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Special Issue: Quantitative climate change information for adaptation to the impacts

Guest Editors: **Gabriella Szépszó**

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Editorial

Special Issue: Quantitative climate change information for adaptation to the impacts

Climate change is a reality, therefore, the regional and local adaptation to its impacts is a priority task with special focus on vulnerable sectors and areas. For targeted and sustainable adaptation strategies, detailed quantitative climate change information is of key essence.

In the last few years, efforts have been started to provide a consistent, objective basis for climate impact assessments in Hungary. The implementation of the *Adaptation to Climate Change in Hungary* Programme funded by the European Economic Area (EEA) Grant FM 2009–2014 began in 2013, and was concentrating on three areas:

1. Development of a National Adaptation Geo-information System (NAGiS) to support strategic planning and decision making related to the adaptation to climate change in Hungary;
2. Local climate change adaptation capacity building;
3. Pilot projects on climate change adaptation measures at local and regional level.

The most essential input of NAGiS is served by the climate data. On the basis of meteorological observations and climate model projections for the future, quantitative impact studies have been carried out in different sectors (hydrology, agriculture, tourism, critical infrastructure, etc.). The programme put special emphasis for using uncertainty information in the investigations and to communicate the uncertainties towards decision makers.

The EEA Grant encourages and supports the establishment of national, bilateral partnerships and international co-operations, especially with the donor countries. A networking workshop on climate change was organized at the headquarters of the Hungarian Meteorological Service in Budapest, June 6 – 8, 2016, with around 60 participants mostly from Central and Eastern Europe and from Norway. Scientific topics of the conference covered the monitoring and assessment of climate change, the adaptation to the climate change impacts, the education and trainings for the users and decision makers. The presentations are available at the event home page: ccworkshop.met.hu.

The European Union's *Copernicus Climate Change Service* (C3S) was also represented at the workshop. The main objective of the Copernicus programme is the monitoring the Earth system with collecting in-situ and dedicated satellite observational data (the Sentinel family) as well as contributing missions, together with developing related environmental services. One of the six thematic streams of the Copernicus Core Services is dedicated to climate change. This Service is operated by the European Centre for Medium-Range Forecasts (ECMWF) on behalf of the European Commission. Past and present climate conditions are assessed by monitoring a number of Essential Climate Variables (ECVs), using atmospheric, surface, and ocean measurements, as well as re-analyses. Access to information about the near- and long-term future of the climate over Europe and worldwide is provided via multi-model seasonal forecast products and decadal-to-centennial climate projections. This publicly accessible meteorological information system is supporting the climate change adaptation in different economic sectors (e.g., energy, agriculture, water management) at European level. The global and pan-European information provided by C3S can also be used as inputs to regional and national climate change adaptation efforts.

Attendance of Copernicus representatives significantly helped to promote how Europe in general prepares for future changes in climate, and how the approach can be applied for a smaller region. The workshop provided room to build multi-lateral partnerships with attendants from Austria, the Czech Republic, Hungary, Norway, Slovakia, Slovenia, and Ukraine. As outcome of the event, several co-operations were established. A project entitled *Copernicus Climate Change Service based on Surface in-situ Observations* is already ongoing with involvement of (among others) the Hungarian and the Norwegian meteorological services. Furthermore, the Hungarian Meteorological Service contributes with regional climate model data to the national project on *Interdisciplinary Research Group for Promoting Climate-Smart and Sustainable Agriculture* led by the Centre for Agricultural Research of the Hungarian Academy of Sciences.

The current Special Issue presents some key topics of the workshop. A review is given about the observations used in the most recent ECMWF re-analysis, ERA5, which describes the past and present state of the Earth system, with quantified information about uncertainty of this estimation. Moving towards local scales, a detailed overview of NAGiS is followed by three scientific articles introducing climate impact and vulnerability studies on drinking water, natural landscapes, and adaptive capacity of natural habitats in Hungary. Climate change effects do not stop at the country borders: besides hydrological impacts on the upper part of River Tisza, we can have an outlook to the conditions of forest fires in Ukraine. Last but not least, the contributions of all the authors and co-authors are highly appreciated as well as the efforts of the reviewers to improve the manuscripts.

Gabriella Szépszó	Judit Bálint	Jean-Noël Thépaut
guest editor Hungarian Meteorological Service	programme manager of the Adaptation of Climate Change Programme	head of the Copernicus Climate Change Service

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Some aspects on the use and impact of observations in the ERA5 Copernicus Climate Change Service reanalysis

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Abstract—The latest reanalysis at the European Centre for Medium-Range Weather Forecasts is the ERA5 system, which is produced in the framework of the European Union's Copernicus Climate Change Service. ERA5 is primarily going to cover the satellite era, i.e. 1979 to near real-time and will be publicly available for the users during 2018. The present article provides information about the observation usage of ERA5 together with an impact assessment of the assimilated data. Though all this is based on some test (scout) ERA5 experiments, however, they are providing a good overview of the evolution of the Global Observing System. The impact assessment is based on the Degree of Freedom to Signal adjoint diagnostic tool. There is a continuous data amount increase from the beginning of the ERA5 period, which is reaching more than 30 times of the assimilated data amount today than that of the 1979s. The data increase is mostly attributed to the satellite measurements, particularly lately to the hyper-spectral infrared observations. Though at every period the satellite data amounts are larger than that of the conventional observations, their impact is not getting larger until the late 1980s. At the same time the per observation impact of the conventional observations always remain larger than the satellite ones, which means that the conventional observations, though small in quantity, still remain essential ingredients of the Global Observing System.

Key-words: ERA5 reanalysis, Copernicus Climate Change Service (C3S), Degree of Freedom to Signal (DFS), Observation Influence (OI), conventional and satellite observations

1. Introduction

Copernicus is a European Union (EU) flagship programme, which focuses on Earth observations from satellites and additionally provides various related environmental services to the European citizens. One of such services is the Copernicus Climate Change Service (C3S), which is coordinated by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Union. C3S consists of various aspects of the climate as climate observations, reanalysis, seasonal predictions, and climate projections. All the related datasets are going to be organized into the Climate Data Store (CDS), which will be publicly accessible.

One of the elements of the CDS, which is directly produced by ECMWF is the reanalysis, which is called ERA5 referring to the fact that it is the 5th generation ECMWF reanalysis (*Hersbach* and *Dee*, 2016). This name also highlights the fact that ECMWF has a long experience dealing with reanalysis, and ERA5 is heavily building on that. In the past, ECMWF produced the ERA-15 (*Gibson et al*., 1997), then ERA40 (*Uppala et al*., 2005), and afterwards the ERA-Interim (*Dee et al*., 2011) reanalyses. ERA5 is relying on all the reanalysis experiences gathered in the last few decades and will surpass ERA-Interim in the very near future. In principle, reanalysis should be done in one go from the beginning to the end of the covered time period. However, in practise, the reanalysis production is split into parallel streams running simultaneously in order to have a timely production. This is a practical necessity, which is facilitated with the use of 1-year spin-up periods at the beginning of each production streams. These spin-up years permit the proper warm up of the data assimilation system and ensures smooth transition between the consecutive streams. Typically these streams for ERA5 cover 5-10 years periods. The entire ERA5 dataset from 1979 to real-time will be available to the users during 2018.

Reanalysis is a relatively modern field of Numerical Weather Prediction (NWP), where the past climate system is described with a state-of-the-art NWP data assimilation system and model using all available observations from the examined period. These observations are the ones, which were already routinely used in numerical modeling, but also ones which are reprocessed since then. A reanalysis system provides consistent and coherent global description of the atmosphere, which is very valuable to various user communities interested in the precise description of the past climate.

Since the aim of this paper is not to describe the ERA5 system in details, hereafter we are only going to provide some details of the main differences (improvements) of ERA5 with respect to its predecessor ERA-Interim. Both reanalyses are covering the so called satellite era (from 1979 onwards), where the satellite observations are dominating as compared to the conventional ones. Though it is noted here that the plan is to extend ERA5 backwards until the 1950s. ERA5 is using a very new assimilation and modeling system of the ECMWF's

Integrated Forecasting System (IFS), since it is using the state-of-the-art version (as it is in 2016), which is around 10 years younger than it is the case for ERA-Interim. Therefore, ERA5 includes 10 years of new NWP developments, which are not available in ERA-Interim (for instance at the time of ERA-Interim, various satellite observations like for instance IASI was not available, and consequently the code was not prepared for its use, and therefore the data was not assimilated). Naturally, the horizontal and vertical resolutions are increased in ERA5 as opposed to ERA-Interim: 32 km and 137 levels compared to 79 km and 60 levels, respectively. New feature of ERA5 is the use of the Ensemble of Data Assimilations (EDA, *Bonavita et al*., 2012) system essentially for the computation of the flow-dependent background error co-variances for the ERA5 data assimilation system. Additionally, EDA can be used to provide uncertainty estimates to the final reanalysis products. This EDA-based uncertainty estimation will be part of the publicly available dataset in the Climate Data Store. EDA is based on a 10-member ensemble with 64 km horizontal resolution. The output frequency of ERA5 is also improved with hourly outputs provided for the users. Beside all these differences, ERA5 is assimilating significantly more data than ERA-Interim thanks to the wide variety of newly reprocessed datasets. All these improvements give a good platform to ERA5 to have superior reanalysis quality than it is the case for ERA-Interim.

It is very important to underline that the experiments used in this study are not the final ERA5 production suites, but tests experiments, which were mainly used to understand the behavior of the Global Observing System (GOS) as it is to be used for ERA5. Particularly, these test (so called “scout”) experiments have reduced horizontal resolution (~64 km), and they are using static background errors. This latter means that climatological background errors were used instead of the information from EDA. Therefore, the information given hereafter is in a very good approximation valid also for ERA5, but it is not exactly the same.

In this article, we are going to give a snapshot of the main aspects of the observation usage in ERA5. Additionally, some information is going to be provided on the impact of observations using an adjoint data assimilation diagnostics tool. In the next chapter, we briefly introduce the methodology applied particularly the main elements of the impact assessment. Section 3 deals with the evolution of the Global Observing System for ERA5 and discusses the impact of the various observations. Finally Section 4 provides summary and conclusions.

2. Impact assessment methodology

There are various ways to assess observation impacts in a data assimilation system. The most widely used method is Observing System Experiments (OSEs), where data assimilation (and ensuing weather forecasts) is run with and without the investigated observations and the observation, impact is deduced based on the performance differences between the two systems (*Kelly* and *Thépaut*, 2007). OSEs can provide impact of given sets of observations to any forecast metric. In the last few decades, adjoint diagnostic tools were developed in order to get a general assessment of the impact of assimilated observations. These tools are able to provide the impact of any observations used in the assimilation system to one specified forecast performance aspect. This forecast performance aspect is typically the reduction of the forecast error, which is attributed to the assimilated observations. Typically there are two such adjoint diagnostics tools (*Cardinali*, 2013): Degree of Freedom to Signal (*DFS*, *Cardinali et al.*, 2004) or Forecast Sensitivity to Observation Impact (*FSOI*, *Cardinali,* 2009). In this study the DFS tool will be used, which is briefly explained hereafter.

As mentioned above, the main question is how the observations can contribute to the decrease of forecast errors. For this, first a forecast error measure has to be defined, which is denoted by J_e. In the ECMWF system, the dry energy norm is used to provide a unique metric (norm) to the different components of the model state variables. The impact of observations on the forecast error can be described as

$$\frac{\partial J_e}{\partial y} = \frac{\partial x_a}{\partial y}\frac{\partial J_e}{\partial x_a}, \tag{1}$$

where y refers to the observations and x_a to the analysis.

The second term in the right hand side is the forecast error sensitivity to the analysis (*Rabier et al.*, 1996), which can be projected to the observations as Forecast Sensitivity Observation Impact (*FSOI*; *Cardinali*, 2009). The first term is the Degree of Freedom to Signal (*DFS*, *Cardinali et al.,* 2004) or Observation Influence (*OI*, which is the *DFS* per datum, i.e., *DFS/n*, where *n* denotes the number of observations for a given observation type), and it can be written using classical data assimilation notations (*Ide et al.*, 1997) as

$$DFS = Tr\left[\frac{\partial H x_a}{\partial y}\right] = Tr\left[K^T H^T\right] = Tr\left[HK\right], \tag{2}$$

where K is the Kalman gain, which is

$$K = (B^{-1} + H^T R^{-1} H)^{-1} H^T R^{-1}, \tag{3}$$

R is the observation error covariance matrix, B is the background error covariance matrix, and H is the observation operator.

It is important to mention that the Observation Influence is complementary to the Background Influence, since it is related to the weight (impact) of observations in the analysis. Hereafter the *DFS* and *OI* results will be presented in the ERA5 reanalysis context. It should be stressed that the impact of observations is not absolute, since it depends on the entire assimilation and modeling system and also on the use of other observations. *DFS* (*OI*) provides information about the influence of the observation in the analysis and not about the fact that this influence is positive or negative. It is strictly speaking true although experiments show that the *DFS* and *FSOI* fractional impacts are generally similar (*Cardinali*, 2013), pointing to the fact that the direction of the impact can be also anticipated.

3. Observations in the ERA5 reanalysis

Prior to the reanalysis production, intensive experimentations are performed in order to make sure that all the expected observations are assimilated, and the reanalysis quality is superior to that of the previous reanalyses. For the case of the Copernicus/C3S/ERA5, the benchmark (reference) reanalysis is ERA-Interim (*Dee et al.,* 2011), and indeed in most aspects ERA5 has a better performance than that of ERA-Interim. One essential way of the abovementioned testing is the preparation and exploitation of "scout runs", which are simplified versions of the final reanalysis. The main simplifications are the lower horizontal resolution and the use of climatological background errors (instead of EDA). This reanalysis test is capable to assess all the observations to be used in the reanalysis production and spot any observation-related problems prior to the more sophisticated and expensive reanalysis production. In this article, we are going to highlight some of the aspects of observations usage in ERA5 using the results of these scout runs. It is believed that this gives a very good idea about the observations assimilated in ERA5, though it is certainly not exactly the same. Additionally, some impact results will be shown using the Degree of Freedom to Signal (*DFS*) diagnostics (*Cardinali et al*., 2004), which provides information on the impact of observations in the analysis (see details in the previous section). Hereafter some snapshots of the Global Observing System were taken at the beginning of each planned ERA5 production streams. These years are 1979, 1989, 1999, 2009, and 2015, respectively.

3.1. Evolution of the observing system in ERA5

First, the temporal evolution of the global observing system as used in ERA5 will be demonstrated. It is no surprise that there is a continuous increase in data amounts from 1979 onwards. *Fig. 1* shows the 6 months data amounts of the representative ERA5 years. Steady and massive increase can be seen particularly from the beginning of the 21st century onwards. This is due to the rapid increase of satellite observations. In 2015, there are more than 30 times more data assimilated than in 1979.

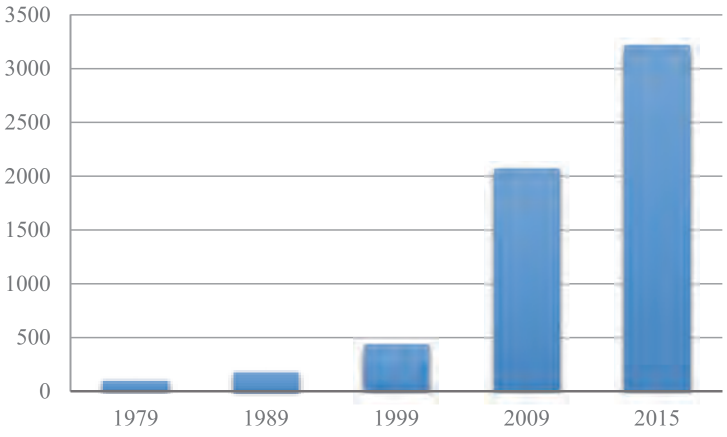

Fig. 1. 6 months of assimilated observation amounts (in million) for the representative ERA5 years.

Fig. 2 shows the absolute amount of conventional and satellite observations. This figure confirms that ERA5 is indeed focusing on the satellite era, i.e., the satellite observation amounts are always larger than that of the conventional ones although the relative amounts are very much different at the beginning and at the end of the reanalysis time window. In 1979, the satellite observations are 65% of the total data amount, while for 2015 it is 90% (though lately there is a sharp increase in conventional data amounts too).

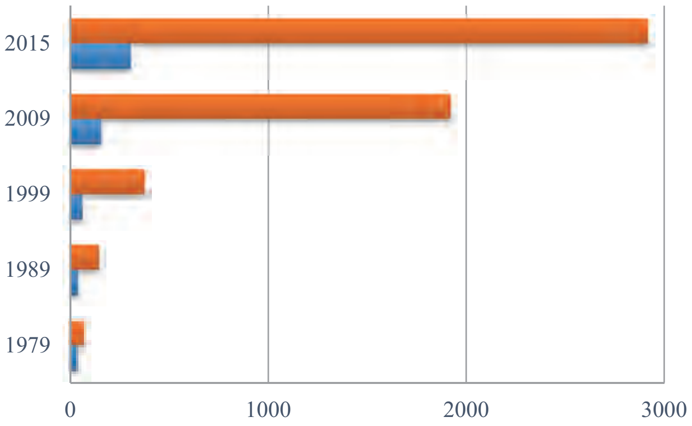

Fig. 2. The absolute amount (in million) of conventional (blue) and satellite (orange) observations in the representative ERA5 streams.

Fig. 3 shows more details of the satellite observations assimilated. It can be seen that the main reason for the huge increase of satellite data is the appearance of infrared radiances, particularly the hyper-spectral data. This covers more than 50% of the total observation amount in the modern Global Observing System. Microwave radiances are the first major satellite data sources, and they are dominating in data amounts until the beginning of the 21st century. SATOB and scatterometer wind data became also essential, particularly due to the fact that with the increase of the satellite data, mostly temperature-related measurements have been added, and the value of the wind observations is getting increased (*Horányi et al*., 2015). Additionally, there is increased amount of ozone observations (which are strongly enhanced with respect to ERA-Interim). From mid-2000s, the GNSS-RO observations are assimilated, and they are essential due to the fact that they are bias free observations, which can be used (beside radiosondes) for anchoring other satellite data (i.e., to be used for satellite bias correction).

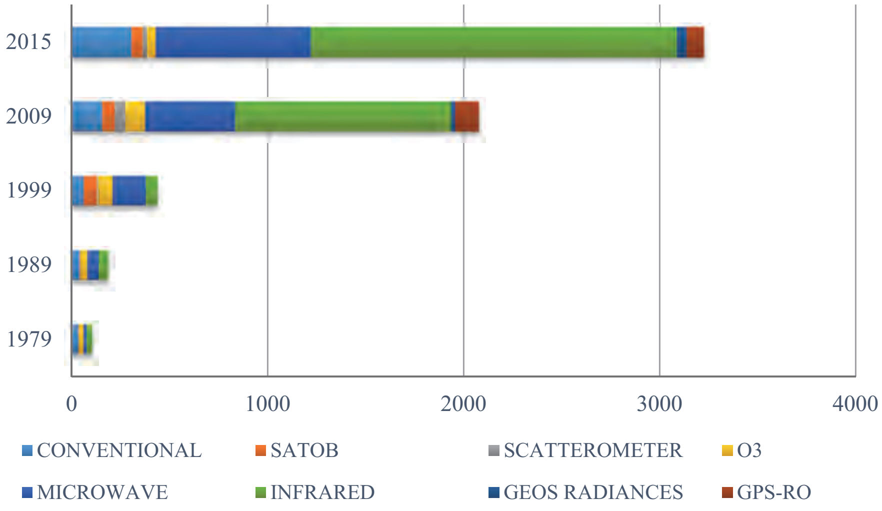

Fig. 3. 6 months observation amounts (in million) for the different observation categories (light blue: conventional, orange: SATOB satellite atmospheric motion vectors, grey: scatterometer winds, yellow: ozone, darker blue: microwave radiances, green: infrared radiances, dark blue: geostationary radiances and brown: GNSS-RO).

Regarding the conventional observations (*Fig. 4*), they are still essential (see some results described in the next section), in spite of their decreasing relative amount compared to satellite data. At the beginning of the time window the radiosondes were dominating, while today the aircraft data are the most dominant conventional data sources. The SYNOP surface observations are relatively unchanged, and the (wind) profilers are getting more in numbers from the 2000s onwards (when the PILOT data is decreasing).

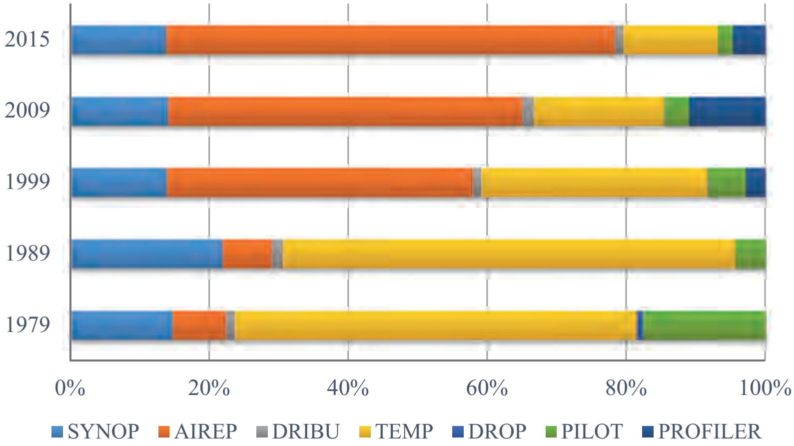

Fig. 4. The relative amounts of the main conventional data sources for the various ERA5 streams (light blue: surface, orange: aircraft, grey: buoy, yellow: radiosonde, darker blue: dropsonde, green: PILOT wind and dark blue: wind profiler observations).

3.2. Observation impact

As described in the methodology section, the DFS (OI) diagnostics can give information about the impact of observations in the analysis. Certainly, there are limitations attributed to this tool (*Cardinali*, 2013), nevertheless it provides a valuable insight on the (relative) merits of the various observations. Hereafter the observation impacts will be assessed for the five selected periods. The figures show fractional observation amounts (in %), DFS (in %), and also OI values. The latter measure provides information on the per observation impact of the given observation type.

1979 suite (*Fig. 5*): It was already mentioned that the fractional observation amount is 65%-–35% in favor of the satellite data. On the other hand, the fractional DFS is 25%-–75% (having larger contribution by the conventional observations). This shows that overall, in spite of the larger satellite observation quantity, the total impact is larger for the conventional data. It is particularly clear for the radiosondes, but also for the other conventional observations, i.e., the DFS proportions are larger than that of the observation amount. It is especially striking in the OI values (right panel), where the per observation impact (the impact of one piece of observation) is significantly larger for every conventional data. It is remarkable that the largest OI is for the buoy observations, which indicates that although they are very small in numbers, but very large in impact (*Horányi et al.*, 2017).

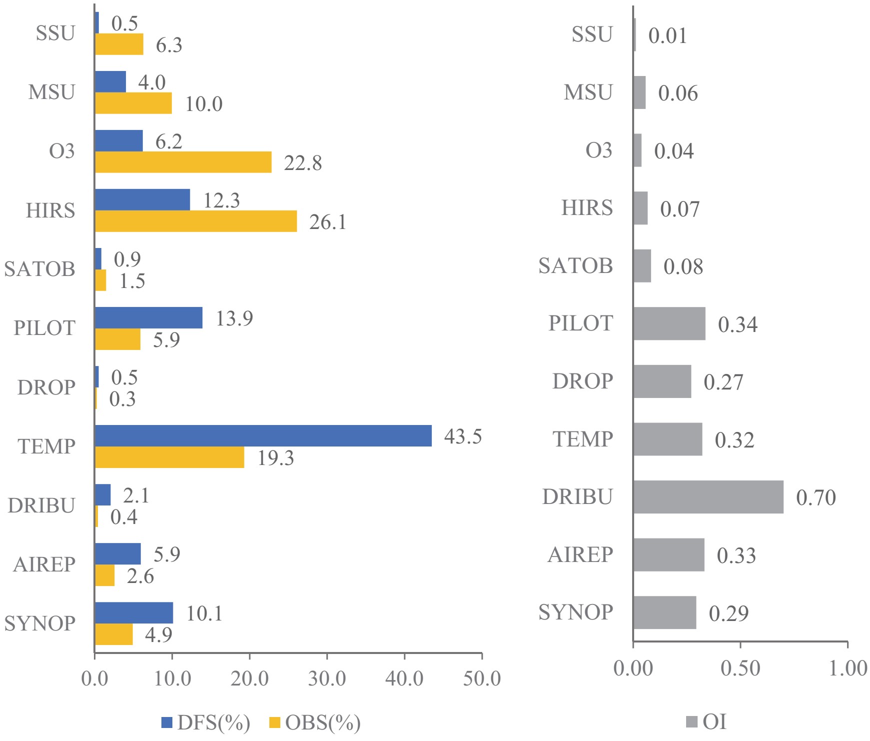

Fig. 5. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 1979. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), satellite atmospheric motion vectors (SATOB), High-resolution Infrared Sounder (HIRS), ozone (O3), Microwave Sounding Unit (MSU) and Stratospheric Sounding Unit (SSU).

1989 suite (*Fig. 6*): The relative satellite observation amount in this period grows to 78%. The respective relative DFS is 60%, i.e., the impact of satellite observations overall is larger than that of the conventional data. This is as expected with the increased amount of satellite data. The discrepancy between the observation amount and DFS is much smaller in this period compared to 1979. Moreover, now the largest impact is for the HIRS data (and its DFS percentage is larger than its fractional observation amount). The OI (per observation impact) values had been dramatically increased for the satellite observations (particularly MSU and HIRS), but they are still smaller than the ones for the conventional observations. There are several factors, which might contribute to the OI increase of MSU and HIRS, for instance, improvements in satellite instrument technology or changes in the GOS, like the rapid increase of satellite data amounts. The total radiosonde impact is just slightly smaller than the HIRS impact.

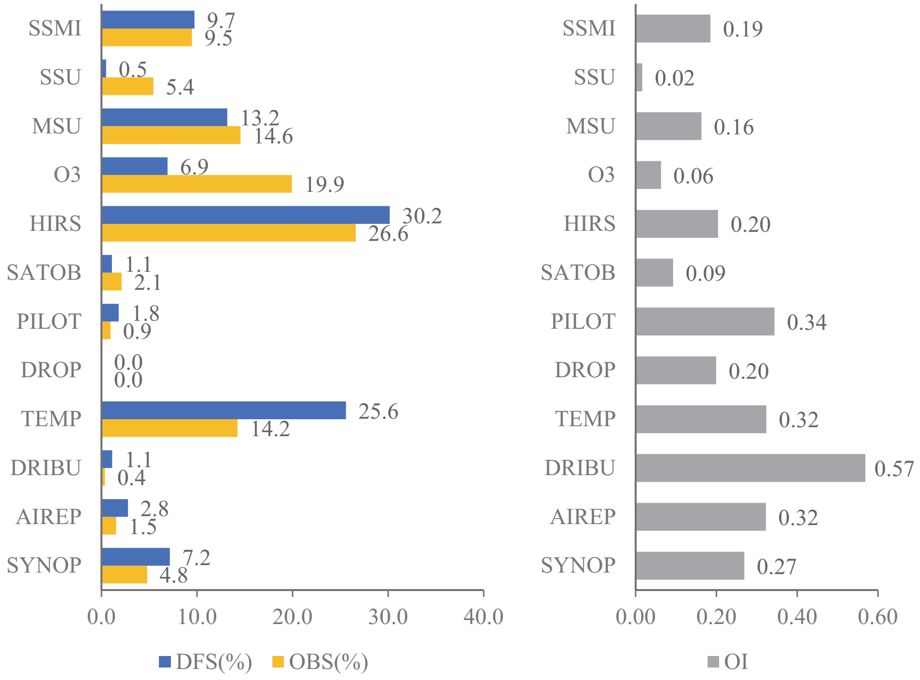

Fig. 6. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 1989. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), satellite atmospheric motion vectors (SATOB), High-resolution Infrared Sounder (HIRS), ozone (O3), Microwave Sounding Unit (MSU), Stratospheric Sounding Unit (SSU) and Special Sensor Microwave Imager (SSMI).

1999 suite (*Fig. 7*): For this period, the satellite observations provide around 85% of the total assimilated data. The impact of the satellite data increased further to 72%. Therefore, from this period onwards, the satellite observations are dominating not only in quantity, but in impact too. The most influential satellite observations are AMSU-A followed by SSMI, HIRS, and SATOB. Among the conventional observations, the aircraft data are getting equally important than that of the radiosondes (the aircraft data amount is larger than the data count for radiosonde observations). Regarding the per observation impact, it is rather similar to the previous period: the conventional observations are much more influential (though the satellites are not that dramatically far behind), and the buoys are the most important observing system in terms of value per observation.

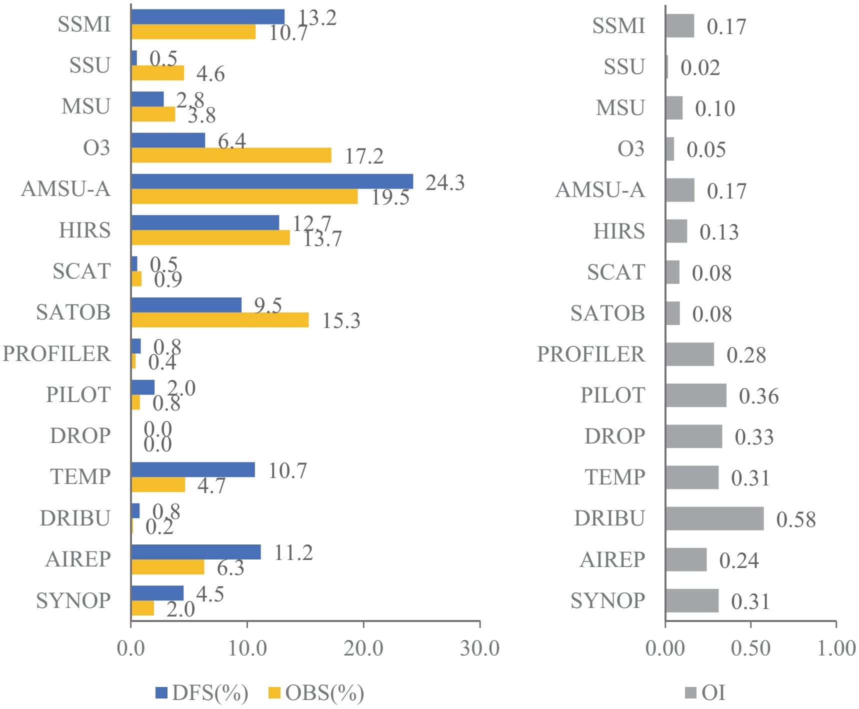

Fig. 7. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 1999. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), wind profilers (PROFILER), satellite atmospheric motion vectors (SATOB), scatterometer winds (SCAT), High-resolution Infrared Sounder (HIRS), Advanced Microwave Sounding Unit (AMSU-A), ozone (O3), Microwave Sounding Unit (MSU), Stratospheric Sounding Unit (SSU) and Special Sensor Microwave Imager (SSMI).

2009 suite (*Fig. 8*): The relative amount of satellite data reaches its present state with around 90%. This is corresponding to 80% of impact, suggesting that still the conventional observations have significantly larger relative impact than their quantity would suggest. The largest satellite impact contributors are AMSU-A, AIRS, IASI, and GNSS-RO, respectively. It shows the emerging of the hyper-spectral infrared instruments and the important introduction of GNSS-RO measurements. In the conventional observations, now the aircraft data have the largest impact surpassing radiosondes. It is worth mentioning that the use of all-sky technology (*Bauer et al*, 2010; *Geer et al*., 2010) for the satellite data improves their impact in the analysis, indicating that improved data assimilation methods can result in better data usage and larger observation impact.

2015 suite (*Fig. 9*): The main change with respect to the previous period is that the largest overall impact is coming from the IASI data, which is not surprising, since they contain around 37% of the total data. Overall, the infrared instruments provide around 40% impact (the other two largest contributions are AIRS and CRIS). Microwave (particularly AMSU-A) are still essential as the conventional observations too. For the conventional data, the influence of SYNOP observations is matching the ones for radiosondes. The Observation Influence (OI) is more homogeneous, though the conventional data are still clearly standing out.

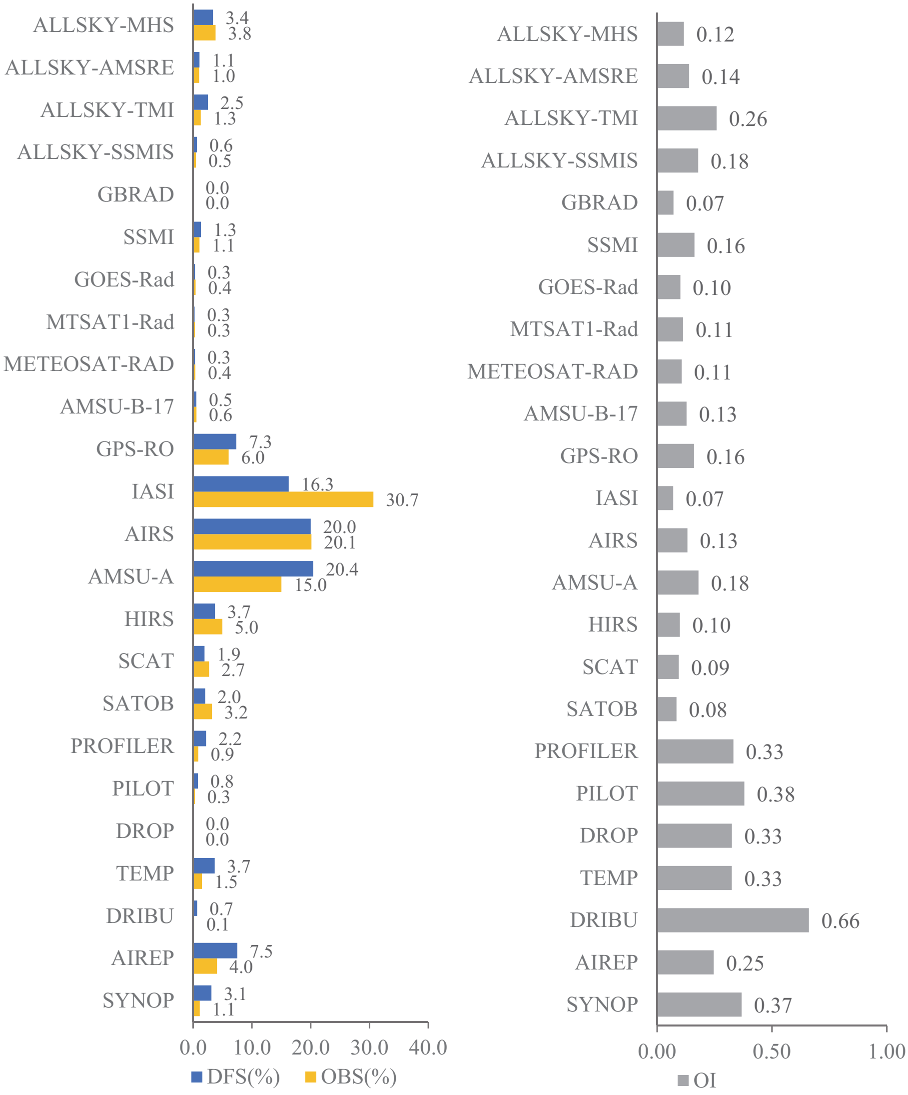

Fig. 8. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 2009. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), wind profilers (PROFILER), satellite atmospheric motion vectors (SATOB), scatterometer winds (SCAT), High-resolution Infrared Sounder (HIRS), Advanced Microwave Sounding Unit-A (AMSU-A), Atmospheric Infrared Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), GNSS-RO (GPS-RO), Advanced Microwave Sounding Unit-B (AMSU-B-17), METEOSAT geostationary radiances (METEOSAT-RAD), MTSAT1 geostationary radiances (MTSAT1-Rad), GOES geostationary radiances (GOES-Rad), Special Sensor Microwave Imager (SSMI), ground based radar (GBRAD), Special Sensor Microwave Imager/Sounder (ALLSKY-SSMIS), TRMM Microwave Imager (ALLSKY-TMI), Advanced Microwave Scanning Radiometer (ALLSKY-AMSRE) and Microwave Humidity Sounder (ALLSKY-MHS).

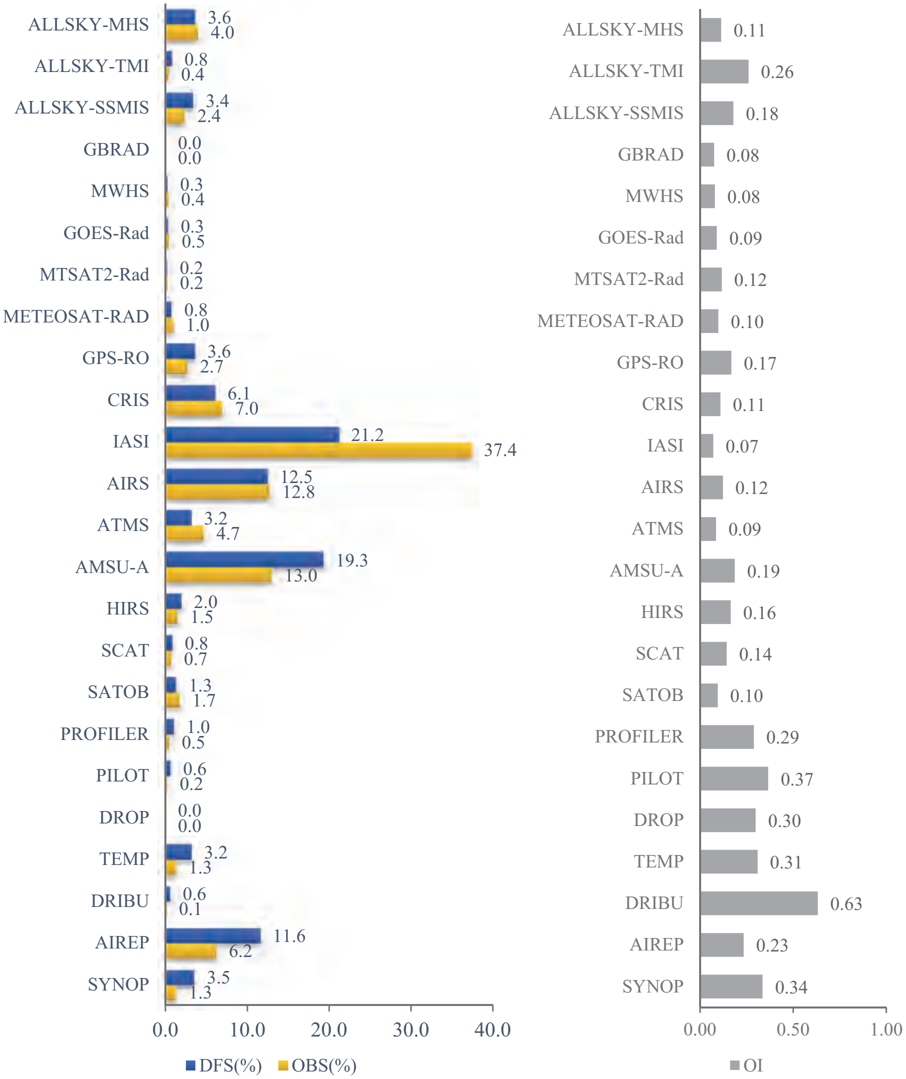

Fig. 9. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 2015. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), wind profilers (PROFILER), satellite atmospheric motion vectors (SATOB), scatterometer winds (SCAT), High-resolution Infrared Sounder (HIRS), Advanced Microwave Sounding Unit-A (AMSU-A), Advanced Technology Microwave Sounder (ATMS), Atmospheric Infrared Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), Cross-track Infrared Sounder (CRIS), GNSS-RO (GPS-RO), METEOSAT geostationary radiances (METEOSAT-RAD), MTSAT2 geostationary radiances (MTSAT2-Rad), GOES geostationary radiances (GOES-Rad), Microwave Humidity Sensor (MWHS), ground based radar (GBRAD), Special Sensor Microwave Imager/Sounder (ALLSKY-SSMIS), TRMM Microwave Imager (ALLSKY-TMI) and Microwave Humidity Sounder (ALLSKY-MHS).

