Climate change and its impact on structural safety

Climate change and its impact on structural safety

Raphaël D.J.M. Steenbergen, Chris P.W. Geurts, Carine A. van Bentum

TNO Built Environment and Geosciences

The Netherlands Organization for Applied Scientific Research TNO,

P.O. Box 49, 2600 AA, Delft, The Netherlands

Extreme climatic events lead to loads on buildings and civil engineering works. Changes in climate will have an effect on the design loads. This paper presents an investigation into the relevance of the climate change scenarios with respect to the loads on buildings by wind, precipitation and temperature. Possible consequences to building codes are illustrated, and research questions are defined.

Key words: Loading on structures, wind, precipitation, temperature

1 General

Buildings are designed to have at least a minimum resistance to the loads that act on the structure, and on building parts such as roofs and cladding. These loads are partially determined by climate effects. Changes in climate therefore may have consequences in the design of newly built structures, as well as the resistance in the existing building stock. Climatic actions on buildings – such as wind, temperature, rain and snow - have intensities that vary in time. Increasing the lifetime of a structure therefore increases the probability that, in a given time frame, the intensity of one of these actions will exceed the value assumed in the design. In order to work on a rational base, a conventional 'design life' for different types of structures must therefore be defined. The working life increases with the importance of the structure. In building codes, these definitions are given. The European standard for structural safety, EN 1990, uses 50 years for building structures and common structures and 100 years for monumental building structures, bridges and other civil engineering structures.

These design lives are typically in the order of the time frames described in the scenarios for climate change. For the impact of climate change on structural safety, the changes in the following climatic actions on buildings are studied following the four climate change scenarios of the KNMI (Dutch Meteorological Institute):

1. Wind load
2. Temperature load
3. Water accumulation due to heavy rain
4. Snow load

These climatic actions are relevant in structural design of buildings and building parts, and these actions are all treated in building standards. In this paper, some background on structural safety is given on which current design rules are based. The effects of climate changes for the Netherlands are described, and translated in terms of the way, the climate effects are modelled in our current design rules. Finally, research questions are formulated, which need to be solved to come to a robust design for building structures including climate change effects. In the Annex, a more detailed analysis of the climate change effects, with respect to wind loading is given, as an illustration of how to include possible effects in the building standards in future.

2 Structural safety and building codes

The calculation of building structures is based on a reliability analysis using probabilistic models for both the loads and the resistance of the structure. All relevant aspects are considered to be stochastic in nature, and are treated stochastically. In this analysis, the probability densities of the resistance *R* of a structure, and of the load effect *S* are predicted. A structure is safe when the probability that *R* is larger than *S*, is acceptably small. This can be expressed as follows:

$$P_f = P\ (S > R) < P_{acceptable}$$

Since *S* is depending on climatic actions and *R* on the material properties, they are both variables with a certain range and *S* and *R* can be described using probabilistic distribution functions. Using statistical methods and adequate models it is possible to calculate the probability of failure P_f. Given the abovementioned variability of the loads in time, P_f is always relative to a defined lifetime of the structure.

For a structure to be acceptably safe, P_f must be smaller than a predefined value that depends on the importance of the building, the type of loss of performance taken into account, and the potential consequences *C* of failure.

The risk is now defined as the probability *P* that failure will occur multiplied by the consequences given that failure occurs, i.e: *Risk*=*P***C*. The level of risk which is accepted is determined more or less by our society. The larger the consequences will be, the smaller the accepted probability *P* of failure will be. These principles have been worked out in our Building Regulations and building codes, both on national (NEN standards) and on European basis (CEN standards; the so-called Eurocodes). The reliability of a structure depends on both loading and structural properties. The structural properties are treated in separate, material dependent standards. The loads are given in a series of standards under number EN 1991.

In these codes, methods to determine a design load are given. The design load and design resistance must have values which are chosen so to obtain a structure that is safe enough during its lifetime. This implies that the design load has a very small probability of exceedance of about 10^{-4} or 10^{-5}. To establish these design loads, statistical distributions are needed of the extreme loads having very long returns periods.

Traditionally, design codes have used past climatic load data to help forecast future loads on buildings. Since this extrapolation to the future is based on historic records of meteorological observations, as fundamental assumption, the possible existence of long term trends with a period of some decades or so is not taken into account.

When climate change influences structural risks, the distribution S of the load, from which the design load results, can probably no longer be based only on measurements from the past, since the future development of the load under climate change has to be included.

In the following sections this is worked out to some detail for the Netherlands. For the four mentioned climatic loads, the current procedure to determine the load is described, the relevant properties in the four KNMI scenarios are discussed, the needed structural adaptations are mentioned and the total increased risk is calculated.

3 Wind load

The wind gives loads on practically all types of building structures. In the Netherlands, it is the only horizontal load on buildings, thus being relevant for the stability of structures. Additionally it leads to design loads for roofing and cladding and their fixings. Storms lead to the largest economical damage, insured and non-insured. Relative small changes in extreme wind speeds will have a large impact to economies, world wide.

3.1 *Current design procedures*

In current codes of practice, wind loads on structures are treated as a static load. The relevant parameters which determine the wind loads are described by the so called wind loading chain (Davenport, 2002). The total wind load effect depends on the characteristics of the wind statistics (first link in the chain), terrain (second link), shape and dimensions of the building (third link), and the structural properties (fourth link). The structural response should be checked against criteria for safety and serviceability (final link).

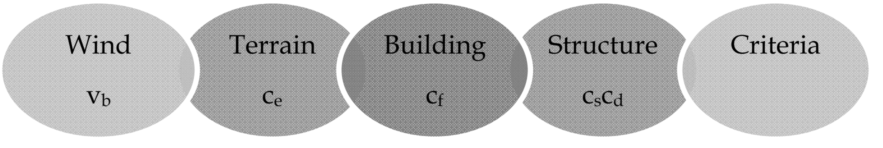

Figure 1: Wind Loading Chain, after Davenport

The first link in the wind loading chain is the statistical analysis of the wind climate. In building codes, the first step is the definition of a basic wind velocity. In the recently published NEN-EN 1991-1-4, a 10-minute mean wind velocity with a return period of 50 years is defined, measured under standard conditions (10 meters height, above terrain with roughness length of 0.05 m). The wind load is proportional to the basic wind velocity squared. This implies that relatively small changes in the wind velocity may have a relatively large effect on the wind loading.

All other parameters in the calculation, such as gust factors, aerodynamic coefficients and models for dynamic resonance of structures, are assumed independent of the mean wind velocity.

3.2 *Design values for the wind velocity*

Values for the basic wind velocity in wind loading standards are based on statistical analysis of the extremes in the mean wind velocity, measured at meteorological stations. In the Netherlands, the basis for these values is the detailed description of the wind climate by the KNMI in the period 1962 to 1976 (Rijkoort, 1983, Wieringa and Rijkoort, 1983). In Annex A, a basic wind velocity, for Schiphol, having a value of 27 m/s is given. Additionally, the design value is derived as having a value of 32.3 m/s. Since all other parameters in the wind loading chain are not influenced by climate change, we are now interested in the effect that climate change may have on the extreme wind velocity. The next paragraph gives an overview of information available from scenario studies, and based on recent observations. The treatment of this information for building design against the wind is discussed in section 3.4.

3.3 *Climate change and severe winds*

3.3.1 KNMI scenarios

The reports of IPCC give very little information on the possible wind velocity changes in Europe. The KNMI has presented more detailed scenarios for the Netherlands. In the KNMI Scientific Report WR 2006-01: 'KNMI Climate Change Scenarios 2006 for the Netherlands' (Hurk et al, 2006). General Circulation Model (GCM) simulations which have become available during the preparation for the Fourth Assessment report (AR4) of IPCC have been used to derive scenarios of sea level change in the eastern North Atlantic basin and wind velocity in the North Sea area. The GCM simulations also were used to span a range of changes in seasonal mean temperature and precipitation over the Netherlands. The KNMI defines four possible scenarios for the climate change: G, G+, W and W+ (from moderate to more extreme). For the four scenarios the effects are summarized in Table 1. The criteria for discriminating the four scenarios are the global temperature increase in 2050 and the change of atmospheric circulation over The Netherlands in the GCM model: for scenario G, a temperature increase of +1 °C is expected and a weak change of atmospheric circulation; for scenario G+, the same increase of +1°C is expected and a strong change of atmospheric circulation; for scenario W, a temperature increase of +2 °C and a weak change of atmospheric circulation and for scenario W+, +2°C and a strong change of atmospheric circulation. Specific scenario values for the global temperature change and the circulation change were chosen in such a way that they represented the underlying variability of GCM results for Western Europe well. Deliberately, the KNMI'06 climate scenarios are not associated with a certain probability of occurring, and no 'most likely' scenario is identified. The scenarios are designed to serve a diverse user community, and a wide range of applications.

