 100% is quite unusual in the traditional statistical sense (100% certainty is not often employed).
- Alternatively, does it mean that there is a 66-100% probability that the 90% ensemble range is equal to 0.17-0.32 m? In other words, should we interpret the given likelihood term as a discrete random variable with two outcomes: "the given 90% range is correct" and "the 90% range is incorrect"?

Another aspect which is not entirely understood by the authors, is the fact that the likelihoods of the different terms are overlapping. For example, supposing that the true likelihood of an outcome is between 90-95%: according to Figure 3, one could both apply the term "*likely*" as well as the term "*very likely*". It is currently not entirely understood which term should thus be chosen here, and what the reason is for the overlap. To prevent this confusion, we believe that a more "natural" way of addressing the likelihood ranges could be by non-overlapping (mutually exclusive) terms, such as presented in Table 4. Working with mutually exclusive likelihood ranges, would ease the direct application of the likelihood terms in traditional risk and reliability calculations (one could for example take the mean values of the respective ranges to be implemented in calculations).

In short, the AR5 provides valuable quantitative information regarding the modelling uncertainties in climate change projections. We believe that the provided information has a potential to be employed in traditional risk and reliability calculations with some minor changes. Most likely, this can be solved with a close collaboration between climate experts and engineers.

Table 4. Proposed likelihood ranges for the 'calibrated likelihood language' from the AR5, which can be employed in traditional risk and reliability calculations as well. Ranges should be interpreted as "a range in which the true likelihood is expected to lie"

Term	Previous likelihood	Proposed likelihood
Virtually certain	99-100%	99-100%
Very likely	99-100%	90-99%
Likely	66-100%	66-90%
About as likely as not	33-66%	33-66%
Unlikely	0-33%	10-33%
Very unlikely	0-10%	1-10%
Exceptionally unlikely	0-1%	0-1%

4.2.2 Modelling uncertainties in regional projections (KNMI'14)

As discussed in Section 2.3, the KNMI'14 investigates modelling uncertainties both qualitatively (*e.g.* by means of overviews) and quantitatively (*e.g.* by means of comparisons against historical data). Similar to the AR5, the KNMI'14 provides the 90% ensemble ranges for several climate variables. For some climate variables, however, the KNMI'14 does not present quantitative information about the modelling uncertainties. In these cases, it is not possible to include modelling uncertainties in the safety assessment of civil structures. Also here, the close collaboration between climate experts and engineers is desired.

4.3 Extreme climate events

For both the global (IPCC) and regional (KNMI'14) climate projections, the starting point is often the 30-year mean value of the climate variable. The reasons for this choice are (1) the 30-year mean value is a relevant quantity from a meteorological and climatological point of view (it is rather stable), and (2) the projection of extreme values is particularly challenging due to the intrinsic rare nature of these events [2]. As discussed in Section 1, however, civil structures need to be designed to withstand extreme climatic actions during their entire design lifetime. As such, engineers are typically interested in extreme values of the climate variables with return periods of up to 50, 100, 1000, or even 10000 years. If a structure is designed based on a projection of 30-year mean climate variable, it would mean that within these 30 years, approximately 15 years of the time, the actual value of the climate variable will be higher than the design value. This situation would inevitably lead to structural failure.

At this stage, little quantitative information is available on future climate extremes (with some exceptions from KNMI'14). Therefore, engineers often pragmatically assume that the projections for the 30-year mean values can be applied to extreme values as well. This approach negates the possibility that climate change affects extreme events differently than mean events, possibly leading to an underestimation of the "true" climate extremes.

5 Conclusions and recommendations

This study investigates how climate change projections can be considered in the probabilistic design and assessment of civil structures, aiming to bridge the gap between structural engineers and climate experts. For this purpose, we first provide an overview of the current knowledge related to the global IPCC [2] and the regional KNMI [8] climate change projections, with a special focus on the (modelling) uncertainties. Next, we discuss how engineers can incorporate the climate change projections and their uncertainties in the probabilistic design and assessment of civil structures. We discussed that for an adequate design and assessment, uncertainties of all kinds should be considered explicitly. This includes uncertainties related to different (climate) scenarios and inexact (climate) models. We conclude that for both the global and regional projections, there currently is a discrepancy between the available information about uncertainties on the one hand, and the information needed for the safety assessment on the other hand. More specifically, it is difficult to incorporate:

1. uncertainties in climate change scenarios;
2. modelling uncertainties in the climate change projections;
3. climate projections for extreme climate variables.

These difficulties lead to the unfortunate consequence that engineers either choose to ignore climate change projections in their assessment completely, or are deemed to make pragmatic decisions themselves to reconcile the available information with the required information. This practice is unfortunate because engineers typically have little to no background in climate change models or projections, which possibly leads to erroneous decisions on their behalf. To prevent this, a possible step towards finding a common ground would be to build up a close collaboration between climate experts and engineers and address these issues as good as possible within the limitations of science.

Acknowledgements
The authors would like to thank Dr. Á. Rózsás and Prof.ir. A.C.W.M. Vrouwenvelder for their contributions to this research.