4. Summary and conclusions

ERA5 is prepared under the umbrella of the Copernicus Climate Change Service of the European Union. ERA5 is the 5th generation atmospheric reanalysis at ECMWF, which has important additional features with respect to its predecessor ERA-Interim. The final ERA5 product will have significantly higher horizontal and vertical resolution, and the assimilation system will include cca. 10 years of Numerical Weather Prediction (NWP) development work. The background error co-variances will be based on a 10-member EDA system, which is also going to be used to provide uncertainty estimations to the reanalysis product. Such a modern, high resolution reanalysis system provides an excellent opportunity to study the evolution of the Global Observing System and the varying impact of the various components of it. In this article, a short overview is given about some aspects on the use and impact of observations in the test versions of the ERA5 reanalysis system. These experimental versions have lower horizontal resolution and use climatological (static) background errors.

Not surprisingly, the assimilated observation amounts had been dramatically increased since 1979 having more than 30 times data today than at the first years of ERA5. While the satellite observation amounts are always larger than the conventional ones, their impact is smaller at the very beginning of the period. The conventional observations remain always essential in the GOS, however in the last decades, the fast growing number of satellite observations can counter-balance their overall impact. The other consequence of the increased amount of satellite observations is that information about the mass variables (temperature, humidity) of the atmosphere is overwhelming with respect to the wind measurements. Therefore, additional wind measurements would be welcome in the GOS. Other interesting aspect is that the per observation impact of the satellite data can be further increased. For instance, the use of all-sky radiances (instead of the clear-sky only) can help to better exploit satellite information and further enhance their impact to the reduction of the forecast error. In the last 10 years or so, GNSS-RO observations became essential in the GOS, since they are bias free observations and therefore, they can be used as anchor measurements for satellite bias corrections. In spite of the emergence of huge amount of satellite observations, the conventional observations will have still crucial role in the modern NWP systems. Particularly, the highest influence of one piece of observation is always belonging to the buoy observations.

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National Adaptation Geo-information System in climate adaptation planning

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Abstract—Climate change impacts determine the long term development possibilities in Hungary. Due to the different vulnerability and adaptive capacity of various regions, the impacts and problems should also be handled in a differentiated way. The key areas of climate safe planning are: water safety, food security, human health security, safety of infrastructure, energy security, natural environment. Successful adaptation to climate change is inconceivable without having a sound knowledge of the impacts of climate change. The National Adaptation Geo-information System (NAGiS) may be used by national, regional, and local decision makers and stakeholders. It provides information on the climate status of the country, on the impacts of strategic risks connected to climate change and other long-term natural resource management issues, and on the correspondent adaptation possibilities, based on indicators, analyses, and impact studies. Data layers of NAGiS were elaborated by the Geological and Geophysical Institute of Hungary and partner projects funded by the Adaptation to Climate Change programme of the EEA Grants. The main parts of the NAGiS are a map-visualization system with 650 data layers; a database containing the calculation results based on modeling (GeoDat with 910 data layers); and a meta-database to help finding relevant data. NAGiS can be a useful tool for climate safe planning, analyzing, decision-support activities in governmental strategic planning; or for municipalities in spatial planning, settlement planning, organizing public services. It can be used in climate policy, energy policy planning, transport, and energy infrastructure design and numerous other fields. The further development of NAGiS is financed by the Environmental and Energy Efficiency Operative Programme. Between 2016 and 2018, the project will elaborate a decision support toolbox for underpinning policy and municipal adaptation measures, based on the development of the databases, methodologies, and evaluation modules of NAGiS.

Key-words: National Adaptation Geo-information System, climate change, GIS, vulnerability, adaptation, climate safety, policy planning, municipal planning, decision support system

1. Introduction

Climate change can have serious impacts on Hungary and determine the long term development possibilities of the country. For the 21st century, climate model projections show that the warming trend that has been witnessed during previous decades will continue (*Sábitz et al.,* 2015). The changes can affect almost all spheres of life: human health, ecosystems, economy, infrastructure systems, agricultural productivity, just to mention some of the most important ones. Settlements have to face with the expected changes, too. The impacts have different territorial scopes, and the vulnerability diverses regionally (*Pálvölgyi et al.*, 2012), Hence, the mitigation and adaptation capabilities of the regions also differ from each other. The problems should also be handled in specialized ways, aiming to find customized solutions based on each area and its capabilities (*Sütő et al*., 2016).

Adaptation has recently become an increasingly important strategic field besides mitigation in international and Hungarian climate change policies (*Antal,* 2015). The strategy of the European Union on adaptation to climate change was adopted in 2013. In parallel, Hungary started the revision of her National Climate Change Strategy 2008, and gave a greater emphasis for adaptation in climate change policy. Local governments also have a strong interest in planning local climate change adaptation activities and other developments based on the known and expectable effects of climate change. Having the relevant, available data and information are inevitable for planning. Ideally, geo-information systems with maps showing the necessary quantitative or qualitative information on relevant topics should be available.

There are different groups of decision support web based applications around the world, according to their types, goals and functions. Some portals *compile available knowledge* (articles, books, papers, project descriptions, best practices) on various topics; others *help interaction between users and exchange of knowledge* by fora; while several web platforms focus on *planning, strategy building for adaptation, and education*. Some systems offer *databases with map visualization*, which can be analyzed and evaluated. European solutions rather help the exchange of information, knowledge, and interactive communication of partners; while in North America, numerous decision support systems can be found as well, which are based on geographic information system (GIS) with databases and maps of concrete territories. Some applications are as follows:

- The primary function of several homepages and applications is the *dissemination of information and education* on the theory and methods of planning (e.g., Urban Adaptation Support Tool[1], UKCIP Adaptation Wizard[2]). They usually lack decision support functions based on

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[1] http://climate-adapt.eea.europa.eu/knowledge/tools/urban-ast

[2] http://www.ukcip.org.uk/

information generated by indicator analyses and map visualization. They can help enhancing planning capacities and decision making in strategic planning on adaptation issues.[3]

- Several web tools are suitable mostly for *awareness raising or introduction into climate change related topics*. They are usually rich in information, but due to the weaknesses of available databases, limited number of indicators, low resolution (giving only country-level or regional overviews), or map visualization deficiencies, they do not provide interactive applications, and can only help getting a basic introduction into climate change problems for decision makers and other stakeholders concerned. Climate-ADAPT Map Viewer[4] and Urban Vulnerability Map Book[5] are from this group. Another example of such solutions is the Climate Wizard[6], which works based on numerous climate and greenhouse gas emission projections, but only with two exposure indicators. The Climate.gov Data Snapshots[7] has an excellent design with a rich and clearly structured homepage, but territorial information is provided only in low resolution. The EPA's Climate Resilience Evaluation and Awareness Tool (CREAT)[8] application can be mentioned here either, with its imaginative, informative solutions (challenge logos, polished map designs, a well structured homepage).

- One of the *best practices of useful decision support tools* is the CLIMSAVE project[9], which uses and visualizes a lot of indicators (impact, adaptation, vulnerability, and economic efficiency) based on a solid theoterical foundation. Another one is the North American CalAdapt[10] supplying a detailed spatial resolution database (on a 10 km × 15 km grid), and the large number of analyzed topics. The logical framework, the detailed information basis and maps make these applications suitable for preparation of climate policy decisions on different territorial levels, or they can be foundations for further web based developments.

Prior to the launch of the NAGiS project, Hungary had no complex and multisectorial data- and information basis, which could have provided information on the expected changes necessary for planning adaptation measures for each region of the whole country. The VAHAVA project (*Láng et al*., 2007) was an important milestone to draw the attention to the importance of climate change adaptation, however, its investigations used the traditional tools

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[3] Other examples of this type are http://DataBasin.org, https://coast.noaa.gov/digitalcoast.

[4] http://climate-adapt.eea.europa.eu/knowledge/tools/map-viewer

[6] http://www.climatewizard.org/

[7] https://www.climate.gov/maps-data/data-snapshots/start

[8] https://www.epa.gov/crwu/build-resilience-your-utility

[9] http://www.climsave.eu/

[10] http://cal-adapt.org/

and approaches. Nevertheless, the theoretical basis for the NATéR analyses can be found in the VAHAVA project. The new element in NATéR is that it contains additional territorial contents to the sectoral approach of the VAHAVA. As a consequence of the insufficiency of data and methodology, analyses on climate change vulnerability and possibilities of adaptation were done only for several areas and were limited in scope (*Sütő et al*. 2016), for instance in the European ESPON Climate project. Though, the National Adaptation Geo-information System (NAGiS) could build on the result of recent researches and evaluations carried out in the field of climate change. Naturally, the ESPON projects concentrated mostly on the European level, but its NUTS-2 and NUTS3-level examinations show some information from lower territorial levels as well. One of the real contributions of NATéR in this regard is the possibility and provision of real territorial level analyses.

In 2013, the Geological and Geophysical Institute of Hungary (MFGI) was awarded a grant of the European Economic Area (EEA) for creating the National Adaptation Geo-information System. The EEA-C11-1 project entitled Establishing the NAGiS was the first initiative launched by the EEA Grants funded Adaptation to Climate Change programme area in Hungary. The fund operator for this programme was the Regional Environmental Center for Central and Eastern Europe (REC), and the donor partner was the Norwegian Directorate for Civil Protection and Emergency Planning (DSB). The EEA-C11-1 NAGiS Project lasted from 24 September 2013 until 30 April 2016. The project promoter was the Geological and Geophysical Institute of Hungary. The National Adaptation Centre (NAC), a unit of the institute was responsible for the implementation process with involvement of plenty of scientific institutes in Hungary (*Kajner*, 2016).

The overall objective of the project was to develop a multipurpose geo-information system that can facilitate the policy-making, strategy-building, and decision-making processes related to the impact assessment of climate change and founding necessary adaptation measures in Hungary. The NAGiS operating principles are in line with international climate protection obligations as well as with EU policies, guiding principles, strategies (e.g., EU 2020, Territorial Agenda 2020).

The three main objectives of the NAGiS project were:

- To support decision-making on the adaptation to climate change by setting-up and operating of a multifunctional, user-friendly geo-information database, based on processed data derived from several other databases.

- Develop the methodology for data collection, processing practices, analytical processes, and climate modeling related to the impact and vulnerability assessment of climate change and corresponding adaptation methods in line with INSPIRE requirements, accommodating to the Hungarian National Spatial Data Infrastructure.

- Operate a web-based "one-stop-shop", an information hub for all stakeholders concerned to obtain reliable, objective information, derived and processed data on climate change and other relevant policy areas.

2. Methodology

Urban, economic, rural development and other planning activities of municipalities, regions, counties can not miss including adaptation issues and measures. Quantitative input data from vulnerability assessments form an inevitable basis (in accordance with international directives) for impact assessments and decision-support analyses on which spatial, regional and sectoral policy planning is based. (*Czira et al*., 2010; *Pálvölgyi* and *Czira*, 2011). In order to successfully integrate climate change issues into policies, it is necessary to define the areas of intervention, which influence the adaptation of regions, sectors the most. The key areas of *climate safe planning* are: water safety, food security, human health security, safety of infrastructure, energy security, natural environment (*Pálvölgyi et al*., 2012). It is important to investigate to what extent the physical environment of everyday life is climate safe, and how it can adapt to the impacts of a changing climate (*Pálvölgyi* and *Czira*, 2011). Therefore, a specific evaluation method and model is needed which can handle the processes in their complexity, taking also into account the whole chain of climatic impacts, including their social consequences as well (*Sütő et al*., 2016).

The climatic impacts to be examined form a complex chain. The direct climatic effects appear in the form of changes which can be described using regional climate indicators. Complex local natural phenomena generated by climate change, interacting with each other (having repercussions on the climate indicators as well) may be identified as indirect climatic and complex natural impacts. Unfavorable socio-economic consequences are produced jointly by the direct climatic impacts and the indirect impacts that natural systems and ecosystems are exposed to (*Sütő et al.,* 2016). The climate change may deepen the existing economic and social differences and may cause new, serious inequalities (*Láng et al*., 2007).

In connection with the assessment of the impacts of climate change, the aim of the Climate Impact and Vulnerability Assessment Scheme (CIVAS) model is to provide a standardized methodological background to quantitative climate impact assessments. The model is based on the approach published in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), but numerous experiences of application can be found in scientific literature. CIVAS has been developed in the framework of the

CLAVIER[11] international climate research project, amongst others to examine the impacts of climate change on ecology and on the built environment. *Fig. 1* gives an overview of the method used during the establisment of NAGiS. (The terminology used by the figure was detailed in IPCC, 2014; *Pálvölgy*i and *Czira*, 2011; *Pálvölgyi et al*., 2010; *Selmeczi et al*., 2016a).

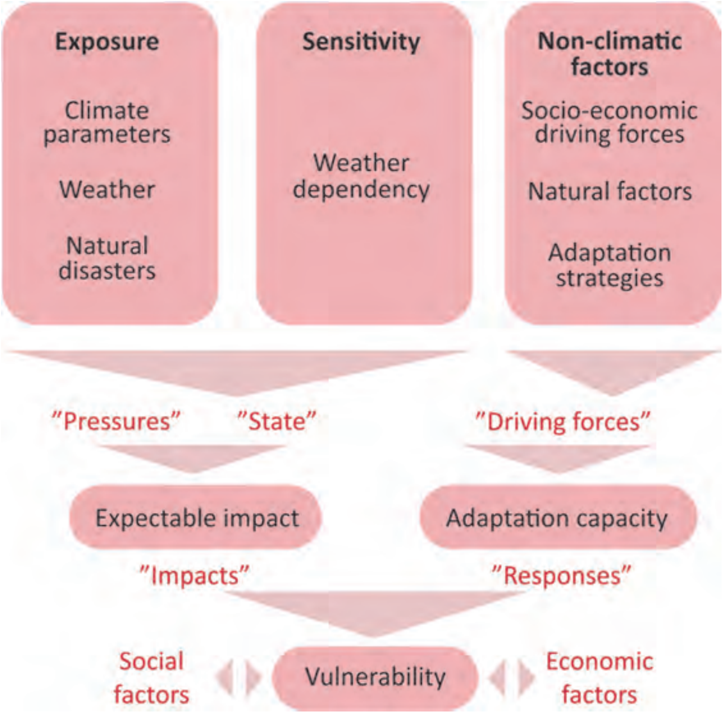

Fig. 1. The structure of the CIVAS model (*Pálvölgyi,* 2008).

The NAGiS is of special importance in Hungary for the complex monitoring of climate change impacts in several sub-topics as well as for providing a basis for mitigation and adaptation solutions. Its development was aimed to outline a comprehensive view on Hungary regarding the above described issues, creating the basis of future monitoring activities at the same time.

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[11] Climate Change and Variability: Impact in Central and Eastern Europe, EU 6th Framework Programme. http://www.clavier-eu.org

3. Scientific investigations and results

3.1. Climate information used for NAGiS

Climate change exposure, sensitivity, potential impacts, adaptability, vulnerability indicators were calculated and developed in NAGiS, using climate information, i.e., measurements and regional climate model (RCM) projections as input data. For the past and present, the CarpatClim-Hu observation database was applied, created with interpolation of measured climate datasets to a 10 km × 10 km grid by the Hungarian Meteorological Service. Four different regional climate models have been adapted by the Hungarian Meteorological Service and the Department of Meteorology of the Eötvös Loránd University and used for analyzing future climate change in detail for the territory of Hungary (*Bartholy et a*l., 2011). Two of these RCMs provide projected climate information (both with the medium A1B SRES anthropogenic emission scenario; *Nakicenovic at al*., 2000) for the users of NAGIS: ALADIN-Climate (*Csima* and *Horányi*, 2008) and RegCM models (*Torma*, 2011). Climate model data cover three climate windows. The 1961–1990 period was used as a reference in most analyses. Future projections were made for the 2021–2050 and 2071–2100 periods.

Climate model simulations are characterized by a set of uncertainties arising from the different approaches to describe the climate system, the approximate way of representing the physical processes involved in the calculations, the impact of the socio-economic changes which can not be forecast, and the natural variability of the climate. Therefore, when investigating future climate, analyses are suggested to be carried out with data of several climate models or simulations, in order to attain a probabilistic approach.

3.2. Projected climate change in Hungary

Since 1900, the annual mean temperature has increased with 1.3 °C in Hungary, which is much higher than the global average of 0.3 °C. The annual mean temperature is expected to increase with 1–2 °C by 2021–2050 and 3–5 °C by the end of the century in Hungary. Spring and winter mean temperature is likely to increase between 1 °C and 2 °C over Hungary by 2050 and approach +3 °C by 2100 according to ALADIN-Climate and RegCM simulations. The model results show that summer temperature rise in far future will be between 3 °C and 5 °C, or even higher – for instance, in August it may exceed 6 °C compared to today's levels. The number of warm extremes is projected to increase significantly, while cold extremes (frost days and extremely cold days) tend to become less frequent (*Sábitz et al*., 2015).

Model results are ambiguous for precipitation change projections. A slight, 10% decrease of annual average precipitation is projected by the end of the century. Summers tend to get dryer: a 5% decrease is projected for the near future, and even 20% less rain may fall on average in the 2071–2100 period. Winter precipitation may decrease by 10% on average (*Sábitz et al*., 2015).

The number of consequent dry summer days is expected to increase, and longer dry summer periods are projected than there are today. Parallel to this, the number of days with higher rainfall (20 mm or above) will also increase in each season, except for summer periods. Floods and inland water problems may get more frequent. The frequency of torrential rains, gale force storms, blizzards, and heat waves is also expected to grow, such as the incidences of extreme water levels and bushfires, the length of drought periods, and as a consequence of all the above, biological diversity is likely to decrease (*Sütő et al*., 2016; NCCS-2, referring to the Hungarian Meteorological Service data).

However, the changes of the climate affect the different parts of Hungary very diversely. The warming in 1981–2015 was stronger in the central part of Hungary and in the Mecsek Mountain. (NCCS-2, referring to the Hungarian Meteorological Service data.) According to the model results, larger warming is projected in the eastern and southern parts of Hungary by the end of this century. Precipitation can be expected to decrease in the southwestern part of the country and stronger, significant decrease may occur according to one of the RCMs (*Sábitz et al*., 2015).

3.3. Data layers based on impact studies

Based on the database and climatic models available in the framework of the NAGiS project, research has been carried out in several thematic fields, examining the vulnerability, exposure, and adaptation potential of particular geographical areas to given impact factors of climate change. NAGiS includes analyses and projections for the main topics described below (we provide some figures just to demonstrate their outcomes).

3.3.1. Changes in shallow groundwater conditions in Hungary

The aim of the groundwater-level monitoring workflow was to elaborate a methodology by which the shallow groundwater table can be modeled under different climate conditions, investigating the impact of climate change on groundwater and characterizing climate sensitivity of shallow groundwater flows. The introduced methodology is valid for the assessment of the impacts and sensitivity at various (regional and local) scales and by diverse methods.

During the examinations carried out, the CarpatClim-Hu database established from the data of hundreds of weather and rainfall observation stations of the Carpathian Basin was used; whereas for determining future groundwater conditions, the results of the ALADIN–Climate regional climate model were applied (*Kovács et al*., 2015b).

Delineation of climate and recharge zones, calculation of water balances using hydrological models, and simulation of groundwater table with numerical models were carried out in the first phase of the research. Predictive modeling was undertaken using regional climate model projections for three time intervals. One of the most important conclusions of the research based on measured data and model simulation results is that recharge rates and groundwater table levels are seriously decreasing in mountainous areas, and this tendency is expected to continue (*Kovács et al.,* 2015b). Nevertheless, the conclusions are drawn based on results of a single RCM, which is needed to be extended with uncertainty estimation later.

3.3.2. Changes in drinking water protection areas

The methodology of vulnerability assessment of drinking water resources was developed in the NAGiS project, including the development of exposure (*Fig. 2*), sensitivity, and adaptation indicators. Furthermore, a complex adaptation indicator was developed for the service area of a selected regional waterworks company, and using these, a complete climate vulnerability assessment was carried out for this pilot area (*Rotárné Szalkai et al*., 2016). The elaborated methodology makes it possible to provide decision makers with comprehensive information on the effects of climate change on drinking water resources. That may help the inclusion of the aspects of climate adaptation and sustainability into sectoral and regional strategic planning.

3.3.3. Changes in the risk of flash floods

Flash flood is a sudden flood caused by heavy rainfall in the course of a relatively short time. It may cause severe damage in mountainous and hilly areas. The intensity of the rainfall and special parameters of the water catchment area of a river (surface cover, hydrography, soil characteristics, geomorphology, gradient) influence the parameters of flash floods. The water catchment area, which includes the settlement endangered by intense rainfall can be delineated according to the lowest point of the rivers crossing the settlement (base level). For this reason, the flash flood risk classification of a settlement is given for the base levels (*Fig. 3*). As a result of our research, all water catchment areas including settlements in mountainous and hilly areas of Hungary were classified for flash flood risk, and the expectable occurrence of extreme downpours was investigated (*Turczi et al*., 2016).

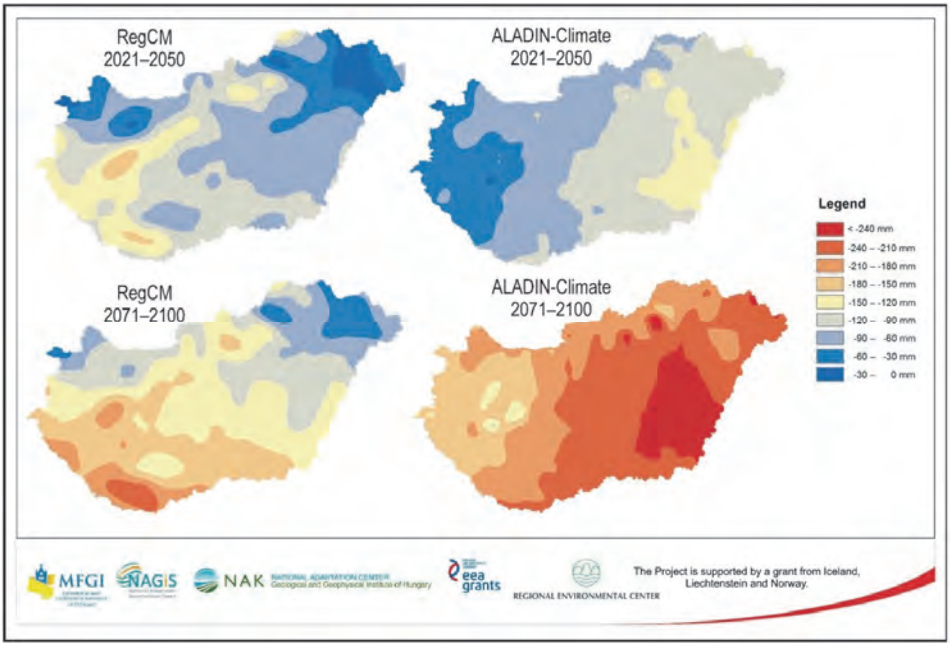

Fig. 2. The expected change of the climatic water balance in the 2021–2050 and 2071–2100 periods, based on RegCM and ALADIN-Climate data (*Rotárné Szalkai et al*., 2016)

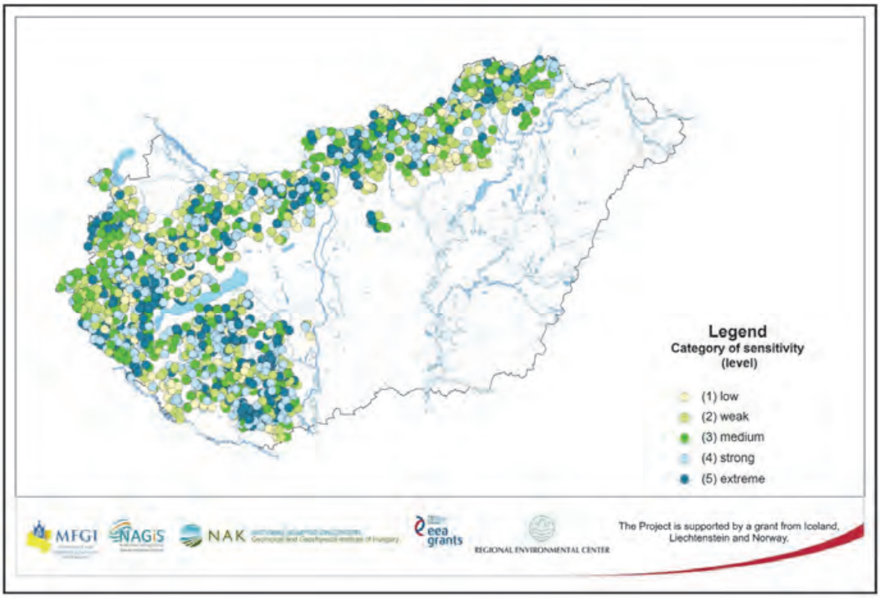

Fig. 3. Sensitivity of base levels and watersheds for flash flood risk in mountainous and hilly regions (NCCS-2, 2017, based on https://map.mbfsz.gov.hu/nater/)

3.3.4. Changes in hydrology of Lake Balaton

The research investigated the expected change of the water balance of Hungary's largest lake, using ALADIN-Climate model results. The changes were calculated for the 2021–2050 and 2071–2100 time windows compared to the 1961–1990 reference period. The most remarkable and robust change is manifest in the estimated temperature rise, as a result of which, increased evaporation is expected both on the watershed and the free water surface. The water budget pattern of the watershed changes due to the increasing territorial evaporation, which leads to a significant decline of runoff. Altogether, the decline of the in-flow side and the increase of the down-flow side can be predicted for the water budget of Balaton, particularly in the second future climate window (2071–2100). The water exchange activity of the lake will substantially deteriorate, here will be more frequent and longer periods without down-flow, and by the last decades of the 21st century, Lake Balaton may become practically a lake without down-flow (*Nováky et al.*, 2016). Nonetheless, these results have to be interpreted with special care and taking into account that uncertainties of the estimations are not quantified.

3.3.5. Vulnerability of natural habitats

Climate vulnerability evaluations of natural habitats provide information on the potential impacts of climate change on the future potential survival of natural habitats where they are present now. The goal of the research was to elaborate a solid foundation for climate vulnerability assessments of Hungary's ecosystems, based on investigations carried out for 12 climate sensitive habitats. In the first phase, the climate vulnerability of Hungarian habitats was assessed. Then the expected climate change impacts (predicted probabilities of presence of habitats as consequences of environmental changes) on the 12 most climate sensitive habitats and the adaptivity of habitats (habitat diversity, natural capital index and connectivity) were calculated (*Somodi et al.*, 2016). Input data for the research was gathered from The Landscape Ecological Vegetation Database & Map of Hungary (MÉTA).

3.3.6. Changes in agricultural biomass production and woodland management

The *AGRAGiS project*[12] examined the climate change impacts on arable farming and forest yield potential. The goals of climate vulnerability assessments on arable farming were the following: 1) giving quantified and spatial estimations for future yields of wheat, barley, rapeseed, corn, and sunflower, that will help to determine expected impacts of climate change; 2) giving quantified and spatial estimations on the adaptive capacity of arable farming; 3) delineating

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[12] EEA-C12-12, Extension of NAGiS to the agri-sector, http://www.agrater.hu

vulnerable areas within Hungary using expected impact and adaptivity data layers; 4) elaborating recommendations for agrotechnological strategies, which may decrease climate vulnerability. The results show serious yield loss in the far-future (2071–2100) concerning spring crops (e.g., corn, see *Fig. 5*). Their crop safety will decrease on the whole territory of Hungary. Autumn crops (e.g., wheat) may produce increasingly higher yields as the end of the 21st century approaches. During the 2071–2100 period, wheat, barley, and rapeseed may have significantly higher crop yields (*Fodor et al.*, 2016).

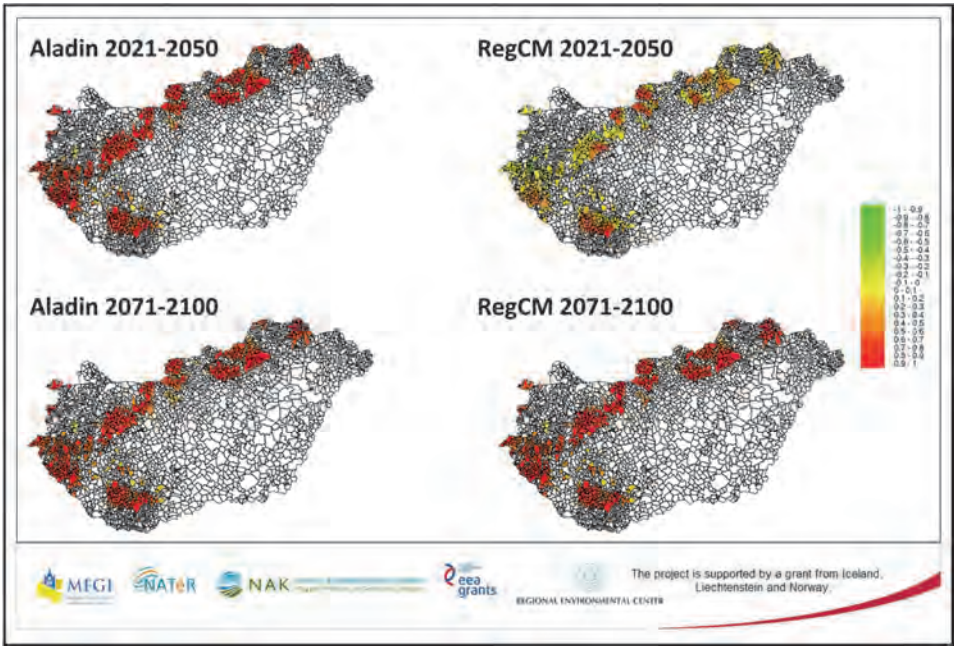

Fig. 4. Potential impact of climate change to existing stand of beech forests K5_K7a – aggregated for settlement boundaries in the 2021–2050 and 2071–2100 periods, based on RegCM and ALADIN-Climate data. Potential impact (PI) is expressed by the difference of predicted probabilities of presence given the climate of the reference period and under climate change scenarios within current locations of the habitat (unidimensional, depending on habitat type, location, and time horizon) (*Somodi et al.*, 2016).

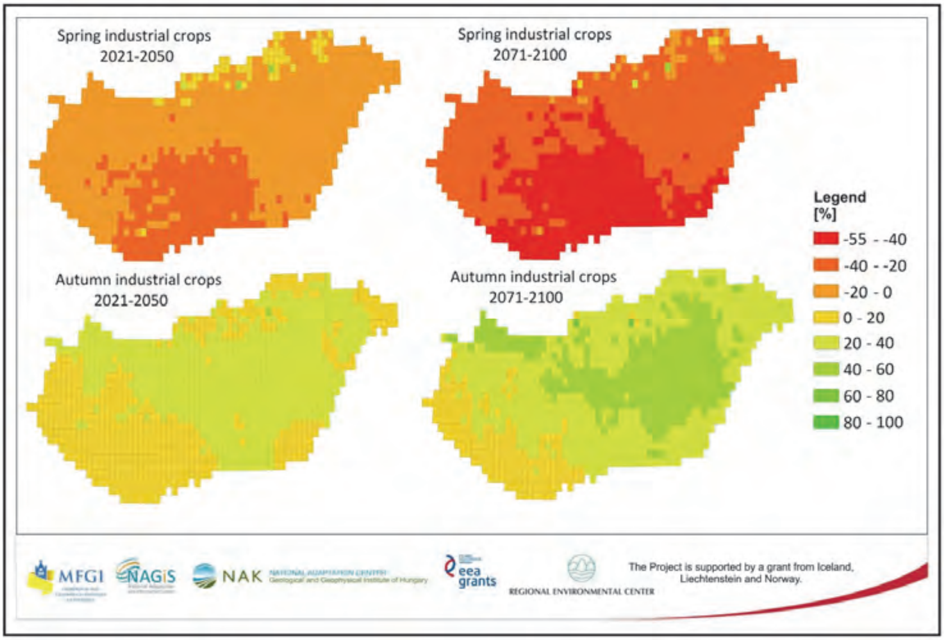

Fig. 5. Relative changes of crop yields as compared to the reference period (1961–1990), in case of spring (corn, sunflower) and autumn (wheat, barley, rapeseed) industrial crops. The yield changes are the average of the values calculated based on ALADIN and RegCM projections (*Fodor* and *Pásztor*, 2015).

The climate vulnerability assessments of forests aimed to investigate, test, and demonstrate methods, which may help the assessment of potential effects of climate change on Hungarian forests, and making adaptation decisions on large areas. The life expectancy, growth rate (yield) of forest tree species are determined mostly by their region, besides genetic features. So, the goal of the research was to understand, how forest climate type areas will shift within Hungary by the middle and end of this century according to the results of the two regional climate models, and what impacts these changes may exert on forest yields. The results show that the changes of climate conditions will make a significant impact on the spatial distribution of woodlands based on climate classification. All this is expected to make a serious effect on the exploitation of current woodland areas. The impacts may be witnessed under different forms: as the change of structure of forests with a main species of great yields but sensitive to climate, as a significant decrease of yields, as a change from economic woodland to protected woodland, or as the decrease of the woodland area because of becoming unsuitable for woodland coverage (*Illés* and *Fonyó*, 2016).

3.3.7. Impacts of heat waves on human health

The expected impacts of heatwaves were investigated by comparing excess mortality for past and future time windows in the *CRIGiS project*[13]. Analyses were elaborated using the CarpatClim-Hu database interpolated for the NAGiS grid and data series of the ALADIN-Climate climate model. Examinations were carried out on district and county level, using measured daily average temperature data between 2005–2014 and daily mortality data to describe the present period. The excess mortality for the present period of the climate model (1991–2020) was calculated taking into account the measured data. The effects of heatwaves on excess mortality was calculated by assessing the joint impact on the growth of heat units of the change of heat wave days and the excess temperature for the two projection time windows (2021–2050 and 2071–2100) of the climate models. The annual average excess mortality will rise with 107-182% in several districts of the country in the next decades, according to the projections (*Páldy* and *Bobvos,* 2016).

3.3.8. Impacts of weather extremes on road accidents

In the CRIGiS project, the impact of extreme weather events on road accidents was examined, too. Based on the the data content of the available database covering the period 2011–2014, a complex sensitivity indicator was formed, using three factors (number of road accidents, personal injuries caused by the accidents, intervention time of fire-fighter units). The two exposure indicators were the summer hot days and winter days with precipitation. Based on these, impact maps were elaborated. The impact maps were compared against the adaptivity indicator (arrival time of fire-fighter units), and vulnerability maps were elaborated for future periods (2021–2050 and 2071–2100) using this method. The results showed that middle and eastern parts of the country may be most vulnerable in summer, while in wet winter times, the capital city and its agglomeration and Transdanubia can be the most vulnerable areas (*Bihari*, 2016).

3.3.9. Climate change impacts on tourism

In the CRIGiS project, several climatic indices were calculated based on meteorological data to investigate the climate change impacts on tourism: the tourism climatic index (TCI) for areas of Hungary, its modified version, the mTCI and the climate index for tourism (CIT). The changes of these indices were quantified for the periods 2021–2050 and 2071–2100. The following variables were applied for determining the TCI: monthly mean temperature, monthly average of daily maximum temperature, monthly average of daily mean

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[13] EEA-C12-13, Vulnerability and Impact Studies on Tourism and Critical Infrastructure, http://kriter.met.hu/en

relative humidity, monthly average of daily minimum relative humidity, monthly average of wind speed as well as monthly average of daily sunshine duration and monthly precipitation sum. In order to determine CIT, the Physiologically Equivalent Temperature (PET) bioclimate index was calculated (that represents thermal conditions) using the data on the daily average of total cloudiness, daily precipitation sum and daily average of wind speed. The results based on the indices are useful for assessing the expected climatological conditions of water, urban and cycle tourism (*Kovács et al.*, 2015a).

3.3.10. Demographic, economic and land use changes

The project entitled *Long-term socio-economic forecasting for Hungary*[14] elaborated projections on the expectable change of the population of districts in Hungary, and the probability of the occurrence of diseases and causes of death, which are related to climate change. Furthermore, future projections for the most important economic indices (GDP, consumption, labour use, etc.) were also elaborated. Besides the socio-economic analyses, expected land use changes were modeled by the Land Change Modeler ArcGis software. The research included a survey on climate change attitudes of the population. The demographic projection results show that dramatic changes can be expected. Following the most probable scenario of the projections, the population of the country will decrease to 8.4 million people by 2051. Spatial differences of the population decrease will be considerable. Though, most districts of the country, will be expecting a population loss of over 30 percent. (*Czirfusz et al.*, 2015)

3.3.11. Testing NAGiS

The operation and practical usability of NAGiS was tested by determining the vulnerability to climate change of the pilot areas Sárvíz River Valley and the region of Aba city (*Selmeczi et al.*, 2016b). Areas in Aba, which are at risk of potential flooding from intense rainfall were delineated. The city's sustainable local water management development plan was elaborated, with regard to the potential impacts of climate change on water uses and the local vulnerability (*Kajner et al.*, 2016).

3.3.12. Development of new climate change scenarios

The impact data layers of NAGiS are mostly based on outputs of 2 RCMs as mentioned above. The *RCMGiS project*[15] aimed at improving these climate data. The most important results of the project were developing the climate model data providing future climate information for NAGiS with application of two

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[14] EEA-C12-11, http://nater.rkk.hu/

[15] EEA-C13-10, New climate change scenarios for the Carpathian-basin region based on changes of radiation balance, http://rcmter.met.hu/en

new anthropogenic emission scenarions (RCP4.5[16] and RCP8.5; *Moss et al.*, 2010); quantifying the uncertainties of climate projections; providing climate model data for impact assessments; training and support for the users to apply projection results and uncertainty information.

4. *Geoinformation developments*

NAGiS has three different user interfaces: a map view, a database interface, and the basic portal as shown in *Fig. 6*.

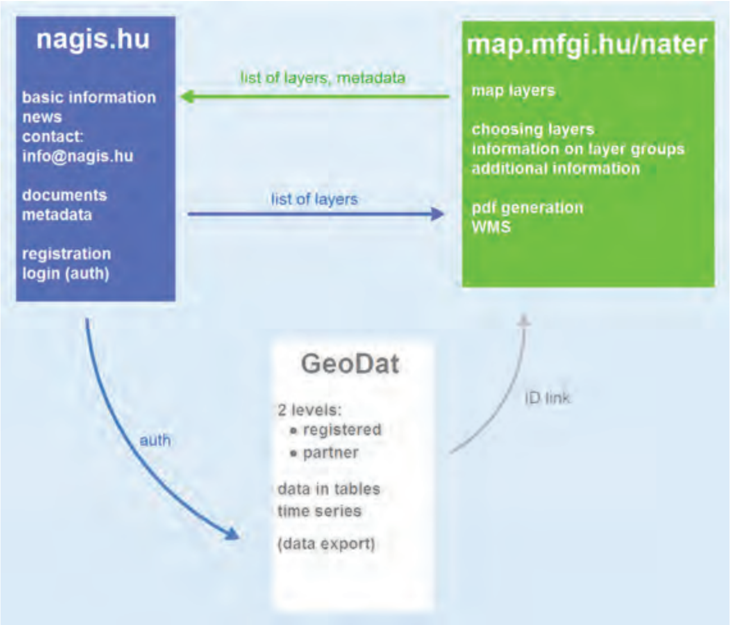

Fig. 6. Structure of the NAGiS portal system (Source: *Orosz et al*., 2016)

4.1. Main elements of the NAGiS

4.1.1. Map-visualization system

This sub-system contains 650 layers with a resolution of 10 km × 10 km, which show the way different aspects of climate change can affect certain areas of the country. Instead of one large database, NAGiS is built of smaller databases or file systems organized in thematic categories. The two main parts of the map system are the dataset stored on the public map server and a larger dataset stored in the internal NAGiS (MFGI / MBFSz) system.

