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General overview of the potential effect of extreme temperature change on society and economy in Poland in the 21st century

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This work gives an overview on how the projected changes in the extremes in Poland might impact human health and economy. For that purpose, statistically corrected data from 7 regional climate models were used. A significant increase of extreme hot events (*i.e.* heat waves, tropical nights) is projected for Central and Southern Poland for the end of the 21st century which might seriously affect a society living in large urban areas. Less extreme cold events improve thermal comfort in winter. The negative impact of the warming will affect energy systems with higher demand for electricity in summer and agriculture: an earlier beginning of the growing season and flower blooming will enhance the risk of frost damages in spring, whereas excessive heat will reduce yields in summer. Polish tourism should benefit from higher thermal comfort (except for hot July and August in the far future and warming in the winter season bringing snow cover depletion in the near future).

Keywords: cold wave, heat wave, heating season, meteorological growing season, Poland, temperature extremes

1. Introduction

According to the WMO (2013), the first decade of the 21st century was the warmest at least since 1850. In the decade 2007–2016, only the years 2008 and 2011 were beyond the 10 warmest years on record and almost each of the years was warmer than the previous one. The IPCC report (2014) presents a global warming of 0.85 °C (from 1880 to 2012). Regional climate projections indicate a significant warming not only for the entire globe but also for Europe and Poland. Future model projections for the A1B emission scenario estimate a further warming of 1.5–3 °C / 2–3 °C for northern/southern Europe by 2050 as compared to the 1961–1990 period (van der Linden and Mitchell, 2009). Anders et al. (2014) reported a summer warming of 1.5 °C in the north (northern Germany and Poland) to 3 °C in the south of Europe (Mediterranean areas) and in winter from about 1.8 °C in the western part of Central Europe to 3 °C in the northeastern parts. Considering the RCP4.5 and RCP8.5 emission scenarios the ENSEMBLE model, developed within EURO-CORDEX experiment (Mezghani et al., 2017), presents temperature increase in Poland up to 1.1–1.3 °C in the 2021–2050 and 2.0–3.6 °C in 2071–2100. The most pronounced warming up to 4.5 °C is expected in winter at the end of 21st century (RCP8.5).

An increase in the mean temperature leads to a shift of the entire temperature distribution towards warming, which in turn has a great impact on temperature extremes (more hot extremes, fewer cold extremes). Not only changes in the mean but also in variance might influence the extremes (which is even more important). For example, an increase in variance leads to more extremely cold and hot days. Furthermore, in particular years the warming signal can be additionally reinforced or diminished by natural variability (Kundzewicz and Kozyra, 2011). In Central Europe and Poland the last most pronounced heat waves took place in 1994, 2006 and 2015 and their frequency is proceed to be doubled in 2020–2049 (Lhotka et al., 2018).

Changes in temperature extremes affect society and economy. For example, an increase in the number of hot or ice days might lead to an increase in mortality and morbidity. Long-lasting episodes of extreme temperature can have significant impacts on health. If the heatwave intensity is above 95th percentile and lasts longer, the risk of death increases remarkably. In Australia the risk of deaths increased by 28% (Cheng et al., 2018). Elderly people are the most vulnerable to heat stress because of changes in their thermoregulatory system (reduced sweating capacity). They mostly suffer from renal and respiratory diseases, cardiovascular diseases or heat stroke (Donaldson et al., 2003). Heat wave events are also related to high mortality, mostly among people over 75 years of age, but the risk is increased even after age 50 years (Kunkel et al., 1996). Not only the elderly are at risk but also newborn babies and children due to their limited thermoregulation abilities and dehydration (Basu, 2009). One of the most striking was the heat wave in 2003 which led to 22,000–35,000 heat-related deaths in Europe in August (IFRC, 2004). Furthermore, more vulnerable to heat stress are women, physical workers, men who are active during hot weather or generally people living in densely built-up urban areas. Additional risk arising from warming is related to vector-borne diseases, *e.g.* transmitted by ticks which currently occur in Scandinavia (Kundzewicz and Kowalczak, 2008). In a warmer climate, the probability of transmission of spirochaete increases, which in turn poses a risk of Lyme disease. Moreover, the shift towards warmer conditions increases the risk of food poisoning. It is estimated that by the year 2050 there will be additional 179,000 cases of food poisoning resulting from climate change (Bentham and Langford, 1995).

