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IMPLICATION OF CLIMATE CHANGES ON DESIGN OF STRUCTURES

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Abstract. The climatic data on which the current generation of the Eurocodes are based are mostly about 20 years old, with some exceptions of recent updates at a national level. The second generation of the Eurocodes for structural design is expected to be nationally implemented within next few years and operational National Annexes should be subsequently developed and the climatic maps revised. Some models for extreme climate actions are still missing within Eurocodes including wind action effects due to non-synoptic storms, which are common in most of the world and are of increasing importance in Europe.

The aim of this contribution is to analyse how the impact of anticipated changes in European climate could affect the assessment of design weather parameters, including the partial factor design approach for structures according to Eurocodes, based on current knowledge concerning projection models of future climate in Europe.

Keywords: Climatic actions, design weather parameters, climate change, probabilistic assessment, partial factors, target reliability.

1. Introduction

For the completion of the second generation of the Eurocodes for structural design and selection of the National Determined Parameters for new National Annexes, the potential impact of climate changes on various types of construction works should be evaluated, mainly for structures with a longer design life as significant buildings or bridges. The aim is to estimate how foreseen changes in European climate could affect the extreme and design weather parameters for the design of structures, based on current knowledge concerning the models of future climate in Europe.

The largest contributors to uncertainty in the estimation of climate actions on structures include:

- Natural variations in climate due to solar activity and other influences.
- Some essential properties of the climate models, their spatial and temporal characteristics.
- The appearance of phenomena that was not previously characteristic for a certain region (such as tornadoes), and therefore there is no collected data on this phenomenon and there are no available reliable models that can be used in the design of structures.
- Uncertainties with the future emissions of greenhouse gases and other resources including volcanic activities or gas releases from sea.
- Political or economic decision on effective reduction of emissions of greenhouse gases in the coming decades.

Though these uncertainties make it difficult to give substantial recommendations on impact of expected climate changes on a regional scale, it is possible to indicate trends of selected basic variables which influence the models of climatic actions on structures, environmental actions or degradation of materials including steel corrosion or concrete carbonation.

2. Trends during the past decades in Europe

The temperature has increased in Europe since the 1960s and considerable differences exist between the regions as well as seasonal variations, with the highest increase in northern and north-eastern parts of Europe during the winter season.

The number of warm days has increased during the period 1971–2000. There are regional variations, with up to 10 days increase in parts of Scandinavia, Central Europe and Southern Europe. Observed trends in number of warm days are illustrated in Figure 1 where warm days are defined as days with temperatures exceeding the 90 percentile of daily maximum temperatures during the period 1971–2000 [1].

A consequence of rising temperatures is the reduction of snow cover and snow mass over the northern hemisphere. For Europe the decrease is estimated to 30 % for the period 1980–2015 but there are considerable variations. Although a decrease in mean snowfall is expected in most regions due to the decrease of snowfall frequency with increasing temperatures, a contrasting response may be experienced for snowfall extremes in other regions, where temperatures still remain below the freezing level during precipitation events, due to the intensification of precipitation rate associated with the temperature growth. Due to more