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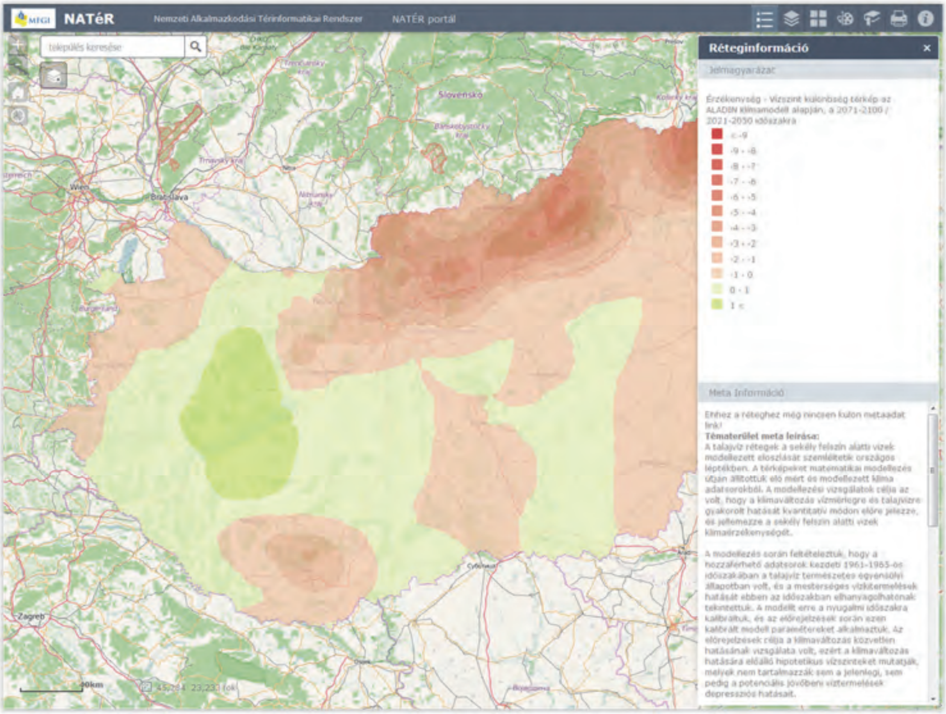
[16] Representative Concentration Pathways



Ehhez a réteghez még nincsen külön metaadat link!
Tématerület meta leírása:
A talajvíz rétegek a sekély felszín alatti vizek modellezett eloszlását szemléltetik országos léptékben. A térképeket matematikai modellezés útján állítottuk elő mért és modellezett klíma adatsorokból. A modellezési vizsgálatok célja az volt, hogy a klímaváltozás vízmérlegre és talajvízre gyakorolt hatását kvantitatív módon előre jelezze, és jellemezze a sekély felszín alatti vizek klímaérzékenységét.

A modellezés során feltételeztük, hogy a hozzáférhető adatsorok kezdeti 1961-1965-ös időszakában a talajvíz természetes egyensúlyi állapotban volt, és a mesterséges vízkitermelések hatását ebben az időszakban elhanyagolhatónak tekintettük. A modellt erre a nyugalmi időszakra kalibráltuk, és az előrejelzések során ezen kalibrált modell paramétereket alkalmaztuk. Az előrejelzések célja a klímaváltozás közvetlen hatásának vizsgálata volt, ezért a klímaváltozás hatására előálló hipotetikus vízszinteket mutatják, melyek nem tartalmazzák sem a jelenlegi, sem pedig a potenciális jövőbeni víztermelések depressziós hatásait.

Fig. 7. A visualized sensitivity data layer of NAGiS: shallow groundwater level difference, 2071–2100/2021–2050, based on the ALADIN–Climate model. (Source: https://map.mfgi.hu/nater)

4.1.2. GeoDat

There are various geo-IT software programs available for creating map databases, but for the raw database containing a large number of thematic data (which constitutes the basic data of NAGiS), there is no off-the-shelf interface available. On that account, the NAGiS project had the GeoDat database management software program developed in a target-oriented manner. It is capable of receiving any kind of data and data series of any point-like object. The GeoDat core system provides a table view of the data as well as advanced research options. A separate module of the application has been designed for the display of time-series data. (*Orosz et al.* 2016)

GeoDat is a database containing the calculation results based on modeling (exposure, sensitivity, expected impact, adaptive capacity, and vulnerability) with 910 data layers. This database-management application was designed for

NAGiS with a supporting background database, built in a standardized system. The background database contains all numerical and alphanumerical data which are considered to be the end products of the project. Its content partially overlaps with the map-based database, but it is much more expanded. It also contains data that is not displayed on the maps.

4.1.3. Meta-database

The database of NAGiS stores several hundred maps and several thousand related work files. The metadata system enables users to find the information they need in the quickest possible way. It facilitates navigation through different kinds of information by a complex search interface. NAGiS metadata can be categorized into four main groups: map metadata, metadata of map figures, research metadata and registry metadata (*Orosz et al*., 2016).

4.1.4. Nagis.hu portal

It is a basic, traditional web portal available at the http://nagis.hu or the http://nater.mfgi.hu addresses for entering the portal system. It enables the users to search metadata or to register and login to the NAGiS system. The maps and the GeoDat database can be accessed from here. It performs the identification of users as an engine portal and transmits the user data to the other two interfaces.

4.1.5. Main hardware elements

The system stores the data retrieved from various data management systems in the NAGiS basic database in a standardized way. The core data is stored in separate tables, whereas time series data is stored in parameter tables. The system enables to identify any point objects and to store all related core data and parameters.

The external data storage unit contains the public data of NAGiS. It was established in an environment and following a structure that are completely identical to that of the internal databases of NAGiS. All data made available for the general public are transmitted here from the internal databases. All actions of public data provision refer to this external data storage system.

IT equipment necessary for the research (e.g., desktop PCs, screens, GIS software, a large scanner, etc.), and for operating the system (e.g., servers, switches, servers, uninterruptable power sources, etc.) were purchased by the NAGiS Project (*Orosz et al*., 2016).

5. *Application of NAGiS*

5.1. Legal framework

The legal foundation for NAGiS was laid down by Act LX of 2007 on the implementation framework of the UN Framework Convention on Climate Change and the Kyoto Protocol thereof. According to Paragraph 3 of the law, the implementation of the adaptation strategy framework (a part of the National Climate Change Strategy) has to be supported by a national adaptation geo-information system and the results of climate vulnerability assessments of the system. According to the law Government Decree No. 94/2014. (III. 21.) on the detailed rules of operation of NAGiS, the NAGiS Operational rules were adopted in May 2014.

NAGiS provides information on the climate status of the country, on the impacts of strategic risks connected to climate change and other long-term natural resource management issues, and on the correspondent adaptation possibilities, based on the indicators, analysis, and impact studies prepared using the data, according to the Government Decree No. 94/2014. The NAGiS is operated by the Mining and Geological Survey of Hungary (MBFSz – the successor of Geological and Geophysical Institute of Hungary). The MBFSz is under the authority of the Ministry of National Development.

Databases have an internal (for the participants of the project and the data administrators), and an external (intended for the public) version. Although the interface is identical, their data content is different. While external databases only contain derived and standardized data, internal databases contain the basic data too. The registry system of users runs according to Goverment Decree 94/2014. Geo-information work was carried out in an ESRI environment in the project (*Orosz et al*., 2016).

5.2. Potential future users of NAGiS in sectoral and spatial strategic planning

NAGiS is a source of information on the climate trends of Hungary; it contains the effects of strategic risk factors like climate change and other issues affecting long-term natural resource management, and the possibilities of adaptation to the changes. It is operated according to the Government Decree 94/2014. The information is based on indicators derived from basic data. At the portal of NAGiS, users may find analyses and impact assessments on the topics mentioned above.

NAGiS can be a useful tool for climate safe planning, analysing, decision-support activities in governmental strategic planning; or for municipalities in spatial planning, settlement planning, organizing public services, primarily in the following fields (*Pálvölgyi et al*., 2016):

- *Climate policy planning:* Founding the realization of climate policy actions for the country, regional and local levels, determining the vulnerability and adaptability of action areas.
- *Energy policy planning:* A potential use can be the sustainability evaluation of land use for food versus enegy crop production. Another field of use can be the re-evaluation of the potential production of conditionally and unconditionally renewable energy sources in regions, with regard to climate change impacts (trends of wind, sun, thermal, biomass, and biogas energy potential).
- *Transport and energy infrastructure design:* Climate proof planning of transport, production, forwarding and distribution infrastucture, enhancing technical conditions of security of supply.
- *Development policy planning:* Climate proof planning of inter alia flood protection works, power plants, bridges, etc.; necessary modification of standards, safety standards, elaboration and application of state subsidy spatial preferences in development policy decision-making (*Hrabovszky-Horváth et al.,* 2013). Evaluation of climate protection investments. Elaboration of the methodology of measuring the contribution of each supported development investment to greenhouse gas and carbon-dioxide emission reduction.
- *Planning in agriculture and rural development:* Impacts of climate change on the agro-ecological potential and the agricultural land use optimized for production conditions. Elaboration of action area types and measures based on the risk of erosion, agricultural water management, land cover, and soil attributes.
- *Spatial, settlement, and regional planning:* Founding climate protection strategies of regions and settlements with different endowments and development conditions. Elaboration of conditions of local adaptation; strengthening climate protection aspects in development programmes, tenders.
- *Planning in tourism:* Impact of climate change on touristic destinations and infrastructure serving the destinations; determining and enhancing the adaptability of tourism regions with different endowments (*Csete et al.* 2013).
- *Planning in the fields of human health and quality of life:* The adaptation tasks of the government and municipalities in the fields of health promotion and the enhancement of life quality are determined by different endowments and incidences, depending on the types and structure of settlements. Planning tasks are determined by the strength and frequency of extreme climatic events influencing people’s life quality at settlements and the measures necessary to react. Furthermore, the safe operation of human health care systems and the accessibility of these are important factors in planning.

NAGiS may directly support the implementation, supervision and evaluation of the second National Climate Change Strategy, and the implementation and evaluation of the Environment and Energy Efficiency Operative Programme (EEEOP).

The main target groups / users of NAGiS include the national, regional, and local government bodies, decisions-makers of public bodies, policy makers; and the population of the areas that are vulnerable to climate change and people who are at risk of extreme weather events.

5.3. A practical example for using the NAGiS in planning

From 2016, EEEOP[17] development sources are available for Hungarian counties, which can be used for the development of county level climate strategies. A methodological resource (MFGI, 2017) was developed for the elaboration of these plans of the counties, which used the NAGiS database and selected maps. This resource gave a common background for planning, based on scientific results for making adaptation analyses of climate strategies of counties. The methodology helped the work of the planning experts in the following topics: vulnerability of drinking water resources, flash flood risk, expected impacts of droughts, vulnerability of natural habitats and forests. In 2017, several counties finished the elaboration of climate strategies. All of them used the NAGiS methodological resources.

6. Summary

Climate change can affect many sectors in Hungary and detailed, relevant, reliable data and information are inevitable for climate adaptation planning. The Geological and Geophysical Institute of Hungary (MFGI) established the National Adaptation Geo-information System (NAGiS) with the financial support of the European Economic Area (EEA) Grant Fund and with involvement of national institutes from different scientific areas. The project developed a multipurpose geo-information system that can facilitate the policy-making, strategy-building, and decision-making processes related to the impact assessment of climate change and the founding of necessary adaptation measures in Hungary. The NAGiS research processes were built on the CIVAS (Climate Impact and Vulnerability Assessment Scheme) model to have a standardized methodological background for quantitative climate impact assessments. Climatological research in NAGiS was based on the CarpatClim-Hu observational database and on projection results of the ALADIN-Climate and the RegCM regional climate models. Climate model data cover three climate windows: the 1961–1990, 2021–2050, and 2071–2100 periods.

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[17] Environmental and Energy Efficiency Operative Programme, financed by the European Union and the Government of Hungary

Calculated climate parameters are available on a uniform 10 km × 10 km resolution grid. Climate change exposure, sensitivity, potential impacts, adaptability, and vulnerability indicators were calculated and developed for water safety, food security, human health security, safety of infrastructure, energy security, and natural environment.

The main parts of the NAGiS are a map-visualization system with 650 data layers; a database containing the calculation results based on modeling (GeoDat with 910 data layers); and a meta-database to help finding relevant data. The system includes research results of the NAGiS project and partner projects of the Adaptation to Climate Change EEA Grants Programme. Data layers on the following main topics are available at the nagis.hu portal: impacts of climate change on shallow groundwater conditions, drinking water protection areas, and on the risk of flash floods in Hungary; estimated change of hydrology of Lake Balaton; vulnerability of natural habitats; impacts of climate change on agricultural biomass production and woodland management; impacts of heatwawes on human health; impacts of weather extremes on road accidents; climate change impacts on tourism; demographic, economic, and land use changes; development of new climate change scenarios. The NAGiS was tested by determining the vulnerability to climate change of the pilot areas Sárvíz River Valley and the region of Aba city.

NAGiS can be a useful tool for climate safe planning, analysing, decision-support activities in governmental strategic planning; or for municipalities in spatial planning, settlement planning, organizing public services, primarily in the following fields: climate policy; energy policy; transport and energy infrastructure design; development policy; agriculture and rural development; spatial, settlement, and regional planning; tourism; human health and quality of life. In 2016, a methodological resource was developed for the elaboration of climate change strategies of Hungarian counties, which used the NAGiS database and selected maps. In 2017 several counties finished the elaboration of climate strategies. All of them used the NAGiS methodological resources.

7. Outlook

The 2013–2016 NAGiS project created the methodological basis built on the CIVAS model for quantifying climate change effects in Hungary, established the hardware system, and created the database, map portal, and meta-database from research results. The decision support tool is a powerful tool for the different territorial levels of Hungarian climate policy. However, the establishement of the system showed the necessary directions of further development. For instance, the project could not make projections on the hydrological impacts of climate change on Hungarian rivers, due to the lack of available climate modeling scenarios of the necessary 10 km × 10 km resolution for the whole Danube River basin. Enhancement of input databases and a better knowledge of uncertainties of model results could make NAGiS data more reliable (recall that some assessments used the results of only a single RCM simulation on the one hand, and on the other hand, even two simulations cannot represent the whole range of the projection uncertainty). The development process revealed a number of other shortcomings too, which will be cured in the next development phase described below.

In November 2016, the project plan of MFGI on the further development of the National Adaptation Geo-information System was granted by the "Adaptation to climate change" priority axis of the Environmental and Energy Efficiency Operative Programme (EEEOP). The aim of the EEEOP priority project is to elaborate a decision support toolbox for underpinning policy and municipal adaptation measures, based on the development of the databases, methodologies, and evaluation modules of NAGiS. In order to support sectoral and climate policy planning and decision-making, the further development of NAGiS will clarify the information on vulnerable sectors and affected parties, furthermore ameliorate climate change impact assessment planning and evaluation methodologies.

The land use modeling methodology of the system will be developed and tested in a pilot area. The project includes underpinning and assessment of climate adaptation tasks of agriculture, tourism, and several critical infrastructure elements. A new addition to the system will be the elaboration of a method for the assessment of geological risk sources with regard to the climate change aspect and interpretation of results.

Development of comprehensive, horizontal tools for social policy and economic development will cover the assessment of impacts of climate change on human health, presenting climate change impact on migration trends within Hungary, and on the country's labour market processes.

Tools for supporting climate policy planning of the government and the county municipalities will be elaborated, and as a part of these, new information technology modules will be created. Such modules will be the settlement adaptation barometer module (SABM), the adaptation decision support module for municipalities (ADSMM) and the online adaptation management information system (AMIS). In connection with these, an online calculator for settlements for the assessment of climate vulnerability of buildings will be developed.

Hydrological assessments will be pronounced during the NAGiS further development too, as it is one of the most impacted natural and economic resources by climate change. Extension of the results of climate models to the Danube River basin, integration of hydrological model results into the system will support to explore the vulnerability of surface waters. The climate vulnerability assessment of drinking water supply services and the investigation of direct and indirect impacts of climate change on shallow groundwaters will be continued. Flooding assessment and hydrological modeling of urban areas will be done within the framework of a pilot project for underpinning water management adaptation measures. The results of these will be used for the elaboration of a handbook for settlements on climate resilient water management of urban areas.

Our goal is to create a geo-information and policy support system, which is as user friendly as possible. Therefore, dissemination of the information on new modules and other results; creating easy-to-use interfaces; trainings and education material development on new modules are important parts of the project, too.

All the above mentioned developments can not be carried out without the modernization of the information technology system, increasing information security level, building electronic accesses and protocols, and modernization of the geo-information methodological tools and digital map visualization. Therefore, the project includes the development of the hardware and software system, too.

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Climate impact on drinking water protected areas

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Abstract—Extreme weather conditions have caused difficulties in the Hungarian drinking water management many times in the past. High demand for drinking water in dry summer periods and the accompanying reduction in water resources lead to insufficiency in the availability of a number of water supplies, therefore causing limitations in water access. In some other cases, as a result of excessive precipitation, floods and flash floods evolved over karstic areas, and several water supplies had to be excluded from operation in order to avoid the risk of infections.

The expected increase in the number of extreme weather conditions and further possible changes in future climate necessitates the analysis of the vulnerability of drinking water resources to climate change. Since 95% of the total drinking water supply in Hungary originates from subsurface layers, significance of groundwater resources is outstanding.

Our work was carried out in the frames of the NAGiS (National Adaptation Geo-information System) project with the aim to devise a methodology for the study and determination of the vulnerability of drinking water supplies to climate. Methods have been chosen according to the CIVAS (Climate Impact and Vulnerability Assessment Scheme) model that has been developed in the frame of the international climate research project CLAVIER (Climate Change and Variability: Impact on Central and Eastern Europe). The CIVAS model, being based on the combined evaluation of exposure, sensitivity, impact, adaptability, and vulnerability provides a unified methodical scheme to quantitative climatic impact assessment.

The investigation involves the analyses of climatic parameters primarily influencing drinking water supplies and hydrogeological characteristics of the geological media that significantly determines vulnerability. Apart from the expected environmental changes, societal and economic processes have also been taken into account. Climate vulnerability has been determined on the basis of the distribution and categorization of the chosen indicators.

Further effects, independent of climate change and caused by anthropogenic activity, result in similar phenomena. It is often difficult to differentiate between natural and anthropogenic effects that occur simultaneously; therefore, anthropogenic activity is necessary to be taken into account.

In the analyses we used data of two different climate models covering two separate future time periods. Results on the basis of both climate model projections suggest that a considerable number of regions in the area under investigation appear to be vulnerable to climate change to a certain extent, and vulnerability intensifies to the end of the 21st century.

Key-words: climate change, vulnerability, exposure, sensitivity, adaptation capacity, drinking water

1. Introduction

In Hungary, 95% of drinking water is produced from subsurface layers, so in our drinking water supplies, the role of groundwater is crucial. Apart from the shallow groundwater primarily used for irrigation, a significant supply of the deep porous aquifer beneath the plains provides the majority of our drinking water. Karstic water of our various mountain ranges plays an important role as well, in some regions being the main drinking water resource. Bank filtered systems also provide a major contribution both as current and long-term future water supply.

Extreme weather conditions have caused problems concerning drinking water supplies in many cases in the past. During dry summer periods, reduced water resources and simultaneous increase of water demand caused water shortage in some areas and often led to water restrictions. In other cases, floods and karst-floods formed due to extreme rainy weather conditions, and consequently some water resources had to be suspended in order to avoid the risk of infection.

Anthropogenic activity, irrespective of climate change, can result in similar phenomena, and when these two are superimposed, distinction is difficult between them. The changing groundwater levels, due to groundwater withdrawal, together with groundwater quality changes caused by anthropogenic impacts are added to the impacts of climate change and amplified.

One part of the NAGiS (National Adaptation Geo-information System) project was to determine and characterize the climate vulnerability of drinking water supplies. The effect of climate change differs spatially, depending on local climate, geology, hydrology, and hydrogeology. Our task within the project was to characterize the most important climate elements of the expected climate change, geological environment, and hydrogeological conditions that mainly determine the vulnerability of drinking water resources. The effects of climate change on water supplies, together with the attenuation and elimination activities, have social and economic consequences as well. Therefore, our study was complemented with the characterization of adaptation possibilities to the changing environment. In the course of our work, a data system containing geospatial elements was built, aiming to improve our basis for planning and developing adaptation and mitigation techniques to any adverse effects.

2. Methods

In order to assess the climate vulnerability of drinking water protected areas, we used the CIVAS model (Climate Impact and Vulnerability Assessment Scheme) established in the CLAVIER (Climate Change and Variability: Impact on Central and Eastern Europe) international climate research project. The CIVAS model uses the approach proposed by the 4th Assessment Report of the Intergovernmental Platform for Climate Change (IPCC, 2007). The philosophy of the CIVAS model is similar to the DPSIR2 ('Driving Force – Pressure –State – Impact – Response') model, which is established and widely used in environmental status assessments in the European Union (*Pálvölgyi et al.*, 2010).

The effects of climate change in the CIVAS model are examined in the exposure → sensitivity → impact → adaptive capacity → vulnerability context. In our study, climate vulnerability assessment has been carried out for the drinking water protected areas and drinking water supply systems. In addition to the expected environmental changes, social and economic processes have been considered. Since anthropogenic activity may exacerbate the effects of climate change on drinking water resources, it is necessary to be addressed in the assessment of climate vulnerability. Therefore, in our work we applied the modified version of the CIVAS model with the following elements.

Exposure is related to climate and the expected climatic changes, for which data can be extracted from archived meteorological data series or climate models. It is characteristic to a geographical location.

Sensitivity is a specificity of the impacted system, a drinking water supply in this case. The sensitivity of the affected system is independent of climate change and primarily determined by the environmental and physical parameters of the system. In case of drinking water supplies, these features are related to the geological and hydrogeological characteristics.

Anthropogenic impacts on groundwater quantity and quality, which are independent of climate change, represent changes due to human activity.

Potential impact is a combined indicator of exposure, sensitivity, and other environmental impacts. It is peculiar to both the geographic location and the impacted system under investigation.

Adaptive capacity is a non-climatic factor, which represents the local social and economic answers to the mitigation of the unfavorable effects of climate change. In case of drinking water supplies, beside social and economic factors, technical factors are also important which maintain the quality and guarantee the security of drinking water services under the changing circumstances.

V*ulnerability* is a complex indicator, which integrates exposure (the expected climatic change at a geographic location), climate sensitivity (the physical characteristics of the natural environment affected by climate change at a given geographic location), and the adaptive capacity (the social and economic abilities to minimize the unfavorable changes).

For the investigation and definition of adaptive capacity indices, information was needed directly from the groundwater supply operator. We did not have the opportunity to consult all the presently accredited 34 regional waterworks, therefore we selected a pilot area, where the adaptive capacity and climate vulnerability assessment methodology could be worked out in detail. The selected area (*Fig. 1*) lies within the operational area of the Danube River Regional Waterworks Corporation (DMRV Zrt.)

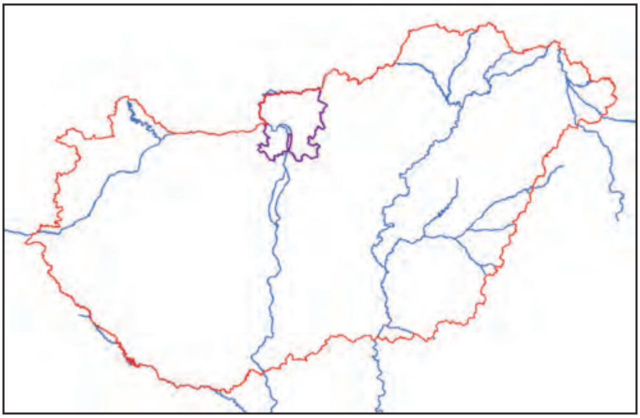

Fig. 1. Study area located in the operational area of the DMRV.

Climate vulnerability was characterized by the spatial distribution and categorization of all the used indicators. The final results have been uploaded into the NAGiS system.

3. Exposure

Climate change seldom has direct effect on drinking water protected areas. The subsurface reserves are mostly indirectly related to surface hydrological and meteorological processes which are subject to climate change. Therefore, climate change results in indirect changes in groundwater reserves and groundwater flow parameters. The factor influencing them is related to surface processes, infiltration, and discharge (including evapotranspiration).

Processes at the areas of infiltration are mainly regulated by the variability of precipitation and the extent of evapotranspiration of the given soil horizon, in the period prior to the precipitation event. The latter is basically the function of temperature change. At the discharge areas of groundwater, the effects of both precipitation and temperature and the closely related evapotranspiration processes are faster and more direct.

Based on the above considerations, the exposure of drinking water protected areas to climate change can be characterized by the investigation of the meteorological parameters influencing infiltration and discharge processes to the highest extent.

A unique groundwater system is the bank-filtration system, the exposure of which is regulated primarily by the meteorological conditions of the catchment area (in many cases having a transboundary character) of the recharging surface water system instead of the nearby area. The exposure of these groundwater systems are characterized mainly by the water level fluctuations of surface water systems. The issue of bank-filtration systems is outside of the frames of this work, however, for a comprehensive analysis, it is needed to be included in future investigations.

3.1. Exposure to climate change

The climate database for our analyses consisted of two types of data. CarpatClim-HU (*Szalai et al.*, 2013; *Bihari et al.*, 2017) data are climatological measurements interpolated to a regular grid, while modeled data comprise simulated data of the ALADIN-Climate and RegCM climate models based on the climate scenario A1B. Grid of the different datasets overlap, therefore the spatial resolution of roughly 10 km is consistent. CarpatClim-HU covers the time range 1961–2010, while data of the climate models are provided for the periods 1961–1990 (the reference period), 2021–2050, and 2071–2100. All datasets have been provided by the Hungarian Meteorological Service.

We used four climate indicators that have been chosen according to the aim of the analyses and the availability of the data necessary for the calculations.

The *aridity index* is defined as the ratio of precipitation and potential evapotranspiration. Potential evapotranspiration has been calculated using Thornthwaite’s method (*Ács* and *Breuer,* 2013).

The Pálfai drought index (PDI) indicates the severity of droughts in the individual years and shows a strong correlation with the decrease of crop yield. PDI has a modified version called the *modified Pálfai drought index* (PaDI) that has been developed in the frames of the DMCSEE project. It shares the applicability of PDI, however, data necessity for the index is less and calculation is simpler (*Hungarian Meteorological Service*, 2012). Therefore, in our study we applied the modified PDI for our investigations.

The quantity of water filtrating under ground is strongly influenced by the annual distribution of precipitation. Precipitation of the winter hydrological half-year mainly determines annual infiltration (*Kessler*, 1954). In order to analyze precipitation trends over the consecutive hydrological half-years, we defined an indicator as the *ratio of precipitation sums of the winter and summer half-years*, where the summer half-year comprises the months from May to October, and the winter half-year is the period between November and the end of April.

For the further investigation into water budget, we determined the *climatic water balances* for the different areas of the country and their possible future changes. Climatic water balance in our analysis is defined as the difference between the annual sums of precipitation and potential evapotranspiration, where potential evapotranspiration has been calculated according to the method of Thornthwaite (*Ács* and *Breuer*, 2013).

As the majority of the chosen indicators yield one value for a year, we determined all the indices in annual resolution. From the annual values decadal and thirty-year means were then calculated.

Possible future changes in the precipitation and temperature conditions were estimated with the analysis of the climate model data available for the NAGiS project. We determined rates and signs of the changes for the 2021–2050 and 2071–2100 time periods compared to the reference period.

3.2. *Past climate*

Different indices for the consecutive decades show slightly different tendencies, however, the main characteristics in the results for the past climate are similar. In general, climate in the area of Hungary had gradually become dryer from 1961 until around the turn of the century, when a more humid period began. A significant decrease in aridity occurred in the first decade of the 21st century.

Fig. 2 shows the spatial distribution of the mean annual climatic water balance values for the reference period (1961–1990), based on CarpatClim-HU data. Analysis of the climatic water balance provides information on the water budget of various regions in the country.

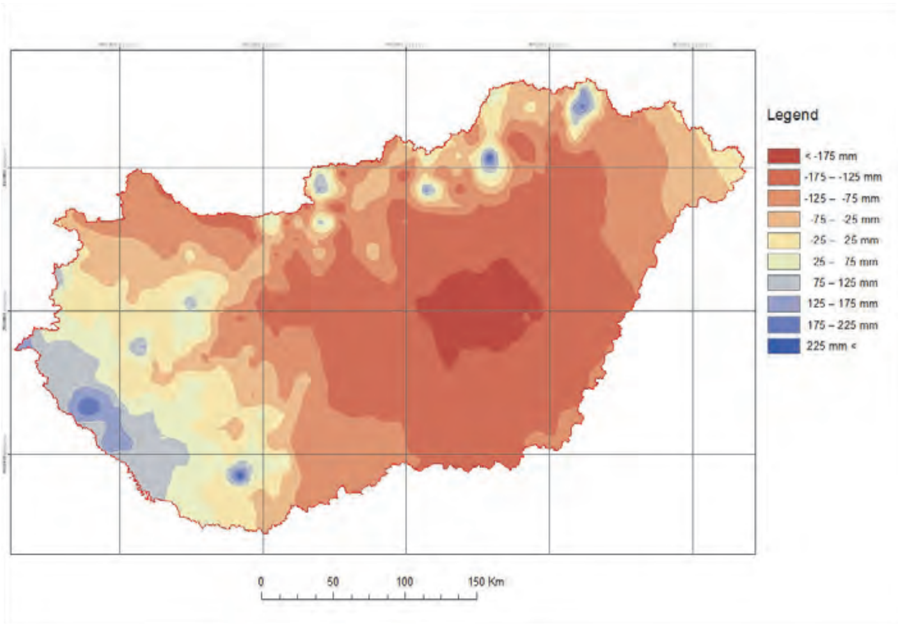

Fig. 2. Spatial distribution of the annual mean climatic water balance in the reference period based on CarpatClim-HU data.

Fig. 2 indicates the areas of Hungary which abounded in precipitation in the reference period, and where water shortage was more general. On the basis of water balance analysis, lowland areas appear to be the most arid regions. Annual water balance is negative for the largest part of the country, meaning that the amount of water, that the area is capable of evaporating under the specific climate conditions, exceeds average precipitation. The largest extent of water shortage is present in the middle areas of Alföld. Along with the increase in altitude, water balance gradually increases and turns into positive, reaching a maximum in hilly areas and the southwestern part of Transdanubia.

3.3. Future climate

It is necessary to note that climate model simulations naturally contain a set of uncertainties that often lead to differences or even contradictions in data calculated by different models (*Szépszó et al*., 2015). The purpose of climate models is to describe the behavior of the climate system, as a whole, that is only possible in an approximate way, due to the complexity of physical processes. The reason behind the uncertainties lies within the differences in approximations, calculation methods, and parametrizations. When investigating future climate, analyses are therefore suggested to be carried out with data of several climate models or simulations.

Projected future changes in the aridity index based on ALADIN-Climate data show a continuous decrease from the western parts of Hungary towards the eastern areas, suggesting the climate to get dryer in the whole country but to a different extent regionally. The drying process is likely to intensify by the end of the 21st century. We can draw a similar conclusion from the calculations using the data of RegCM. Aridity is expected to intensify generally in the future, although the spatial distribution of the changes differ from the one based on ALADIN data.

The two models estimate mainly similar future changes concerning the modified Pálfai drought index. According to the results, intensification of aridity is most probable in the middle and southern parts of the country and less affected are the northern, northwestern, and northeastern regions.

The models yield different estimations for the changes in the rate of precipitation sums of the winter and summer hydrological half-years for the 2021–2050 period. ALADIN data suggest slight changes being negative in most areas and positive in the southern and eastern parts. RegCM indicates negative changes for the whole country, with the largest extent relating to the eastern regions. However, an unambiguous increase in the values of precipitation rates is expected for the end of the 21st century on the basis of both model projections, which means an increase in winter and a decrease in summer precipitation. Based on these results we draw the conclusion that projections of climate models suggest a shift in precipitation amounts toward the winter half-years for most parts of Hungary, which tendency means that the summer half-years are probable to get more arid in the future.

The projected changes in the mean annual climatic water balance are summarized in *Fig. 3*. Both of the climate models estimate the water balance to shift to the negative side of the spectrum throughout the whole area of Hungary. ALADIN places the largest decrease in the water budget to the eastern parts of Alföld, while RegCM estimates it to occur in the southwest regions. Less affected areas are expected to be the western, northern, and northwestern regions. Drying tendencies are likely to intensify with time till the end of the 21st century.

The research carried out in the frame of the CLAVIER project provided results in accordance with our conclusions. Analyses based on data provided by the REMO climate model indicate a widespread decrease in summer precipitation for the middle areas of Europe, while winter precipitation is expected to increase.

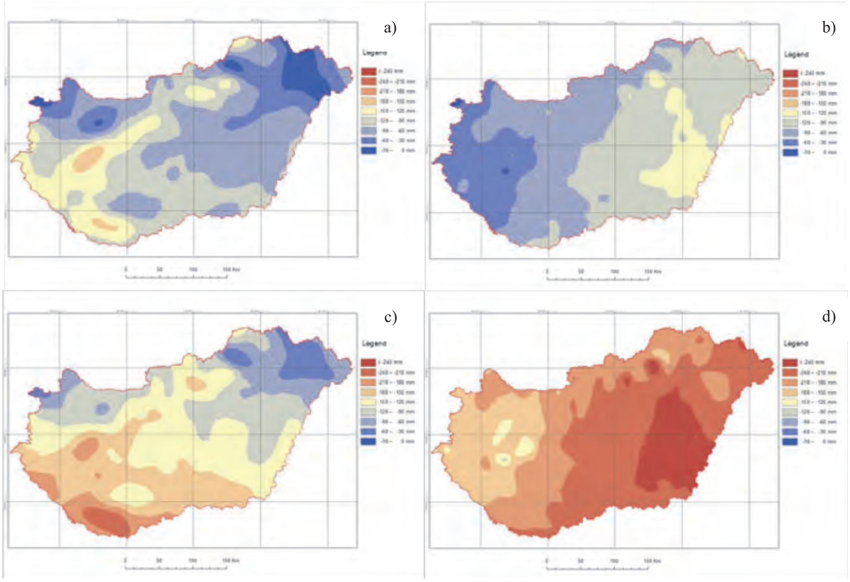

Fig. 3. Spatial distribution of the changes in the climatic water balance for the 2021–2050 (a, b) and 2071–2100 (c, d) periods on the basis of RegCM (a, c) and ALADIN-Climate (b, d) data.

4. *Climate sensitivity of drinking water protection areas*

The effect of climate change on groundwater is not so direct and intense as in case of the surface water system. Often, what we observe is the result of changes that have been happening over several years. As the change has been continuous for a long time in most cases, upon termination of the unfavorable effect, the original status can be achieved slowly.

The infiltrating water is transported either through the available subsurface pore space or fissure network of the karst system. Due to the subsurface conditions, the movement of groundwater is significantly slowed down, and processes are acting on a longer time scale. The degree of porosity is regulated by geological processes, therefore, the climate sensitivity of drinking water supplies is determined by the geological and hydrogeological properties of the recharge and drinking water protected areas.

Based on the different climate sensitivity of the groundwater systems and on the hydrological constraints, climate sensitivity categories can be established (*Table 1*).

Table 1. Climate sensitivity categories of drinking water systems

Type of aquifer	Climate sensitivity category	Intensity of climate sensitivity
porous aquifer	porous aquifer < 30 m	very sensitive
	porous aquifer 30–100 m	moderately sensitive
	porous aquifer >100 m	no direct effect
karst system	karstic aquifer with well developed channel network	very sensitive
	open karst system	sensitive
	confined karst system connected to recharge area	moderately sensitive
	deep karst system, part of regional groundwater flow system	no direct effect
bank filtration system	bank-filtration system	sensitive
	alluvial aquifer affected by watercourse	sensitive
fractured aquifer	fractured aquifer	moderately sensitive
surface water	surface water	very sensitive

Based on the drinking water database (available in the frames of cooperation of General Directorate of Water Management and Geological and Geophysical Institute of Hungary), categorization has been carried out on all the 2018 drinking water protected areas of Hungary into the climate sensitivity categories listed in *Table 1*.

The categorization of drinking water protected areas regarding climate sensitivity is not clear in all cases. If the aquifer can not be categorized unambiguously into one of the categories, first the dominant character is considered as a basis, and indication is made to the secondary aquifer type. An example for this is the discrimination among the confined karstic aquifers, as these are hydraulically connected to the unconfined karstic aquifers, and in case of the confined karstic aquifers, climate sensitivity is determined by the travel-time of water particles. There are no sharp boundaries among the bank-filtration water system and the alluvial aquifer affected by the watercourse, and the transitions are related to the similarity of the environments. In our consideration, a drinking water protected area is considered as a bank-filtration system, where the contribution of the surface water component is more than 50%. In order to define the percentage of the contributing sources, we used the values determined by numerical flow modeling of the diagnostic measurements in the „National Groundwater Protection Program”. In porous aquifers, it is frequently the case that wells are penetrating to different depths. In this case, according to a „worst-case-scenario”, the depth of the shallowest well gives the basis of the climate sensitivity qualification. Due to this reason, in the dominantly shallow porous aquifers, there are wells often taping deeper aquifer horizons (30 to 100 m, rarely greater than 100 m), and based on their secondary character, they belong to the less climate-sensitive category.

Fig. 4 shows the climate sensitivity of the drinking water protected areas using centroid coordinates of each drinking water protected area.

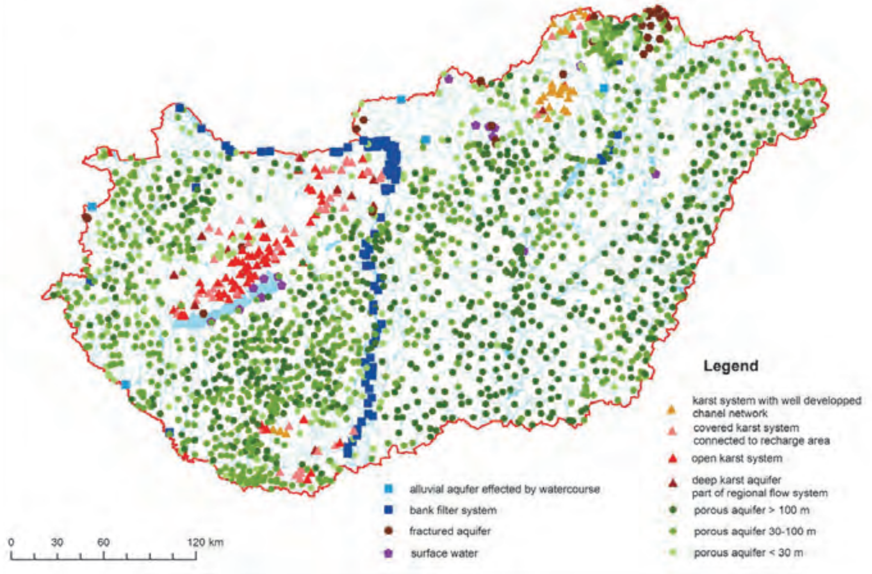

Fig. 4. Climate sensitivity of the drinking water protected areas

Applying the sensitivity categories we also determined the intensity of the climate sensitivity of drinking water protected areas (*Fig. 5*).