One of the economy sectors highly related to climate conditions is agriculture. Crop productivity and its quality strictly depend on temperature and soil water storage. The north of Europe is mostly affected by positive aspects of climate change where new crop species can be introduced, whereas southern Europe has to face harder climate condition, such as heat stress and water shortage. One of the most commonly used indicators for agriculture is the growing season which is determined by temperature. The increasing duration of growing season and intensification of agriculture (higher food demand) might result in shifting crop production towards the north of Europe. A heat wave event is very often followed by drought. More frequent and intense heat waves may reduce yields in Central and Southern Europe. According to Olesen (2002), currently the most productive regions are situated in great plain areas (South East England, Benelux, France, Germany and Poland). Warmer winter conditions may lead to fruit tree blooming too early and damage after spring frost.

Heat stress can also affect animals. The influence can be direct and indirect. Temperature related illnesses and deaths are the direct consequences of heat episodes. Hahn and Mader (1997) found a relationship between cattle deaths and temperature. Indirect impact is related to changes in microbial populations, vector-borne diseases, infectious agents, food and water shortages or food-borne diseases. Metabolic diseases might have a negative impact on livestock production and reproduction system. Martin et al. (1975) observed a higher infant mortality rate and Amundson et al. (2006) a reduction in pregnancy rate due to heat stress. Additionally, the growth of the foetus might be slowed down. Furthermore, heat stress may reduce milk, meat and egg production. Lacetera et al. (1996) found losses in milk production in dairy cows. The 2006 heat wave in California brought losses of US$ 1 billion in milk and animals (Collier and Zimbelman, 2007). This problem might seriously affect Polish economy where dairy cows account for 90% of all cattle. Extreme warm conditions foster the multiplication of pathogens in feed and this can lead to higher susceptibility to infections. Increasing temperature gives rise to bluetongue viruses or growth of mycotoxins which affect organs and tissues. Hot conditions are dangerous to pigs because of their low sweating capacity, especially in the case of periparturient sows (D'Allaire et al., 1996).

Finally, temperature changes can also affect the tourist industry. Frequent and long-lasting heat waves in southern Europe might shift summer holiday destination to the north. On the other hand, warmer winters and less snow lead to a shortened ski season or even to the closure of lowland ski resorts.

There are two main goals of this paper. Firstly, to assess extreme temperature changes in different parts of Poland in the 21st century based on the mean of regional climate model projections. Secondly to give a general idea of the potential effect of temperature change on human wellbeing and economy. It is hard to directly and precisely measured the effect of temperature change on human and economy. But understanding its relationships, the time and the direction of that impact can be specify. In the first part of the study we introduced data sources and methodology. Each dataset was statistically corrected with regard to Polish climate conditions. Then, we calculated indices which represent heat and cold stress conditions for the human body and indices which characterize the relation between temperature and agriculture, energy and tourism. In the second part of the study, the shifts in temperature were presented. The temperature changes through selected indices (such as heat/cold waves, number of ice, frost days, growing season, heating or cooling season) gives the general idea of the future potential effects on human body and economy. Furthermore, these results were discussed and compared to other studies. The last part of the paper is devoted to the conclusion.

2. Data

2.1. Data source

We used projections of 7 regional climate models (RCMs) of maximum, minimum and mean temperatures for two future periods: 2021–2050 (near future) and 2071–2100 (far future), as well as 1971–2000 (reference period). Most of them were provided by the ENSEMBLES project: HIRHAM1, HIRHAM5, RegCM3, RACMO2, RCA with a resolution of 25 km (http://ensemblesrt3.dmi.dk/). The CLM model with a resolution of 22 km was developed in Max Planck Institute (cera-www.dkrz.de) and the WRF model with a resolution of 30 km was released by NCEP/NCAR, the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma and the Federal Aviation Administration (FAA), and applied to the conditions of Central Europe by the Department of Meteorology and Climatology, University of Lodz. The majority of models was forced by ECHAM5r3, except HIRHAM (HadCM3Q0) and CLM (GME). The RCMs were chosen on the basis of best agreement with the observation data for 1971–2000. The observation data for the reference period were obtained from 40 weather stations of the Institute of Meteorology and Water Management, the National Research Institute (Fig. 1). The datasets from all of the 40 stations were homogenized. It was tested with use of Alexandersson and t-Student tests (Alexandersson, 1986; Wibig, 1990). Afterwards, the temperature datasets were gridded with a resolution of 0.25°. For that purpose, we averaged the data from each circle with a diameter of 100 km (Déqué, 2007).

