IDŐJÁRÁS

QUARTERLY JOURNAL
OF THE HUNGARIAN METEOROLOGICAL SERVICE

Special Issue: Climate change and impacts from global processes to local effects

Guest Editor: **Mónika Lakatos**

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VOL. 120 * NO. 1 * JANUARY – MARCH 2016

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service

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Indexed and abstracted in Science Citation Index Expanded™ and Journal Citation Reports/Science Edition
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Editorial

Special Issue: Climate change and impacts from global processes to local effects

Climate is changing and will continue to change in the future as more and more greenhouse gases are emitted to the atmosphere by human activities. The heat-trapping greenhouse gases in the atmosphere reached new record levels in 2015. Carbon dioxide crossed the barrier of 400 ppm during the northern hemisphere spring in average.

The most obvious revealing of the changes are the rising temperatures, disrupting the natural pattern of the seasons, increasing the frequency and intensity of certain extreme weather events, such as heatwaves, heavy rainfall, and droughts in many regions.

The effects of climate change are different from region to region. The climate change is expected to result in significant changes in the Carpathian Region to affect ecosystems and human activities. The 40th Meteorological Scientific Days addressed the presenting of the recent results available in research of climate change, impact, vulnerability, and adaptation in Hungary. This Special Issue of the jubilee academical event emphasizes that improved scientific research is needed to a better understanding of the human induced climate change at national and regional levels, its impacts, and solutions for adaptation.

In December 2015, the world's governments unanimously adopted the Paris Agreement, providing for rapid and deep cuts in greenhouse gas emissions. This historic agreement commits all countries to undertake ambitious efforts to respond to the urgent threat of climate change. On the chance of success I wish the readers exciting exploration of this issue.

Mónika Lakatos
Guest Editor

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 120, No. 1, January – March, 2016, pp. 1–40

The anthropogenic climate change hazard: role of precedents and the increasing science-policy gap[1]

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(Manuscript received in final form January 12, 2016)

Abstract—There are some parallelisms and similarities since the 1960s in the identification, attribution, scientific communication, and the subsequent initial policy setting processes of the acidification, ozone layer depletion, and climate change hazards. The anthropogenic factors behind the latter one were hypothesized well before the discovery of the cause-effect relations of the two other problems; nevertheless, later on the policy approaches to address the "acid rain" and "ozone shield" issues served to some extent as precedents for building up the international climate policy mechanisms. The analysis of these knowledge and policy development cases is of particular interest in light of the widening climate change science-policy gap, whilst efficient international policy and legal regimes have been built up for tackling the acidification and ozone depleting phenomena. Concerning the global climate policy regime, the consideration of its progress covers the time period since the early 1970s by 2015 when its most recent building block was adopted.

Key-words: acidification, ozone layer depletion, climate change, environmental precedence, science-policy gap

> "*Let us suppose that the climate changes by one degree during a century, which anyway could be considered as a tremendous change, but nowadays would we be able to detect such a change?*" (*Róna*, 1909)

> "*The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880 to 2012.*" (*IPCC*, 2013–2014)

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[1] This paper is the extended and updated version of the author's presentation at the Hungarian Academy of Sciences.

1. Introduction

Phases. Various factors were leading to the almost simultaneous intensification of the scientific research activities and the first general international policy reflections by the late 1970s on emerging large-scale atmospheric hazards, namely, the acidification, the ozone layer depletion, and the climate change problems. The formulation of the evidence-based hypotheses on their anthropogenic drivers, sources of the atmospheric emissions, and possible implications was relatively shortly followed by ascertaining the cause-effect relations and the adoption of increasingly rigorous international agreements only for the acidification and ozone depletion problems. It has happened differently for the climate change issue. In general, the earlier chronologies of these scientific and policy-making processes were segmented and separately analyzed from different perspectives (e.g., in the case of acidification by *Levy*, 1995; the ozone layer policy history by *Morrisette*, 1989; the development of climate change policy regime by *Gupta*, 1997 and *Bodansky*, 2001). The parallel and partially interlinked science-driven policy-making for these three atmospheric problems is studied in this paper through the following phases: (i) the "*inception phase*" by the late 1970s associated with the detection of these hazards, the scientific search for their cause-effect relations, and the initial political reactions; (ii) the verification and the "*international policy setup phase*" by about the turn of the 20th century, which is characterized by reaching much higher confidence level in the attribution of these hazardous phenomena to certain anthropogenic factors affecting the natural mechanisms and also by the development of the relevant international policy regimes; and (iii) the following "*divergent phase*", when the effective solution of the acidification and ozone layer hazards was already on track, meanwhile the science-policy gap was widening for the global climate change problem. The "inception phase" is actually coincides with the birth of a new and prosperous branch of atmospheric sciences, namely the air chemistry (*Mészáros*, 1981), which is *inter alia* dedicated to the subjects of those atmospheric processes, the interrelated science-policy aspects of which are considered in this paper. More generally, the evolution of the international environmental cooperation and the adoption of numerous multilateral agreements were closely linked to the progress in environmental science in its entirety, the "scientization" as it was called by *Brauch* and *Sprong* (2011), and to the changes on the global political scene in the second half of the 20th century (*Clark et al.*, 2001; *Faragó*, 2006).

Precedents. The policy-setting cases for acidification and ozone depletion served in some degree as precedents during the early period of the elaboration of the international mechanisms for tackling global climate change. This effect was profoundly justified because of some similarities in the socio-economic drivers, the applicability of the general principles of international environmental cooperation, the most typical response options (abatement/mitigation policies), and the specific situations of the various country groups. But, it turned out rather soon, there were considerably distinct aspects of the climate change policymaking that could not be overcome at such a pace, as it occurred for the two other environmental issues. These aspects stem from the complexity of the climate system *per se*, and also from the multiplicity, particular technology aspects, and the inertia of those economic sectors, which contribute to the escalation of this global problem. Therefore, the two above-mentioned precedential policy processes could have productive effects (directly or indirectly) only for a while on development of the international climate policy architecture. In course of time, this diversion became even more apparent as the science-policy gap was rapidly widening in terms of the improved scientific knowledge and the increasingly inadequate level of the overall climate policy responses.

The beginning. The human-induced climate change hazard was hypothesized and the acidifying air pollution problem was already noticed well before the middle of the previous century. Notably, the possibility of global warming caused by fossil fuel combustion was raised at the end of the 19th century (by *Arrhenius* in 1896 and by *Chamberlain* in 1899). Based on a limited set of surface temperature data series and information on "artificial production of carbon dioxide" from fossil fuel combustion available that time, *Callendar* (1938) asserted that global warming had begun and provided a draft assessment for its rate. In terms of the acidifying air pollutants, the harmful effects of emissions from a Canadian metal smelter on the neighboring areas of the USA can be mentioned as an early case of such a transboundary pollution. These effects were observed from the 1920s and resulted in an international conflict between the two countries. The conflict was settled by an arbitration procedure without any deep theoretical analysis of the pollution propagation, and the decision simply referred to the "injury by fumes in or to the territory of another state (..), when the case is of serious consequence and the injury is established by clear and convincing evidence" (*UN*, 2006). As a matter of fact, these environmental hazards together with the ozone layer problem became prevalent several decades later, when rapidly increasing attention was paid to them by the scientific community, their genuine mechanisms could be discovered, and the first concrete recommendations were formulated for their mitigation. That is why we focus on the parallelism and certain similarities of these scientific and policy-making processes from the mid-20th century.

Drivers. Before turning to the above-mentioned phases of detection and management of these atmospheric problems, some of those common *socio-economic drivers* are highlighted, because of which these hazards started to manifest themselves at a quick pace in the post-WW2 era, and in turn, the late 1960s and early 1970s marked the beginning of more focused scientific research nearly simultaneously in these environmental issues and the subsequent initial international political reactions. The post-war economic recovery followed by an economic boom in the OECD (formerly OEEC) countries, the rapid reconstruction and development in Eastern Europe from the 1950s, and the socio-economic changes in many developing countries went together with growing demand for natural resources and increased pollution in very diverse forms. These environmental pressures were significantly enhanced by the global population explosion and changing consumption patterns. The growth in the key economic sectors (energy, transport, agriculture, such industrial activities as metallurgy, chemical industry, etc.) was inadvertently leading to the intensification of large-scale atmospheric and other environmental problems (water pollution, loss of biological diversity, deforestation, chemical hazards, waste streams). Moreover, there are rather evident reasons that explain why these three atmospheric hazards were drawing increased attention with almost the same time lag, namely, the time period needed by these accumulating environmental pressures for exceeding some critical thresholds. Of course, other factors were also essential in this regard, like the fast development of environmental monitoring technics, systems and networks, methodologies, numerical models, and the international scientific cooperation.

2. Simultaneous knowledge development on emerging atmospheric hazards and the initial policy reactions

"The combustion of coal, oil, and gas (..) results in the discharge into the air of sulphur dioxide, carbon dioxide, carbon monoxide, oxides of nitrogen (..) Little is known, e.g., of what happens to our most common pollutant, SO_2, once it has been discharged into the atmosphere." (*PSAC*, 1965)

"It is recommended that in establishing standards for pollutants of international significance, Governments take into account the relevant standards proposed by competent international organizations (..) in planning and carrying out control programmes for pollutants distributed beyond the national jurisdiction." (*UNCHE*, 1972)

The massive atmospheric emission of disparate pollutants from human activities since the mid-20th century have triggered the increased interest of the research community to see whether these environmental pressures would lead to extensive adverse effects. Besides revitalizing some earlier conceptions or developing new ones in this regard, it was clear that first of all, sound environmental observations were necessary for reliable scientific investigations and conclusions. The International Geophysical Year (IGY) in 1957–58 offered a good opportunity to launch regular and internationally standardized environmental measurements. The data series from these measurements, the assessments of sources and volumes of airborne emissions, and the clarification of the relevant biogeochemical cycles greatly contributed to knowledge development concerning climate change, acidification, and ozone layer depletion by the late 1970s (i.e., during the above mentioned "inception phase"). As a consequence, these and some other emerging environmental hazards were acknowledged by policymakers, and the initial coordinated responses were agreed upon at their international meetings in 1972 (Stockholm) and 1975 (Helsinki). In this context, the atmosphere plays a particularly important role: "air pollutants move quickly and cover greater distances than do pollutants in watercourses or the marine environment. The atmosphere is in fact the planet's largest single shared resource" (*Kiss* and *Shelton*, 2007).

2.1. Systematic observations and initial findings

Observing atmospheric CO_2 changes. The hypothesis on the possibility of human-induced climate change could be better tested from the mid-20th century, when the after-war economy boost and industrial development resulted *inter alia* in rapidly growing fossil fuel based energy production. *Revelle* and *Suess* (1957) described it as a dangerous process and insisted on having more precise measurements and assessments: "Present data on the total amount of CO_2 in the atmosphere, on the rates and mechanisms of CO_2 exchange between the sea and the air (..) are insufficient to give an accurate base line for measurement of future changes in atmospheric CO_2. An opportunity exists during the International Geophysical Year to obtain much of the necessary information." As a follow-up, the rate of increase of the anthropogenic CO_2 emissions and atmospheric concentrations was re-assessed in 1958 (*Callendar*, 1958; *Bolin* and *Eriksson*, 1958), and accurate measurements of the atmospheric CO_2 started at the Mauna Loa Observatory in the same year. It was confirmed soon that this value had annually a "small but persistent increase" (*Keeling*, 1960). Based on that discovery, the USA President's Scientific Advisory Committee formulated its opinion that the changing chemical composition of the atmosphere *may* lead to a significant change of the climate already by the end of that century (*PSAC*, 1965).

Concerns about the SO_2 releases. The same period of time marked the increased attention to man-made atmospheric discharges of various pollutants, their transport and deposition, with a particular focus on the sulfur cycle (*Eriksson*, 1963). Similarly to the case of the carbon-dioxide, it became evident that for the sake of more accurate assessments, first of all systematic monitoring was necessary. The European Air Chemistry Network (EACN) was established in the middle of 1950s and substantially extended during the IGY. This issue was also raised on the other side of the Atlantic (*PSAC*, 1965): "The combustion of coal, oil, and gas in our homes, vehicles, and factories results in the discharge into the air of sulphur dioxide, carbon dioxide, carbon monoxide, oxides of nitrogen, and partially burned hydrocarbons. (..) Many of these pollutants released unintentionally or as a by-product are long-lasting, come from a multitude of sources, and are subject to transportation over great distances in air, water, or living organisms. All three characteristics make them very difficult to control. (..) The problem of air pollution calls for much research."

Systematic observations of O_3. It is noteworthy that the Global Ozone Observing System also started its operation in 1957 in the framework of the IGY (*WMO*, 2014). Initially it was based on an existing international monitoring network; afterwards, it was gradually extended, internationally standardized, and two decades later complemented with satellite measurements. Initially, the measurements were made from the ground, however, their series did not show any considerable trends by the 1970s.

2.2. *Evidence-based identification of cause-effect relations*

CO_2 emissions. The growing observational network, the Global Atmospheric Research Programme (GARP) from 1967, and the first simple global climate models (developed by *Manabe* and *Wetherald* in 1967, by *Budyko* in 1969, and by *Sellers* also in 1969) provided more information on the global climate system. It made possible better (conditional) assessments of the potential consequences of the steadily increasing CO_2 releases from fossil fuel combustion together with other greenhouse gas emissions. These developments were reflected in the scientific communication already in the early 1970s. According to *Keeling* (1970), the increasing human population in the 21th century "along with their other troubles, may also face the threat of climatic change brought about by an uncontrolled increase in atmospheric CO_2 from fossil fuels." *Bolin* and *Bischof* (1970) have derived estimates of the atmospheric CO_2 for the forthcoming decades by accepting certain assumptions, for instance on further rates of global fossil fuel combustion. It is remarkable that their estimate was 371–378 ppm for the year 2000, which proved to be very close to the factual value of 370 ppm obtained at Mauna Loa Observatory as the annual average for 2000 with its peak monthly value of 372 ppm in May that year.

SO_2 emissions. Those years became also memorable for understanding the transboundary "sulfur problem". The evidence-based hypothesis on the long-range transmission of airborne acidifying pollutants was raised by *Odén* (1968) by studying the series of precipitation chemistry measurements from the EACN. Systematic analyses by a couple of North-European researchers (supported by the Scandinavian Council for Applied Research) offered more arguments on this matter and resulted in setting up the international Cooperative Technical Programme to Measure the Long Range Transport of Air Pollutants by the OECD in April 1972 (*OECD*, 1977). These efforts were assisted by the establishment of the Background Air Pollution Monitoring System (BAPMoN) in 1970 and by a multi-annual programme on the Biogeochemical Cycles under the aegis of the Scientific Committee on Problems of the Environment (SCOPE) of the ICSU (*Svensson* and *Soderlund*, 1976). The tentative observational data and analytic studies confirmed the assumption on the long-range transport of those pollutants. Similarly to the CO_2 releases, the increasing fossil fuel combustion was primarily "blamed" for these emissions and their harmful

effects on ecosystems. Based on these studies, the Swedish experts decided to present this issue as a case study to the UN Conference on Human Environment to be held in June 1972 (*Bolin et al.,* 1971, 1972). Because of substantial scientific uncertainties and other reasons, representatives of a few key Western European emitters strongly denied the idea of the long-range atmospheric transmission of these pollutants (i.e., the possibility that pollutants from their sources can reach Scandinavian regions).

CFC emissions. The potentially harmful human effects on the stratospheric ozone layer have also piqued the interest of the research community just in the same time period. This quasi-coincidence was obviously triggered by the socio-economic drivers mentioned above (economic growth, technological progress, new production and consumption patterns, etc.). The recognition of the possibility of endangering the ozone layer did not stem from actual observations, but from theoretical studies. In the early 1970s, two specific human activities were identified as those, which can directly interfere with natural factors in controlling the ozone content in the lower stratosphere. *Crutzen* (1970) revealed that the nitrogen oxides emitted from the surface may influence the ozone photochemistry in the stratosphere, but the sources of these nitrous oxides remained unclear, that is, where those originate from (in respective volumes) and how they reach high-level altitudes. In retrospect, it seems so evident that the stratospheric supersonic transport aircrafts (SST) were named as important anthropogenic causes of this problem, since they directly released nitrogen oxides up there (*Johnston*, 1971). One year later it turned out that the NASA's space shuttle operations using solid rocket boosters of the Space Transportation Systems (STS) caused high amount of hydrogen chloride emissions in the stratosphere that might also contribute to the ozone destruction (*Stolarski* and *Cicerone*, 1974). Assumptions on the SST and STS as the main dangers for the ozone layer did not prove valid (the overall amounts of these emissions could not explain an extensive ozone depletion); nevertheless, those ideas were catalyzing very intense scientific research in this area. The attention was turned to the halocarbons when their very stable chemical property, persistence, and accumulation in the atmosphere was discovered (*Lovelock et al.*, 1973). The invention of chloroflourocarbons resulted in a breakthrough, *inter alia*, in the refrigerator industry and a boost of the production of these halocarbons from the 1950s. It was a crucial milestone in the scientific recognition, when *Molina* and *Rowland* (1974) demonstrated that these synthetic chemical compounds (notably, $CFCl_3$ and CF_2CL_2, i.e., CFC-11 and CFC-12) are responsible for the increasing volumes of chlorine in the stratosphere and in turn, for the ozone depletion. They also had a clear argument for the still missing detection of the "thinning" of the ozone layer by these halocarbons: it could not be "immediately felt after their introduction at ground level because of the delay required for upward diffusion up to and above 25 km."

2.3. First international policy reactions

Other preconditions. Therefore, the period of the late 1960s and early 1970s was crucial in the identification of the human causes for all the three large-scale atmospheric hazards, as it was indicated above together with demonstrating some common factors behind these processes and the parallelism of these discoveries. In spite of the considerable scientific uncertainties, the first general policy responses were already agreed upon internationally during those years. Besides the strengthened environmental observing systems and the increased concerns of the scientific community over the rapidly growing environmental pressures from different human activities, there was another important precondition for that progress, notably, the favourable geopolitical situation or more specifically, the global political atmosphere of the *détente* (*Clark et al.*, 2001; *Faragó*, 2006). This condition was essential in general for the initiation of international deliberations on the increasing environmental risks and eventually, for achieving consensus on the basic principles of cooperation and the initial concerted actions. The general tone was set by a UN resolution (*UNGA*, 1968), according to which: the General Assembly decided to convene the United Nations Conference on the Human Environment (UNCHE) in 1972, in particular because of "the continuing and accelerating impairment of the quality of the human environment caused by such factors as air and water pollution (..), which are accentuated by rapidly increasing population and accelerating urbanization". Among the various intensifying environmental problems (including those associated with the extraction of natural resources, chemical pollution, etc.), special attention was paid to the atmosphere-related ones, since primarily these could induce dangerous large-scale transboundary or even global ecological and socio-economic impacts.

UNCHE outcomes. Because of conflicting political and economic interests of various country groups (in Europe and also between the developed and developing countries) and the still rather limited scientific knowledge on the environmental issues concerned, the preparation of the UNCHE and its outcome documents was exceptionally complicated (*Engfeldt*, 2009). Eventually, that event could be considered as the first historical milestone in global environmental cooperation. The most important provisions of the adopted documents in relation to the subject of this study clearly demonstrate that the initial international political reflections were quite similar and rather cautious in terms of the anthropogenic factors of these large-scale atmospheric hazards (*UNCHE*, 1972). First of all, it was agreed that the relevant *monitoring systems* should be further developed, notably by setting up a global network of stations "for monitoring properties and constituents of the atmosphere on a regional basis and especially changes in the distribution and concentration of contaminants" (recommendation 79/b), and more specifically, by properly monitoring the environmental effects of energy use and production, including "the environmental levels resulting from emission of carbon dioxide, sulphur dioxide, oxidants, nitrogen oxides (NO_x), heat and particulates, as well as those from releases of oil and radioactivity" (r. 57/a). (The "oxidants" in this listing, supposedly was an implicit compromise wording already referring to ozone.) Reference was also made to the importance of the internationally coordinated *research programmes* to learn more on the causes and the possible impacts of air pollution and climate change (r. 57/b, r. 79/d) and to understand better "the causes of climatic changes whether these causes are natural or the result of man's activities" (r. 79/d). Beyond that, the very general principles and objectives were also agreed on the *mitigation policies*, which aim "to minimize the release to the environment of toxic or dangerous substances" (r. 71), to plan and carry out "control programmes for pollutants distributed beyond the national jurisdiction" (r. 72), and to bear "the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction" (principle 21). The adoption of the recommendations and principles by the conference can be considered as the beginning of the modern era of international environmental cooperation marked by strengthened science-policy links and numerous multilateral agreements: "The Stockholm Conference had immense value in drawing attention to the problem of environmental deterioration and methods to prevent or remedy it. The Conference was global both in its planetary conception of the environment, and in its view of institutional structures and world policies." (*Kiss* and *Sheltin*, 2007)

Sceptics. The histories of the three atmospheric topics considered here had also something else in common in those years, namely, the appearance of *counter-positions and sceptical views* by rejecting with counter-arguments or by simply denying the possibility of significant human influence on the natural processes in question. In general, scepticism in natural science is an important methodological approach; however, in these cases besides questioning the validity of the attribution of these hazards at least partially to some human activities and referring to differing scientific arguments, the denial of the hypotheses was sometimes seemingly backed by particular economic interests. For the acidification and ozone depletion problems, such a reminder might be pertinent in view of the recurrent debates on degrees of certainty and confidence in the context of anthropogenic climate change and the justification of the precautionary approach in policymaking. When in the early 1970s the hypothesis on the transboundary air pollution causing acidification in the North European countries was reaffirmed by Scandinavian experts, the possibility of such long-range transport was refused by many West European representatives, as recollected by *Seip* (2001): "British and Norwegian authorities came in conflict on the acid rain issue particularly since Great Britain was the largest contributor of acidifying deposition in Norway". Even after that the above-referred OECD project resulted in convincing observational information on this issue and the need for international regulation was raised in 1978, the initiative to draw up a convention on the reduction of sulphur dioxide emissions was "battered by delegations of the EEC countries, especially by France, the United Kingdom and the Federal Republic of Germany. In the course of the discussion, the United Kingdom's delegation expressed unequivocal doubt about the validity of the hypothesis of the transboundary character of acid rain" (*UNECE*, 2004b). Similarly, in the early 1970s, there were strong opponents of the SST and STS theories either by raising clear-cut and correct scientific thoughts (e.g., about negligible amounts of NOx emissions by SST and STS) or clearly representing some economic interests (in connection to the supersonic transport airplanes by the "Brussels Group" as documented by *Engfeldt*, 2009 and *Hamer*, 2002). After 1974, the scientifically much more established discovery of the ozone-depleting potential of CFCs was heavily challenged by the concerned industry groups: "both manufacturers and users of CFCs opposed any effort to regulate CFCs in aerosol spray cans. They questioned the validity of the theory, pointing out the uncertainties and noting the lack of supporting evidence" (*Morrisette*, 1989). Concerning the global climate change hazard, in the 1960s and early 1970s, both the theories on forthcoming global cooling (the beginning of a new glacial period) and on human induced global warming were promoted and communicated in parallel. This course has changed considerably when the scientific assumptions, evidences, and results were critically assessed in 1979 by the (first) World Climate Conference and by the Ad Hoc Study Group on Carbon Dioxide and Climate in the USA. The declaration of the Conference (*WMO*, 1979) and the report of the Group (*Charney et al.*, 1979) already focused on the global warming scenarios caused by increasing atmospheric CO_2 amounts from fossil fuel combustion, deforestation, and land use change. The "sceptical era" was generally overcome by about the late 1980s for the acidification and ozone depletion problems, but it has been prolonged for the climate change hazard for some understandable reasons.

The Helsinki process. The focus on the environmental problems was strengthened in the broad context of international cooperation and security. Formally, the Helsinki process leading to the 1975 Conference on Security and Co-Operation in Europe (CSCE) was a pan-European initiative yet of global significance. The negotiations have culminated in the adoption of the Final Act in 1975, which incorporated a chapter dedicated to the enhancement of environmental cooperation. This chapter of the document was not only reconfirming the most essential provisions of the UNCHE (e.g., the responsibility for transboundary and global environmental degradation, importance of preventive measures for the avoidance of environmental damages, development of environmental monitoring networks), but it stated more concretely the necessary steps regarding the acidification and the climate change problems. Obviously, the more definite formulation was made possible by the specific regional dimension of the CSCE (devoted to the East-West relations and the pan-European cooperation). In terms of these two atmospheric issues, there were already affirmative references to the *transboundary pollution* and to the *anthropogenic factors* (as compared to the "cautious" recommendations by the UNCHE). Accordingly, the participating States agreed (i) to develop an international programme for the monitoring and evaluation of the long-range transport of air pollutants, starting with sulphur dioxide and with possible extension to other pollutants; for the "desulphurization of fossil fuels and exhaust gases, pollution control of heavy metals, particles, aerosols, nitrogen oxides, in particular those emitted by transport, power stations, and other industrial plants; systems and methods of observation and control of air pollution and its effects, including long-range transport of air pollutants" and also (ii) to study the changes in climate "under the impact of both natural factors and human activities" (*CSCE*, 1975). The ozone layer issue also became a delicate topic during the preparations for the CSCE, as the discovery of the ozone-destroying effect of the CFCs was published in June 1974 (*Molina* and *Rowland*, 1974), and already in December that year, the U.S. House of Representatives held a hearing on this matter. Presumably, the U.S. representatives raised this theme during the international expert meeting in Oslo in December 1974 (*US-DoS*, 1974), where the proposals for the environmental chapter were discussed for the CSCE.

Consequently, in the late 1960s and early 1970s besides some other environmental problems, not only the scientific awareness and communication were significantly strengthening more or less simultaneously for the three rapidly emerging atmospheric hazards, but already these issues were addressed internationally by the policymakers. These *initial policy recommendations* agreed upon at the high-level meetings in 1972 and 1975 concentrated on the development of the environmental monitoring systems and the promotion of the international research cooperation in these areas in order to better understand the processes, their natural and anthropogenic drivers, the potential adverse impacts. Moreover, the general need for controlling the emissions of the relevant pollutants was also indicated but without any concreteness and targets. Already a few years later, the specific policy-planning started and some very concrete first measures were taken: a World Plan of Action on the Ozone Layer was adopted in 1977 by the UNEP; between 1977 and 1979 the non-essential use of CFCs were banned in the USA, Canada, Norway, and Sweden; the negotiations on controlling transboundary air pollution began at the end of 1978 under the UNECE auspices; and some policy-related aspects were already raised in connection with different climate change scenarios at a conference held in 1978 at IIASA.

3. Setting up the international response policy regimes

(On the policy regime of the 1979 Convention on Long-Range Transboundary Air Pollution:) "As a precedent, the regime has contributed to the adoption of global treaties and rules on air pollution." (*Byrne*, 2015)

"The Montreal Protocol (..) offers the precedent of international negotiation and agreement on global environmental problems." (*Morrisette*, 1989)

From the late 1970s, the research activities were intensified, the cause-effect relations were much better identified, the basic international mechanisms and response policies were formulated and gradually advanced for all the three large-scale atmospheric issues. The international policy framework established for the acidification and ozone layer problems served to some extent as precedents for the climate change negotiations. In the following, several key precedential components of both the pan-European acid rain policy regime and the global policy architecture for the ozone layer problem are highlighted; then the analogous features and building blocks of the international climate change policy settings are presented in order to demonstrate (*mutatis mutandis*) the "re-use" of the previously agreed and proved procedures.

3.1. Precedent-setting regional agreements to combat transboundary acidifying pollution

Reaffirming the acidification hazard. The long-range transport of the acidifying pollutants was profoundly ascertained in the late 1970s as much more observational data and improved numeric models became available. In this regard, the European Monitoring and Evaluation Programme (EMEP) played an important role owing to the systematic collection and provision of standardized atmospheric chemistry data from 1977 onward. The "acid rain" problem started to receive higher political attention internationally when the report of the above mentioned OECD programme was published in 1977 with the following conclusions (*OECD*, 1977): "Man-made emissions of sulphur dioxide in Europe are derived mainly from combustion of sulphur-containing coal and fuel oil. (..) The programme has confirmed that sulphur compounds do travel long distances (..) in the atmosphere and has shown that the air quality in any one European country is measurably affected by emissions from other European countries." This was an important catalyst to the international policy negotiations, but the real push for general acceptance of the need for urgent abatement measures was that when the long-range atmospheric transport of pollutants and the acid rains generated by them were made responsible for the extensive forest degradation in Germany (*Hinrichsen*, 1983). *Ulrich* (1983) categorically stated that the "emissions of strong acid formers like SO_2 and NO_x leads to the poisoning of the ecosphere (..) The only environmental factor for forest which has been changed is the 'chemical climate' by air pollution. There is therefore no doubt that this change is the driving force for a development in the ecosphere which is characterized not only by tree and forest die-back, but also by the acidification of waters and by disappearance of species at an increasing rate. The data about load, carrying capacity and visible damage are more than enough to claim a rapid and considerable reduction of air pollution to avoid a possible ecological catastrophe". It was followed by a significant expansion of the atmospheric chemistry observational network, refined assessments of sulphur emissions from different sources, and further development of the transport models, which altogether produced much clearer information on the widespread scale of this pollution problem, and on its anthropogenic factors (*Mylona*, 1993). The stages of science development and its influence on strengthening the acid rain policy regime are presented in detail by *Levy* (1995), *Menz* and *Seip* (2004), and also in the analytic review of the 25 years of the Convention on Long-range Transboundary Air Pollution (*UNECE*, 2004b). These studies demonstrated that the international policy-making from the 1980s closely followed and adequately reflected the advancement of "acidification science" with the adoption of increasingly ambitious targets and emissions reduction commitments for all relevant pollutants in order to minimize their harmful effects.

The acid rain policy regime. The Helsinki conference (1975) and the conclusion of the OECD programme on the Long Range Transport of Air Pollutants (*OECD*, 1977) were followed by launching in 1978 the negotiations on a pan-European agreement on transboundary pollution. Both the basic scientific and political prerequisites existed for that motion. As regards the latter, the visit of G. H. Brundtland, the Norwegian prime-minister to Moscow in 1978 and the bilateral consent on the importance of this matter proved to be one of the most significant political factors for the start of the multilateral negotiations. Eventually, the Convention on Long-Range Transboundary Air Pollution (CLRTAP) was adopted in Geneva in November 1979 and afterwards, in the succeeding two decades, it was complemented with a series of protocols on monitoring, on abatement of sulfur and nitrogen emissions, and on reduction of the adverse impacts. The *international acid rain policy regime* comprises of the provisions of this set of legal instruments, the agreed targets and policies together with the means of implementation introduced by a series of the Parties' decisions. We restrict our focus to the acidifying air pollutants (AAPs), however, from the early 1990s, this pan-European cooperation was broadened to cope more generally with transboundary air pollution, including abatement policies for VOCs, heavy metals, and POPs, and taking into account the harmful "multi-effects" of all these pollutants.

The framework agreement. The 1979 convention was a *framework type legal instrument*, as it was only demonstrating the general political consensus on the environmental risk caused by air-borne pollutants, however, without determining any particular obligations for the Parties on controlling the emissions of the AAPs. One reason for that was the still considerable level of uncertainties, so that implicitly, a precautionary approach was adopted by "recognizing the existence of *possible* adverse effects, in the short and long term, of air pollution including transboundary air pollution" (*UNECE*, 1979). Thanks to rapid verification of the transboundary movement of these pollutants and their adverse impacts, the precautionary approach was soon replaced by very concrete preventive measures in the first sulphur protocol in 1985, as the Parties already expressed their concern "that the present emissions of air pollutants *are causing* widespread damage" (*UNECE*, 2004a). Afterwards, more stringent legally binding emission reduction obligations were included in a series of subsequent protocols. It has meant a *stepwise or gradual strengthening* of the targets and obligations, which ultimately resulted in the very effective management of this environmental problem.

Quantified emissions control commitments were formulated by means of defining the reference levels (base years) and the limitation or reduction targets (*UNECE*, 2004a): in 1985 the 30% emission reduction for sulphur by 1993 compared to its 1980 level; in 1988 the stabilization of the NOx emissions or transboundary fluxes generally by 1994 at the level of 1987; more ambitious reduction levels in the second sulphur protocol in 1994. Eventually, the 1999 Gothenburg protocol took into account the combined adverse effects and set even more stringent reduction targets for all relevant pollutants: 65% for SO_2, 44% for NOx, 17% for NH_3 by 2010 below their 1990 emission levels. (This protocol was further amended later.)