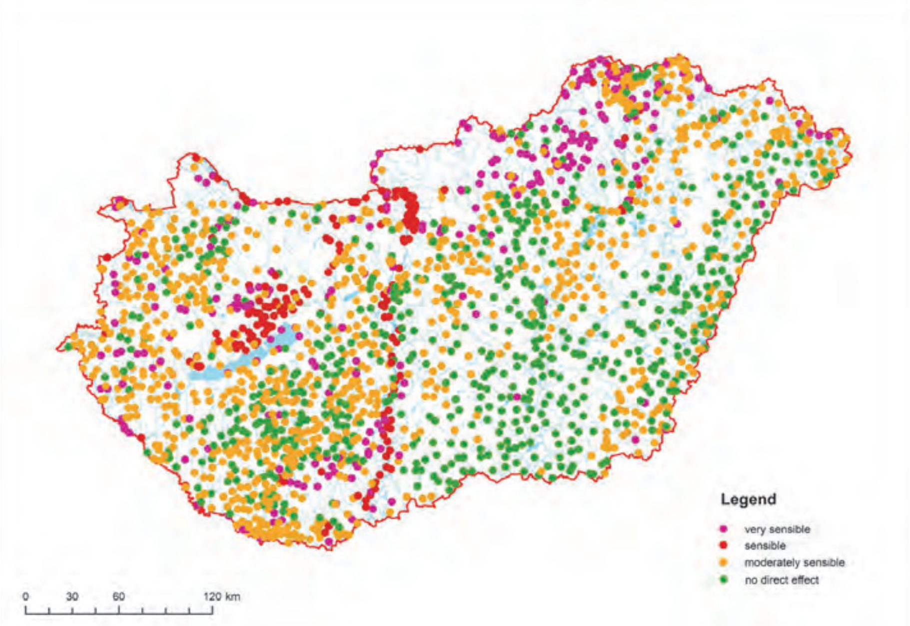

Fig. 5. Intensity of the climate sensitivity of drinking water protected areas.

4.1. Current demand on groundwater resources

It is difficult in all aspects to differentiate between the effects of climate change and other anthropogenic activities. In groundwater systems these are superimposed and amplify each other. For this reason, it is essential to consider the water production data of the past decades for the investigation of climate change. The effect of overexploitation of water resources is now a global pressure on water resources (*Green et al*., 2011). The production of groundwater, primarily for drinking water purposes, has increased significantly in Hungary since the 50s. The increased water exploitation can result in further significant water level decline, and in specific regions, it can even reach the limits of the exploitable quantities.

We carried out the investigation of groundwater level decline due to exploitations so far, using monitoring data of our groundwater monitoring network and by the interpretation of simulation results of numerical groundwater flow models. Based on the results, we determined the intensity of overexploitation.

5. Results regarding the pilot area

A pilot area was selected to characterize the adaptation capability and vulnerability to climate change. This pilot area (the operation territory of DMRV), situated at the Danube Bend, is mainly of mountainous character.

5.1. Climate sensitivity of the pilot area

Due to the geological settings, the drinking water resources are located in a concentrated way. There are only a few drinking water protected areas situated in the distribution area of volcanic formations with limited groundwater potential. The bank-filtration systems of greater volume drinking water potential and prognostic supply potential are located alongside the river Danube.

In addition to the display of drinking water protected area centroids on the thematic climate sensitivity category map, we also assigned these to the settlements, in order to provide a basis for the climate vulnerability assessment, which can be determined in relation to settlements. For the assignment, we identified the settlements directly supplied by the respective drinking water protected areas. However, for emergency cases, DMRV has the technological capacity within its operational area which enables any regional water supply to be governed to secure water supply of another region. As the drinking water supply of a settlement is often provided by more than one drinking water protected area, the climate sensitivity categorization is implemented on the basis of the least sensitive drinking water protected area (*Figs. 6* and *7*).

5.2. Climate adaptation of settlements regarding water supply

As a result of climate change, the extent and frequency of summer heat wave periods are expected to increase significantly and also changes in the distribution of precipitation are expected to take place. In the winter semester, precipitation is expected to increase, while in the summer semester, which is the vegetation growing season, it is expected to decrease. As a result, water demand of the population is anticipated to increase, partly due to domestic water use, as well as water used for irrigation in the private sector. Therefore, regarding climate adaptation, the current status and upgradeability of the infrastructure and the water demand of the population are the main factors.

In addition to climate exposure and climate sensitivity, we need to define climate adaptation for the climate vulnerability assessment of the settlements regarding drinking water supplies. For the investigation of adaptation we used the social-economic indices of the National Settlement Development and Planning Information System (TeIR) of the KSH-T-STAR and NAV SZJA databases, and data relevant to the status of the water supply system infrastructure in the pilot area provided by DMRV.

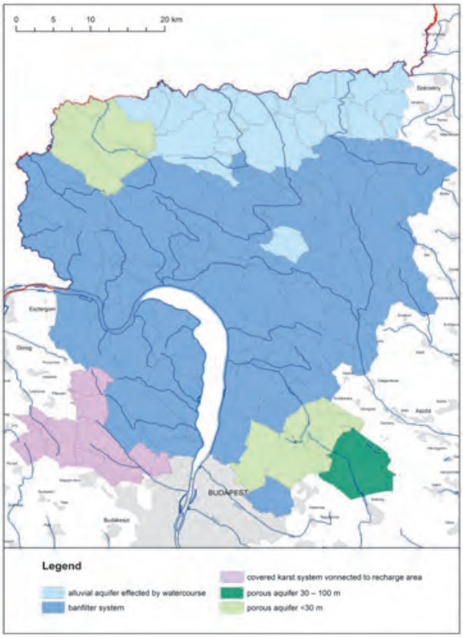

Fig. 6. Climate sensitivity of drinking water protected areas of the settlements based on the least sensitive direct water supply type, within the operational area of the DMRV.

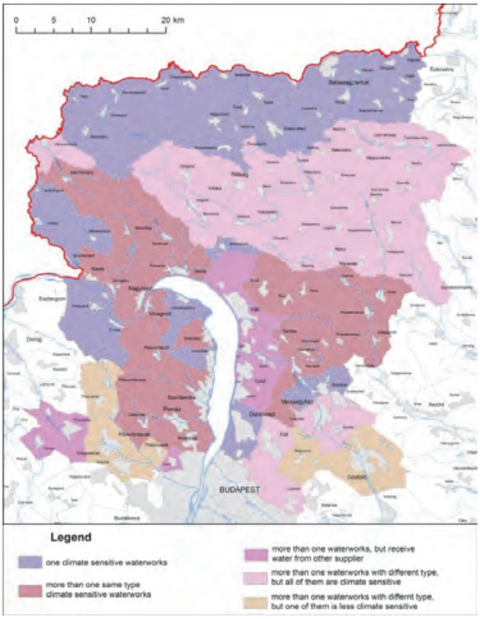

Fig. 7. Climate sensitivity of drinking water protected areas of the settlements based on the number and climate sensitivity of the direct water supply, within the operational area of the DMRV.

In the first stage of the investigation, we delineated data needs and classified data specificities, in cooperation with the DMRV. The important tasks of this stage were the screening of data for errors, checking and correction of outlying values.

It was an important aspect in the assessment, that data should possibly represent a single, specific year; however, this could be satisfied only partially. Data related to the status of the infrastructure is up-to-date, that is representative of the present conditions, while the social-economic indices are available uniformly for the year 2013.

With regard to the above, we used the following specific indices for the determination of climate adaptation:

1) The infrastructural factors of climate adaptation:
    a) the number of drinking water protected areas directly supplying a given settlement,
    b) the expandability of the drinking water protected area (category),
    c) the potential to increase drinking water supply capacity (category).
2) The social-economic factors of climate adaptation:
    a) drinking water consumption per inhabitant, 2013 (m^3/per capita),
    b) all domestic income per inhabitant, 2013 (HUF/per capita/year).

In the further stages of the investigation, we related category values to each indices, then by summing up the category values, we determined the intensity of climate adaptation for each settlement.

5.3. The infrastructural factors of climate adaptation

Regarding water supplies, the intensity of climate adaptation is fundamentally influenced by the number of drinking water protected areas directly supplying a settlement, as well as the upgradeability of the water supply system infrastructure. Using data obtained from the DMRV, we could define the number of operating drinking water protected areas supplying each settlement (*Fig. 8*). We also investigated whether drinking water protected areas can be extended or water supply system infrastructure supplying a settlement can be increased. Meanwhile, it is important to emphasize that as a result of water supply network establishment, the drinking water supply can always be secured by appropriate water governance. We defined three categories regarding water supply security in climate adaptation (*Fig. 8*). We considered conditions the least favorable, when a settlement is supplied solely by a single drinking water protected area. Consequently, the most favorable case is when more than two drinking water protected areas supply the given settlement. In this respect, there are significant differences throughout the operational area of DMRV. Along the river Ipoly, settlements are usually supplied only by a single drinking water protected area, but in the Budapest area, most of the settlements are supplied by more than one drinking water protected areas.

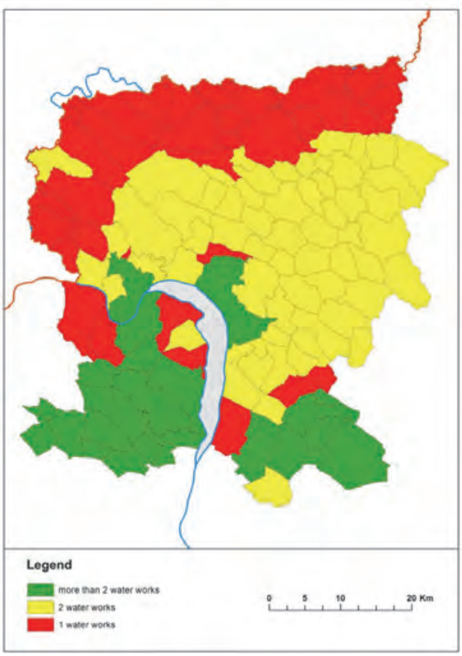

Fig. 8. Number of drinking water protected areas supplying settlements in the operational area of DMRV, 2015 (Source of data: DMRV).

Regarding the upgradeability of the drinking water protected areas, the situation is more uniform. Within the pilot area, for the majority of the settlements, there are drinking water protected areas where both the extension and the capacity increases are possible, according to the data provided by DMRV. Extension of a drinking water protected area involves the possibility to establish a new production well. While the increase of capacity means the increase of existing production capacities, exchange, or modernization of existing production wells. Development of drinking water protected areas can be hindered mainly by the built-up of the area or the contamination of the water resources; however, it requires great financial investment, in general. There are two significant connected areas in the southern section along the river Ipoly and the Danube Bend, where related problems arise.

5.4. Social–economic factors of climate adaptation

The fundamental objective of climate adaptation investigation is to determine the capability of society to respond to challenges caused by climate change. In case of drinking water supplies, the most important socio-economic questions are the water demand of the population and the ability of the individuals and communities to tackle the problems. The public water demand can be defined simply based on the water consumption per person indices, the situation is, however, more complex. The main issue in this context is whether the individual or the local community has the capability to take necessary measures in tackling the problems. To answer this question, the figure of all domestic income per person, which is representative of the public income ratio, is well suited, since development of a region is primarily determined by the income of the population (*Faluvégi*, 2000). With the investigation of population income we gain information on the differences in the state of development. Based on the research carried out by *Bíró* and *Molnár* (2004) it can be stated, that there is a strong, direct relationship between the economic and infrastructural developments, therefore it is justified to investigate income ratio in the study of climate adaptation.

This relationship is well indicated by the strong correlation of public income ratio and water consumption figures as well. There is a clear positive, linear correlation between population income ratio and water consumption with the exception of certain outlying values. These outlying values are related to unique impacts. The highest amount of water consumption per person was observed for Visegrád in 2013, primarily due to tourism.

Regarding the territorial differences in water consumption (*Fig. 9*), there is a significant duality in the region. Settlements of the Budapest agglomeration, the area of the Danube Bend, and the Lower-Ipoly Valley are characterized by higher water consumption, while the settlements of Nógrád County have mostly lower (30 m^3/per capita) consumption figures.

There are also significant regional differences in the income ratios of the area. The income ratio is the highest in the area of Budapest, in the settlements of the agglomeration. There are average values in the area of the Danube Bend, of Vác, and Balassagyarmat. In the remaining part of the pilot area, the income ratio per inhabitant is low.

5.5. Determination of climate adaptation of the settlements

As a result of the detailed investigation on the individual impact factors, we determined the climate adaptation of the settlements rearing water supply (*Fig. 10*). In the investigation, we considered the number of drinking water protected areas responsible directly for water supply, the potential to develop water supply, the public water demand, and the indices related to the income ratio of the population with equal weights. With respect to climate adaptation, it can be judged positively if there are more than one drinking water protected areas which supply a settlement, or there is a potential to extend the drinking water protected area and develop its capacity, and if the population has low water demand and favorable income ratio.

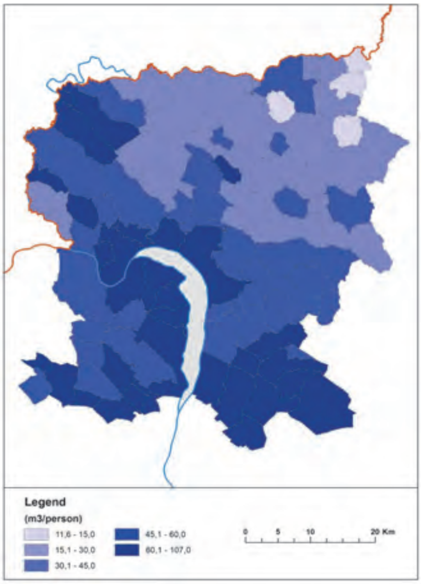

Fig. 9. The specific water consumption of settlements in the operational area of the DMRV, 2013 (Source of data: DMRV, KSH T-STAR).

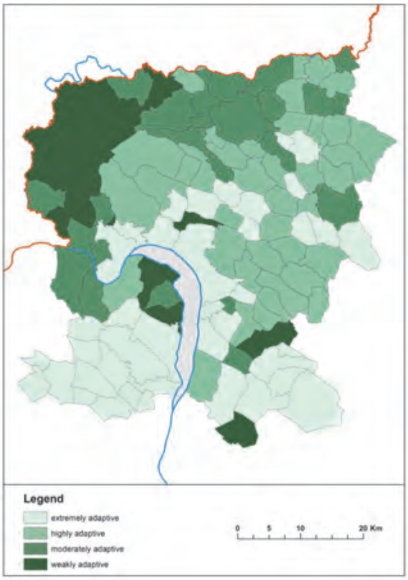

Fig. 10. Climate adaptation of the settlements regarding water supply.

We classified climate adaptation into four categories on the following basis: extreme, high, moderate, and weak adaptations. Regarding climate adaptation, the least favorable region is proved to be the Lower-Ipoly Valley area. In this area all of the investigated indices are poor. The majority of the settlements are supplied by only one drinking water protected area, and the potential to develop the water supply system is limited, but the water consumption is high and the income ratio of the population is low.

The settlements in the right bank of the Danube River Bend are also in poor conditions, regarding climate adaptation. Problems are mainly due to deficiencies in the infrastructure and high water consumption of the population.

5.6. Climate vulnerability assessment of drinking water protected areas

The climate-vulnerability of drinking water protected areas is derived from the combined assessment of exposure, climate sensitivity, and adaptation according to the introduced methodology.

We identified categories in order to characterize the intensity of climate vulnerability. In deriving the categories, exposure, climate sensitivity, pressure, and adaptation factors are considered with uniform weights for the derivation of the combined indicator. Indicator values and climate vulnerability categories are defined in a way that they could be applicable country-wide, following the same methodology.

The combined exposure indicator is thus calculated on the basis of UNEP aridity index and the meteorological water balance value.

The climate vulnerability of drinking water protected areas was determined based on the data of both of the two climate models for the two future time periods. Figs. *11* and *12* well indicate areas with different intensities of climate-vulnerability, already present in the period 2021–2050, according to both models. As time progresses, the intensity of climate vulnerability is expected to increase for the period between 2071 and 2100.

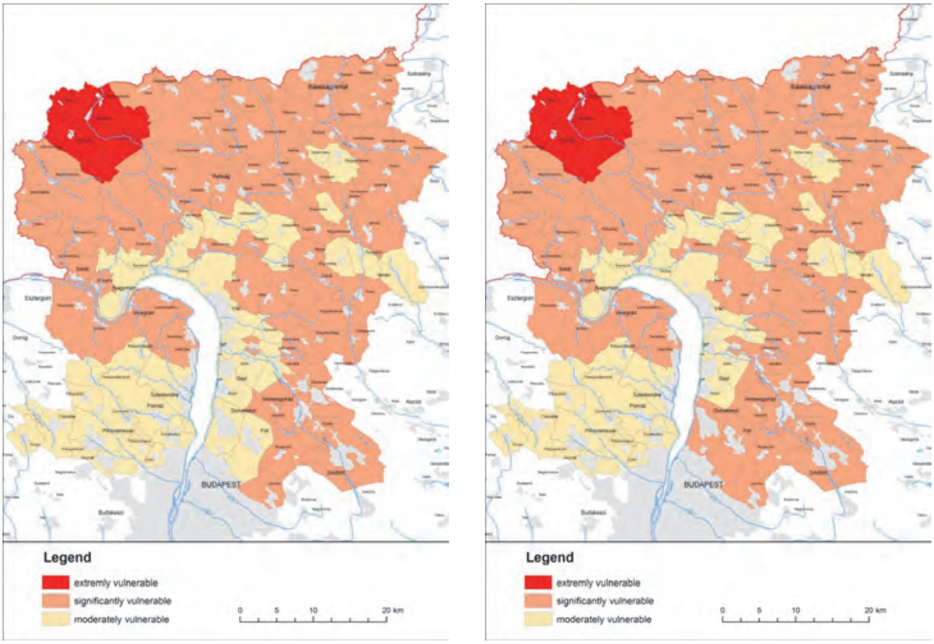

Fig. 11. Climate vulnerability of drinking water protected areas using the ALADIN (left) and RegCM (right) models for the period 2021–2050.

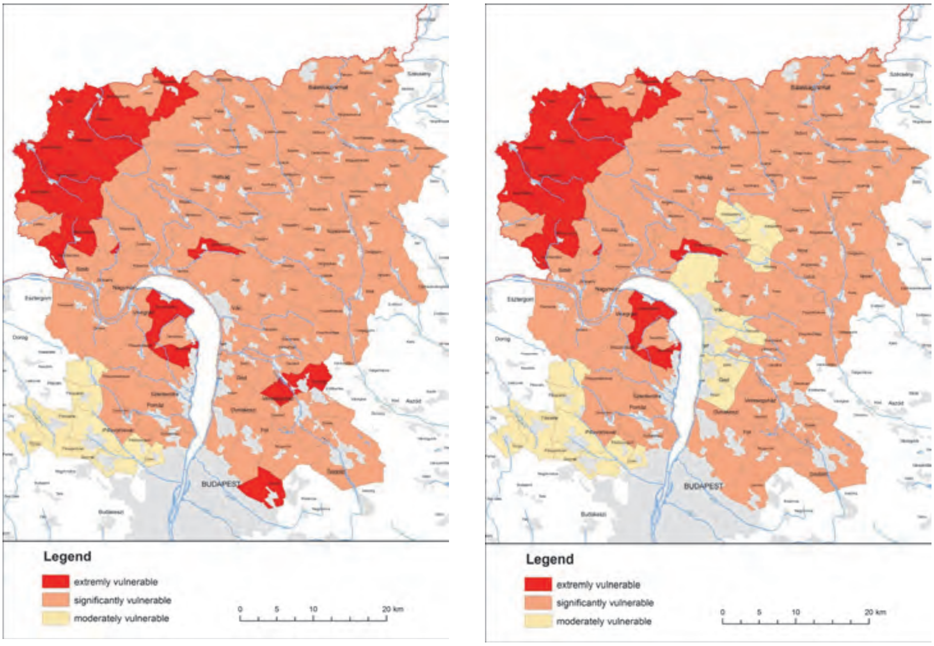

Fig. 12. Climate vulnerability of drinking water protected areas using the ALADIN (left) and RegCM (right) models for the period 2071–2100.

6. Conclusions, recommendations

We can conclude from the results of our investigation that the climate exposure of the drinking water protected areas is not uniform in the different regions of the country. However, regarding the European scale, it is within a relative narrow range. As a result of climate change, the amount of infiltration responsible for groundwater recharge is expected to decrease. This process is somewhat balanced by changes in the annual distribution of precipitation, that is expected to increase in the winter half-year.

Climate model projections naturally involve uncertainties, therefore in future research, it is important to reduce this uncertainty with the use of new, high-resolution climate model data. In addition to the clarification of climate-exposure, further investigation is needed for the characterization of the exposure of bank-filtration systems.

The drinking water protected areas have different climate sensitivity depending on their geological and hydrogeological settings. In supplying drinking water, drinking water protected areas of less climate sensitivity need to be assigned a greater role. Despite their sensitivity to climate change, bank-filtration systems are of major importance and can be the basis of perspective water supplies, as they have great reservoir capacities and constantly renewable reserves. It is advisable to replace the karstic and shallow-porous drinking water protected areas of increased climate vulnerability by new drinking water protected areas of greater security.

The status of groundwater, the effects of climate change and groundwater pressures need to be monitored on a regular basis. Similarly, it is necessary to register water consumption, typical consumer habits, and underlying social and economic factors. By the regular periodic evaluation of these observations, the identification and characterization of changes, it is possible to develop the appropriate climate adaptation measures.

In order to reduce the effects of climate change, we need to put greater emphasis on adaptation. Regarding the supply of water, regional supply systems can provide greater security, due to the importance of groundwater governance and the trans-regional redirection of water, as applied successfully already, nowadays.

In the regional developments, besides the climate vulnerability of the drinking water protected areas, we need to take into consideration the underlying social and economic factors. A constant drinking water supply can be guaranteed by the utilization of the drinking water reserves exclusively for drinking purposes, and the supply for other uses from different reserves, thus by the separation of the two systems.

As a part of the climate adaptation strategy, water consumption habits are necessary to be changed, towards a conscious and economic water use.

The investigation of the climate vulnerability of drinking water protected areas needs further research. It is necessary to extend the methodology of climate vulnerability assessment to a nation-wide scale, with the detailed assessment of climate exposure, climate sensitivity, water demand, and climate adaptation, accompanied by the participation of the other regional public waterworks.

As a result of climate change, there might be changes in the chemical composition of groundwater as well. It is of the utmost importance to consider these changes in the bank-filtration systems and the changes in the processes determining pollution propagation. These processes are expected to change according to the different climate scenarios and their detailed examination is needed, for preventive purposes.

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Vulnerability of natural landscapes to climate change – a case study of Hungary

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Abstract—Climate change is expected to exert considerable influence on natural ecosystems all over the world, though not all ecosystems are equally vulnerable to the changes. In this paper, an assessment framework of vulnerability of natural habitats to future climate change is presented, examining Hungary, Central Eastern Europe as a case study. A climate change impact, adaptation and vulnerability (CCIAV) assessment following IPCC traditions was applied, which operationalizes the concepts of exposure, sensitivity, potential impact, adaptive capacity, and vulnerability for natural ecosystems. Potential impact was quantified for the periods 2021–2050 and 2071–2100 based on regional climate models ALADIN-Climate and RegCM. Although the potential impact of future climate change was predominantly negative on the most climate sensitive forested habitat types of Hungary, for some of the grassland types we experienced positive predicted responses. Loess steppes and annual saline vegetation may thus partially benefit from climate change. The most climate vulnerable Hungarian regions are the Transdanubia (West Hungary) and the Northern Mountains (North Hungary) in terms of natural vegetation.

Key-words: climate vulnerability assessment, potential natural vegetation, habitat distribution model, global climate change, potential impact, habitat, prediction

1. Introduction

Vegetation is highly vulnerable to the predicted climate change both globally (*Berry et al.,* 2014) and in the Carpathian Basin (*Kovács-Láng et al.,* 2008, *Czúcz,* 2010; *Mátyás et al.,* 2010; *Czúcz et al.,* 2011b; *Móricz et al.,* 2013). By 2080, half of the 1350 European plant species studied by *Thuiller et al.* (2005) will become endangered by climate change. According to *Hickler et al.* (2012), the impact will be so great that also forestry and nature conservation will be significantly affected. It has also been proven that climate change detected during the last decades affected the distribution of species and survival of populations (*Parmesan,* 1996; *Walther et al.,* 2002; *Moore,* 2003; *Parmesan* and *Yohe,* 2003; *Edwards* and *Richardson,* 2004).

Based on the classification of *Hughes* (2000), *Walther et al.* (2002), *Rosenzweig et al.* (2007), the impacts of, and responses to, climate change are: 1) physiological and morphological changes; 2) phenological changes; 3) changes in the distribution; 4) changes in the composition and internal interactions of communities (including the food network), ecosystem structure and dynamics (including succession), ecosystem stability, ecosystem services; 5) genetic adaptation; 6) extinction. In this paper, we study changes in the potential distribution (3) of natural habitats, which expresses potential impact of climate change.

For assessing vulnerability to climate change, several methodological /conceptual frameworks have been developed (*Füssel* and *Klein,* 2006; *Polsky et al.,* 2007; *Cheng,* 2013; *Fritzsche et al.,* 2014), including the climate change impact, adaptation and vulnerability (CCIAV) assessment framework based on the terminology and concept of the Intergovernmental Panel on Climate Change (IPCC) as defined for the 3rd and 4th assessment reports (*Parry* and *Carter,* 1998; *Carter et al.*, 2007). The framework is sometimes called climate impact and vulnerability assessment scheme (CIVAS, e.g., *Csete et al.,* 2013). The CCIAV assessment adapted in this paper for natural habitats is a 2nd generation vulnerability assessment according to the classification by *Füssel* and *Klein* (2006), and is applied in several fields and regions (e.g., *Allen Consulting Group,* 2005). The implemented vulnerability concept is compatible with the risk concept of the 5th assessment report of IPCC (*Hoffmann et al.,* 2017). Although based on the three main components of the CCIAV (exposure, sensitivity, and adaptive capacity), the concept of vulnerability scoping diagram (VSD) of *Polsky et al.* (2007) and vulnerability framework of *Turner et al.* (2003) differ, since they suggest more permissive combination logic of the three components than the CCIAV concept implemented in this paper.

According to the framework, vulnerability to climate change is measured as the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with the adverse impacts of climate change (*Schneider et al.,* 2001). The vulnerability of an object is determined by the potential impact of climate change and by the capacity of the object to adapt to the changing conditions. Potential impact is further determined by the exposure of the object to climate change, as well as by its sensitivity (*Fig. 1*). This framework can be applied to any object exposed to climate change. In our case, the objects include both natural and semi-natural ecosystems (habitat types). They have several relevant physical and biological properties determining their sensitivity, as well as adaptive capacity, which dependencies enable us to explore the climatic vulnerability of ecosystems using a modeling approach (*Czúcz et al.*, 2009, 2011a).

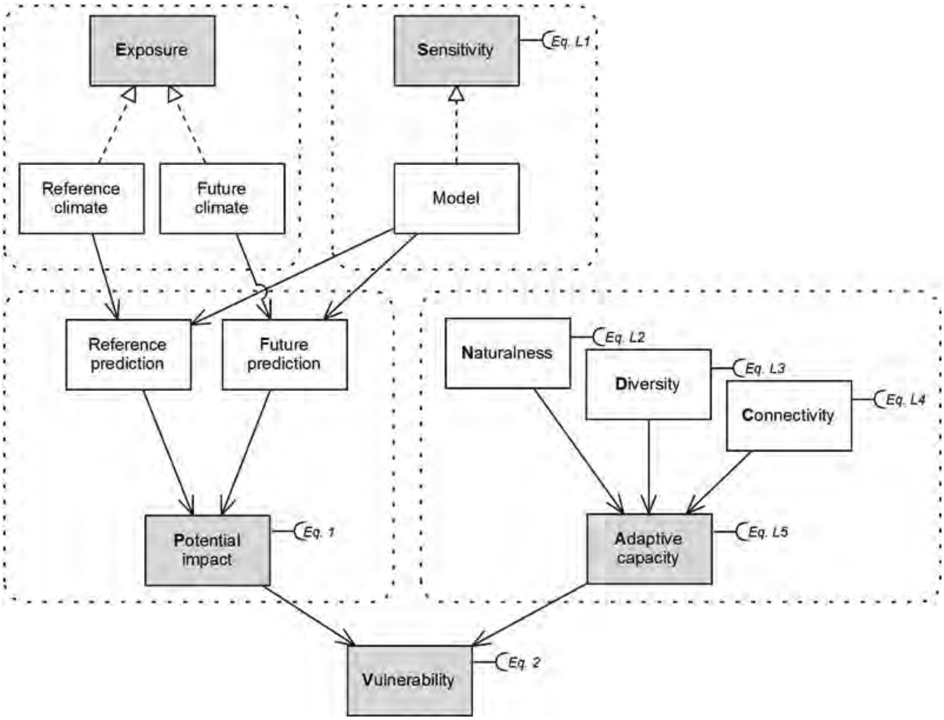


Fig. 1. Methodological flowchart of our research. Elements of climate change impact, adaptation and vulnerability (CCIAV) concept are shadowed, initial letters used hereinafter as abbreviations are typed bold, and equations/sources of calculation of sensitivity, potential impact, adaptive capacity, and vulnerability are also marked. For equation numbered with an initial *L*, please refer to *Lepesi et al.* (2017, in this issue, Section 2.2 and 2.3).

With respect to natural habitats, we define exposure (E) as the projected degree of change in the bioclimatic variables at a given location for a specific time horizon (*Table 1*). A separate study in this journal issue deals with the determination of climate sensitivity (S) for our calculations (*Lepesi et al.*, 2017, in this issue, Section 2.2), where we defined S of a habitat type as the degree to which climate-related factors influence the natural distribution of the habitat. In our study, exposure and sensitivity were directly determined from climate data and habitat distribution models, respectively (*Fig. 1*). Although the sensitivity of a habitat is best represented by the multivariate habitat distribution model itself, sensitivity to a certain exposure dimension, i.e., to climate in our case, can be characterized by its partial derivatives for communication purposes. Nonetheless, potential impact (P) measurement should be based on the original multivariate models. P is expressed by the difference of predicted probabilities of presence given the climate of the reference period and under climate change scenarios in a given location (logically, within the occurrence locations of the habitat). Adaptive capacity (A) is a relatively independent element of the modeled system, which should always be treated and communicated separately from the main impacts (*Hoffmann et al.,* 2017). We defined A as the capacity of the site and its landscape context to support successful adaptive processes for the studied habitat, which we describe in detail in a separate study in this issue (*Lepesi et al.*, 2017, in this issue, Section 2.3). While exposure is related to changes in climatic system, sensitivity and adaptive capacity is attributed to the natural/physical environment (*Fritzsche et al.,* 2014) and the inherent characteristics of the habitat. Vulnerability (V) is defined as the combination of potential impact and adaptive capacity. In this paper, we focused on the detrimental effects of climate change only and interpreted vulnerability in case of a negative impact only. The term 'vulnerability' can be resolved in several ways (*O'Brien et al.,* 2007). It is context-specific, and the factors that make a system vulnerable depend on the nature of the system and the type of effect in question (*Brooks et al.,* 2005; *Fellmann,* 2012).

In this paper we aimed at 1) implementing the CCIAV scheme of IPCC to natural habitats; 2) predicting the potential impact of future climate change on the distribution of the most climate sensitive climax and subclimax natural habitats of Hungary; 3) assessing the vulnerability of the habitats to future climate change according to two prediction periods and two climate models.

Table 1. The key elements of the CCIAV assessment framework and the definition and practical implementation of them followed in this study

Key element	**Abbreviation**	**Definition**	**Dependence**
Exposure	E	degree of change in the bioclimatic variables at a given location for a specific time horizon	timeline, climate model, location
Sensitivity	S	degree to which climate-related factors influence the natural distribution of the habitat	habitat type
Potential impact	P	difference of predicted probabilities of presence given the climate of the reference period and under climate change scenarios in a given location	habitat type, timeline, climate model, location
Adaptive capacity	A	capacity of the site and its landscape context to support successful adaptive processes for the studied habitat	habitat type, location
Vulnerability	V	combination of potential impact and adaptive capacity (only negative impact considered in this study)	habitat type, timeline, climate model, location
Overall vulnerability of natural vegetation	$\bar{V}$	maximum of the V of the most climate sensitive habitats at each location	timeline, climate model, location

2. *Materials and methods*

2.1. Potential impact

Our case study is based on our previous findings on potential distribution of climax and subclimax habitats of Hungary in the reference period (1977–2006) and two prediction periods (2021–2050, 2071–2100), according to two regional climate models (ALADIN-Climate 4.5; *Csima* and *Horányi,* 2008; RegCM 3.1; *Torma*, 2011; *Torma et al.,* 2011). Please refer to *Somodi et al.* (2017) and *Bede-Fazekas* (2017) for details of the data used and the habitat distribution models applied. Based on expert decision, a minimum threshold of relative importance of climate predictors was chosen to select the most climate sensitive habitats.

Further analyses were conducted for only on these 12 selected habitats. Please refer to *Lepesi et al.* (2017, in this issue, Section 3.1) for further details of the most climate sensitive habitats. The presented vulnerability assessment framework can, however, be applied to any habitat/species whose potential distribution can be predicted to a reference and a future period, based on any kind of environmental predictor data and any kind of modeling approach.

The first step to assess vulnerability is to quantify the potential impact (P) of climate change on the distribution of the climate sensitive habitats. P was defined as the difference between the probability of potential presence of the habitat in the future and that in the reference period (Eq. (1)), where f is the model function that returns predicted probability based on hydrological (H), topographical (T), edaphic (E), and climatic (C) predictors. To assess P, habitat distribution models (*Somodi et al.,* 2017) were applied to the reference and future environmental settings given both time periods and climate models separately. Thus, P is available in four combinations for each of the habitats investigated (2 periods × 2 climate models).

$$P = f\left(H, T, E, C_{reference}\right) - f\left(H, T, E, C_{future}\right) \tag{1}$$

Since the codomain of f is the interval of *[0; 1]*, P ranges from –1 to 1 with –1–0 representing positive impact of climate change on the habitat, while 0–1 represents adverse impact. This representation was chosen so that the target of this study, the negative climate impact receives large values.

2.2. Vulnerability

Vulnerability (V) depends both on P and adaptive capacity (A). The larger the P, the more vulnerable the habitat. This is in accordance with the core of the CCIAV concept: systems that are highly exposed, sensitive, and less able to adapt are vulnerable (*Allen Consulting Group,* 2005). High V can be mitigated with high A. The operationalization of the adaptive capacity concept is detailed in *Lepesi et al.* (2017, Section 2.3) in this issue. Codomain of A is the set of *{0; 1; 2; 3; 4}*, where *4* indicates the highest capacity to adapt to changing climate. Hence, the lack of adaptive capacity is defined as *5–A*. During our vulnerability analysis, we concentrated on the detrimental effects of climate change only, therefore only positive Ps (unfavorable climate impact) were considered (Eq. (2)).

$$V = \begin{cases} 0, & if \quad P \leq 0, \\ P * (5 - A), & if \quad P > 0. \end{cases} \tag{2}$$

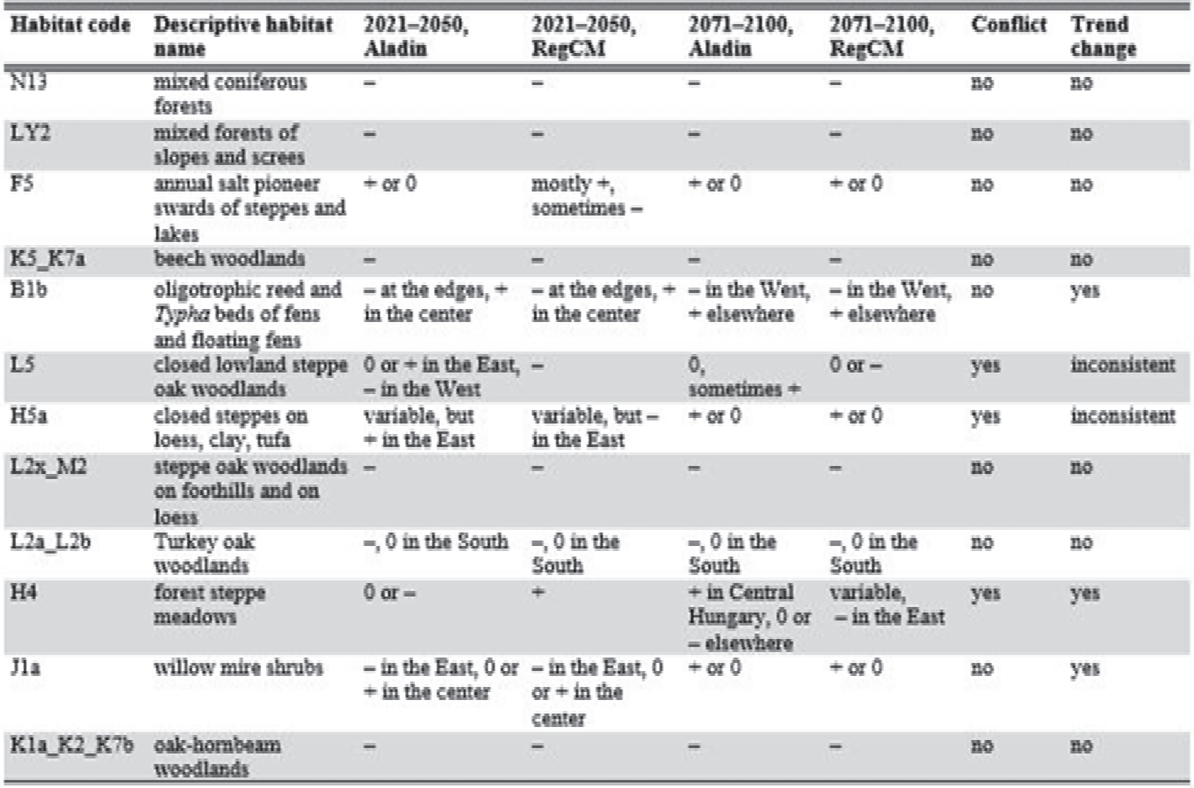
This formula ensured that lower A and higher negative impact (higher P) lead to higher V. Range of V is the interval of *[0; 5]*. Values were calculated separately for climate models and periods in the future, since potential impact and vulnerability can vary over time (i.e., they are dynamic) by climatic stimuli (*Smit* and *Wandel,* 2006; *Adger et al.,* 2007; *Fellmann,* 2012). High level aggregated indicators for the two studied time periods and the two climate models, i.e., the overall vulnerabilities ($\bar{V}$) of natural vegetation were estimated as the maximum of the V of the most climate sensitive habitats (*Lepesi et al.* 2017; in this issue, Section 3.1). This applied to each location where one or more of such habitats are present according to the MÉTA habitat database (*Molnár et al.*, 2007; *Horváth et al.*, 2008) in the reference period. To be consistent with the input data, all the layers of the vulnerability assessment, including the maps of P, were aggregated (upscaled) to the horizontal resolution of the climate models (0.1°) by calculation of the maximum values within the coarse cells. All calculations were performed in the R statistical programming environment (*R Core Team*, 2017).

3. Results

3.1. Potential impact of climate change

As expected, the potential impact of future climate change is predominantly negative on the twelve most climate sensitive habitats *(Table 2*). Sensitive forests are likely to be negatively affected (*Fig. 2*). The exception is L5 (closed lowland steppe oak woodlands), where climate models highly disagree regarding the outcome. A similar pattern emerged for forest steppe meadows (H4). Results for these two habitats have to be handled with care therefore. The two wetland types are likely to benefit at least partially from climate change. The most likely reason for this is an increased winter precipitation with climate change. Loess steppes (H5a) also have the potential to benefit from climate change. A benefit is especially striking for annual saline vegetation (F5), which is in good accordance with its adaptation to soil salinity, typical for arid climates (*Fig. 3*). Potential impact maps are available at *NATéR* (2017).