For wind loading studies we are interested in the extreme wind velocities. This is not given in Table 1, but (Hurk et al, 2006) give some information on the trends expected for the 4 scenarios.

The expected change of the wind velocity is given in terms of the daily mean wind exceeded on average once per year. The predicted trends for IJmuiden are given in Fig. 2, together with the observed values since 1950. Similar plots can be made for other meteorological stations.

Table 1. Summary of effects of four possible scenarios for the Netherlands in 2050, relative to 1990 (Van den Hurk et al. 2006)

Scenario		**1990**	**G**	**G+**	**W**	**W+**
		Summer				
Mean temperature	°C		+ 0.9	+ 1.4	+ 1.7	+ 2.8
Yearly warmest day	°C		+ 1.0	+ 1.9	+ 2.1	+ 3.1
Summer days ≥ 25 °C						
NW Netherlands		8	11	14	16	22
NE Netherlands		20	27	30	34	41
Central Netherlands		24	30	34	39	47
SE Netherlands		28	36	41	44	53
Mean precipitation	%		+ 2.8	- 9.5	+ 5.5	- 19.0
Wet day frequency	%		- 1.6	- 9.6	- 3.3	- 19.3
Precipitation on wet day	%		+ 4.6	+ 0.1	+ 9.1	+ 0.3
Potential evaporation	%		+ 3.4	+ 7.6	+ 6.8	+ 15.2
		Winter				
Mean temperature	°C		+ 0.9	+ 1.1	+ 1.8	+ 2.3
Yearly coldest day	°C		+ 1.0	+ 1.5	+ 2.1	+ 2.9
Mean precipitation	%		+ 3.6	+ 7.0	+ 7.3	+ 14.2
Wet day frequency	%		+ 0.1	+ 0.9	+ 0.2	+ 1.9
		Yearly				
Yearly maximum daily mean wind velocity	%		0	+ 2	- 1	+ 4

To the adequately span the uncertainty range of the wind speed changes derived from the GCM analyses in the KNMI’06 climate scenarios, the outer values of the 10% and 90% quantiles are used for the scenarios without and with circulation change, respectively, resulting in -1% for W and +4% for W+. The G and G+ scenarios are constructed by dividing these values by 2 and rounding to integer values.

It is remarked that these predictions do not give any information about wind velocities with averaging time of less than a day. For wind loading studies, typical averaging times of 10 to 60 minutes are relevant, and additionally information on the gust loading is required.

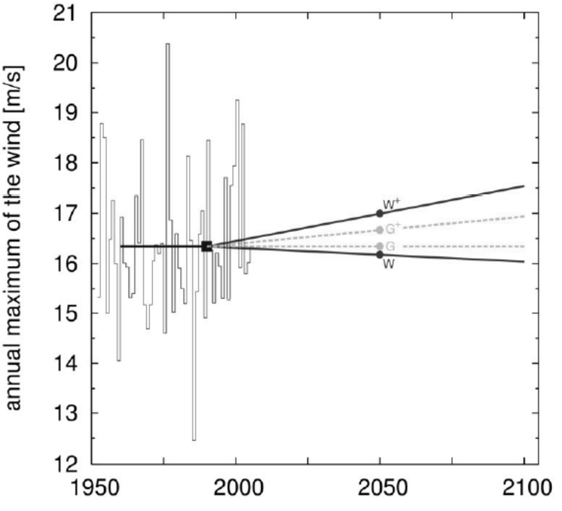

Figure 2: Predictions for the annual maximum daily mean wind in IJmuiden, and observations in the period 1950-2005 (Hurk, 2006)

3.3.2 Observed changes of extreme wind velocities

Besides the KNMI scenarios, it might be of use to see how the extreme wind velocities have developed over the past decades. As said before, the current building codes use the data measured up till 1976. In Figure 3, the amount of hours, in which a wind velocity of 15 m/s was exceeded, is given for Schiphol, during the observation period 1950 – 2005. During the period till 1976, on average 80 hours have been observed exceeding 15 m/s. A second analysis period has been applied by the KNMI in the Hydra project, for the data obtained

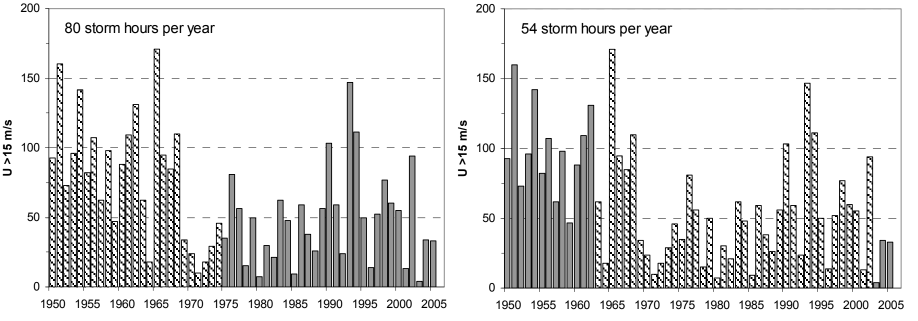

Figure 3: Number of hours per year in which 15 m/s has been exceeded. Both Figures show the same data: At the left, the period 1950-1975 is highlighted: 80 storm hours per year. At the right: the period 1963 – 2003 is highlighted: 54 hours per year.

in the period between 1962 and 2002. In this period, on average 54 hours per year have been observed, exceeding 15 m/s. The data in Figure 3 show a decreasing trend in storminess over the past 20 years, compared to the period of 30 years before. The timeframe studied is probably too short to conclude in general about possible climate change effects, and a single station might not be representative for the effects on a larger spatial scale.

Smits et.al (2005) have done an extensive statistical analysis of the wind climate data in the above mentioned period 1962 -2002. They have concluded that the results for moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year) indicate a decrease in storminess over the Netherlands between 5 and 10% per decade.

This result is inconsistent with National Centers for Environmental Prediction–National Center for Atmospheric Research or European Centre for Medium-Range Weather Forecasts reanalysis data, which suggest increased storminess during the same 41 year period. Smits et al discuss this difference and conclude that it is likely that the decrease in storminess observed in Dutch station records of near-surface wind in the past four decades is closer to reality than the increase suggested by the reanalysis data.

Observations from German weather stations are presented by (Hortmanns, 2007). These observations suggest a negative trend in the observed annual mean geostrophic winds, see Figure 4.

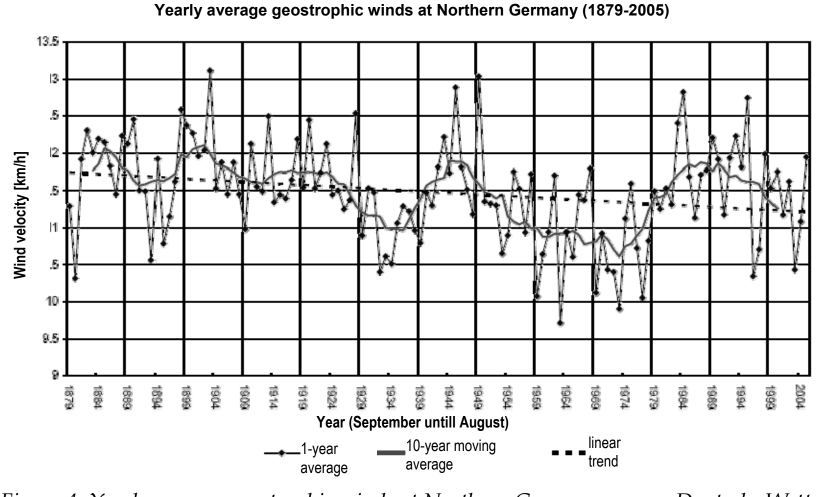

Figure 4: Yearly average geostrophic winds at Northern Germany; source Deutsche Wetter Dienst, presented by Hortmanns (2007)

Kasperski (1998) performed an analysis of the wind velocities at Dusseldorf airport, and found a trend leading to a increase of the average number of storms per year from roughly 21 in the sixties to 36 in the nineties. In that study also an increase has been found in mean wind velocity of 1.25 m/s in 36 years. The increase in the number of storms per year and the increase in their intensity lead to an increasing overloading risk.