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Appendix A: Key Figures - KNMI’14 climate projections (KNMI, 2014)

Season	Variable	Indicator	Climate 1951-1980	Climate 1981-2010 ref. period
	Global temperature rise:			
	Change in air circulation pattern:			
Year	Sea level at North Sea coast	absolute level	3 cm below NAP	3 cm above NAP
		rate of change	1.2 mm/year	2.0 mm/year
	Temperature	mean	9.2 °C	10.1 °C
	Precipitation	mean amount	774 mm	851 mm
	Solar radiation	solar radiation	346 kJ/cm²	354 kJ/cm²
	Evaporation	potential (Makkink)	534 mm	559 mm
	Fog	visibility < 1 km	412 hours	300 hours
Winter	Temperature	mean	2.4 °C	3.4 °C
		year-to-year variation	-	± 2.6 °C
		daily maximum	5.1 °C	6.1 °C
		daily minimum	-0.3 °C	0.5 °C
		coldest winter day per year	-7.5 °C	-5.9 °C
		mildest winter day per year	10.3 °C	11.1 °C
		frost days (min < 0 °C)	42 days	38 days
		ice days (max < 0 °C)	11 days	7.2 days
	Precipitation	mean amount	188 mm	211 mm
		year-to-year variation	-	± 96 mm
		10-day amount exceeded once in 10 years	80 mm	89 mm
		wet days (≥ 0.1 mm)	56 days	55 days
		≥ 10 mm	4.1 days	5.3 days
	Wind	mean wind speed	-	6.9 m/s
		Highest daily mean wind speed per year	-	15 m/s
		between south and west	44 days	49 days
Spring	Temperature	mean	8.3 °C	9.5 °C
	Precipitation	mean amount	148 mm	173 mm
Summer	Temperature	mean	16.1 °C	17.0 °C
		year-to-year variation	-	± 1.4 °C
		daily maximum	20.7 °C	21.9 °C
		daily minimum	11.2 °C	11.9 °C
		coolest summer day/year	10.3 °C	11.1 °C
		warmest summer day/year	23.2 °C	24.7 °C
		summer days (max temp ≥ 25 °C)	13 days	21 days
		tropical nights (min temp ≥ 20 °C)	< 0.1 days	0.1 days
	Precipitation	mean amount	224 mm	224 mm
		year-to-year variation	-	± 113 mm
		daily amount exceeded once in 10 year	44 mm	44 mm
		max hourly intensity per year	14.9 mm/hour	15.1 mm/hour
		wet days (≥ 0.1 mm)	45 days	43 days
		≥ 20 mm	1.6 days	1.7 days
	Solar radiation	solar radiation	149 kJ/cm²	153 kJ/cm²
	Humidity	relative humidity	78%	77%
	Evaporation	potential evaporation (Makkink)	253 mm	266 mm
	Drought	mean highest precipitation deficit during growing season	140 mm	144 mm
		highest precipitation deficit exceeded once in 10 years	-	230 mm
Autumn	Temperature	mean	10.0 °C	10.6 °C
	Precipitation	mean amount	214 mm	245 mm