Table 2. Potential impact (*P*) of climate change on the twelve most climate sensitive habitats (*Lepesi et al*. 2017; in this issue, Section 3.1) ordered according to their sensitivity. The table summarizes the spatial pattern of potential impact within the country (–: negative, 0: neutral, +: positive). We also indicate if any conflict between predictions of climate models has been identified, and if a change in trends was discernible between the two periods. Habitats are encoded according to Bölöni et al. (2011). For actual distribution of the habitats, please refer to Bölöni et al. (2008, 2011) and Molnár et al. (2008).



Habitat code	**Descriptive habitat name**	**2021–2050, Aladin**	**2021–2050, RegCM**	**2071–2100, Aladin**	**2071–2100, RegCM**	**Conflict**	**Trend change**
N13	mixed coniferous forests	–	–	–	–	no	no
LY2	mixed forests of slopes and screes	–	–	–	–	no	no
F5	annual salt pioneer swards of steppes and lakes	+ or 0	mostly +, sometimes –	+ or 0	+ or 0	no	no
K5_K7a	beech woodlands	–	–	–	–	no	no
B1b	oligotrophic reed and *Typha* beds of fens and floating fens	– at the edges, + in the center	– at the edges, + in the center	– in the West, + elsewhere	– in the West, + elsewhere	no	yes
L5	closed lowland steppe oak woodlands	0 or + in the East, – in the West	–	0, sometimes +	0 or –	yes	inconsistent
H5a	closed steppes on loess, clay, tufa	variable, but + in the East	variable, but – in the East	+ or 0	+ or 0	yes	inconsistent
L2x_M2	steppe oak woodlands on foothills and on loess	–	–	–	–	no	no
L2a_L2b	Turkey oak woodlands	–, 0 in the South	–, 0 in the South	–, 0 in the South	–, 0 in the South	no	no
H4	forest steppe meadows	0 or –	+	+ in Central Hungary, 0 or – elsewhere	variable, – in the East	yes	yes
J1a	willow mire shrubs	– in the East, 0 or + in the center	– in the East, 0 or + in the center	+ or 0	+ or 0	no	yes
K1a_K2_K7b	oak-hornbeam woodlands	–	–	–	–	no	no

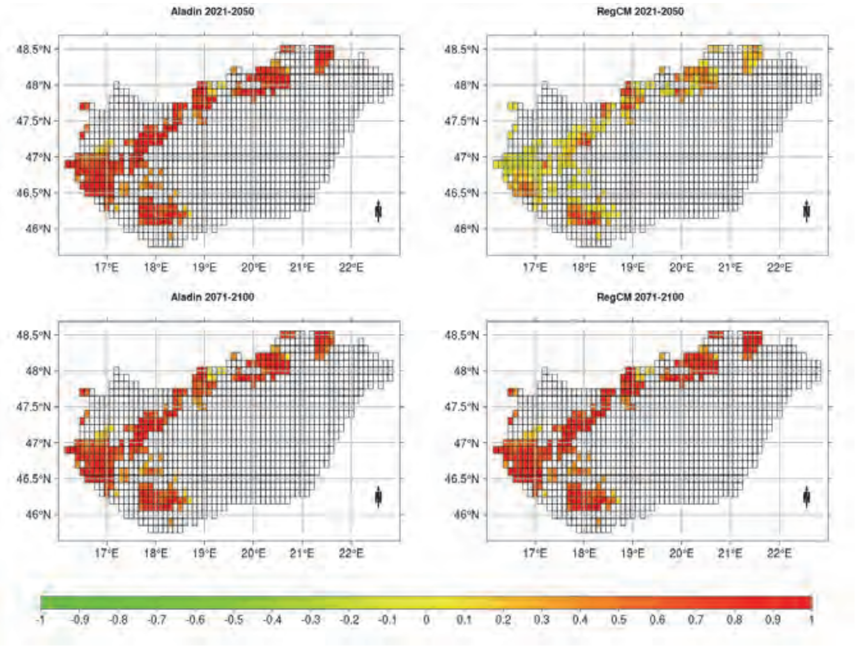


Fig. 2. Potential impact (*P*) of climate change to existing stands of beech forests (K5_K7a). Subfigure titles refer to the climate model and the future period in relation to which *P* was examined. Unfavourability of *P* increases from green to red.

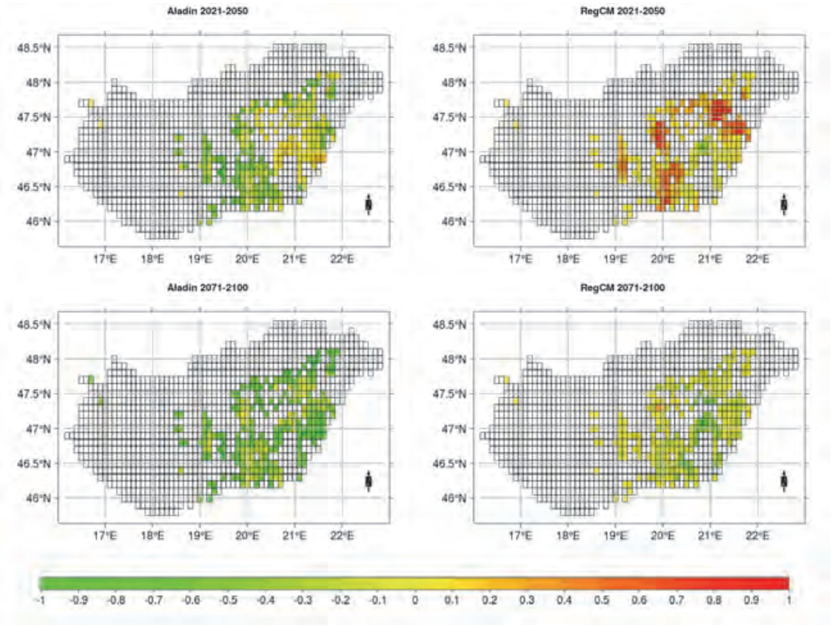


Fig. 3. Potential impact (*P*) of climate change to existing stands of annual salt pioneer swards of steppes and lakes (F5). Subfigure titles refer to the climate model and the future period in relation to which *P* was examined. Unfavourability of *P* increases from green to red.

3.2. Vulnerability of habitats

The estimated vulnerability to future climate change has high variance across the habitats, periods, regional models and regions (*Table 3*). An agreement between the two models indicates robust results. Some habitats seems to be consequently vulnerable (N13) or vulnerable in most of the periods/models/regions (L2a_L2b, K5_K7a, K1a_K2_K7b; *Fig. 4*), while others may not be remarkably vulnerable (F5, B1b, H5a, H4, *Fig. 5*). Although RegCM shows higher *V* in general, long-term (2071–2100) vulnerability of natural habitats is consistent given the two climate models. Natural vegetation appears most vulnerable in Western and Northern Hungary, as well as in the easternmost corner of Hungary. This is probably in connection with forests being the dominant natural vegetation there. Models disagree, however, in the degree of short-term (2021–2050) *V*.

Table 3. Vulnerability (V) to climate change of the twelve most climate sensitive habitats ordered according to their sensitivity. The table summarizes the spatial pattern of vulnerability within the country (0: low, --: medium, –: high; relative to the highest value). Habitats are encoded according to *Bölöni et al.* (2011). For the name of habitats please consult to *Table 2.*

Habitat code	**2021–2050, Aladin**	**2021–2050, RegCM**	**2071–2100, Aladin**	**2071–2100, RegCM**
N13	–	–	–	–
LY2	variable, mainly 0 and --, – in the South	variable, mainly 0 and --, – in the South	variable, mainly 0 and --, – in the South	variable, mainly 0 and --, – in the South
F5	0	Variable	0	0
K5_K7a	--	0	--	--
B1b	0, -- and – in the West	0, -- and – in the West	0, -- and – near Lake Balaton	0, -- and – in the West
L5	0	Variable	0	0, -- and – in the East
H5a	0	variable, mainly 0 and --	0	0, -- in the West
L2x_M2	0, sporadically --	Variable	0, sporadically --	variable
L2a_L2b	–, 0 and – in the Southwest	– in the North, 0 in the Southwest	–, 0 and – in the Southwest	–, 0 and – in the Southwest
H4	variable, mainly 0 and --	0	0	variable, mainly 0 and --
J1a	0, -- and – in the East and Southwest	0	0, -- and – in the East and Southwest	0
K1a_K2_K7b	--, sporadically –	0 and --, – in the Northwest	--, sporadically –	--, sporadically –

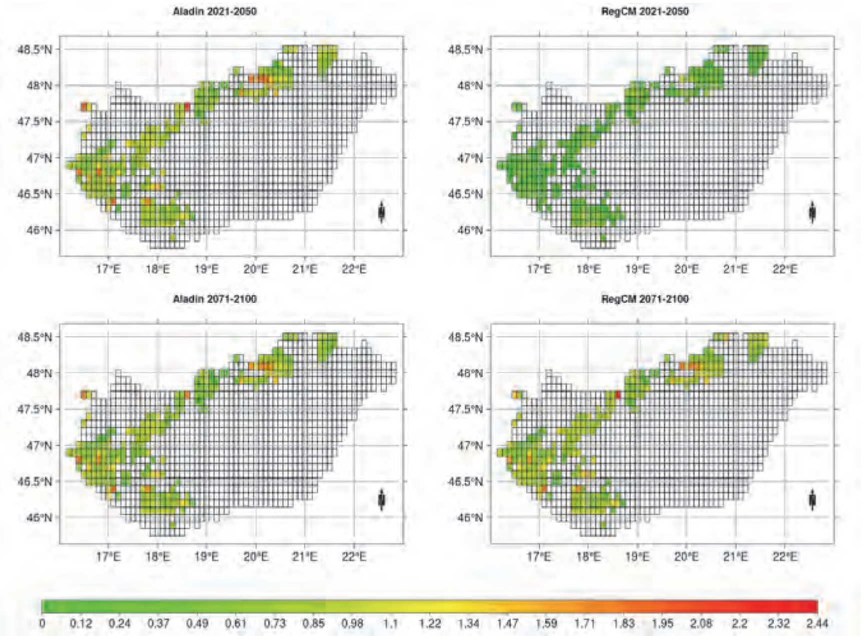


Fig. 4. Vulnerability (*V*) of the existing stands of beech forests (K5_K7a). Subfigure titles refer to the climate model and the future period in relation to which *V* was examined. *V* increases from green to red.

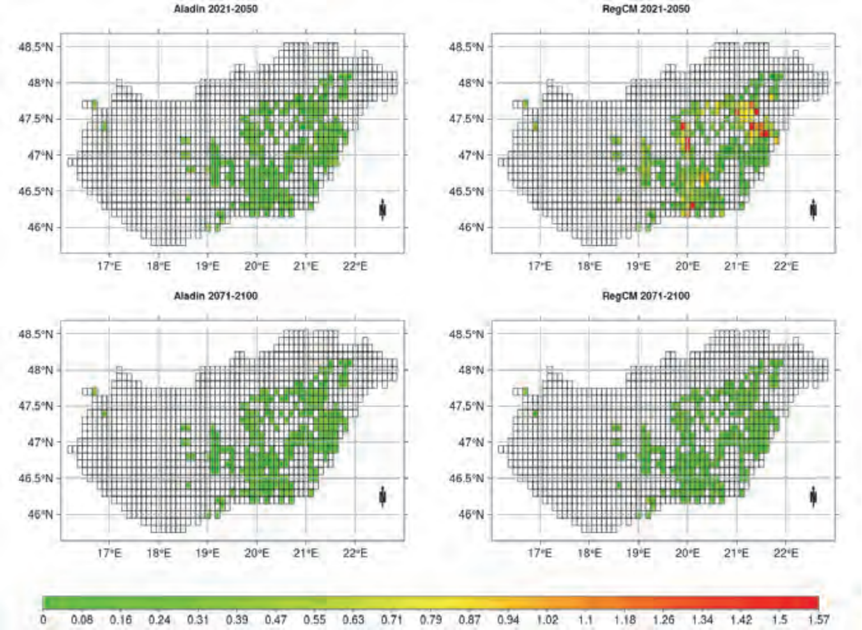


Fig. 5. Vulnerability (*V*) of the existing stands of annual salt pioneer swards of steppes and lakes (F5). Subfigure titles refer to the climate model and the future period in relation to which *V* was examined. *V* increases from green to red.

Overall vulnerability of the twelve most sensitive habitats is only sporadically striking (*Fig. 6*). Except for the 2021–2050 period according to RegCM model, in which case the vulnerable spots are not arranged systematically, Western and Northern part of Hungary is more vulnerable than the Southeastern one. While Aladin shows a similar overall pattern in case of the two prediction period, RegCM shows considerable differences. According to the short-term estimations using RegCM, V is lower in Central Transdanubia and higher in the Southeast part of the Great Hungarian Plain than at the long term. Additionally, to the broader pattern we see an increased V South to Lake Balaton and in the North-western areae. South to Lake Balaton, there are closed forests at the edge of their environmental tolerance, therefore they are particularly vulnerable to climate change.

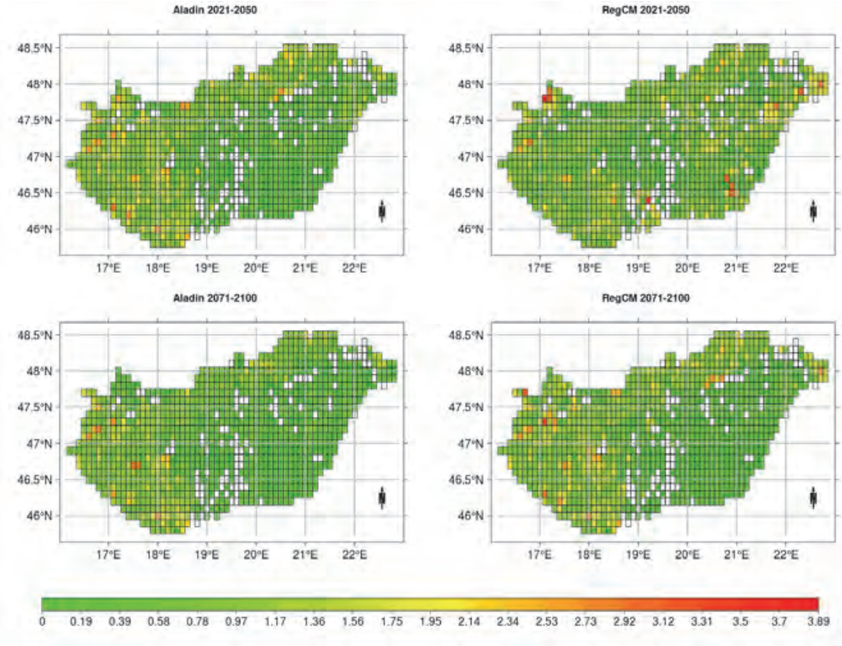


Fig. 6. Overall climatic vulnerability of the most climate sensitive habitats of Hungary ($\bar{V}$). Subfigure titles refer to the climate model and the future period in relation to which $\bar{V}$ was examined. $\bar{V}$ increases from green to red.

4. Discussion

4.1. Discussion of the framework

The analysis presented shows that the elements of the CCIAV framework can be effectively interpreted in, and adapted to, specific sectorial contexts, such as natural habitats. The specific solutions (components of *A*, aggregation schemes etc.) can be used as an orientation in further similar studies. Furthermore, the entire analysis can be reused as an embedded part of a large multi-sectoral CCIAV assessment.

Potential impact (P) of climate change was estimated, in any location, as the difference of future and reference probability of presence (Eq. (1)). In methodological terms, calculation of the difference of habitat suitability indices (for species) results in the same approach (e.g., *Vallecillo et al*., 2009). The presented method is more detailed than the widespread gain/loss/turnover calculations (e.g., *Hamann* and *Wang*, 2006; *Harrison et al*., 2006; *Benito Garzón et al*., 2008; *Ogawa-Onishi et al*., 2010; *Robiansyah*, 2017) and their aggregated form, the change of climate envelope richness (e.g., *McKenney et al*., 2007; *Attorre et al*., 2011), since it estimates P on a continuous scale instead of the binary output of gain/loss method (or the sum of the gains/losses in case of the change climate envelope richness. Furthermore, the latter ones can only be used in case of binary presence/absence output of distribution models that need a threshold often specified unfoundedly and subjectively (*Jiménez-Valverde* and *Lobo*, 2007; *Lobo et al*., 2008; *Liu et al*., 2015). Some researchers present P by simply displaying current and future potential distributions side by side (e.g., *Kriticos et al.,* 2003; *Guo et al*., 2016), or partly (e.g., *Trájer et al*., 2014) or fully (e.g., *Bede-Fazekas et al.,* 2014) overlapping each other, instead of calculating the difference. Since those methods pass the responsibility to the reader to draw conclusions, we suggest calculating and presenting P in a difference map, possibly next to the current and future distribution maps (similarly to maps presenting potential impacts on environmental factors, e.g., *Blanka et al*. (2013), *Mezősi et al*. (2014)). Calculation of P, and therefore V, is not inextricably linked to climate change (*Glick et al*., 2011); the proposed framework can be applied in, inter alia, land cover change assessments as well.

The most central part of a CCIAV assessment is quantifying vulnerability (V). Although some researchers consider V simply as the inverse of resilience (*De Wrachien et al*., 2008), we argue that V is essentially a (set of) high-level aggregated indicator(s), which establish a balanced information over all of the individual CCIAV components. The main goal of V is to give a quick but insightful overview of the assessment outcomes for decision makers, policy uses and the general public. As there are many valid possible policy and decision-making contexts, there is no single default aggregation formula or V indicator either. The construction of a V indicator and the resulting vulnerability map highly depends on the decisions taken during its construction, which should ideally be customized for a specific policy context and designed in a participatory process involving key stakeholders. The overall vulnerability index of the twelve most sensitive habitats presented in this paper is only one option, created for a general nature conservation-planning context. This unweighted statistic can be used for framing general policy discussions, but we encourage all users of our data sets to use custom weightings of V of the selected habitats, or, even more, aggregating strategies for P and A components tailored to their specific needs and the problem in focus. For country-wide assessments we suggest to develop a structured aggregation model (e.g., multi-criteria decision analysis, MCDA) with the involvement of all relevant stakeholders.

Although some authors (e.g., *Downing et al.,* 2001) have argued that vulnerability is a relative, rather than absolute, measure (*Füssel* and *Klein*, 2006), we developed in this paper an easy to use vulnerability index for an interval scale within [0; 5]. Note, however, that the calculated adaptive capacity index is relative (*Lepesi et al.*, 2017, in this issue, Section 4.2), hence, vulnerability is relative as well.

Although only positive Ps (unfavorable climate impact) were considered during the calculation of V since we concentrated on the detrimental effects of climate change, if necessary, also negative Ps can be used. This may result in negative Vs, which is somewhat contradictory to the meaning of the word 'vulnerability' but nevertheless can be easily interpreted.

4.2. Interpretation of the results

As most of the zonal habitats of Hungary can be found among the twelve most climate sensitive habitats (*Lepesi et al.*, 2017, in this issue, Section 3.1), our results give a reliable overview about the expected ecological impacts of climate change. As a general rule, the modeled *P* was predominantly negative for forested habitat types, but for grassland types we experienced at least partially positive predicted responses in most of the cases. This result is congruent with the expectation that Hungary, lying roughly at the biogeographic boundary between forest and steppe zones (*Zólyomi,* 1989; *Molnár et al.,* 2012), should experience a shift towards more open habitat types. Furthermore, the natural vegetation of mountainous areae, predominantly forests, appears to be more vulnerable than that of the lowlands. This foreshadows that maintaining forests in Hungary might become more difficult (*Czúcz et al.,* 2011b) and that more open habitat types may become more sustainable. It is also important to note that the lower level of *P* and *V* in the lowland landscapes applies only to the natural landscape elements there (i.e., space covered by natural or seminatural vegetation). The *V* of agricultural fields or settlements can greatly differ from this pattern.

We can be most confident in estimations if the results regarding all climate periods and climate models consistently suggests reliable results. This kind of consistence was experienced for all zonal forests and two of the grasslands, for example. Estimations should be handled with care however, when climate models disagree in outcome or when trends change between the two future periods. We did experience such patterns, as well. In such cases, future research should cover more climate models and wider time periods to reduce uncertainty. On the other hand, it is important to view uncertainty as a necessary component of any climate projections, as well as the impact assessments relying on them (*Heikkinen et al.,* 2006; *Hanspach et al.,* 2011; *Beale* and *Lennon,* 2012; *Thuiller,* 2014). Uncertainty should not be considered as a shortcoming of the analysis, rather as an informative warning that the behavior of some objects or subsystems is less predictable and their prediction is therefore less reliable (*Heuvelink et al.,* 2007; *Gerharz et al.,* 2010). This can be caused by several factors, including uncertainties in the input data, a limited understanding of system functioning, but also can be an inherent characteristic of the object in question, which cannot and should not be eliminated. Low prevalence of a habitat (e.g., steppe oak woodlands on foothills and on loess – L2x_M2), therefore too few data records used for training of the habitat distribution model, can increase uncertainty of potential impact and vulnerability estimations. This may result in under or overprediction. Informed decisions need to be aware of the sources and magnitude of uncertainties.

Future research needs to be directed towards assessing a wider range of climate scenarios, time periods and habitats as well as providing detailed analysis of the *P* and *V* results for questions in the field of ecology.

4.3. Application of the results

The maps produced allow a wide range of applications. There are several policy sectors where the final and intermediate results of a climatic vulnerability assessment on natural ecosystems can provide easily interpretable and relevant inputs (*European Environment Agency*, 2005; *Glick et al*., 2011). However, there is a great need for adaptation policy frameworks and effective result communication to incorporate the output of the assessments in adaptation strategies (*European Environment Agency*, 2005). Major applications of vulnerability assessments are expected in the field of nature conservation and restoration prioritization, as well as in landscape evaluations (*Loidi* and *Fernández-González*, 2012). Prioritizing requires the identification of vulnerable systems (*Allen Consulting Group*, 2005). Indeed, maps from a habitat-oriented vulnerability assessment can effectively support the prioritization of the different stands of a threatened habitat type for nature conservation (*Glick et al*., 2011; *McNeeley et al*., 2017). Locations, which are least vulnerable to climate change, are likely the ones that can be most cost-effectively conserved in their current state. Hence, vulnerability assessments enable efficient allocation of financial resources (*Upgupta et al*., 2015; *McNeeley et al*., 2017). On the other hand, high V does not mean that a stand should be given up by nature conservation (*Glick et al*., 2011), it rather shows that in those location a nature conservation action should take the form of promoting natural processes, i.e., the natural transformation of a stand to a less sensitive habitat or even to a habitat that endures the new climate better. Emphasis is put on natural processes here, which can also be a target of conservation and may thus serve biodiversity protection, as well as ecosystem service maximization (*Prach* and *del Moral*, 2014; *Prach et al.,* 2016).

For restoration and forestry planning, it is also crucial to consider the future state of the location. Modern restoration theory and practice is moving away from restoring past vegetation and aims at creating self-sustainable stands (*Somodi et al.,* 2012; *Török et al.,* in press), which maintain themselves under the actual, as well as the future climatic conditions. To this end, it is important at each studied location to identify the list of habitats that find their requirements both now and in the future, and least vulnerable habitats should be selected as restoration targets. For example, according to our results and that of other studies (*Mátyás et al*., 2010; *Czúcz et al*., 2011b), beech forests (K5_K7a) seem to be relatively inappropriate to become such restoration targets, and forestry decisions may have to weight in their vulnerability at places. However, ecosystems with natural species composition and dynamics generally need less maintenance efforts and provide a more balanced portfolio of ecosystem services than artificial green spaces, thus natural habitat types should be preferred as restoration targets wherever possible.

As our analysis was designed and restricted to existing stands, our results are not fully informative for local restoration periodization purposes. However, the messages that emerged from this vulnerability analysis are useful for restoration considerations as well. Grasslands (loess steppes and saline ones) that appeared to benefit from climate change in our analysis are among the potentially most promising (sustainable and cost-effective) restoration targets (c.f., the similar results of *Czúcz,* 2010). From forests, turkey oak woodlands (L2a_L2b) appear to be the best candidates, because their high *A* balance the negative direct *P* that even this forest type seems to face.

Landscape evaluation and landscape planning can benefit from the use of our results (*Loidi* and *Fernández-González,* 2012; *Bede-Fazekas,* 2017). Any adjustment in the elements of ecological networks or green infrastructure has to consider whether the proposed change in the network will make it more or less vulnerable under climate change. Furthermore, restoration efforts may be efficiently directed to network elements with high vulnerability.

Broad-scale landscape architecture, i.e., spatial and regional planning, and landscape rehabilitation may gain information from our result that enables them to be more scientifically sound and to be more prepared for potential land use conflicts (*Golobič* and *Žaucer,* 2010; *Crist et al.,* 2014). Those landscape architecture and rehabilitation projects that are informed by our results are able to reflect more on ecological processes and let the decision makers cost-effectively avoid conflicts and disasters that are connected to natural patterns and processes to a certain degree, including infrastructure investments on vulnerable areae, policy-driven land use change (e.g., afforestation, *European Environment Agency*, 2005), top-down designation of nature reserve areae (*Glick et al.,* 2011), etc. Recognizing the future perspectives on P, A, and V of (semi)natural habitats should significantly and essentially alter some widely used and non-informed landscape planning strategies (*Bede-Fazekas,* 2017).

5. Conclusions

Our results indicate that the CCIAV framework of IPCC can be effectively adapted to (semi)natural habitats. According to our simple and straightforward implementation of the framework, vulnerability of habitats and overall vulnerability of the vegetation can be assessed based on adaptive capacity and the potential impact of climate change calculated from predicted potential distribution maps. The results show that vulnerability highly vary across regions, climate models, prediction periods and habitats. Hence, detailed ensemble approach is always necessary when only one, easily interpretable vulnerability indicator of the vegetation is aimed to be developed and presented to decision makers.

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Adaptive capacity of climate sensitive habitats to climate change in Hungary

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Abstract—Several natural habitats are expected to be sensitive to climate, and their vulnerability to future climate change can be further increased by their insufficient capacity to adapt to the changes. Therefore, it is increasingly pressing to set up methodologies for assessing sensitivity and adaptive capacity of natural ecosystems for enhancing detailed climate change impact, adaptation, and vulnerability assessments. In this paper, we first provide a methodology to quantify the sensitivity of a natural habitat based on habitat distribution models. Next, we selected the 12 most climate sensitive habitats of Hungary as a case study. We also developed a composite adaptive capacity index, which was applied to the selected habitats and used as an input in the climate change impact, adaptation, and vulnerability assessment described. Our adaptive capacity index consists of three main components describing the naturalness, diversity, and connectivity of the studied natural habitats. According to our results, adaptive capacity of the climate sensitive habitats of Hungary is generally lower than it needs to be to cope with the predicted climate change of the 21st century.

Key-words: sensitivity, global climate change, habitat, adaptation, connectivity, naturalness, diversity

1. Introduction

In the assessment of climate change effects, the most widely used methodological framework is the climate change impact, adaptation, and vulnerability (CCIAV) assessment developed by the Intergovernmental Panel on Climate Change (IPCC; *Parry* and *Carter,* 1998; *Carter et al.,* 2007; *IPCC*, 2007), sometimes also named as Climate Impact and Vulnerability Assessment Scheme (CIVAS). According to this framework, vulnerability to climate change is the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with, the adverse impacts of climate change. The vulnerability of an object is determined by the potential impact of climate change and by the object's capacity for adaptation (also termed adaptive capacity) to the changing geophysical, biological, and socio-economic conditions. The potential impact is determined by the exposure to the climate change and climate sensitivity.

This paper focuses on compartments of the framework linked to the objects affected by climate change and are independent of the climate change effect itself: sensitivity (*S*) and adaptive capacity (*A*). The framework can be applied to several kinds of objects/systems that are exposed to the changing climate. Here we studied habitat types, units of natural and semi-natural ecosystems. Since habitats have several relevant biological and physical properties that influence their *S* and *A*, by studying these characteristics we could determine these key elements of vulnerability assessments (*Czúcz et al.*, 2011; *Glick et al.,* 2011). Similarly to the concept of potential impact (*Glick et al.,* 2011), *A* is not inextricably linked to climate change, the term can be applied to a broader range of stresses (*Yohe* and *Tol,* 2002).

Impacts of climate change, adaptive capacity, and vulnerability can be studied from a variety of approaches. They are explorable both from the perspective of society (*Haddad,* 2005; *Walker et al.,* 2002) and, as in this paper, from the perspective of nature (*Parmesan* and *Yohe,* 2003). Note, however, that the two can not be separated sharply from one another (*Adger et al.,* 2005, *McNeeley et al.,* 2017).

According to *IPCC* (2007, Glossary), *S* is the degree to which a system is affected by climate variability or change. The effect may be direct or indirect, as well as adverse or beneficial. The *S* of a system can be characterized by the degree of direct impact (either adverse or beneficial) that is caused by a 'unit change' in the climatic environment (*Czúcz,* 2010). *S* may depend on innate physiological or biological variables (*Glick et al.,* 2011).

When calculating *S* of habitats/associations, both species composition and structure should be taken into consideration (*Bartha,* 2004). It can be measured at various scales from global (*Smith* and *Hitz,* 2003) to regional. In this paper, we focus at the national scale identifying the most climate sensitive habitats (*CSH*s) of Hungary based on the predictor selection of potential distribution models that relate the distribution of habitats to environmental variables.

The adaptive capacity indicator framework used in our study unites the indicators or conceptual models of several disciplines. Such frameworks share a common question of interest: how can a system, through its internal reorganization, cope with or mitigate the external effects it is exposed to. Different mechanisms of autonomous or planned adaptation can be triggered or implemented in preparation for or in response to impacts of climate change (*Adger et al.,* 2005). Characteristics of the system that can be estimated from its current state frequently determine its future behavior (*Kelly* and *Adger,* 2000) at various scales from global systems to local populations of a species (*Kimbras,* 2004).

The *A* of habitats to climate change can also be estimated from their current characteristics, including the broader landscape context they are embedded in (*Czúcz et al.,* 2011). *A* in this case corresponds to the feasibility of the implementation of adaptation (*Füssel* and *Klein,* 2006), or more explicitly, *A* is 'the ability of a system to adjust to climate change' in order to 'moderate potential damages, to take advantage of opportunities, or to cope with the consequences' (*IPCC*, 2007, Glossary). For the 'components' of a habitat, i.e., the species constituting it, *A* may be considered a factor of their internal traits (e.g., their ability to migrate, evolve, or modify their behavior) or external conditions (e.g., barriers) (*Glick et al.,* 2011). In the case of ecosystems, adaptation is predominantly autonomous adaptation, which 'does not constitute a conscious response to climatic stimuli but is triggered by ecological changes' (*IPCC*, 2007, Glossary). Consequently, adaptation includes not only genetic evolutionary adaptation (*Glick et al.,* 2011), but also any systemic adjustment processes: local resilience, refugium-based adaptation, and migration-based adaptation (*Czúcz et al.*, 2011).

Based on all these theoretical considerations, we next built a framework for *A* based on the quantification of the most important adaptive processes. Due to the lack of species-level data at such a wide range of habitats, as well as due to the theoretical complexity of integrating them (even if they were at hand) at so large numbers as they occur in natural habitats, we excluded genetic adaptation from this framework. In addition, this mechanism is considered to be of little practical relevance anyway, as the evolution of most macroscopic organisms will not be able to cope with the expected rapid climate change (*Gienapp et al.,* 2008). Accordingly, our framework of *A* relies on the other three adaptive mechanisms: natural capital index naturalness indicator (local resilience), Shannon diversity index (refugium-based adaptation) and connectivity (migration-based adaptation).

The most important goal of this study was to provide inputs for a detailed climate change impact, adaptation, and vulnerability (CCIAV) assessment (*Bede-Fazekas et al.*, 2017, in this issue) by

- creating the methodological basis of sensitivity analysis of natural habitats based on ecological habitat distribution models;

- selecting the most climate sensitive habitats (*CSH*s) of Hungary as a case study;
- developing an adaptive capacity index for habitats, based on naturalness, diversity, and connectivity measures;
- estimating the adaptive capacity of *CSH*s of Hungary.

2. Materials and methods

2.1 Potential natural distribution models

Analysis of *S* and *A* of the habitats was based on previously built habitat distribution models used for modeling the potential natural vegetation of Hungary, as detailed in *Somodi et al.* (2017) and *Bede-Fazekas* (2017). These models were Boosted Regression Tree models (BRT; a.k.a. Gradient Boosting Model, GBM; *Friedman et al.,* 2000; *Friedman,* 2002; *Schapire,* 2003) built for each of the major natural habitat types of Hungary separately. The use of BRT as a predictive ecological model is relatively new (*De'ath,* 2007; *Elith et al.,* 2008), but several studies have pointed out its outstanding predictive power (*Elith et al.,* 2006; *Bühlmann* and *Hothorn,* 2007; *Guisan et al.,* 2007). Training of these models relied on observed vegetation data originated from the Hungarian Actual Habitat Database (MÉTA; www.novenyzetiterkep.hu/english/node/70; *Molnár et al.*, 2007; *Horváth et al.*, 2008) and hydrologic, edaphic (*Pásztor et al.,* 2015), topographic (USGS*,* 2004), and climatic (*Szalai et al.,* 2013) environmental variables. The predictors were aggregated to the hexagons of MÉTA database using descriptive statistical measures (minimum, maximum, mean, and standard deviation) or extracted to the center of the hexagons [please refer to *Somodi et al.* (2017) and *Bede-Fazekas* (2017) for details].

Based on these distribution models, we made predictions to two future periods (2021–2050, 2071–2100). For both of the prediction periods, two regional climate models provided the climate data with similar temporal (daily) and horizontal (0.1°, approximately 10 km) resolution as that of the reference climate data (1977–2006). The two models, ALADIN-Climate 4.5 (*Csima* and *Horányi,* 2008; hereinafter: Aladin) and RegCM 3.1 (*Torma*, 2011; *Torma et al.,* 2011), are based on the A1B emission scenario of IPCC SRES (*Krüzselyi et al.,* 2011; *Sábitz et al.,* 2015). Scenario A1B describes the radiative forcing of 850 ppm CO_2 concentration by 2100 (*Nakićenović et al.,* 2000). In terms of the forcing, A1B is equivalent to the RCP8.5 scenario by the middle of the century, and runs between RCP6.0 and RCP8.5 by the end of the century (*Burkett et al.,* 2014). While Aladin was developed under an international collaboration by Météo France (*Spiridonov et al.,* 2005), RegCM was built by the US National Center for Atmospheric Research and further improved by the International Centre for Theoretical Physics in Trieste (*Giorgi et al.,* 1993a, 1993b). Finally, *Torma et al.* (2008) adapted

RegCM to the Carpathian Basin. ARPEGE-Climat/OPA and ECHAM5/MPI-OM provided the boundary conditions for Aladin and RegCM, respectively (*Krüzselyi et al.,* 2011).

In case of the reference climate dataset and the four future climate datasets, monthly average of minimum, maximum, and mean temperatures and monthly precipitation sum were calculated from the daily series, and then averaged over the 30-year periods. Future monthly data were bias corrected with additive (temperature) and multiplicative (precipitation) bias terms (i.e., Delta Change method), using the period 1961–1990 for calculation of the bias by comparison of observed and modeled climate. The coarse-resolution monthly climate surfaces were downscaled to the resolution of the vegetation data with regression kriging, a method integrating kriging (*Krige,* 1966) and linear regression, in a way similar to the downscaling of the reference climate data. Kriging is an exact, non-convex, linear, stochastic, and local (in some case with global trend) interpolator, that produce a gradual surface (*Hartkamp et al.,* 1999; *Li* and *Heap*, 2014). Although some types of kriging are univariate, regression kriging is multivariate, since it uses auxiliary variables (*Li* and *Heap*, 2014). From the fine-resolution climate data, seasonal averages/sums and 19 bioclimatic variables (*Nix,* 1986) were calculated. Please refer to *Somodi et al.* (2017) and *Bede-Fazekas* (2017) for further details about the data used, data preprocessing, predictor selection, and building the models of the habitats.

2.2 Sensitivity of habitats

BRT offers the possibility of automatic variable selection based on the frequency of explanatory variables in the subtrees of the model (*Elith et al.,* 2008). It also provides an estimation of variable importance for predictors remaining in the final, simplified model according to a formulae developed by *Breiman et al.* (1984) and *Friedman* (2001) and implemented in the package 'gbm' (*Ridgeway,* 2017) of R statistical environment (*R Core Team*, 2017). Importance is calculated based on the number of times a variable is selected for splitting, weighted by the squared improvement to the model as a result of each split, and averaged over all trees" (*Friedman* and *Meulman,* 2003).

Since importance is a measure that helps to assess how influential a variable is, climate sensitivity (S) of a habitat can be estimated by summation of the relative importance of all the climatic predictors in its final model:

$$S = \sum_{c \in C} \left(\frac{1}{M} \sum_{m=1}^{M} I_c^2(T_m) \right), \tag{1}$$

where c is one of the climatic predictors C, M is the number of trees, and $I_c^2(T)$ is the squared importance of the subtree T according to *Breiman et al.* (1984)). A 0.55 minimum of relative importance was chosen to select the most climate sensitive habitats (*CSH*s). The threshold was chosen based on expert decision, so that the climate predictors have at least 0.5 relative importance, i.e., their importance outweights that of all other variables together. On the other hand, we limited the range of habitats to one fifth of the studied habitats (n = 60). Thus, 12 habitats were selected for further analyses.

2.3 Adaptive capacity of habitats to climate change

The adaptive capacity (*A*) of the habitats was estimated based on three components: local resilience, refugium-based adaptation, and migration-based adaptation. Two of the three components were first calculated at the resolution of the MÉTA database (consisting of 35 ha 'hexagons', see *Molnár et al.*, 2007; *Horváth et al.*, 2008), while the third one (refugium-based adaptation) was directly computed at the level of the climate grid cells. One of the three indices (migration-based adaptation) was computed habitat-wise, while the other two indices characterize the landscape/environment, and thus, produce the same map for any of the studied habitat types. Components of *A* were only calculated for the 12 selected *CSH*s (see Chapter 3.1. for details). To be compatible with the input data of the habitat distribution models, all the *A* estimation outputs were eventually aggregated (upscaled) to the horizontal resolution of the climate models (0.1°). All the calculations were implemented in the R statistical environment (*R Core Team*, 2017).

Local resilience is best estimated by the naturalness (*N*) of the landscape (*Cook,* 2002, *Czúcz et al.,* 2012). Accordingly, we chose the vegetation-based natural capital index, a habitat-level naturalness metric based on the MÉTA database (*Czúcz et al.,* 2008) to represent local resilience. The natural capital index of a MÉTA hexagon (*N'*) is expressed as the product of ecosystem quality and quantity, while the *N* of an entire grid cell was defined as the maximum of the *N'*s of the hexagons found within the grid cell of interest:

$$N'_i = \frac{1}{\sum_{h\in H} A_h} \sum_{h\in H}(Q_h A_h)\,;\; N_g = \max_{i\in g} N'_i, \tag{2}$$

where *A* is the area and *Q* is the quality of habitat *h* that is element of the habitat pool *H*, *i* is the studied location (MÉTA hexagon) found within the grid cell of interest *g*.

Refuge-based adaptation is more successful if the landscape is more heterogeneous, and this aspect can be best quantified by landscape diversity indices (*Czúcz et al.,* 2011). We choose the widespread Shannon diversity metric (*Shannon,* 1948) to quantify this aspect based on the habitat data from the MÉTA database. Habitat frequencies (i.e., number of the hexagons where the habitat is present) within the cells of the climate grid were used as input, thus we estimated the habitat diversity (*D*) of a grid cell as

$$D_g = -\sum_{h \in H_g} \left(p_h * \begin{cases} \ln p_h, if\ p_h > 0 \\ 0, if\ p_h = 0 \end{cases} \right), \tag{3}$$

where *h* habitat is the element of the *H* habitat pool of the grid cell of interest *g*, and *p* is the frequency of the habitat.