Some differentiation was demanded by the countries as the required level of emissions reduction was gradually raised, so that the countries' different situations could be acknowledged in relation to: the responsibility for and contribution to this common environmental problem; the adverse effects; the abatement costs; and/or their capabilities to control these emissions. Such a differentiation of the commitments was introduced on a *country-by-country basis* when more ambitious reduction targets for sulphur were agreed in 1994, and also when the comprehensive "multi-pollutant and multi-effect" protocol was adopted in 1999 (*UNECE*, 2004a). According to this last protocol, country-specific reduction commitments were set for sulphur, nitrogen oxides, and ammonia (and also for VOCs).

Joint implementation was permitted by the 1994 protocol, according to which two or more Parties could jointly fulfil their emissions reduction commitments (if it seemed to lead to cost savings). As a matter of fact, the use of this option would actually mean *emission trading* between the Parties in such a way that the "host Party" undertake additional reductions to be accounted for the "donor Party", which pays for those "transferred" emission units, but not directly for any project resulting in those extra emission reductions. In reality, this instrument was never used, as the Parties could not agree on the specific conditions and rules of its application.

The active science-policy interaction was essential for the development of proper policies and mechanisms in this international cooperation. A close relation was established between the convention-related organs (primarily, the main governing organization, i.e., the Executive Body) and those international institutions (the Steering Body of the EMEP, Meteorological Synthetizing Centres), which regularly delivered information to the negotiators on the new observational and research results. Moreover, the Parties set up their own permanent working groups with the mandate to evaluate the scientific and technological developments, and if necessary, to recommend additional measures (Working Groups on Strategies, on Effects and on Abatement Techniques).

Enforcement. At last, we refer to the *compliance mechanism* that included procedures and institutional arrangements (Implementation Committee), which were adopted within the 1994 and 1999 protocols and aimed at reviewing the fulfilment of commitments and supporting the Parties to comply with them. It was a soft enforcement instrument, as the emphasis was on providing assistance to the Parties concerned, and actually, no sanctions could be proposed at all against a Party, which was found in non-compliance even with the emissions control obligations under the CLRTAP and its protocols.

3.2. The ozone layer policy regime as a global precedent for the climate policy mechanisms

Ozone science development. Contrary to the acidification problem, the scientific recognition of the ozone layer depletion hazard did not start with the actual observation of this dangerous phenomenon, but with the scientific cogitation in early 1970s about those substances, their anthropogenic sources and chemical reactions which could influence the stratospheric ozone. The potential risk of modification of the ozone layer by human activities was reconfirmed by reports (published by WMO, UNEP, U.S. NAS), which summarized the growing body of scientific results on this matter, and starting from 1977, these triggered the decisions to ban or at least to reduce the "non-essential use" of the CFCs in some countries. The UNEP undertook the international coordination from 1977 based on the "World Plan of Action for the Ozone Layer", and in 1981, the decision was made to begin drafting a global convention to protect the ozone layer (*Morrisette*, 1989). Understandably, concrete commitments could be adopted only after 1984, when the stratospheric ozone hole above the Antarctica was discovered and the assumptions on the role of CFCs in the ozone destruction were confirmed (*Farman et al.*, 1985). The thorough analysis of various ozone depleting substances (ODS), their chemical mechanisms, varying status of the ozone layer, and the adverse impacts of its depletion, as well as, the technological search for the "ozone friendly" chemical compounds were leading to gradual strengthening of international policy responses. Below, we turn only to some of those key elements of this international policy regime, which directly or indirectly served as precedents for the climate policy negotiations and their outcomes. A few of these elements somehow replicate those instruments at global level which were developed for the pan-European acid rain policy regime, whilst others were specifically introduced, for instance, to facilitate effective participation of the developing countries in the common endeavour to cope with this global hazard.

The gradual approach to the ozone layer depletion problem was similar to that for the acidification, namely this global issue was also addressed by the international community in a stepwise manner starting with a *framework type convention* (*UNEP*, 1985), which was followed by a protocol (*UNEP*, 1987) and a series a subsequent amendments and adjustments. Extension of the list of the controlled substances and setting new reduction targets occurred due to advancement in ozone science and technology (development of the substituting chemical compounds). The 1985 Convention emphasized only the importance of the *precautionary measures* and accordingly did not include any concrete immediate quantified objectives, but contained only a future oriented provision: "The Parties shall take appropriate measures (..) to protect human health and the environment against adverse effects *resulting or likely to result* from human activities which *modify or are likely to modify* the ozone layer" and named those hazardous substances which at that stage were "thought to have the potential to modify the chemical and physical properties of the ozone layer". As the discovery of the ozone hole was communicated shortly after concluding the convention, the negotiations were speeded up, and the 1987 Montreal Protocol (MP) already determined quantified reduction targets for the production of some ODS. The subsequent amendments and adjustments (*UNEP*, 2012) substantially extended the list of controlled substances and set more stringent reduction obligations for the Parties.

The basic commitments were formulated as required *quantified reduction rates* to be reached by some deadlines compared to a reference level (1986). In the 1987 Montreal Protocol, the longest term target was defined for 1999 and it aimed at a 50% reduction for the most "prominent" substances (five types of CFCs) by that year and beyond. For other substances (halons), a *stabilization obligation* was accepted, namely, the requirement that their national production volume should not exceed the reference level. In response to the increasing awareness of the ozone layer thinning danger and the ozone depleting potential of those substances, already in 1990, the deadlines for the 50% reduction target were moved backward to 1995, and it was agreed to fully phase-out the use of these synthetic chemical compounds from 2000. The further amendments and adjustments by 1999 did not only extend the lists of the substances, tightened the deadlines, and increased the reduction rates (ultimately referring to a consumption and production level that "does not exceed zero"), but also for many ODS even banned import from and export to the countries which were not Parties to the MP.

Some differentiation in terms of the controlling commitments were agreed already in 1987 in favour of the developing countries with relatively low level per capita ODS consumption. With this provision, the apparently less responsibility for the ozone depletion hazard and also the developmental needs of these countries were recognized. This group of countries became entitled for a ten years delay for the compliance with some of the Protocol's key obligations. The subsequent amendments and adjustments regularly turned back to and refined the terms of this differentiation.

Trading with production quotas and joint implementation as optional complementary instruments were defined by the 1987 Montreal Protocol. Under specific circumstances, the former one was an option for any two Parties according to which those could trade in a portion of production of some ODS, as long as the aggregated level of their productions would not exceed the sum of production limits set out for those Parties (*UNEP*, 2012). This opportunity was used by Australia and New Zealand in 1997. The joint implementation or *joint fulfilment* mechanism in principle could be applied by a group of countries, such as the members of the European Community.

Science-policy relations were of high significance for this matter, as well, especially for evaluation of the effectiveness of the agreed commitments and for provision of advices about additional, more ambitious targets, based on the advanced knowledge on the ozone depleting mechanisms and abatement options. For this purpose, expert panels were established with the mandate to provide scientific and technological assessments and proposals (Panels for Ozone Scientific Assessment, Environmental Effects Assessment, Technology and Economic Assessment).

Enforcement. A comprehensive procedure was put in operation for the evaluation of the occasional *non-compliance* of the Parties regarding the implementation of their commitments under the MP. The elaboration of this mechanism began in 1990, it was adopted in 1992, and substantially widened in 1998 (*UNEP*, 2012). It included detailed proceedings and an institutional component (Implementation Committee). Basically, recommendations were made for the Parties which were found in non-compliance with the control or the reporting obligations, moreover, financial means could be offered as assistance to achieve compliance. Beyond that, in principle, more serious measures could also be taken, such as the suspension of the rights of a Party to trade with production quotas, however, the use of the sanctions was generally avoided (*Sarma*, 2005).

A financial instrument was initiated in 1989 by the Parties to the Montreal Protocol "to recognize the urgent need to establish international financial and other mechanisms to enable developing countries to meet the requirements of the present and a future strengthened Protocol, thereby addressing the ozone depletion and related problems" (*UNEP*, 2012). Its operation started on an interim basis in 1990, but already two years later it was made final. This Multilateral Fund received financial contributions from the "non-developing countries", that is from the developed countries and the "countries with economies in transition" (EiTs) with a clear understanding that without such an instrument and technological support, the majority of the developing countries (DCs) would not be able to reduce and gradually phase out the ODS. In 1990, the financial assistance for capacity building was considered by the DCs as a condition for implementation of the control measures by them. The agreement on financial contributions involved that the Central and Eastern European countries (that is the EiTs) also became donors, whilst they started to face serious problems to fulfil their own obligations under the MP. Ultimately, it was the Global Environment Facility (GEF) that offered some financial assistance to these countries for meeting the ODS controlling targets.

A specific condition for entry into force (EiF) of the Protocol is also noteworthy, and essentially it was replicated for the international climate change policy regime with more or less similar justification. In general, it is customary to set a reasonable threshold number of acceding countries that should be reached for a multilateral agreement for its coming into force. (In this respect, "becoming a Party" in broad sense requires the deposition of the instrument of ratification, acceptance, approval, or accession.) In the case of the MP, one more essential condition was added, according to which it would enter into force provided that at least eleven such instruments had been deposited by countries "representing at least two thirds of 1986 estimated global consumption of the controlled substances". Determining such a bottom line for the aggregated reduction volume of the ODS consumption by those countries guaranteed the effectiveness of the implementation of this agreement. It was evident that the objectives of the MP could not be reached without the active participation of the "big consumers" of the ODS. Those years, the USA and the European Community together were responsible for more than half of the global consumption, while the large group of the developing countries only for about one seventh of that total amount (*UNEP*, 2005).

3.3. Replication of some precedential features in the international climate policy setup

Policy-relevant climate science: the outset. A new period started in the scientific understanding of and the elevated concern over the climate change hazard from the late 1970s. What was known and also the remaining knowledge gap concerning the cycles of the greenhouse gases (GHGs) and the effects of their increasing atmospheric concentrations were summarized *inter alia* in the *Charney* report (1979) and at international level, by the (first) World Climate Conference (*WMO*, 1979). According to our timeline terminology, the Conference's declaration properly reflected the end of the "inception phase" and the outset of the next phase for ascertaining the validity of the earlier assumptions on this complex issue: "Carbon dioxide plays a fundamental role in determining the temperature of the earth's atmosphere, and it appears plausible that an increased amount of carbon dioxide in the atmosphere can contribute to a gradual warming of the lower atmosphere, especially at high latitudes (..) but the details of the changes are still poorly understood". During the following decade, the expanding observational systems, the improved global climate models, as well as the synthetization of the multidisciplinary research results in the framework of the World Climate Programme and the programmes of many international organizations (ICSU, UNEP, WMO, IIASA, etc.) substantially contributed to the fast science development on climate variability and change (*Faragó*, 1981, 1991). In the second half of the 1980s, a series of international meetings were devoted not only to the discussion of the new scientific achievements, but also to the possible actions to mitigate this hazard. Experts reviewed the state-of-the-art of climate change science at the meetings held in 1985 and 1987 (Villach, Bellagio), which were followed by international conferences between 1988 and 1990 (Toronto, The Hague, Nordwijk), where already scientists and policymakers exchanged views on the probable adverse consequences and the policy options (*Bodansky*, 2001).

<u>*Climate change policy regime*</u>. The year of 1988 can be seen as the actual beginning of construction of the international climate change policy regime with several exceptionally important developments: the first proposal for a concrete GHG-emissions control target was formulated at the Toronto meeting, the IPCC[2] was established as the main channel of scientific information to the policymaking community, and the UN resolution was adopted on the "Protection of global climate for present and future generations of mankind" (*UNGA*, 1988). The findings of the first IPCC report in 1990 were essential motivations for the outcomes of the 2nd World Climate Conference and also for a further UN resolution at the end of that year, which were leading to the international negotiations from 1991 and ultimately, to adoption of the global agreement on climate change in 1992. The foundations of the policy regime defined by this UN Framework Convention on Climate Change (*UNFCCC*, 1992) were later on considerably complemented by the Kyoto Protocol (KP) in 1997 and by a series of decisions enframed in the Marrakesh Accords (MA) passed in 2001 by the Conference of the Parties (COP). The Convention was enacted in 1994, the Protocol's entry into force occurred ten years later, after which the terms of a

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[2] Intergovernmental Panel on Climate Change

new round of negotiations were discussed in 2005 (Montreal) and agreed in 2007 (Bali Action Plan) on the continuation of the KP for the post-2012 period and the elaboration of a new global agreement. Eventually, (i) the KP was "prolonged" in 2012 by its Doha Amendment (DA) with new emission reduction commitments for the industrialized countries (ICs) for the 2013–2020 period, and (ii) a new universal legal instrument was adopted at the end of 2015. The latter one is the Paris Agreement (PA), which is also under the UNFCCC likewise the Kyoto Protocol and its Doha Amendment, but the PA is elaborated as a complex set of mechanisms and procedures for the post-2020 period with various general obligations *for all Parties*. (As a matter of fact, the PA established and defined only the "skeleton" of those mechanisms and procedures so that the concrete rules of their operation ought to be defined in the forthcoming years. Unfortunately, it is also valid for the Parties' concrete commitments: in particular, the PA does not include any concrete global and country level emissions control targets with the respective deadlines, and such nationally determined targets will be regularly determined, updated/upgraded, and communicated later.) Henceforth, we devote our attention to some of the *substantial components of the international climate policy architecture*[3]*, which had their precedents in acid rain and ozone layer policy regimes* (*Table 1*). Some of these elements appeared in other contemporary multilateral legal instruments, however, the influence of the policy mechanisms of the two other large-scale atmosphere-related environmental processes was especially prominent for the climate change issue. As the protocols on sulphur and nitrogen emissions were finalized in 1985 and 1988, respectively, and the Montreal Protocol on ozone layer protection was concluded in 1987, the fresh experiences on compromise-settings within those negotiating processes had also their reflections on the climate negotiations launched at the beginning of 1991.

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[3] The present discussion of the international climate policy regime takes into account some key components of the Framework Convention, the Kyoto Protocol, the Marrakesh Accords, the Doha Amendment, some decisions by the Parties, and the Paris Agreement.

Table 1. Evolvement of the international policy regimes since the late 1970s and some of their analogous features (introduced by the acid rain and/or ozone layer regimes and replicated in the climate change policy settings)

	Acid rain policy regime	**Ozone layer policy regime**	**Climate change policy regime**
	1978- negotiations ***1979: "framework" Convention***	1977: World Plan of Action on the Ozone Layer (UNEP)	1979: World Climate Conference
1980-	***1985: Helsinki Protocol (sulphur)*** ***1988: Sofia Protocol (nitrogen)***	1981- negotiations ***1985: "framework" Convention*** ***1987:Montreal Protocol*** *(MP)*	1988: Toronto Conference 1989: Hague and Nordwijk Conferences
1990-	1994: Oslo Protocol (sulphur) 1999: Gothenburg Protocol (GP) (multi-pollutants)	1990-1999: Amendments and Adjustments of the MP	1990: 2nd World Climate Conf. 1991- negotiations ***1992: Framework Convention*** *(UNFCCC)* ***1997: Kyoto Protocol*** *(KP)* (completed with the 2001 Marrakesh Accords)
2000-	2012: Amendment and Adjustment of the GP	2007: Further adjustment of the MP	2005/2007/2011- new rounds of negotiations (Montreal, Bali, Durban) 2012: Amendment of the KP (Doha) ***2015: Paris Agreement*** *(PA)*

Feature and building block	**Acid rain policy regime**	**Ozone layer policy regime**	**Climate change policy regime**
Stepwise approach: gradual strengthening of the mitigation obligations	"framework" convention followed by protocols and a series of decisions	"framework" convention; its concretizing protocol followed by amendments, adjustments	framework convention; protocol (and decisions) and its amendment; a new, framework type "global" agreement (2015)
Mitigation obligations: quantified targets	quantified emissions control targets (AAPs)	quantified production control targets (ODS)	KP: quantified emissions control targets (GHGs); PA: nationally determined targets/efforts
Differentiation: differentiated obligations (for response policies and measures)	country-by-country targets (1994 Protocol)	MP: longer term compliance period for the developing countries	KP: concrete mitigation targets for ICs PA: targets to be communicated later; general reference to actions, enhanced efforts by DCs
Flexibility instruments: for cooperative fulfilment	joint implementation (1994 Protocol, but w/o rules)	joint fulfilment; trading with volumes of ODS-production	KP: joint implementation; trading with emission allowances; PA: cooperative mechanism/approach
Science-policy interface: institutional arrangements	expert level working group on effects, EMEP Steering Body	expert panels on strategies, effects, etc.	expert level body on scientific advice and close link with IPCC
Financial mechanism: for assisting developing countries		Multilateral Fund (1990-) (GEF to assist EiTs 1992-)	GEF climate portfolio (1996-); Green Climate Fund (2010-)
Compliance mechanism: for the facilitation and enforcement of implementation	facilitative mechanism (1994-)	facilitative mechanism, incl. potential sanctions (1992-)	KP: compliance mechanism, incl. potential sanctions (2001-) PA: facilitative mechanism
Conditions for entry into force: aggregated indicator		MP: threshold for aggregated production by the ICs	threshold for aggregated emissions (KP:) by the ICs, (PA:) by all Parties

Phased approach. Similarly to the acid rain and ozone layer policy regimes and for analogous reasons, the climate negotiations resulted in *gradually strengthened outcomes* by starting with a framework convention in 1992 and continuing with some more ambitious commitments and actions from 1997 on. In this case, such a stepwise approach was justified not only by slowly dissipating scientific uncertainties (e.g., on the forcing factors or the possible future behaviour of the system), but also by the prolonged discussions on the differentiated responsibilities for this global hazard and the considerable inertia of the key GHG emitting economic sectors. The responsibility was and remained a critical question, since it stemmed from the huge differences in the historical and gradually varying GHG emissions and in the consequent shares of the countries in the increase and excess of the atmospheric concentrations of these gases. Despite the framework character of the 1992 convention (according to its title and general substance), yet it contained an important commitment on emissions control by the industrialized countries, *viz.* the stabilization of their emissions by 2000 compared to the 1990 reference level (as a default baseline, while EiTs were entitled to have some flexibility in this regard). It was followed by the 1997 Kyoto Protocol already with a moderate emissions reduction commitment by almost the same country group, and by the 2012 Doha Amendment of the KP with even more stringent emission reduction obligations, but for a considerably smaller group of the industrialized countries. The particular *quantified emission limitation and reduction objectives* (QELRO) and commitments (QELRC) were defined in the 1997 KP and later in its 2012 amendment on a country-by-country basis similarly to the 1994 (second) sulphur protocol. Contrary to that approach, the 2015 Paris Agreement did not include any quantified mitigation target, but (i) it only concretized the ultimate objective of the Convention by referring to 2 °C and 1.5 °C as the critical limit values for the global average surface temperature increase above pre-industrial levels; and (ii) for the temperature goal, it included a rather general roadmap for the overall emissions control, i.e., to *reach global peaking of GHG emissions as soon as possible and to undertake rapid reductions thereafter*, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century (in other words, to reach decarbonisation or zero net GHG emissions). As their contributions to the global response to climate change, the progressive quantified emissions control targets by the PA's Parties will be nationally determined and communicated later.

Differentiation. The concept of the common but differentiated responsibilities (CBDR) was unanimously accepted as the guiding principle for this policy regime. In particular, it meant the acknowledgment of the differences in the above-mentioned historical GHG emissions. Its consequence was the strong *differentiation of the obligations between the developed and developing countries*. In this regard, the countries' respective capabilities and national circumstances were also considered as important factors. This approach was clearly reflected in the emissions controlling provisions of the KP and DA, which set legally binding quantified *commitments* for the industrialized countries[4] (ICs) and referred to the mitigation *actions* of the developing countries (DCs) in line with the key preambular paragraph of the Convention: "Noting that (..) per capita emissions in developing countries are still relatively low and that the share of global emissions originating in developing countries will grow to meet their social and development needs". Moreover, the developed countries were also expected to undertake the provision of financial and technological assistance to the DCs in order to build and enhance their capacities for the assessment of emissions, development of climate response policies, and preparation for the adverse climatic impacts. The Paris Agreement repeated such a distinction, namely, by referring to emission reduction *targets* of the ICs and mitigation *efforts* of the DCs to be nationally determined, however, already encouraging the DCs to set also emissions control targets at a later stage. Some differentiation was also provided for other components of this policy regime (e.g., for the national communications on emissions and measures).

An international emission trading system was established by the KP in 1997. It was initiated by the USA by referring to its efficient internal (federal) SO_2 allowance trading scheme. Moreover, the *joint implementation* instrument was introduced as another flexibility mechanism, by means of which one industrialized country could transfer emission reduction units (quotas) originating from a project to another such country that partly or fully financed the project. In international terms, the KP's trading system was somewhat similar to the bilateral trading option for CFC production quotas under the 1987 MP, however, there was a very limited practical utilization of the latter one. A joint implementation option was agreed for the sulphur emissions by the 1994 protocol to the CLRTAP, but as it was indicated above, that was never used by any Parties in lack of the agreed rules for its application. Nevertheless, these two international precedents and operation of the above mentioned federal scheme in the USA provided useful background for the elaboration of the terms for those two supplementary mechanisms of the climate change policy regime. (The Clean Development Mechanism of the KP realized a very much different, innovative approach.) Because of significant differences in experiences and positions on such flexibility instruments, only the general provisions for the *market-based and non-market cooperative mechanisms* were included in the Paris Agreement, which applicability depends on when and how their terms and concrete procedures will be determined.

Science-policy relations. The state-of-art scientific knowledge closely motivated the rapid progress in the acid rain and ozone layer policy regimes, and some dedicated institutional arrangements were made in both cases to

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[4] We use the term of "industrialized countries" (ICs) for the group of the developed countries and the countries with the economies in transition, which are listed in the Annex I of the UNFCCC and referred to also in the Annex B of the KP.

systematically channel the new observational and research information to the negotiators (through working groups and expert panels). These experiences have contributed to setting up the relevant institutional mechanisms for an interactive science-policy dialogue to assist the climate negotiations. For this purpose, the role and functions of a permanent advisory body were already defined by the 1992 Convention[5], and a close working contact was maintained with the IPCC. The periodically published assessment reports of the IPCC had significant influence on the multilateral negotiations and their outcomes: e.g., the conclusions of the 1990 first report on the Convention (1992), the outcomes of the second report in 1995 on the Kyoto Protocol (1997), and the policy relevant scientific assessments of the fifth report (2013/2014) on the elaboration and adoption of the Paris Agreement (2015).

Enforcement. A comprehensive mechanism was elaborated for the evaluation of occasional *non-compliance* of a Party with its commitments under the KP, which rules were adopted only in 2001 (as part of the Marrakesh Accords). The lessons from such instruments established earlier were taken into account, as well as, the very complex nature of reporting on the GHG emissions, various climate policies, and measures by the Parties, and as a consequence, the elaborateness of the KP's mechanism went well beyond that of the compliance systems for the acid rain and the ozone layer policy regimes: "The Kyoto Protocol has thus given rise to a non-compliance procedure, which is among the most elaborate and innovative of its kind, while the Compliance Committee (..) is one of the most powerful and independent committees of its kind established by an environmental convention" (*Maljean-Dubois*, 2010). For the sake of enforcement, one possible *sanction for non-compliance* could lead to the temporal suspension of the eligibility of a Party for using the KP's flexibility mechanisms. This option reminds a similar opportunity within the ozone layer policy regime, however, with more serious implications in the case of the KP. Recently, a more cautious formula was included in the Paris Agreement obviously because of the universal nature of certain obligations: a mechanism for the *facilitation of implementation* of and *promotion of compliance* with the provisions of the PA and the relevant committee with *only facilitative and non-punitive functions* (which concrete terms of reference should be determined later).

Financial assistance for the developing countries was considered as a crucial prerequisite for their participation in the common global climate protecting endeavour, so that the financial mechanism was established and outlined already in the framework convention, which operation was undertaken by the Global Environment Facility (GEF). Primarily, it aimed to assist the developing countries and, to a less extent, the countries with economies in

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[5] "A subsidiary body for scientific and technological advice is hereby established to provide the Conference of the Parties (..) with timely information and advice on scientific and technological matters relating to the Convention." (UNFCCC, Art. 9.1) The author of this paper was elected as the first chairman of that body (SBSTA), and in that capacity (*ex officio*), he was also the member of the Bureau of the COP.

transition. In a sense it was comparable to the Multilateral Fund for the Montreal Protocol together with the support from the GEF to the EiTs. Moreover, such a similarity became even more apparent when the COP of the climate convention established its "own" Green Climate Fund in 2010 to channel financial resources to DCs to support their mitigation and adaptation related actions.

A specific condition for entry into force (EiF) has guaranteed that the KP could have its legal power only if the key "players" become Parties to it. This idea was similar to the special EiF criteria of the Montreal Protocol. Besides the requirement of having already at least 55 ratifyers, there was an additional condition, namely, this group of the Parties had to incorporate industrialized countries (ICs listed in Annex I of the Convention), which accounted in total for at least 55 percent of the total CO_2 emissions for 1990 of all the ICs. This very high threshold can be better understood by taking into account that in 1990 the Russian Federation and the USA together were responsible for more than half of that total. (Of course, this situation has profoundly changed when the USA pulled out of the Protocol.) The Paris Protocol formally repeats the similar 55–55 condition for its entry into force, however, because of its global nature, not exclusively the ratifying industrialized countries' emissions will be added up to meet the 55 percent emission threshold, but the annual emissions of all the ratifyers (those from the group of the developing countries, as well).

In sum, important precedential features of the acid rain and the ozone layer policy regimes had their positive effects on the construction of the climate change policy architecture, however, as it will be demonstrated below, after a while, the evolvement and effectiveness of the climate change policy mechanisms considerably diverged from those for the two other atmospheric issues.

4. Increasing science-policy gap in addressing the global climate change hazard

"The production and consumption of the majority of harmful ozone-depleting chemicals has been successfully phased out, in both developed and developing countries." (*UNEP*, 2012)

"Noting with grave concern the significant gap between the aggregate effect of Parties' mitigation pledges (..) and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2 °C or 1.5 °C above pre-industrial levels." (*COP Decision 2/CP.18*, 2012)

Effectiveness of acid rain and ozone layer policy regimes. When the 1997 Kyoto Protocol entered into force in early 2005, it was the general expectation that the international treatment of the climate change hazard will somehow follow the examples of the relatively rapid and effective development of the international policy mechanisms for tackling the "acid rain" (more generally, the long-range air pollution) and the ozone layer depletion problems. Due to the increasingly stringent measures, the emissions and transboundary transmissions of the AAPs have drastically dropped in the pan-European region. In the same way, thanks to gradually enhanced provisions of the MP, the production, consumption, and atmospheric release of an ever expanding group of ODS was taken under control, eventually many of these substances were phased-out and substituted by "ozone-friendly" ones for various applications. In these cases, the rapidly enriching knowledge base has had its decisive effect on policymaking besides many other supportive factors.

The climate change science-policy paradox. Contrary to the above cases, a growing gap could be observed primarily between the actual levels of the globally aggregated GHG emission reductions and the level of reductions that was from time to time recommended by the large group of scientists backing the work of the IPCC, the UNEP, and various international academic organizations. Since 1990, the IPCC has regularly published science-based assessments, *inter alia*, on those levels of global emission reductions, which would make possible, with certain degrees of confidence, the avoidance of dangerous human interference with the climate system. These were accompanied by evaluation of the mitigation potential of the economic sectors and by recommendations for specific mitigation and adaptation policies ("climate-friendly" measures in various sectors, sustainable forest management, opportunities for increased climate resilience, etc.). In addition to that, the UNEP issues Emissions Gap Reports (EGR) since 2010, and the scope of its reports is the comparison of the theoretical emissions reduction pathways for remaining below the presumably still safe global temperature increase limits with the actual, agreed, or pledged global emission reductions. In this section of the paper, the increasing deviations of the international policy responses from these science-based advices and the key factors of these deviations will be discussed. We consider the evolution of the science-policy interplay in terms of the influence of growing scientific awareness about the global climate change hazard on the international climate policy cooperation for the last four decades. This process was more or less analogous to those for the acidification and ozone depletion hazards for about two decades, however, for various reasons, there is a widening science-policy gap concerning especially the abatement or mitigation targets since the turn of the century in case of the climate change problem (*Table 2*). This is a *climate change science-policy paradox*, i.e., the contradiction between the increasing knowledge level on an environmental problem and the aggregated effect of the actions to cope with that problem. There are other forms of paradoxes embedded in the climate policies as contradictory feedbacks (*Fölster* and *Nyström*, 2010; *Jordan et al.*, 2012).

Table 2. Timeline of climate change science-policy relations
(S: short-term emissions control, L: longer-term emissions control; /1990 or /2000 is the reference year; "emissions" refer to GHG-emissions; * is for the "2°C limit" after 2007)

	Emissions control targets: science-based recommendations*	**Emissions control targets: policy approach or commitment**
1985-	1985 Villach; 1987 Villach, Bellagio S) stabilization of ICs emissions L) stabilization of the atmospheric concentrations	1988 Toronto; 1989 The Hague, Nordwijk, UNEP S) 20% reduction or stabilization of the ICs emissions by 2005 L) stabilization of the atmospheric concentrations
1990-	1990-1992 IPCC AR1 (1990 WG-III, 1992 Supplement) S) stabilization of ICs emissions L) stabilization of the atmospheric concentrations	1992 UNFCCC S) stabilization of ICs emissions by 2000 (/1990) L) stabilization of the atmospheric concentrations 1994 The Convention enters into force (EiF)
1995-	1995 IPCC AR2 S) reduction of ICs emissions L) stabilization of global CO_2-emissions within several decades followed by substantial reductions (/1990) 2001 IPCC AR3 S) reduction of the ICs emissions beyond KP levels L) stabilization of global emissions within few decades	1997 Kyoto Protocol (KP) S) 5% reduction of the ICs emissions by 2012 (/1990) L) reference to the ultimate objective of the Convention (stabilization of the atmospheric GHG concentrations) 2001 Marrakech Accords completing the rules for the KP 2004 Protocol's special EiF criteria are fulfilled (EiF: Febr. 2005)
2005-	2007 IPCC AR4 S) stabilization of global emissions within 10–15 years; 25–40% reduction of ICs emissions by about 2020 (/1990) L) global emission reductions: at least 50% by 2050; 80–95% reduction of the ICs emissions by 2050 (/1990) 2010 UNEP-EGR S) increase of global emissions: less than 17% by 2020 (/1990)	2005 Mandate for dialogue on long-term actions (Montreal) 2007 Mandate for negotiations on future actions (Bali) 2009 Copenhagen Accord (CA), a general reference to IPCC AR4; S) peaking of global and nat'l emissions "as soon as possible" according to CA: "Cancun pledges" by countries in 2010 2010 UNEP-EGR S) global effect of "pledges": 30–40% increase by 2020 (/1990) 2012 Doha Amendment to the KP S) 18% reduction of the ICs emissions by 2020 (w/o 5 ICs) (/1990)
2013-	2013-2014 IPCC AR5 S) emission peak years for all regions in 2010-2020; ca. 30% reduction of ICs CO_2-emissions by 2030 (/2010) L) 40-70% global emission reductions by 2050 (/2010) 2014, 2015 UNEP-EGR (scenarios from IPCC AR5 database) S) increase of global emissions: less than 14% by 2030 (/1990)	2015 INDCs by Oct 2015 (UNFCCC, 2015[1], UNEP-EGR, 2015[2]): S) global effect of INDCs[1]: 37–52% increase by 2030 (/1990) S) global effect of INDCs[2]: 40–54% increase by 2030 (/1990) 2015 Paris Agreement S) global peaking "as soon as possible" L) zero net emissions in the 2nd half of this century

4.1. The scientifically recommended and the actually accepted levels of mitigation responses

Initiatives for the climate change policy regime. The scientific community started to urge the policy measures on the climate problem from the mid-1980s. The conclusions of the 1985 Villach conference included the following recommended actions based on the assessment of the climate change hazard (*Villach*, 1985): "Governments (..) should take into account the results of this assessment in their policies on social and economic development, environmental programmes, and control of emissions of radiatively active gases. (..) Major uncertainties remain in predictions of changes (..) Nevertheless, the understanding of the greenhouse question is sufficiently developed that scientists and policy-makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments." As a follow-up, two expert-level meetings already focused on concretizing the policy areas which, according to the joint meeting report, should cover both the limitation and adaptation strategies. The priority actions for the former one included the re-examination of long-term energy strategies, reduction of deforestation, and increase of forest area, moreover, the limitation of the growth of non-CO_2 GHGs in the atmosphere. The report also suggested the examination "of the need for an agreement on a law of the atmosphere as a global commons or the need to *move towards a convention* along the lines of that developed for ozone" (*WMO-UNEP*, 1988). These science-based suggestions strongly motivated the outcomes of those conferences, which took place in 1988 and 1989 with the participation of many government representatives, as well. Their policy-oriented declarations included already some quantified proposals for emissions control and some other actions (afforestation, controlling other GHG emissions, international financial means, etc.). In this regard, the key points by the Toronto conference (1988) were as follows: *stabilization* of the atmospheric concentrations of CO_2, for which emission reductions of more than 50% would be necessary for long-term, and as an initial global goal, the reduction of emissions by approximately 20% of 1988 levels by the year 2005 should be achieved. The high-level meetings held in The Hague and Nordwijk in 1989 emphasized the need of *urgent stabilization of the emissions by the industrialized countries* (ICs) as a first step. The UNEP Governing Council reiterated a similar requirement for all the emissions of carbon dioxide and other greenhouse gases at its meeting in 1989 (Nairobi). As we see, these *international policy reactions were in line with the science-based recommendations at least with those that concerned the most immediate actions* (emission stabilization, launching negotiations).