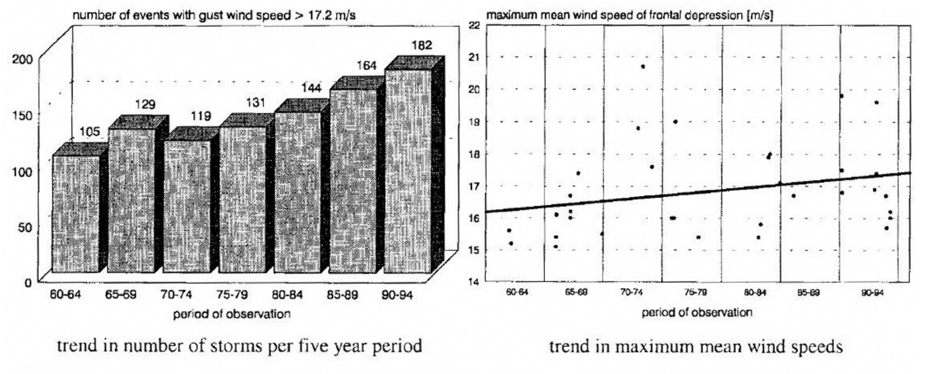

Figure 5: Observed trends for the number of storms per five year period, and the maximum mean wind velocities of frontal depressions from Düsseldorf Airport, 1960 – 1995, from Kasperki

Ulbrich (2007) presented a range of wind climate scenario simulations and concluded that there is a consistent increase of intensity and frequency of extreme winds in northwestern Europe, with some variation in results from the models applied.
Klein Tank (2007) concluded that:

5. The IPCC fourth Assessment Report identifies significant changes in extremes, but information on extra-tropical storms is limited;
6. Over Europe, the majority of climate models project the storm tracks to move North-Eastward;
7. This has important consequences for the areas with strongest winds, but natural variability is still larger than the change signal.

It is difficult to derive wind velocities with very large return periods from trend analysis of direct observations because the available series are much shorter than e.g. 10 000 years. Computer models do not have these limitations. Computer models can also take into account the future climate change as a result of the world wide increase of greenhouse gases, and of the simultaneous occurrence of very rare events, not yet included in the observations available. Van den Brink (2005) has studied winds at large heights with the help of computer models, and predicts values for the wind velocities with large return periods, both for the current climate and for a changed climate 'quoted as greenhouse climate'. The results are shown in Fig. 6.

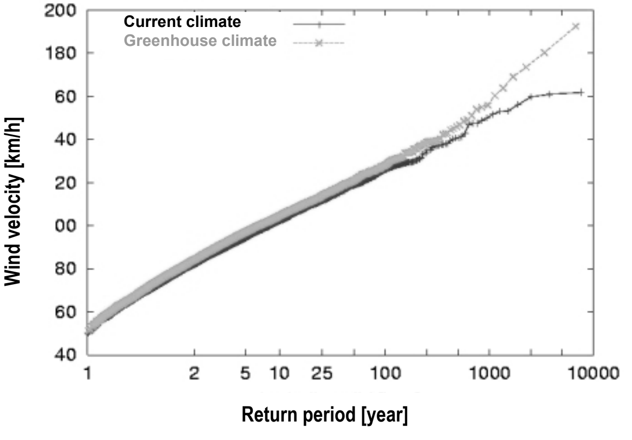

Figure 6: Gumbel plots of the 12-hour mean wind velocity at 2 km above the North Sea
(Van den Brink, 2005)

Van den Brink (2005) gives slightly higher values for the wind velocities for return periods up to about 500 years. For larger return periods, climate change will lead to at least 10% higher wind velocities. It is yet not clear if this pattern also occurs for smaller heights that are important for buildings (below 200 meters). This would be an important question for further research.

The scatter in all observations presented before is quite large, and possible trends are much smaller than the observed scatter. Both negative and positive trends have been observed, for meteorological stations not far away from each other. An aspect which should not be forgotten is that surface observations are easily disturbed by local effects. For the Netherlands, terrain effects are routinely removed from the data, and the analysis is done based on potential wind velocities. This is however not standard practice in all countries, and trends in observed wind velocities might well be caused by these effects.

3.4 *Impact on structural safety and building standards*

In the actual design, the possible trends caused by climate change have not been taken in to account. Focusing on these trends, the KNMI scenarios provide an increase in the yearly maximum daily mean wind velocity of 0% (G), +2%(G+), -1%(W) and +4%(W+).
In all of the observed trends and scenarios, mean wind velocities have been studied, with different averaging time. The observed data differ in nature and in statistical relevance. No results have been found for possible trends in gust wind velocities. Under stormy conditions, gusts are induced by mechanical turbulence (by terrain roughness) mainly, so therefore it is assumed that the maximum gust wind velocity changes proportional to the (hourly) mean wind velocity.
To translate these values to new design values for the wind velocity, extreme values with return values of typically 1000 years are needed, see Annex A.1. In Annex A.2, a possible approach is presented for how to derive these values from the scenarios. This may lead to increasing extreme wind speeds, however a number of choices are made which are not really certain. This introduces new uncertainties, which need to be identified, and where possible quantified.
When we want to include this information in our building standards we need the following information.

8. What is the likelihood that either one of the scenarios will be seen in future. For sake of simplicity, we can assume that all scenarios have the same likelihood of occurrence.
9. How can we translate the wind properties in the scenarios, now given as daily mean values, into extreme value with a typical averaging time of seconds.
10. Is the trend described best by a linear development of the wind velocity? This is easy to apply in structural safety scenarios.
11. How do trends in wind velocity relate to other trends, e.g. in the exposed value, or terrain developments?

Up to now, no detailed study has been performed to link the scenarios of IPCC and KNMI to the way we treat the wind loading on buildings. Some work has been done by Kasperki (2000), but this has not yet lead to inclusion of possible climate change effects in our codes. This work should be carried out in the near future, to be able to decide whether or not to include this effect in the next generation of building standards. Since national standards are now being replaced by European codes, this work should not be limited to the Netherlands, but a European approach is needed here. Collaboration between meteorological offices, research institutes and building sector is strongly recommended in this work.

4 Temperature loads

Differences in temperature cause structures to expand and become smaller. These movements should be taken into account by proper design of tolerances in the structures. This is relevant for design of all types of structures, especially where different materials meet each other, or when long structures (e.g. bridges, towers and masts) are built.

4.1 Actual design

Thermal actions on buildings due to climatic and operational temperature changes shall be considered in the design of buildings where there is a possibility of the ultimate or serviceability limit states being exceeded due to thermal movement and/or stresses. In EN 1991-1-5, rules are specified and in the National Annex of this standard, temperature values are provided for The Netherlands. Climatic and operational thermal actions on a structural element are specified using the following basic quantities:

12. A uniform temperature component ΔT_U given by the difference between the average temperature T of an element and its initial temperature T_0.
13. A linearly varying temperature component given by the difference ΔT_M between the temperatures on the outer and inner surfaces of a cross section, or on the surfaces of individual layers.
14. A temperature difference ΔT_P of different parts of a structure given by the difference of average temperatures of these parts.

