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Regional change of climate extremes over Hungary based on different regional climate models of the PRUDENCE project

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Abstract—On the basis of different regional climate model (RCM) outputs of the PRUDENCE project, several precipitation-, temperature-, and wind-related extreme parameters were investigated at the Hungarian Meteorological Service: the occurrence of extreme precipitation events, the rate of frost, summer, hot, and extremely hot days, the number of heat waves, hot and freezing periods, and the frequency of the maximum wind speed exceeding given thresholds. The changes of these extreme events were computed for the period of 2071–2100 with respect to the reference period of 1961–1990 focusing on the Hungarian territory. The chosen regional models, which were driven with the same or similar general circulation models, are using 50 km horizontal resolution and two (A2 and B2) climate change scenarios. The investigations based on several models serve as an excellent opportunity to explore those uncertainties in the projections, which are due to the different regional climate models and different emission scenarios. Besides the abovementioned analysis of the future trends, the results of the reference period were validated with Hungarian (gridded) observational time series. In the paper the evaluation of the regional extreme parameters for the past over the Carpathian Basin is briefly introduced, and the changes of these extreme characteristics are summarized based on the RCM outputs of the PRUDENCE project. The results indicate, that by the end of the 21st century the number of days with precipitation would slightly decrease over Hungary, whereas the frequency of the days with heavy precipitation would expectedly be enhanced. The warm extremes, heat waves, and hot periods will occur more often, which were accompanied by the reducing number of cold extreme events. The occurrence of intensive and stormy winds will likely increase, however, the projected change has very small magnitude.

Key-words: regional climate modeling, PRUDENCE project, extreme indices, uncertainty, regional climate change

1. Introduction

The spatially coarse (recently around 100 km) resolution global models are unable to correctly simulate extreme climate characteristics since their low "coverage" smoothes out the extreme values otherwise present in the atmosphere. Since the raw results of global climate models do not provide sufficient details, regionalization techniques are needed to obtain more information about the regional aspects of the climate change. Additionally to the application of higher or variable resolution general circulation models, two further methods are known for gaining smaller scale information based on the global results: the statistical downscaling (*Wilby et al.,* 1998) and the technique with the use of high-resolution limited area regional climate models (*Giorgi* and *Bates,* 1989). Hereafter the present article is uniquely dealing with results obtained with this dynamical downscaling technique based on regional climate models.

The regional climate models belong to the dynamically-based techniques, which physically refine the raw global results on regional scale. In that case the regional model is focusing only on a selected limited area (e.g., on Europe) with finer horizontal resolution, and the large scale processes are taken into account by the (lower – like sea surface temperature – and lateral boundary) forcings provided by the global results. Due to the higher resolution not only a more precise description of the surface characteristics (e.g., the orography) is possible, but also the dynamical processes accounted by this kind of models are certainly adapting to these more accurate conditions.

In spite of all the advantages coming from the fine resolution, today's regional climate models and their simulations are still exacerbated by multiple deficiencies (which can vary from one model to other one), which are intensively studied by a number of international cooperations initiated in last decade (see e.g., *Jacob et al.,* 2007). Nevertheless, for satisfying the increasing demands the models are also applied to realize climate change simulations parallelly with the model developments. For that reason it is crucial at the design of the experiments for the future to consider not only single, but also several simulations of various models, because only the ensemble approach provides appropriate tool to specify the uncertain (and certain) aspects in the projections.

Inevitably the most important regional climate modeling project, which already gives concrete climate projections for Europe with relatively high resolution, is the PRUDENCE project (Predicting of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects, *Christensen et al.,* 2007). The main scientific objectives of the project were, on the one hand, to provide high-resolution regional climate change projections for the period of 2071–2100 and, on the other hand, to characterize the reliability of the climate change projections, with special emphasis on the distinction of the obtained variabilities coming from the differences between the regional models and the internal variability of the climate system. The results of the project serve as good basis to the ensemble consideration of climate change, since numerous model simulations were carried out with a range of global and regional climate models. The uncertainties in the projections did not purely come from the differences between the applied climate models (from the dissimilarities of their dynamical core and physical parameterizations), but also the future tendencies were forced by two basically different scenarios (one from the pessimistic and one from the optimistic groups) for greenhouse gas and aerosol emissions. The outcomes and outputs of the regional simulations of the PRUDENCE project have been public since the end of the project, and they have been directly accessible from the project's web page (http://prudence.dmi.dk) since 2006.

Being one of the essential indicators of the climate change, the extreme events and their future tendencies are intensively studied area of the climate researches. In 1997, the workshop on "Indices and Indicators for Climate Extremes" (*Karl et al.*, 1999) and later on the CCl/CLIVAR (World Meteorological Organization – Commission for Climatology/Climate Variability and Predictability) working group of World Meteorological Organization are dedicated to define extreme indices for the different meteorological parameters (mainly for the temperature and precipitation) in order to establish their common use. The STARDEX project (Statistical and Regional dynamical Downscaling of Extremes for European regions; *Goodess,* 2003) was initiated in 2001 to comprehensively evaluate the statistical and dynamical downscaling methods in order to reconstruct the observed past extremes and to construct regional scenarios for the future. In the framework of STARDEX, the past tendencies of several chosen extreme indices were analyzed in detail for Europe based on long observational time-series (e.g., *Haylock* and *Goodess*, 2004), and furthermore, the model simulations of the PRUDENCE project provided a good basis for the intercomparisons with the statistical methods (e.g., *Schmidli et al.,* 2007). The PRUDENCE's model simulations were thoroughly validated (for the mean precipitation, minimum, maximum, and mean temperature) by *Jacob et al.* (2007) for eight geographical regions in Europe. The projections were exhaustively investigated in the context of extremes by *Beniston et al.* (2007), which gave a detailed overview about the change of heat waves, heavy precipitation, drought, wind storms, and storm surges based on several RCMs' simulations; *Schär et al.* (2004) found that the future temperature variability will intensify with the largest degree in Central and Eastern Europe bringing severe consequences to the (increasing) number of heat waves; despite the general summer precipitation reduction and the warming trends projected by the majority of the RCMs over relevant part of the continent; *Christensen* and *Christensen* (2003) showed that there are many regions where enhancing frequency of the large precipitation events can be expected for the future together with more frequent flooding episodes. Particularly for the Carpathian Basin several studies aimed to explore and detect the trends of extreme events in last decades mainly on the basis of observational datasets: the work presented in

Bartholy and *Pongrácz* (2007) was carried out on long time series of Hungarian station data, while by *Lakatos et al.* (2007) already the homogenized time series were analyzed.