Stages of mitigation policy development. From the early 1990s, the negotiations generally resulted in the shorter term mitigation obligations for subsequent decadal periods. The 1992 convention comprised of emission stabilization objectives for the ICs at the 1990 level by 2000. The 2007 Kyoto

Protocol set reduction obligations for them with the targets expressed as the annual averages for the 2008–2012 period. The Doha Amendment in 2012 defined new emission reduction commitments for a "shrunken" group of ICs by 2020. The negotiations on a new global instrument started about a decade ago and its preparations became more concentrated after 2012 with the intention to reach a deal on more ambitious actions for the post 2020 period. After 2009, many countries communicated their pledges and intentions with more or less concrete national targets for 2030 or some other target date. Eventually, that new agreement was concluded at the end of 2015, however without any concrete emission reduction "roadmap". The negotiations during all these stages could rely on inputs from the research community. The series of assessment reports of the IPCC from 1990 and the Emission Gap Reports (EGR) by the UNEP from 2010 presented scenarios with global emissions estimates, aggregated emissions of the industrialized countries, and relevant emission pathways, adherence to which could guarantee with some chance to stay below the 2 °C global warming limit. In order to demonstrate the changing science-policy gap, we now compare the science-based global emission recommendations with the global targets from the above-mentioned legal instruments or with aggregated effects of the countries' "pledges" provided at the later stages of this negotiating process.

The Convention. The IPCC published its first report in 1990 and issued supplemental assessments in early 1992. These reports included scenarios for GHG emissions control, and specifically, the IPCC's third working group (on the response strategies) provided initial evaluations on the feasibility of meeting the different quantitative targets. Besides a general reference to the urgency of the *stabilization of these emissions*, the 1990 and 1992 reports made clear that "in the near term, no significant progress in limiting global emissions will occur without actions by the industrialized countries. Some countries have already decided to stabilize or reduce their emissions". The rationality for a phased approach was also pointed out (*IPCC*, 1990–1992): "The IPCC recommends a programme for the development and implementation of global, comprehensive and phased action for the resolution of the global warming problem under a flexible and progressive approach." The existing uncertainties and the need for further in-depth studies warranted the carefulness of such formulations, i.e., the inadequacy of information available at that stage to make sound and detailed policy analyses. These complex IPCC messages had their equally cautious imprints on the ministerial declaration of the Second World Climate Conference (November 1990, Geneva) and also on the outcomes of the international negotiations, which culminated in adoption of the UN Framework Convention on Climate Change (UNFCCC). The convention included (i) short term obligations, such as the *emission stabilization commitment for the industrialized countries* (listed in the Annex I) by 2000 at the default 1990 reference level (base year) and a general provision for all Parties (i.e., also for the developing countries) to elaborate their national climate change programmes; and (ii) the long-term ultimate objective of the *stabilization of atmospheric GHG concentrations* at a level that would prevent dangerous anthropogenic interference with the climate system (*UNFCCC*, 1992). Obviously, both the scientific and policymaking communities wished to have some more time for getting more information on the climate change process, its expected impacts, and on the technical and economic feasibility of stronger policies. The Convention entered into force in 1994, and some years later it had a universal membership. Afterwards, the implementation and adequacy of this agreement was regularly discussed during the annual sessions of the Conference of the Parties (COP).

The Protocol. The next comprehensive assessment of the IPCC was completed in 1995 (*IPCC*, 1995). The refined scenarios for CO_2 *concentration stabilization* were linked to the relevant *emission pathways,* and it was made clear that even if global CO_2 emissions were maintained at then levels, they would lead to a nearly constant rate of increase in atmospheric concentrations for very long time. It was deduced that only the urgent halting of the emission growth followed by a systematic decrease of these emissions could lead to presumably still safe stabilization levels of the atmospheric GHG concentrations. More concretely, for instance, it was indicated that the 450 ppmv CO_2 stabilization scenario could be achieved only if global anthropogenic CO_2 emissions returned to the 1990 levels within approximately 40 years from that time, and dropped substantially below those levels subsequently. It was also clear from these scenarios and the related assessments that in order to achieve that global emission peaking, the industrialized countries had to commit themselves to considerable emission reductions (by taking into account their higher historical emissions, i.e., the CBDR principle). The new round of negotiations started in 1995 (based on the so-called "Berlin Mandate") and eventually those were leading to the preparation of the Kyoto Protocol (KP) and its adoption in 1997. The Protocol set an average 5% reduction obligation for the group of the industrialized countries (Annex I Parties) compared to the 1990 level of their emissions, to be achieved in the period of 2008–2012. *Although it was much lower than the GHG reduction levels stemming from the scientific evaluations, nevertheless, it was considered as a moderate but important short-term first stage in a stepwise approach.* In a sense, it still followed to some extent the initial phases of the acid rain and the ozone layer policy regimes. The detailed rules for some of the critical components of the KP were approved in 2001 (Marrakech Accords), and at last the KP came into force in early 2005 (already w/o the USA but thanks to the ratification by the Russian Federation in 2004, which was a decisive act in view of the specific EiF condition).

Coming to a standstill. In the meantime, the IPCC's third report was issued in 2001 and had some catalytic role on deliberations on the future climate policy cooperation that began in 2005 (after the KP entered into force). Based on that report, it was evident that for stabilizing the atmospheric CO_2 concentrations e.g., at 450 ppmv level, the *global emissions should reach a ceiling within a few decades* and already on short term, it "may require emission reductions during the period 2008 to 2012 in Annex I countries that are significantly stronger than the Kyoto Protocol commitments" (*IPCC*, 2001). Contrary to the essence of these conclusions, in 2005 (Montreal) the Parties could hardly reach consensus even on the formats and general objectives of dealing with the post-2012 period. It can be considered as the beginning of a rapidly widening gap between the global climate change science and the international policy responses. At least, the dispute on formalities of the future negotiations and their general directions could be resolved in 2007, and the clear-cut messages of the fourth IPCC report had some influence in that regard (*IPCC*, 2007). The report, especially, its part contributed by the third working group of the IPCC, clearly stated that: (i) keeping the 2° C objective within reach requires stabilization of the atmospheric concentration of GHGs in line with the lowest stabilization level assessed, i.e., 450 ppmv CO_2eq; (ii) this will assume that the *global GHG emissions peak within the next 10 to 15 years*, and then those are substantially *reduced at least by 50% below 1990 levels by 2050*; and (iii) the groups of the industrialized (ICs) and the developing countries (DCs) contribute to those short and long-term CO_2eq reduction goals in line with their different shares in the overall emissions. These pertinent short and long-term reduction targets *in 2020 and 2050 for the ICs are 25-40% and 80-95%*, respectively, while for the DCs their contributions were suggested as follows: substantial deviation of the emissions from baseline by 2020 in some developing regions and substantial deviation from baseline in all developing regions by 2050. These science-based assessments were indirectly cited in the 2007 negotiating mandate (Bali), however, after two years of intense deliberations instead of agreeing on new targets and commitments, the only concrete product of the Copenhagen summit (2009) was that the delegates took note of an accord that included indications for: *deep cuts in global emissions*; *peaking of global and national emissions as soon as possible*; *quantified economy wide emissions targets by the industrialized countries by 2020*. While these general provisions were not complemented with any concrete goals, all Parties were invited to submit their "pledges": quantified economy wide emissions targets for 2020 by the Annex I Parties and further mitigation actions by the non-Annex I Parties. These submissions were reviewed at next COP session (Cancun), and the total effect of these "Cancun pledges" was also compared with the emission pathways consistent with a "likely" chance of meeting the 2° C threshold (*UNEP*, 2010). The results of this gap analysis demonstrated the need to *limit the growth of overall emissions by 2020 to a maximum of 17% in contrast to the 30-40% range of the global emission increase* that was deduced from those pledges and the four policy scenarios (a combination of the unconditional and conditional pledges with "lenient" or strict rules of compliance).

"Prolonging" the Kyoto Protocol as a transient solution. We now turn our attention to the legally binding deal, which was arranged in 2011 and finalized in 2012 as an amendment to the KP by extending it to a second commitment period. This Doha Amendment (DA) included quantified emission limitation or reduction commitments (QELRC) by a group of the industrialized countries with the target year of 2020. The aggregated unconditional commitments equalled to 18% emission reduction, however, already five industrialized countries did not take part in this deal, namely: Canada, Japan, New Zealand, Russia, and the USA. Many participants of the deal indicated also a conditional higher emission reduction target (e.g., the EU-28 a 30% reduction besides the unconditional 20% target). If one were combining the emissions control "low pledges" of those five countries (e.g. 4% below the 1990 level by the USA) with the unconditional commitments by the ICs inscribed in the DA, then such a virtual aggregated target would result in a less than ten percent reduction by 2020 below the 1990 level by all the ICs (listed in the convention). Whatever would be the exact estimate for this whole group, *the aggregated target for 2020 could mean a significant decline from the science-based emission reduction range for the ICs that was derived in the 2007 IPCC report*. Moreover, the DA covered only about 15% of the global GHG emissions (*Sterk*, 2012), since it did not address the goals of the above mentioned five ICs, neither the actions by the DCs by 2020. Therefore, it remained unclear, how the overwhelming majority of the countries plan their concrete measurable, reportable, and verifiable mitigation and other climate related policies and measures. Nevertheless, the Doha Amendment is an essential achievement: without its adoption, apparently, no progress could be achieved at all in the parallel negotiations of a new global instrument.

New policy-relevant scientific assessments. The year of 2013 brought about a new stage both in the communication of new scientific results and the international climate policy cooperation. The first part of the fifth report of the IPCC was published in 2013 and it was followed by other volumes of the report in 2014. The statements on the human interference with the global climate system, on the scenarios of its future state, and on the expected impacts reflected a much higher level of confidence. Comprehensive information was also provided on the possible mitigation and adaptation strategies. Regarding the future emission pathways, besides the general indications of the need for substantial emissions reductions over the next few decades and for near zero net anthropogenic emissions by the end of the century, more concrete GHG emission reduction assessments were given for 2050 and some estimates only for the CO_2 emissions for 2030. The apparently most essential statement on the mid-century global emissions was as follows: "Emissions scenarios leading to GHG concentrations in 2100 of about 450 ppm CO_2eq or lower are likely to maintain warming below 2° C over the 21st century relative to pre-industrial levels. These scenarios are characterized by 40% to 70% global anthropogenic GHG emissions reductions by 2050 compared to 2010." For the same warming threshold (actually, for the relevant range of long-term CO_2eq concentration scenarios, i.e., for 430–530 ppm CO_2eq), regional emissions peak years were derived by means of different models, and CO_2 emission reductions in 2030 over the 2010 levels were also presented in the report (*IPCC*, 2013–2014). According to these calculations, *the peak years for all the regions were set between 2010 and 2020 in order to be in line with the above-mentioned scenarios; therefore, the global emissions ought not to grow after the end of the present decade.* But what might be much more informative for the negotiators, those were the assessments of the transient mitigation efforts by the regions (which lead to those 430–530 ppm CO_2eq scenarios in 2100): "The contribution of different regions to mitigation is directly related to the formulation of international climate policies. In idealized implementation scenarios, which assume a uniform global carbon price, the extent of mitigation in each region depends most heavily on relative baseline emissions, regional mitigation potentials, and terms of trade effects. (..) In general, emissions peak in the OECD-1990 sooner than in other countries with higher baseline growth. Similarly, emissions are reduced in the OECD-1990 countries by 2030 relative to today, but they may increase in other regions, particularly the fast-growing Asian and MAF regions." The concrete quantitative estimates (for the 430–530 ppm CO_2eq scenarios) suggest *the average 32% regional CO_2 emission reductions in 2030 below the 2010 emission levels for the group of the ICs* (the OECD members in 1990 and the EiTs), 35% reduction in average for the Latin-American region, and show a range of emissions control rates around zero (i.e., stabilization) for the Asian region and the MAF (Middle East and Africa). The above assessments offered important orientation values for the ongoing negotiations. The overall scale of these most recent emission-related figures for the 2° C criterion seems to be even more demanding than the ones from the previous assessments, in particular for the industrialized countries as a whole. By using the same scenarios from the IPCC database, the UNEP report (*UNEP*, 2014) offered even more relevant information for the gap assessments, namely the *global GHG emission levels in 2030* "for a likely chance of staying within the 2 °C limit" following a least-cost pathway from 2020 which are: 42 $GtCO_2$eq (range: 31–44), or *+14% relative to 1990 emissions and –14% relative to 2010 emissions*. The use of 1990 default reference year and emissions level is essential not only for comparability purposes (with former assessments and commitments), but also for realizing the very significant actual changes, which clearly demonstrate the inadequacy of the existing policy responses since the early 1990s. Before turning to the most recent "offers", let us compare these theoretically critical thresholds with the actual data: *global emissions have grown since 1990 by more than 45%* and were approximately 54 $GtCO_2$eq in 2012 (*UNEP*, 2014).

International climate policy cooperation beyond 2020. Now the basic question is that, how and to what extent these new science-based assessments were taken into account in the course of preparation and finalization of the new agreement adopted in 2015 for the post-2020 period. The too general, unquantified emissions control "roadmap" and the requirements of the Paris Agreement for all the Parties to communicate later their concrete emission-related contributions were already mentioned above and obviously, these provisions are not applicable at these stage for any science-policy gap assessment. The "recommended" global emissions reduction pathways presented by the IPCC or the UNEP would be valuable for top-down distribution approaches (based on the common but differentiated responsibilities), but as a matter of fact, the negotiations were again centered around a bottom-up process (likewise the KP and the DA). As a matter of fact, the majority of the countries (or country groups in the case of the EU) individually formulated and communicated their possible emissions control targets beyond 2020 in the framework of the "intended nationally determined contributions" (INDC). Obviously, the consideration of the aggregated global levels of these (unconditional and conditional) quantified national targets for 2030 or 2050 is especially important in light of the "reasons for concern" depicted by the IPCC in its latest report. The synthesis of these intended contributions submitted by October 2015 represented three quarters of Parties to the Convention and 86 percent of global emissions in 2010, and the aggregate effect for 2030 would be 56.7 (53.1 to 58.6) $GtCO_2eq$ in 2030 (*UNFCCC*, 2015). In relative terms, these estimates would mean 11–22% increase of the aggregated emissions in 2030 in relation to the 2010 level, or *37–52% increase in relation to the global emission level in 1990.* A rather similar assessment is derived in the Emission Gap Report (*UNEP*, 2015), namely, 54 $GtCO_2eq$ (range: 52–57) for 2030, which corresponds to *46% (range 40–54) relative increase compared to the 1990 level.* These clearly indicate a huge deviation from those targets which were considered necessary theoretically, and it means a further significant increase in the science-policy gap in tackling this hazardous global environmental process.

4.2. Some basic factors behind the difficulties with the climate change policy regime

There are several factors which may explain the complications with the international climate change policy-making. Their nature and significance can be better understood in a comparison with the acidification and ozone depletion cases. Four distinctive problematic areas are mentioned below; however, there are obviously other more or less critical ones, which should be taken into consideration to make the international policy regime more responsive to the climate change challenge.

The operation of the global climate system governed by internal and external, natural and anthropogenic factors seems to be much more complex than the mechanisms of the acidification and ozone layer depletion processes. As a consequence, the detection of the present climate change signal and its attribution to different drivers (forcing factors) is rather problematic because of the relatively low *climate change signal-to-noise ratio* (where the "noise" is the climatic variability in this context) and because of the diverse interactions and characteristic timescales of natural and human-induced contributions to the GHG cycles and to the impacts of the changing climatic conditions. The problem of signal-to-noise ratio also appears in the climate modelling (*IPCC*, 2001); moreover, it necessitates careful approach to climate impact assessments and adaptation strategies as the impacts of the short-term and long-term processes overlap (*Czelnai*, 1980). The complexity of the system, in particular, the problems related to the detection of the global climate change signal are clearly manifested in a more prolonged and slower decrease of the *scientific uncertainty level* concerning the anthropogenic influences on the climate system and in turn, a longer time length between the improved degree of scientific knowledge and the agreements on the related international policy frameworks. That timespan was about one decade in case of the acidification and ozone depletion problems, but it took several decades for the climate change issue (with regard to the time periods between the confirmation of the adequate attribution hypotheses and the adoption of the first multilateral legal instruments).

The substantial historical differences in responsibilities of various countries and country groups for the emerging climate change hazard have been a crucial factor together with their *differing vulnerabilities, capabilities, socio-economic problems, and interests*, in influencing the international negotiations. The recognition of the mutual interdependence was the most important motivation ("push factor") to seek common ways and means for the solution of the three environmental problems discussed in this paper, but the above mentioned differences mattered much more seriously to the global climate policy-making case compared to the other two atmospheric problems.

All key economic sectors somehow have their part in the climate change problem as GHG emitters and/or bearers of the impacts: energy sector, transport, various industrial activities (e.g., metallurgy, cement production), agriculture, forestry, healthcare, water management, nature conservation, etc. This means that for all these sectors and socio-economic activities efficient mitigation and/or adaptation policies should be developed at all levels. Therefore, it necessitates *economy-wide* national measures, while many of these policy areas have essential international dimensions in our globalized world. Sectoral policy-making is especially challenging for those areas that are characterized by substantial *inertia*, which is typical of fossil fuel based energy and transport systems (also because of the so-called "lock-in" effects); to some extent, such inertia characterizes certain agricultural and industrial activities, as well. This situation was somewhat simpler for the other two environmental problems, especially in case of the ozone layer policy regime.

Technologies. At last, availability and effectiveness of the *abatement and control technologies* should be noted. For the acidification problem, relatively cost-effective emission source-oriented and end-of-pipe "technological fixes" could be shortly developed, such as the desulfurization of coal, crude oil or natural gas before their further utilization, the flue gas desulfurization technologies (which provide gypsum, a widely used material), or more generally, the industrial scrubbers for the AAPs, moreover, the catalytic converters for vehicles to reduce nitrogen emissions. The phase-out of the ODS and their replacement with "ozone-friendly" substitutes have become appropriate to cope with the ozone layer depletion hazard, which were accompanied by the disposal of the ODS from their surplus stocks or those recollected from various appliances. With the GHGs, in general, the situation is much more difficult, since there are no such relatively simple, cost-effective, widely applicable technological solutions. Some of the remarkable barriers to the existing carbon neutralizing technologies (including the so-called "negative emissions technologies", i.e., different land use, forestry related sequestration methods, or the rather controversial carbon capture and storage options) are referred to by *UNEP* (2014). Therefore, the gradual but comprehensive and environmentally sound *decarbonisation of the entire economic systems* based on sustainable production and consumption patterns, and parallel preparations for the already seemingly unavoidable changes can only be considered as the adequate strategy for tackling this global environmental problem.

5. Conclusions

The knowledge development and the initial steps in the international policy regime building in relation to the global climate change problem have been analyzed, as these proceeded parallel to the somewhat analogous processes for acidification and ozone layer depletion by the late 1970s. This synergy during the "inception phase" had some role not only in facilitating the enhancement of the global environmental observing systems and the international scientific cooperation, but also indirectly in conducting the relevant detection and attribution studies. With the rapid research progress on acidification and ozone layer depletion, the corresponding multilateral policy mechanisms were not only established and gradually strengthened within a relatively short time period, but some of their important features and building blocks served also as precedents or prototypes for the climate change policy architecture. But the climate change issue proved to be a much more complex problem, so the proper international policy responses could not be formulated so smoothly as it occurred for the other two large-scale atmospheric issues and their anthropogenic drivers. This kind of increasing asymmetry was also evaluated in this paper throughout the "international policy setup phase" by about the turn of the

20th century and the subsequent "divergent phase" for these environmental problems.

Some of the important factors behind this lagging of the climate change response policies were also mentioned, and none of them can be easily overcome. Yet, all those should be tackled adequately. The reason for this is clearly stated by the recent IPCC report (*IPCC*, 2013–2014): "Without additional mitigation efforts beyond those in place today, and even with adaptation, warming by the end of the 21st century will lead to high to very high risk of severe, widespread, and irreversible impacts globally (high confidence)." The directions of the further scientific research tasks are outlined by the IPCC and the World Climate Programme (i.e., its research component, WCRP); furthermore, an integrated concept is foreseen by the "Future Earth" programme, which is the ICSU initiative devoted to all key environment-related processes, their interactions, and possible future effects, including those associated with the climate change process. Concerning the science-based complex climate policy-making challenges, references were already made to the need of an economy-wide approach; however, it should be re-emphasized that the climate policy-making problem is not a self-contained one, but inherently linked to a large range of other challenges (e.g., addressing the unsustainable resource use and land management, increasing waste streams, loss of biodiversity). Anyway, in light of the already solid scientific achievements and the possibility of the abrupt and irreversible changes, accurate policy responses are necessary amid remaining uncertainties, as it was so formulated by Stephen H. Schneider, to whom the Synthesis Report of the latest IPCC assessment report was dedicated (*IPCC*, 2013–2014): "Policymakers struggle with the need to make decisions that have far-reaching and often irreversible effects on both environment and society with sparse and imprecise information. (..) Strictly speaking, a surprise is an unanticipated outcome; by definition it is an unexpected event. Potential climate change and, more broadly, global environmental change are replete with this kind of surprise because of the enormous complexities of the processes and relationships involved (such as coupled ocean, atmosphere, and terrestrial systems) and our insufficient understanding of them. (..) as the rate of change of CO_2 concentrations is one imaginable condition for surprise, the system would be less rapidly forced if decision makers chose to slow down the rate at which human activities modify the atmosphere. This would lower the likelihood of surprises." (*Schneider* and *Kuntz-Duriseti*, 2002). These ideas are even more valid in view of the latest observations and assessments. In principle, such an approach was reflected in the recently adopted new global deal, the Paris Agreement that stressed the need for an effective and progressive response to the urgent threat of climate change by reaching global peaking of greenhouse gas emissions as soon as possible and undertaking rapid reductions thereafter in accordance with best available science. But the setting of the relevant and concrete policy targets was postponed and consequently, as it was demonstrated in this paper, there is still a rapidly increasing science-policy gap in tackling this hazardous global problem.

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IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 120, No. 1, January – March, 2016, pp. 41–51

Analyses of temperature extremes in the Carpathian Region in the period 1961–2010

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(Manuscript received in final form October 7, 2015)

Abstract—The harmonized data derived in CARPATCLIM project has enabled the presentation of the most comprehensive picture of trends of extreme temperatures in the Carpathian Region. A set of climate change indicators derived from daily temperature data, focusing on extreme events, was computed and analyzed in this study. Annual extreme indices for the period 1961–2010 were examined. Trends in the gridded fields were calculated, mapped, and tested for statistical significance. Results showed significant changes mainly in temperature extremes associated with warming. A large part of the region showed a significant decrease in the annual occurrence of cold nights and an increase in the annual occurrence of warm nights. The growing season starts earlier in more than third part of the region. The trend and proportion of the area that sign significant change of warm extremes strengthen the obvious warming in the Carpathian Region.

Key-words: CARPATCLIM, Carpathian Region, climate indices, temperature extremes

1. Introduction

The impacts of climate change on society come forward mainly through extreme weather and climate events, such as heat waves, droughts, heavy rainfall, and storms. The climate change evokes increasing frequency of climate extremes

(*Easterling et al.*, 2000; *Moberg et al*, 2006; *Alexander et al.*, 2006; *Seneviratne et al.*, 2012; *Donat et al*, 2013, *IPCC*, 2014).

Climate change is expected to result in significant changes in the Carpathian Region to affect ecosystems and human activities (*UNEP,* 2007). To describe the changes of extremes, a sort of climate indices is used in general as prevailing indicators of changes in extremes. The European Climate Assessment and Dataset (ECA&D) (*Klein Tank* and *Konnen*, 2003) contains climate indices from countries across Europe located in the Carpathian Region amongst them.

The purpose of the current study is to analyze the trends of temperature extremes in the Carpathian Region by means of a high-quality and high-resolution (0.1° × 0.1°) daily gridded dataset constructed in the framework of the CARPATCLIM Project (www.carpatclim-eu.org). A set of indices follows the definitions recommended by the WMO CCl/CLIVAR Expert Team on Climate Change Detection and Indices (ETCCDI) was computed and analyzed in this paper. The CARPATCLIM dataset currently represents the most comprehensive, homogenized, and harmonized gridded dataset of daily in-situ data available for the Carpathian Region. It has been used to climate variability and trend studies (*Spinoni et al.,* 2015a) and drought investigations (*Spinoni et al.,* 2013) for instance. The Carpathian Region are subjected to climate change and also to weather-related extremes such extreme temperatures and heavy rainfall based on CARPATCLIM dataset (*Lakatos et al.,* 2013, *Spinoni et al.,* 2015b).

In the next sections, we describe the dataset and the method to derive grids of the different extremes indices and the analysis of this dataset over the Carpathian Region. After the introduction, the data and the definition of climate indicators are set up. Then, after the description of the trend estimation and the results showed on graphs and maps, a brief summary concludes the paper.

2. Data

Studying the spatio-temporal changes of climate extremes can be implemented through the analysis of observations reliable both in time and space. In this paper we used the CARPATCLIM (Climate of Carpathian Region & Digital Atlas of the Region) dataset for calculation of trends of several climate indicators to detect changes in temperature extremes in the Carpathian Region. As result of a Hungarian initiative on creation high quality dataset over the Carpathian Basin, the European Commission financed the CARPATCLIM project to supply the data demand of Joint Research Center (JRC) Desert Action activity (*JRC*, 2010). The consortium led by the Hungarian Meteorological Service together with 10 partner organizations from 9 countries in the Carpathian Region with the JRC created a multi-variable, gridded daily dataset.

The outcome of the CARPATCLIM project are 0.1°(~10 km×10 km) resolution homogenized, gridded daily time series of various meteorological parameters from January 1, 1961 to December 31, 2010. The target area is partly includes the territory of the Czech Republic, Slovakia, Poland, Ukraine, Romania, Serbia, Croatia, Austria, and Hungary (*Fig. 1*).

The method and software used for data quality control, homogenization, data completion, and data harmonization was the Multiple Analysis of Series for Homogenization software (MASH version 3.03; *Szentimrey* 1999, 2008, 2011). Interpolation of the homogenized time series were carried out by applying the MISH (Meteorological Interpolation Based on Surface Homogenized Data Basis version 1.03; *Szentimrey* and *Bihari*, 2007) method. The complete procedure is described in details in the project deliverables which can be found on the website of the project: www.carpatclim-eu.org/pages/deliverables/ and *Spinoni et al.* (2015a).

The final outcome of the CARPATCLIM are quality controlled, homogenized, in-situ daily time series and gridded fields along with metadata catalogue containing the documentation of the datasets. The daily grids with the metadata are freely accessible for scientific purposes on the website of the project: www.carpatclim-eu.org.

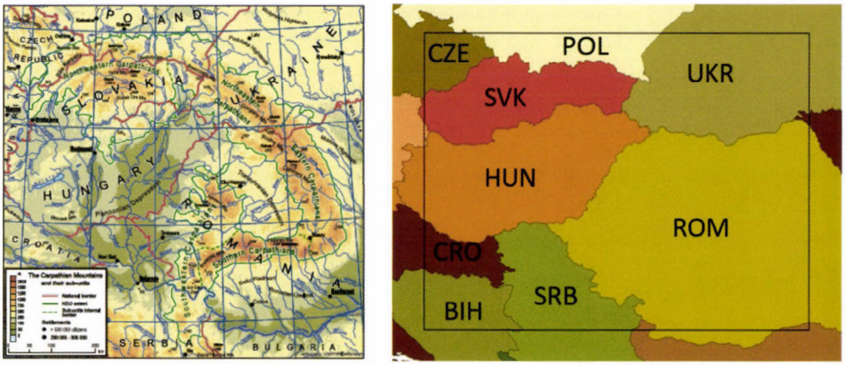

Fig. 1. The target area of the CARPATCLIM between latitudes 50°N and 44°N, and longitudes 17°E and 27°E approximately (left), and the political boundaries (right). (HUN: Hungary, SVK: Slovakia, CRO: Croatia, SRB: Serbia, ROM: Romania, UKR: Ukraine, BIH: Bosnia Hercegovina is not included in the project)

The preliminary analysis of the changes indicates that the temperature trend is variable in space in the Carpathian Region (*Spinoni et al.*, 2015a; *Lakatos et al.*, 2013). To do a further investigation into the spatio-temporal temperature trends in the Carpathian Region, we analyzed the trends of extreme temperature related indicators. Results are presentedin the next section.

3. Climate indices

The climate change indices (climate indicators) shown in this paper (*Table 1*) were calculated from the homogenized, gridded daily observations of maximum, minimum and daily average temperatures at each grid point of the region in question. We note that the daily average temperatures were derived as arithmetic means of homogenized daily maximum and minimum temperatures according to the CARPATCLIM consortium member's agreement (*CARPATCLIM Deliverable 3.7,* 2013). Percentile required for some of the temperature indices (*Table 1.*) were calculated for the climatological standard period 1961–1990.

Table 1. List of extreme temperature indices calculated and analyzed. Indices in bold represents those that are publically available in the CARPATCLIM dataset

Indicator name	**Indicator definitions**	**Units**
Cool nights TN10p	Cool nights when daily min temperature<10th percentile	days
Cool days TX10p	Cool days when daily max temperature<10th percentile %	days
Warm nights TN90p	Warm nights when daily min temperature>90th percentile %	days
Warm days TX90p	Warm days when daily max temperature>90th percentile %	days
Growing season length (5degree) GS5L*	**Annual count between first span of at least 6 days with TG>5 °C and first span after July 1 of 6 days with TG<5 °C (where TG is daily mean temperature)**	days
Growing season start (5degree) GS5Start	Daynumber at the end of the first span of at least 6 days with TG>5 °C (where TG is daily mean temperature)	daynumber
Growing season end (5degree) GS5End	Daynumber for the end of the last span of at least 6 days with TG>5 °C (where TG is daily mean temperature)	daynumber
Ice days ID	Annual count when daily maximum temperature<0°C	days
Severe cold days ECD	**Annual count when daily minimum temperature <–10 °C**	**days**
Frost days FD	**Annual count when daily minimum temperature <0 °C**	**days**
Summer days SU	**Annual count when daily max temperature >25 °C**	**days**
Hot days HD	**Hot days Annual count when daily max temperature >30 °C**	**days**
Extremely hot days EHD	**Annual count when daily max temperature >35 °C**	**days**
Warm spell duration WSDI	Annual count when at least six consecutive days of max temperature >90th percentile	days
Cold spell duration CSDI	Annual count when at least six consecutive days of min temperature <10th percentile	days

*Indices bolded are available on monthly and yearly scale in CARPATCLIM, except growing season length as it is available yearly

4. Trend estimation and results

The focus of this paper is to assess detailed regional changes of extreme temperatures in the Carpathian Region. The spatial high resolution of the gridded data can clearly highlight the regional trends. Linear trend was fitted to the indices series at each grid point, as it is widely used measure for presenting the changes. Although it is not certainly the best fit to the indices series, the results are comparable to other studies focusing on areas surrounding the Carpathian Region. Decadal changes of indices are shown on maps represent the 50 years period. The test of significance is based on student test (*Szentimrey*, 1989). Dots on maps indicates grid points where trends are significant at 5% significance level.

In this section the trend analysis for annual temperature indices are presented. The trends with their significance are featured on maps in some cases and in tables in other cases for space constraints, because all the indices were analyzed (*Table 1*). The time series plot of the indices supplemented occasionally by the 21-point smoothing functions (*Davis*, 1973) enables to demonstrate the decadal variations of the observed temperature extremes since the 1960's.

5. Annual indices

The temperature-related indices show significant warming trends widely in the Carpathian Region. Warming trends are generally stronger for indices derived from daily minimum temperature than for those derived from daily maximum temperature. This finding is in agreement with global studies, e.g., *Alexander et al.,* 2006 and *Donat et al.,* 2013.