The temperature of the inner environment, T_{IN}, and the temperature of the outer environment, T_{OUT} for structural calculations are specified in Table 2. These temperatures are the outside temperatures. Indoor temperatures are assumed not to change, when we have to deal with the extreme loads on structures. The surface temperatures in summertime are related to the outside temperature and the amount of solar radiation. Although the scenarios do not specify any values for radiation, it is likely that this will increase as well. To what extent this will lead to an additional increase in surface temperature, should be further examined.

Winter time extremes may also be higher. The difference between summer and winter extremes remain roughly the same in all scenarios.

Table 2: Temperature values given in NEN-EN 1991-1-5/NB

Location	**Season**		**Temperature**
Inside	Summer		17ºC
	Winter		17ºC
Outside	Summer		30 ºC
		Bight light surface	+20 ºC
		Light coloured surface	+30 ºC
		Dark surface	+45 ºC
	Winter		-25 ºC
Ground	Summer		10 ºC
	Winter		10 ºC

4.2 *Changes in temperature due to climate change*

The possible changes in temperature, coming from (Hurk et al, 2006) are collected in Table 3.

Table 3: Temperature changes from KNMI climate change report

Scenario		**G**	**G+**	**W**	**W+**
	Summer				
Yearly warmest day	°C	+ 1.0	+ 1.9	+ 2.1	+ 3.1
	Winter				
Yearly coldest day	°C	+ 1.0	+ 1.5	+ 2.1	+ 2.9

4.3 *Impact on structural safety*

The difference in temperatures can be added immediately to the temperatures expected to occur on structures which are exposed to the outdoor climate (e.g. facades, masts, bridges). For many of these structures, the difference in temperature extremes is the relevant loading. In those cases, climate change does not have an effect.

For those elements where both indoor and outdoor temperatures play a role, this may give rise to higher loads.

The outside temperatures are increasing; in summer it can be until 3.1 ºC warmer outside. This means that structures have to be able to withstand larger temperature differences between inside and outside, so structural systems may need to be adapted.
Also the difference between the extreme temperature and the temperature at the moment of the construction will be larger; this means that more care should be given to dilations to take up larger expansions. When drafting future design codes, this could be included in a new version of table 4.

5 Ponding

Ponding is the phenomenon that a roof deflects under rainwater loading, which means that additional rainwater runs to the deflected spot, giving more loading and more deflection, etc.. this effect is relevant for relatively light weight, steel structure flat roofs. In the Netherlands, ponding leads to approximately 20 collapses per year (Kool et.al, 2003, Snijder, 2006).

*5.1 **Actual design***

Since 1993, ponding is addressed in the Dutch Building code. Usually, this loading is smaller than the design snow load, which is described in the next section. For well-constructed roofs equilibrium is reached and the roof is able to carry the loading.

The basis for the calculation is the extreme rainfall averaged over a time interval of 5 minutes with a return period of 50 years. The amount of rain in a certain time interval is defined as the precipitation intensity. The precipitation intensity in the Dutch building code is based on measurements of the Dutch meteorological institute (KNMI) in De Bilt over the period 1906-1990. The year maxima of the 5 minute rainfall are fitted by a Gumbel distribution and extrapolated to a 5 minute rainfall with a return period of 50 years. The procedure is similar to Annex A. Using this procedure the precipitation intensity is determined as $0.0466 \cdot 10^{-3}$ m/s corresponding to a rainwater depth of 14 mm (de Borst, 2004, Tomà, 1980, Buishand and Velds, 1980, Smits, 2004 Buishand and Wijngaard, 2007). The computation of the current reliability index in the Dutch building codes is not given in this paper (see van Bentum and Vrouwenvelder, 2006).

*5.2 **Changes in precipitation due to climate change***

Table 6 shows a number of precipitation values for four scenarios (KNMI'06). The values present climatological mean values. The scenario value quantifies the change of the 30 year mean around 2050 relative to 1990. The 30-year means do not allow an interpretation of the typical interannual variability (Hurk, 2006). Figure 7 plots the observed precipitation with interannual variability compared to the four scenarios.

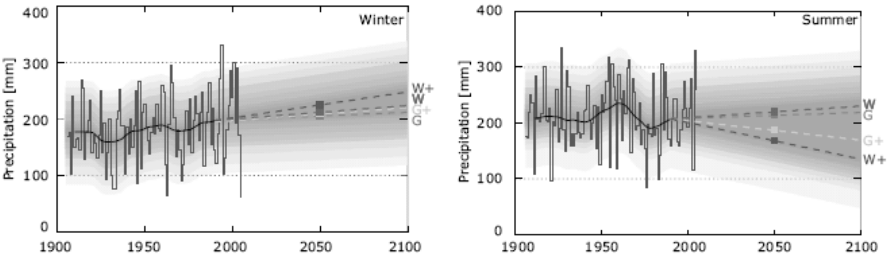

Figure 7: Time series of observed precipitation (mm/3 months in period 1901-2005). The black line is the running 30-year mean of the observations. The dotted lines are the scenarios. The shaded area represents the boundaries of the highest and lowest scenario. Left precipitation in wintertime (December, January, February); right in summertime (June, July, August).

Figure 9 shows that the 2050 scenario values are relatively close to the 1990 reference. In all scenarios the precipitation amount in the winter increases. In the W+ and G+ scenarios this is partly due to an increase in the wet day frequency. The main effect is however the thermodynamic increase of precipitation with increasing temperature. In the summer the wet day frequency decreases in all scenarios. The decrease is most pronounced in the G+ and W+ scenarios. The increase of precipitation intensity within the showers leads to an increase in precipitation in the W and G scenarios.

The influence of the wet day frequency and the precipitation intensity is also shown in Figure 8, where the changes in intensity are given for the 1-day, 5-day and 10-day precipitation. In the winter the mean precipitation increase is mainly due to the precipitation on wet days, and this is strongly dependent on circulation. Extreme precipitation changes in winter are close to changes in the mean precipitation. In summer a change to drier circulation types tends to reduce the wet day frequency and hereby the mean precipitation. However, the mean wet day precipitation is virtually left unchanged. In the wet regime the wet day precipitation increases considerably, but the number of wet days hardly changes. The extreme precipitation therefore strongly depends on the scenario.

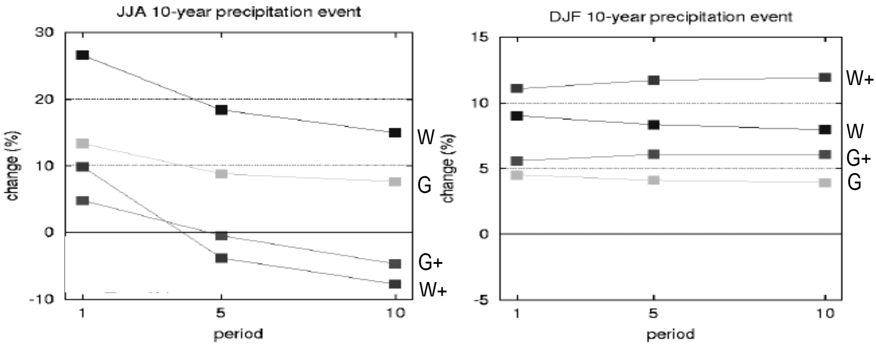

Figure 8: Changes in intensity for 1-day, 5-day and 10-day precipitation sums with a return period of 10 years for each of the scenarios. Calculations are based on observations for 13 stations in The Netherlands. Left intensity change in summertime (June, July, August); right in wintertime (December, January, February).

5.3 *Impact on structural safety*

The building code uses an extreme value, the precipitation within a 5 minutes time interval, which cannot be directly translated from the KNMI'06 scenarios. Table 6 shows the variables of the four scenarios on which an estimate for the 5 minutes precipitation can be based. Due to the small changes in 10-day precipitation in relation to the average precipitation, the average precipitation change probably is a good indication for the 5 minutes precipitation change in winter. The varying precipitation intensity in summer in the four scenarios indicates that the shortest duration of precipitation, being 1-day, probably gives the best estimate. Values for a return period of 50 years are not available. Buishand and Velds study indicates that for 1-day precipitation the year maximum is found in 78% of the cases in the summer half year. For 10-day precipitation only 54% of the cases had it maximum in summer. For the estimate of the 5 minutes precipitation the summer period seems more important.