Present article is intended to provide an overview about the outcomes of the efforts, which have been made at the Hungarian Meteorological Service in order to estimate the future trends of the extreme events over Hungary based on the results of the regional climate models applied in the PRUDENCE project. The article is structured as follows: in the next section, on the one hand, a limited overview is provided about various sources of the uncertainties in the regional projections of the PRUDENCE project and, on the other hand, a brief description is given about the investigations carried out by the Hungarian Meteorological Service for the Carpathian Basin on the basis of the results of different RCMs. Section 3 considers in detail the projected change of the investigated extreme characteristics of precipitation, temperature, and wind speed; finally, Section 4 discusses the conclusions based on the extreme characteristics presented in the previous section.

2. Methodology of the investigations for Hungary

To achieve the aforementioned objectives in the PRUDENCE project, a hierarchical model system was applied with complex interactions between its components: the large scale circulation was described by coupled atmosphere-ocean models (AOGCMs) through long transient climate change simulations on 300 km horizontal resolution. These AOGCMs provided the atmospheric radiative forcings and the matching sea-surface boundary conditions for the time-slice experiments (covering the “discrete” periods of 1961–1990 and 2071–2100) to be carried out by stand-alone advanced high (150 km) resolution atmospheric general circulation models (AGCMs). Finally, these refined global results served as initial and lateral boundary conditions for the finest resolution regional simulations, which already focused on the European region with 50 km grid spacing. The preference of the relatively far future projection period was motivated by the assumption, that the future signal will be in this manner strong enough to draw robust conclusions on the expected climate change. As far as radiative constraints for the future are concerned, two different SRES emission scenarios (*Nakicenovic et al.*, 2000) were considered in the project: the A2 and B2 ones, which provide pessimistic and optimistic realizations of the emission levels in the 21st century (see *Fig. 1*).

The complex system sketched above takes into account multiple sources of uncertainties (*Christensen et al.*, 2007):

1. The large scale forcings for the higher resolution AGCMs were produced by different AOGCMs;
2. Several AGCMs were used to conduct the higher resolution global runs;

3. The radiative forcings in the future for the global models were described by two greenhouse gas and aerosol emission scenarios;
4. 8 RCMs were integrated to provide regional climate projections for the future.

Therefore, the different kind of uncertainties in the model simulations can be characterized through multiple ensembles of model integrations. Besides analyzing the future tendencies of the extreme precipitation, temperature, and wind events focusing for our region of interest (i.e., Hungary), the present article is dedicated to assess only and uniquely those uncertainties in the projections, which are due to the different regional climate models and different emission scenarios.

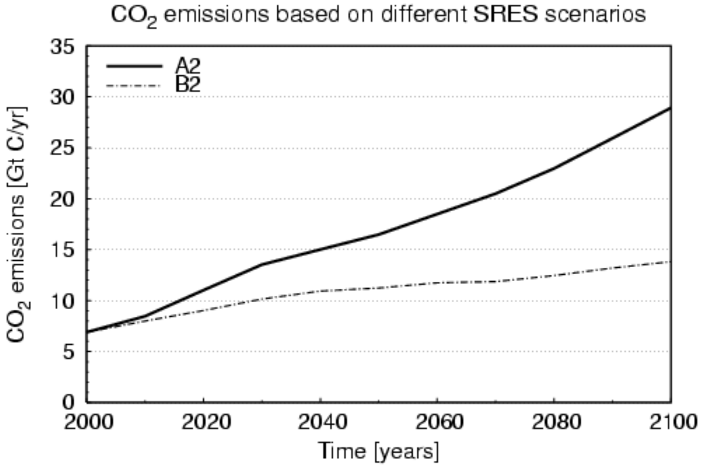


Fig. 1. The total future anthropogenic carbon dioxide emission (in gigatons of C per year) based on two reference scenarios: A2 (solid line) and B2 (chained line). (The diagram was constructed based on the data of *Nakicenovic et al.,* 2000.)

For that purpose daily outputs of five regional climate models applied in the PRUDENCE project were considered for Hungary: the HIRHAM, RegCM, PROMES, RCAO, and HadRM3P models (for additional information about the underlying model simulations see *Table 1*). The reasons for choosing these model simulations were, on the one hand, that for each integration the large scale forcings were provided by the same (or very similar in the case of HadAM3P, which is a successor of the HadAM3H model with few changes in the physical parameterizations) atmospheric general circulation model and, on the other hand, these RCMs were driven with both of the SRES scenarios (A2 and B2) applied in the project.

In the evaluation of the simulated extreme characteristics for the past, some observational time series were also taken into account in order to draw conclusions about the real spatial distribution of the examined parameters and to assess the performance of the models. For that purpose a gridded dataset on 0.1-degree horizontal resolution was applied, which was generated by interpolation based on Hungarian surface observations (*Szentimrey* and *Bihari,* 2007). This validation was limited to the daily precipitation amount and the daily minimum and maximum temperature.

Table 1. The main characteristics of the model simulations used for the investigations at the Carpathian Basin: the institute being responsible for the experiment, the applied regional model, the employed SRES scenario, and the global model which provided the driving data for the regional climate models

Institute	**RCM**	**Reference**	**Scenario**	**Driving data**
Danish Meteorological Institute (DMI)	HIRHAM	*Christensen et al.*, 1996	A2, B2	HadAM3H
Hadley Centre	HadRM3P	*Jones et al.*, 1995	A2, B2	HadAM3P
The Abdus Salam International Centre for Theoretical Physics (ICTP)	RegCM	*Giorgi* and *Mearns*, 1999	A2, B2	HadAM3H
Swedish Meteorological and Hydrological Institute (SMHI)	RCAO	*Döscher et al.*, 2002	A2, B2	HadAM3H
Universidad Complutense de Madrid (UCM)	PROMES	*Castro et al.*, 1993	A2, B2	HadAM3H