For example, the frequency of cool nights (TN10p) (*Fig. 2a*) based on daily minimum temperatures is shown to have significantly decreased more than three-quarter to the region during the past 50 years from 1961 to 2010. The greatest magnitudes of the trends up to 8 days per decade are found over the bordering region of Ukraine and Romania, Poland, and fewer regions in Serbia. Regionally averaged the frequency of cool nights in the Carpathian Region has decreased by about a third (17 days) between the 1960s and the first decade of the 21st century (the average annual frequency during the 1961–1990 base period is by definition 53.3 days).

Correspondingly, the frequency of warm nights (TN90p) (*Fig. 2b*) in all grid points increased significantly. Regionally averaged, the frequency of warm nights has increased by about one and a half month (44 days) during the examined period (the average annual frequency during the base period is by definition 54.4 days). The strongest change occurred in the annual occurrence of warm nights (TN90p) among the temperature indices. The largest increasing is detected in wide regions in the territory of Serbia.

Examining daytime temperature extremes, the changes in cool days (TX10p) (*Fig. 2c*) and warm days (TX90p) (*Fig. 2d*) resulted in smaller variations compared to the cool and warm nights frequency changes. The trends of cool days are significant in the half of the Carpathian Region. The decrease is the highest between 4 and 5.3 days per decade, respectively, in the mid-Transdanubian regions and in the northern edge Hungary. Negative but non-significant change appears in the regions of the Pannonian Plain, the mountainous region in Romania, and the Romanian Plain. The warming trend results in more frequent warm days everywhere in the area. The warm days increasingly grow from northeast to southwest, by 40 days on average in the Carpathian Region.

Changes in percentile based indices seem to have occurred around the mid-1980s (*Fig. 3*). It denotes one decade lag to the mid-1970s, when the mean global temperature rise is reported (*Folland et al*, 2001).

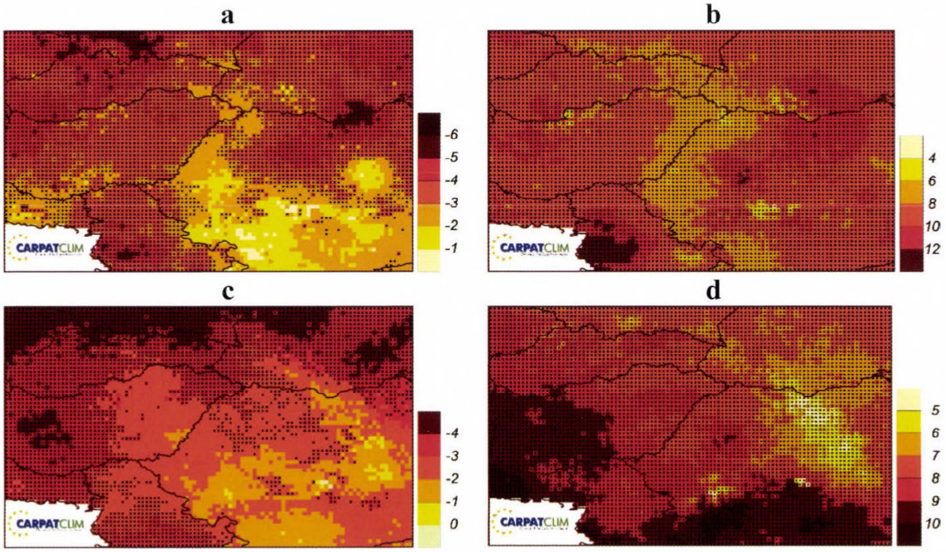

Fig. 2. Trends (in annual days per decade shown on maps) for annual series of percentile temperature indices for 1961–2010. (a) cool nights (TN10p), (b) warm nights (TN90p), (c) cool days (TX10p), (d) warm days (TX90p). Dots indicates regions where trends are significant at the 5% level.

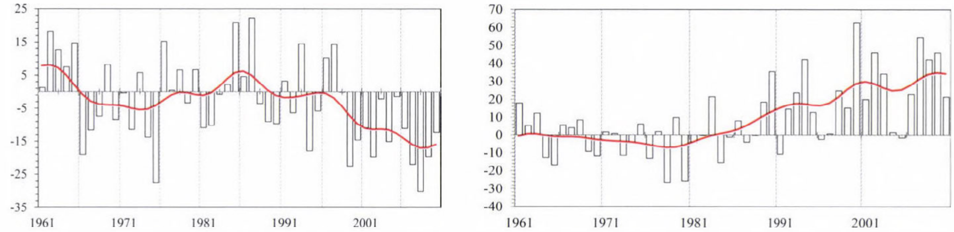

Fig. 3. The time series (columns) show the regional average annual values (in days per year) for cool nights (TN10p) (left) and warm days (TX90p) (right) as anomalies relative to the 1961–1990 mean values. The red line shows the 21-point Gaussian filtered data.

The effects of climate change clearly appear in agriculture and forestry in the region (*UNEP*, 2007). Production of these sectors is strongly influenced by the length of the growing season of the different species. Start date, end date, and the length of the vegetation period of the cold-tolerant (5 degree) species are investigated in this paper. *Fig. 4* shows that the growing season starts earlier, except for some sparsely located regions in higher elevation with statistically non-significant trend. Regions out of the Carpathians in Ukraine and Romania indicate either more than one month shift ahead. In the Transdanubian region in Hungary, in territory of Croatia and Serbia, the rowing season starts earlier, by 3 weeks in general.

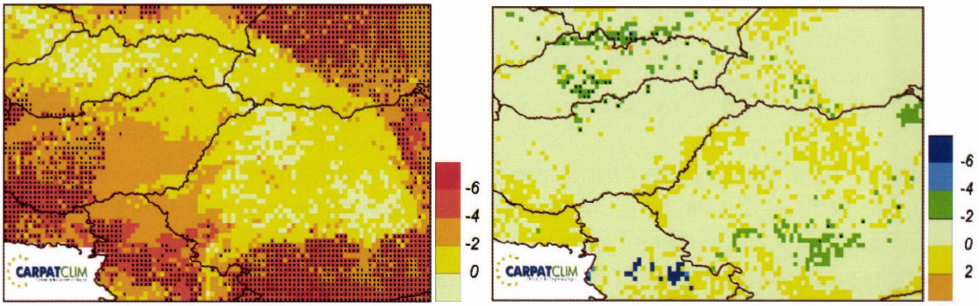

Fig. 4. Trends (in annual days per decade shown on maps) for annual series of growing season (5degree) start (GS5Start) (left) and growing season (5degree) end (GS5End) (right) for 1961–2010. Dots indicates regions where trends are significant at the 5% level.

The time series of the regionally averaged annual anomalies of growing season (5degree) start (GS5Start) show strong year by year variability (*Fig. 5*) of the starting date of the vegetation period. After tending towards to the earlier date to nighties, a slight increasing appear in the course. The years in the last decade of the 20th century put in the highest positive and negative anomalies.

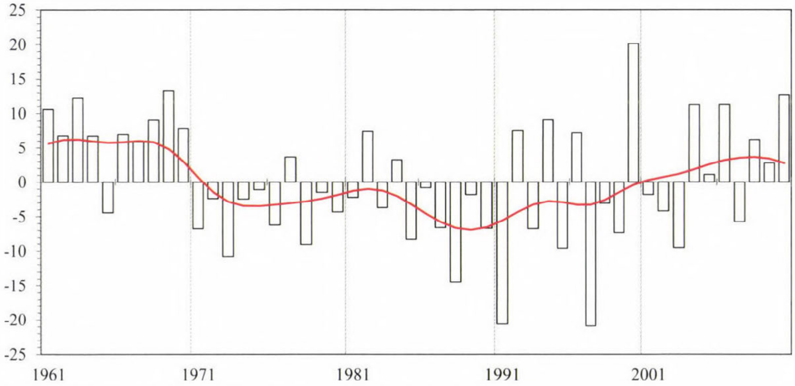

Fig 5. The time series (columns) show the regional average annual values (in days per year) for growing season (5degree) start (GS5Start) as anomalies relative to the 1961–1990 mean values. The red line shows the 21-point Gaussian filtered data.

The end of the 5°C vegetation period is not affected clearly by the warming tendency in the Carpathian Region (*Table 2*). The advanced start indicates longer growing season in the same but narrowed region as the GS5 significantly decreased (*Table 2*).

From the trend maps shown above, it can be seen that a wider area shows significant change in indices derived from minima than maxima. *Table 2* contains the areal average of the trend and the proportion of the area where the changes are significant by indices. The significantly increasing in warm nights and warm days show unanimously warming trend in the region. Significantly fewer cool days cases appear in more than a half part of the area, and less than a third part of the area non-significant change in cool nights cases. The growing season starts earlier in more than a third part of the region. The trend and proportion of the area that sign significant change of warm extremes strengthen the obvious warming in the Carpathian Region.

Table 2. Trends (in annual days per decade) for each index along with the percentage of grid points show either significant increase or decrease at the 5% level during the 1961–2010 period in the Carpathian Region

Indicator name	**Trend**	**Significant increase [%]**	**Significant decrease [%]**
Cool nights TN10p	–3.4	0	77.1
Cool days TX10p	–3.0	0	57.3
Warm nights TN90p	9.0	100	0
Warm days TX90p	8.1	100	0
Growing season length (5degree) GS5L	1.8	10.3	0
Growing season start (5degree) GS5Start	–2.5	0	30.3
Growing season end (5degree) GS5End	–0.7	0	0.7
Ice days ID	–1.8	0	16.7
Severe cold days ECD	–1.4	0	22.0
Frost days FD	–2.5	0	38.7
Summer days SU	3.7	97.9	0
Hot days HD	2.5	89.6	0
Extremely hot days EHD	1.4	40.0	0
Warm spell duration WSDI	4.1	96.1	0
Cold spell duration CSDI	–3.6	0	9.9

6. Conclusion

The focus of this paper was to assess detailed regional changes of extreme temperatures in the Carpathian Region. The CARPATCLIM dataset currently represents the most harmonized and comprehensive gridded dataset of several climate variables based on in situ observations in the Carpathian Region. A 15 pieces set of indices follows the definitions recommended by the WMO CCl/CLIVAR Expert Team on Climate Change Detection and Indices (ETCCDI) was computed and analyzed in this paper. Decadal changes and significance of indices are shown on maps represent the 50 years period, from 1961 to 2010.

According to our analyses, changes in cool nights and warm days have occurred around the mid-1980s according to the time series of areal averages of the indices. The significant increase in warm nights and warm days show unanimously warming trend in the region. Significantly fewer cool days cases appear in more than a half part of the area, and less than a third part of the area shows non-significant change in cool nights cases. The growing season starts earlier in more than third part of the region. In general, trends are stronger for indices derived from daily minimum temperature than for those derived from daily maximum temperature. The trends of the annual extreme temperature indices strengthened that the warming signal is obvious over the Carpathian Region. This type of study dealing with the investigation of climate extremes, observed trends, changes in frequency and intensity could contribute to the establishment of the adaptation strategies in the region. The seasonal changes of the temperature extremes and precipitations are also affect the natural ecosystems, agriculture, and the human health in the region. Our futher analyses will focus on those aspects.

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Quarterly Journal of the Hungarian Meteorological Service
Vol. 120, No. 1, January – March, 2016, pp. 53–71

Analysis of climate change influences on the wind characteristics in Hungary

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(Manuscript received in final form July 3, 2015)

Abstract—Due to intense human presence and various anthropogenic activities, global climate change has been detected. Increasing temperature values and an overall warming are projected, which will certainly affect the global circulation patterns and regional climatic conditions throughout Europe. As an indirect consequence, global warming may also alter the wind conditions in the Carpathian Basin. In order to provide reliable projections for the future, the first task is to analyze wind climatology of the recent past using various tools from mathematical statistics.

In this paper, detailed analysis of observed wind fields, trends of different percentiles, return values, wind related climate indices, and their spatial distributions are discussed over Hungary using the homogenized Hungarian synoptic data sets and the homogenized and gridded CARPATCLIM database. Wind related climate indices are defined to evaluate the frequency occurrence and the trend of moderate and strong wind days at the stations in the last few decades. The annual daily maxima of wind speed and wind gust are determined on the basis of available time series fitted to the generalized extreme value distribution at every station and grid cell. 50-year and 100-year return values are estimated from these fitted distributions.

In addition, simulated wind climate variability is evaluated for the future periods of 2021–2050 and 2071–2100 relative to the 1961–1990 reference period. Since projected wind speed is highly overestimated by the simulation of the regional climate model RegCM for the reference period (1961–1990), a bias correction is necessary to apply to the raw simulated wind data using CARPATCLIM as a reference database. The bias correction method is based on fitting the empirical cumulative density functions of simulated daily time series to the observations for each gridcell using monthly multiplicative correction factors.

Key-words: Hungarian wind climate, extremes, homogeneity, CARPATCLIM, RegCM climate model

1. Introduction

Based on the observations, global climate change has reduced the Pole to Equator temperature gradient, which certainly affects the large scale circulation as well as regional climatic conditions. Besides the changes of mean climatic values, the entire distribution is changing, thus influencing intensity and frequency of climate extremes (*AghaKouchak et al.*, 2012). Various physical processes in the atmosphere lead to extreme values of meteorological elements. Weather and climate extremes (e.g., heat waves, extreme cold/hot conditions, too little/excessive precipitation, extreme winds) may especially affect exposed and vulnerable human and natural systems, therefore, development of appropriate action plans need detailed information on the past and future changes of extremes. It is essential to understand how and why climate extremes have changed recently, and how they will likely to change in the future.

Mid-latitude wind climate can be mainly determined by considering cyclogenesis processes and track analysis of high and low pressure systems over the continent. The surface winds are often depending on local conditions such as topography, geographical location, distance from large water bodies, and differential surface heating (*Oliver*, 2005). Examples of specific local wind include land/sea breeze, mountain/valley breeze, foehn winds formed by pressure or temperature gradient force. Moreover, local wind and instability can also be originated from (dust) storms.

Regional and local wind climate have direct effects on human activity, for instance, on aviation, urban planning (via impact on building design and air pollution), industry, energy sector, military operations, etc. Therefore, researchers, engineers, architects, designers need information about local wind climate as fine as possible. In most of the cases, their tasks and duties are strongly connected to appropriate analysis of meteorological and climatic problems, or they need to apply results of the analysis of regional or local wind fields to more specific, further impact studies. Moreover, many practical and theoretical problems in meteorology and climatology require accurate measurements of wind speed, direction, and gust. In order to ensure high quality of meteorological measurement systems, standards of measurements have been set by the World Meteorological Organization (WMO). Wind speeds are measured as 10-minute averages, wind gusts are the maximum speeds recorded within the 10-minute averages' period (*WMO*, 2008). The standard exposure height is 10 meter.

Direct wind climatological analysis of changes is hampered by the lack of several-decades-long, good quality, and homogeneous surface wind observations. Homogeneity of climate data is especially important when analyzing extremes, especially, at fine spatial scale. A climatological time series can be considered homogeneous if its variability is solely caused by changes in weather and climatic conditions (*Aguilar et al.*, 2005). However, wind as a meteorological element is especially sensitive to uncertainties caused by relatively small changes related to the measuring process, in the vicinity of the measuring equipment. For example, installation of a small building or changes in vegetation cover near the measuring equipment, or changes in instrumentation and measuring methods can produce bias in wind measurements (*Wan et al.,* 2010). When such a change occurs, it can result a discontinuity in the time series or a false trend (*Menne* and *Williams Jr*., 2009). Therefore, quality control and homogenizing of available daily wind speed and wind gust data sets (1975–2012) were completed (*Péliné et al*., 2014) in order to assess Hungarian wind climate trends, variability, frequency, and intensity of extreme wind events as reliable as possible. For this purpose, the MASH (Multiple Analysis of Series for Homogenization) procedure developed at the Hungarian Meteorological Service (*Szentimrey,* 1999) was applied to homogenize 19 Hungarian stations' daily wind speed and wind gust data sets.

The word "extreme" refers to many different issues in the climate research literature, so there is no unique, precise climatological definition of an extreme (*Stephenson*, 2008). For instance, extreme may be associated to a climate variable or an impact of specific climatic conditions. In the case of a climate variable (e.g., temperature, precipitation, wind speed, etc.), extremes can be well defined as a rarely occurring value, i.e., with small probability, in the tail of the probability density function ($f(x)$) of the given climate variable. In the case of an impact, an extreme can be less well defined, since quantity of impacts cannot be described in a unique way. It is important to mention that on one hand, rare events (e.g., tornado) may not necessarily cause damage, and their impact does not always lead to a disaster; on the other hand, non-extreme events (e.g., strong wind or regularly occurring storm) may cause devastating effects and severe damages in the environment. In this paper, we are focusing on the analysis of climate variables themselves.

Based on the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) published by the International Panel on Climate Change (*IPCC*, 2012), extreme weather or climate events are the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are often referred to collectively as 'climate extremes' (*Seneviratne et al*., 2012). They can be defined quantitatively in two ways: (1) related to their probability of occurrence, e.g., percentiles and return frequencies, (2) related to a specific (possibly impact-related) threshold.

Although the wind speed value itself is rarely used to define extreme events (e.g., mesoscale convective complex, cyclone, thunderstorm, squall lines, etc.) (*Peterson et al*., 2008), wind speed thresholds may be used to characterize the severity of the phenomenon (e.g., the Saffir-Simpson scale for tropical cyclones). Changes in wind extremes may be resulted from changes in the intensity or location of their associated phenomena (e.g., change in local convective activity) or from other changes in the climate system such as the movement of large-scale circulation patterns (*IPCC*, 2012). Wind extremes may be described by a range of daily/monthly/yearly quantities such as high percentiles, maxima, or wind-related climate indices after checking data series for homogeneity.

Our main aim is to analyze the wind climate in Hungary, specifically, to estimate temporal and spatial distributions of mean and extreme wind speed. For this purpose, different percentile values and their trends are calculated, moreover, return values and wind-related climate indices are determined using observed (station and gridded) and projected (from climate model simulation) data sets.

2. Applied data and methodology

2.1. Applied statistical distributions

For the sake of practical simplicity and to reduce complex characteristics of time series during the analysis, data distributions are often estimated by mathematical functions that depend on a few parameters only, so the analysis task is simplified to estimation of these parameters.

The special cases of the three-parameter generalized extreme value (GEV) or Fisher-Tippet distribution (*Palutikof et al.*, 1999) is widely used in meteorology, which includes Gumbel (type 1), Frechet (type 2), and Weibull (type 3) distributions. Distribution of averaged wind speed (with averaging period of 10 min) may be estimated by the two-parameter Weibull distribution, whereas distribution of maximum wind speed during a given period can be described by Gumbel distribution (*Wilks*, 2006).

The Weibull distribution is governed by two parameters, i.e., a scale factor (λ [m/s], being proportional to the mean wind speed), and a form factor or shape parameter (k [dimensionless], describing the shape of the distribution).

The Weibull distribution function $F(u)$ can be written as follows:

$$F(u) = 1 - \exp\left(1 - \left(\frac{u}{\lambda}\right)^{k}\right), \tag{1}$$

where u is the wind speed with an averaging period of 10 min, λ is the scale factor, and k is the shape parameter.

From this, the Weibull probability density function $f(u)$ can be expressed as follows:

$$f(u) = k \cdot \left(\frac{u^{k-1}}{\lambda^{k}}\right) \cdot \exp\left(-\left(\frac{u}{\lambda}\right)^{k}\right). \tag{2}$$

Average wind speed $[\bar{u}]$ of the whole analyzed period can be described by the Weibull parameters using Gamma function (Γ) as follows:

$$[\bar{u}] = \lambda \cdot \Gamma\left(1 + \frac{1}{k}\right), \tag{3}$$

$$\Gamma(x) = \int_0^\infty e^{-u} u^{x-1}\, du. \tag{4}$$

For k=1 and 2, the Weibull distribution is identical to the exponential and Rayleigh distribution, respectively. For k=3.4, the Weibull distribution is similar to the Gaussian distribution (*Wilks*, 2006; *Emeis*, 2013).

Wind speed extremes can be characterized with estimation of high percentiles, wind speed related climate indices, and return values using different specific periods. The return value is a threshold value, which can be defined by a fitted model (*von Storch* and *Zwiers*, 1999). The value of the analyzed variable may occur or be exceeded once on average during the specific return period.

The probability of occurrence of extreme values can be described by a Gumbel distribution (*Gumbel*, 1958). Probability density function $f(x)$ and cumulative frequency distribution function $F(x)$ are expressed in Eqs. (5) and (6), respectively:

$$f(x) = e^{-x} e^{-e^{-x}}, \tag{5}$$

$$F(x) = e^{-e^{-x}}. \tag{6}$$

For estimation of return values, the inverse of Eq.(6) should be calculated (*Emeis*, 2013), which is the following percentile function $G(p)$:

$$G(p) = -\ln\left(-\ln(p)\right). \tag{7}$$

In practice, independent maxima of the time series (for example, yearly maxima of wind speed or wind gust) are sorted in ascending order, then, these sorted values are plotted against $G(p)$. Data, which follow a Gumbel distribution form a straight line, in conformity with its definition. Estimations of return values for specific return periods (e.g., 50 years or 100 years) are quite straightforward by using this graph. The extreme value expected to occur once in 50 years or 100 years can be calculated from the equation of the fitted extrapolated straight line ($u_{max} = a \cdot (-\ln(-\ln(p))) + b$). For example, if the return period $T = 100$ years then the probability of occurrence $p = \frac{1}{T} = 0.01$ in any particular year within this entire period, thus, $G(p = 0.99) = 4.6$, and the return value (u_{max}) can be calculated from the equation of the fitted linear line.

The probability for the 100-year return value to appear in a chosen 100-year period is $P = 1 - 0.99^{100} = 0.634$.

2.2. *Wind indices*

In order to analyze the extreme wind characteristics, climate indices can be used. Similarly to the widely used temperature and precipitation related climate indices (e.g., *Bartholy* and *Pongrácz*, 2007), wind related climate indices are defined in this study. They consider daily average wind speed as well as daily maximum wind gust values. Three types of indices are used here: (i) the number of days above or below a certain threshold value, (ii) the number of periods of consecutive days above or below these thresholds, and (iii) the maximum length of these periods. The applied time frame includes yearly, seasonal, and monthly basis. *Table 1* summarizes the indices evaluated in this paper.

Table 1. List of used wind related climate indices, their definitions and units.

No.	Index	Definition	Unit
1–3	wavgGTXX	Yearly/seasonal/monthly number of days with average wind speed exceeding XX m/s; $v_{avg} > XX$ m/s, where XX = 15, 10, 8	days
4–6	wavgLTXX	Yearly/seasonal/monthly number of days with average wind speed below XX m/s; $v_{avg} < XX$ m/s, where XX = 1, 3, 5	days
7–9	CwXXD	Yearly/seasonal/monthly number of periods of consecutive days with daily average wind speed exceeding XX m/s, where XX = 15, 10, 8	–
10–12	CwXXD	Yearly/seasonal/monthly number of periods of consecutive days with daily average wind speed below XX m/s, where XX = 1, 3, 5	–
13–15	CwXXDmax	Yearly/seasonal/monthly number of maximum consecutive days with daily average wind speed exceeding XX m/s, where XX = 15, 10, 8	days
16–18	CwXXDmax	Yearly/seasonal/monthly number of maximum consecutive days with daily average wind speed below XX m/s, where XX = 1, 3, 5	days
19–23	CgXXD	Yearly/seasonal/monthly number of periods of consecutive days with daily maximum wind gust exceeding XX m/s, where XX = 15, 20, 25, 30, 35	–
24–29	GustGTXX	Yearly/seasonal/monthly number of days with daily maximum wind gust exceeding XX m/s; $v_{gust} > XX$ m/s, where XX = 15, 20, 25, 30, 35	days

2.3. Bias corrected outputs of RegCM regional climate model

In order to estimate the future changes in wind related climate extremes, regional climate model outputs serve as the basis. For this purpose, simulation of the RegCM regional climate model (*Torma et al.*, 2008, 2011) is used in this paper. For the reference period (1961–1990), model outputs overestimate the average wind speed for the Carpathian Basin. The overestimation of the yearly average wind speed is about 2 m/s, and the seasonal overestimation is the highest in winter (2.6 m/s in the gridcell centering 47.5°N and 19°E, which represent the Budapest agglomeration area). Therefore, simulated wind data should be bias-corrected for assessing extreme wind conditions as realistic as possible.

The probability density function (PDF) or the cumulative density function (CDF) describe completely the statistical properties of a dataset. If two data sets results in the same PDF or CDF then they can be considered statistically identical. The applied correction method is based on the study of *Pongrácz et al.* (2014), which uses the differences of the monthly empirical CDFs of RegCM model outputs and CARPATCLIM gridded data sets for the reference period. First, multiplicative correction factors $f_{multiplicative}$ are calculated on a monthly basis for the past (i.e., 1961–1990):

$$f_{multiplicative} = \frac{F_{obs}^{-1}(y)}{F_{model}^{-1}(y)} = \frac{x_{obs}}{x_{model}}, \tag{8}$$

where the probability-quantile of observations is x_{obs} and the probability-quantile of raw simulated data is x_{model}. Thus, the raw model data with CDF value p is corrected, and it becomes equal to CDF value of the observations. Then, these calculated factors are applied to the future periods (2021–2050, 2071–2100).

3. Results

Homogenized wind speed (1975–2012) and wind gust (1975–2013) measurements, as well as homogenized and gridded data sets of the CARPATCLIM (1961–2010) database are analyzed in order to assess Hungarian wind climate trends, variability, frequency, and intensity of extreme wind events. Average yearly wind speed is modified significantly by a homogenization procedure (*Péliné et al.*, 2014). Consequently, the fitted linear trends of average and different percentile values also changed at many stations compared to those before the homogenization. These differences emphasize that inhomogeneities in climatological time series may lead to false values and misinterpretations of detected changes.

The generalized extreme value distribution is fitted to the annual maxima of wind speed at every station and all the CARPATCLIM grid points, which were used to estimate 50-year and 100-year return values. *Fig. 1* summarizes these return values for 19 Hungarian synoptic stations based on the data sets during 1975–2012. The smallest and the largest return values are about 10 m/s and 25 m/s at Paks and Siófok, respectively.

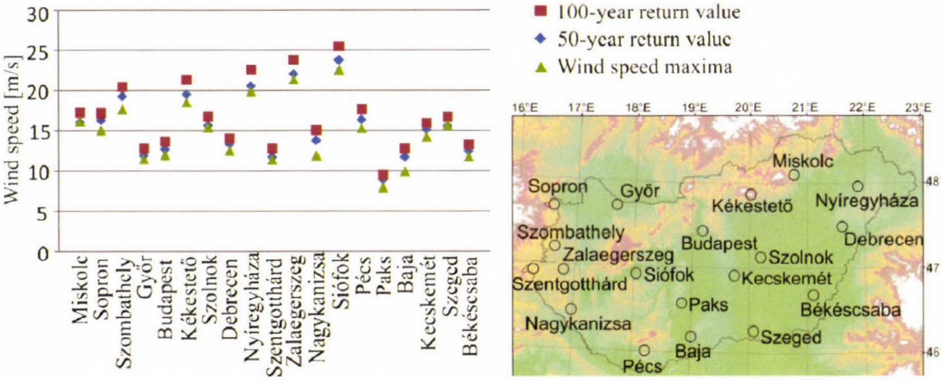

Fig. 1. Wind speed maxima and different return values [m/s] at the analyzed 19 stations calculated from 38-year time series (1975–2012).

In order to evaluate the spatial distributions of return values, gridded datasets can be used more efficiently. For this purpose, the quality-checked, homogenized, and interpolated gridded CARPATCLIM data series covering Hungary are used. *Fig. 2* shows both the 50-year and 100-year return values for the country, which result slight differences from the values calculated on the basis of station measurements. This is partially due to the fact, that daily wind speed of station data is calculated from at least eight measured data for a particular day, whereas CARPATCLIM daily 10-meter wind speed data sets have been created using three wind speed data (07, 14, and 21 UTC) from each day due to data availability for the whole period. (In the 1960's, data were recorded more rarely, in the 1960's than in the last few decades, so the night-time was less represented than nowadays).

Climate model experiments driven by gridded reanalysis fields (which are generated from measured and observed data) are essential, and provide important knowledge for modern climate research. However, the question arises how the different reanalysis data sets are reliable for estimation of wind climate parameters and validation of climate models. Global reanalysis data sets, i.e., ERA Interim, are used in our study, which is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) for researchers and climate modelers. ERA Interim is remarkably improved compared to the earlier ERA-40 reanalysis data sets (1957–2002) due to applied data assimilation methods and inclusion of more types of observations, e.g., satellite measurements (*Berrisford et al.*, 2009). In our study, datasets of wind components with fine resolution (0.50°) for the Carpathian Basin (45°–49.5°N and 15°–24°E) are analyzed for 1979–2012.

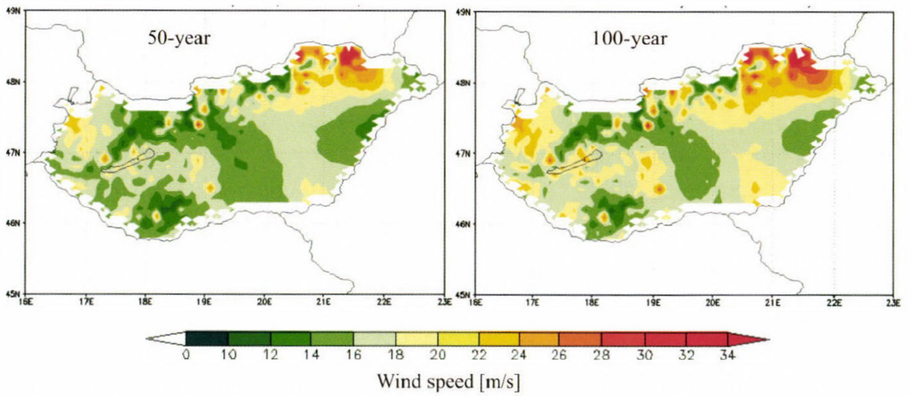

Fig. 2. 50-year and 100-year return values [m/s] calculated from CARPATCLIM data series (1961–2010).

Homogeneity of 10-meter daily average wind speed of 190 grid points of ERA Interim data sets is checked with MASH 3.03 software (*Szentimrey*, 2011) for the Carpathian Basin between 1979 and 2012. Results of homogenization proved that these gridded data series are homogeneous. Values of the applied test statistics for the characterization of inhomogeneity of time series were almost unchanged before and after homogenization and remained under the critical value (20.57; significance level: 0.05) at 72% of grid points. Values of yearly relative estimated inhomogeneity and yearly relative modification of time series differed from zero at 15% of all the grid points.

Weibull distributions are fitted in order to compare extremes of reanalysis and measured data series. Shape parameter (k) of the Weibull distribution describes frequencies of larger wind speeds. The larger the value of k, the smaller the variability of wind speed. Increasing scale parameter (λ) when constant shape parameter is assumed occurs as an elongation of the probability density function (pdf) along the abscissa with decrease and right-shift of the maxima of pdf (*Wilks*, 2006). Variability of scale parameter is smaller in ERA Interim grid points (3.06–3.83) compared to the synoptic stations (2.13–4.51). Values of the Weibull shape parameters of the reanalysis grid points are between 2.10 and 2.65, which are clearly larger than that is found in case of the stations data (1.38–2.16). This overestimation of the Weibull shape parameters reduces the variability of wind climatic conditions and the probability of extreme wind speed (*Rodrigo et al.*, 2013).

The main disadvantage of homogeneous gridded reanalysis data series is that spatial difference cannot be reproduced by reanalysis data unlike in case of station measurements. Monthly scale parameters of both station and gridded data averages are close in spring and summer, when regional differences are relatively small. The monthly average shape parameters are almost equal in June, however, in all the other months, overestimations are found at ERA Interim grid points compared to the station data.

Shape parameters are shown in *Fig. 3* as a function of scale parameter of the fitted Weibull distributions. Smaller shape parameter can occur in winter due to higher cyclone activity. Larger scale parameter was found in spring, when both the value and variability of monthly average wind speed are the largest. Average station shape parameters are generally overestimated by the average gridpoint shape parameters, similar conclusion is valid for the scale parameter. The only exception occurs in spring, when average station scale parameters are underestimated by the average gridpoint scale parameters. Because the scale parameter depends on wind speed, that is why the wind speed is overestimated, except in spring. The smallest differences (biases) of calculated parameters are observed in June and July.