Scenario change values for climate around 2050 (2036 – 2065)				Scenario change values for climate around 2085 (2071 – 2100)				Natural variations averaged over 30 years
G_L +1 °C low value	G_H +1 °C high value	W_L +2 °C low value	W_H +2 °C high value	G_L +1.5 °C low value	G_H +1.5 °C high value	W_L +3.5 °C low value	W_H +3.5 °C high value	
15 to 30 cm	15 to 30 cm	20 to 40 cm	20 to 40 cm	25 to 60 cm	25 to 60 cm	45 to 80 cm	45 to 80 cm	± 1.4 cm
+1 to 5.5 mm/year	+1 to 5.5 mm/year	+3.5 to 7.5 mm/year	+3.7 to 7.5 mm/year	+1 to 7.5 mm/year	+1 to 7.5 mm/year	+4 to 10.5 mm/year	+4 to 10.5 mm/year	± 1.4 mm/year
+1.0 °C	+1.4 °C	+2.0 °C	+2.3 °C	+1.3 °C	+1.7 °C	+3.3 °C	+3.7 °C	± 0.16 °C
+4%	+2.5%	+5.5%	+5%	+5%	+5%	+7%	+7%	± 4.2%
+0.6%	+1.6%	-0.8%	+1.2%	-0.5%	+1.1%	-0.9%	+1.4%	± 1.6%
+3%	+5%	+4%	+7%	+2.5%	+5.5%	+6%	+10%	± 1.9%
-110 hours	-110 hours	-110 hours	-110 hours	-120 hours	-120 hours	-120 hours	-120 hours	± 39 hours
+1.1%	+1.6%	+2.1%	+2.7%	+1.3%	+2.0%	+3.2%	+4.1%	± 0.48%
-8%	-16%	-13%	-20%	-10%	-17%	-15%	-24%	-
+1.0 °C	+1.6 °C	+2.0 °C	+2.5 °C	+1.2 °C	+2.0 °C	+3.1 °C	+3.8 °C	± 0.46 °C
+1.1 °C	+1.7 °C	+2.2 °C	+2.8 °C	+1.4 °C	+2.1 °C	+3.5 °C	+4.4 °C	± 0.51 °C
+2.0 °C	+3.6 °C	+3.9 °C	+5.1 °C	+2.7 °C	+4.1 °C	+5.6 °C	+7.3 °C	± 0.91 °C
+0.6 °C	+0.9 °C	+1.7 °C	+1.7 °C	+1.0 °C	+1.2 °C	+2.8 °C	+3.1 °C	± 0.42 °C
-30%	-45%	-50%	-60%	-35%	-50%	-70%	-80%	± 9.5%
-50%	-70%	-70%	-90%	-60%	-80%	-90%	< -90%	± 31%
+3%	+8%	+8%	+17%	+4.5%	+12%	+13%	+30%	± 8.3%
+4.5%	+9%	+10%	+17%	+6.5%	+12%	+16%	+30%	-
+6%	+10%	+12%	+17%	+8%	+12%	+18%	+25%	± 11%
-0.3%	+1.4%	-0.4%	+2.4%	+0.3%	+1.0%	-1.1%	+3%	± 4.7%
+9.5%	+19%	+20%	+35%	+14%	+24%	+30%	+60%	± 14%
-1.1%	+0.5%	-2.5%	+0.9%	-2.0%	-0.5%	-2.5%	+2.2%	± 3.6%
-3%	-1.4%	-3%	0.0%	-2.0%	-0.9%	-1.8%	+2.0%	± 3.9%
-1.4%	+3%	-1.7%	+4.5%	-1.6%	+6.5%	-6.5%	+4%	± 6.4%
+0.9 °C	+1.1 °C	+1.8 °C	+2.1 °C	+1.2 °C	+1.5 °C	+2.8 °C	+3.1 °C	± 0.24 °C
+4.5%	+2.3%	+11%	+9%	+8%	+7.5%	+15%	+12%	± 8.0%
+1.0 °C	+1.4 °C	+1.7 °C	+2.3 °C	+1.2 °C	+1.7 °C	+3.2 °C	+3.7 °C	± 0.25 °C
+3.5%	+7.5%	+4%	+9.5%	+5%	+9%	+7.5%	+14%	-
+0.9 °C	+1.4 °C	+1.5 °C	+2.3 °C	+1.0 °C	+1.7 °C	+3.0 °C	+3.8 °C	± 0.35 °C
+1.1 °C	+1.3 °C	+1.9 °C	+2.2 °C	+1.4 °C	+1.7 °C	+3.4 °C	+3.7 °C	± 0.18 °C
+0.9 °C	+1.1 °C	+1.6 °C	+2.0 °C	+1.0 °C	+1.4 °C	+2.7 °C	+3.1 °C	± 0.43 °C
+1.4 °C	+1.9 °C	+2.3 °C	+3.3 °C	+2.0 °C	+2.6 °C	+4.2 °C	+4.9 °C	± 0.52 °C
+22%	+35%	+40%	+70%	+30%	+50%	+100%	+130%	± 13%
+0.5%	+0.6%	+1.4%	+2.2%	+0.9%	+1.2%	+6.5%	+7.5%	-
+1.2%	-8%	+1.4%	-13%	+1.0%	-8%	-5%	-23%	± 9.2%
+2.1 to 5%	-2.5 to +1%	+1.4 to 7%	-4 to 2.2%	1.2 to 5.5%	-2.5 to 1.9%	-0.9 to 10%	-8.5 to 2.3%	-
1.7 to 10%	+2 to +13%	+3 to +21%	2.5 to 22%	2.5 to 15%	2.5 to 17%	5.5 to 40%	+5 to +40%	± 15%
5.5 to 11%	+7 to +14%	+12 to 23%	+13 to 25%	+8 to +16%	+9 to +19%	+22 to 45%	+22 to 45%	± 14%
+0.5%	-5.5%	+0.7%	-10%	+2.1%	-5.5%	-5%	-16%	± 6.4%
4.5 to 18%	-4.5 to 10%	+6 to +30%	-8.5 to 14%	+5 to +23%	-3.5 to 14%	+3 to +40%	-15 to 14%	± 24%
+2.1%	+5%	+1.0%	+6.5%	+0.9%	+5.5%	+3.5%	+9.5%	± 2.4%
-0.6%	-2.0%	+0.1%	-2.5%	0.0%	-2.0%	-0.6%	-3%	± 0.86%
+4%	+7%	+4%	+11%	+3.5%	+8.5%	+9%	+15%	± 2.8%
+4.5%	+20%	+0.7%	+30%	+1.0%	+19%	+14%	+50%	± 13%
+5%	+17%	+4.5%	+25%	+3.5%	+17%	+15%	+40%	-
+1.1 °C	+1.3 °C	+2.2 °C	+2.3 °C	+1.6 °C	+1.6 °C	+3.8 °C	+3.8 °C	± 0.27 °C
+7%	+8%	+3%	+7.5%	+7.5%	+9%	+6.5%	+12%	± 9.0%