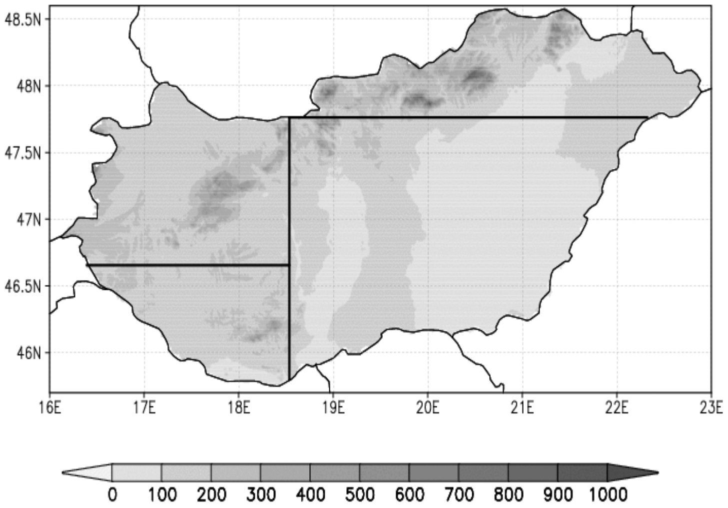


Fig. 2. Orography of the entire domain (i.e., Hungary) and sub-areas (separated with lines) defined for the investigations. (The orography on the map was generated from the data provided by the MISH software on 30-second horizontal resolution.)

In this study the threshold approach is used, i.e., it is examined whether certain fixed thresholds (whose majority was defined based on the recommendations of the WMO-CCl/CLIVAR Working Group) were exceeded or not for given parameters. The investigated changes of the different extreme parameters are always considered with respect to the reference (1961–1990) period of the same model (the changes with respect to the observations are not discussed). The analyses were carried out considering spatial averages not only over the entire country, but also for sub-areas within the country (namely, northeastern, northwestern, southeastern, and southwestern parts of Hungary).

These sub-domains were selected after simple consideration of the geographical and climatic conditions of Hungary (*Fig. 2*). The computations were carried out separately for each gridpoint over Hungary, and the values of figures and tables were obtained by averaging them for the entire country or the regions.

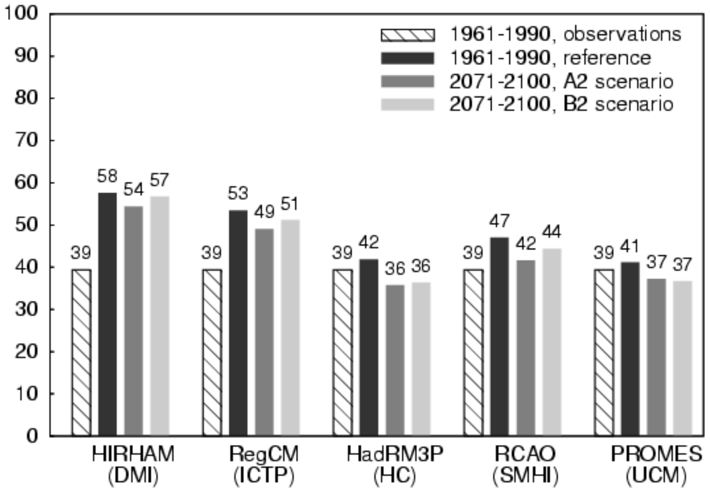
3. Results

Precipitation

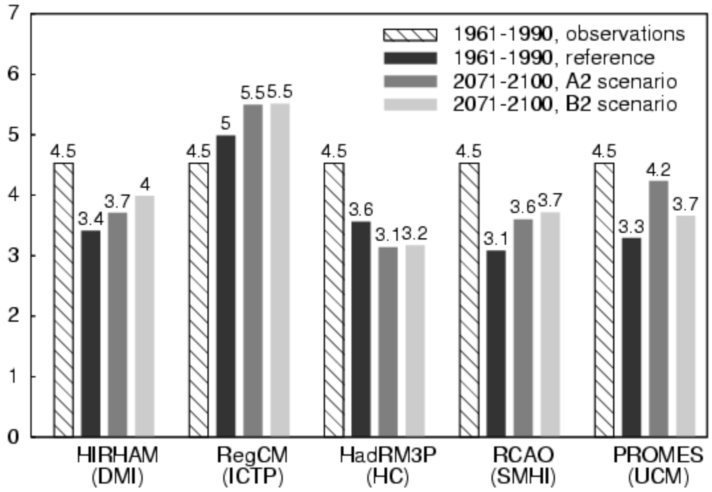
Based on the results of the selected RCMs, the changes of the number of days with precipitation, heavy and very heavy precipitation (with daily amount exceeding 0.1, 10, and 20 mm, respectively) were investigated. Comparing the results for the reference period to the observed values it can be generally concluded, that the models mainly overestimate the number of events with small precipitation, while they rather underestimate the occurrence of the days with heavier precipitation; the only exception is the RegCM model, which projects too many events in every category (see *Fig. 3* and *Table 2*). As far as the future trends are concerned, it can be noticed, that for the A2 scenario the frequency of the days with precipitation will probably slightly decrease, however, at the same time some increase can be expected for the occurrences of the extreme precipitations (with the only exception of the Hadley Centre's model, which simulates rather decrease of the heavy precipitation with more than 10 mm daily amount). The former minor reduction proves to be much smaller for the B2 scenario, which is also valid for the days with very heavy precipitation (i.e., for the threshold of 20 mm/day), while in the case of events over the 10 mm daily amount the majority of the models projects slightly larger increase for the more optimistic B2 scenario. Nevertheless, it has to be remarked, that the tendencies concluded above mean very small changes, therefore, the differences between these signals are probably not significant. Therefore, for making sure of the correctness of these qualitative conclusions, the concrete values of the relative changes projected by the different models and the standard deviation between them are also calculated.

Table 3 provides some additional quantitative details to the conclusions mentioned above. Although for the thresholds of 0.1 and 10 mm the mean changes are similar to each other in magnitude (more or less around –10 and 10%, respectively, with some "extreme" values), the standard deviation for the higher threshold is too large compared to the magnitude of the mean change. This fact indicates that for the 10 mm/day threshold the signal is rather "uncertain", so this figure should be interpreted with special care. On the other hand, the situation is "better" for the 20 mm/day threshold (even though the absolute value of the standard deviation is higher than in the 10 mm/day case): the projected change is approximately 45% with a lower level (27%) of standard deviation, which can be interpreted in a way that the increase of heavy precipitation events is rather certain, however, its exact value is more uncertain (between around 5 and 65%).