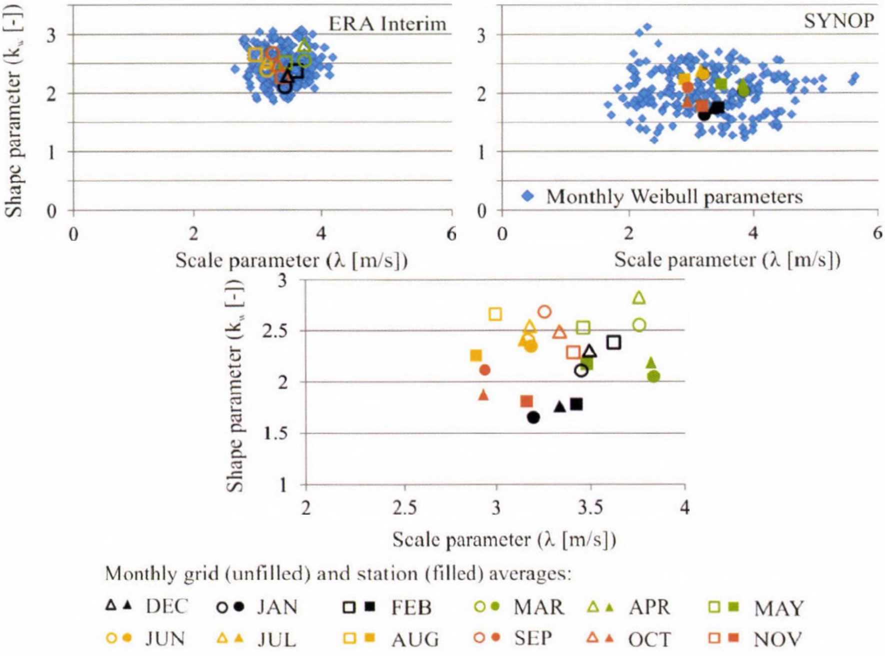

Fig. 3. Parameters of the Weibull distribution fitted to daily wind speed data series of grid points (upper left) and stations (upper right) in every month (blue) and in different seasons (winter – black, spring – green, summer – yellow, autumn – brown). Monthly grid (empty symbols) and station (filled symbols) averages are plotted in the lower diagram.

From the results discussed above, it can be concluded that significant differences exist between the statistical distributions of ERA Interim and synoptic station data, therefore, the further analysis of frequency occurrence, trend of moderate and strong wind days, and wind related indices are all based on more reliable measured data sets for Hungary.

Analysis of the indices listed in *Table 1* can answer whether the frequencies of windy, gusty days and calm periods have increased or decreased in the recent past. This is especially important from urban aspects, since air pollution in cities is a major environmental issue leading to many potential health problems.

Yearly number of days with average daily wind speed below 1 m/s, 3 m/s, and 5 m/s has increased during the analyzed period at most of the stations. Changes are statistically significant (on 0.05 confidence level) in all stations in case of 5 m/s (wavgLT5), and most of the stations in case of smaller thresholds (wavgLT1, wavgLT3). Yearly number of days with average wind speed exceeding 8 m/s has significantly decreased at every station, however, declining of the yearly number of stormy days (wind speed exceeding 15 m/s) is significant at four stations only (Szombathely, Szolnok, Zalaegerszeg, and Siófok).

Yearly number of periods of consecutive days (lasting 1–10 days) with daily average wind speed below 1 m/s (Cw1D) is shown in Fig. 4. These wind related climate indices decreased in Siófok for periods with different lengths, the longest recorded period lasted 10 days, which occurred in 1982. Increasing trends are found in Győr, which is in good agreement with the results of our previous analysis (*Péliné et al.*, 2014) concluding that the average wind speed declined at this station.

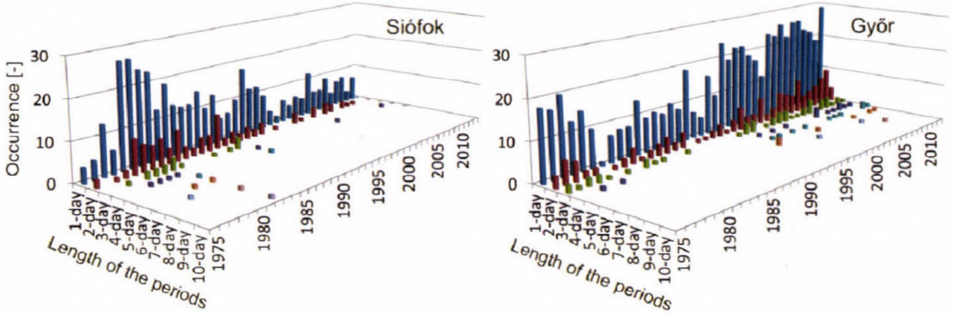

Fig. 4. Yearly Cw1D wind speed indices in Siófok and Győr calculated from homogenized data series.
Trend coefficients of the significant (confidence level: 0.05) changes are the following:
Siófok : 1-day: -0.31, 2-day: -0.12, 3-day: -0.04
Győr : 1-day: +0.41, 2-day: +0.12

Yearly numbers of maximum consecutive days below or above a certain daily average wind speed (below 1 m/s and 3 m/s, or above 8 m/s) are summed for all stations and for all years. Temporal changes of these cumulative indices are plotted in *Fig. 5*. Summed yearly numbers of maximum consecutive days below 3 m/s (above 8 m/s) wind speed, Cw3Dmax (Cw8Dmax) have increased (decreased) significantly, unlike Cw1Dmax, where the detected change is not significant.

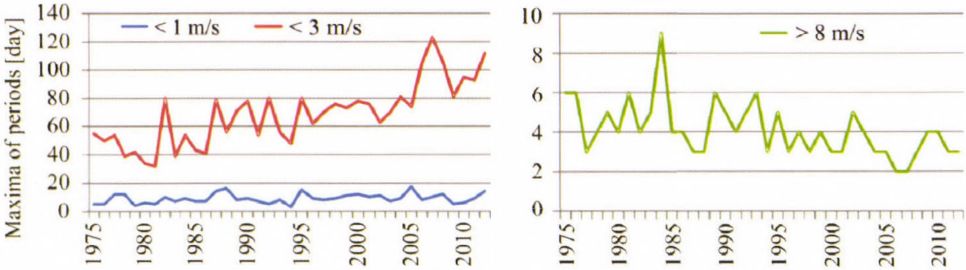

Fig. 5. Temporal changes of yearly Cw1Dmax, Cw3Dmax, and Cw8Dmax wind speed indices summed for all stations and calculated from homogenized data series.

Yearly and monthly number of days with daily maximum wind gust exceeding 15, 20, 25, 30, 35 m/s are calculated for every station from homogenized wind gust time series covering the time period 1975–2013. The temporal changes are estimated by fitting linear trends, for which the calculated trend coefficients are summarized in *Fig. 6*. Yearly trend coefficients of GustGT15 and GustGT20 indices are all negative in all stations, the decreasing trends are statistically significant (at 0.05 level). Due to the more rare occurrences of higher wind gusts, the trend coefficients tend not to be significant in case of GustGT25, GustGT30, and GustGT35. For instance, in case of the highest analyzed wind gust threshold (GustGT35), significant changes are found only at two stations (Miskolc and Zalaegerszeg).

In most of the months (from June to January, and also in April), decreasing trends can be detected at all the stations, similarly to the annual trends. Besides the general decreasing monthly trend coefficients, increasing monthly trends are also found at some stations in March. The lower graph of *Fig. 6* summarizes the linear trend coefficients for March. Overall, significant changes (with confidence level of 0.05) are found only at a few stations (Miskolc, Szentgothárd, Szolnok, Nyíregyháza, and Szombathely in case of different indices). Monthly trends are mostly small and not significant in February and May. However, all these results should be evaluated as a complex issue in the context of other wind-related climate indices. For instance, although the values of the rarely occurring GustGT25 index show increasing trend in March in Szombathely, most of the other wind-related indices (e.g., wavgGT8, wavgGT10, and wavgGT15) calculated from the daily average wind speed at this station have decreased significantly.

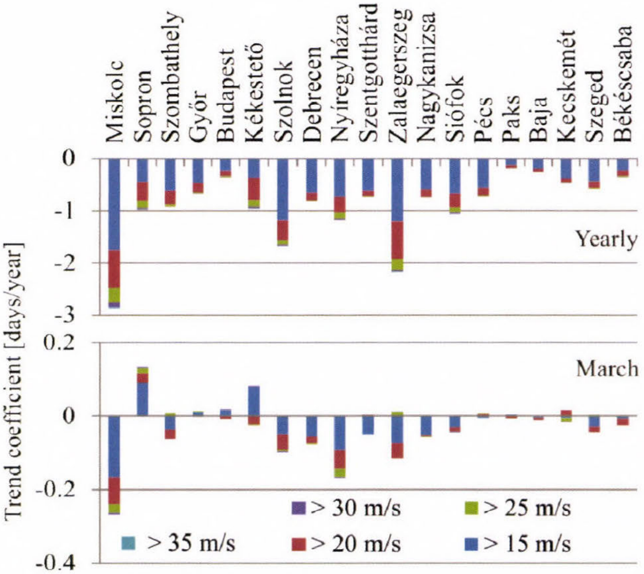

Fig. 6. Fitted linear trend coefficients of yearly (upper graph) and monthly (March, lower graph) number of days with daily maximum wind gust exceeding 15 m/s, 20 m/s, 25 m/s, 30 m/s, and 35 m/s wind gust at the analyzed stations calculated from homogenized data series (1975–2013).

Significant changes (confidence level: 0.05) are found in March as follows:

decreasing trend:	GustGT15: Miskolc, Szentgotthárd
	GustGT20: Miskolc, Szolnok
	GustGT25: Miskolc, Nyíregyháza
increasing trend:	GustGT25: Szombathely

In addition to the analysis of the recent past wind fields, the projected changes in the future are also important for possible impact analysis. For this purpose, simulated wind data are evaluated for the future periods of 2021–2050 and 2071–2100 relative to the 1961–1990 reference period.

First, validation of simulated data is illustrated for a selected gridpoint, located at 47.5°N and 19.0°E, which represents Budapest. Similarly to the other gridpoints within Hungary, the monthly mean wind speed calculated from CARPATCLIM data is overestimated substantially by the RegCM simulation in the 1961-1990 reference period (*Fig. 7*). The maximum and minimum bias of the monthly mean wind speed at this selected location is 2.7 m/s in January, and 0.8 m/s in June, respectively. The range of monthly wind speed biases changes with percentiles, in some months it reaches 4 m/s (*Fig. 8*). Percentile differences are the smallest in May and June, when small averaged differences (biases) of the calculated Weibull parameters have also been found between ERA Interim and observed data.

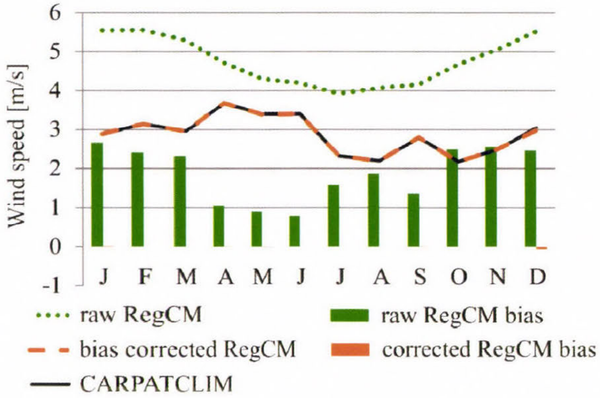

Fig. 7. Comparison of RegCM simulation and CARPATCLIM data: annual distribution of monthly mean wind speed (lines) and monthly mean wind speed bias (columns), for the gridpoint 47.5°N and 19.0°E, for the period 1961–1990.

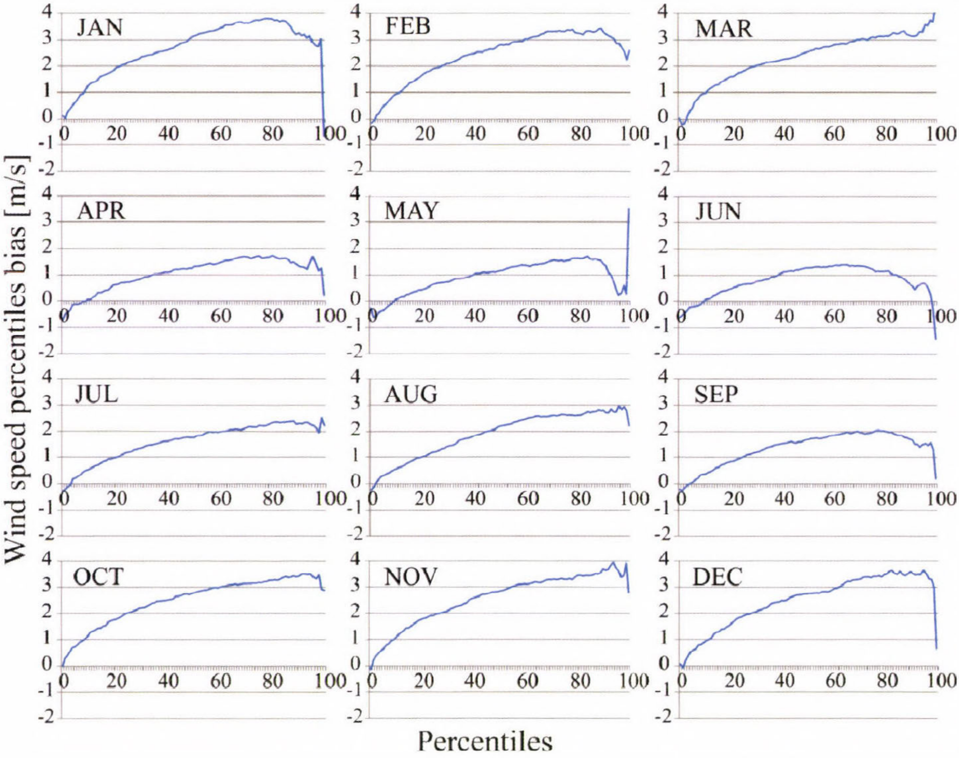

Fig. 8. Wind speed monthly percentiles biases calculated from differences of raw RegCM outputs (i.e., before completing any bias-correction) and CARPATCLIM for the gridpoint 47.5°N and 19.0°E covering the period 1961–1990.

Since projected wind speed is highly overestimated by the simulation of the regional climate model RegCM in the reference period (1961–1990), a bias correction is certainly necessary to apply to the raw simulated wind data using CARPATCLIM as a reference database. The bias correction method is based on fitting the empirical cumulative density functions of simulated daily time series to the observations for each gridcell using monthly multiplicative correction factors.

Fig. 9 compares the distributions of RegCM model outputs (raw and bias-corrected simulated wind data) to the CARPATCLIM wind data for the gridpoint 47.5°N and 19.0°E (representing Budapest) over the period 1961–1990. The charts clearly demonstrate that the differences between the two wind fields' distributions can be eliminated using the bias correction technique. (Similar good agreements are reached for each gridpoint.)

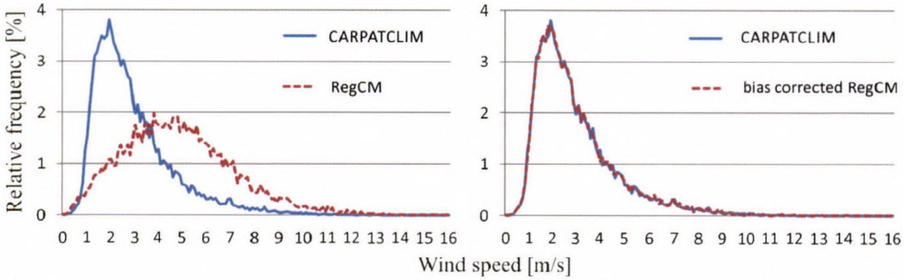

Fig. 9. Effect of bias correction of the simulated wind data. Comparison of relative frequencies of wind fields of CARPATCLIM to RegCM experiment for the period 1961–1990, for the gridpoint 47.5°N and 19°E, for raw simulated data (left) and bias-corrected data (right).

After determining the multiplicative correction factors on a monthly basis that correct the simulated wind speed of RegCM experiments, spatial distributions of the differences between the bias-corrected RegCM outputs and the CARPATCLIM wind speed data are calculated and mapped for different percentile values (0.50, 0.90, and 0.99) for the reference period 1961–1990, and for the projected periods (2021–2050 and 2071–2100). In case of the median and the upper decile (i.e., 0.50 and 0.90 percentiles, respectively), the difference in the reference period is less than 0.1 m/s in every gridcell for the whole year except in December, when the bias is between 0.1 m/s and 0.2 m/s. In the tail of the distribution larger differences can be found, for example, in case of the 0.99 percentile, the difference is reaching 1 m/s in some gridpoints (the monthly average difference value for all the percentiles is –0.04 m/s in the selected gridpoint in December).

For the evaluation of the projected climate change, bias-corrected RegCM outputs are used. Projected mean and extreme changes of wind conditions are analyzed. Differences between the future and past bias-corrected RegCM wind speed fields are mapped (*Fig. 10*) for different percentile values (0.90 and 0.99) for both analyzed future periods.

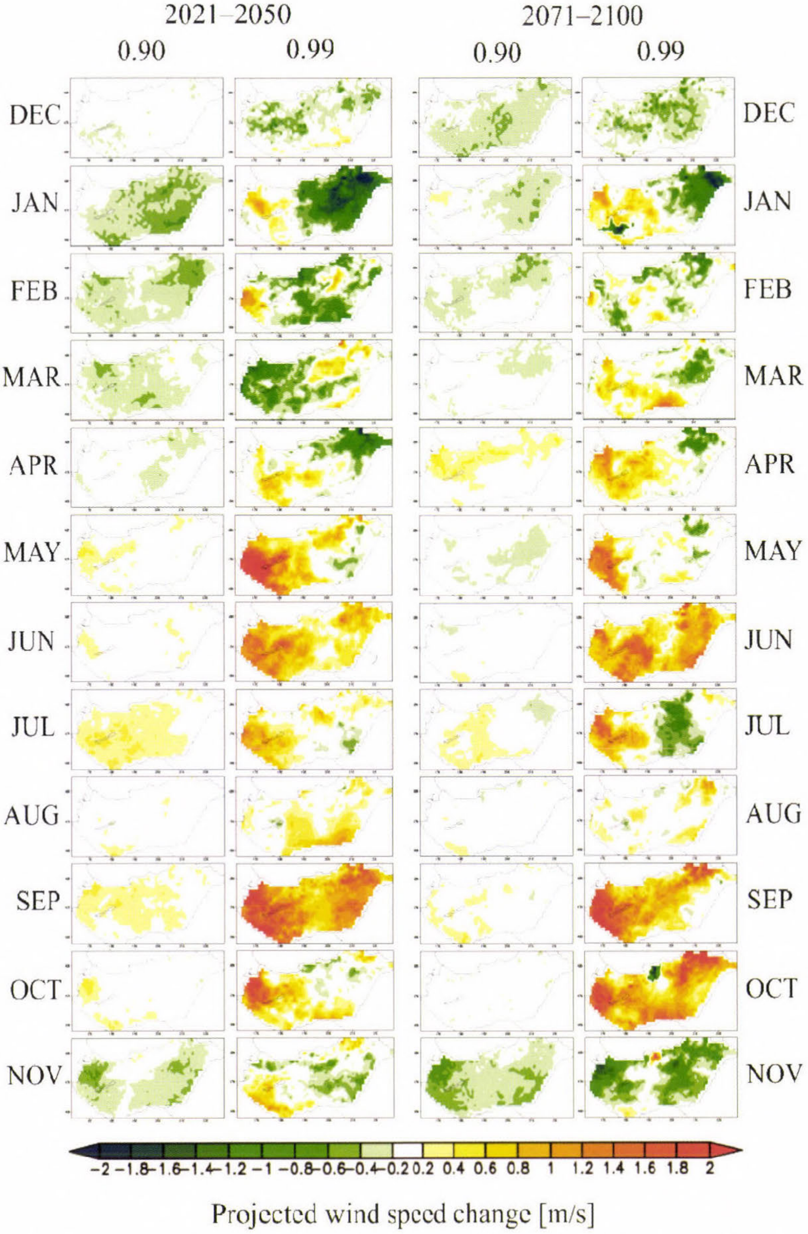

Fig. 10. Spatial distributions of the projected monthly mean changes of the 0.90 and 0.99 percentile values calculated from the bias-corrected RegCM wind speed data for the future periods (2021–2050 and 2071–2100).

Projected monthly changes in the 0.90 percentile are relatively small (the maximum is 0.6 m/s) for both periods, whereas changes in the 0.99 percentile values are projected to exceed 2 m/s in several regions in the country. Differences of the medians do not exceed 0.4 m/s.

4. Summary and conclusions

Our analysis of homogenized observed station and gridded wind data show overall decrease in the annual mean wind speed, which is consistent with the reduced Pole to Equator meridional temperature gradient in a warmer globe. Similar decreasing trend is also concluded by *Spinoni et al.* (2014) using CARPATCLIM data sets wind speed decrease in every season in Hungary.

Our results can be summarized as follows.

(1) Comparison of the raw and homogenized wind speed (1975–2012) and wind gust (1975–2013) measurements leads to different results, which highlight that inhomogeneities may mislead our conclusions.

(2) Wind climate extremes can be described by a range of daily/monthly/yearly quantities such as high percentiles, maxima, return values, and wind indices. For instance, overestimation of the Weibull shape parameters in ERA Interim reanalysis data (1979–2012) compared to synoptic stations reduces the variability of wind conditions and the probability of extreme wind speed. That is why the use of homogenous, quality-controlled, and reliable (measured) data series are essential when completing a reliable wind climatological analysis with special focus on extremes.

(3) GEV distributions are fitted to the annual daily maxima of wind speed at all the measuring stations and all the grid points of CARPATCLIM (1961–2010) database, which are used to estimate 50-year and 100-year return values. The return values are generally in the interval between 14 m/s and 20 m/s in most of Hungary, however, they exceed 26 m/s in the northeastern region of the country (in Nyíregyháza among the stations). The differences can partially be explained by the different calculation method of daily wind speed.

(4) Regarding the wind speed indices, yearly occurrence of days with small average wind speed has become more frequent, and the yearly number of days with average wind speed exceeding the larger thresholds has decreased. These negative trends are generally significant. Yearly number of periods of consecutive days with daily average wind speed below 3 m/s has also decreased significantly. Wind gust related indices has also decreased in general.

(5) Since simulated wind speed time series (using RegCM) highly overestimate the measurements in the reference period (1961–1990), and thus, do not reproduce the distribution of the CARPATCLIM daily wind speed values, a bias correction is applied to the simulated wind data using CARPATCLIM as a reference. Differences of the percentile values (between

raw simulated data of RegCM and the CARPATCLIM wind) are the smallest during months May and June. Similarly, the smallest biases of ERA Interim data compared to the station measurements are found in June and July. These results indicate that the larger bias values may be associated with winds resulted by winter storms.

(6) The application of bias correction substantially reduced the average monthly bias (practically to zero). The differences of the percentiles in the reference period are generally small, except in the tail of the distribution, where it can reach 1 m/s in some gridpoints in case of the 0.99 percentile value.

(7) Projected monthly changes in the median and the 0.90 percentile are relatively small (below 0.4 m/s and 0.6 m/s, respectively) for both future periods (2021–2050 and 2071–2100), however, estimated monthly changes of the 0.99 percentile may reach 2 m/s.

Acknowledgements—We are grateful to the Hungarian Meteorological Service and the Geoinformation Service of the Hungarian Defence Forces for the wind data of the Hungarian synoptic meteorological stations and CARPATCLIM data sets. This work was partially supported by the AGRÁRKLIMA2 project (VKSZ_12-1-2013-0034). Research leading to this paper has been supported by the Hungarian National Science Research Foundation under grant K-78125, and K109109.

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IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 120, No. 1, January – March, 2016, pp. 73–84

Impact of climaticfactors on yield quantity and quality of grain crops

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(Manuscript received in final form June 28, 2015)

Abstract—Weather impacts may have direct or indirect influence on the performance of agricultural production and food industry. The present problems are various, however, they can be sorted into two major groups: (1) factors that can be related to climate change processes like water scarcity, drought, meteorological extremities (temperature anomalies – frost, heat days, duration of unfavorable periods; precipitation – heavy rains, hail storms, land slide; air – storms, high wind, alterations of radiation and its postulates, (2) economic, social, and policy problems, that may have negative impact on the adaptability to meteorological factors in general and climate change processes in particular regarding food and agricultural production.

Changes in temperature may be of less importance concerning agriculture. Apart from a wide range of physiological problems, warming may have beneficial impacts as well; 1 °C rise in mean temperature may induce some 7 to 9 days of increment of the vegetation period, which could give a chance to use a +100 FAO group in maize production. On the other hand, warming of the summer period can be considered unfavorable. That may result in deterioration of sexual reproduction of most annual plants.

Changes in precipitation have more severe and determining consequences for crop production. Limited availability to water in the vegetation period may cause various direct deteriorating effects in cropping. Also, mild and dryer winter periods can be harmful contributing to epidemics and gradations of pests and diseases. Weed cenoses are also affected by climate change processes.

Economic vulnerability of agriculture in general and that of crop production in particular can be detected in most fields of the food chain. It is hard to estimate losses, but trends and the magnitude of these can be assessed. Grain crops represent a major source of arable output in Hungary. Half of the arable land is used for wheat and maize cropping. The grain yield of these two crops range from 9 to 15 million tons annually due to weather influences of the very crop year. The gap between them represents some 270 billion HUF on today's prices.

Key-words: climatic factors, crop production, yield quantity, yield stability

1. Introduction

Since the beginning of the human civilization, when man first tried to cultivate plants and recognized that crop plants do not give the same yield in each year, moreover, sometimes the differences could be very high, there is a profound interest to seek and learn possible reasons of that. According to the level of certain historical ages, this variance was explained by some supernatural forces. In accordance with the progress of society, more and more rational explanations were found up to now. On the basis of rationality, only scientifically approved causes could be accepted (*Jolánkai* and *Birkás*, 2007; *Jolánkai et al.*, 2008). In this way, crop science and practice become reasonable gradually. There are numerous factors that are having effect on yield (*Tarnawa* and *Klupács*, 2006), and among them there are some that could be influenced by the farmer and also a few others that could not be. The first group is the set of elements of agronomic management, the second group is the set of factors of environment (*Várallyay et al.*, 1985). In the set of environmental factors, there are some with more or less impact on yield (*Klupács et al.*, 2010), but according to former observations, weather plays a significant role (*Szöllősi et al.*, 2004). Even because crop production is not an indoor practice but mostly outdoor; the weather and climate may have high impact on that (*Láng et al.*, 2007). Weather impacts and climate change processes may have direct or indirect influence on the performance of agricultural production and food industry (*Veisz et al.* 1996; *Anda,* 2005; *Bozó et al.* 2010). Climate change impacts on crop production are due to weather anomalies and uncertain processes (*Varga-Haszonits,* 2003).

As the yields still show lower or higher fluctuation from the long term averages or trends, it should be more than useful to explore how they depend on each element of climate (*Pepó*, 2010). Certain crop species respond to climatic impact in different ways. The performance of maize crop is highly influenced by radiation and temperature (*Anda* and *Lőke,* 2004). The grain yield of maize is rather influenced by precipitation (*Anda et al.* 2002; *Lente* and *Pepó* 2009). Grain yield of wheat may vary in accordance with the weather conditions of the crop year. Yield stability depends on the optimum distribution of precipitation during the vegetative phenophases. Grain yield of wheat may vary in accordance with the weather conditions of the given crop year (*Bocz et al.,* 1983; *Pepó et al.*, 1986; *Pepó,* 2010; *Pepó* and *Győri,* 2005).

Changes in temperature may be of less importance concerning agriculture. Apart from a wide range of physiological problems, warming may have beneficial impacts as well; 1 °C rise in mean temperature may induce some 7 to 9 days of increment of the vegetation period, which could give a chance to use a +100 FAO group in maize production. On the other hand, warming of the summer period can be considered unfavorable (*Ladányi et al.,* 2001; *ADAM,* 2008). That may result in deterioration of sexual reproduction of most annual plants. Climatic conditions may have an impact on the performance of crop production. Apart from the growth and development of the crop plant, water availability within the crop site may be responsible for various phytosanitary problems, such as weed infestation, disease infections, and gradations of insect pests (*Nagy* and *Ján,* 2006, *Ács et al.,* 2008; *Várallyay,* 2008; *Pásztorová et al*., 2011).

Recently, one of the most severe harm induced by insects may be related to the spread of western corn rootworm *Diabrotica virgifera virgifera* Le Conte (*Kiss* and *Edwards,* 2003). Spread of this insect species has been recorded since 1992 in Central Europe due to an anthropogenic failure. The pest has been imported from overseas during the Yugoslav war with a humanitarian aid transport to Europe. This insect has conquered gradually the whole territory of the Carpathian Basin in recent years. The gradation of Diabrotica in Hungary has started in 1996 and has been completed by 2002 (*Zsellér Hatala* and *Széll,* 2001; *Vidal et al.,* 2005; *Jolánkai et al.,* 2006).

Availability of water is a major stressor in relation with yield quality and quantity performance of winter wheat. Cereals represent a most plausible source of human alimentation in the world. Wheat provides a basic staple for mankind. This crop is one of the most important cereals in Hungary with a high economic value. Utility, market, and alimentation value of the crop is highly affected by climatic conditions and within that annual weather performances, as well as soil moisture conditions (*Ács et al.*; 2008; *Koltai et al*., 2008; *Skalová et al*., 2008; *Várallyay*, 2008). The aim of wheat production is twofold; to provide quantity and quality. Milling and baking quality of wheat is mainly determined by the genetic basis, however, it can be influenced by management techniques (*Pollhamerné,* 1981; *Nagy and Ján*., 2006, *Varga et al*., 2007; *Vida et al.,* 2005). In our previous studies, we have reported results regarding the role of water availability impacts on the quantity and quality of grain crops (*Gyuricza et al.,* 2012; *Horváth et al.* 2014; *Jolánkai et al.,* 2014). Since main quality indicators – protein, farinographic value, gluten content for wheat, as well as protein, starch, and fibre for maize – have a rather diverse manifestation, extensive studies were performed to gain more information concerning the behavior of them.

The present paper is intended to provide some information on the performance of wheat and maize, the major grain crop species produced in Hungary. The work of the research team was based on two sources, once on the results of long term small plot field experiments, while on the other hand, on the use of national databases of meteorology and agriculture.

2. Materials and methods

The materials and methods of the present study cover a rather broad field, since there are three slices of the research work done by the Szent István University, Crop Production Institute, Hungary (hereinafter SIU). Most of the results are based on experimental research, however, some evaluations were implemented by using national public data, or observation results published.

In long term field trials, a wide range of winter wheat *Triticum aestivum* L. varieties and maize *Zea mays* L hybrids were tested. The small plot trials were dirun at the Nagygombos experimental field. The soil type of the experimental field is chernozem (calciustoll). Annual precipitation of the experimental site belongs to the 550–600 mm belt of the northern edges of the Great Plain in a 40 years average, 1961–2000, while the average depth of groundwater varies between 2 and 3 metres.

Experiments have been conducted in split-plot design with four replications. The size of each plot was 10 m^2. Plots were sown and harvested by plot machines (standard Wintersteiger cereal and maize specific experimental plot machinery series). Various identical agronomic treatments were applied to plots. Plant protection and plant nutrition applications were done in single and combined treatments. All plots were sown with identical series of wheat varieties and maize hybrids for studying their performance in relation with agronomic impacts. Regarding water availability impacts, experimental mean values of respective treatments and homogenized bulk yield samples were used only. Precipitation records have been evaluated in relation with yield quantity and quality. Wheat grain quality parameters like protein, farinographic value, and wet gluten content were processed, as well as maize quality parameters; protein, starch, and fibre content. Quality characteristics were determined at the Research Laboratory of the SIU Crop Production Institute, according to Hungarian standards (*MSZ,* 1998). Grain yield samples and quality figures were correlated with precipitation parameters. Analyses were done by statistical programmes with respect to the methodology of phenotypic crop adaptation (*Eberhart* and *Russell* 1966; *Finlay* and *Wilkinson* 1963; *Hohls,* 1995).

The gradation of the western corn rootworm was analyzed from a point of view of crop production. The beetle has conquered within almost ten years the whole territory of the Carpathian Basin. The spread of Diabrotica in Hungary has started in 1996 and has been completed by 2002. Climatic factors of the gradation were evaluated. The meteorological database of the research referring to precipitation as well as temperature data was provided by the Hungarian Meteorological Service (OMSZ). Yearly and monthly data of precipitation and temperature of the respective years have been used during the evaluation. The spreading of the insect was recorded by digital mapping with the use of planimeter. Distances have been determined by GPS coordinates of the locations. Gradation reports and data of the spreading were obtained from the Ministry of Agriculture of Hungary as well as that of the phytosanitary authorities (NÉBIH). In the study, there were no entomological evaluations. All information regarding entomological aspects were adopted from specific reports on Diabrotica (*Kiss* and *Edwards,* 2003; *Zsellér Hatala* and *Széll,* 2001). Statistical evaluations, crop ecological model adaptations, and correlation calculations were done by regular methods (*Sváb,* 1981; *Finlay* and *Wilkinson,* 1963).