2.2. Data validation and correction

In order to verify the data, we compared seasonal percentile datasets from single models and multi-models (model averages) to observations. For a comparison of temperature distributions, we applied the Two Sample Kolmogorov-Smirnov Test and the Skill Score test (Perkins et al., 2007). For further study, we used an ensemble model (multi-model mean) as both tests showed its best

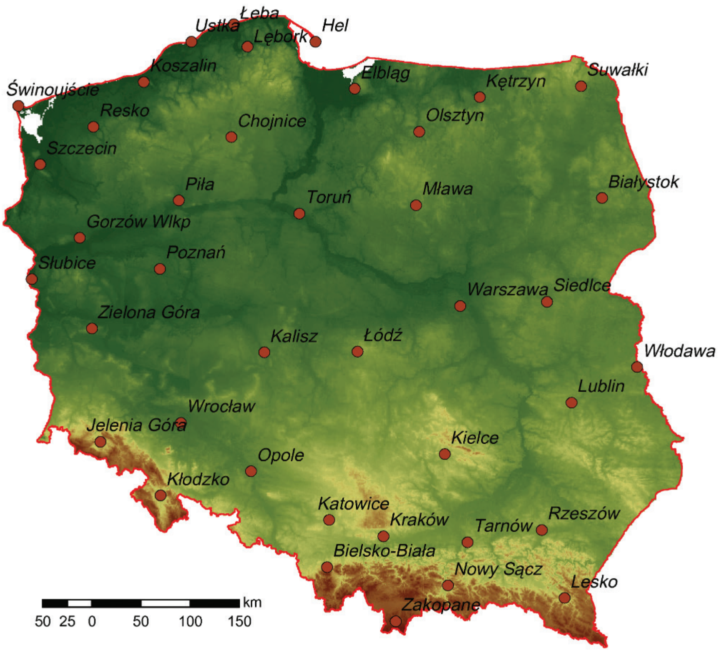


Figure 1. Location of synoptic stations.

agreement with the observed climate conditions in Poland (better than a single model). It was also found by Knutti et al. (2010) that a single model dataset shows worse agreement than the multi-model average. The multi-model and observation data distributions were the most coherent for mean temperatures. The maximum temperature was usually underestimated (mostly in spring and summer) and the minimum temperature was overestimated (mostly in summer). Since our biggest difficulties were with the representation of extreme high/low maximum/minimum temperatures by RCMs, we decided to correct the modelled data for the future scenario (Mcorr). For this purpose, we used distribution based bias correction (DB) which is one of the Model Output Statistics methods. In the DB method the bias factor between observation and model reference (O_{ref} and M_{ref}) is calculated independently for each percentile on the base of quantile-quantile (Q-Q) plots. Then the future scenario model data (*Mscen*) are corrected with the bias (Déqué, 2007; Piani et al., 2010; Wibig and Jędruszkiewicz, 2015):

$$M_{corr} = M_{scen} + (O_{ref} - M_{ref}) \tag{1}$$

This method is valuable with regard to different biases among all temperature distribution (*e.g.* high underestimation in upper tail of maximum temperature). Using the DB, we corrected the maximum, minimum and mean temperature percentiles separately for each season of 2021–2050 and 2071–2100 periods.

3. Methods

3.1. Temperature indices

The number of days when maximum and minimum temperatures exceed absolute thresholds were calculated. The absolute thresholds comprised of selected indices introduced by the Joint CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (Peterson et al., 2001):

- Summer days (*SU*): Annual number of days when daily maximum temperature > 25 °C
- Tropical nights (*TR*): Annual number of days when daily minimum temperature > 20 °C.
- Frost days (*FD*): Annual number of days when daily minimum temperature < 0 °C.
- Ice days (*ID*): Annual number of days when daily maximum temperature < 0 °C.