Relative frequency of the precipitation exceeding 0.1 mm/day [%]



Relative frequency of the heavy precipitation exceeding 10.0 mm/day [%]



Relative frequency of the heavy precipitation exceeding 20.0 mm/day [%]

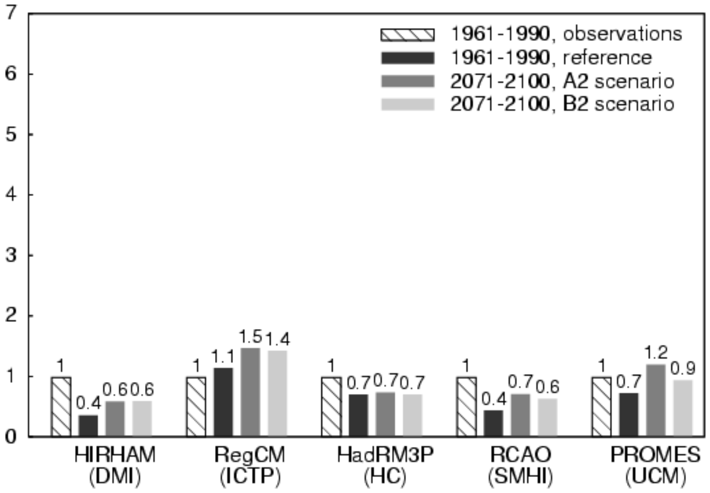


Fig. 3. Relative frequency of the daily precipitation amounts above different thresholds over Hungary. The groups of bars represent the different models, and the first two bars within each group denote the reference period (based on observations for the first one and on model results for the second one), the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

Table 2. The mean differences (in %) between the frequency of the simulated and observed extreme characteristics (R0.1, R10, R20: precipitation events exceeding 0.1, 10, and 20 mm/day, respectively; TN0: frost days; TX30: hot days) for the period of 1961–1990 over Hungary. The values of "Mean" represent average of these departures (in %)

Model	**R0.1**	**R10**	**R20**	**TN0**	**TX30**
HIRHAM	19	–1.1	–0.63	–6	4.1
RegCM	14	0.5	0.12	2	6.7
HadRM3P	3	–0.9	–0.28	1	10.7
RCAO	8	–1.4	–0.54	–14	5.6
PROMES	2	–1.2	–0.26	–5	–0.4
Mean	9	–0.8	–0.32	–4	5.3

Table 3. The changes (in %) of the frequency of different extreme characteristics (V5 and and V10: wind events exceeding 5 and 10 m/s in the maximum) for the period of 2071–2100 with respect to the period of 1961–1990 over Hungary based on different model simulations. The values of "Mean"/"Std. dev." represent average/standard deviation of the changes (in %) computed from the results of the different models. All the values are valid for the A2 SRES scenario

	Precipitation			**Temperature**				**Wind speed**	
Model	**R0.1**	**R10**	**R20**	**TN0**	**TX30**	**Freezing period**	**Heat wave**	**V5**	**V10**
HIRHAM	–5.5	8.5	64.3	–62.9	141.6	–54.2	58.2	–3.2	3.7
RegCM	–8.3	10.3	29.0	–67.3	87.6	–27.8	80.9	–	–
HadRM3P	–14.7	–11.9	4.7	–52.1	97.1	–44.4	46.2	4.8	17.9
RCAO	–11.6	16.6	62.4	–69.9	129.0	–62.7	59.1	1.5	31.1
PROMES	–9.5	28.6	65.6	–59.6	260.5	–46.4	196.4	0.2	14.2
Mean	–9.9	10.4	45.2	–62.4	143.2	–47.1	88.1	0.8	16.7
Std. dev.	3.5	14.7	27.3	7.0	69.3	13.0	61.8	3.3	11.3

Temperature

In the case of temperature, the changes of relative frequency for summer, hot, and extremely hot days (defined as days when the maximum temperature exceeds the 25, 30 and 35 ºC, respectively) were investigated as "warm" extreme indices, while the tendency of frost days (defined as days when the minimum temperature is below 0 ºC) was examined as "cold" extreme taking into account again both the observations and model results. For the warm parameters one can generally conclude, that for each of them frequency increase can be expected by the end of the 21st century, both for entire Hungary and for every sub-region. (Only the results related to hot days over Hungary are presented in *Fig. 4* and *Table 3.*) Although lots of differences can be noticed (e.g., already for the reference period) between the models, it can be generally pinpointed, that:

- The simulations for both scenarios indicate frequency increase of the warm extreme events;
- Between the two scenarios (A2 and B2), the B2 one shows more moderate changes (which is not surprising at all, because the B2 scenario is the more optimistic one, i.e., considering smaller anthropogenic emissions of greenhouse gases and aerosols, see *Fig. 1*);
- The *absolute* increase of the warm and hot days for the future exceeds in general with 10 percent according to the more pessimistic A2 scenario, while in the case of extremely hot days, the absolute increase is more moderate (around 4–8 percent).

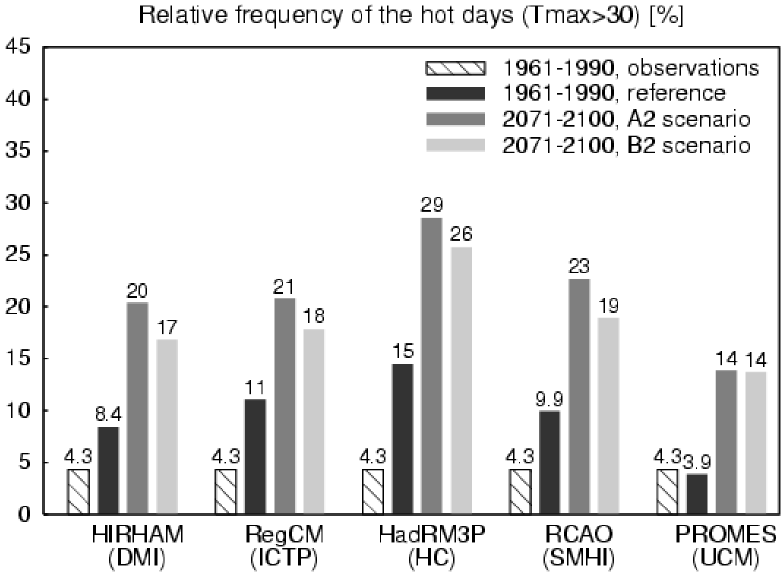


Fig. 4. Relative frequency of hot days over Hungary. The groups of bars represent the different models, and the first two bars within each group denote the reference period (based on observations for the first one and on model results for the second one), the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

More particularly, regarding the change of the number of hot days over Hungary it can be seen, that the majority of the investigated RCMs significantly overestimates the number of hot days for the past (*Fig. 4* and *Table 2*): the models simulate twice or even three times larger frequency than it was observed with the only exception of the PROMES model, which almost correctly reflects the true conditions (rather with a minor underestimation). In spite of the large uncertainty for the past, the projected positive tendency is obvious for every experiment (as it can be also easily read from *Table 3*). The mean of the signals over the entire country is 143% (i.e., the hot days will occur approximately 2.5 times more frequently in the future than in the past), and the simulated changes range the interval of 97–260%. The upper extreme (260%) is coming from the PROMES results and it is due to the fact that its reference is (correctly) the lowest among the models, and therefore, the relative increase is the largest (in spite of the fact that the PROMES model provides the lowest absolute change).