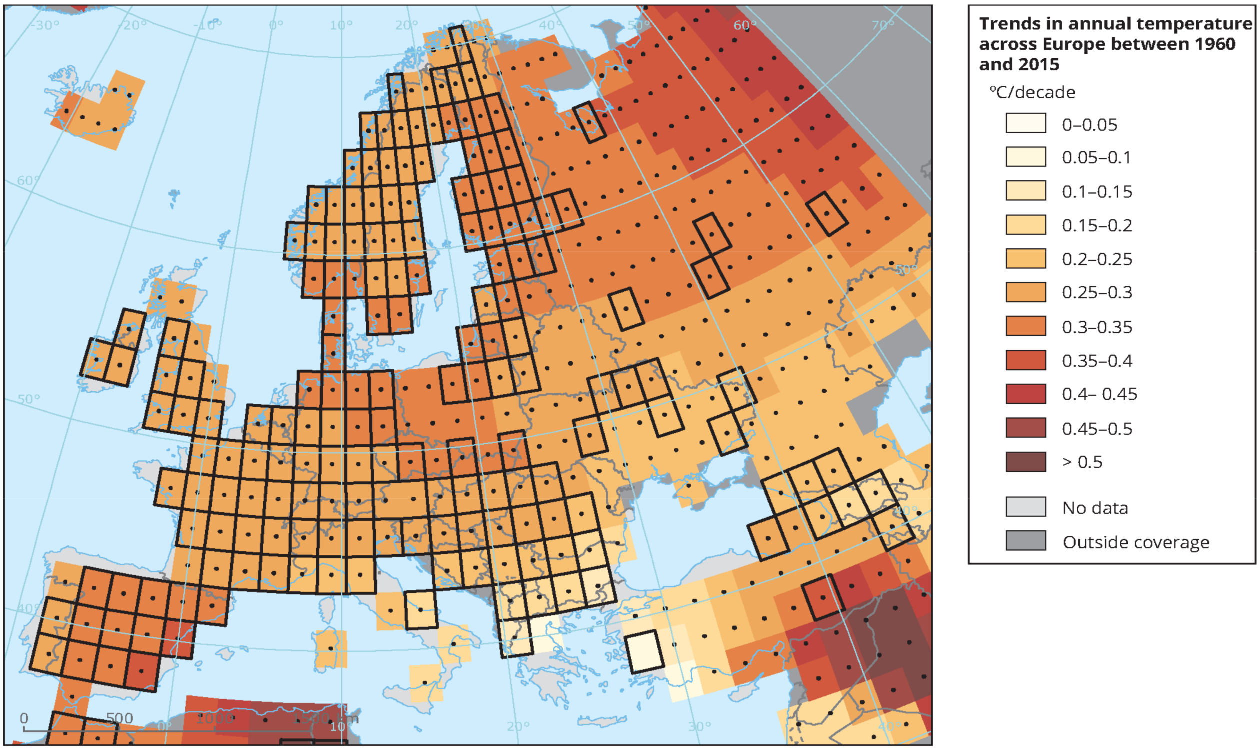

Figure 1. Observed trends in number of warm days during the period 1971-2000.

precipitation, the snow mass at the highest altitudes in Norway has increased. This is further evidenced by observed exceptional snowfall events occurred, e.g. in the winter season of 2005/2006 in Central Europe where many roofs of buildings and stadiums were seriously damaged or collapsed due to extraordinary long-term winter snow accumulation without its melting; this has triggered a revision of the Czech National snow map.

Studies of extratropical cyclones and wind data from the past decades show high variability but no significant trends, and hence it is impossible to find any clear trends for extreme wind speeds in Europe. A raise in atmospheric greenhouse gas concentrations may cause some of the atmospheric conditions conducive to tornadoes such as atmospheric instability due to increasing temperature and humidity.

Development of monthly average temperatures based on measurements of the oldest Czech Meteorological station in Klementinum in Prague in the past three 50-year periods is illustrated in Figure 2 [2]. An increasing trend with time is apparent for each month.

3. Trends in Europe towards 2100

All parts of Europe are expected to become warmer towards the end of the century with the strongest increase in areas at high altitude such as the Alps and parts of Scandinavia during summer and north-eastern parts of Europe during the winter, where the increase in average temperature could exceed 6 °C under the highest emission scenario of RCP8.5. Such increase is

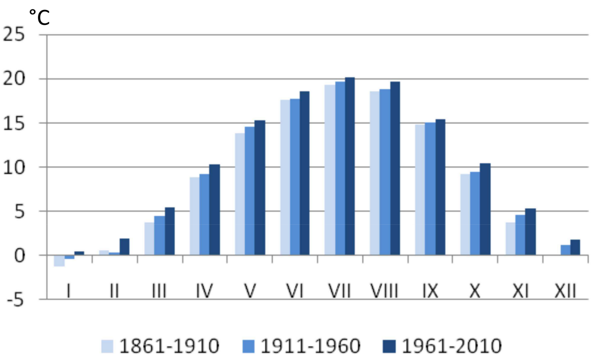

Figure 2. Development of average temperatures (in °C) based on records from the Klementinum meteorological station in Prague since 1861.

expected to increase the frequency and magnitude of heat waves [3] while the number of periods with cold temperatures is likely to decrease.

The climate models indicate a future decrease in annual precipitation between 10 to 20 % in part of southern Europe and an increase between 10 to 20 % in northern Europe under the medium emission scenario of RCP4.5. The signals for RCP8.5 are similar but stronger with up to 30 % decrease in southern Europe and 30 % increase in northern Europe. The frequency and intensity of heavy precipitation events are expected to increase, especially in Scandinavia and eastern Europe, but also southern Europe could experience an increase of such events, despite the reduction in annual precipitation. This may increase frequency and/or magnitude of local and possibly also of large floods.

Increased temperatures in the winter would lead to a decrease in snow cover and snow mass and in the length of the snow-covered season. The snow mass is expected to decrease between 10 % and 30 % towards the end of the century according to EEA report [3] but the trend is probably nonlinear and regional variations should be expected. Increased precipitation could lead to higher snow loads in inland areas at high altitudes, and consequently the snow mass could increase to a maximum in such areas before they decrease towards the end of the century.