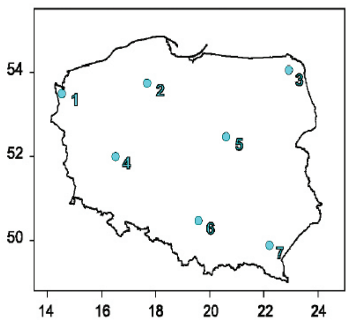
Furthermore, the entire distributions of minimum temperatures in winter and maximum temperatures in summer were compared for different parts of Poland (different climate conditions) and periods (reference and two future periods). The list of grid points for which the temperature distributions were compared are set in Tab. 1.

For more complex characteristics of extreme temperature conditions, the number and duration of heat and cold waves were calculated. A heat wave is defined as at least 3 consecutive days when the following conditions are met (Huth et al., 2000):

- daily maximum temperature reached at least 30 °C on at least three days,
- mean maximum temperature during heat wave was at least 30 °C,
- daily maximum temperature did not drop below 25 °C.

Table 1. Grid point locations.

1	53°30'N; 14°30'E
2	53°45'N; 17°30'E
3	54°00'N; 23°00'E
4	52°00'N; 16°00'E
5	52°30'N; 20°30'E
6	50°30'N; 19°30'E
7	50°00'N; 22°00'E



A cold wave, by the definition introduced by Dubrovský et al. (2006), is a period of at least 3 consecutive days when:

- daily minimum temperature dropped to or below –12 °C on at least three days,
- mean minimum temperature was –12 °C or lower,
- daily maximum temperature did not exceed –5 °C.

3.2. Growing season

The growing season is one of the most important and commonly used indicators in agriculture. In this study, the meteorological growing season (*MGS*) determined by Huculak and Makowiec (1977) is applied. The beginning of *MGS* is considered to fall on the first day when the daily mean temperature is 5 °C or higher, this day giving rise to such a set of cumulative standard deviations from the 5 °C temperature which remain positive for the first part of the year. On the other hand, the end of the *MGS* is the day preceding the earliest day when the daily mean temperature is lower than 5 °C. At the same time, this day has to give rise to a negative set of cumulative standard deviations from the 5 °C temperature, lasting until the of the year.

3.3. Heating and cooling season

The cooling season is the period of time when there is a need to use cooling devices (*e.g.*, air conditioners) due to high outdoor temperature. The human thermoneutral conditions occur when the temperature reaches 18–23 °C. The thermoneutral conditions appear when the energy consumption of human body reaches its lowest value, *i.e.* ca 22 °C (Prek, 2006). But the need for cooling is a very subjective feeling depending on season, climate zone, activity or individual vulnerability. For this reason, it is impossible to find a universal indicator. For the purposes of this study, we introduced a new indicator (*DNC* - days needing cooling) which seems to be the most appropriate for Polish climate conditions. The *DNC* in an annual number of days with potential use of cooling devices. These potential days are defined as at least 3 consecutive days ($3T_{max}$) when the maximum temperature reaches 25 °C or more:

$$DNC = \sum_{n}^{i} 3T_{max} > 25°\text{C} \tag{2}$$

The maximum temperature threshold of 25 °C was set for two reasons. Firstly, it is one of the extreme temperature indicators (summer days), when there is a need for cooling. Secondly, it was proven by Saman et al. (2008) that cooling energy consumption increases when this threshold is exceeded.

The heating season (*HS*) is a period of time when there is a constant demand for heating buildings. In practice, the start and end of the heating season is set by individual recipients. In this study, the beginning/end of *HS* is defined as the third out of five consecutive days when the daily mean temperature was lower/higher than 10 °C. The 10 °C threshold was set based on the study of Kolendowicz et al. (2010). The period of 3 days was extended to 5 due to very warm conditions projected for the end of the century, which in turn results in the *HS* being too short or even absent in individual years.

4. Results and discussion

4.1. Extreme temperature change

Changes in the summer maximum temperature distributions in the 2021–2050 mostly apply to a decrease in variance (Fig. 2). This results in a smaller number of days with temperatures below 20 °C and above 27 °C (except the south east) and many more in the range of 20–27 °C. In the 2071–2100 period, the variance will increase but will still remain at a lower level than in the reference period. Furthermore, the shift towards warming in the entire distribution is expected in southern Poland as compared to 1971–2000, which in turn will lead to more days with the maximum temperature above 27 °C and fewer days with average conditions. Only in the north western part of Poland the number of days with extreme high temperatures will remain on the same level or even decrease.