The present paper produces three slices of the results of the ongoing research in relation with weather impacts on grain production. Such an assessment has a diverse nature. Once, it is beneficial regarding the abundance and the duration of baseline data. On the other hand, it is restricted to the available structure, moreover, it is bound mainly to annual figures giving less chance for deep layer evaluations. However, the study could provide some novel specific information on crop performance.

3. Results and discussion

3.1. Yield stability

Hungarian agriculture is run mainly by rainfed technologies regarding field crops, since less than 7 percent of the arable land is equipped for irrigation. Changes in precipitation have more severe and determining consequences for crop production. Limited availability to water in the vegetation period may cause various direct deteriorating effects in cropping. Economic vulnerability of agriculture in general and that of crop production in particular can be detected in most fields of the food chain. It is hard to estimate losses, but trends and the magnitude of these can be assessed. Grain crops are a major source of field crop output. Half of the arable land is used for wheat and maize cropping. The grain yield of these two crops range from 9 to 15 million tons annually due to weather influences of the very crop year as it is indicated in *Figs. 1* and *2*. The gap between the total yield of the two crops represents some 230 billion HUF on today's prices (an estimated value of 386.6 billion HUF for the minimum and 616.2 billion HUF for the maximum within the time range).

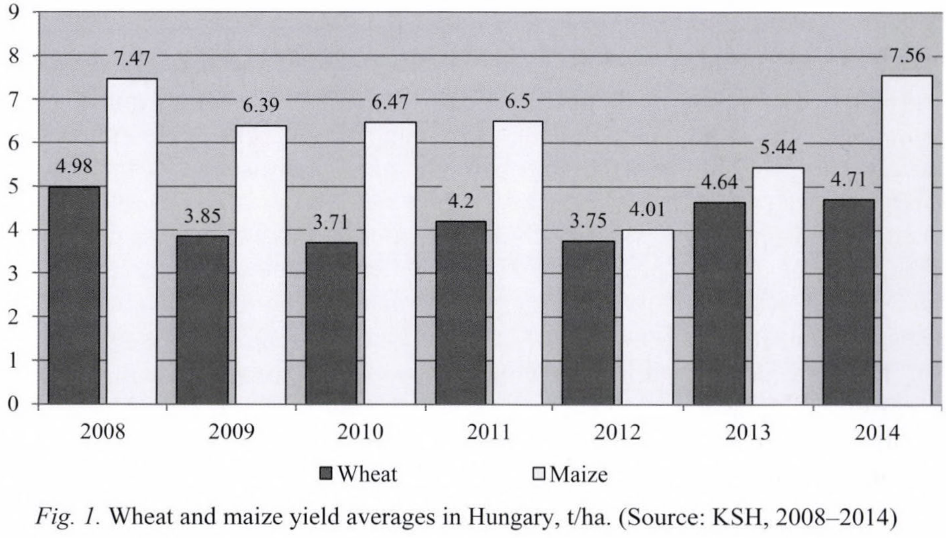

Fig. 1. Wheat and maize yield averages in Hungary, t/ha. (Source: KSH, 2008–2014)

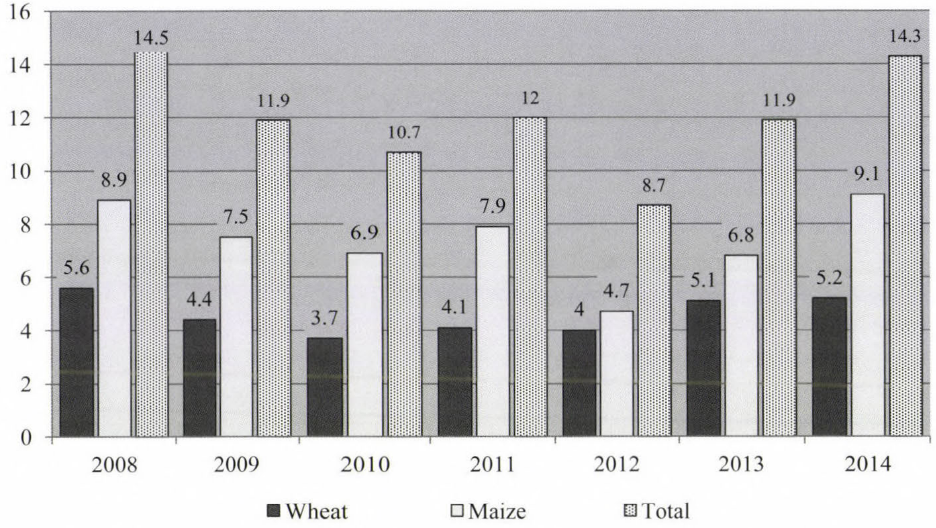

Fig. 2. Wheat and maize yields in Hungary, million t. (Source: KSH, 2008–2014)

3.2. Insect pest gradation

Availability to water during the vegetation period may cause various direct deteriorating effects in cropping. Also, mild and dryer winter periods can be harmful contributing to epidemics and gradations of pests and diseases. Weed cenoses may also be affected by climate change processes.

The basic hypothesis of the work was related to the performance of maize crop of the respective periods. Since all live populations in general and the reproductive activities of them in particular depend on the food availability, an assessment was implemented to find correlating factors. *Fig. 3* presents data on the annual spread of the insect pest with the maximum distance of migration of the respective crop year and the maize kernel yield. It has been observed that the magnitude of gradation was usually bigger in crop years with high grain yield. This phenomenon may be explained by the better habitat conditions of the actual crop year provided by the good plant performance. The trend of gradation has similarities with that of the maize kernel yield of the respective years, however, various other factors had to be evaluated as well. For example, there were crop years with 2 t yield differences when the gradation maximum distance was identical.

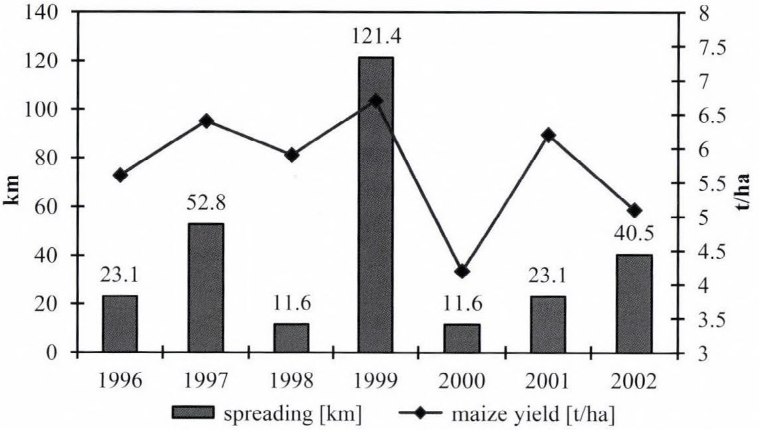

Fig. 3. The annual spread of *Diabrotica virgifera virgifera* and maize yields of respective years, 1996–2002.

In accordance with European entomological reports, the spreading of the insect has been performed by a pattern of concentric circles. The speed of gradation, the size and shape of the annually conquered area was different in each crop year observed. The correlation between maize yields and the magnitude of gradations indicated further studies in the field of meteorological data. In the study, precipitation of various periods within the crop year were evaluated in accordance with the life cycle information of the insect. Annual mean precipitation, the precipitation of the first six months of the year, and that of June month were checked. Temperature means of the respective periods were evaluated also. *Table 1* provides information on the correlation between the gradation and these meteorological data.

Table 1. Correlation between *Diabrotica* gradation and meteorological factors (1996–2002)

	r	*P*
Maize yield	0,683	0,95
Annual mean precipitation	0,248	ns
First 6 months' precipitation	0,236	ns
June precipitation	0,881	0,99
Annual mean temperature	–0,538	ns
First 6 months' temperarture	–0,604	ns
First 3 months' temperature	–0,196	ns

The research results of this study suggest that the amount of precipitation and temperature data had an indirect effect on the spread of the insect. Significant correlations were found in the case of annual harvested maize yields as well as the amount of precipitation of June month with the magnitude of the gradation of *Diabrotica virgifera virgifera* Le Conte. Since the study was based on crop production and geographic methodology using open access databases and observation results concerning gradation, further entomological studies are needed to clear the background of the results obtained.

3.3. Yield and quality of grain crops

Annual amounts of precipitation and winter wheat yields have been examined in a 15-year time range, while the same for maize has been investigated in a 9-year period at the Nagygombos experimental field of the SIU, Gödöllő. *Figs. 4* and *5* illustrate annual changes of yield and some quality parameters in accordance with the precipitation mean values. Yields and main quality characteristics were correlated with water availability.

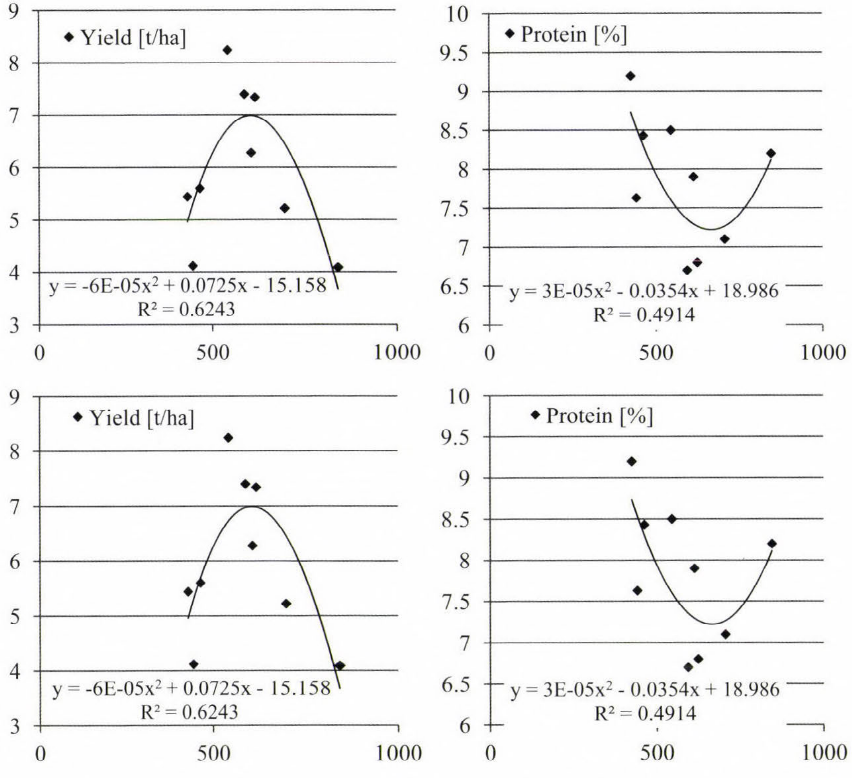

Fig. 4. The performance of grain yield, protein, starch, and fibre values of maize crop, Nagygombos, 2002–2010.

Yield quantity of maize crop proved to be highly variable. Years with low as well as too high precipitation had yield deteriorating effects. The highest yields were obtained in crop years of 600–700 mm. Protein values were smaller in rainy years. Starch values did not prove to have any correlations with precipitation. Fibre content values in certain crop years were randomly changing, however, no systematic trends could be observed.

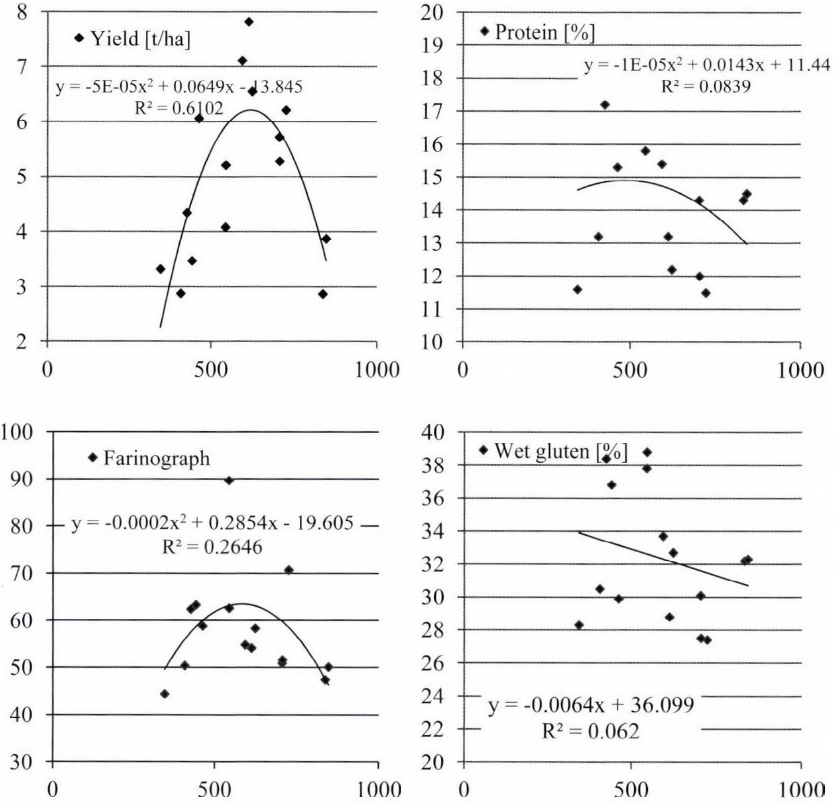

Fig. 5. The performance of grain yield, protein, farinographic value, and wet gluten % of wheat crop, Nagygombos, 1996–2010.

Yield figures were in accordance with annual precipitation patterns with an exception of some years when the distribution was irregular, e.g., in 1999 year, when 837 mm rainfall, one of the highest in the period examined was recorded, however, a severe drought spring was followed by an extreme moist summer obstructing the yield formation ripening, and harvest. Also, the year 2010 with the ever highest annual precipitation, 847 mm measured at the experimental site resulted in poor yield performance for both wheat and maize crops due long periods of water logging. Apart from these two years, the annual precipitation was in accordance with the water consumption of the respective crop species and their C3 and C4 physiological patterns.

Quality manifestation of winter wheat yields have been impacted by annual precipitation in general in accordance with previous reports (*Klupács et al.* 2010; *Pepó,* 2010). *Fig. 5* provides data regarding the changes in yield quality characteristics. Yield figures were in accordance with annual amounts of precipitation with two exceptions regarding the 1999 and 2010 crop years. Wet gluten, protein, and farinographic values had no significant relations with annual precipitation.

4. Conclusions

Weather impacts may have direct or indirect influence on the performance of agricultural production and food industry. Water availability can be considered as a basic factor related to yield quality and quantity performance of grain crops.

Yield stability of grain crops may be highly variable according to weather impacts. Yield losses may influence the whole of agricultural production. Grain crops are a major source of the output of field crops. Half of the arable land is used for wheat and maize cropping. The grain yield of these two crops range from 9 to 15 million tons annually due to weather influences of the very crop year. The gap between them represents some 270 billion HUF on today's prices.

The present study also summarizes results of an observation regarding the influences of climatic factors on the spread of an insect pest *Diabrotica virgifera virgifera* Le Conte. The research results suggest that the amount of precipitation and temperature data had an indirect effect on the spread of the insect. Significant correlations were found in the case of annual harvested maize yields as well as the amount of precipitation of June month with the magnitude of the gradation. Further entomological studies are needed to clear the background of the results obtained.

In an agronomic long-term trial, the impact of water availability on wheat and maize crop has been evaluated. Various crop years have had different impacts on crop yield quantity. Yield figures were not in significant correlation with annual precipitation in general. However, with an exception of two years of extremely high precipitation yield figures, they were in accordance with that. Moisture availability had diverse influence on quality manifestation. High precipitation has often resulted in poorer quality. Maize yields have been performing in a broader range than that of wheat. Maize quality parameters proved to be more stable than yield figures except for fibre content values.

Acknowledgements: Authors are indebted regarding support received from TÁMOP and VKSZ 12-1-2013-0034 – Agrárklíma 2 fund of the Government of Hungary.

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IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 120, No. 1, January – March, 2016, pp. 85–101

Some physiological responses of agricultural crops to global warming

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(Manuscript received in final form March 13, 2015)

Abstract—Food production is largely affected by weather variables; the year-to-year yield variations are due to changes in air temperatures, precipitation, and other meteorological elements. The crop-weather relationship is interaction, therefore, the agriculture is also responsible for greenhouse gas emissions (land clearing, fossil fuel use, rice cultivation, livestock production, N fertilization). The advantage of agricultural models is that they could simulate the above relations quantitatively. However, there are a variety of dynamic models dealing with crop-environment interactions in different levels from local to global one. The start of the studies used to be the cognition of crop growth and development by description of governing physiological and physical processes. The economic models close the range of investigations through impact estimation of climate change on the whole agricultural sector.

The first part of this study is devoted to some selected basic crop-environment relations from the literature. The second half of the work is dealing with on-site case study for maize, whereby different scenarios were established to project the crop response (stomatal resistance, photosynthesis) to various aspects of global climate change. The results of the crop microclimate simulation model were treated with restraint, because the majority of weather influences might have additive or synergistic impacts causing more severe damages than simulation models ever estimate. A simple example may be a stressed crop that become more sensitive to damaging pests and diseases excluding fully from most of the dynamic models. Despite known weaknesses of crop-environment models, the end-users (farmers, politicians) can respond more specifically to climate change besides such widely applied interventions as using warmth- or drought tolerant species, altering dates of planting and harvesting, irrigation, modification of cultivation systems, etc.

Key-words: climate change, agriculture, physiological processes, simulation model, maize

1. Introduction –brief selection from the related literature

Increasing demand for food is caused by the world's population growth and higher per capita income of well-developed countries. In addition to the amount of food, its distribution between different regions is also uneven; abundance and shortage of food are present at the same time. The most important task of the agriculture is to meet the higher demands, and to overcome the increasing risks with better management regarding agricultural food production. After FAO 2009's origin report, the number of people suffering from hunger is over a billion. Not encouraging for the future, that we have to nourish nine billion people by 2050 (*Godfray et al.,* 2010). The reasons of hunger are manifold from low agricultural productivity, lack of knowledge about cultivation facilities, poorness, overpopulation, poverty, etc. Luckily, majority of the above mentioned difficulties are not characteristic for Hungary, although there is also a contingency to improve the Hungarian agricultural production. The Carpathian Basin occupying a transition region of the precipitation pattern in Europe is probably one of the most sensitive places regarding impacts of global warming (*Torma et al.* 2010, *Giorgi* and *Coppola,* 2007). Whilst the climatic projections for different regions of Hungary may vary temporally (they are getting better and better), the sensitivity remains the same, which is caused by the special pool-type geographical position of the country.

Not to mention of all social causes of uneven food distribution, only one of the possible reasons will be discussed, namely the weather. The most vulnerable farmers are the rainfed crop growers due to extremely high rainfall variability (within a season and between seasons), and the intentions that force them to avoid risks, the meteorological hazards. The global climate change concerns both sides. *Easterling et al.* (2007) found that even a 2 °C warming in global air temperatures by 2100 (IPCC low emissions; SRES: B1) may destabilize the current farming systems reconfiguring the contemporary food distribution. The size of land for cultivation is strictly limited. One of the most important tasks in mitigating the negative impacts of global warming may be to produce more production from less land (*Vermeulen et al.*, 2012).

Consequences of global climate modification include warming, variation in precipitation events, and shifting of seasonal (phenological) cycles. Among these three terms, the precipitation projections are the most uncertain. Phenology (length and timing of the various phenological stages) comprises periodic life cycle of crops largely depending on weather conditions. The phenological phases are governed by the interaction of genetic characteristics and weather conditions (in temperate climate mostly temperatures and day length), that are modified by land cultivation to gain the highest yield (*van Bussel et al.*, 2011, *Kirby et al.*, 1987). In phenological observations, the impact of temperature has of primary importance. Air temperature directly determines the ratio of the biochemical processes (enzyme activity, cell die). Temperature has no less significant impact on the sequence of development stages. Phenological shifts modify the distribution of the species ranges, e.g., migrations toward higher elevation and latitude (*Vitassea et al.* 2011, *Bertin*, 2008). The extension of the photosynthetically active period may effect crop growth positively on the mid- and high latitudes (*Menzel* and *Fabian,* 1999) due to enhancing the carbon-uptake period, which stems from earlier leaf emergence and later leaf senescence. At the same place, shorter season for field crops could have rather negative impacts through blocking the formation of the yield components (*Chmielewski et al*., 2004). Surprisingly, in Germany, despite of warming of the last two decades, no strong effect on fruit (apple) yield formation was observed so far (*Chmielewski et al*., 2004). However, a question may arise: till what time?

During the past few decades, most of the studies were focusing on the changes of the natural vegetation only, and limited number of papers were dealing with the trends of agricultural crops (*Schelling,* 2000), despite their significance in reducing negative influences of climate change. Direction and magnitudes of observed phenology trends showed a different picture over Europe between the time period of 1986 and 2006 using satellite images (*Ivits et al*., 2012). The authors reported that until north-eastern Europe deployed a trend to an earlier and longer vegetation period, in central Europe the length of the season exhibited rather stable indicating a shift towards an earlier start of the entire growing season. At the same time, the Mediterranean areas displayed a phenological shift towards later dates with both earlier and shorter growing seasons, depending on the actual place of observation. On the basis of a twenty six years analysis *Brown et al.* (2012) found, that one third of the cereal's growing area has experienced changes in the length of the growing seasons on global level; on most areas the length of the growing seasons was with 2.3 days/year longer on average, since 1981. The above authors reported both negative and positive trends in the start of the vegetation period depending on the country and region studied. Considerable variability among crop species and observation ways has to take into account to get well-appreciated future phenological estimations. In the past three decades, variation in weather (temperature, precipitation, solar radiation) jointly increased the wheat yield in northern China by 0.9–12.9%, however, they reduced wheat yield in southern China by 1.2–10.2%, with a large spatial difference (*Tao et al*., 2014). The above authors reported that the wheat growth period before anthesis and the whole growing season were shortened, however, the length of reproductive growth period was significantly prolonged. In Europe, Hungary included, an earlier beginning of the growing season and a longer growing period may be waited. In Hungary, *Gaál* (2008) reported 12-17 days longer vegetative period for 2050, favorable for the warm season plants. Non-standard results were also born in the literature such as from *Brown et al.* (2012). The authors concluded that due to variations in weather effects on crop production, in the northern hemisphere the humidity based, while in the southern hemisphere, the accumulated growing degree days concept fitted better, when phenological models were applied. This concern likely may be expanded on larger scale only. It is well known by many investigators that significant differences are expected on country level.

Perennial crops as fruit trees and grapes are the most vulnerable classes considering the negative effects of global warming. For European temperate tree species, an average increase of the growing period of 11 days has been reported from the 1960s to the end of the 20th century by *Menzel* and *Fabian* (1999). *Richardson et al.* (2013) chronicled phenological advances of approximately 3–8 days for each 1 °C growth in air temperature for the same group of trees. *Taylor et al.* (2008) assumed that one of the reasons of the extended vegetation period may be the elevated CO_2 that delayed the autumn coloration and senescence in trees. The warming trend in our present climate is expected to continue, so in case of grapes, the ripening period will be characterized by higher temperatures worsening the berry quality (*Fila et al.*, 2014). This means that the Italian traditional grape growing areas will be in serious risk. *Jones* (2012) in Quebec suggested to explore new cultivation areas, previously cool regions, where the climate change towards for more favorable environmental conditions for grapes. The current Hungarian grape growing regions may shift into another maturity group due to more rapid phenological development (*Ladányi,* 2008).

At the very beginning of climate change impact studies, the most controversial part was the possible effect of elevated CO_2 on crop physiological processes. Studies in phenological shifts are important, because physiological processes related to the carbon cycle, plant-water relation, or nutrient uptake are directly mediated by phenology (*Noormets et al.*, 2009). *Richardson et al.* (2013) reported spring onset of photosynthesis by about 3 days at +1°C anomaly in spring air temperature that grew the photosynthetic activity and respiration by 35 ± 5 and 20 ± 3 $gCm^{-2}/°C^{1}$, respectively in a deciduous forest. Finally, the photosynthetic gains were positive, $+9\pm2$ $gCm^{-2}/°C^{1}$ on the study site. It is important to mention that in dry conditions, the influence of precipitation may exceed the effect of higher temperature on the intensity of carbon-assimilation. *Ma et al.* (2007) gave a good example for a grassland at California, in which 1 mm increment in springtime precipitation gave 2 gCm^{-2} growth in daily productivity of the ecosystem.

Doubling of the current ambient CO_2 raised the growth with 10–20 and 40–45% in C_4 and C_3 crops, respectively (*Ghannoum et al.*, 2000). Increasing atmospheric CO_2 concentration has long been known to stimulate C_3 photosynthesis better than photosynthesis of C_4 crops. The C_4 crop's photosynthesis regarded an improved version of the C_3 pathway that raises the level of the photosynthetic efficiency in addition to lower evapotranspiration rate. The advantage of C_4 crops is the lower photorespiration in comparison to C_3 ones. The C_3 crops will benefit net photosynthetic rate, stomatal resistance, and transpiration water loss. The photosynthetic way of C_4 crops was implemented due to the less favorable environmental conditions of their native places (dry and hot environments). The C_4 crops have higher production rates than that of the C_3 ones because of the gains in the used water and CO_2 values. On ecosystem level, the type of the photosynthetic pathway impacts the carbon fixation, on the one hand influencing the size of food resources for animal feeding purposes, and on the other hand effecting the amount of CO_2 released back to the atmosphere.

One of the possible impacts of increasing CO_2 levels may be the increase in stomatal resistance, causing less transpiration intensity (*Ainsworth et al.*, 2002), lowering the latent heat loss that increases canopy surface temperatures (*Bernacchi et al.*, 2007). This process will likely increase in heat and drought stress, declining the crop productivity (*Cias et al.*, 2005). *Leaky et al.* (2009) noted that in addition to higher photosynthetic activity of C_4 crops at elevated CO_2 level, the concomitant reduced water use and lower stress levels could play a more important role than the increased photosynthesis.

Although the crop response patterns could not be generalized (*Richardson et al.,* 2013), each one-day increase in the length of the growing season rose the yearly evapotranspiration water loss by 1.6 mm on a Mediterranean grassland (*Ryu et al.*, 2010). Contrary to the results of *Rye et al.* (2010), *Richardson et al.* (2013) found weak correlation between length of the growing season and yearly evapotranspiration total in both deciduous (9 species) and evergreen (12 species) forests (*Richardson et al.*, 2010).

However, it is obvious that phenology effects canopy microclimate, less information is available about the multitude ways in which phenology influenced canopy feedbacks to regional-scale weather patterns (*Penuelas et al.*, 2009). More observations are necessary to get reliable results for levels excessing microclimate.

The water budget–crop canopy relationship is a less known process in spite of its everyday practical use in irrigation, in which water inputs such as precipitation and irrigation, and outputs as evapotranspiration and outflows have to be considered. Precise estimation of water balance terms is almost impossible, because they use a lot of variables and parameters that are inferring and roughly measured from the sides of soil (water storage, infiltration rate, hydraulic conductivity, etc.), plant (phenology, root depth, volume, hydraulic properties, hydraulic conductivity, different types of leaf resistances, crop level characteristics, etc.), agronomic practices (cultivation, canopy level characteristics, etc.), actual weather conditions impacting the crops (interception), and climate change (changing meteorological elements excluding precipitation and temperatures) (*Savé et al.*, 2012, *IPCC* 2007). A model prediction for maize in Portugal showed an increase in actual evapotranspiration of maize in spring, when soil water content was still enough to cover the increased water demand of crop. Oppositely to observations for spring, in summer, a decline in maize evapotranspiration was observed due to soil moisture reduction, in total providing an increase in irrigation necessity of the studied area (*Savé et al.*, 2012). The general tendency of climate modification suggests that in temperate climate, a moderate increment in the irrigation necessity can be waited until 2050, while by the end of the 21th century, an extension of the irrigation period should be waited, irrespective to investigated crop species. The higher water use of vegetation may interact with the environment providing a feedback that currently seems to be difficult to quantify accurately. Due to the complexity of maize physiological responses to variation in environmental conditions, and to early initiation of the season, the shortening of 33% in the growing period (10 days) may be waited using B1 SRES scenario (*Warrington et al.*, 1999). This number was registered much higher in apple trees up to 20–25 days by the above authors for the Mediterranean area. Summing the earlier comments, we assume increasing irrigation water amounts during this century ranging from 40 to 250% depending on the crop species and growing area of the agricultural crops (*Savé et al.*, 2012).

2. Simulation of maize photosynthesis and stomatal resistance: an on-site case study

2.1. The purpose of the on-site simulation

The likely effect of increased evapotranspiration and modification in plant growth as a result of global warming are less known, however large amount of investigations was devoted to this topic (*Graaff et al.*, 2006). Due to the foregoing special behaviour of C_4 crops, it seems to be evident, that their response to elevated CO_2 received less attention than the more sensitive C_3 crops. In this study use of maize was motivated because C_4 stomata are as responsive, and in some cases more so, than C_3 stomata (*Anda* and *Dióssy,* 2010, *Triggs et al.*, 2004). We aimed to project the impacts of climate change on some maize microclimate and crop properties applying the Crop Microclimate Simulation Model (CMSM) of *Goudriaan* (1977) driven by scenario output from regional climate model. Drivers of climate change (meteorological elements and crops) interact with each other under field conditions. As the systematic synthesis regarding the impact of different meteorological and crop feature combinations is not very common, we wanted to investigate the variations in microclimatic elements and maize physiological properties resulted from climate modification side by side. Though conclusion of *Ehleringer* and *Thure* (2002) seems notable as they assume that at rising CO_2 levels the ambient gas concentration will once again cross a threshold value, where C_4 plants loose their competitive advantage over C_3 plants from the standpoint of reduced photorespiration and enhanced light-use efficiency. Maybe results of this case study should contribute to preparations in mitigating negative impacts of future climate modifications.

In order to develop proper long-term adaptation and mitigation strategies, detailed observations about on-site weather-crop responses concerning influence of climate modification are also necessary. In this study the modelling tool was applied to estimate the possible impacts of climate change on physiological characteristics of maize grown at Keszthely (Hungary). To achieve this goal, thirty-year crop and climate observations served as an archive of inputs for the CMSM model (*Goudriaan,* 1977). The principle of analogy was applied when choosing the proper crop and weather inputs for a specified scenario.

2.2. The modelling outline of crop features and inputs

Oppositely to other simulated microclimate and crop characteristics, the CMSM calculates the net photosynthesis (F) empirically on canopy level (*Goudriaan,* 1977; *Goudriaan* and *van Laar,* 1994):

$$F = (F_m - F_d)[1/\exp(R_v \varepsilon / F_m)] + F_d , \tag{1}$$

where F_m is the top of assimilation, F_d is the dark respiration, R_v is the absorbed short wave radiation (per LAI), ε is the slope of the curve of F-R_v at low light intensities, or light use efficiency ($17.2 \cdot 10^{-9}$ kgJ^{-1} for maize). The size of respiration was assumed to be –0.1 of the F_m (*Goudriaan,* 1989).

The Eq. (1) was the basis in simulation of leaf stomatal resistance (r_{leaf}) as follows:

$$F = \frac{1.83 \cdot 10^{-6}(C_e - C_r)}{1.66 r_{leaf} + 1.32 r_{b,h}} , \tag{2}$$

$$r_{leaf} = \frac{1.83 \cdot 10^{-6}(C_e - C_r)}{1.66F} - 0.795 \quad [\mathrm{sm}^{-1}], \tag{3}$$

where $r_{b,h}$ is the boundary layer resistance, 1.66 is the ratio between diffusivities for CO_2 and water vapor, $1.83 \cdot 10^{-6}$ converts CO_2 concentration into kgCO_2 m^{-2} at 20°C, C_e is the external CO_2 concentration, C_r is assumed regulatory CO_2 concentration, 1.32 is coming from conversion of r_{bh} for CO_2.

The sensible heat flux (Q_{Hi}) in the i layer is as follows:

$$Q_{Hi} = \rho c_p \frac{(T_{ci} - T_{ai})}{r_{aHi}} , \tag{4}$$

where T_{ai} is air temperature in the i layer [K], T_{ci} is canopy temperature in the i layer [K], r_{aHi} is aerodynamic resistance for sensible heat transfer in the i layer [sm^{-1}], ρ is air density [kgm^{-3}], c_p is specific heat of air [Jkg^{-1}/K^{1}].

The latent heat flux (λE_i) in the i layer is:

$$\lambda E_i = \rho c_p \{e_s(T_{ci}) - e_s\} / [\gamma(r_{awi} + r_{ci})] \tag{5}$$

where e_s $(T_{ci}) - e_i$ is difference between saturation vapour concentration at plant temperature and actual vapor concentration [m^3m^{-3}], r_{awi} is aerodynamic resistance for water vapour transfer in the i layer [sm^{-1}], r_{ci} is crop resistance in the i layer [sm^{-1}], γ is psychrometric constant [0.5 $gm^{-3}K^{-1}$].