Wind in future climate is highly dependent on tracks of extratropical cyclones as well as their intensity, and the signals are unclear as different model studies show some divergence in the results. However, there are indications of increasing intensity of strong thunderstorms, especially for northern and central Europe [1, 4].

4. National climatic maps

Current national maps in Eurocodes which are used as a reference for the design of structures have a number of limitations including:

- They are mostly 10 to 15 years old.
- They are sometimes based on a limited number of records of measurements and some measurement techniques are deemed to be obsolete (commonly associated with much larger measurement uncertainty in comparison to available modern techniques).
- They were developed at a national level and in some cases discontinuities across borders appear (for instance Croce et al. [5] revealed common differences along borders above 1 kN/m^2 for the characteristic ground snow load in Europe).
- The processing of the data is inconsistent among countries and often limited to standard techniques.

The potential effects of climate changes are not reflected in the present national climatic maps, and an adaptation may thus be needed to consider relevant observed and future changes in extreme temperatures. The relevancy of these changes needs to be carefully examined considering the type of climatic action and specific climatological conditions of a particular region.

5. Climate change coverage

5.1. Wind

The approach in EN 1991-1-4 for wind actions assumes that the strongest wind actions arise from synoptic storms. This could be considered for the case for well behaving wind climate and simplified in the present generation of Eurocodes. It is well known that winds have a rather heterogeneous nature. Three major wind circulation classes can be distinguished: a global circulation, a synoptic circulation and a local circulation.

Winds belonging to the first class are mild and do not represent any threat for the construction works. Winds of the second class can be very strong, and among them are extratropical cyclones (also synoptic storms), tropical cyclones (hurricanes or typhoons) and monsoons. These winds each manifest themselves in a limited part of the earth surface. Winds belonging to the third class have a wide variety, from mild thermal breezes to disruptive tornados, and their possibility and probability of occurrence is strongly related to the geographic location and to orography maps which are used as a reference information for structural design.

In the last decades the European wind climate has shown an apparent change, making winds other than those arising from synoptic storms stronger than they used to be. Both changes raise the question whether or not it is still appropriate that EN 1991-1-4 gives provisions only for wind pressures derived for synoptic storms, the answer to which is difficult to give and its potential impact is high.

Therefore, among non-synoptic winds of interest for structural design are tropical cyclones, monsoons, tornados, downburst outflows, and some local thermal winds.

High-intensity tornados commonly strike outside Europe, and until few years ago only a limited number of small to moderate intensity ones usually stroked the coasts. However recently significant tornados appeared in some European countries including tornado in the south Moravia where 5 people died and about two hundred people were injured, more than 200 houses completely destroyed.

With climate change, the number of such rare phenomena as tornadoes may increase. The main characteristic of a tornado is the intensity class, which characterizes the degree of damage from a tornado. The main characteristics of the tornado are determined on the basis of intensity class. The influences of tornadoes for structural design can be characterized by the following parameters:

- The probability of appearance a tornado of a certain intensity class in a certain region. Accordingly, climate change can affect both the intensity class (degree of damage) and the number of tornadoes in the region.
- The probability of the impact of a tornado on a specific object. It depends on the intensity class, in particular on the width and length of the tornado. For a certain intensity class, this probability depends more on the density and the size of the object in a region under consideration.

Downburst outflows, which are common in most of the world, are also recently becoming stronger and stronger in Europe, and this could be potentially an effect of climate changes. Wind-induced damage occurred to small structures in the last years has in most cases to be ascribed to downburst outflows, and the nature of their meteorological features as well as of the action they exert on structures is currently a hot research topic in the field of wind engineering. A mature loading model, for incorporation in design codes has been unavailable yet, even though it is clear that this should be a separate one from that used for synoptic winds, and not merely a modification of design speeds.

5.2. Snow

Although a decrease in mean snowfall is expected in most regions due to the decrease of snowfall frequency, a contrasting response may be experienced for snowfall extremes, e.g. in Central parts of Europe in the winter period 2005–2006. Analysing daily precipitation extremes, the increase of surface air temperature due to global warming leads to a decrease of snowfall fraction but also to an increase of precipitation rate during extreme events. Therefore, the temperature rises and facilitates the melting of snow and increases the fraction of precipitation falling as rain, however it can increase the intensity of the single snow events, leading to higher ground snow loads in some regions.

In respect of snow patterns, European regions belong to various climates such as maritime, continental, or cold, often with significant dependence of the ground snow loads on altitude of the site. The climate in lowlands of Western-Central Europe and in the Mediterranean is characterised by an intermittent snow cover, i.e. single of a few snowfalls followed by often complete melting. In contrast, the climate in mountains such as in the Alps and in the cold northern regions is characterised by a sustained and accumulating snow cover.