For the frost days, the RCMs behave rather differently from each other during the reference period: three of them underestimate the number of the cold extreme events, while the remaining two are rather perfect (with a very-very slight non-significant overestimation) – see *Fig. 5* and *Table 2*. The absolute errors do not have such large magnitude than it was the case for the hot days, due to the anyway more frequent occurrence of the event. The sign of the projected change is opposite with respect to the hot days: by the end of the 21st century, decrease of frost days has to be envisaged according to every experiment. On top of that, considering the very low value of the standard deviation (7%) in *Table 3* it can be stated with large confidence, that the simulated reduction of 60% can be identified as very sharp and convincing projection for the future. All this is valid not only for the A2 scenario, but also for the (more optimistic) B2 one with the restriction that the probable change is lower (about 40%; not shown).

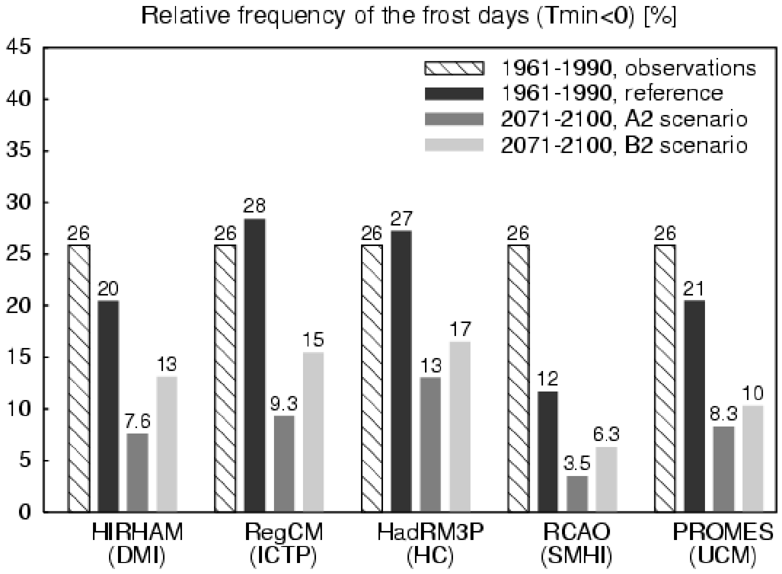


Fig. 5. Relative frequency of frost days over Hungary. The groups of bars represent the different models, and the first two bars within each group denote the reference period (based on observations for the first one and on model results for the second one), the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

In the case of temperature, not only the tendency of the occurrence of the days with maximum, minimum, and mean temperature exceeding given values, but also their persistence on consecutive days is of interest. For instance, from the aspects of human health the expected frequency of heat waves in future has also great importance, while for the building industry or forestry the changes of freezing periods in winter and hot periods in summer are also meaningful parameters to be considered. *Fig. 6* provides some information about the simulated frequency of heat waves (defined as periods of at least 3 consecutive days, when the daily mean temperatures exceed 25 ^{o}C) over Hungary both for the past (reference) and the future. The results of the five investigated models clearly indicate that the occurrence of this event will increase by the end of the 21st century with slightly different magnitudes for the individual model simulations, but with more than 50 percent in most of the cases for the A2 scenario (see *Table 3*). The mean of the signals projected by the ensemble of RCMs is approximately 88% due to the "outlier" value (196%) simulated again by the PROMES model (however, it has to be mentioned, that the future frequency of the heat waves produced by PROMES is in good agreement with the other models' result, and the reason for the large relative deviation is coming from the significant differences in the reference period.)

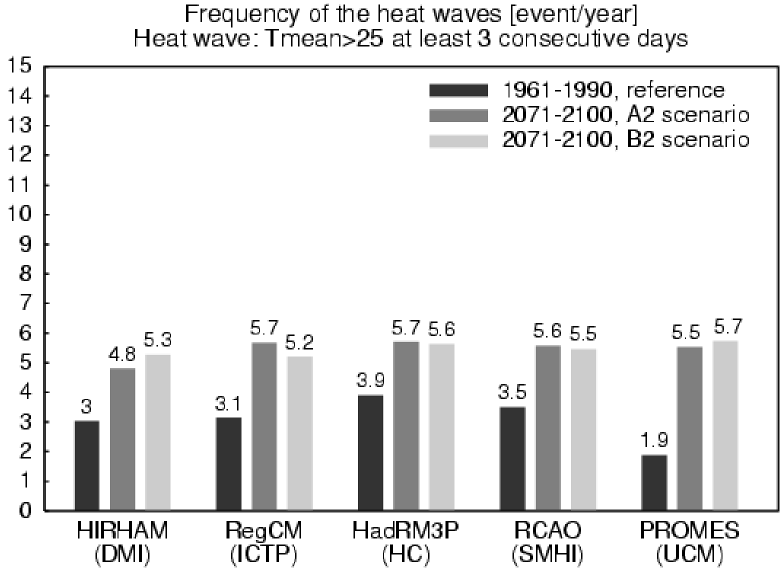


Fig. 6. Frequency of the heat waves over Hungary. The groups of bars represent the different models, and the first bar within each group denotes the reference period, the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

Regarding the hot periods (defined as periods of at least 3 consecutive days, when the daily maximum temperatures exceed 35 ºC), a dramatic level of change is anticipated for the last decades of the 21st century: it will increase from the former 0.5–3 to 2–6 events per year (not shown). It is worth noting, that both in the case of heat waves and hot periods, there are no significant differences between the results for the two emission scenarios.