Migration-based adaptation relies on the quantification of the connectivity (*C*) of the landscape. There is a wide variety of landscape connectivity assessment options. A major dichotomy exists along whether the indices reflect structural or functional features of the landscape. Among the former, several measures are based on the presence of corridors, others on distances or graph theory also, accounting for transversability. There are measures based on the amount of habitat in the landscape, too, which can also be extrapolated towards percolation-related measures. Connectivity indices reflecting functional aspects of the landscape often rely on the probability of moving and use matrix permeability as well (*Kindlmann* and *Burel,* 2008).

As our study involves habitats, rather than individual organisms, functional connectivity indices would not be appropriate. The many constituting species are likely to have different functional requirements, e.g., matrix permeability. On the other hand, the structural aspect of connectivity can be useful, because the proximity of similar patches, the presence of corridors, and other landscape elements can undoubtedly enhance the migration process for various constituent species of the habitat, even if to a different degree per species. Therefore, we quantified the migration-based *A* by an index based on Euclidean distance (*Czúcz et al.,* 2011) accommodated to presence-absence data. Connectivity of a habitat in a MÉTA hexagon (*C'*) is calculated from the frequency of patches of the same habitat type within the search distance from the focal patch weighted by an exponential distance kernel, while the maximum of the *C'*s found within the grid cell of interest results in the C_g of the cell:

$$C'_i = \sum_{j | D_j < D_o} E e^{-\alpha D_j}\ ;\ C_g = \max_{i \in g} C'_i, \tag{4}$$

where *j*s are the patches those *D* distance to the studied patch is lower than the previously specified D_0 threshold, *E* is the extent/area of the studied patch (since we used habitat presences, this parameter was set to 1), *α* is an appropriately chosen dispersal parameter, and *i* is the studied location (MÉTA hexagon) found within the grid cell of interest *g*.

The indicator can be fine-tuned with the help of the dispersal parameter, which should reflect the dispersal ability of the modeled species or species groups. The search distance should be large enough to contain the bulk of the quickly decaying exponential kernel. Based on *Czúcz et al.* (2011), we set α to 0.5 km^{-1} and D_0 to 1 km.

Each of the three component indices were rescaled into a 5-grade ordinal scale $\{0; 1; 2; 3; 4\}$. The first two were rescaled evenly between their minimum (0 in all cases) and maximum values, while the third was rescaled using the boundaries that emerged from the simulations of *Czúcz et al.* (2011). The maximum of these indices was taken as the *A* of the habitat in question in a specific spatial unit (i.e., cell of the input climate grid):

$$A_g = \max\left[\left(\begin{cases} 4, \ if \ N_g = \max\limits_{g\in G} N_g \\ \left\lfloor 5 * \frac{N_g}{\max\limits_{g\in G} N_g} \right\rfloor, else \end{cases}\right); \left(\begin{cases} 4, \ if \ D_g = \max\limits_{g\in G} D_g \\ \left\lfloor 5 * \frac{D_g}{\max\limits_{g\in G} D_g} \right\rfloor, else \end{cases}\right); \left(\begin{cases} 4, \ if \ C_g \geq 9.41 \\ 3, \ if \ C_g \in [6.28; 9.41) \\ 2, \ if \ C_g \in [3.14; 6.28) \\ 1, \ if \ C_g \in [1.07; 3.14) \\ 0, \ else \end{cases}\right)\right] \tag{5}$$

where *g* is the studied cell of climate grids *G*, *N* is naturalness, *D* is diversity, *C* is connectivity.

3. Results

3.1 Sensitivity of habitats

Based on the relative importance of climate-related predictors compared to other predictors retained in the habitat models (*Table 1*), the twelve most climate sensitive habitats are mixed coniferous forests (N13), mixed forests of slopes and screes (LY2), annual salt pioneer swards of steppes and lakes (F5), beech woodlands (K5_K7a), oligotrophic reed and *Typha* beds of fens and floating fens (B1b), closed lowland steppe oak woodlands (L5), closed steppes on loess, clay, tufa (H5a), steppe oak woodlands on foothills and on loess (L2x_M2), Turkey oak woodlands (L2a_L2b), forest steppe meadows (H4), willow mire shrubs (J1a), and oak-hornbeam woodlands (K1a_K2_K7b). In all of the other studied habitats, the relative importance of climate variables were lower than the previously selected 0.55 threshold.

Table 1. Sensitivity analysis of the modeled habitats ordered according to the relative importance of climate variables in their final models (sensitivity, *S*). Number and relative frequency of climate predictors are also shown. Horizontal line indicates the 0.55 threshold of relative importance, which separates the most climate sensitive habitats from the other ones. Habitats are encoded according to *Bölöni et al.* (2011).

Habitat code	**Descriptive habitat name**	**Number of climate variables**	**Frequency of climate variables**	**Relative importance of climate variables**
N13	Acidofrequent coniferous forests	2	1.00	1.00
LY2	Mixed forests of slopes and screes	2	0.67	0.75
F5	Annual salt pioneer swards of steppes and lakes	4	0.67	0.67
K5_K7a	Beech woodlands	7	0.44	0.62
B1b	Oligotrophic reed and *Typha* beds of fens, floating fens	6	0.60	0.61
L5	Closed lowland steppe oak woodlands	7	0.50	0.60
H5a	Closed steppes on loess, clay, tufa	7	0.41	0.60
L2x_M2	Steppe oak woodlands on foothills and on loess	7	0.47	0.60
L2a_L2b	Turkey oak woodlands	7	0.44	0.59
H4	Forest steppe meadows	7	0.47	0.58
J1a	Willow mire shrubs	6	0.46	0.58
K1a_K2_K7b	Oak - hornbeam woodlands	7	0.47	0.55
J6	Riverine oak-elm-ash woodlands	7	0.58	0.54
M7	Continental deciduous rocky thickets	1	0.50	0.53
LY4	Mixed relic oak forests on rocks	6	0.50	0.53
F2	Salt meadows	6	0.46	0.52
F1a	Artemisia salt steppes	5	0.50	0.52
J5	Riverine ash-alder woodlands	7	0.50	0.52
B6	Salt marshes	6	0.40	0.52

Table 1. continue

Habitat code	**Descriptive habitat name**	**Number of climate variables**	**Frequency of climate variables**	**Relative importance of climate variables**
F4	Dense and tall *Puccinellia* swards (alkaline vegetation)	5	0.50	0.52
J2	Alder and ash swamp woodlands	6	0.50	0.51
M6	Continental deciduous steppe thickets	4	0.44	0.50
B4	Tussock sedge communities	3	0.43	0.49
H2	Calcareous rocky steppes	6	0.40	0.47
LY3	Limestone beech forests	4	0.50	0.46
G2	Calcareous open rocky grasslands	3	0.38	0.42
L1_M1	Downy oak woodlands	7	0.47	0.41
L4a_L4b	Acidofrequent oak woodlands	5	0.38	0.39
H3a	Slope steppes on stony ground	5	0.42	0.39
G3	Siliceous open rocky grasslands	3	0.43	0.37
M5	Poplar-juniper steppe woodlands	3	0.38	0.34
B1a	Eu- and mesotrophic reed and Typha beds	6	0.33	0.31
H5b	Closed sand steppes	6	0.43	0.31
J3_J4	Riverine willow shrubs and willow-poplar woodlands	7	0.50	0.30
LY1	Forests of ravines (mesic rocky forests rich in *Acer pseudoplatanus*)	2	0.40	0.29
G1	Open sand steppes	6	0.43	0.28
M3	Open salt steppe oak woodlands with openings	1	0.14	0.17
H1	Closed rocky grasslands, species rich *Bromus pannonicus* grasslands	0	0.0	0.00
M4	Open sand steppe oak woodlands with openings	0	0.0	0.00

All seven climate predictors were included in the final models of K5_K7a, L5, H5a, L2x_M2, L2a_L2b, H4, and K1a_K2_K7b. The model of B1b and J1a lacks one climate predictor only: isothermality and precipitation of the coldest quarter, respectively. F5 has four climate predictors, while N13 and LY2 have two climate predictors. The model of LY2 includes one non-climatic predictor only (standard deviation of topographic position index), while the model of N13 is completely climate-dependent.

3.2 Adaptive capacity of habitats to climate change

Since the country-wide landscape-level habitat diversity (*D*) can be of relatively broad interest (see Chapter 4.2.), we detail this intermediate result (*Fig. 1*). *D* is relatively low in the lowlands (both in the northwest of Hungary and in the Hungarian Plains) except in Nyírség (eastern Hungary) and near to the lower section of River Tisza. Extremely low *D*s occur sporadically, evenly distributed across the country. *D* takes its highest value in the mountain regions, including the Northern Mountains (northern and northeast Hungary) and the Transdanubian Mountains (northern part of Transdanubia). In summary, pattern of *D* shows tendency to be high in territories that are (1) forested or accommodate woody natural vegetation, (2) less disturbed by agriculture, (3) situated in higher altitudes. Note that the latter may be a proxy for the former ones.

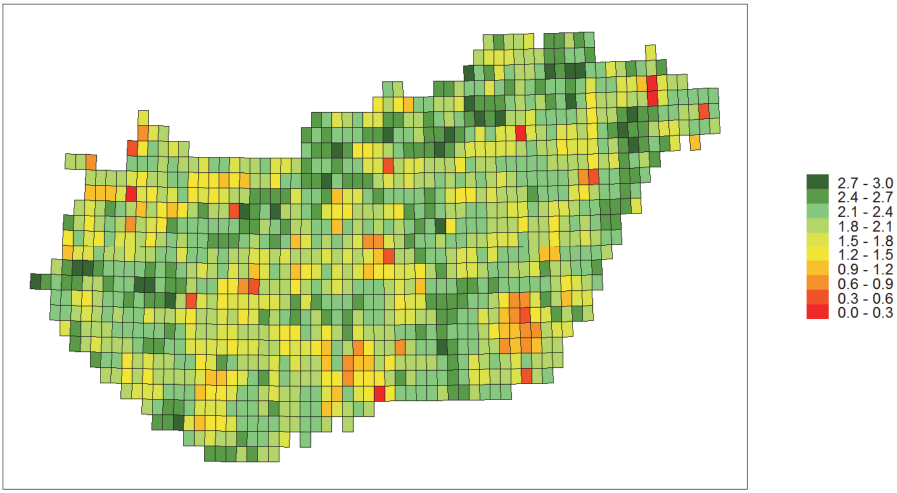

Fig. 1. Shannon diversity (*D*) of climax and subclimax habitats of Hungary calculated at the resolution of the input climate grid (0.1°). *D* increases from red to green.

Many of the *CSH*s are zonal and widespread types and thus have relatively high *A*, which has the potential to greatly mitigate the potential impact of climate change. Most widespread zonal habitats, such as oak-hornbeam woodlands (K1a_K2_K7b), beech woodlands (K5_K7a; *Fig. 2*), and others which form larger blocks in the current landscape have high *A* in the center of the blocks, which decreases towards the edges and reaches low *A* values. Turkey oak woodlands (L2a_L2b), however, are so widespread that this pattern does not apply to them and have high *A* even at the edges of its current patches, which ensures the best *A* among the *CSH*s (*Fig. 3*). There are habitats with variable pattern, but typically medium to high *A*: floating fens, oligotrophic reed and *Typha* beds of fens (B1b), closed lowland steppe oak woodlands (L5), closed steppes on loess (H5a), semi-dry grasslands, forest-steppe meadows (H4), mixed forests of slopes and screes (LY2).

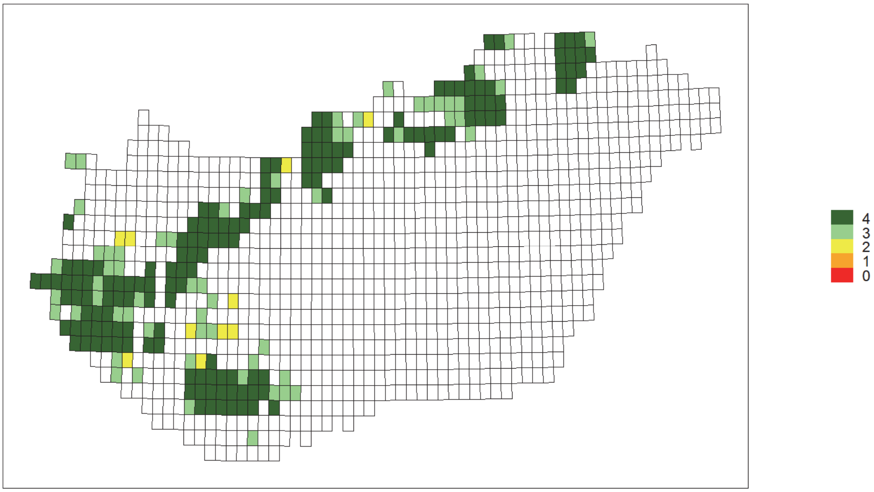

Fig. 2. Adaptive capacity (*A*) of beech forests (K5_K7a) in its existing stands. *A* increases from 0 to 4 (red to green).

An important aspect of the *A* of closed steppes on loess, clay, tufa (H5a) is that there is a high *A* area in the southeast of Hungary, while its *A* is low in the southwest (*Fig. 4*). It is also worth to note that relatively lower *A* areas of mixed forests of slopes and screes (LY2) appear aggregated north to Lake Balaton and in the Mecsek Mountains, which points out areas likely to become vulnerable. In this analysis, willow mire shrubs (J1a) appears to be one of the types that has the lowest *A* overall, which coincides with its ecology. This habitat typically appear in small depressions in the landscape surrounded by other vegetation or even agricultural land. So neither its *C* nor characteristics of its surroundings (*D*, *N*) predestine for high *A*. Closed lowland steppe oak woodlands (L5) also has low *A* values, which can be attributed to the fragmentedness of this type. Opposed to J1a, L5 would not be fragmented under natural conditions, but as it is a habitat of the lowlands, it became a frequent victim of human landscape transformation.

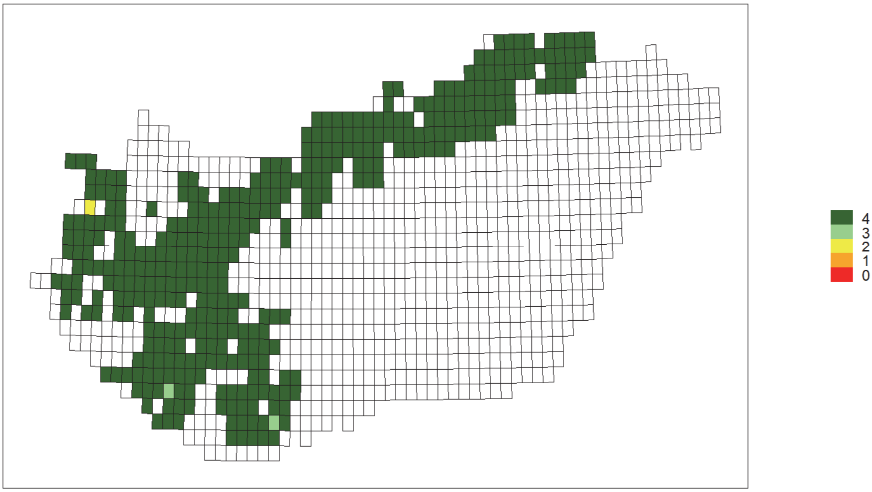

Fig. 3. Adaptive capacity (*A*) of turkey oak woodlands (L2a_L2b) in its existing stands squares. *A* increases from 0 to 4 (red to green).

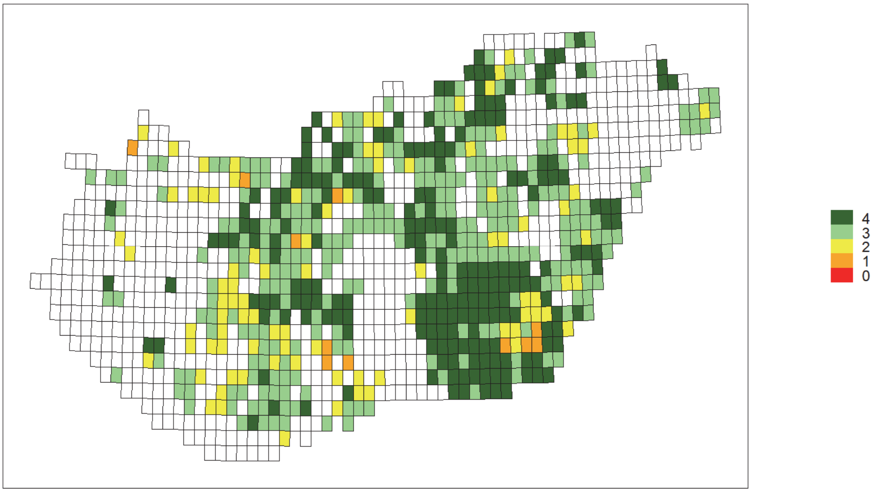

Fig. 4. Adaptive capacity (*A*) of closed steppes on loess, clay, tufa (H5a) in its existing stands. *A* increases from 0 to 4 (red to green).

4. Discussion

4.1 Sensitivity of habitats

Sensitivity (*S*) of the studied habitats to climate, both in case of highly and hardly sensitive ones, is generally well justified. Note, however, that our results can only be interpreted in the context of Hungary, since the training database of the habitat models our work was based on was limited to Hungary. Although our *S* measure is not able to separate the different aspects of climate, according to a research on the predictor selection of the predictive habitat models used in our sensitivity analysis, *S* of the habitats of Hungary is generally related to drought (*Bede-Fazekas,* 2017). This finding is in accordance with the literature (e.g., *Ladányi et al.,* 2010; *Rasztovits et al.*, 2012, 2014).

S of habitat N13 (mixed coniferous forests) is outstanding, although more pronounced dependence of edaphic parameters would have been expected (*Bölöni et al.,* 2011). It can be assumed that a more balanced model, and therefore lower *S*, should have emerged if areas outside Hungary were taken into account. Among the *CSH*s, *S* of only B1b (oligotrophic reed and *Typha* beds of fens and floating fens) seems to be overestimated if the ecological demands of the habitat cited in the literature (*Bölöni et al.,* 2011) are taken into account. Our findings on the high *S* of B1b, LY2 (mixed forests of slopes and screes) and L5 (closed lowland steppe oak woodlands) contradict the results of *Czúcz* (2010). Hence, previous findings of *Czúcz* (2010) about the higher *S* of zonal forests and lower *S* of grasslands and shrublands are just partially confirmed by our results. However, our results, in general, correspond to the conclusion of *Czúcz* (2010): those habitats that are distributed in the mountain regions depend more on, and therefore are more sensitive to climate than the ones located in the lowlands.

Among those habitats whose *S* is lower than 0.35 (*Table 1*), the model of M5 (poplar-juniper steppe woodlands) and H5b (closed sand steppes) might underpredict their *S*. It should be noted, however, that their reliance on sandy soils may elucidate the relatively low importance of climatic predictors. Our results on the hardly sensitive habitats, except for H1 (closed rocky grasslands, species rich *Bromus pannonicus* grasslands), are in line with the findings of *Czúcz* (2010).

4.2 Adaptive capacity of habitats to climate change

A system will be less vulnerable, i.e., it can survive in the long term against the environmental adverse effects, if it has low *S* while high *A* (*Smit et al.,* 1999). Although it may seem that average *A* of the habitats of Hungary is relatively high, we must draw attention to the fact that the rescaling of the adaptation components applied in Eq. (5) stretches the scale and masks the absolute values. Based on a closer investigation of the values of *N, D* (for Hungary), and *C* (for the habitats of Hungary), we must conclude that, in average, *A* is much lower than what would be necessary to be able to cope with the predicted climate change in an autonomous way. According to *Glick et al.* (2011), *A* of a habitat is equal to its ability to accommodate or cope with climate change impacts with minimal disruption. Hence, habitats of Hungary need external support to increase their *A* and their adaptive capacity. Although no components that would describe capacities for planned adaptation (i.e., economic resources, or critical infrastructure) are incorporated in our composite index, further research on the *A* of habitats can benefit from exploring the possible interventions for enhancing the resilience of natural ecosystems.

Although the habitats occurring at higher elevations are more climate sensitive (*Czúcz,* 2010), historical anthropogenic impacts have transformed the lowland vegetation to a far greater degree (*Molnár et al.,* 2012; *Nogués-Bravo et al*., 2008; *Mezősi et al*., 2017), which, in turn, could significantly decrease the *A* of the habitats. This effect was only indirectly studied in this paper through the following relationships: 1) *N* is lower for historically degraded habitats; 2) *D* is lower where humans had historically extirpated natural habitat types (*Luoto et al.*, 2003); and 3) *C* is lower where humans had made the landscape more fragmented. Anthropogenic effects can cause change in the abiotic environment as well (e.g., level of groundwater). Hence, some habitats may be present at, or extinct from, a certain location induced by non-natural processes. The predictive habitat models used in our research could not separate the results of these processes from the natural patterns and impacts, which has to be taken into account when interpreting our results.

One of the three component indices that make up the *A* composite index, the landscape-level habitat diversity (*D*) can be of particular interest even out of the context of vulnerability assessments. This index (1) was computed at the climate grid resolution, (2) is not habitat specific, and (3) has not yet been calculated for Hungary in this way. Therefore, although it is only an intermediate result, it can still be of relatively broad interest. The habitat diversity of the country is used to be characterized only by proxies based on species number, which have a high (yearly) temporal resolution, but a very low (national) spatial resolution (e.g., *Hungary,* 2015). Our estimation is the first attempt to characterize the country-wide fine-resolution habitat diversity pattern (*Fig. 1*), a task urged earlier (*Molnár* and *Horváth,* 2008) and incorporated in the Hungarian biodiversity monitoring system (*Fekete et al.,* 1997). However, we want to stress that diversity measures are highly dependent on scale (*Tóthmérész*, 1995), thus the current estimation is only to be interpreted in the frame of the current study. Pattern of *D* suggests that territories less disturbed by agriculture are more diverse in terms of habitats. Impacts of agriculture on the diversity has been previously proven for Hungary (*Fésüs et al.,* 1992) and globally (*Glick et al.,* 2011) as well. *D* shows some similarities to *N* in terms of their pattern (*Czúcz et al.,* 2008). Shannon diversity of habitats of Hungary is low similarly to the natural capital index (naturalness) of the country (*Czúcz et al.,* 2008, *Hungary,* 2015). *N* is also correlated with shape- and size-related landscape indices (*Szilassi et al.,* 2017), therefore with connectivity, as well.

There is a general agreement that *A* is high in the center of large homogeneous landscape blocks and decreases towards the edges. This is certainly the consequence of the way how the *C* component of *A* was defined, which can exhibit much larger values at the core of such blocks. This pattern is scale-dependent (*Hernando et al.,* 2017) and have been found by several other studies (e.g., *Riitters et al.,* 2000; *Saura* and *Pascual-Hortal,* 2007).

Although genetic diversity can facilitate evolutionary adaptation of a habitat (*Glick et al.,* 2011), our suggested composite *A* index did not contain genetic adaptation-related measures, since they are hardly interpretable in the context of habitats. Although species-level genetic *A* can, in theory, be integrated in a habitat-level index, it seems unfeasible due to its data intensity and unsoundness in methodological terms. Nonetheless, as diversity of functional traits can assist adaptation (*Bussotti et al.,* 2015), species diversity or functional diversity within a habitat may serve as a proxy for genetic diversity, and therefore genetic *A*, of the habitat.

Component indices of *A* can also be used in other research areas. The natural capital index, measurement of *N*, can provide comprehensive and substantial information on the state of an ecosystem, and on quantitative and qualitative changes in ecosystem services (*Kelemen,* 2013). The Shannon index, measurement of *D*, is widely used in subdisciplines of ecology (e.g., *Pakeman,* 2001), and found to perform excellently in some comparative research, (e.g., *Morris et al.,* 2014). However, a study focusing on *D* should apply a multiscale approach rather (*Podani et al.,* 1993; *Tóthmérész*, 1995; *Bartha*, 2008; *Güler et al.,* 2016). All the indices of migration-based adaptation, e.g., dispersal potential index (*Glick et al.,* 2011) beyond *C*, can describe the permeability of the landscape, and therefore, function as landscape evaluation measures.

4.3 Discussion of the research and application

There is a great need for CCIAV assessments on natural habitats (*Bede-Fazekas,* 2017). To our knowledge, only one CCIAV assessment on habitats of Hungary were done (*Czúcz,* 2010). Our research fills the scientific gap, since it is more detailed and based on updated input data and ecological models. Note, however, that our findings are limited to *CSH*s of Hungary, while *Czúcz* (2010) conducted his research on all the climax and subclimax habitats of the country. The *S* and *A* analyses presented in this paper provide inputs for a CCIAV assessment on habitats of Hungary (*Bede-Fazekas et al.*, 2017, in this issue). Our results can, however, provide input for other CCIAV assessments, whose method or exposure data differ from those of *Bede-Fazekas et al.* (2017). The three adaptation capacity indicators we implemented to habitats and presented in this paper now fill the gap to which *Molnár* and *Horváth* (2008) have drawn attention.

Since most of the zonal habitats of Hungary can be found among the *CSH*s, studying the *A*, potential impact and vulnerability give a reliable overview about the ecological impacts of climate change on Hungary. In studies describing the ecological impacts of climate change, species distribution models are much more frequently applied than habitat distribution models (*Ferrier* and *Guisan,* 2006). Species data are widely available, and the interpretation of the results is also relatively straightforward. Nevertheless, if such simple impact models need to be integrated into a more integrative vulnerability assessment framework, then individual species will become too particular. We think that in such cases, habitats can serve as an efficient proxy for species, since species' *S* are likely to be influenced, in many cases, by *S* of their habitats (*McCarty,* 2001). Moreover, vice versa, *S* of a habitat is usually determined by *S* of its component species (*Glick et al.,* 2011). Applying habitat distribution models in CCIAV assessments thus seems to be an efficient strategy, which means an important motivation for additional methodological research in the field of habitat distribution models.

The database that our research produced (*NATéR,* 2017) may serve as a basis for a wide variety of applications. *S* and *A* of natural habitats may provide an important and easily interpretable input for numerous disciplines. Our results might be integrated in further research conducted in the field of forestry or agronomy. Forestry studies deal typically with smaller entities, i.e. species, than our research. Hence, cooperation may result in more detailed *S* studies. There are several policy sectors, where the intermediate results of a CCIAV assessment on natural ecosystems, including *S* and *A*, can provide relevant and easily interpretable inputs (*European Environment Agency,* 2005, *Glick et al.,* 2011). Major applications of the results of our case study are expected in the field of landscape evaluation, nature conservation, restoration prioritization, forestry planning, landscape design, and landscape rehabilitation. Our methodological results can be implemented in further CCIAV assessments and may induce or facilitate further theoretical research on the sensitivity and adaptive capacity calculations based on habitats. We see a great need for the development and testing of complex adaptability indicators. It may also be necessary to develop suitable sensitivity metric for each ecological modeling approach beyond BRT.

Our research bears a number of development potential. A more detailed sensitivity analysis can be carried out by studying the predictor selection of the distribution models and interpreting those climatic variables that have the highest relevance for a certain habitat (*Bede-Fazekas,* 2017). Further research is needed to analyze not only the patterns but also the specific values of *A* in each grid cell, especially those that are outliers.

5. Conclusion

In this paper we focused on providing inputs, i.e., sensitivity (*S*) of habitats and their adaptive capacity (*A*), for a detailed climate change impact, adaptation, and vulnerability (CCIAV) assessment (*Bede-Fazekas et al.*, 2017, in this issue). We have methodologically established the measurement of *S* of natural habitats when distribution model of the habitat is based on the boosted regression trees (BRT) algorithm. *S* is suggested to be calculated from the relative importance of climatic predictors among all of the studied predictors. We selected the most climate sensitive habitats (*CSH*s) of Hungary as a case study and found that mixed coniferous forests and most of the zonal forests are highly sensitive to climate, similarly to annual salt pioneer swards of steppes and lakes, closed steppes on loess, clay, tufa, forest steppe meadows, willow mire shrubs, and some other grassland or shrubland habitats.

We developed an *A* index for habitats, based on naturalness (natural capital index), diversity (Shannon diversity index), and connectivity measures and estimated the *A* of *CSH*s of Hungary. According to our results, willow mire shrubs and closed lowland steppe oak woodlands are those *CSH*s that have the lowest capacity to adapt to climate change, while Turkey oak woodlands may be the most adapted habitats among the studied ones. Shannon diversity of Hungary is relatively low in the lowlands and takes its highest value in higher altitudes, including the Northern Mountains and the Transdanubian Mountains. In summary, adaptive capacity of the climate sensitive habitats of Hungary is generally lower than it needs to be to cope with the predicted climate change of the 21st century.

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Application of RCM results to hydrological analysis

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Abstract—It is a well-known fact that the characteristics and frequency of different hydrological processes (particularly the extremes – both droughts and floods) are definitely sensitive to climate change. Since extreme hydrological conditions often result in severe socio-economic impacts, it is essential to estimate reliable future tendencies, for which cooperation of experts in hydrology and climate modeling is a key step. In this study, the DIWA hydrological model is applied for the Upper Tisza Basin; the necessary meteorological time series are provided by the RegCM4 regional climate model simulation and the CARPATCLIM dataset. The calibrated DIWA model is run for the past and two future time periods. The comparison of the runoff characteristics concludes that an increase in winter and a decrease in summer are projected in the target watershed area.

Key-words: Upper Tisza Basin, RegCM4, DIWA hydrological model, climate change

1. Introduction

There is a recent growing need not only for climate change analyses, but more complex, detailed, and reliable impact studies as well. Therefore, more and more investigations focus on the relation between climate change and different socio-economic sectors. These assessments with particular focuses are important, as they can provide a useful basis for decision makers in order to build adaptation strategies in time and to mitigate climate change induced potential hazards.

Due to the rapid population growth, more than 7 billion people are currently living in the world (http://www.worldometers.info/world-population/); hence food-security – which is certainly determined by the climatic conditions – is a key issue. Therefore, several agricultural studies linked to climate change are published in the recent years (e.g., *Trnka et al.,* 2014; *Dobor,* 2016). According to *Betts* (2005), a complex, integrated approach is necessary for these studies to consider anthropogenic land cover changes besides the modified climatic conditions and the direct response of crops to CO_2 concentration, which also plays an important role in yield production. *Long et al.* (2005) found that rising CO_2 concentration results in a smaller surplus of yields in those areas, where a warming-induced increase of yield is projected; moreover, higher tropospheric O_3 concentration level causes a 20% yield loss generally. Among the complex impact-focused studies, some take into account not only climate change, but food production, trade, and consumption (*Fischer et al.,* 2002) or the issue of food quality (*Porter* and *Semenov,* 2005), as well. All in all, using different models and considering different aspects, most of the studies conclude that yield loss is likely to occur in the future (*Rosenzweig et al.,* 2013; *Mall et al.,* 2017).

Besides agriculture, other impact studies related to socio-economical and ecological aspects are completed for various regions using regional climate model (RCM) outputs. For instance, tourism is definitely affected by climate change (*Kovács et al.,* 2017), both in warmer regions where the beach can be considered as the main attraction (*Amengual et al.,* 2014) and in colder areas where snow and winter sports are the key sectors (*Damm et al.,* 2014). Climate change plays an important role in the energy performance of buildings too, which was addressed by *Nik* (2016) for specific buildings in Geneva and Stockholm. In addition to these economical sectors, ecological aspects are also studied in relation to the climate change. The detected and possible future shifts of natural vegetation (*Szelepcsényi et al.,* 2016) and species (*Morin* and *Thuiller,* 2009) are clearly determined by climate and its variations as abiotic factors. Moreover, the entire biogeochemical cycle and the involved processes are also closely built-up into the complex climate system of the Earth, thus, they are interrelated to climatic conditions and their changes (*Blenckner et al.,* 2002; *Meier et al.,* 2012).

Connection between climate change and hydrological processes is quite a widespread research topic, as both the lack and the excess of water may result in severe hazards. On the one hand, climate change impact on floods is analyzed by *Hirabayashi et al.* (2013) for the world: they found that flood frequency will increase in the future in southeast Asia, southern India, eastern Africa, and in the northern parts of the Andes; nevertheless, there are also other regions where flood frequency is projected to decrease. Investigating

Europe, *Madsen et al.* (2014) concluded that snowmelt peak flows will occur earlier during spring because of regional and global warming; moreover, flood water levels will decrease in the areas where snow-melting is the dominant factor in forming floods. Extreme precipitation also plays a key role in flood hazard: in the future it is projected to increase in the British Isles, western Europe (*Dankers* and *Feyen,* 2008), and northern Italy, while in some parts of Germany, Sweden, and the Baltic countries, a decrease in 100-year return values of discharge is estimated (*Rojas et al*., 2012). In addition, there are many flood analyses focusing on different smaller regions (e.g., *Cameron et al.,* 2000; *Kay* and *Jones,* 2012; *Falter et al.,* 2015). A special type of floods, the so-called flash flood is especially dangerous: it appears very suddenly (therefore, it is extremely difficult to predict when it occurs) and concentrates to a relatively small area, where it can cause severe problems. In order to be more prepared for these events and to better understand their processes, several investigations focus on this topic (e.g., *Reed et al.,* 2007; *Velasco et al.,* 2013; *Garambois et al.,* 2014; *Hejazi et al.,* 2014; *Hofierka* and *Knutová,* 2015). On the other hand, the lack of water also has negative effects, e.g., on drinking water supplement, shipping, or agricultural production. Hence, analyses concerning water scarcity (e.g., *Gosling* and *Arnell,* 2013; *Gleick,* 2014; *Schewe et al.,* 2014) are as important as flood related studies. The study of *Lehner et al.* (2006) takes into account not only climate change, but other factors, such as demographic, socio-economic, and technological trends; according to the results, flood frequencies are likely to increase in the future in northern Europe, while in the southern parts of the continent, drought frequencies are projected to increase.

Radvánszky and *Jacob* (2008, 2009) analyzed the projected hydrological changes of the entire catchment of the river Tisza. Their analysis is based on the REMO (*Jacob* and *Podzun,* 1997) regional climate model, the HD (*Hagemann* and *Dümenil,* 1998) hydrological model, and the A1B (*Nakicenovic* and *Swart,* 2000) emission scenario. They concluded that by the end of the 21st century river discharge will decrease in February, March, summer, and autumn months, while in April and May, an increasing trend is estimated. In this paper, we focus on a smaller subcatchment of the Tisza, near the river source, namely, the Upper Tisza catchment using a hydrological model driven by regional climate model outputs. The main goal of our study is to evaluate the possible future climatic and hydrological changes, which are essential to adapt to the regional environmental changes and to prepare adequate strategies for optimal water management at regional/local level. In the next section, the applied data, models, and methods are presented, and then, our results are shown. Finally, we summarize the investigation and the main conclusions.

2. Data and methods

Hydrological processes are clearly determined by the main characteristics of the catchment, i.e., climate, topography, soil type and thickness, land use, vegetation type, and coverage. The physically-based DIWA (Distributed Watershed; *Szabó,* 2007) hydrological model, which is used in this study, takes into account all these parameters for each grid cell. DIWA separates constant and seasonally variable parameters. Furthermore, DIWA considers all the essential processes of the hydrological budget equation, i.e., precipitation, interception, evaporation and transpiration, infiltration, snow accumulation, and snow melting, as well as surface, subsurface, and channel runoff (*Fig. 1*).

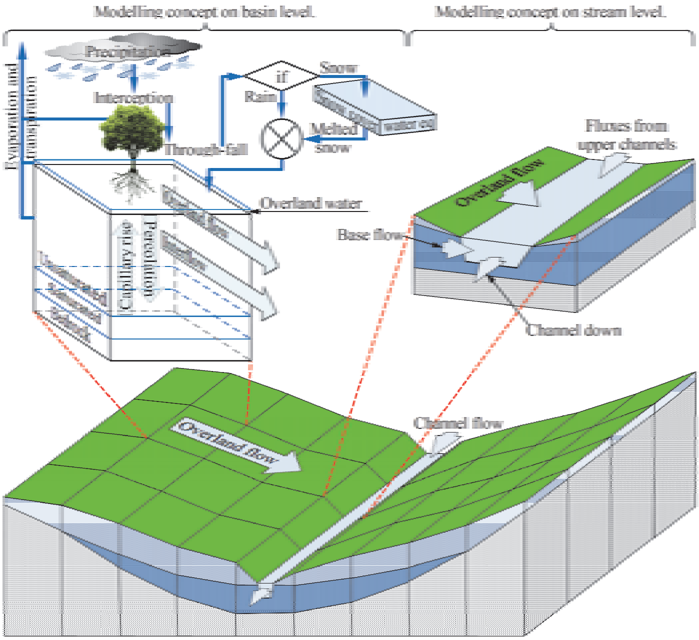

Fig. 1. Schematic description of the DIWA hydrological model.

The present study focuses on the Upper Tisza catchment, which is located in Central Eastern Europe, covering parts of Ukraine, Romania, and Hungary. The target area has a quite complex topography: its highest point exceeds 2000 m, while the lowland parts of the catchment in the south and east lie below 400 m; the overall average height is 800–900 m (*Fig. 2a*). The climatic conditions of the target catchment changes with topography are: temperature is lower and precipitation is greater in the higher elevations than in the lowland areas. The annual mean temperature is 3–10 °C and the annual mean precipitation total varies between 600 mm and 1400 mm. The dominant soil type of the region is sandy loam (*Fig. 2b*), which contains 50–80% larger sand particles (with size > 63 μm) and 20–50% smaller (silt or mostly clay) particles, hence somewhat more nutrients than pure sand soils resulting in improved fertility. As a consequence, sandy loam soil drainages water quickly, as it cannot hold a larger amount of water. Other soil types, i.e., clay loam, loam, and sand can be found in the southern parts of the catchment. The Upper Tisza catchment is covered by broad-leaved and coniferous forests mainly (*Fig. 2c*). In the lower parts of the area, non-irrigated arable lands, pastures, natural grasslands, woodland, scrubs, and agricultural fields can be found – that is why the urban area is relatively small in the catchment.

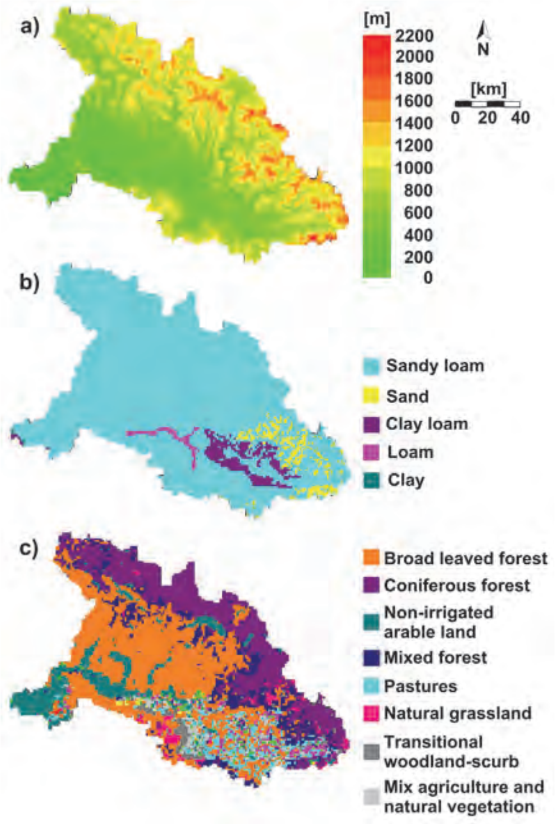

Fig. 2. Topography (a), soil types (b), and land cover (c) distributions in the Upper Tisza Basin.