More details about model structure, functioning and on-site validation of simulated variables were published earlier by *Anda* and *Dióssy* (2010), *Anda* and *Kocsis* (2008) and *Dióssy* and *Anda* (2009).

A short growing season maize acted as test crop in the model. The inputs were site and plant specific parameters and variables (geographical position of the study place, plant height, maize leaf density in three different crop layers), soil properties (actual soil moisture, physical soil characteristics) and locally collected meteorological data (on hourly basis). The meteorological elements were observed at Agrometeorological Research Station of Keszthely by using standard QLC-50 type automatic climate station. In the reference scenario (1961-90) monthly average soil moisture of -7 bar water potential was applied as an average soil moisture in July (*Table 1*). The crop characteristics such as plant height, LAI and leaf density were measured at the station between 1981 and 2010. In selection of crop characteristics for different scenarios, analogy was looking from the on-site historical measurements during the past three decades. The reference run and the present (past decade: 2004–2013) had 340 and 380 ppm (*Haszpra et al.*, 2012) atmospheric CO_2 concentrations in July, respectively. In addition five scenarios were created, in which the projections had doubled CO_2 level (760 ppm) that corresponded with the RCP6 scenario (*Moss et al.*, 2010). As the highest value, a medium range forecast for atmospheric CO_2 composition by the RCP6 scenario was applied with smooth transition towards concentration stabilization level after 2100 achieved by linear adjustment of emissions around 2100 (*vanVuuren et al.*, 2014). The RCP6, among other Representative Concentration Pathways, was adopted by the IPCC fifth Assessment Report (AR5) in 2014 (IPCC, 2014). Number 6 (Wm^{-2}) means the range of radiative forcing for 2100, relative to pre-industrial values. Associated temperature rise projection is 3.2 degrees. The intercellular CO_2 level was kept in one third of the open air one (*Anda* and *Kocsis,* 2008).

Model runs were exemplified for an "average" day in July (warmest and driest months at Keszthely).

From the model outputs, crop properties were presented for the middle (cob) layer of fully grown maize. The layer of cob formation is assumed to be the most intensive regarding the crop physiological processes.

Table 1. Summary of the used scenarios

Scenario	**Air temp.**	**Soil moisture**	**CO_2 conc. Ambient air**	**LAI**	**Abbrev.**
	Means for month July				
Reference	**20.3 °C**	**–7 bar**	**340 ppm**	**2.8**	**Ref***
Actual	20.8 °C	–7.7 bar	380 ppm	2.8	Act
$2 \times CO_2$	20.3 °C	–7 bar	760 ppm	2.8	$2 \times CO_2$
Scenario 1.	+2 °C*	–25%*	760 ppm	2.5	Scen1
Scenario 2.	+4 °C*	–40%*	760 ppm	1.5	Scen2
Scenario 3.	+6 °C*	–55%*	760 ppm	1.5	Scen3

Assuming normal distribution of both samples, paired *t*-test was used to evaluate differences between model runs performed by SPSS 17.0 Program Package. In accordance to the null hypothesis, if the mean value of differences is equal to 0, then the two samples are statistically the same. The significance level was fixed at 5%.

2.3. Discussion of the simulation results

Presently, new scenarios are applied describing the recent and future atmospheric composition including CO_2 level. These new scenarios allow a smooth transition to the future projections harmonizing with historical data (*Moss et al.*, 2008). In the projected global average air temperatures, four multi-gas emission scenarios were adapted from literature and updated for release as Representative Concentration Pathways (RCPs), with the range from 1.5 to 4.5 °C for the lowest RCP3-PD and for the highest RCP8.5 scenarios, respectively (*Moss et al.*, 2010). The range of radiative forcing are 3 and 8.5 Wm^{-2} in the scenarios RCP3-PD and RCP8.5, respectively. The assumption complemented and actualized the previous scenario-based estimations of atmospheric composition known as SRES scenarios (SRES: Special Report on Emissions Scenarios, *Nakicenovic et al.*, 2000). Scenarios in this study was about in the middle of RCP ones.

The opening of the pores that can be expressed by the stomatal resistance values has of primary importance in crop photosythetic activity due to regulation of admitted CO_2 and released water vapor. The balance between these two decisive factors may be the promise of high crop productions.

The CMSM assumes the closed pores as 2000 sm^{-1} that happens when the wilting point (–14 bar soil water potential) or sunset is reached. The midday minimum r_s of 379 sm^{-1} was calculated by the model for cob level that is about three times higher than that of the on-site measured absolute minimum r_s value for July.

In our model estimation, the lowest daily mean r_s of 577 sm^{-1} was observed in the Ref scenario (*Fig. 1*). In each scenario the daily mean r_s values significantly increased compared to the index of the period of 1961–90. A moderate but highly significant increment of 13.7% ($P<=0.001$) in daily average r_s of present days was simulated, probably due to warmer July temperatures (+0.5°C) and reduced monthly rainfall sums (–22%) during the past decade. Result of this simulation was in accordance to findings of *Erdélyi* (2008), who observed shortened phenological phases in maize due to temperature rises in Hungary. The only doubled CO_2 had the highest impact on maize r_s; the growth of 59.1% was highly significant ($P<=0.001$) with respect to Ref. The elevated CO_2 level itself narrowed the pore openings more than a half that reduced the daily mean water loss about 0.5 mm on an average day in July. On a monthly basis it is equivalent to 15 mm water decline for the whole month. This reduction in transpired water amount may be the on-site positive impact of global warming. Regarding the three scenarios with gradually intensified warming and drying, the daily average r_s increases were 54.2% ($P<=0.001$), 41.6% ($P<=0.014$) and 45.4% ($P<=0.006$) in Scen1, 2 and 3, respectively comparing to the r_s values of the reference period. There is an apparent contradiction between the increases of r_s in Scen1 being higher than in Scen2 and 3, but only until biological variables are taken into account by involving the size of LAI. The possible reason might had been the way of crop – and weather – input selection, the used analogies from the past. On the basis of local measurements, drastic LAI decline from LAI=2.5 to LAI=1.5 was performed in the last two scenarios (Scen1, 2), where the lower transpiring surface size and r_s might regulate the rate of transpiration together. Results of this study suggested that simulation of Scen1 kept the r_s values close to the resistance curve of only raised CO_2 scenario, implying that the negative consequences resulted from variable modifications included to Scen1 avoided strong variation in the r_s.

Tendency in daily change of r_s values was similar in model runs with the particularity that the simulated r_s values were similar to each other at high solar radiation, just about solar noon. In the case of high solar angles, the stomatal resistance values of the different scenarios were closer to each other and to the Ref run as well.

Besides daily mean r_s values, the opening time of the pores was also shifted in some of the model scenarios. Earlier on-site studies showed that the opening of pores in July used to be at 6 a.m. under clear-sky weather conditions (*Anda* and *Lőke,* 2003, *Anda et al.*, 1997). In reality, the stomatal resistance measurements of the early morning hours may be hampered by cloudiness or dewfall. The 6 a.m. pore opening was simulated only in the first three scenarios (Ref, Act, Scen1); opening time of all the other scenarios were shifted to 7 a.m. The stomatal closure time of the last three scenarios was delayed one hour either; it was 8 p.m. instead of 7 p.m. Duration of "active" pores remained the same in each scenario.

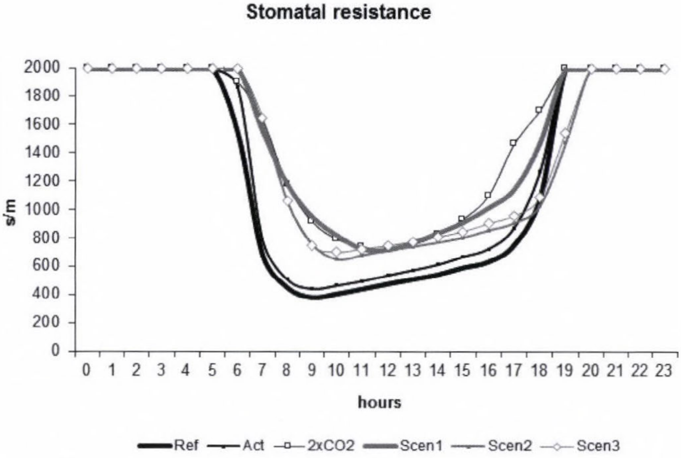

Fig. 1. Diurnal variation of simulated stomatal resistance ($r_s sm^{-1}$) in maize for Keszthely, during an average sample day in July. Results are presented for the cob level. Inputs of different scenarios and their abbreviation are in the text. Closure of stomata was assumed as 2000 sm^{-1}.

The CO_2 is one of the basic materials in photosynthesis; the higher the CO_2 concentration is, the more intense the biological process will be. The favorable effect of increased CO_2 level is widely applied long ago as CO_2-fertilization under closed growing conditions (greenhouses). The gain in carbon assimilation depends on the other physiological process, on the rate of respiration as well. At nighttime, there was no difference in respiration intensity of used scenarios (*Fig. 2*); see negative data of the *Fig. 1* by night.

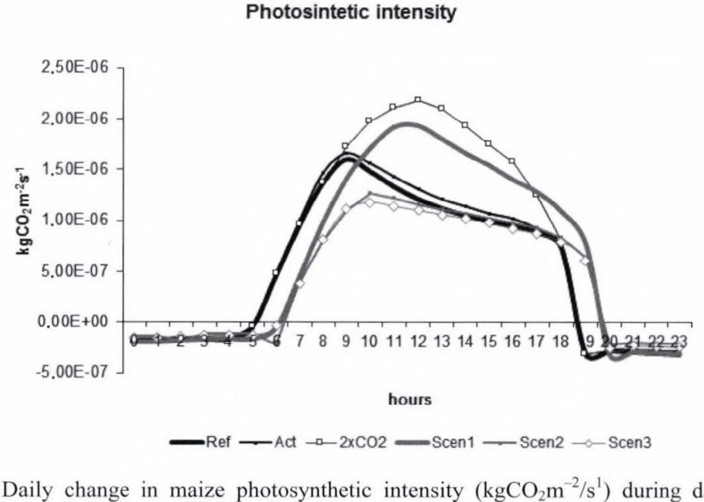

Fig. 2. Daily change in maize photosynthetic intensity ($kgCO_2m^{-2}/s^1$) during daytime hours and respiration rate ($kgCO_2m^{-2}/s^1$) by night in different scenarios for Keszthely.

Ref run was the lowest photosynthetic activity treatment in this study. Higher photosynthetic rates were simulated in all other scenarios in spite of increased r_s values, likely due to elevated CO_2 concentrations. During the past decade, the Ref photosynthesis value increased to 6.2% ($P<=0.001$) indicating an on-site positive direction of present climate modifications. Summary of the statistical analysis of different scenarios was placed in *Table 2*. Supposing otherwise unchanged weather, the Scen with doubled CO_2 level produced the highest increase of 36.1% ($P<=0.003$) in daily mean photosynthetic rate. This favorable influence could not be entirely realized with significant weather changes. As it was presented earlier in data for r_s, temperature increase of +2 °C increased with 22.7% ($P<=0.065$) rather than decreased the intensity of photosynthesis. A moderate decline was present in Scen1 with respect to doubled CO_2 scenario. We assume that this temperature rise of 2 °C together with moderate soil moisture decline does not provide a strong threat for growing maize at the surroundings of Keszthely. Photosynthesis dropped only in cases with warming exceeding +4°C and stronger soil moisture cuts. In spite of doubled CO_2, like a tendency, the daily mean photosynthesis rates were reduced by 14.1% ($P<=0.493$) and 18.6% ($P<=0.273$) in the Scen2 and 3, respectively. In these two latter scenarios, not only the expected warming but strong reduction in precipitation was also taken into account.

The energy retained by plant stands is distributed among the energy-users. The largest of all the users is the energy spent for evapotranspiration (about 70%) as latent heat flux that protects the crops from overheating. About one-third part of net radiation dissipates from the canopy as sensible heat, forming the microclimate of crops. Only a few percent of energy is utilized in the process of photosynthesis. There was a real surprise, that significant changes in both energy fluxes were only observed at doubled external CO_2 concentrations (*Figs. 3* and *4*). Elevated carbon-dioxide closing stomata gap decreased the transpiration of maize. Decline of 15.6% ($P<=0.001$) in the latent heat flux of Scen $2xCO_2$ was simulated when comparing to Ref run. The other scenarios of latent heat fluxes did not differ statistically either from each other or Ref (see also *Table 2*). The opposite modification occurred for sensible heat fluxes. Elevated CO_2 ($2xCO_2$) increased the sensible heat flux with 21.9% ($P<=0.001$) in comparison to Ref. Similarly to latent heat fluxes, in addition to Scen of $2xCO_2$, there was no significant modification in the sensible heat fluxes in any scenarios when compared to Ref one.

Table 2. Paired Samples Test of the outputs of the scenarios
(Significant results are in bold)

	Paired Differences					**t**	**df**	**Sig. (2-tailed)**
				95% Confidence Int. of the Differences				
	Mean	**Std. Dev.**	**SE**	**Lower**	**Upper**			
Stomatal resistance								
Ref - Act	–55.542	75.277	15.366	–87.328	–23.755	–3.615	23	**.001***
Ref – 2×CO_2	–257.042	289.505	59.095	–379.289	–134.794	–4.350	23	**.000***
Ref - Scen1	–233.458	258.245	52.714	–342.506	–124.411	–4.429	23	**.000***
Ref - Scen2	–148.208	273.335	55.794	–263.628	–32.789	–2.656	23	**.014***
Ref - Scen3	–169.500	274.221	55.975	–285.293	–53.707	–3.028	23	**.006***
Photosynthetic intensity								
Ref - Act	–3.67E-8	4.3E–8	8.77E-9	–5.48E-8	–1.85E-8	–4.179	23	**.000***
Ref – 2×CO_2	–2.51E-7	3.67E–7	7.49E–8	–4.06E-7	–9.65E-8	–3.357	23	**.003***
Ref - Scen1	–1.61E-7	4.07E-7	8.31E-8	–3.33E-7	1.09E–8	–1.938	23	.065
Ref - Scen2	4.53E-8	3.19E-7	6.51E-8	–8.93E-8	1.8E-7	.697	23	.493
Ref - Scen3	6.85E-8	2.99E-7	6.1E-8	–5.78E-8	1.95E-7	1.122	23	.273
Sensible heat flux								
Ref - Act	–1.202E0	5.334E0	1.088E0	–3.454E0	1.050E0	–1.104	23	.281
Ref - 2×CO_2	–1.116E1	1.347E1	2.750E0	–1.685E1	–5.477E0	–4.060	23	**.000***
Ref - Scen1	–5.53E0	2.37E1	4.84E0	–1.56E1	4.49E0	–1.142	23	.265
Ref - Scen2	–1.36E0	2.15E1	4.39E0	–1.04E1	7.71E0	–.311	23	.759
Ref - Scen3	1.42E0	2.14E1	4.38E0	–7.63E0	1.05E1	.325	23	.748
Latent heat flux								
Ref – Act	–4.208E-1	4.336E0	8.851E-1	–2.251E0	1.410E0	–.475	23	.639
Ref - 2×CO_2	1.370E1	1.516E1	3.0964E0	7.298E0	2.011E1	4.426	23	**.000***
Ref - Scen1	6.272E0	3.311E1	6.760E0	–7.713E0	2.025E1	.928	23	.363
Ref - Scen2	1.580E0	3.703E1	7.560E0	–1.405E1	1.722E1	.209	23	.836
Ref - Scen3	–3.529E-1	3.793E1	7.743E0	–1.637E1	1.566E1	–.046	23	.964

* Significant difference

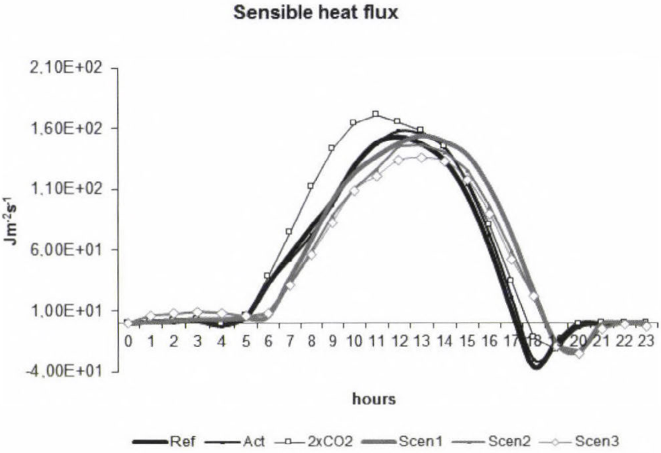

Fig. 3. Daily change in maize sensible heat flux (Jm^{-2}/s^1) in different scenarios for Keszthely.

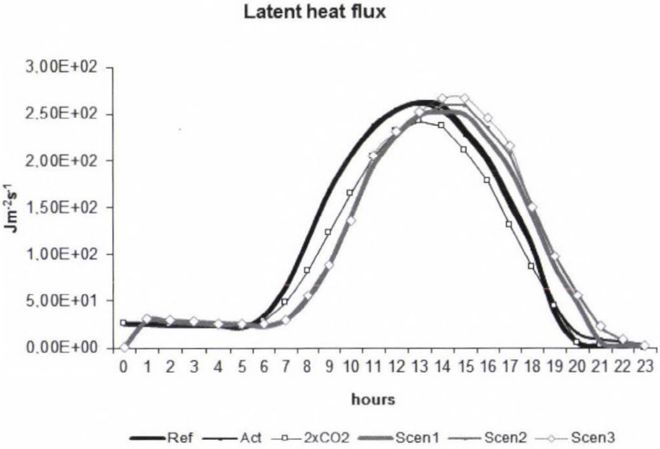

Fig. 4. Diurnal variation of latent heat flux (Jm^{-2}/s^1) in maize for Keszthely, during an average sample day in July.

3. Conclusion

In accordance to projected future weather scenarios, our region is expected to have more frequent and longer drought periods than at present. On the basis of scenarios, an increased importance of irrigation is expected when mitigating the on-site negative impacts of future climate change.

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Quarterly Journal of the Hungarian Meteorological Service
Vol. 120, No. 1, January – March, 2016, pp. 103–125

Climate change effects on structural reliability in the Carpathian Region

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(Manuscript received in final form September 23, 2015)

Abstract—Climate change affects not only the natural but also the built environment. The latter comprises large part of societal wealth, and it is a crucial component of developed economies. The focus of this paper is the quantitative assessment of the reliability of load bearing structures in changing climate. Despite its significance, relatively few quantitative studies are available on this topic, and particularly the Carpathian Region has been analyzed insufficiently. Therefore, the aim of this paper is (*i*) to present two quantitative studies on structures and climate change for the Carpathian Region, and (*ii*) to give an overview about approaches in civil engineering in relation to climate sciences, thus to trigger and facilitate future cooperation. The first part of the study is about the carbonation-induced corrosion of reinforced concrete structures analyzed considering six climate change scenarios. The results show that the depassivation probability can double from the beginning to the end of the 21st century. For structures executed in 2000, the effects will be subtle within the first half of the century, whilst the considerable changes are expected in the other 50 years. The second part of the study is about ground snow load and its effect on structural failure probability. It focuses on probabilistic models and statistical uncertainties, and draws attention to the significance of uncertainties arising from the insufficient number of observations. These uncertainties are typically neglected in current civil engineering practice, and they are especially important for climate change, for which the historical observations are not representative of the future environment. Bayesian statistical approach is used to handle these uncertainties. The analyses show that statistical uncertainties can have several order of magnitude effect on failure probability, thus their neglect is not justified. Additionally, long-term trends in historical snow observations are analyzed using stationary and non-stationary generalized extreme value distributions. Statistically significant decreasing trends ($p < 10\%$) are found for numerous locations, but they are practically significant only for a few in respect of structural reliability. The results of both studies indicate that climate change can have significant practical consequences on structures and should be considered by civil engineering profession. Revision of design standards and further research in cooperation with meteorologist seem to be needed to explore and reduce the impacts of climate change on load bearing structures in the Carpathian Region.

Key-words: climate change, civil engineering, reliability, probabilistic analysis, Bayesian statistics, snow action, non-stationary models, concrete carbonation, durability, Carpathian Region

1. Introduction

The basic objective of civil engineering is to design, build, and operate facilities which serve societal needs. This is to be accomplished among various uncertainties, e.g., uncertain material properties, uncertain future usage, very rare natural or manmade hazards. The designers must then ensure that the frequency of failures does not exceed a level acceptable by society. A major source of uncertainty is associated with actions such as wind, snow, earthquakes, traffic which should be reliably predicted and anticipated during the design process. Currently applied models for representation of these actions are prevalently based on historical experience and on the assumption of stationarity. However, observations of the past decades and sophisticated climate models imply that relying solely on past experience may be misleading. It is expected that climate change will (and very likely already did) considerably alter environmental conditions and extremes (*IPCC,* 2012; *Milly et al.*, 2008; *Retief et al.*, 2014). Thus, there is an urgent need to revise current design provisions and to incorporate the predicted effects of climate change.

Since engineering works are crucial components of industrialized societies and intended to be used by many generations – their service life is often over 100 years –, it is imperative to consider the expected effects of climate change. It is substantially cheaper to reduce the impacts of climate change today by designing resilient structures rather than to cope with more severe impacts by rehabilitations of existing structures in future. It is estimated that in 2010, climate change had already contributed to economic losses about 1% of global GPD; a considerably increase is expected in the future (*DARA*, 2012).

The potential adverse effects of climate change on structures are recognized and investigated for several regions and countries, e.g., Ireland (*CIACC*, 2009), Canada (*ACC*, 2008), and the United Kingdom (*IECCA*, 2011). These studies mainly focus on identifying and enumerating the effects and possible issues. Only relatively few quantitative numerical studies are available. Numerical researches are conducted in Australia within the framework of a national flagship program (*Nguyen et al.*, 2010; *Stewart* and *Wang*, 2011; *Wang et al.*, 2010).

To the authors' knowledge, few studies have been focused on construction works in the Carpathian Region and most of them intended to draw attention to the issue of climate change without any quantitative analysis (*Lenkei*, 2007; *Timár*, 2010; *VAHAVA*, 2010) or focusing on building physics and energetics (*Medgyasszay et al.*, 2007). A study by *Horváth* and *Pálvölgyi* (2011) is quantitative but not focused on structural or reliability aspects. That is why the authors conduct quantitative analysis of climate change on load bearing structures to provide first insights and to support decision making. The aims of this paper are:

- to present two quantitative studies dealing with typically neglected though important aspects in civil engineering;
- to give a broader view about relation of civil engineering with meteorology, thus to facilitate cooperation between experts, and to bridge the gap between engineering and climate sciences;
- to draw attention of civil engineers to challenges related to climate change.

The contribution summarizes the main findings of the previous conference contributions by the authors (*Rózsás* and *Kovács*, 2013a; *Rózsás et al.*, 2015; *Rózsás* and *Vigh*, 2014), and extends them by providing a broader perspective. The first study is dealing with carbonation induced corrosion of concrete structures considering six climate change scenarios. The second study is focused on modeling of extreme snow events, long-term trends in meteorological observations, and their effect on failure probability with special focus on statistical uncertainties. Both topics seem to be underestimated and often neglected in the present practice.

2. Climate change and civil engineering

2.1. Impacts of climate change on civil engineering structures

There is a virtually unanimous consensus among climate scientist that climate change is an ongoing process, largely caused by human activity, and urgent, large-scale measures are needed to avoid dangerous, irreversible, practically uncontrollable consequences (*Anderegg et al.*, 2010; *IPCC*, 2014; *Leshner et al.*, 2009; *UNFCCC*, 2010).

Climate change response strategies can be divided broadly into two categories: mitigation and adaptation (*IPCC*, 2001). These two strategies are often interrelated, i.e., by enhanced corrosion protection of bridges, future durability issues are moderated (adaptation) along with decreasing the greenhouse gas emissions by reducing traffic congestion and detours due to reduced maintenance (mitigation). Given the predicted severe consequences of climate change (*Warren*, 2011), surprisingly few studies are focused on large scale mitigation only. A notable exception is the research group of Mark Jacobson, which demonstrated that transition to renewables in the US of the all-purpose energy system (for electricity, transportation, heating/cooling, and industry) is economically and technologically feasible by 2050 (*Jacobson et al.*, 2015).

Table 1 summarizes some effects of climate change which bear relevance to construction works.

Corrosion related issues deserve special attention, since durability requirements and regulations are typically underdeveloped in standards. Furthermore, the corrosion related effects and costs are enormous but they are typically considerably underestimated, partially as they are not accompanied by singular catastrophic events. The most costly natural disaster in history, the 2011 Tōhoku earthquake and tsunami with $235 billion damage as high estimate (*WB*, 2011), is only one-fourth of the annual corrosion related losses in the US (over $1 trillion). The latter number is estimated using the 2013 level GDP of the US and approximating the sum of direct and indirect corrosion costs to be 6% of the GDP (*Koch et al.*, 2001).

The aging and deteriorating bridges are common and urgent issue worldwide. As an example, in Hungary 60% of the bridge population is over 50 years old (*KKK*, 2012), and 25% of highway bridges are rated with local or global deficiencies (rating 4 or 5 on a 5 scale measure with 5 as the worst) (*Tóth*, 2012); similar figures apply for the Czech Republic. Moreover, the infrastructure comprises a great amount of national wealth in every country, e.g., in the UK at least 50% (*Long*, 2007). In Hungary, the transportation infrastructure is about one-fifth of the total national wealth, and it generates 5–6% of the GDP. 2–3% of GDP is annually devoted to its development (*KKK*, 2008).

2.2. Design standards – Eurocodes

Standards and design provisions are the main instruments of everyday engineering practice, aiming to design and construct reliable structures. Practicing engineers have typically insufficient knowledge or lack of time to conduct advanced analyses beyond provisions in standards; therefore, it is largely the responsibility of the research community to address challenges and needs of society. The importance of this task is well illustrated by that the built environment comprises about 80% of the national wealth of developed nations (*Sarja*, 2005).

Table 1. Selected projected impacts of climate change with relevance on load bearing structures.

Description	Climate	Struct. eng.
For the Central European region, the mean recurrence time of the current (1981–2000) 20 years return period daily precipitation maxima is expected to reduce to 16–10 years for 2046–65 period, and to 16–7 years for 2081–2100 period. The ranges are covering 50% of the considered climate models and corresponding to B1, A1B, and A2 scenarios (*IPCC*, 2012).	Precipitation	Floods, slope stability, landslides, scours
For the Central European region, the mean recurrence time of the current (1981–2000) 20 years return period daily temperature maxima is expected to reduce to 10–2 years for 2046–65 period, and to 6–1 years for 2081–2100 period. The ranges are covering 50% of the considered climate models and corresponding to B1, A1B, and A2 scenarios (*IPCC*, 2012).	Temperature	Expansion joint, rail track buckling, increased stresses
Using the 1951–80 period as reference, the monthly temperature during northern hemisphere summers are expected to increase significantly. The percentage of global land area with over 3 and 5 sigma reference thresholds are predicted to increase from less than 1% to 19% and from less than 1% to 2–3%, respectively, by 2100 for RCP2.6 scenario. The percentage of the global land areas in the same order for RCP8.5 scenario are 87% and 58% (*Dim* and *Alexander*, 2013). The former scenario or concentration pathway (RCP2.6) is very likely already unattainable, and the latter (RCP.8.5) represents the most severe, business-as-usual case with increasing greenhouse gas emission to the end of the 21st century.		
The probability of mega-heatwaves, such as the 2003 and 2010 summer extremes in Europe, are predicted (A1B scenario) to increase 5 to 10 times within the next 40 years (*Barriopedro et al.*, 2011).		
For some regions in Australia (Cairns, Townsville, Rockhampton, and Brisbane), climate change induced mean wind damage losses can increase by \$2.8, \$7.1 and \$15 billion by 2030, 2050, and 2100, respectively. For new constructions, the increase of the wind pressure design value is a cost-effective adaptation measure (*Stewart* and *Wang*, 2011).	Wind	Roofs, claddings
For reinforced concrete structures, *Stewart et al.* (2011) found that in Australia the carbonation-induced corrosion damage risk can increase by 40–460% at the end of the 21st century, compared to year 2000 as reference. The same study demonstrated that chloride ion induced damage risk can increase by 6–15%.	Combined*	Corrosion
Nguyen et al. (2013) studied the atmospheric corrosion of metal fasteners in timber construction for Australia under the A1FI scenario (most severe among considered scenarios) using the most severe global circulation models, and found 40% and 20% increase in corrosion rate for Brisbane and Melbourne, respectively, by 2100 comparing with 1990 as reference.		

*The combination of multiple meteorological changes can be important for corrosion, where typically the interplay of multiple factors is crucial, e.g., wet-dry surface alteration and temperature change.

To illustrate where and how climate change and climate research are connected to standards, the conceptual framework of standardization and its relation to engineering practice is depicted in *Fig. 1*. The process starts with gathering theoretical and empirical information to identify the physical and probabilistic models required to represent the behavior of various structures and their loads. These coupled physical-probabilistic models are applicable to structural design. However, they are excessively complex for everyday use. Therefore, the probabilistic models are replaced with approximate deterministic methods, where sufficient reliability is achieved by application of safety factors. These factors are calibrated to more advanced probabilistic models to ensure the target reliability, which should represent an optimum value for the whole society considering human, environmental, and economic aspects (*Steenbergen et al.*, 2015). This procedure is conceptual since the subject is overly complex and uncertain, thus these calculations cannot be precisely completed. The acceptable level of failure probability is typically expressed in terms of target reliability, which is based on expert judgement, comparative analysis of human risk acceptance and perception, and limited quantitative analysis. In Europe, for a typical building, the annual target failure probability of 10^{-6} is selected for structural failure. It should be noted that this is a nominal value for decision making, and does not correspond to actual failure rates that are typically governed by uncertainties not covered in standards such as human errors and negligence. These account for about 80% of the observed failures (*Melchers*, 2002; *Melchers et al.*, 1983).

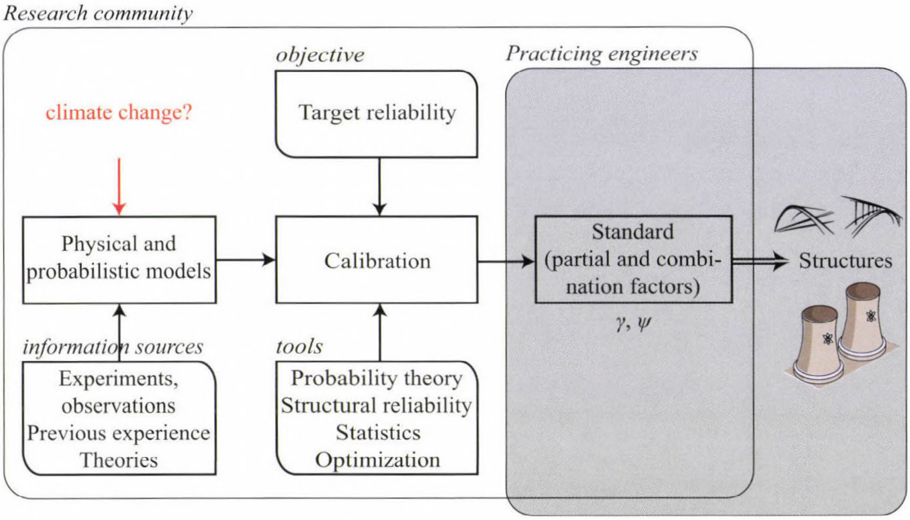


Fig. 1. Conceptual framework of standard calibration and its connection to engineering practice.

Hereafter, we focus mainly on the common European standard for basis of design – EN 1990 (hereafter 'Eurocode' for brevity). It is based on the limit state concept, i.e., the boundary between meeting (safe) and failing to fulfill a demand (failure) is sharp, characterized by a sudden change in performance. This is illustrated in *Fig. 2* along with the requirements and limit states of the Eurocode. The three principal requirements that a structure should fulfill are:

- structural resistance (avoid partial or full collapse);
- serviceability (not to impede usage, operation);
- durability (limit deterioration).

These are treated in the framework of ultimate (ULS) and serviceability limit states (SLS). The basic approach to verification of the limit states in the Eurocode is the partial factor method.