As far as the freezing periods (defined as periods of at least 3 consecutive days, when the daily minimum temperatures are not higher than 0 ºC) are concerned, there is a large uncertainty between the models for the reference period (the results vary from 4 to 10 events annually – see *Fig. 7*), however, on the contrary, there is a good agreement between them regarding the future trends: the frequency of the freezing periods will uniformly decrease (with approximately 50% in the case of A2 scenario) – with large confidence as it is indicated by the especially low (13%) standard deviation value (*Table 3*). The sign of the change for the B2-case is the same, but its magnitude is smaller: about 30% (not shown).

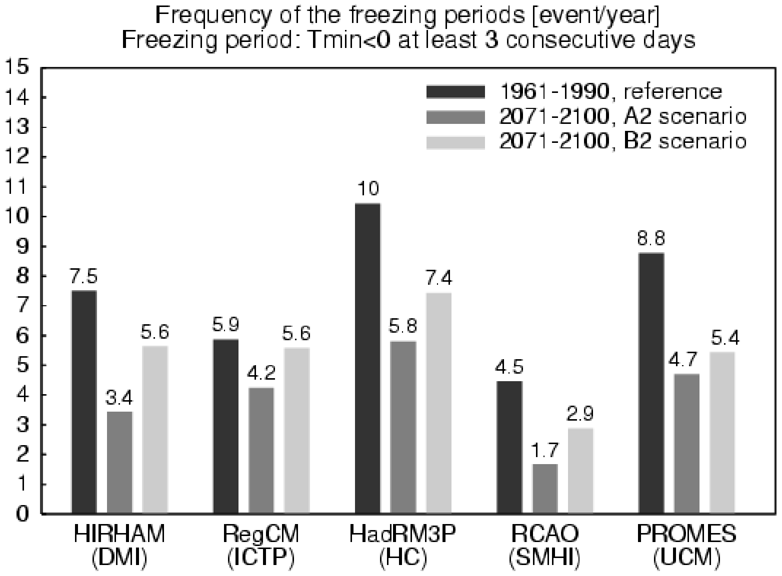


Fig. 7. Frequency of the freezing periods over Hungary. The groups of bars represent the different models, and the first bar within each group denotes the reference period, the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

It is worthwhile to pay special attention to the behavior of the PROMES model: its temperature simulation for the past seems to be the uniquely correct one compared to the observations in the case of warm values (remember the hot days), whereas in the cold range its performance is rather “ordinary” with some deficiency. Although in the case of persistence characteristics the observed values are not calculated and their occurrence is relatively rare over Hungary, it is rather clear, that less heat waves (and hot periods) are peculiar to the simulation of PROMES model for the past than it was projected by the other models, while the number of freezing periods is rather similar to the others. Another important feature is in that respect, that later (in the future) the model “compensates” its low level of the heat waves in the past: the simulated occurrence is almost the same as it is for the other models – it is not valid either for the hot (extremely hot and warm) days or the hot periods, however, the outstanding large magnitude of the changes leads to the conclusion, that the PROMES model projects much more heated climate conditions by the end of the 21st century than it was typical in the reference period.

Wind speed

The extreme characteristics' investigations for 10-meter wind speed take into account only the results of four regional climate models – the RegCM model is excluded due to the lack of wind data. Before the analyses of model results, maybe it is worthwhile to look at the spatial distribution of the relative frequency of mean wind speed exceeding given thresholds based on observational data (*Fig. 8*): the windiest parts of the country are in the elevated points of the North-Transdanubian regions (north from the Lake Balaton). Higher values occur also at the northwestern boundary of the country, and over the southeastern and northeastern part of the Great Hungarian Plain. (This spatial distribution can be explained by the topographical features of Hungary, namely that the typical northwesterly flow naturally enters the basin through the valley between the Alps and Carpathians, while the eastern part of the basin is under the influence of the mountainous flow blowing from the North Carpathian range.)

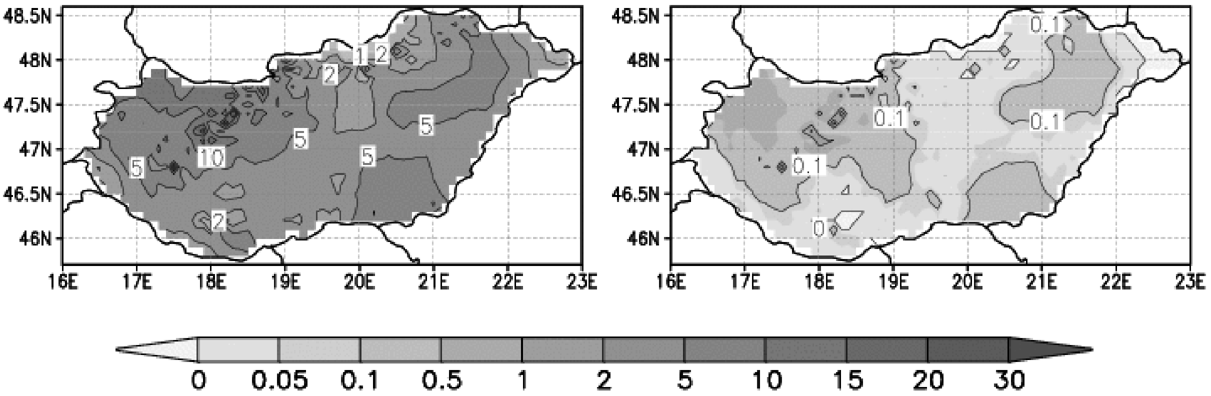


Fig. 8. Relative frequency (in %) of the observed daily mean 10-meter wind speed over Hungary exceeding different thresholds: 5 m/s on the left and 10 m/s on the right. The maps are generated on 0.1-degree horizontal resolution.

As far as the model simulations are concerned, firstly the tendencies for the entire country were examined for the relative frequency of such events, when the daily maximum of 10-meter wind speed exceeds given limit values. The range of investigated thresholds covers the interval between 0 and 20 m/s, however, in *Fig. 9* only the results of 5, 7, 10, and 14 m/s are presented, respectively. It is hard to conclude any significant tendency in the case of the lower daily wind maxima, while in the case of the higher ones, the trends are a bit more easily interpretable (as it is also clearly quantified in *Table 3* for the simulations driven by the A2 SRES scenario). Particularly, for the threshold of 5 m/s the relative changes projected by individual models are very small positive ones (except the HIRHAM model): the mean of the models' ensemble is 0.8%; while the standard deviation between the signals is too large (3.3%) compared to the mean change. On the contrary, the frequency of the daily wind maxima exceeding the threshold of 10 m/s indicates an increase with generally larger magnitude (16.7% in average) accompanied with a standard deviation (11.3%) remaining under the signal of the relative change. All this just means that the increase of the stronger wind events is rather significant with respect to the uncertain "situation" for the lower thresholds.