Vegetation plays an important role in the hydrological cycle by transpiration and interception (which serves as the basis for evaporation from plant surfaces). These processes show a substantial seasonality because of the annual cycle of vegetation; therefore, DIWA takes into account the leaf area index (LAI) on a monthly basis. In the case of higher LAI, transpiration and interception are higher as well. It can clearly be seen that LAI values above 4 occur only in the northeastern – higher elevated – parts of the domain in January (*Fig. 3a*), while LAI is above 6 in more than the half of the entire area in July (*Fig. 3b*). Furthermore, LAI values in July exceed even 18 in some regions (mainly in the coniferous forest areas).

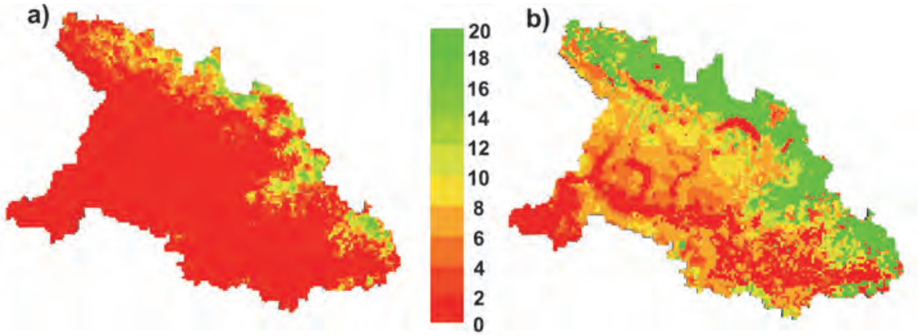

Fig.3. Distribution of the leaf area index in January (a) and July (b) in the Upper Tisza Basin.

Beside the main characteristics of the catchment, DIWA also needs meteorological input data for the simulation. In this study, the necessary time series (precipitation, mean and minimum temperatures) are provided by the CARPATCLIM database (*Spinoni et al.,* 2015) and the RegCM4 (*Elguindi et al.,* 2011) regional climate model. Currently, CARPATCLIM is considered as a reference, hence it is based on station measurements – which are interpolated to a regular grid (0.1°) using the MISH algorithm (*Bihari* and *Szentimrey,* 2013). The time series are available for 50 years (1961–2010) with a daily time step. The homogenization was solved by the MASH software (*Bihari* and *Szentimrey,* 2013). To assess the projected future changes, RegCM4 simulations with 10 km horizontal resolution (*Pieczka et al.*, 2017b) are used, nested into the 50 km resolution run, which is driven by the HadGEM global climate model (*Collins et al.,* 2011). The transient simulation encompasses 130 years (1970–2099) with a daily time step. In our investigation, RegCM4 takes into account a high anthropogenic impact via the RCP8.5 scenario (i.e., the estimated change of radiative forcing is 8.5 W/m^2 compared to the pre-industrial conditions). According to this scenario, population and GHG emission will grow in the future with high energy consumption and moderate technical development. Considering land use changes, pastures and agricultural areas will increase, while natural vegetation will decrease by the end of the 21st century (*van Vuuren et al.,* 2011).

The applied methodology is summarized in *Fig. 4.* First of all, the calibration of the DIWA hydrological model is completed for the Upper Tisza catchment. Then, DIWA simulation using CARPATCLIM data is validated for a two-year-long time period (containing both extreme high and persistent low runoff periods) using observations. The RegCM4 climate model is run for the Central European region (i.e., 43.8–50.6°N; 6–29°E). In order to assess how well the RegCM4 simulation performs, the RCM-outputs are compared to the CARPATCLIM dataset for a 30-year-long historical time period (1971–2000). If the agreement is not fully satisfactory, a bias correction method can be applied to the raw RCM-outputs, and the bias-corrected time series can be validated again to the CARPATCLIM data. Projected future climate conditions can be analyzed on the basis of both the raw and bias-corrected RCM-outputs. As a next step, simulations with DIWA are completed for the past, using meteorological data provided by the CARPATCLIM and the historical run of RegCM4. The simulated runoff values are then used for hydrological validation. If the simulation is successful for the past (i.e., the reconstruction of hydrological conditions is satisfactory), experiments can proceed for the future using simulated meteorological time series of RegCM4. Finally, a detailed statistical analysis and comparison of runoff outputs for different time periods and/or input meteorological parameters are completed. Note, that in this study we analyze only the climatic impacts on runoff; other factors (i.e., topography, land use, soil type, vegetation coverage) are considered to remain constant during the 21st century.

3. Results and discussion

The results of the hydrological simulations are presented in this section: after the calibration and validation, seasonal runoff is analyzed for three 30-year-long time periods (reference 1971–2000, and future 2021–2050, 2069–2098).

The calibration of DIWA is completed for the target area by fine-tuning different parameters, namely, the water-storage capacity of the surface, the saturated hydraulic conductivity of the so-called O-horizon (i.e., concentrated organic layer, which consists of decaying plant and animal tissues), the critical temperature of snowmelt, and the numerical diffusion. We used CARPATCLIM data for the calibration, which are considered as reference against RegCM4 outputs. Observations are available for a couple of years for Tiszabecs gauge (48.1°N; 22.8°E), so we could validate the runoff values from the CARPATCLIM driven DIWA simulation against them (*Fig. 5*). There is an extremely large runoff value on the 310th day of the calibration period (May 1, 2000–April 30, 2002): the DIWA simulation reproduces this peak, however, the observation is slightly underestimated. In general, an underestimation of observations can be found in the hydrological winter period (from November to March, indicated by grey background in *Fig. 5*), which is probably because of snow accumulation/melting. A longer period with low values occurs between the 150th and 192nd days of the calibration period, which is realistically simulated by DIWA. To sum up, it can be concluded that the DIWA simulation is in an acceptable agreement with observations, as its timing is adequate and there are no systematic errors. Therefore, the calibration process is considered to be successful.

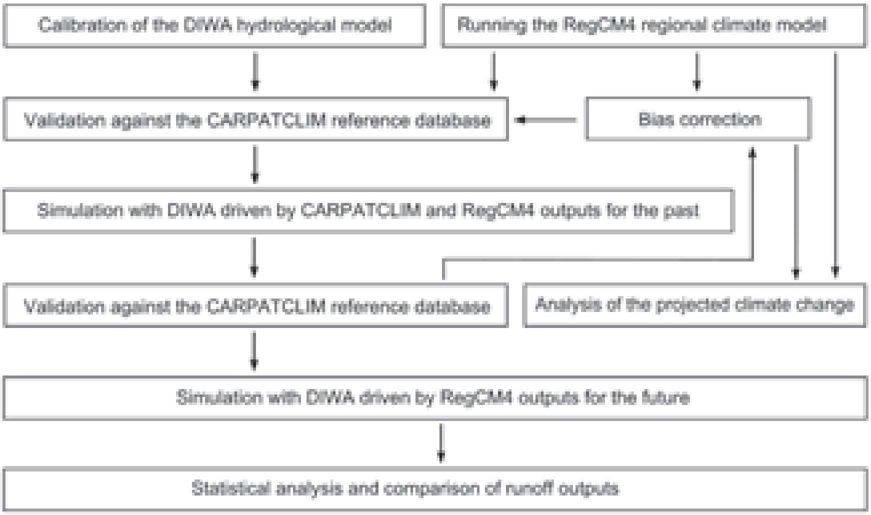

Fig.4. Main steps of the presented analysis.

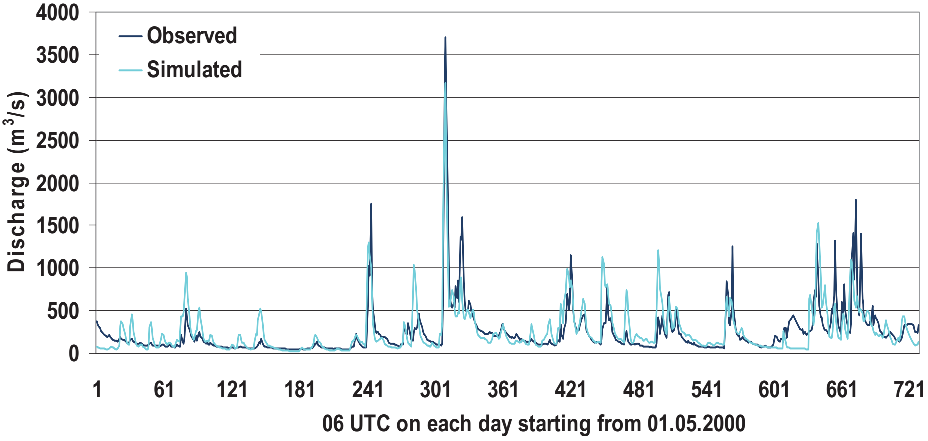

Fig. 5. Calibration of the DIWA hydrological model for Tiszabecs gauge (48.1°N; 22.8°E) using CARPATCLIM data as driving meteorological input for the May 1, 2000–Aril 30, 2002 period (reference: observations). Grey background indicates winter (from November to March).

Time series from RCM simulations are used for estimating future tendencies. In order to test how reliable the RegCM4 outputs are, DIWA simulations for 1971–2000 are compared using (i) CARPATCLIM and (ii) RCM meteorological data as input on a Q-Q plot comparing the empirical distributions of simulated hydrological time series (*Fig. 6*). On the one hand, the winter runoff values are overestimated when DIWA uses RCM outputs. The largest difference occurs above the 65th percentile, when RegCM4-driven DIWA simulates one and a half times higher runoff values than CARPATCLIM-driven DIWA. On the other hand, a slight underestimation can be found in summer. This discrepancy probably appears, because the RegCM4 historical simulation overestimates precipitation throughout the year, except in summer (*Pieczka et al.,* 2017a). In order to eliminate these systematic errors, applying a bias correction to the raw RCM outputs is advisable. However, the bias correction might distort the physical consistency of climate simulations, which becomes an important issue when more than one meteorological variable are used in the subsequent impact study. Therefore, we used only raw RCM data here to analyze the likely hydrological trends in the future. (Note that the projected discharge values might not be realistic due to the general overestimation of precipitation.)

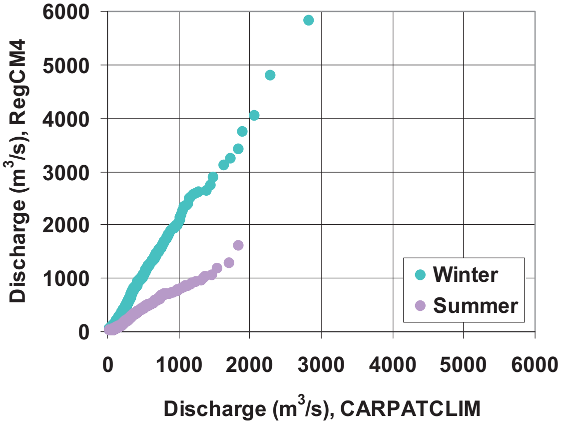

Fig. 6. Seasonal Q-Q plots of the hydrological simulations using the RegCM4 and CARPATCLIM time series for the 1971–2000 period.

Considering the annual distribution of daily runoff values at Tiszabecs gauge, substantial changes are estimated by the end of the 21st century (*Fig. 7*). The most pronounced decrease is projected for April: the 90th percentile of calculated daily runoff values is likely to decrease by 55%; furthermore, the upper quartile, the median, and the lower quartile are also estimated to become lower by 48%, 49%, and 30%, respectively. In 1971–2000, snowmelt dominantly occurred in spring; less snow is likely to accumulate in the future winters because of the overall warming. Therefore, discharge peaks – induced by melting in spring – will not be as high in the future as they were in the past reference period. Moreover, the decrease of discharge is also projected for summer, especially August, which is in line with the RegCM4-simulated drying projection in the Carpathian Basin, including the Upper Tisza catchment. The results show that mainly the difference between the lower and upper quartiles are likely to decrease from June to September. In July and August, the 90th percentiles are also projected to decrease, so the variation of runoff values in these two months will probably become smaller. The simulated changes of the median are –42%, –53%, and –65% in June, July, and August, respectively. On the contrary, from November to February, an increase of the runoff values is estimated. In January and February, both the upper quartile and the 90th percentile are projected to become much higher by 2069–2098, presumably because of the estimated increase of precipitation totals in these months. The median is also likely to increase by 188% in January and 125% in February. In the case of the 10th percentile, no substantial change is likely to occur in any month of the year. Considering the annual distribution of runoff, the highest values of the 75th and 90th percentiles occurred in March and April in the late 20th century, while the lowest percentile values were detected in January, July, and August. This temporal distribution is likely to be somewhat restructured by the late 21st century: the highest runoff is shifted towards the winter months and the lowest values are still likely to occur in late summer (i.e., August).

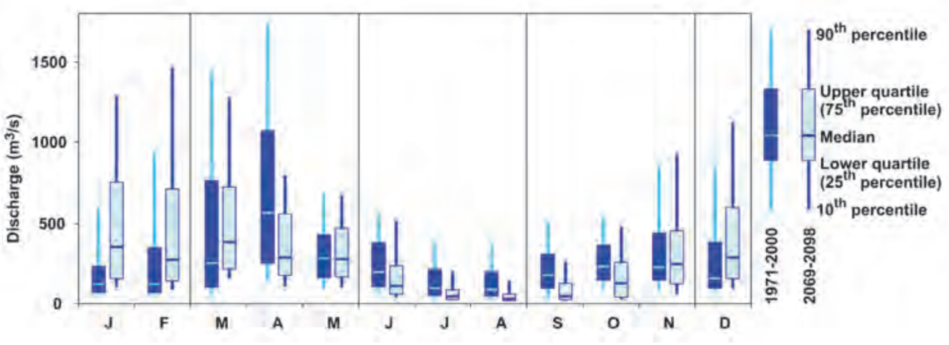

Fig. 7. Annual distribution of the 10th, 25th, 50th, 75th, and 90th percentiles of runoff values calculated for each month at Tiszabecs gauge (48.1°N; 22.8°E), based on the daily averages of the 30-year-long time periods (1971–2000 and 2069–2098).

Considering the seasonal empirical distribution functions of runoff (*Fig. 8*), a clear decrease is projected for the future, except in winter (*Fig. 8a*). Only a slight shift is estimated in winter by the middle of the 21st century compared to the reference period, which is projected to be followed by a larger increase of runoff values by the end of the 21st century, especially in the case of the low (< 5th percentile) extremes (their relative change exceeds 100%). The projected change of runoff is caused by the general increase of total precipitation and the overall warming in the area: as a result of higher temperature values, snow accumulation will be substantially less than in the recent past. Moreover, a greater portion of precipitation is likely to occur in the form of rain instead of snow, which leads water to proceed faster into the runoff process. The shapes of the empirical distribution functions in winter are quite similar to each other for the different 30-year-long periods.

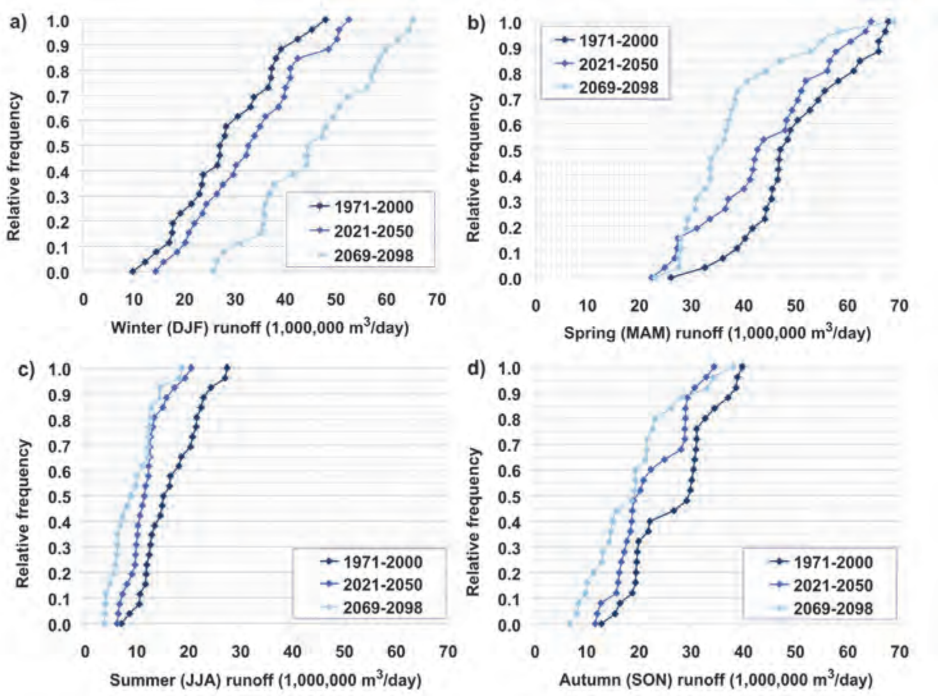

Fig. 8. Comparison of simulated seasonal average runoff distributions at Tiszabecs gauge (48.1°N; 22.8°E).

In spring, a decreasing tendency is expected (*Fig. 8b*), which can also be explained by the projected changes of snow accumulation. In the Upper Tisza catchment, snowmelt is dominant in March and April – if less snow will be accumulated in winter then less water will appear during the spring melting, thus, less water flows into the rivers as well. Furthermore, low and high extremes are not projected to change substantially; values between the 5th and 95th percentiles are likely to decrease (significantly by the end of the 21st century).

According to the RegCM4-driven DIWA simulation, the smallest runoff values occurred in summer during the late 20th century, the runoff is estimated to decrease in the future (*Fig. 8c*). Greater runoff values (above the 65th percentile) are likely to decrease already by the middle of the 21st century, and then, no further substantial change is projected by the late 21st century. The projected shift of the distribution in the smaller runoff values (below the 65th percentile) is more balanced throughout the century: the relative average changes are –26% and –49% by 2021–2050 and 2069–2098, respectively. This overall summer decrease of runoff can be explained by a general projected summer drying in the catchment.

Similarly to spring and summer, a decrease of runoff is likely to occur in autumn (*Fig. 8d*), which is mainly due to the projected decrease of precipitation totals relative to 1971–2000. Larger change compared to the reference is estimated mainly by 2069–2098. However, in the case of high extremes (> 90th percentile), a larger decrease is projected by 2021–2050 than 2069–2098.

4. Conclusions

Hydrological simulations using RCM-outputs are presented in this study for the Upper Tisza catchment. For the analysis, the physically based, distributed DIWA hydrological model driven by the RegCM4 regional climate model taking into account the RCP8.5 scenario was used. Validation shows that RegCM4 simulations usually overestimate precipitation, except in summer (compared to the CARPATCLIM reference database). This bias appears in the case of hydrological simulations as well; therefore, this paper focuses on the analysis of projected changes via distributions instead of the actual values.

The yearly average of runoff values is estimated to decrease; however, both monthly and seasonal scale analyses reveal different trends within the year. (i) Analyzing the simulated discharge values on a monthly scale, one can conclude that decreasing tendency is likely to occur in spring (especially in April) and summer, while a substantial increase is projected for the winter months, especially in the case of higher (75th and 90th) percentile values. (ii) According to our results focusing on seasonal scale, an overall decrease of runoff values is projected for spring, summer, and autumn, which can mainly be explained by the simulated decrease of precipitation totals in these seasons. On the contrary, a substantial runoff increase is estimated in winter related to the general increase of winter precipitation and the reduction of snow accumulation due to higher temperatures. It is also important to note that both the low and high extreme runoff values are likely to change (except in spring). Our results confirm a former analysis for the Upper Tisza catchment (*Pongrácz et al.,* 2013), which used a previous version of DIWA driven by bias-corrected RCM simulation (i.e., PRECIS outputs (*Bartholy et al.,* 2014) bias-corrected by the percentile-based method) with coarser (i.e., 25 km) horizontal resolution, taking into account the SRES A1B scenario. Although a quite different RCM and a different scenario were used here, the opposite hydrological trends of winter and summer are projected in our study as well. These similarities are very promising, however, it is important to note that in order to provide as valuable input as possible for decision makers in water management, more hydrological model experiments are needed using different hydrological models, different driving RCMs, and all available scenarios.

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Impact of climate change on natural fire danger in Ukraine

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Abstract—This research focuses on the objective assessment of the pyrological regime in climate change conditions. The present state (1981–2010) of climatic characteristics determining the natural fire danger in Ukraine is investigated. For all physicogeographical zones, the change in the pyrological regime, its significance throughout the current climatic period were estimated. Since the beginning of the 21st century, there has been an increasing tendency in fire danger. It resulted in increasing number of forest fires and theirs areas. In most regions of Ukraine, authenticity of such changes is 90–99%.

The impact of climate change on the number and area of forest fires in the country (e.g., in the Kherson region) is discussed. The article presents the quantitative relationships of the level of fire danger in the region with the thermal regime, humidity and wind regimes. The decisive influence of air temperature on the degree of natural fire danger is proved. The effect is most marked by the area of fires and much less by their numbers.

Possible changes of climatic characteristics and extreme weather conditions in Ukraine in 2021–2050 relative to the current climatic period for the scenario SRES A1B and their impact on forest fires were found.

Key-words: climate change, climatic projection, forest fire, fire danger

1. Introduction

Meteorological conditions are major factors in determining fire safety and fire regulations of forestry services. Air temperature and soil humidity, rainfall, and wind speed affect the conditions of fire, speed and features of its development, strategy and tactics of suppression. Averaged over long time, these characteristics describe the pyrological vulnerability of climate, which defines the propensity of the territory for forest fires. In Ukraine, for the assessment of fire danger, a composite index is used that takes into account air temperature, dew point, and daily amount of precipitation. It is a basis for determining the class of fire danger in terms of weather. Temporal changes in meteorological conditions caused by climate change strongly affect pyrological regime and fire safety of the regions.

It is apparent that the weather conditions in Ukraine, like on the planet in general, are changing (UNFCCC, 2009, 2012; *Balabukh et al.,* 2013, 2014). Many of the registered changes of the climate system, according to reports of the Intergovernmental Panel on Climate Change (IPCC), are unusual or unprecedented in recent decades or even millennia (IPCC, 2013). They have mostly negative consequences and will be strengthened in the future. It is expected that by the end of the 21st century, in Eastern Europe, the risk of fire danger will increase, particularly in the southern regions, increasing the risk of forest and peat fires. In Ukraine, we observe a significant increase in the number of forest fires and their area, which is likely due to climate change. For the past 30 years (1981–2010), the annual number of forest fires has increased by 2.6 times. The North Black Sea region suffers the most from wildfires in Ukraine. In 2007, 95% of forests in the Kherson oblast and Crimea were affected by forest fires of varying intensity (*Zibtsev*, 2010).

Taking into account this all-round facts, the main task is to study of pyrological characteristics of the climate in Ukraine, their regional features, and changes throughout 1981–2010, and to examine the projections of fire danger change in the 21st century. This information allows us to define regions most suffer from nature forest fire danger, predict the changes of areas distribution, and develop the reduction of adaptation measures concerning negative effects.

2. Data and methods

The main climate characteristics, which affect the fire danger, are those that determine the processes of drying-wetting wood-burning materials. The air temperature (average, minimum, and maximum values), relative humidity (daily average and minimum values), annual precipitation, number of days without rain, wind regime, number of days with thunderstorms, duration of the warm season, vegetative period belong to them.

The estimation of pyroclimatic regime includes the calculation of fire indexes – the special mathematical formulas that formalize the influence of basic meteorological parameters on the wildfire. Such indexes and systems for the assessment, monitoring, and prediction of fire hazard have been developed to solve the natural firefighting challenges in different countries around the world. The most known of them are the Canadian Wildland Fire Information System – CWFIS the Fire Monitoring, Mapping, and Modeling – Fire M3

(Canada), the National Fire-Danger Rating System – NFDRS (USA), and the European Forest Fire Information System – EFFIS.

In Ukraine, the nature forest fire danger is calculated using the Nesterov composite index (*Nesterov*, 1949). Its main advantage is the easy calculation which based on observation data. According to *Gubenko* and *Rubinstein* (2012), this index has fairly gross correction for precipitation and does not take into account the duration of period without rain. The equation for Nesterov composite index is:

$$КПО = КПО_{n-1} * K_{on} + \left[t \left(t - t_d \right) \right]_n , \tag{1}$$

where $КПО_n$ is the value of Nesterov composite index that is calculated for the current day, *n* (°C); $КПО_{n-1}$ is the value of Nesterov composite index, which is calculated for the previous day, *n-1* (°C); K_{on} is the adjustment precipitation coefficient (it is equal to 1 if the rainfall is less than 3 mm, or to 0 if it is greater than or equal to 3 mm); t is the air temperature (°C); t_d is the dew-point (°C); $t - t_d$ is the dew-point deficit (°C).

According to the $КПО_n$ value, the fire danger is classified into five categories:

$КПО_n < 400$ °C – fire security (I category);
$400 \leq КПО_n < 1000$ °C – low fire danger (II category);
$1000 \leq КПО_n < 3000$ °C – moderate fire danger (III category);
$3000 \leq КПО_n < 5000$ °C – high fire danger (IV category),
$КПО_n \geq 5000$ °C – very high fire danger (V category).

If $КПО_n$ is more than 10000 °C, it is an extreme fire danger.

The research of pyrological characteristics of climate and its temporal fluctuation was conducted for the period 1981–2010 using daily temperature, wind speed, precipitation and relative humidity data from the 187 meteorological stations across of Ukraine. Calculation of the characteristics of climate change that affect the frequencies of forest fires was conducted for the period 2021–2050 relatively to the recent climatic period (1981–2010) according to the regional climate model REMO with resolution of 25 km derived from global model simulation ECHAM5 (ECAP, 2009). Based on these data the average values of the selected indicators for the two specified periods were determined. The next step was calculation of their changes and theirs significance. Since these two periods are independent and climatic indicators are subject to normal distribution, the estimation of the significance of the expected change was carried out according to the Student's t-criterion, and the probability (*p-value*) of this change was determined *(Sachs,* 1976).The zero hypothesis is that both samples have the same mean values: $H_0 : \overline{x_1} = \overline{x_2}$. If the calculated value of the t-criterion is greater than its critical value, the hypothesis of the equality of means is rejected. That is, with the probability *p,* the difference is significant.

The calculations were made for the scenario A1B, which belongs to the first group and involves the growth of the population by the middle of the 21st century with the subsequent reduction of emissions. It is the average between scenarios B1 and A2 and the balanced use of fossil and renewable energy sources. According to its characteristics, the SRES A1B scenario corresponds to the scenario RCP6.0 proposed in the IPCC Fifth Assessment Report (IPCC, 2013).

The main tendencies of climate change were defined for the whole area of Ukraine. The analysis of the climate change impact on the nature forest fire was conducted by the example of the Kherson region, which is the most vulnerable area to natural fire danger in Ukraine. This is the hottest and driest region of Ukraine, where man-made pine forests dominate, which are the most vulnerable to forest fire (*Hodakov* and *Zharikova*, 2011*; Zibtsev,* 2010).

For spatial distribution (mapping) we used the Information and Reference System “"Natural Elemental Meteorological Events in Ukraine”, which was developed at Ukrainian Hydrometeorological Institute, Department of Synoptic Meteorology (*Balabukh et al.,* 2010).

All terms and definitions that have been used in this article are presented in *Table 1*:

Table 1. Definition of terms applied in Ukraine

Term/designation	Definition
warm days	Annual count of days when daily minimum temperature is equal to or greater than 0 °C.
summer days	Annual count of days when daily mean temperature is equal to or greater than 15 °C.
hot days	Annual count of days when daily maximum temperature is equal to or greater than 25 °C.
warm period	Time period from April to October.
number of days with atmospheric drought	Annual count of days when average daily relative humidity is less 50% and maximum daily air temperature is more than 25 °C.
number of days without rain	Count of days when daily precipitation (R) is less than 0.01 mm.
vegetation days	Count of days when daily mean temperature is equal or greater than 5 °C, when vegetation of agricultural plants is beginning.
active vegetation days	Count of days when daily mean temperature is equal or greater than 10 °C, when vegetation of agricultural plants is intensive.

Their using is regulated by the relevant government documents: standards, guidelines, manuals. Some of them do not match with the definitions of indicators used in several international projects, but they are mandatory to be defined this way in Ukraine.

For estimation of the observed climate change, we used linear trend coefficient calculated using the least squares method. The significance of the change was evaluated according to the Student's criterion (t-test): the probability of that the value of the t-criterion is equal to or exceeds the value calculated by the actual data was determined (*Sachs,* 1976). All statistical analyses were performed using StatSoft, Inc, STATISTICA 6.0.

For indication of the assessed likelihood of an outcome or a result, we used the next terms: “virtually certain” 99–100% probability ($p > 0.01$), “very likely” 90–100% ($0.1 \geq p > 0.01$), “likely” 66–100% ($0.34 \geq p > 0.1$), “about as likely as not” 33–66% ($0.67 \geq p > 0.34$), “unlikely” 0–33% ($0.90 \geq p > 0.67$), “very unlikely” 0–10% ($0.99 \geq p > 0.9$), “exceptionally unlikely” 0–1% ($p > 0.99$) (IPCC*,* 2013).

3. Results

3.1. The state of natural fire danger in Ukraine throughout the current climatic period

Air temperature is one of the most important factors influencing the possibility of wood-burning materials flaming. The spatial-temporal analysis of pyrological indicators of the thermal regime has shown that the south areas of Ukraine have the thermal conditions most favorable for the occurrence of forest fires (*Figs. 1 and 2*). The highest average and mean of maximum values of air temperature per year are observed in this region. These values can be 9 °C and 14 °C, or more. In summer, these values exceed 21 °C and 28 °C. On the southern part of Ukraine, the warm days count more than 300, and the vegetation period is more than 235 days. In this area, there can be 130 summer days and more than 80 hot days. The sum of positive average daily air temperatures ranges from 2300 °C in the northeast of the country to 4000 °C – in the south. The sum of negative average daily air temperatures rises from north-east to south-west from –550 °C in the Sumy and Kharkiv regions to –200 °C and more in the Crimea. Moreover, for all territory of Ukraine, the sum of positive daily average temperatures prevails. In the south part of the country, the difference between the sum of positive and negative daily average temperatures reaches 3500 °C. The sum of maximum daily air temperatures that exceed 25 °C in south is 200% greater than in the northeastern and northwestern regions of the country, and it equals to 2500 °C and more.

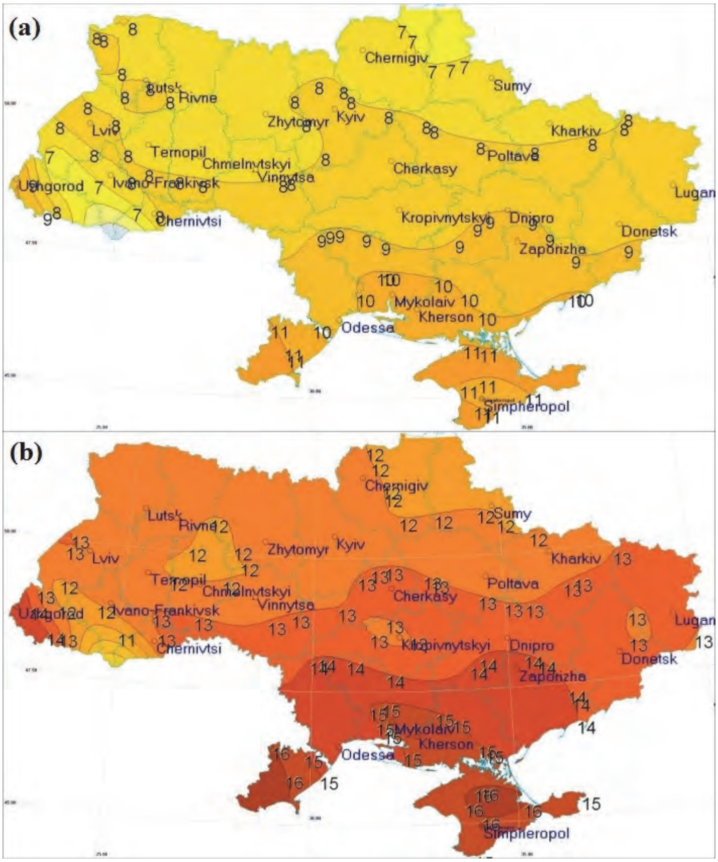


Fig.1. Average (a) and mean maximum (b) values of air temperature per year in 1981–2010.

Besides thermal regime, precipitation is also an important factor that affects nature forest fires. The presence of sufficient moisture in the atmosphere, especially in summer, reduces the frequency of forest fires. In the current climatic period (1981–2010), the field of average annual precipitation in Ukraine maintains a zonal distribution of isolines, influenced by the Crimea and the Carpathian Mountains. The values gradually increase from south to north in the range of 400 to 650, respectively. In mountainous areas, there is a natural increase in precipitation caused by physical and geographical conditions. It is the wettest zone, where the annual precipitation is above 1100 mm. The most arid zone is the southern area (steppe zone). The annual precipitation varies between 380–550 mm per year. Thus, it is the main risk zone for this component of pyroclimatic regime. The rest of territory has a sufficient, but unstable wetting, which ensures partial opportunities for reducing the frequency of forest fires (*Fig. 2*).

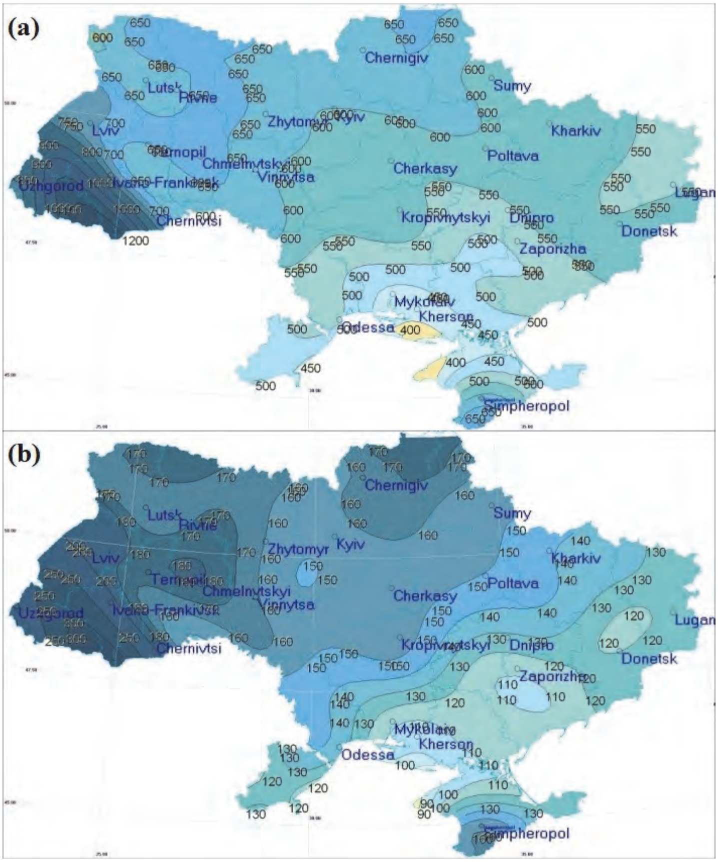


Fig. 2. Average annual precipitation (a) and amount of precipitation in summer (b) in 1981–2010.

In summer, in the steppe zone less than 200 mm precipitation fall, and in spring and autumn – less than 125 mm. At the same time, in some areas of the Kherson and Mykolaiv regions, precipitation may be less than 100 mm in summer. Deficiency of precipitation contributes to a significant increase in fire danger in this region.

Relative humidity also affects the nature fire danger, in particular, the intensity and the type (lowland ore overhead) of the fire. In the presence of sufficient moisture in the atmosphere, the combustion temperature is reduced due to heat losses by evaporation. If relative humidity is 40–50% or more the lowland fire is dominant. When it is lowered to 30%, the fire danger substantially increases and if it is 20%, the lowland fire may become the overhead fire (*Ozhogin,* 1939). The average humidity of air throughout the fire danger season in Ukraine is in the range of 40–65%, which contributes to the formation of mainly lowland fires. The number of days with average daily relative humidity less than 30% grows from 10 days on northwest to 35 days on southeast during the warm period, while on the coast areas it is decreasing again (*Fig. 3*). The same trends are typical for humidity less than 50%. That is, the southern and southeastern regions of the country are the most arid and favorable for the emergence of lowland fires that can become overhead fires.

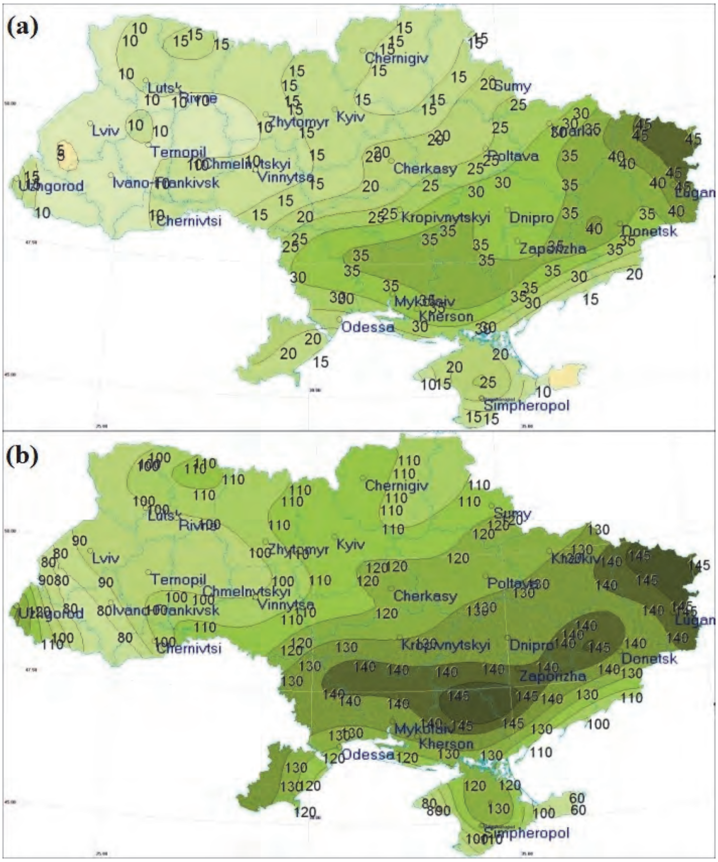


Fig. 3. Average number of days with average daily relative humidity less than 30% (a) and 50% (b) throughout the warm periods in 1981–2010.

Over the long absence of precipitation, when the daily amount of precipitation is less than 0.01 mm, the average daily relative humidity is less than 50%, and the maximum daily air temperature is more than 25 °C, there are favorable conditions for the formation of atmospheric drought. The largest number of days with atmospheric drought (15–20 days per year) was observed in the steppe and eastern forest steppe zones (10–15 days per year). In the central forest steppe it is 3–4 days per year, in the Polissya region it is 1–2 days, and in the rest territories it is even less. The probability of forest fire formation significantly increases in the absence of precipitation.

The largest number of days (about 5 months – 150 days or more) without rain ($R < 0.01$mm/day) throughout warm period was observed in the eastern areas of country (*Fig. 4*). To the north and northwest, this number is decreasing, and in the Carpathians it is the smallest (about 3 months – 110 days or less).

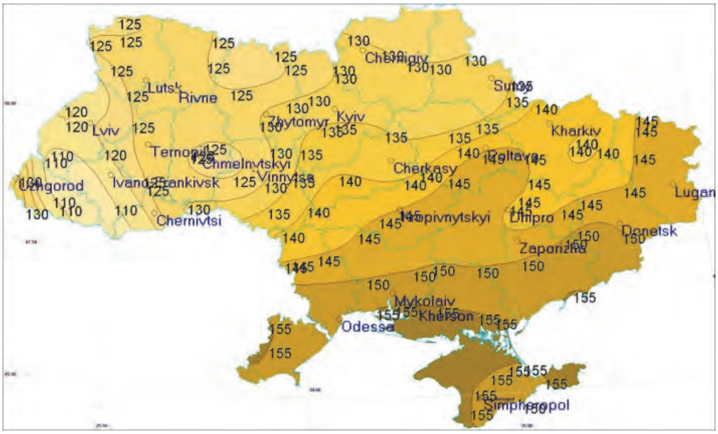


Fig. 4. Number of days without rain throughout the warm periods in 1981–2010.