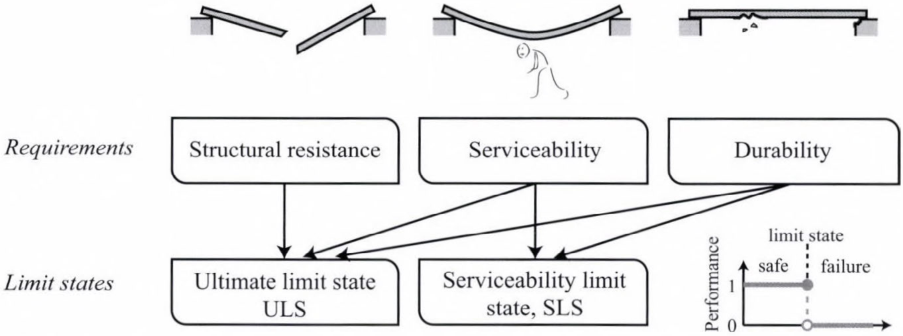


Fig. 2. Illustration of the requirements and limit states of Eurocode.

As other design standards, Eurocodes are more advanced in respect of physical models for structural resistance, and most of the research efforts are still devoted to these. The probabilistic and durability models are less developed; however, this biased focus is not justified. The disproportional development of physical and probabilistic models renders the advances in the former less effective (*McRobie*, 2004), e.g., the impact of 10% improvement in a resistance model of steel members is overweighed by the uncertainties in the probabilistic load models. Regarding durability, the economic cost of corrosion is enormous, typically much larger than those associated with structural failures, e.g., in the US the total cost of weather-related disasters for 22 years ($380 billion) is comparable to the annual direct cost of metallic corrosion ($276 billion, 3% of the US, GDP). Moreover, the indirect costs, associated with the loss of productivity, are estimated to be equal of direct costs (*Koch et al.*, 2001). In respect of climate change, these findings suggest that probabilistic analysis and durability issues are of utmost importance.

2.3. Methodology

Analysis and plan of responses to climate change are inherently probabilistic and interdisciplinary issues. This probabilistic nature is in-line with engineering work, which has to cope with numerous uncertainties by means of the probability theory, statistics, and structural reliability. In reliability analyses, the failure probability of structures and structural elements is estimated using the limit state concept. A limit state function ($g(\mathbf{X})$) is typically formulated as the difference of capacity and demand:

$$g(\mathbf{X}) = capacity - demand, \tag{1}$$

thus $g(\mathbf{X}) < 0$ describes exceedance of the limit state (*Fig. 3*). All relevant basic variables ($\mathbf{X}$) are represented as random variables with their probability density functions. The failure (violation of limit state) probability then can be calculated as the integral of the joint density function $f_{\mathbf{X}}(\mathbf{x})$ of basic variables over the $g(\mathbf{X}) < 0$, failure region:

$$P_{\mathrm{f}} = P\left(g(\mathbf{X}) < 0\right) = \int_{g(\mathbf{X})<0} f_{\mathbf{X}}(\mathbf{x}) \cdot d\mathbf{x}\,. \tag{2}$$

The above – typically high-dimensional – integral is usually approximated by numerical techniques especially tailored for the particular features of structural reliability problems (*Lemaire et al.*, 2010; *Melchers*, 2002). The design point (*Fig. 3)*, associated with the highest density value on the failure surface ($g(\mathbf{X}) = 0$) is an important element of reliability analysis, that provides information about the importance of random variables and failure probability. Although in this paper the comparisons and conclusions are solely based on the failure probabilities, structural reliability analyses are often extended to risk-based decision making problems considering economic and environmental consequences, and human safety as well (*Köhler*, 2011).

Both in civil engineering and climate sciences, coupled physical-probabilistic models are used to represent complex systems and to propagate uncertainties. In climate sciences, estimates of the first two moments (mean, standard deviation) of random variables are typically sufficient, in civil engineering, full specification and propagation of random variables are necessary to calculate low failure probabilities.

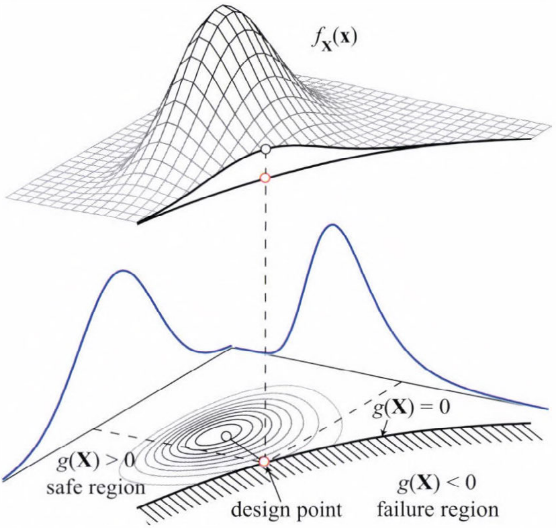


Fig. 3. Illustration of the limit state function, design point, and the safe and failure performance regions.

3. Probabilistic analysis of reinforced concrete structures exposed to carbonation

3.1. Carbonation of reinforced concrete structures

Concrete is the most widely used manufactured material worldwide as its constituents are widely available, it can be casted into almost any shape, and it has favorable physical properties to work together with steel reinforcement. A particularly important property is that concrete provides an alkaline environment, which prevents the atmospheric corrosion (oxidation) of the embedded steel elements, i.e., ensures the passivation of steel. Carbonation of concrete is a chemical process which leads to lower pH value and corollary to the depassivation of steel. Since the oxidation product (rust) has smaller density than the steel, the process leads to cracking and spalling of concrete (*Fig. 4* - the numbers of states are related to those in *Fig. 5*), and ultimately can induce serviceability and structural resistance problems.

3.2. Probabilistic analysis

Carbonation is the most common corrosion cause of reinforced concrete that affects almost every structure. It is mainly driven by the CO_2 concentration of the surrounding air which diffuses into the concrete and reacts with it (*Fig. 4*); thus, the expected increase of CO_2 in the future might considerably accelerate the process. To investigate this, time-variant probabilistic analysis (*Melchers*,

2002) is performed considering six climate change scenarios. For simplicity, only the depassivation period is taken into account, which is typically longer than the propagation period (*Fig. 5*), and it is expected to give good indication of the possible changes regarding the entire corrosion process.

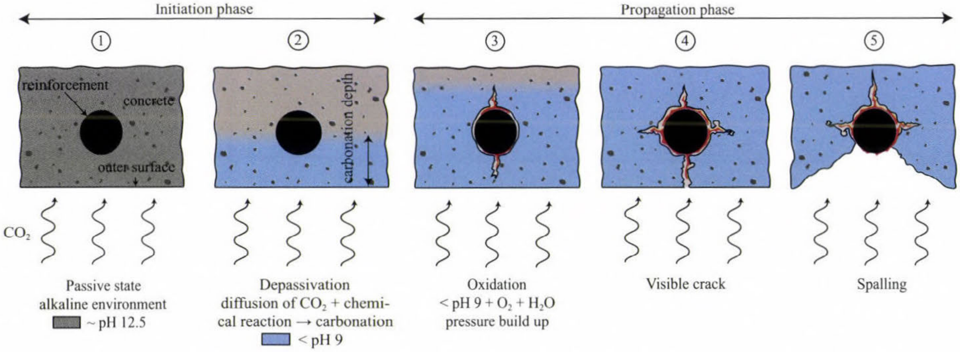


Fig. 4. Carbonation process of reinforced concrete, illustration of initiation and propagation phases.

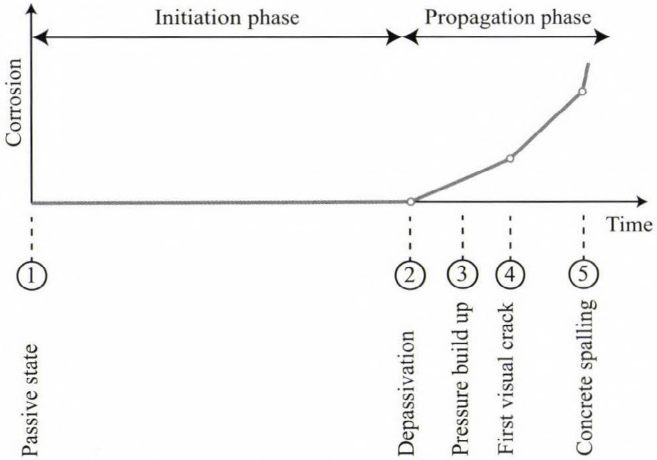


Fig. 5. Evolution of carbonation-induced corrosion in time.

The corrosion model and probabilistic description of basic variables provided by *fib* - the International Federation for Concrete Structures is adopted (*CEB/fib*, 2006). The corrosion model based on Fick's law of diffusion was extended by the authors to the case of time-varying CO_2 concentration (*Rózsás* and *Kovács*, 2013b). Six SRES climate change scenarios are considered: three scenarios within the rapid economic growth family A1: the A1FI (fossil intensive), A1T (predominantly non-fossil), and A1B (balanced) scenarios, and additionally the A2 (regionally oriented economic), B1 (global environmental sustainability), and B2 (local environmental sustainability) scenarios (*IPCC*, 2007) with probabilistic representation of CO_2 level, number of rainy days, and relative humidity. Additionally, a reference scenario corresponding to a constant CO_2 level for the year 2000 is considered as representing the provisions solely based on past experience.

Reliability analyses are completed for a hypothetical structure built in 2000, assuming 100 years design working life. The structure is thus expected to operate without major structural maintenance within this period. The minimal durability provisions of EN 1992-1-1 for design of concrete structures and the superseded Hungarian national standard (*ÚT*, 2002) are analyzed. The latter is motivated by the fact that significant portion of the Hungarian bridge inventory is constructed according to the pre-Eurocode national standards. It is anticipated that the neighboring countries in Central Europe had similar provisions, thus the results are indicative for their conditions as well.

The depassivation probabilities for each decade in the 2000–2100 period are calculated using crude Monte Carlo simulation. Various exposure classes (XC2, XC3, XC4) and cement types (CEM I 42.5 R, CEM I 42.5 R+FA) are considered to cover a large range of reinforced concrete structures. The exposure classes correspond to different environmental conditions differentiated by the duration and frequency of wet and dry phases (*CEN*, 2000, 2004). For example, XC2 class belongs to wet, rarely dry environment which is typical for industrial floors and building foundations, and XC4 represents cyclic wet and dry environment which is applicable for bridge piers, piles, and bridge superstructures.

4. Results

The time-course of the depassivation probabilities are illustrated in *Fig. 6*, the blue lines are representing the six climate change scenarios, while the yellow stands for the reference model.

The SRES scenarios are unanimously predicting increase in the depassivation probability compared with the reference model. The difference between the climate change scenarios and reference model becomes more substantial with increasing time. With the exception of EC-XC4, the durability provisions yield to greater depassivation probability than the selected 10% target (*CEB/fib*, 2006). The deficiency in the ÚT provisions is particularly apparent for CEM I 42.5 R cement, for which the target probability is reached within 30–40 years, even with the reference model, and the depassivation probability at 2100 is about 0.4 (*Fig. 6*). This means that for 4 out of 10 such structures, the depassivation of the reinforcement can be expected. The expected changes in carbonation depth (*Fig. 4*) and depassivation probability for the 2000–2100 reference period are summarized in *Table 2.* The numbers show that although the smallest relative changes are expected for the ÚT provisions, in absolute terms they are performing the worst (*Fig. 6*). Additionally, albeit the EC-XC4 provision has the largest relative increase (>100%), it still complies with the 10% limit value.

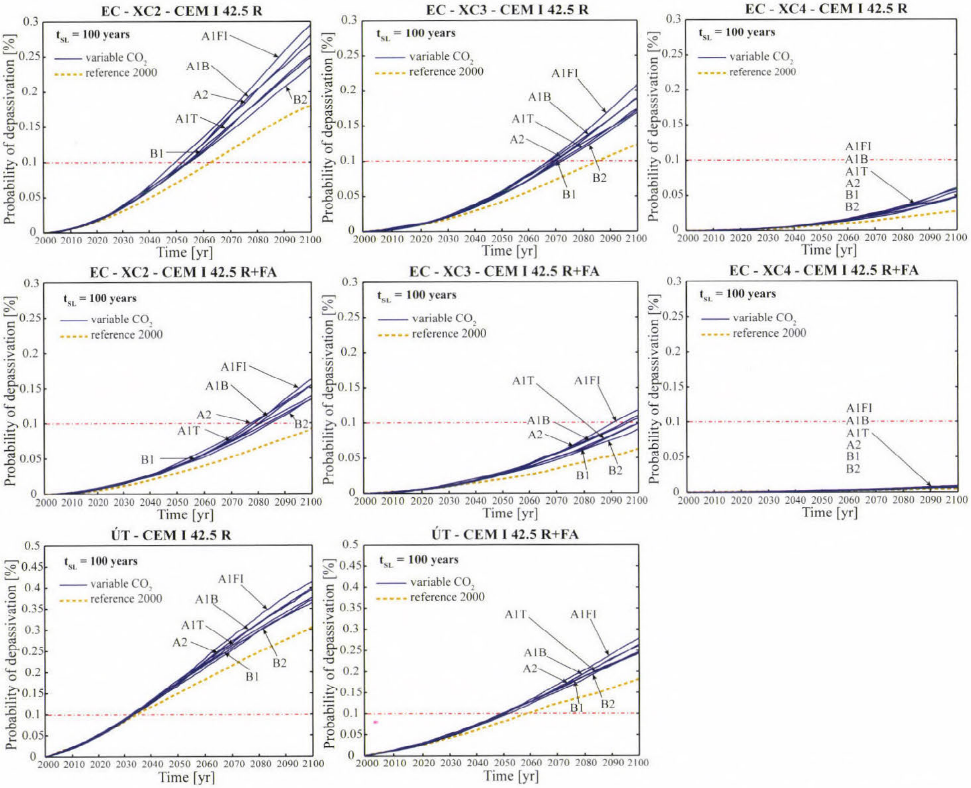


Fig. 6. Probability of depassivation corresponding to a hypothetical structure built in 2000 with 100 years design working life (t_{SL}), and using the provisions of Eurocodes (EC) and the superseded Hungarian national standard (ÚT) for multiple exposure classes (XC2-4), cement types (CEM I 42.5 R, CEM I 42.5 R+FA), and climate change scenarios (A1FI, A1T, A1B, A2, B1, B2). The selected target probability is 10% (*Rózsás* and *Kovács*, 2013a).

Table 2. Increase in carbonation depth (x_c) and depassivation probability (P_f) compared to the reference model, the intervals cover the considered six climate change scenarios (*Rózsás* and *Kovács*, 2013a).

		CEM I 42.5 R		CEM I 42.5 R+FA	
Standard	**Exposure class**	Δx_c **[%]**	ΔP_f **[%]**	Δx_c **[%]**	ΔP_f **[%]**
Eurocode	XC2	11 – 20	33 – 61	13 – 21	55 – 90
	XC3	12 – 21	44 – 73	12 – 20	50 – 82
	XC4	12 – 20	70 – 115	10 – 19	65 – 100
ÚT	–	11 – 20	21 – 36	13 – 21	33 – 55

The following conclusions are drawn from the probabilistic analysis:

- It is expected that the increased CO_2 concentration will lead to practically significant increase of depassivation probability compared with the reference model based on concentration corresponding to year 2000. The probability can increase by 115% until the end of the 21st century (*Table 2*).
- Most of the analyzed EC and ÚT durability provisions do not meet the considered 10% target probability, not even for the reference scenario (no climate change). By 2100, the EC and ÚT regulations can yield to 2.5 and 4.0 times greater depassivation probability, respectively, than the target, considering the most commonly used CEM I 42.5 R cement type (*Fig. 6*).
- For structures built in 2000, the effect of climate change is expected to be subtle till the middle of the 21st century, the practically significant effects are predicted for the second half of the century.

The findings indicate that the revision of the current durability provisions would be timely. To select appropriate adaptation measures, the analysis should be extended with the propagation phase of the corrosion and with economic cost analysis. These findings are deemed indicative, even if the presented analysis is intentionally simplified. For large structures, spatial variability in material and geometry characteristics needs to be taken into account, and the optimum target reliability may be different from the level indicated by the *fib* bulletin (*Holický*, 2011; *Sýkora* and *Holický*, 2013).

5. Snow extremes and structural failure probability

5.1. The effect of statistical uncertainties

In contrast with the serviceability and durability requirements, the target failure probability for ultimate limit states – associated with partial or full collapse of structures or structural members – is several orders of magnitude smaller. It is typically determined by distribution fractiles to which no observations are available (*Fig. 8*). For example, for meteorological extremes, commonly 50–100 years of observations are available, but failure probabilities of about 10^{-4} in 50 years should be calculated and justified. Therefore, it is of crucial importance to account for statistical uncertainties which arise from the scarcity of available information. It is alarming that the current practice in civil engineering commonly neglects these uncertainties and uses 'best' point estimates such as maximum likelihood estimates, thus leads to deceptive confidence.

Coles et al. (2003) report the 'embarrassingly frequent' occurrence of events believed to be quasi-impossible, and partially attribute this to the neglect of statistical uncertainties in probabilistic models. Statistical uncertainty is composed of parameter estimation uncertainty and model selection uncertainty. The former is the uncertainty in the identification of the parameters of a particular probabilistic model, while the latter is the uncertainty in the identification of the generating model type. Both of these uncertainties are illustrated in *Fig. 7*, parameter estimation uncertainty by confidence bands, and the model selection uncertainty by considering multiple models. *Fig. 7* shows the annual ground snow maxima for two representative locations of the Carpathian Region: Budapest represents low-land areas with Fréchet-like distribution (skewness<1.14), and the Slovakian Tatra Mountains represents mountainous areas with Weibull-like distribution (skewness<1.14). The data are obtained from the CARPATCLIM project as snow water equivalents in daily temporal resolution covering the 1961–2010 period (*Szalai et al.*, 2013).

The interval coloring in *Fig. 7* and *Fig. 8* is 'ink-preserving', i.e., the same 'amount of ink' is used for every vertical section, hence creating a linear transition from the narrowest (dark blue) to the widest interval (white). In a particular 2×2 figure, equal ranges have the same color on each subplot, thus the models are directly comparable based on coloring as well. *Fig. 7* shows that moving away from the observations, the confidence bands are substantially widening. The difference between the models is remarkable, especially the narrow confidence band of the Gumbel distribution, which often does not encompass the largest observations.

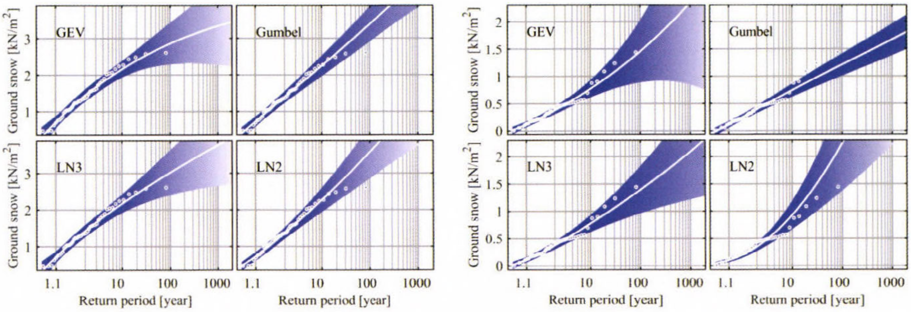
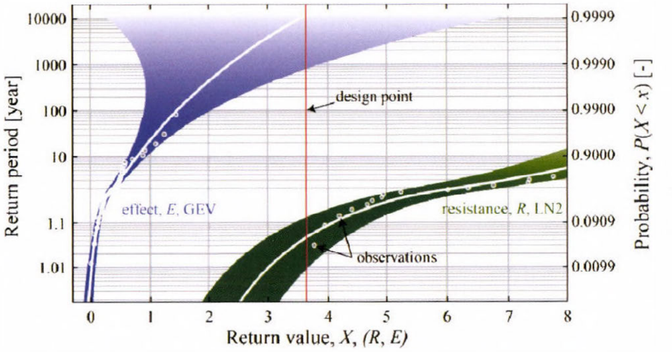


Fig. 7. Illustration of statistical uncertainty for annual maxima of ground snow load in Gumbel space, maximum likelihood fit with 90% confidence band (delta method). Slovakian Tatra Mountains (left), Budapest (right). GEV – generalized extreme value distribution, LN3 – three-parameter lognormal distribution, LN2 – two-parameter lognormal distribution.



$g = R - E$

$R \sim \text{GEV}$; $E \sim \text{LN2}$

	mean	CoV	n_{obs}
R	6.4	0.3	20
E	0.4	0.7	49

$P_{\mathrm{f}} = 1.8\times10^{-5}$

Fig. 8. Illustration of parameter estimation uncertainty and its relation to design point for a simplified reliability problem, maximum likelihood fit with 90% confidence band (delta method). *E* is inferred from the annual ground snow maxima of Budapest, also used in *Fig. 7*.

5.2. Reliability analyses

Failure probability is determined by the very uncertain tail of distributions. *Fig. 8* shows cumulative distribution functions of resistance and effect random variables for a simple limit state function. The probabilistic models of the random variables are inferred from a limited number of observations, and the parameters are selected to represent a lightweight steel structure subjected to snow load. The parameter estimation uncertainty is substantial as the confidence bands at the design point (red line) show. This small example well illustrates that using only the point estimates (white lines) conveys false confidence in the models.

The confidence interval around the maximum likelihood point estimate (ML) illustrates the extent of parameter estimation uncertainty. However, this frequentist approach does not allow incorporating parameter estimation uncertainty directly into failure probability. This can be accomplished within the Bayesian paradigm, which bases the inference on the relative evidence of the parameter values given a dataset (*Spiegelhalter* and *Rice*, 2009). Additionally, it treats the distribution parameters as random variables, thereby enabling to integrate them into the failure probability. Herein Bayesian posterior predictive distribution (BPP) is chosen to take into account parameter estimation uncertainty (*Aitchison* and *Dunsmore*, 1980). For comparison, Bayesian posterior mean (BP) as Bayesian point estimate is also considered, this represents a model without parameter estimation uncertainty. For all Bayesian calculations, vague priors are used.

To compare these approaches and to further illustrate the effect of statistical uncertainties, a steel frame is analyzed in the following section (*Rózsás* and *Vigh*, 2014). Reliability of such lightweight structures is often dominated by snow load. The simple 2D steel frame, illustrated in *Fig. 9*, with a span of 12 m and bay width of 5 m is subjected to self-weight, permanent load, wind load, and snow load. The hypothetical structure is located in Budapest, the annual snow maxima presented in the right side of *Fig. 7* are used to infer the distribution parameters.

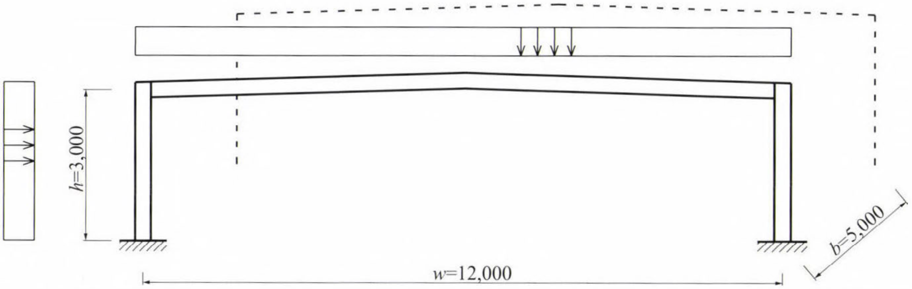


Fig. 9. Steel frame exposed to permanent, snow, and wind load (*Rózsás* and *Vigh*, 2014).

The structure (cross-section dimensions) is designed in accordance with Eurocode 3 (*CEN*, 2005) with full (100%) utilization. Parametric study is completed, in which:

- the ratio of the snow load to the whole load effect, χ, is varied and the structure is accordingly redesigned for each case;
- two distribution types and
- three distribution parameter estimation techniques are tested for annual maxima of the ground snow load.

6. Results

Left part of *Fig. 10* compares the annual failure probabilities calculated by different parameter estimation techniques, using Gumbel distribution. It appears that BP and ML may underestimate the statistical uncertainties and the failure probability of the structure. It is clear that this effect becomes more significant with an increasing snow load ratio.

For different distribution types and parameter estimations, right part of *Fig. 10* shows the failure probability in function of the snow load ratio. It is confirmed that the probability of failure may considerably increase if the snow load follows GEV distribution. It is also shown that GEV is more sensitive for the incorporation of parameter estimation uncertainty.

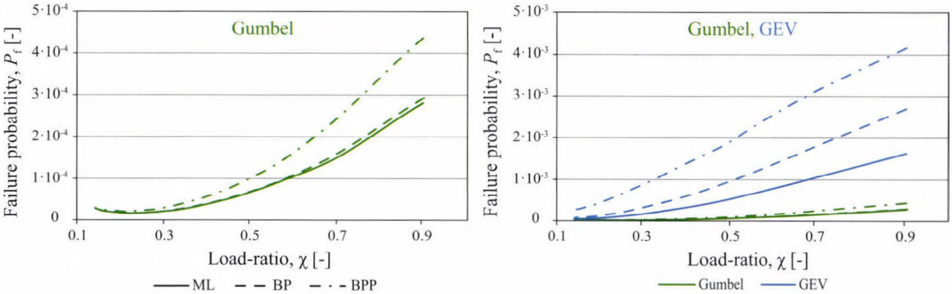


Fig. 10. Effect of distribution parameter estimation techniques on annual failure probability (P_f) in respect of load ratio (χ).
ML: Maximum likelihood, BP: Bayesian posterior; BPP: Bayesian predictive posterior.

Fig. 10 confirms that:

- The parameter estimation uncertainty in snow model has a significant effect on the reliability, in case of Gumbel and GEV distributions the incorporation of this uncertainty yields to about 1.4 and 5 to 6 times greater failure probability, respectively.
- The GEV-ML model leads to about 7 times greater failure probability than the Gumbel-ML model which is adopted in the Eurocode.

The consideration of these uncertainties can be especially important for safety critical facilities such as nuclear power plants.

6.1. Non-stationary extremes - long-term trends in time

The analyses in the preceding sections are based on stationary probabilistic models; however, some studies concerning snow precipitation found decreasing trend in Europe. *Birsan* and *Dumitrescu* (2014) have analyzed historical observations from Romania and detected decrease in snowfall days (82% of stations) with substantial decrease in snow depth (18% of stations) and snow coverage (29% of stations). *Marty* and *Blanchet* (2012) have found statistically significant ($p<5\%$) decreasing long-term trends in annual maxima snow depth for the Swiss Alps.

Time trends in annual maxima of ground snow load and their effect on structural reliability have been insufficiently studied for the Carpathian Region so far. Therefore, the long-term trends in annual snow maxima are analyzed for the entire region using the data from CARPATCLIM database (*Szalai et al.*, 2013).

Initially, a straight line is fitted to the annual maxima in least square sense. The slope parameter (m) with a representative location is illustrated in *Fig. 11*. Decreasing trend in annual snow maxima is found for 97% of the studied region.

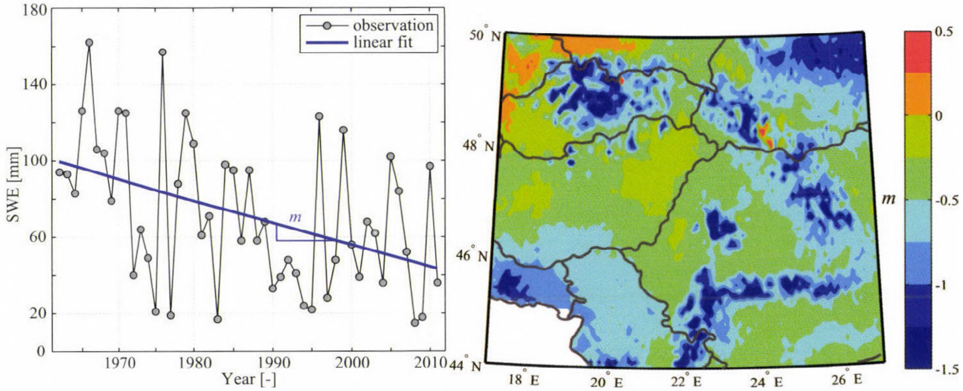


Fig. 11. A representative location with decreasing trend (left), and map of the linear trend line's slope parameter *m* in mm/year (right) (*Rózsás et al.*, 2015).

Then, stationary and various non-stationary univariate generalized extreme value distributions are fitted to each grid points. Maximum likelihood method is used for parameter identification, and likelihood ratio and Akaike information criterion based comparison are applied to detect statistically significant trends. The Akaike weight (*Burnham* and *Anderson*, 2002) based comparison of stationary and non-stationary (linear trend in location parameter) models are presented in *Fig. 12*. The likelihood ratio and Akaike weight based comparisons identified numerous locations with statistically significant (p<10%) trends. However, further reliability analyses revealed that these trends are often not practically significant in respect of structural reliability. This is mainly attributed to the considerable uncertainty of the probabilistic snow model in the range of the design point. For locations where practically significant trend is identified the change is favorable, i.e., the increase of reliability can be expected.

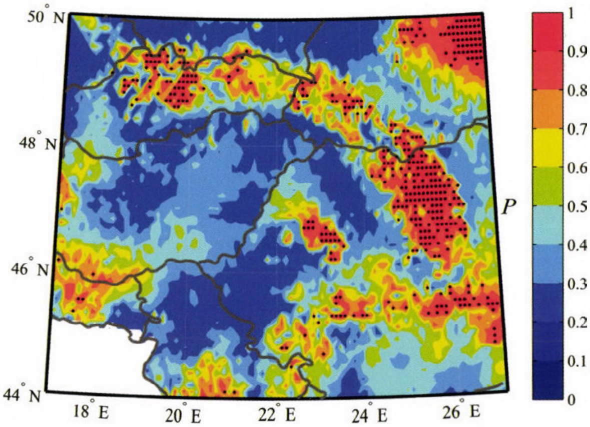


Fig. 12. Akaike weight based comparison of stationary and non-stationary (linear trend in location parameter) generalized extreme value distributions. $P > 90\%$ locations are marked with black dots. P expresses the probability that the non-stationary model fits better the data than the stationary in Kullback-Leibler divergence sense (*Rózsás et al.*, 2015).

Similar calculations are completed for the Carpathian Region considering climate projection until the end of the 21st century. The preliminary results indicate decreasing trend in ground snow load and negligible effect on strucural reliability for some selected locations (*Kámán*, 2014). However, it requires further research to decide whether the results of global circulation models can reasonably predict such extremes which needed in structural reliability analyses.

7. Summary and concluding remarks

In this paper, we argued that civil engineering structures comprise great value and are crucial components of industrialized societies, thus the investigation of climate change impacts is necessary. An overview about civil engineering and its relation to climate change and climate sciences is given to facilitate future cooperation. Two numerical studies for the Carpathian Region suggest:

Concrete carbonation

- It is expected that the increased CO_2 concentration will lead to practically significant increase of depassivation probability compared with the reference model, with year 2000 level concentration. The probability can increase by 115% until the end of the 21st century.
- For structures built in 2000, the effect of climate change is expected to be subtle till the middle of the 21st century, the practically significant effects are predicted for the second half of the century.
- Uncertainty in projected environmental parameters affects significantly structural reliability estimates and improved quantification of this uncertainty by climate scientists and statisticians is needed.

Snow load

- Statistical uncertainties in probabilistic models of annual maxima of ground snow load can have significant effect and may considerably increase (with order of magnitude) the failure probability. Their neglect can lead to practically significant underestimation of failure probability.
- Analyzing historical observations, statistically significant decreasing trend ($p<0.1$, $P>0.9$) is found in annual maxima of ground snow load for numerous locations; however, practical significance is found only for a few, and the changes are favorable from reliability point of view.
- As the aforementioned conclusions can be generalized for other climatic actions, in particular for wind speeds, essential contribution of meteorologists and statisticians to civil engineering includes improved projections for trends and extremes in local weather events, and specification of uncertainties for large, 500-1000 years return period events.

Based on these findings, revision of design standards and further joint research of meteorologists and civil engineers are recommended to explore and reduce the impacts of climate change on load bearing structures. Steps are to be made as soon as possible due to the inertial effect of today decisions on climate system (*WBGU*, 2009).

Acknowledgements: The personal communications and help from the Hungarian Meteorological Service's researchers in respect of meteorological data and climate change models are greatly acknowledged, especially those of Gabriella Szépszó. This work was partly supported by the

International Visegrad Fund Intra-Visegrad Scholarship (contract no. 51401089), by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, and by the Czech Science Foundation (project no. P105/12/G059). The meteorological data were made available by the CARPATCLIM Database © European Commission - JRC, 2013. The calculations were completed using Matlab (*MATLAB*, 2014), R (*R Core Team*, 2014), and FERUM (*Der Kiureghian et al.*, 2006), the work and commitment of the developers of these applications are highly appreciated. All the related codes/scripts, processed data, and results are available from the corresponding author.

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Published by the Hungarian Meteorological Service

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HU ISSN 0324-6329