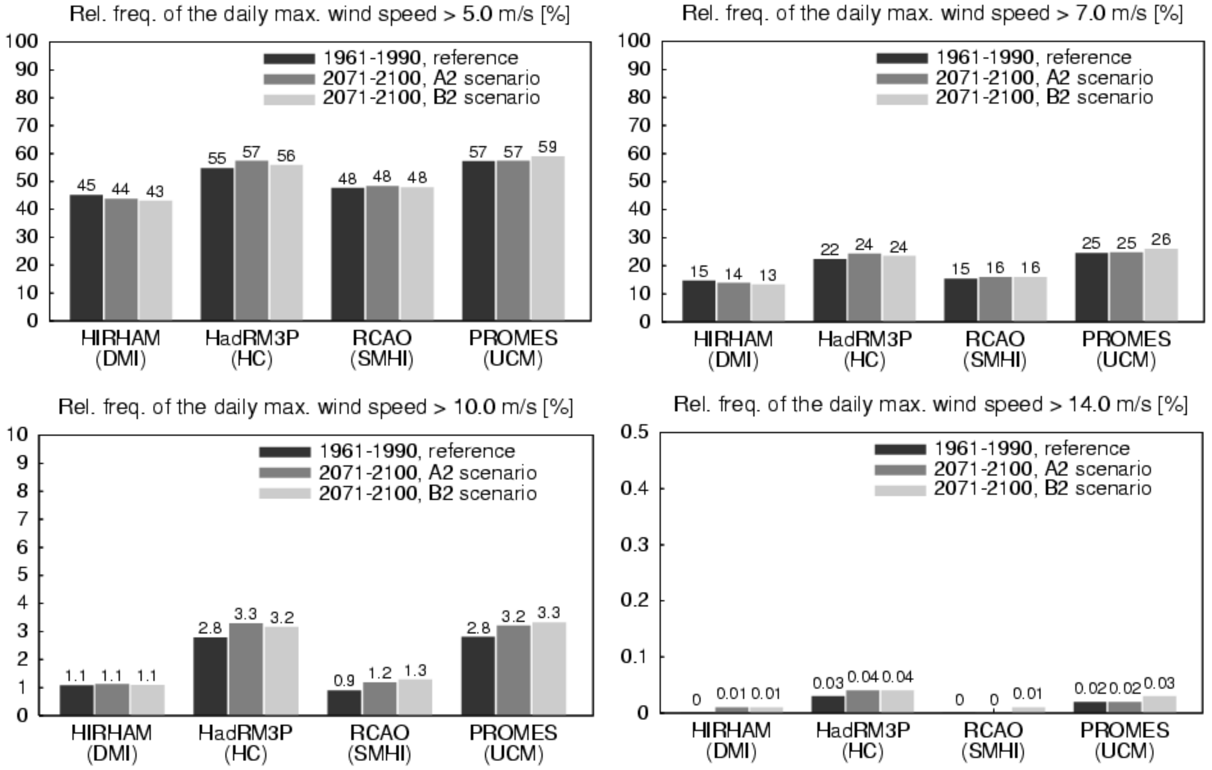


Fig. 9. Relative frequency of the simulated daily maximum 10-meter wind speed over Hungary exceeding different thresholds. The groups of bars represent the different models, and the first bar within each group denotes the reference period, the last two ones refer to the period of 2071–2100 with the use of different SRES scenarios (A2 and B2, respectively).

The separate examination of the results over different geographical regions provides further valuable insight into the future wind patterns. According to the quantitative results for the threshold of 10 m/s (*Table 4*), it can be generally pinpointed, that the more pronounced (and uniformly positive) changes are found over the least windy parts of the country, namely over the northeastern and southwestern regions, where also the standard deviations between the model results are the most "acceptable" (for the northwestern and southeastern parts of Hungary the standard deviations are too large with respect to the magnitude of the signal). This argumentation is not only valid for the ensemble mean, but also for the individual model results with the only exception for the RCAO model (which produces the strongest change besides the northeastern region also at the southeastern one). Furthermore, it is noteworthy, that the HIRHAM model simulates systematically the lowest degree of change for almost every sub-area (the only exception is the northeastern sub-domain).

Table 4. The changes (in %) of the frequency of the event, that the daily maximum of 10-meter wind speed exceeds 10 m/s, for the period of 2071–2100 with respect to the period of 1961–1990 over different regions (NW: Northwestern, NE: Northeastern, SE: Southeastern, SW: Southwestern Hungary, and HU: entire Hungary) based on different model simulations. The values of "Mean"/"Std. dev." represent average/standard deviation of the changes (in %) computed from the results of the different models. All the numbers indicate the simulation results driven by A2 SRES scenario, except the last column, where the values in the brackets refer to the B2 SRES scenario

Model	**NW**	**NE**	**SE**	**SW**	**HU**
HIRHAM	3.5	29.6	–1.2	10.5	3.7 (0.9)
HadRM3P	27.4	30.4	11.4	32.2	17.9 (13.3)
RCAO	24.1	35.9	37.9	27.2	31.1 (42.2)
PROMES	11.8	17.0	12.6	20.6	14.2 (18.5)
Mean	16.7	28.2	15.2	22.6	16.7 (18.7)
Std. dev.	11.1	8.0	16.4	9.4	11.3 (17.3)

The results for the lower threshold values slightly differ from all this, particularly for the 5 m/s (not shown): the average signals have quite similar magnitudes for each region, they do not reach (except for the northeastern part of Hungary) the –1 or 1 percent, while the standard deviation between the simulated changes exceeds the degree of the change in every case. The HIRHAM model is again in noticeable contrast with its counterparts: it is the only model, which projects a decrease of the frequency of the event for each sub-area. This behavior of HIRHAM (i.e., non-significant decrease of the frequency of lower wind maxima and almost negligible increase of the frequency of higher maxima) might indicate that its simulated circulation and mean wind patterns are a bit different from those of the other models.