The change in precipitation sum can also be expressed in adapted return intervals. For the fourth assessment report no adaption is published yet, therefore the adaptation made by Können (2001) is used. Können translates the climate change projections of the second assessment report and third assessment report into precipitation scenarios. The scenarios do not exactly fit on the G, G+, W and W+ scenarios. Table 5 shows the change in return period for the 1-day and 10-day precipitation. Important to mention is that the return periods for the wet and dry scenarios are estimated under the (unproven) assumption that

Table 4: KNMI'06 scenarios for precipitation

	G **+1°C**	**G+** **+1°C**	**W** **+2°C**	**W+** **+2°C**
Winter				
average precipitation amount	+4%	+7%	+7%	+14%
10-day precipitation sum exceed once in 10 years	+4%	+6%	+8%	+12%
Summer				
average precipitation amount	+3%	-10%	+6%	-19%
1-day precipitation sum exceed once in 10 years	+13%	+5%	+27%	+10%

Table 5: Change in return period due to climate change

		+1°C **wet**	**+1°C** **dry**	**+2-3°C** **wet**	**+2-3°C** **dry**
Year			-		
average precipitation amount	700-900mm	+3%	-	+6%	-5%
1-day precipitation sum exceed once in 1 years	34mm	0.9yr		0.8yr	1.6yr
1-day precipitation sum exceed once in 10 years	53mm	8yr	-	7yr	17yr
1-day precipitation sum exceed once in 100 years	73mm	78yr	-	62yr	200yr
Winter			-		
average precipitation amount	350-425mm	+10%	-	+20%	-5%
10-day precipitation sum exceed once in 1 years	62mm	0.7yr		0.5yr	1.5yr
10-day precipitation sum exceed once in 10 years	98mm	6yr	-	5yr	17yr
10-day precipitation sum exceed once in 100 years	136mm	47yr		25yr	200yr

the number of wet days remains the same. A result is that the sign of the changes in the mean and extreme precipitation is the same. As can be seen in table 6, recent projections of future climate indicate that reduced precipitation in summer is likely to be associated with small changes or increased levels of extreme precipitation at midlatitude land areas (Christensen and Christensen, 2003 in Hurk, 2006). This is one of reasons that KNMI revised the climate scenarios in 2006.

Due to climate change the extreme precipitation will probably increase. The change in 5-minutes precipitation with a return period of 50 years is not published yet. For 1-day precipitation in summer with a return period of 10 years a maximum increase of 27% in precipitation is foreseen. Using this increase, the precipitation intensity will increase to $0.592 \cdot 10^{-3}$ m/s. In the design of roofs it will be necessary to add more rainwater discharge capacity and more roof slope. Additional stiffness of the structure and its components is another solution. An increase in precipitation can also be expressed as a decrease of the return period. The return period of the 1-day precipitation, having a maximum over all seasons of 53 mm, can reduce to 7 years in a wet climate. Further research should focus on the translation of the KNMI scenarios to the 5-minutes precipitation with a return period of 50 years and on the impact on the design of roofs and its economic consequences (for example material use).

6 Snow load

Extreme snowfall give vertical loads on roofs, which have to be carried by the roof structure itself, and this load has to be transported to the foundation by the main structure. It is relevant in all designs, in particular for buildings. Recent damages in the Netherlands, about 100 collapses in November 2005, have renewed attention for this loading and the possible relation with climate change.

6.1 Actual design

Snow loading is determined by the number of days with snow cover and the period with continuous snow cover (called run length), the distribution of the annual maximum snow depths and distribution of snow depths (Buishand, 1986). The annual maximum snow depths of observations in the period 1955/1956-1982/1983 is the basis of the current building code in The Netherlands and in the National Annex of the Eurocode. The annual maximum snow depths of 13 synoptic stations in The Netherlands are fitted by a Gumbel

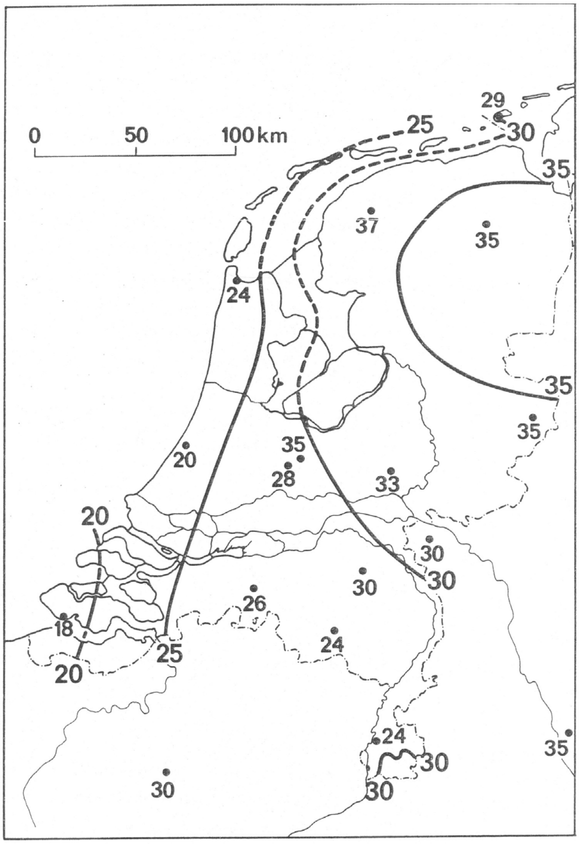

Figure 9: Estimates of 50-year snow depths (cm)

distribution and extrapolated to the 50-year snow depth (see Figure 9). The procedure is similar to the wind procedure in Annex A. The maximum 50-year snow depth is 35 cm.

The study from Buishand also shows that the mean annual number of days with snow cover ranges from 12 in the south-west to 31 in the north-east. The mean annual numbers of days with snow cover decreases with increasing mean winter temperature by about 10 per 1°C. The mean run length is slightly over 4 days and the distribution of the run lengths is similar over the country.

The bulk weight density of snow varies. In general it increases with the duration of the snow cover and depends on the site location, climate and altitude. For fresh snow a bulk weight density of 1.0 kN/m^3 is normally used and for wet snow 4.0 kN/m^3. Settled snow

of a couple days old, the typical run length of 4 days, has a bulk weight density of 2.0 kN/m³.
Combining the snow depth and its weight a snow loading on the ground of 0.7 kN/m³ is used in the building codes. The elaboration in reliability indices is not made in this paper.

6.2 *Changes in precipitation due to climate change*

Table 6 shows a number of precipitation values for four scenarios during the Winter (Hurk et. al, 2006). In all scenarios the precipitation amount in the winter increases. In the W+ and G+ scenarios this is partly due to an increase in the wet day frequency. The main effect is however the thermodynamic increase of precipitation with increasing temperature. The mean precipitation increase is mainly due to the precipitation on wet days, and this is strongly dependent on circulation. Extreme precipitation changes in winter are close to changes in the mean precipitation.

Table 6: KNMI'06 scenarios precipitation for winters

	G **+1°C**	**G+** **+1°C**	**W** **+2°C**	**W+** **+2°C**
Winter				
average temperature	+0.9°C	+1.1°C	+1.8°C	+2.3°C
coldest winter day per year	+1.0°C	+1.5°C	+2.1°C	+2.9°C
average precipitation amount	+4%	+7%	+7%	+14%
10-day precipitation sum exceed once in 10 years	+4%	+6%	+8%	+12%
number of wet days	0%	+1%	0%	+2%

6.3 *Impact on structural safety*

No distinction is made in rain, hail and snow in the KNMI'06 scenarios. Whether the expected increase in precipitation will lead to more frequent or an increase in snowfall is therefore unclear. The effects of changes in snow cover has not been analysed systematically in the whole scenario definition chain including regional climate models and observations (Van den Hurk, 2006). The higher average temperatures probably lead to less snowfall. However, the frequency of front passages also affects the snowfall and its influence is still subject of further research (Kool et al, 2003).