Kvande et al. [6] investigated the predicted effects of climate change on the ground snow loads in Norway. They concluded that the expected global temperature increase would, in the majority of the country, lead to decreasing ground snow loads in 2070–2100. Yet, in some inner areas, an increase of ground snow loads is predicted with the expected impact on structural reliability.

Regarding milder snow climate regions, the statistical analysis of recorded ground snow loads in Central Europe has revealed statistically significant decreasing trends in annual maxima for the Swiss Alps and the Carpathian region. However, an increase in the variability of the meteorological effects might result in more frequent heavy snowfalls especially in some mountainous regions as for example deemed to be demonstrated by recent roof failures in Bavaria; see [7] for an overview.

Further, snow load on the ground is a basic variable, which is nowadays based on the statistically evaluated measurements of the snow water equivalent (SWE). In the past the snow height and density were measured, providing largely uncertain estimates of ground snow loads in comparison to SWE: Verification and site-specific re-calibration of old measurements is commonly needed to have consistent time series for revisions of snow maps.

In summary, unambiguous recommendations regarding the modelling of ground snow load extremes affected by the climate change cannot be provided considering the state-of-the-art knowledge. This is why it is widely accepted that the models for climatic loads should be continuously developed and periodically revised, at minimum each 15 years. Expected trends of significant time-dependent parameters should be given.

5.3. Thermal actions

It is evident that the temperatures are increasing over several previous decades and this trend is expected to continue towards the end of this century. Both summer average temperatures and winter average temperatures increase. According to the CEN/SC1.T5 Report on climate changes [4], the winter mean temperature is expected to rise more in northern Europe than in Central Europe or Mediterranean, whereas summer warming will likely be less intense in northern Europe. The trends in temperature can be summarized as follows:

- A number of cold days over most parts of Europe seems to be decreasing since the mid-20th century.
- Hot days and heat waves are becoming more frequent.
- Most places in Europe will very likely experience more hot extremes and fewer cold extremes as global temperature increases.
- The magnitude of hot extremes is expected to increase faster and more severely than mean temperatures over large parts of Europe. In fact, observed variations of temperature extremes results already in being much more significant than variations of mean temperature values [2, 8].

Several factors influence the magnitude of resulting temperatures and their effects on structures including structural materials and their thermal properties, colour and type of surface, geometry of the structure, its exposition to sun, shading by surrounding objects and vegetation, air humidity, geographical and geomorphological position of the site etc. It is also necessary to consider the accuracy of measurements (selected cross-sections, instrumentation), time period and procedure of evaluation. Daily temperatures (instantaneous part) and seasonal temperatures (long-term part) influence the thermal action effects on the structure.

The increase in frequency and magnitude of heatwaves due to climate changes have impacts on temperature sensitive structures, mainly having a longer design life such as bridges. Increasing temperature demands should be considered in the design of these structures or their parts.

Anticipated increase of shade air temperature due to climate changes will magnify the uniform component of the thermal action, resulting in volume changes for unrestrained structures (including elongations of bridges) and increase of internal forces for restrained structures (e.g. for frame or arch bridges). EN 1991-1-5 gives the relationship between the shade air temperature and the uniform temperature component for bridges made from different materials. The relationship given is valid for a daily range of 10 °C which could be also influenced by changing trend of temperatures. Ranges of daily temperatures should be nationally checked for the potential updating of the relationship [9].

Expected increase of solar radiation will mainly amplify the temperature difference component, which affects temperature profiles in structures, leading to additional stresses e.g. for continuous multi-span bridges or for joints of structures made of different materials.

The recommendation on periodically statistically re-evaluation of the characteristic values of shade air temperatures is given in revised EN 1991-1-5.

6. Estimation of factor of change

In order to cover climate change influence on snow loads, the factors of change (FCs) can be applied. Factors of change can be derived analysing long series of high-resolution climate projections in moving time windows. The procedure can be summarised in the following steps based on CEN/SC1.T6 [1]:

- Collection of high-resolution climate projections of the investigated climate variables for the observation period (to be compared with recorded data for the same period) and for the future period.
- Extraction of annual maxima considering time periods t of fixed length shifted by e.g. ten years each other of past observations.
- Extreme value analysis in each time period to derive characteristic values of the investigated climate variables.