In Ukraine, precipitation amount of 3 mm/day plays an important role in causing fires. It is a parameter that has to be taken into account when assessing the degree of fire risk in the country. It is believed that if the daily precipitation amount is 3 mm, the natural fire danger decreases and the comprehensive indicator of fire danger Nesterov is zeroed. In south region, the number of days with daily precipitation more than 3 mm may be 70 throughout the warm period. The maximum duration of the period with daily precipitation less than 3 mm (the period when $КПО_n$ increases) reaches 55 days or more, while in the western part of the country it is twice less (*Fig. 5*).

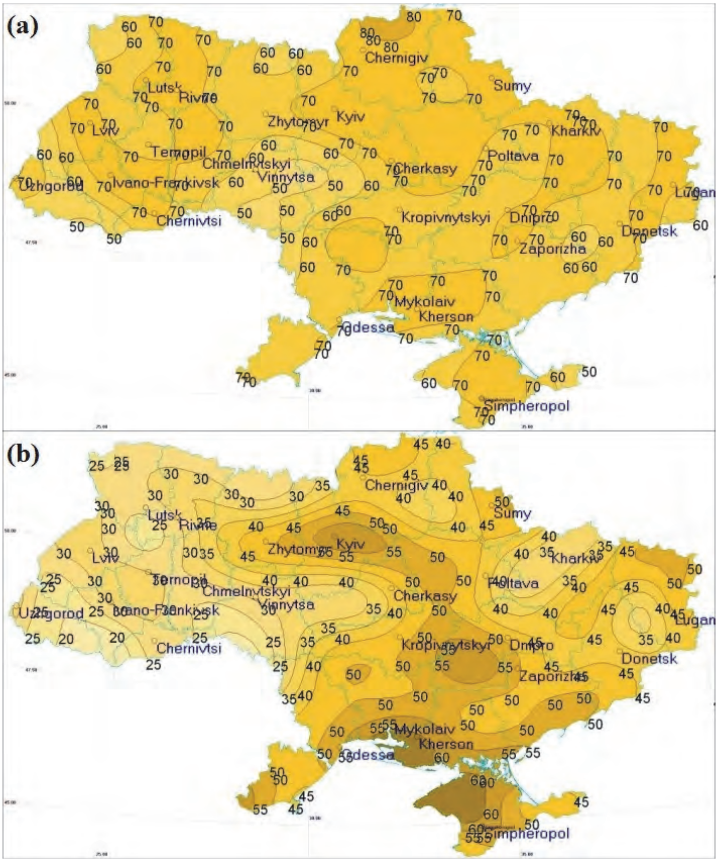


Fig. 5. Number of days with precipitation less than 3 mm (a) and maximum duration of period with that condition throughout the warm periods in 1981–2010 (b).

Since the forest fires depend on several factors and their interactions, climatic conditions favorable for the occurrence of natural forest fires are often described using different indices. In Ukraine and the post-Soviet territory, the Nesterov composite index (*КПО*) is the most known index that is used to analyze the impact of meteorological conditions on the forest fires, as well as on the monitoring and forecasting of forest fires. Application of the Nesterov index is regulated by the relevant government documents: standards, guidelines, and manuals.

The analysis of the spatial distribution of *КПО* index has shown that in Ukraine, the natural fire danger is rising from northwest to southeast gaining the highest values in August, especially in the Kherson and Mykolaiv regions, where *КПО* daily mean values exceed 250 °C or more, and *КПО* maximum values reach 50000 °C, which is 10 times higher than limit for the very high fire danger (V category) (*Fig. 6*).

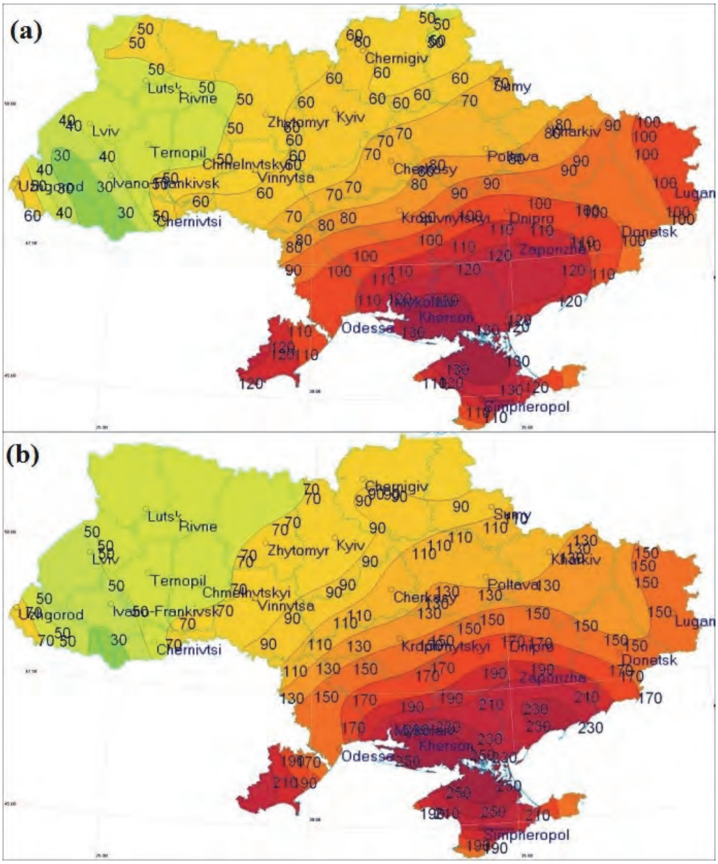


Fig. 6. *КПО* daily mean values for the warm periods (a) and the August (b) in 1981–2010.

Maximum days with very high fire danger (≥5000 °C) in warm period have increased by 30 days or less in the west and northwest areas to 80–90 days or more in the southeast. At the same time, in the southern part of the country there can be one or two months (35–50 days) with extreme fire danger (≥10000 °C), while in the northwest this value is 2–3 times lower (*Fig. 7*).

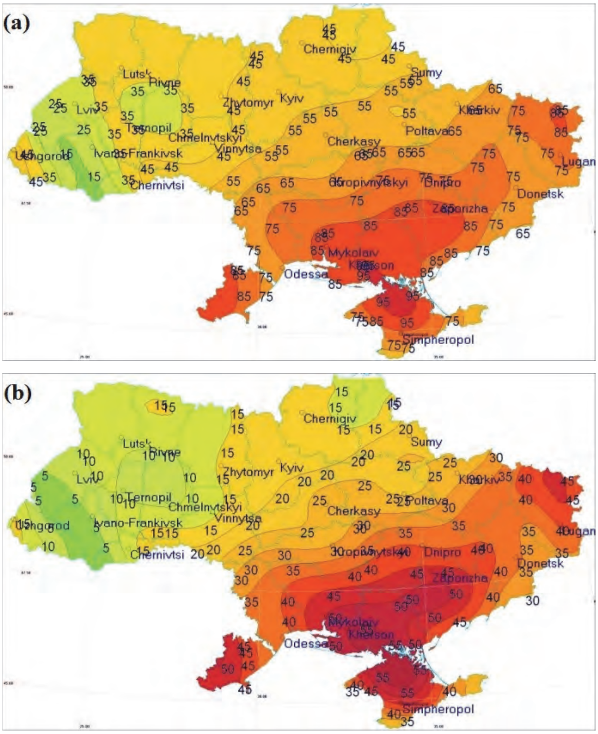


Fig. 7. Maximum number of days marked with V category: very high fire danger (≥5000 °C) (a); extreme fire danger (≥10000 °C) (b) in the warm periods in 1981–2010.

It follows from the results, that in the current climatic period, the most favorable climatic conditions for the emergence of natural fires in Ukraine are observed in the south and southeast of the country, especially in the Kherson and Mykolayiv regions. Since the Kherson region is characterized by man-made pine forests, which are the most dangerous for ignition, this region is the most fire-hazardous in Ukraine.

3.2. The main characteristics of trends of natural forest fires in Ukraine

A steady growth of the number of forest fires and their area has been observed for the past decades in Ukraine. Over the past 30 years (1981–2010), the annual number of forest fires in the country has increased by 2.6 times. Areas affected fire slightly increased since 1987, but after 1991, they have risen by 3–5 times (*Zibtsev,* 2010). It is largely due to climate change. Since the mid 70's, the steady transition of the anomaly of the average annual global air temperature is above 0 °C relatively to the basic climatic period of 1961–1990 (IPCC, 2013). However, in Ukraine, such transition is observed only in the late 90's due to an increase in the minimum, maximum, and average daily air temperatures (*Balabukh et al.,* 2013).

The rate of air temperature change (average, minimum, and maximum values) approximately equals to 0.3 °C per 10 years in 1961–2013 is. The average annual air temperature has risen by 0.8 ºC relatively to the climate normal (1961–1990) for the last twenty years (1991–2013). This is due to increasing of maximum and minimum temperatures in Ukraine (*Fig. 8*).

The changes were more intense in the current climatic period. According to the results of t-test analysis, it is "virtually certain" that the average annual temperature has increased in most of the country, and it is "very likely" for the rest of its territory. These changes are about 0.57 °C / 10 years, which is more intense than in 1961–2013 (0.3 °C / 10 years) and significantly exceeds the rate of change of global surface temperature (0.13 °C / 10 years in 1995–2012) (*Balabukh et al.,* 2014; IPCC, 2013). However, the rates of temperature change are uneven across the country. The highest rate of change was in the steppe and the eastern forest steppe region it was 0.6–0.7 °C / 10 years with a maximum in the Sumy region. In the central forest steppe region the process of rising was slightly slower, just 0.5–0.6 °C / 10 years. In Polissya and the western forest steppe, the rate was 0.3–0.4 °C / 10 years.

The rate of change also varies during the year. In summer, the average air temperature increased more intensely than in other seasons. It has grown from 0.7 °C / 10 years in the northwest of the country to 0.9 °C / 10 years in the south. Over Ukraine it was 0.83 °C / 10 years. The largest air temperature increase was in January (1.7 °C / 10 years), August (1.6 °C / 10 years), and July (1.5 °C / 10 years). The average temperature in spring has risen by 0.5 °C. This is due to an increase in May (0.7 °C / 10 years). Temperature in autumn changed by 0.4 C / 10 years. Growth of the minimum temperature prevailed in the winter season, the same for maximum prevailed in the summer.

Annual average maximum temperature also increased. The rate was 0.6 °C /10years. But, it rose from northwest to south and southeast. Thus, in the western forest steppe, the values were 0.4–0.5 °C / 10 years, while in the steppe and eastern forest steppe they were 0.6–0.7 °C / 10 years, reaching 0.72 C / 10 years in the Lugansk region. The analysis of annual variation of rate has shown that maximum values were in summer. In summer the average rate was 1.0 °C / 10 years, with a maximum value of 1.0–0.1 °C / 10 years in the steppe and eastern forest steppe regions.

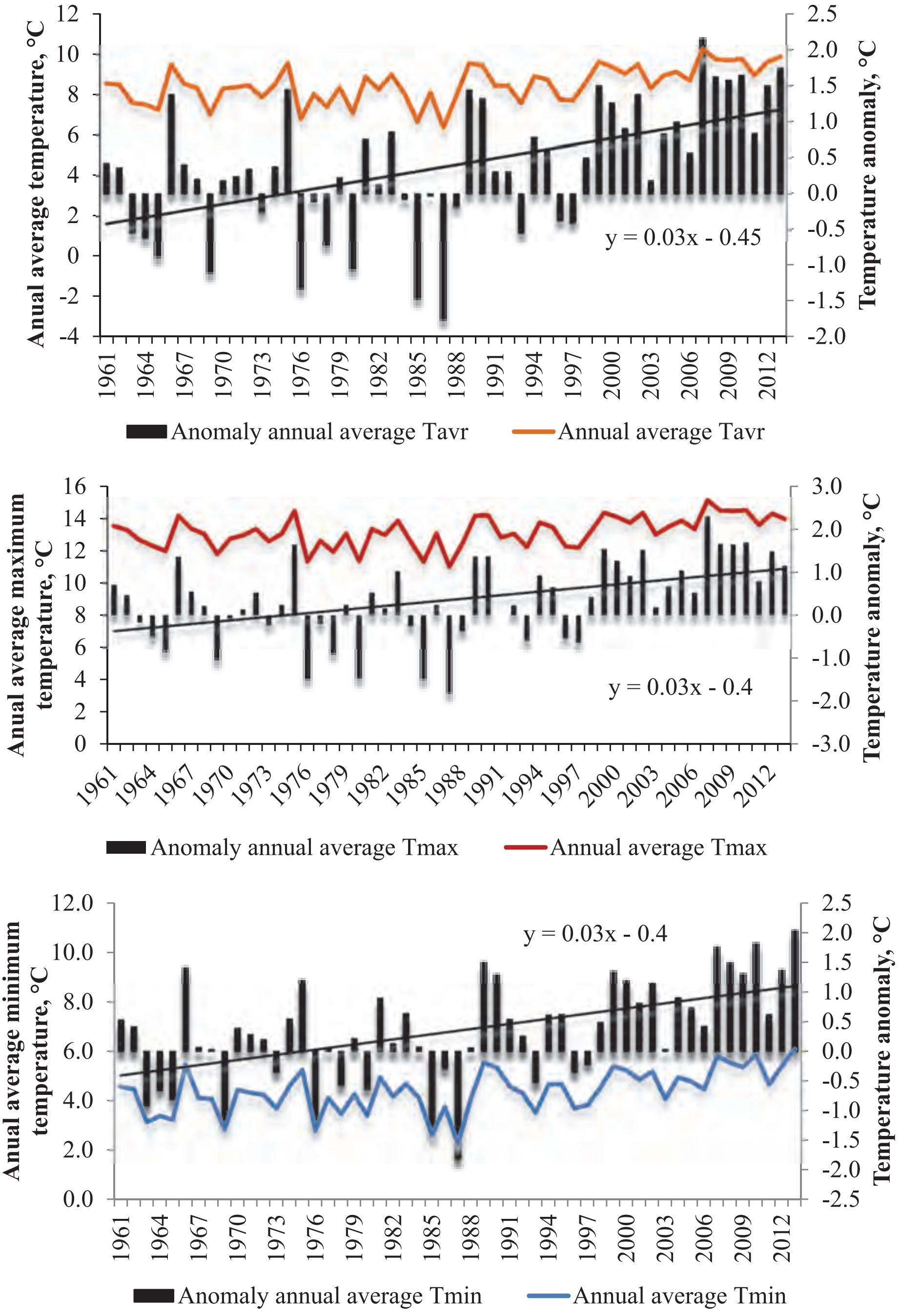


Fig. 8. Annual average (a), mean maximum (b), and mean minimum (c) land-surface air temperatures and theirs anomalies (°C), relatively to the climatic norm in 1961–2013, in Ukraine.

Significant increasing of the air temperature in the whole year resulted in the increasing number of warm days in Ukraine on average by 8 days per 10 years (*Fig. 9*). Throughout the 1981–2010 period, it is “very likely” that its duration has grown to 7–11 and 6–9 days in forest steppe and steppe regions, respectively. Such changes are “likely” to be occurring in the Polissya region too.

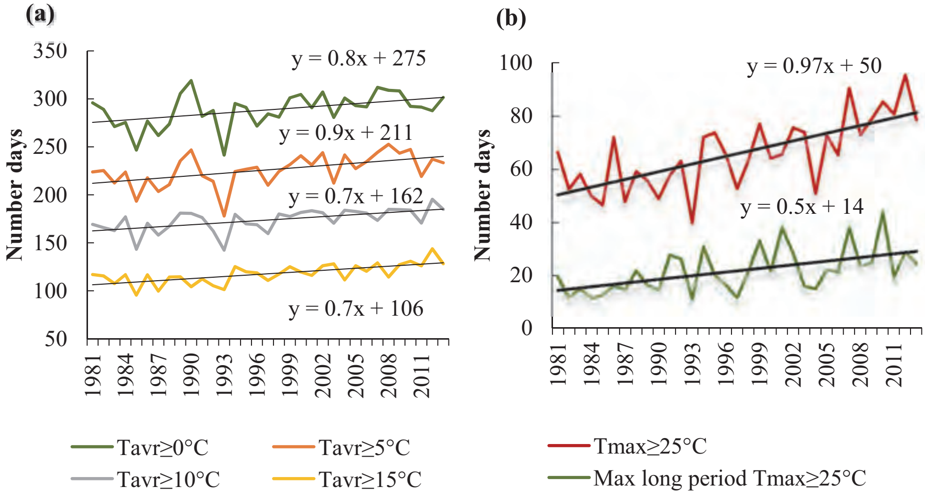


Fig. 9. Trends of annual number of warm days (daily mean temperature ≥0 °C), summer days (daily mean temperature ≥15 °C), vegetation days (daily mean temperature ≥5 °C) and active vegetation days (daily mean temperature ≥10 °C) (a), hot days (daily maximum temperature ≥25 °C) and maximum duration of periods with daily maximum temperature ≥25 °C (b) in Ukraine in the period 1981–2013.

For Ukraine it is “very likely” and “likely” that the number of vegetation and active vegetation days increases for 9 and 7 days, respectively. The intensity of these changes decreases from west to east. Due to the rise of temperature, the number of summer days, when the average daily temperature is above 15 °C increases. The rate of change is 7 days / 10 years and it is “virtually certain” (*Fig. 9*). In the west of the country, these changes are greatest (7–10 days / 10 years). In the northern and southern regions, the number of summer days “very likely” increases by 3–5 days / 10 years, and in the central and eastern regions – “likely” by 2–3 days / 10 years.

It is “virtually certain” that the number of hot days, when the daily maximum temperature is above 25 °C, is also rising. Generally for Ukraine, the rate of change is 9–10 days / 10 years. The maximum duration of the period with this temperature also increases by 5–6 days / 10 years.

3.2.1. Regime of humidity

Since the beginning of the 21st century, the precipitation, unlike air temperature, has not changed significantly, although in the current climatic period, it likely increased by 2–3% per 10 years. There was a redistribution of rainfall between seasons. In autumn, total precipitation, “very likely” increased by 13% / 10 years; in the spring this growth was 200% lower, only 5–6%/ 10 years, and for the winter and summer seasons, in Ukraine there were not significant changes. However, these changes were very heterogeneous throughout the country, especially in summer.

The greatest fire danger is characterized for summer. In this period, the total precipitation has reduced on a considerable territory of the country. The most intense changes are observed for the Polissya and eastern forest steppe region, where the precipitation deficit “very likely” has increased to 23% / 10 years. In return, in the western forest steppe, especially in the Ivano-Frankivsk region and Volhyn, their sum significantly increased and reached 37 and 29% / 10 years.

Although the average amount of precipitation per year in the current climatic period in Ukraine grew a little bit, it is “very likely” that a number of days with precipitation significantly decreased almost throughout the country. The intensity of the change rose from the west (6–9 days / 10 years) to the south and south-east (10–11 days / 10 years). The maximum duration of period with rain ($R > 0.01$ mm/day) was also reduced by 1–2 days / 10 years almost throughout the country.

Significant increasing of duration of period without rain that was accompanied by a significant increase in air temperature, especially its maximum values, led to an increase in the number of days with atmospheric drought. “Likely”, its number has grown by 2–3 days / 10 years general, for Ukraine. The aridity increased the most intensively in the steppe (3–7 days / 10 years) and eastern forest steppe (3–5 days / 10 years). The increase of the repeatability of arid conditions in the zone of sufficient atmospheric humidification, covering Polissya and the northern forest steppe areas is a dangerous tendency. It is “likely”, that in this region the number of arid days increased by 1–2 days / 10 years.

It is “very likely”, that throughout the current climatic period in Ukraine, the average annual, spring and summer relative humidity decreased by 0.7, 1.6, and 1.5% per 10 years, respectively. “Likely”, it increased in winter (0.4% / 10 years) and did not have significant changes in autumn (0.4% / 10 years). This process was observed almost throughout the country, and it was the most intense in the eastern forest steppe (1.4% / 10 years in Sumy region) and in the northern Steppe (0.6–1.2 / 10 years). A very intense reduction of moisture in the atmosphere was observed also in the Chernihiv region (1.5% / 10 years).

In spring, the atmospheric circulation changed and the essential increase in temperature led to notable decrease in average-for-season relative humidity (*Lipins'kyy*, 2003). The intensity of process is intensifying from west, northwest to south southeast. In the west forest steppe the rate is 0.9–1.3% / 10 years in contrary to the south steppe, where it equals to 2.3% / 10 years. The maximum rate of the change was 2.5% / 10 years in the Cherkasy region. The same trends were typical for the summer. In autumn, the average-for-spring relative humidity "unlikely" changed, except for the south steppe, where it probably increased.

An estimation of inter-year variability of the degree of fire danger for all regions of Ukraine in 1981–2010 was conducted. Based on results of analysis during this period in the country, there is a growth in the maximum number of days with an extreme fire danger. The most significant changes (1–2 days/ 10 years) are observed in the north and northeast areas of the country. These changes are not typical for the whole fire season. October, May, and September are exceptions. During these months, fire safety did not change almost throughout the country, and in some areas it even decreased. But in April, June, and August, a number of days with V category of fire danger is getting bigger in Ukraine.

Since the natural fire danger strongly depends on a combination of various meteorological factors, its temporal and spatial changes have a different scale, and sometimes even the direction of the trend is changing. That is, they are characterized by distinct regional features due to the climatic and microclimatic features of the territory that needs further research.

Thus, regional climate changes in Ukraine that affect fire danger are consistent with global changes in the thermal regime: the average for the year and seasons, and the minimum, maximum, and average temperatures increase; the number of warm and summer days increases; the number of days with active vegetation increases; the number of hot days and the duration of the hot period increase, the aridity during the warm period and the number of days with extreme fire danger increase.

3.3. Impact of climate change on the natural forest fires in Ukraine

A comprehensive analysis of the climatic parameters of the thermal regime, the regime of humidification, and the number and areas of forest fires, conducted by the example of Kherson region, where the greatest natural fire danger has been identified in Ukraine, showed that climate change significantly influences the fire danger.

The research showed that the risk of fire in the Kherson region largely depends on the thermal, moisture, and wind regimes. 10 weather stations across the region were used to characterize the territory. The influence of temperature is crucial. It is established that the temperature more affects the area of fires and much less affects their number (*Table 2*).

Table 2. Relationships between the number of forest fires per year (y) and the climatological conditions (x) in the Kherson region of Ukraine

Meteorological parameters	**Pearson's correlation**			**Regression**
	r(x,y)	**t**	**(1-p)value**	
average temperature in October	0.60	3.0	0.008	$y = 42.1x - 257$
maximum temperature in October	0.59	2.9	0.010	$y = 36.9x - 367$
minimum temperature in October	0.55	2.7	0.017	$y = 39.1x - 67$
minimum temperature in September	0.58	2.8	0.012	$y = 45.5x - 354$
the average temperature in September	0.53	2.5	0.022	$y = 37.4x - 438$
maximum temperature in September	0.45	2.0	0.061	$y = 24.9x - 355$
number of days without rain	0.44	1.9	0.079	$y = 4.1x - 104.3$
maximum duration of hot days periods	0.40	1.8	0.096	$y = 2.5x + 187$
number of days with thunderstorm	0.40	1.8	0.096	$y = 2.5x + 100$
maximum daily wind speed	0.39	1.7	0.113	$y = 5.1x + 142$
average annual temperature	0.25	1.0	0.312	$y = 34.3x - 167$
average summer temperature	0.23	0.9	0.367	$y = 21.9x - 293$
amount of precipitation in July	–0.40	–1.7	0.104	$y = -1.4x + 270$
annual precipitation	–0.40	–1.8	0.098	$y = -0.4x + 397$
annual average relative humidity	–0.41	–1.8	0.092	$y = -7.9x + 709$
amount of precipitation during the summer	–0.47	–2.1	0.051	$y = -0.9x + 328$

It is established that in the northwest Black Sea region (south of Ukraine), the number of fires per year depend on the air temperature mainly in October and September: the higher the average, minimum, and maximum temperatures during this period, the greater the number of fires that may occur in the region (*Table. 2*) Generally, in South-Eastern Europe, the greatest number of forest fires is observed in the summer-autumn period. The increase in air temperature and aridity in recent years leads to an increase in the risk of forest fires in the autumn, not only in Ukraine, but also in some EU countries, in particular, Hungary, Slovakia, and Czech Republic (European Commission, 2006). The same tendencies are typical for many regions of Russia (*Roshydromet*, 2008).

Analysis of the regression model calculations presented in *Table 2* shows, that the increase in the average monthly temperature by 1 °C can cause the growth of annual forest fires by almost 20%. The increase in the frequency of forest fires substantially depends ($r = 0.4$) on the maximum duration of hot periods, the number of days without rain, the wind speed, and the average number of days with thunderstorm. The greater the importance of these factors, the more likely they strengthening wildfires.

Analysis showed that increasing of annual precipitation by 20%, particularly throughout the fire danger period, can lead to a decrease in the number of forest fires in the region by 18%, and an increase in the average annual relative humidity by 10% may cause a decrease in the number of fires almost by 40%. It is established that in increase in the number of days without rain can lead to an increase of annual number of fires almost by 20%. It also can grow by 13% with a 5 m / s increase in the maximum daily wind speed.

The area of fires in the northern Black Sea region mostly depend on the maximum duration of hot periods, the number of hot days and the atmospheric drought (r = 0.76–0.60). During the 1996–2013 period, the annual average area of forest fires, in the Kherson region, amounted to 3.1 hectares. It is established, that the increase of the drought duration periods and increase of the duration of the period of hot days leads to an increase in the average area of fires by 130% and 65%, respectively. Growth of the number of hot days, when the maximum daily temperature exceeds 25 °C and 30 °C during 10 days, can lead to an increase of the area fires by 60% and 80%, respectively (*Table 3*).

Table 3. Relationships between the average annual area of forest fires (y) and the climatological conditions (x) in the Kherson region of Ukraine

Meteorological parameters	**Pearson's Correlation**			**Regression**
	r(x,y)	**t**	**(1-p)value**	
maximum duration with of periods with maximum daily temperature ≥ 25 °C	0.76	4.7	0.000	y =0.2x–7.3
number of days with maximum daily temperature ≥ 30 °C	0.68	3.7	0.002	y =0.25x–6.0
number of days with maximum daily temperature ≥ 25 °C	0.60	3.0	0.008	y =0.18x–13.2
average summer maximum temperature	0.61	3.1	0.007	y =2.5x–67
average summer temperature	0.59	2.9	0.011	y =2.9x–62
average summer minimum temperature	0.52	2.5	0.026	y =3.1x–51
average temperature in October	0.58	2.8	0.012	y =2.0x–19
minimum temperature in October	0.55	2.7	0.017	y =2.0x–10.7
maximum temperature in October	0.55	2.6	0.018	y =1.7x–23.7
number of days with atmospheric drought (maximum daily temperature ≥ 25 °C and maximum daily relative humidity ≤ 50%)	0.60	3.0	0.008	y =0.4x–2.9
average annual maximum temperature	0.55	2.6	0.019	y =3.4x–50
average annual temperature	0.51	2.4	0.030	y =3.5x–35
average annual minimum temperature	0.44	1.9	0.070	y =3.0x–17
average spring maximum temperature	0.50	2.3	0.034	y =2.6x–37
average spring temperature	0.45	2.0	0.062	y =2.8x–29
number of days with fog	–0.39	–1.7	0.109	y =–0.24x+12
amount of precipitation during summer	–0.41	–1.8	0.094	y =–0.04x+8.4
amount of precipitation in July	–0.41	–1.8	0.088	y =–0.07x+6.4
annual average relative humidity	–0.58	–2.9	0.011	y =–0.6x+39

The area of forest fires also significantly depend on the average, minimum, and maximum temperatures in summer, spring, and the whole year (r = 0.61–0.45). Thus, the growth of annual average temperature and temperature during the summer by 1 °C can lead to an increase in the average area of fires almost by 110 and 90%, respectively. Like the number of fires, their area in the Kherson region also depends on the air temperature in October, but this affect is somewhat less.

The presence of sufficient moisture in the atmosphere contributes to the reduction of forest fire frequency. *Table 3* shows that in the Black Sea region of Ukraine, the number of forest fire decreases when total precipitation in summer, especially in July, is growing and atmosphere has the less moisture content. The precipitation has large heterogeneity and variability in time. According to the World Meteorological Organization recommendations, their change is considered significant if it equals to 20% or more.

Unlike the number of fires, their area in the north part of the northern part of the Black Sea region mostly depends on the maximum duration of the hot period, the number of days with heat, and the atmospheric drought (r = 0.76–0.60) (*Table 2*). In 1996–2013 the annual average area of forest fires in the Kherson region was 3.1 ha. It is proven that increase in duration of drought and maximum duration of hot periods by 10 days lead to an increase in the average area of fire by 130 and 65%, respectively. Growth of hot days, when the maximum daily air temperature exceeds 25 and 30 °C, by 10 days may lead to an increase in the fire area by 60% and 80%, respectively.

Based on *Table 2*, the fire area greatly depends on minimum, maximum, and average air temperatures in summer, spring, and the whole year (r = 0.61–0.45). So, increase in annual average temperature and temperature in summer by 1 °C may cause an increase in the average fire area almost by 110 and 90%. Like a number of fires, the fire area also depends on air temperature in October; however, this effect is somewhat less.

Availability of sufficient moisture in the atmosphere also contributes to reducing the average area of the fire, which greatly depends on the relative humidity, rainfall during summer (especially in July), and the number of days with fog. It is established that the increase in the annual amount of precipitation by 20% could reduce the average area of the fire by 32% (*Table 2*).

3.4. Projections of changing in natural fire danger

According to the results of the regional model REMO-ECHAM5 presented in the framework of the European project Ensemble-based Predictions of Climate Changes and their Impacts (ECAP, 2009), the projections of changes in the average long-term indicators of the thermal and humidification regimes in Ukraine were simulated by the middle of the 21st century (2021–2050), relatively to the current climatic period (1981–2010) for the scenario SRES

A1B. Analysis of the results shows that by the middle of the 21st century, in Ukraine, a further increase in the temperature is expected according to the SRES A1B scenario. It is “virtually certain” that the annual average, mean maximum and mean minimum temperatures in Ukraine show an increasing tendency compared to the period of 1981–2010. However, these changes will be uneven and strengthened from west to east, peaking in the east (*Fig. 10*).

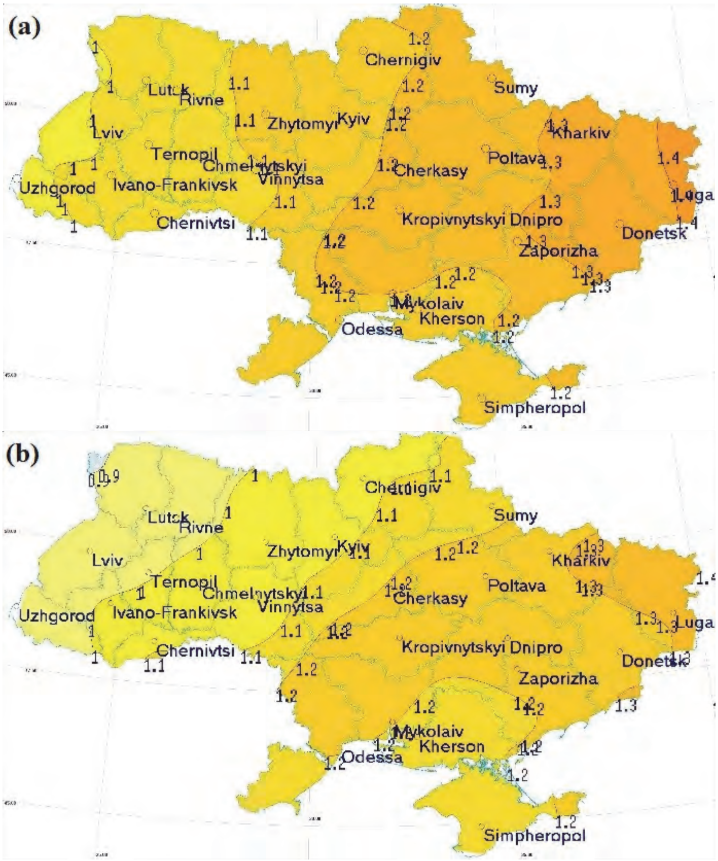
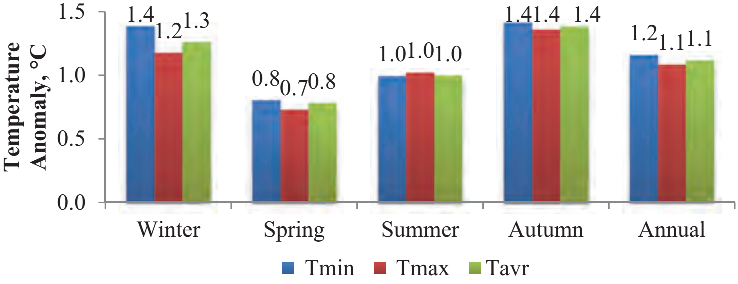


Fig. 10. Projected change in the annual mean (a) and mean annual maximum (b) air temperatures in 2021–2050, relatively to the period 1981–2010. Changes calculated by the RCM REMO-ERCHAM5 model for SRES A1B scenario.

The greatest growth is most expected in autumn and winter *(Fig. 11*). This increase in the minimum temperature in winter is greater than the maximum (1.4 and 1.1 °C, respectively). The most significant change may be the increased extreme temperatures in February (a minimum of 2.1 °C and a maximum of 1.7 °C). Extreme monthly average temperature in autumn could grow by 1.3 °C in summer – by 0.9–1.0 °C, and in spring – by 0.6–0.7 °C. The greatest changes (1.9 and 1.7 °C) can be expected in October. By the middle of the 21st century, minimum temperature likely increases in December (1.1 °C), although in the last two decades it has not changed, and in some regions decreasing was observed.

(a) average seasonal and annual air temperatures



(b) monthly mean temperatures

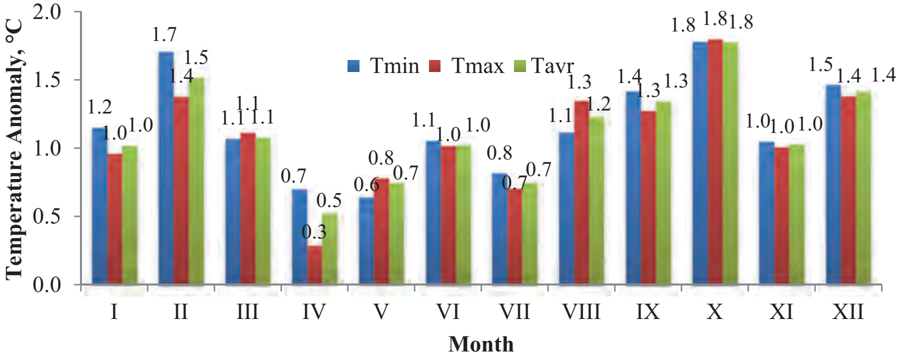


Fig.11. Projected change in the average seasonal and annual air temperatures (a) and monthly mean air temperature in 2021–2050, relatively to 1981–2010 period. Changes were calculated on the RCM REMO-ERCHAM5 model for SRES A1B scenario.

It is "virtually certain" that according to scenario A1B, annual average air temperature could grow by 1.1 °C (*Fig. 11)* and could be 9.8 °C in 2021–2050, against the value of 8.7 °C in 1981–2010, what will lead to an increase in the average area of fire almost by 10%, while its number will increase by 5%. In the west and central forest steppe regions this change may be 1.1 °C or less, and in the north steppe, particularly in Luhansk, this change may be 1.3 °C or more (*Fig. 10*). Accordingly, fires can be more extensive. Major changes are expected in winter and autumn, and it can be more than 1.6 °C in this region. In summer, the growth of the average season temperature can be from 0.7 to 1.3 °C, and in spring it can be 0.6–0.9 °C and more. By the middle of the 21st century it will lead to an increase in the number of forest fire by 13% and in their areas by 20% in Ukraine.

With a probability of 99%, it is expected that the average maximum temperature per year in 2021–2050 will increase in Ukraine by 1.2 °C, and will contribute to an increase in the average area of fires by 15% (*Fig. 11*). This growth will intensify from the northwest (0.9 °C) to the southeast and will reach a maximum (1.3 °C) in the Lugansk region. The biggest changes are expected in autumn and winter: generally for Ukraine they are 1.4 and 1.2 °C. In summer, average-for-season maximum temperature will grow by 0.7–1.3 °C. Herewith its values will be 28.5 °C or more across the steppe zone and Lugansk region, and it will be 25°C in Polissya. It will result in a significant increase in the fire danger. Those tendencies are the same for autumn. Changes above 1.5 °C will be observed almost throughout the country, and will reach a top in the east.

By the middle of the 21st century, with a probability of 99%, it is expected that the duration of hot periods will increase by 2–3 weeks compared to the current climatic period of 1981–2010 (from 12–15 days in the western forest steppe to 18–20 days in the eastern forest steppe). Across Ukraine the warm period could be 10–10.5 month (or even 11 month in the Crimea) by the middle of the 21st century. At the same time in Polissya, the number of warm days will reach 300 days per year, which was typical for the southern steppe on the beginning of the century. The duration of vegetation and active vegetation periods will significantly increase by 7 and 11 days, which will help to accumulate more biomass and, accordingly, to cause more intense fires.

Generally for Ukraine it is “very likely” that a number of hot days will increase by 10 days. In the northern and western regions its change will be 5–7 days, but in the southern region it will be 12–15 days. The number of hot days per year will exceed 100 days in the south steppe. It has the most significant influence on the growth of fire danger and may result in an increase in the average area of fires 1.3–1.4 times. It is expected that period with extreme fire danger will grow.

By the middle of the 21st century in Ukraine, the humidification regime may change, although the change of the annual precipitation is “unlikely”. It is expected that the precipitation will be redistribution between seasons: during the warm season, its amount will decrease almost all over the country, except

Polissya, and the winter season, when it will "very likely" grow almost by 13% or more.

The number of days with precipitation and days without rain will not have significant change until the middle of the 21st century compared with the current climatic period. Exceptions are certain districts in the southern steppes and Crimea where it is "likely", the number of days with precipitation will decrease by 1.2%, and the number of days without rain will increase by 3–4%. It is "likely" that the maximum duration of the period with precipitation will increase, and the period without rain will decrease by 4–5%. An increase in the number of arid days is "virtually certain", it could be by 40–60% more. The biggest changes are possible in the Polissia, forest steppe, and Transcarpathia regions, what will increase the fire risk in these regions.

Based on analysis of the projections of the change in relative humidity, the moisture content in the atmosphere by the middle of the century may also change, although these changes will be ambiguous across the country and throughout the year. The annual average relative humidity will increase across territory of Ukraine. In the Polissya, Lviv, Vinnitsa, and Sumy regions, the probability of these changes will be above 70%.

In summer the relative humidity will decrease rather than grow. Such changes are likely to reach 2–3% in the steppe, especially in the southern part. In the autumn, the moisture content in the atmosphere will increase throughout the country. The biggest change (up to 2%) will be in the western, central forest steppe, Polissia, and Transcarpathia regions.

4. Conclusions

As a result of the climate change analysis in Ukraine, it was found that over the past decade the thermal mode, moisture, and wind frequency have changed significantly, affecting the number and area of forest fires. These changes led to an increase in the fire risk in the region. Evaluation of possible changes in these characteristics to the middle of the 21st century showed that under the SRES A1B scenarios, it could be expected further increase in the temperature throughout the year, growth in the number of hot days and in the sultry duration period. Since these processes are accompanied by an increase duration of the drought period, these changes significantly affect an increase of the fire risk: the number of forest fires and their area can significantly increase by the middle of the 21st century in Ukraine.

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