All mentioned parameters: the number of days with snow cover, the distribution of the annual maximum snow depths and the run lengths and distribution of snow depths, can change due to climate change. Using the precipitation values in the scenarios the relative change of the parameters and therefore the change in snow load cannot be determined. The snow cover should be incorporated in the definition of the four KNMI scenarios before the current models can be checked and the impact on roofs, main structure and foundations of buildings can be investigated.

7 Adaptation strategies

The most direct way to deal with effects of climate change in structural engineering, is to adjust the building codes. Increasing the loads due to wind, precipitation and temperature, may create a more robust set of building standards with respect to the loads. There are different strategies to follow, when to change our current loading rules in this respect:

1. We do not change our codes until there is full evidence that problems occur, and we have a clear picture of the extent to which changes occur.
2. We change our codes so, that we can design safely for the next fifty years; periodically, we evaluate the need to update the codes again.
3. We change our building codes by including a climate change factor, which can depend on year of construction, to follow the trends in climate.

The extent to which these standards should be adapted is not yet determined. It requires a more detailed study to the extent of which these loads will change. Such studies should include the climate information on the spatial and time scales, relevant for structural design. The translation from climate change scenarios towards loads on buildings now requires very rude assumptions, thus introducing uncertainties. These may lead to conservative, uneconomic design, or to designing at a too high risk, being unsafe. Also, the occurrence of very rare events, which have not yet been observed, but may become relevant in typical design life times, should be included in such a study.

8 Discussion

This paper focuses on the effects of changing extreme climate events to structural loads on structures, and the possible needs to adjust building standards. Building standards are used for new design of buildings or building elements. The existing building stock is usually not included. There is, on a European scale, no code available for checking existing structures. If we consider existing buildings, designed and built according to the current loading standards, we find that the overall level of safety will decrease with increasing climatic loads.

In the Netherlands a lower level of safety is prescribed when checking existing buildings. This is reached by taking a lower partial safety factor, e.g for wind loading, taking a value of 1.0, instead of 1.5. This choice is made to cover slight material degradation, without the need to demolish and rebuild a large amount of buildings. This safety factor of 1.0 is also valid, motivated by the fact that existing buildings have already proven to be able to withstand recent loads, so this decreases the uncertainties. Now we have to deal with uncertainties in the climatic loads, we also need to include this in the way we treat our existing buildings. The effect of climate to the existing building stock may also be of special interest for the insurance industry.

Adaptation of existing buildings is very difficult to organise. It is the responsibility of building owners, and it could be stimulated to take climate change effects into account when maintenance is carried out or additions to buildings are planned. We need to develop instruments for building owners to make proper decisions on this matter, and to design and carry out measures to cope with these effects.

Since risk is defined as probability of failure times the consequences of that failure, an analysis of the risk of structures requires knowledge on the trends in the loads, but also a critical view on the trends in consequences of failure of structures. Some relevant trends are:

1. The increase of the overall building stock. In the Netherlands the total amount of buildings is still increasing with an average value of 0.75 % per year (source: Milieu en Natuurplanbureau).
2. The total value of individual buildings will increase. The use of more expensive materials and products, especially in facades and roofs, which are directly exposed to the outside, is growing (Geurts, 2007). The most expensive part in a building usually

is the building façade. This building part is directly exposed to all climatic influences. Having more exposed value in the building façade means that design for extreme weather conditions may become more critical in the overall design of the building.

3. We build in areas that are more vulnerable to climatic effects. High rise apartment buildings along the sea shore, or developments in the polders may lead to higher required levels of performance, against wind, rain and water.
4. Sophisticated calculation models and better knowledge lead to structures, designed to just fulfil the structural requirements (design on the edge). This could lead to a decrease in redundancy present in building structures. An increase of the climatic forces may then directly be followed by an increase in damage.

Changes in climate do not occur from one day to another. The current safety philosophy is based on an accepted risk during the lifetime of the structure. If e.g. the wind loading is the leading effect, an increase of 8% in 100 years may be relevant. The uncertainties involved however are large. Structural safety deals with extreme effects which may last only seconds (e.g for wind loads) or minutes (e.g. ponding). The climate effects are described in the scenarios in terms of days or longer. We now assume that the trends for the short terms are similar to the trends in the longer time scales; however we do not know whether this is right. Besides, we are sometimes interested in combinations of climate effects. Extreme snowfall is related to precipitation extremes and temperature. These combinations require combined statistics. We need more, and more reliable, information on the climate effects, before we can definitively changes building standards or guidelines.
Finally, we must also not forget those scenarios, which may lead to lower loads, which may be the case for snow loads. It is time to carry out objective research to the impact of our climate to building structures, in order to distinguish between realistic developments and hypes.

References

Bentum, C.A. van and Vrouwenvelder, A.C.W.M. “Nieuwe factor γ_M: De probabilistische achtergrond van de modelfactor”, 2006, Technisch dossier Bouwen met Staal, Zoetermeer

Borst, J. de, “Wateraccumulatie op lichte vlakke daken”, 2004, PAO cursus, Delft

Brink, H.W. van den, Können, G.P. and Opsteegh, J.D. , 2004, “Statistics of extreme synoptic-scale wind speeds in ensemble simulations of current and future climate”, *Journal of Climate*, 17, 4564-4574.

Brink, H. van den, 2005. “*Extreme winds and sea-surges in climate models*”, dissertation University of Utrecht.

Buishand, T.A. and Velds, C.A. “Klimaat van Nederland 1, Neerslag en verdamping”, 1980, *KNMI*, De Bilt

Buishand, T.A., “Het sneeuwdek in Nederland”, wetenschappelijk rapport WR-86-6, 1986, *KNMI*, De Bilt

Buishand, T.A. and Wijngaard, J.B. “Statistiek van extreme neerslag voor korte neerslagduren”, Technical report TR-295, 2007, *KNMI*, De Bilt

CEN, 2004-2008, Eurocode series EN 1990 - 1999: “Structural design”,

Centraal Bureau voor de Statistiek, ”Bevolkingsprognose 1998-2050”, *Maandstatistiek van de Bevolking*, december 1999-1.

Davenport, A.G., “Past, present and future of wind engineering”, *Journal of Wind Engineering and Industrial Engineering*, 90, 2002, pg. pg 1371-1380.

Geurts, C., 2007, “Building technology, codification and storm damage”, *Severe Storms over Europe – A Cross-Border Perspective of Disaster Reduction*, second workshop, summary report, Hohenkammer, Germany, pg. 40-41

Hortmanns, M., 2007, “The Structural Eurocode EN 1991-1-4 and its implementation via national law”, *Severe Storms over Europe – A Cross-Border Perspective of Disaster Reduction*, second workshop, summary report, Hohenkammer, Germany, pg. 42

Hurk, B. van den, Klein Tank, A., Lenderink, G., Ulden, A. van, Oldenborgh, G.J. van, Katsman, C., Brink, H. van den, Keller, F., Bessembinder, J., Burgers, G., Komen, G., Hazeleger, W. & Drijfhout, S., 2006. “KNMI climate change scenarios 2006 for the Netherlands”, *KNMI*, De Bilt, report WR 2006-01.

IPCC “Fourth Assessment report”, 2007, see www.ippc.org

Kasperski, M.. 1998. “Climate change and design wind load concepts”, *Wind and Structures*, Vol.1, no. 2 (1998), 145-160.

Kasperski, M., Geurts, C., “Reliability and code level”, *Wind and Structures*, volume 8, number 4, july 2005, pg. 295-304.