The factor of change in terms of ratio for snow loads can be determined

$$FC_{k,CM}(n) = \frac{c_{k,CM}(n)}{c_{k,CM}(n=1)} \quad (1)$$

and for temperatures

$$FC_{k,CM}(n) = c_{k,CM}(n) - c_{k,CM}(n=1). \quad (2)$$

The multiplicative format seems to be more appropriate for snow loads while an additive format is applied for temperatures [4].

Future trends of the investigated variable are finally determined applying the factors of change to the characteristic values, obtained from the real measurements in the observed period ($c_{k,observed}$).

Assuming that the first-time window corresponds to the observation period used for the definition of the actual design value, the future characteristic can be specified for snow

$$c_k(n) = FC_{k,CM}(n)c_{k,observed} \quad (3)$$

and for temperatures

$$c_k(n) = FC_{k,CM}(n) + c_{k,observed} \quad (4)$$

Similar procedure can be given for precipitations or icing. The factors of change could be used for the development of maps, which can be compared with the current climatic load maps in the Eurocodes, providing guidance for potential amendments and improvements.

However, the same approach is less physically consistent and therefore less representative in the case of wind actions. It was observed that different phenomena giving rise to wind actions (synoptic storms, thunder storms, tornadoes, downbursts etc.) are changing following different trends. Recent observations have revealed a reduction of extreme winds coming from synoptic storms, and an increase of extreme winds coming from downburst outflows and tornados.

It appears that effects of climate change could decrease structural reliability over time. Consequently, the required target reliability may not be reached for the design working life of the construction. To maintain the required reliability level, climatic actions would need some adaptation to consider the effect of climate change. Note that the implementation of the ck-factor may need to be accompanied by adjustment of the partial factor for the climatic load as design values can be more sensitive to uncertainties increasing due to predicting climate change effects than the characteristic values. However, unlike the characteristic values based solely on the ground snow loads, the design values account also for large uncertainties in time-invariant components of the climatic load effects and thus relative influence of uncertainties due to climate change may be small.

7. Concluding remarks

Both average temperature and temperature extremes are expected to increase towards the end of the century. A consequence is that heat waves can be expected to occur more frequently and be longer and warmer in the future. In southern Europe the annual precipitation is expected to decrease while it is expected to increase in the north. Annual precipitation decreases also in the central Europe. More events with heavy precipitations are expected over most of Europe.

Historical trends and climate models indicate a reduction of snow mass but there are large regional differences. The trends are non-linear, and inland areas at high altitudes may experience increasing snow loads due to increased precipitation. However, these increases are of marginal interest for structural design – most of buildings are concentrated in lowlands where no or statistically insignificant decreases are often predicted. Similar developments could be expected for atmospheric icing.

Wind records exhibit considerable variability and no clear long-term trends. It is impossible to draw clear conclusions regarding future wind climate but there are indications of increasing wind speeds associated with most severe extratropical cyclones over northern and central Europe. Associated increases of design or assessment requirements may be critical for a number of existing structures as wind pressures depend on the quadrate of wind speed. Further research is needed on the effects of downburst outflows and other extreme winds including tornados on civil and industrial structures, with the expectation that in a reasonable time this could provide suitable tools for updating EN 1991-1-4.

The ongoing changes in the climate are expected to continue during the coming decades towards 2100 and become even more relevant due to the delayed impacts of past and current greenhouse gas emissions. This will potentially affect also structural design since the basic assumption of stationary climate for the determination of climatic loads will be not satisfied in a changing climate.

CEN/SC1.T5 Report [4] recommended revision of relevant climatic variables at minimum 10 to 15 years intervals. Although data from climate models provide information about future trends for climatic parameters, there is considerable dispersion in the data depending on parameter as well as emission scenario. As stated in the Report, quantification of future extremes with accuracy required for design purposes is not feasible. Regular re-examination of weather parameters considering uncertainties in extremes of climate actions should be used for verification and updating of related partial factors.

Beyond the scope of this contribution is flooding that is a major natural hazard in most of Europe and that is strongly affected by global temperature changes. Numerous studies have indicated that risks related to river flooding increase in many European regions (such as North-Western and Northern Europe) while in some regions both increases and decreases are locally expected, depending on specific conditions of various sub-regions. Though first attempts have been already made to reflect the climate change effect in designing safety measures against river flooding, considerable research efforts are still needed to provide the recommendations for optimum adjustments of design procedures with respect to the climate change effect on river flood frequencies and magnitudes [7].

Climate change studies often focus on areas with predicted increases in climatic loads. However, in some regions the climate change seems to decrease the load effects (reducing probability of occurrence and/or magnitude) and thus less strict design or assessment requirements might be considered, providing for economic savings. However, large uncertainty related to the climate change effects often surpasses the positive effect of decreased hazards. Monitoring of the structure may reduce these uncertainties.

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