It is also interesting to see, that in contradiction of the results concluded at the temperature extremes, there are two models (both for lower and higher thresholds of daily maximum), which project larger changes for the more optimistic B2 scenario.

According to all this, it can be generally said, that any tendentious change is rather concluded in the case of higher wind speeds, and according to the results, for the higher thresholds some compensation can be expected between the presently windiest and the less windy parts of Hungary; nevertheless, it should not be forgotten, that these signals are very-very small ones and their significance are doubtful and arguable.

4. Summary, conclusions

In the last years several efforts were carried out world-wide in order to estimate the regional impacts of the global climate change, from which the PRUDENCE project (completed in 2004) provided the first comprehensive projections for the European region. At the Hungarian Meteorological Service the 50 km resolution results of five regional climate models used in the project were analyzed, and the tendencies of precipitation-, temperature-, and wind-related extreme parameters were intensively examined providing a good basis for the preparation of National Climate Strategy of Hungary, which is a guideline for the Hungarian policy makers to define the main track of the adaptation policy to the impacts of the climate change in Hungary. The projected changes of the extreme characteristics were investigated for the period of 2071–2100 with respect to the period of 1961–1990 focusing on the territory of Hungary. The choice of these simulations was mainly motivated by the fact, that these RCMs were driven with both of the SRES scenarios (A2 being a pessimistic one and B2 being an optimistic one). With this type of consideration of model outputs only a part of the uncertainties in the projection can be specified, namely the uncertainties due to the application of different regional climate models and different emission scenarios. However, it has to be underlined, that in the PRUDENCE project much more model simulations were accomplished, which were carried out on the one hand with the use of other RCMs and on the other hand with the use of further driving global models. Therefore, the real spectrum of the uncertainties is surely broader, which fact was also confirmed by recent studies (e.g., in *Déqué et al.,* 2007 it was showed that the variability introduced by the choice of the driving GCM has the largest contribution to the range of uncertainty).

According to the results detailed above it can be generally concluded, that in spite of the fact, that between the individual model simulations there are lots of differences over Hungary, the main tendencies of the future extreme features are characterized rather similarly.

In the case of precipitation it is emphasized, that for the end of the 21st century the reduction of the number of days with precipitation has to be considered, while at the same time the frequency of the days with heavy (and very heavy) precipitation will expectedly increase (and consequently, the number of days with light precipitation will be reduced). These conclusions are valid for both of the applied SRES scenarios with generally more considerable level of the change for the more pessimistic one, however in the case of heavy precipitation over 10 mm daily amount, the B2 scenario provides larger increase. Nevertheless, it has to be mentioned here, that these changes have very small magnitude, therefore, the results have to be taken into account with careful consideration. It would be also useful to examine the seasonal distribution: e.g., in *Pongrácz et al.* (2008) it was concluded, that the precipitation events become more frequent in winter and more seldom in summer over the Carpathian Basin (based on the results of ETH's (Swiss Federal Institute of Technology) CHRM model, which model's results were not the subject of our study), but what is even more interesting, that the occurrence of extreme precipitation days will be intensified in winter and reduced in summer.

Regarding the temperature extremes, the model results render the increase not only for the individual warm extremes (warm, summer, and hot days), but also the heat waves and hot periods will occur more often. As further consequence of the regional climate change over Hungary, the frequency of frost days and freezing periods will be expectedly reduced. All this (i.e., the decrease of cold and increase of warm extremes) fits well to our view about the mean warming tendencies over Hungary. Additionally, it should be noticed, that compared to the other investigated parameters these temperature signals are quite sharp and convincing ones, it is especially valid for the cold temperature extremes. On the other hand, with regard the persistence characteristics further analyses would be desired, because on the basis of these results there is no information about the tendencies of the duration of heat waves, hot and freezing periods. For instance, since the three as well as the more than three consecutive days exceeding given threshold are considered with equal weight in the present analyses, the future situation with more and longer warm periods can be imagined with the same probability as the situation with more but shorter ones.

As far as the wind events are concerned, no significant changes could be detected in the range of lower and "ordinary" wind speed values, the occurrence of intensive and stormy winds will likely increase, however, the projected change has very small magnitude. An interesting issue is, that while for the temperature extremes the more pessimistic A2 scenario provides more dramatic signals uniformly for every model, in the case of wind, there are several models, where the optimistic B2 one simulates slightly more pronounced changes. Regarding the wind-related investigations it has to be mentioned, that the daily maximum wind speed is not the most appropriate indicator for the extreme storm events. In the background of this fact is, that in the case of the chosen RCMs, this variable was calculated purely based on the 10-meter wind speed without application of any gust parameterization, and this empirical formulation led to the under-representation of strong wind events in the simulations (further details are provided in *Rockel* and *Woth*, 2007).

It has to be mentioned, that the accomplished analyses were based on simple examinations, where it was checked, whether different fixed thresholds for given parameters were exceeded or not. Nevertheless, it is evidenced, that this fixed threshold approach is not satisfactory at every case, e.g., there are regions (gridpoints) and seasons, where and when the given thresholds are not considered as extremes, but "usual" values. For that reason it is planned to continue the analyses on the basis of the percentile approach with the further extensions for seasonal investigations and for several new extreme indices. Finally, as it was indicated by the results, in the case of certain extreme parameters not only the signals are modest, but also the absolute occurrence of the event. The question is naturally arising, whether these changes are statistically significant or not. The follow-on of the recent work aims to investigate the statistical significance of the obtained results in order to be in the position to have more solid conclusions regarding the future change of the extreme characteristics over Hungary.

The valuable outcomes of PRUDENCE project provide the first regional projections for Europe (for two emission scenarios); PRUDENCE was followed by the ENSEMBLES project, in which the main focus is on the pervasive quantification of the uncertainties originating from different sources in the regional climate simulations. Nevertheless, it is underlined, that these results do not substitute the further application of finer resolution climate simulations and analyses. These investigations are already ongoing in Hungary at the Hungarian Meteorological Service and Eötvös Loránd University with the use of adapted high-resolution regional climate models. Several simulations of four regional climate models (ALADIN-Climate, REMO, PRECIS, and RegCM) are already accomplished or planned to be carried out for the Carpathian Basin on high (25 and 10 km) resolution taking into account different emission scenarios (besides the widely used and rather realistic A1B also the A2 one) and lateral boundary conditions in order to compose a small ensemble, which will serve as a great opportunity to explore the certainties and uncertainties in the model results focusing over our area of interest.

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