Klein Tank, A., 2007 “Influence of climate change on extreme weather events: new findings from IPCC-AR4” *Severe Storms over Europe – A Cross-Border Perspective of Disaster Reduction*, second workshop, summary report, Hohenkammer, Germany, pg. 6-8

Können, G.P., “Climate scenarios for impact studies in the Netherlands”, 2001, *KNMI*, De Bilt

Kool, E.J., Kolner, W.P.P., Meer, . J van der “Instortingen van lichte platte daken”, onderzoek 15056/177 2003, *VROM* inspectie

Kool, E.J. and Schmidt, T.H. “Bouwkundige schades t.g.v. sneeuwval, onderzoek naar de gebeurtenissen in het weekend van 26/27 november 2005”, 2006, *VROM* inspectie, Arnhem

Rijkoort, P.J., 1983, “A compound Weibull model for the description of surface wind velocity distributions”, Scientific Report WR 83-13, *KNMI*

Smits, A., Klein Tank, A.M.G., Können, G.P., “Trends in storminess over the Netherlands”, 1962-2002. *International Journal of Climatology*, 25, 1331–1344 (2005); Downloadable at www.knmi.nl/samenw/hydra

Smits, A., J.B. Wijngaard et al., “Statistiek van extreme neerslag in Nederland”, 2004, *KNMI*, De Bilt

Snijder, H.H., “Ponding of roof structures”, *Heron* Volume 51, 2006, Delft

Tomà, A.W., “Het beoordelen van vlakke daken op wateraccumulatie”, 1980, Staalbouwkundig genootschap

Vrouwenvelder, A.C.W.M., Faber, M., 2001: “*Probabilistic Model Code*”, Joint Committee on Structural Safety.

Ulbrich, U., 2007, “Severe storms in Europe: Does climate change influence their frequency and intensity?”, *Severe Storms over Europe – A Cross-Border Perspective of Disaster Reduction*, second workshop, summary report, Hohenkammer, Germany, pg. 9-11.

Wieringa, J. and Rijkoort, P.J., 1983, “*Windklimaat van Nederland*”, Staatsuitgeverij, Den Haag, the Netherland.

Appendix Wind loads in current and future building codes

8.1 Background of our current codes

The general expression for the wind load, which is applied in the European wind loading standard EN 1991-1-4, is:

$$p_{rep} = \tfrac{1}{2} \rho \, v_b^2 \, c_e \, c_f \, c_s c_d$$

where p_{rep} is the characteristic value for the wind loading, v_b is a basic wind velocity, ρ the density of air, and the c-factors take the effects of exposure (c_e), aerodynamic resistance (c_f), and effects of the structure ($c_s c_d$) into account, respectively. All these factors correspond to one of the links in the wind loading chain, as is shown in the Figure 1.

The design value is found by multiplication of the characteristic value with a partial safety factor:

$$p_d = \gamma_d \, p_{rep}$$

The design load has a predefined level of exceedance during the lifetime of the structure. The safety factor takes into account that all variables in the calculation are stochastic in nature, and has a value which is chosen so, that the required level of exceedance is reached.

We now assume that we only take the uncertainties in wind velocity as basis for the design. All other parameters (c_e, c_f, c_s, c_d) are treated as deterministic in this approach.

In the Western part of The Netherlands (meteorological station Schiphol Airport) the mean wind velocity v has a Weibull distribution with a mean equal to 5.2 m/s with a standard deviation of 2.6 m/s. For structural purposes we are not interested in the daily wind but in the extremes. These extremes are well described by the Gumbel extreme value distribution. The Gumbel distribution is given by:

$$F_V(\xi) = \exp\{-\exp(-a(\xi - u))\}$$

The mean value and the standard deviation of this distribution are given by:

$$\mu = u + \frac{0.577}{a} \qquad \sigma = \frac{\pi}{a\sqrt{6}}$$

The yearly maximum of the hourly averaged wind velocity has the following parameters for the Schiphol data:

$u_1 = 20$ m/s; $\alpha_1 = 0.56$ s/m

or, expressed in the mean and standard deviation:

$\mu_1 = 21$ m/s; $\sigma_1 = 2.3$ m/s

Taking the maximum of a number of independent stochasts being all Gumbel distributed with the same parameters, than the maximum of these stochasts is also Gumbel distributed but with other parameters: The mean value changes, the standard deviation remains the same. The transfer term for the mean value is:

$\Delta u = \ln(n) \,/\, a = 0.8\, \sigma \ln(n)$

Using this procedure for three wind areas in the Netherlands the basic wind velocity is determined. For example for meteorological station Schiphol, representative for wind region 2, the Gumbel parameters of the meteorological data are:

$u_1 = 20$ m/s; $a_1 = 0.56$ s/m

$u_{50} = 20 + \ln(50)/0.56 = 27$ m/s; $a_{50} = 0.56$ m/s

$\mu_{50} = 21 + \ln(50)/0.56 = 28$ m/s; $\sigma_{50} = 2.3$ m/s

where the indices 1 and 50 denote the return period in years.

In this way for Schiphol a basic wind velocity v_b=27 m/s is found.

For design purposes, the Netherlands have been subdivided in three regions, each with another value for the basic wind velocity, these values are given in Table A1.

Table A1: Values for the basic wind velocity, used in the Dutch National Annex to EN 1991-1-4; This value is defined as the mean 10-minute average value at 10 metres height above terrain with roughness length z_0 = 0.05 m.

Wind region	Basic wind velocity
I	29.5 m/s
II	27 m/s
III	24.5 m/s

In Fig. A2, the distribution of the momentary hourly averaged wind velocity, the yearly maximum and the 50 year maximum are indicated.

For a return period of 50 year the probability that the wind velocity is smaller than this characteristic wind velocity is:

$$P\{u < u_{50}, 50 year\} = \left(1 - \tfrac{1}{50}\right)^{50} = 0.37$$

The characteristic value for the loading results from a detailed analysis using the Gumbel distribution. This analysis is not given here; the result is:

$X_k = \mu - 0.45\sigma$

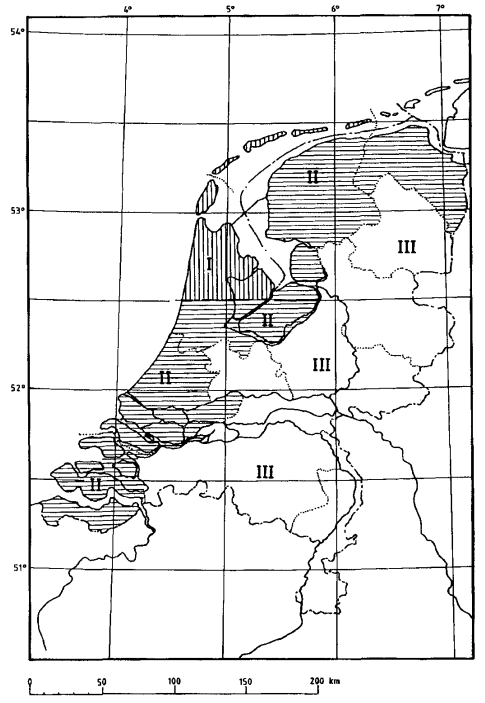

Figure A1: Wind-climatic regions for design of building structures in the Netherlands.

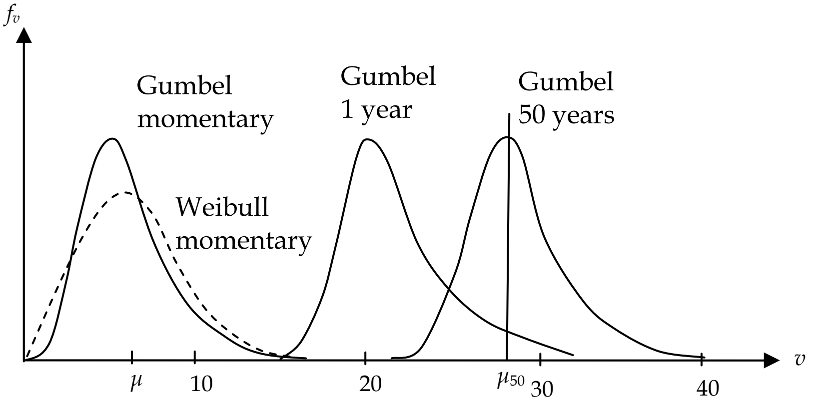

Figure A2: Wind velocity distribution for the Western part of The Netherlands, momentary, the yearly maximum and the 50 year maximum.

In our current building codes, the partial safety factor in wind loading calculations is taken equal to $\gamma = 1.5$ for 'normal structures'. Application of this safety factor is equivalent to taking a higher value of the mean wind velocity, which has a longer return period.
We assume a model factor $\gamma_\theta = 1.05$, taking into account the variation in the other parameters than the mean wind velocity, such as terrain influences, pressure coefficients etcetera. The design load is now found by the mean wind velocity + a peak factor g times the standard deviation, multiplied by this model factor:

$$Q_d = 1.05\left(m_{50} + g\sigma_{50}\right)$$

The partial safety factor for the wind loading is defined as the relation of the design wind load Q_d and the characteristic wind load Q_k :

$$\gamma = 1.5 = 1.05\left(\frac{Q_d}{Q_k}\right) = 1.05\frac{\left(\mu_{50} + g\sigma_{50}\right)^2}{\left(\mu_{50} - 0.45\sigma_{50}\right)^2}$$

Evaluation leads to:

$$1.05\frac{\left(27 + g\times 2.3\right)^2}{\left(27\right)^2} = 1.5 \Rightarrow g = 2.29$$

The peak factor as a function of the reliability index can be derived from the Gumbel distribution:

$$g = \left(-\frac{\sqrt{6}\times 0.577}{\pi} - \frac{\sqrt{6}}{\pi}\ln\left\{-\ln\left(\Phi\left(\alpha\beta\right)\right)\right\}\right) = 2.29$$

This provides for $\alpha\beta$: $\alpha\beta = 1.9$.
The factor α is the sensitivity factor for the loading, from NEN-EN 1990, Basis of Structural Design results the value $\alpha = 0.7$
We obtain:

$$\beta = \alpha / 0.7 = 2.7$$

The design wind velocity for Schiphol becomes:

$$u_{d,current} = 27 + 2.29\times 2.3 = 32.3 \text{ m/s.}$$

For this wind velocity of 32.3 m/s a return period is found of:

$$\Delta u = \frac{\ln n}{0.56} = 32.3 - 20 = 12.3 \text{ m/s, so } n \cong 1000 \text{ years}$$

The calculations made above have been assumed to be representative for wind region II in the Netherlands. For the other two zones, similar calculations have been carried out. These basic wind velocities are implicitly assumed to be independent of time, as no trend in the wind climate statistics is taken into account.

8.2 Future codes, including climate change effects

The new design wind velocity can be subdivided into a certain characteristic value and a partial safety factor for the load. We choose to maintain the safety factor $\gamma = 1.5$ so that only the characteristic value of the wind velocity has to be adapted. The characteristic value follows from the new design value of the load, divided by $\gamma = 1.5$.

While calculating the characteristic value, we make the following assumptions:

4. The extreme value distribution of the wind load remains in the future also Gumbel distributed.
5. The model factor remains unchanged, i.e., we assume that only the mean wind velocity is affected by climate change.
6. The extreme gust wind velocities change linearly with the yearly maximum daily mean wind velocity.

Under normal physical circumstances, the first assumption is conservative for wind velocities with a large return period. It holds that the wind velocities with a large return period have a smaller probability of occurrence than indicated by the Gumbel distribution; a linear relation on a Gumbel scale is than a conservative assumption. However, in the study by Van den Brink, the opposite appears: the wind velocities with a large return period increase with respect to the linear relation, but it has not been proved that this relation holds for heights that are important for buildings.

Using the mean value $\mu(\overline{v})$ and the standard deviation $\sigma(\overline{v})$ of the hourly-averaged (or 10-min averaged) wind velocity, the parameters u and a can be achieved.
In further research, therefore, the mean value $\mu(\overline{v})$ and the standard deviation $\sigma(\overline{v})$ of the hourly averaged wind velocity in the future have to be investigated. These values have to be extracted from the climate change models of the KNMI.
At this moment, the KNMI climate change report only indicates that the yearly maximum daily averaged wind velocity can increase until 4% in scenario W+. The relation to the

above mentioned parameters $\mu(\overline{v})$ and $\sigma(\overline{v})$ cannot be derived. Because of this, several sub scenarios are distinguished. These are shown in Table A2.

Tabel A2: scenarios for the changes in parameters in the Gumbel distribution

KNMI scenario	$\mu(\overline{v})$	$\sigma(\overline{v})$
G	-	-
G+	+2%	+0%
	+0%	+2%
	+2%	+2%
W	-1%	0%
	0%	-1%
W+	+4%	+0%
	+0%	+4%
	+4%	+4%

Further research is needed in order to investigate the change of the Gumbel parameters, while only the change in the yearly maximum daily averaged wind velocity is used for the change in $\mu(\overline{v})$ or $\sigma(\overline{v})$. It may be possible that for example $\sigma(\overline{v})$ increases more than the yearly maximum daily averaged wind velocity, this provides higher extreme value for the future.

For one scenario from Table 3 the new characteristic value of the wind velocity for wind region II is calculated. The other scenarios in Table 3 can be elaborated in the same way in order to obtain the new characteristic values for the wind velocity.

The scenario with an increase of 4% in the mean of the hourly averaged wind velocity $\mu(\overline{v})$ for W+ is elaborated. The standard deviation $\sigma(\overline{v})$ is assumed to remain the same:

$$\mu(\overline{v}) = 5.41 \text{ m/s}; \qquad \sigma(\overline{v}) = 2.3 \text{ m/s}$$

The parameters u and a can be calculated with:

$$a = \frac{\pi}{\sigma\sqrt{6}}; \qquad u = \mu - \frac{0.577}{\alpha}$$

$$a = 0.56 \text{ m/s}; \qquad u = 4.38 \text{ m/s}$$

The yearly maximum of the wind velocity results using a transfer term of:

$$\Delta u_1 = 15.8 \text{ m/s}$$

The yearly maximum of the hourly averaged wind velocity has a Gumbel distribution with:

$u_1 = 20.18$ m/s; $\quad a_1 = 0.56$ m/s

$\mu_1 = 21.21$ m/s; $\quad \sigma_1 = 2.3$ m/s

The new wind velocity with a return period of 50 year results using a transfer term of:

$$\Delta u_{50} = \frac{\ln 50}{a} = 7 \text{ m/s}$$

The new wind velocity with a return period of 50 year is Gumbel distributed with:

$u_{50} = 27.18$ m/s; $\quad a_{50} = 0.56$ m/s

$\mu_{50} = 28.21$ m/s; $\quad \sigma_{50} = 2.3$ m/s

We assume that the reliability index remains the same: $\beta = 2.7$ and $\alpha\beta = 1.9$, so the peak factor remains: $g = 2.29$.

The new design wind velocity becomes:

$$u_{d,new} = 28.21 + 2.29 \times 2.3 = 33.5 \text{ m/s.}$$

We now assume that the same safety factor $\gamma = 1.5$ is applied:

$$\gamma = 1.5 = 1.05 \frac{(33.5)^2}{\left(u_{k,new}\right)^2}$$

This provides the new characteristic wind velocity $u_{k,new} = 28$ m/s in the case of W+.

Remark: it is also possible to introduce a slightly higher model factor in order to account for the higher model uncertainty for the future.

If $\sigma(\overline{v})$ also increases, a higher value is found for the new characteristic wind velocity.

During the lifetime of a future structure, the loading is higher at the end, compared to the beginning. So, the risk of failure is higher at the end of the engineering lifetime compared to the beginning. Since in our building standards, the level of safety is calculated 'on average during the lifetime', it is sufficient to account for a mean increase of loading during the lifetime.

The wind load is proportional to the second power of the wind velocity, so for the design wind load this means an increase with a factor:

$$\frac{\frac{28^2 + 27^2}{2}}{27^2} = 1.038$$

This means an increase of 3.8%, for designs made today. However, the climate change effects are projected to increase during the coming decades. This means that we may need to adjust our building codes very frequently. Also, defining a wind load which depends on the year of construction may be an option.

8.3 Approach for other climatic loads

The example given here is a first estimate of the effects of climate change on wind loads. This approach is relevant to the other climatic loads too. Earlier studies could be used, by including the possible trends caused by climate change, to generate a new set of design values.