In the near future, changes in the minimum temperature in winter will mostly refer to remarkable warming in the first part of its distribution (Fig. 2). This means fewer days with temperatures below –7 °C in the west and –10 °C in the east and more with temperatures around 0 °C (–5 °C / 5 °C). In the far future, the winter distribution of minimum temperatures will be more symmetric and the variance will significantly decrease. This will result in a shift of almost the whole distribution towards warmer conditions. As regards these changes, in winter in the western and north western parts of Poland the temperature will most likely not drop below 0 °C on more than 50% of days.

Similar results were obtained in the study of absolute thresholds. During the cold half of the year, the most severe climate conditions occur in the north eastern and eastern parts of Poland and in the mountain areas with 120 frost days and 50–60 ice days or more (Fig. 3). On the other hand, the mildest climate is observed in the Odra Valley (western and south western parts) and on the Baltic coast with less than 100 frost days and 30 ice days. This results from increasingly continental climate towards the east and a stronger impact of the Atlantic in the west and of the Baltic in the north western areas. In the near future, the number of frost and ice days will decrease remarkably by about 20 and 10 days, respectively. In the far future, a further decrease (of up to 20 days) will mostly affect frost days. For ice days, the further direction of multi-model projections is more diverse. Firstly, a decrease in the number of ice days is hardly visible and refers mostly to the northeastern and mountain regions. Secondly, a slight increase is projected for the western parts (up to 10 days

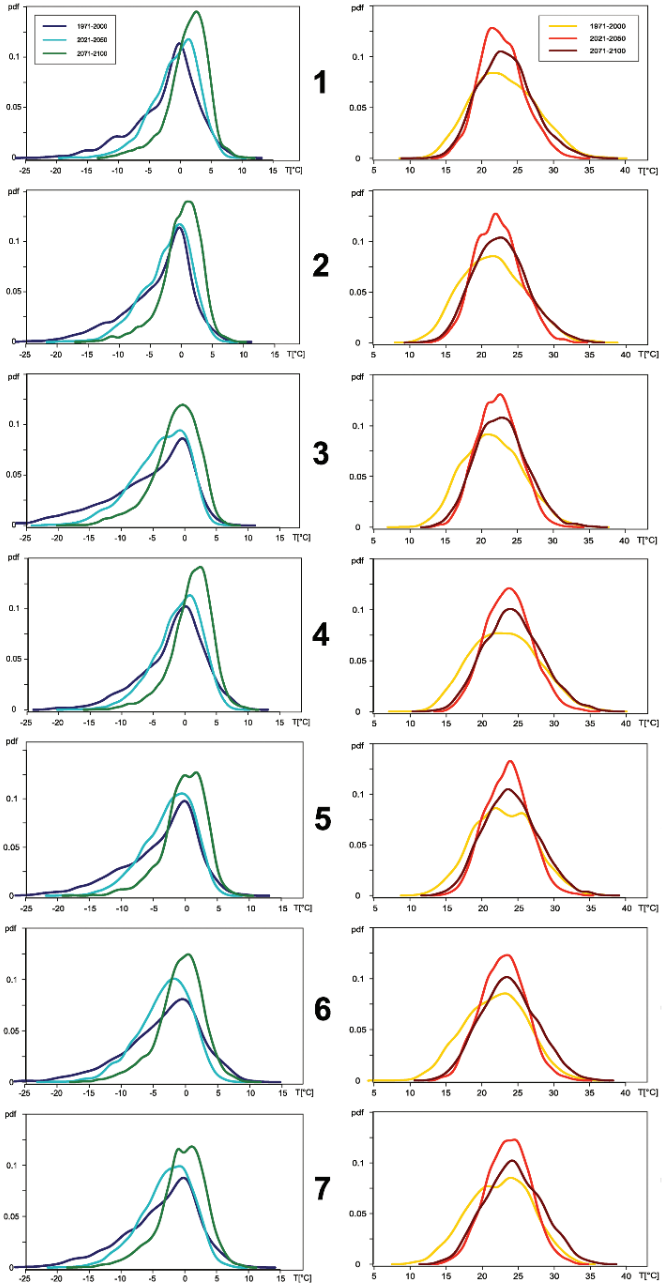


Figure 2. Probability density functions (PDFs) of the minimum temperature in winter (*left*) and maximum temperature in summer (*right*) for the selected points (see Tab. 1) in 1971–2000, 2021–2050 and 2071–2100.

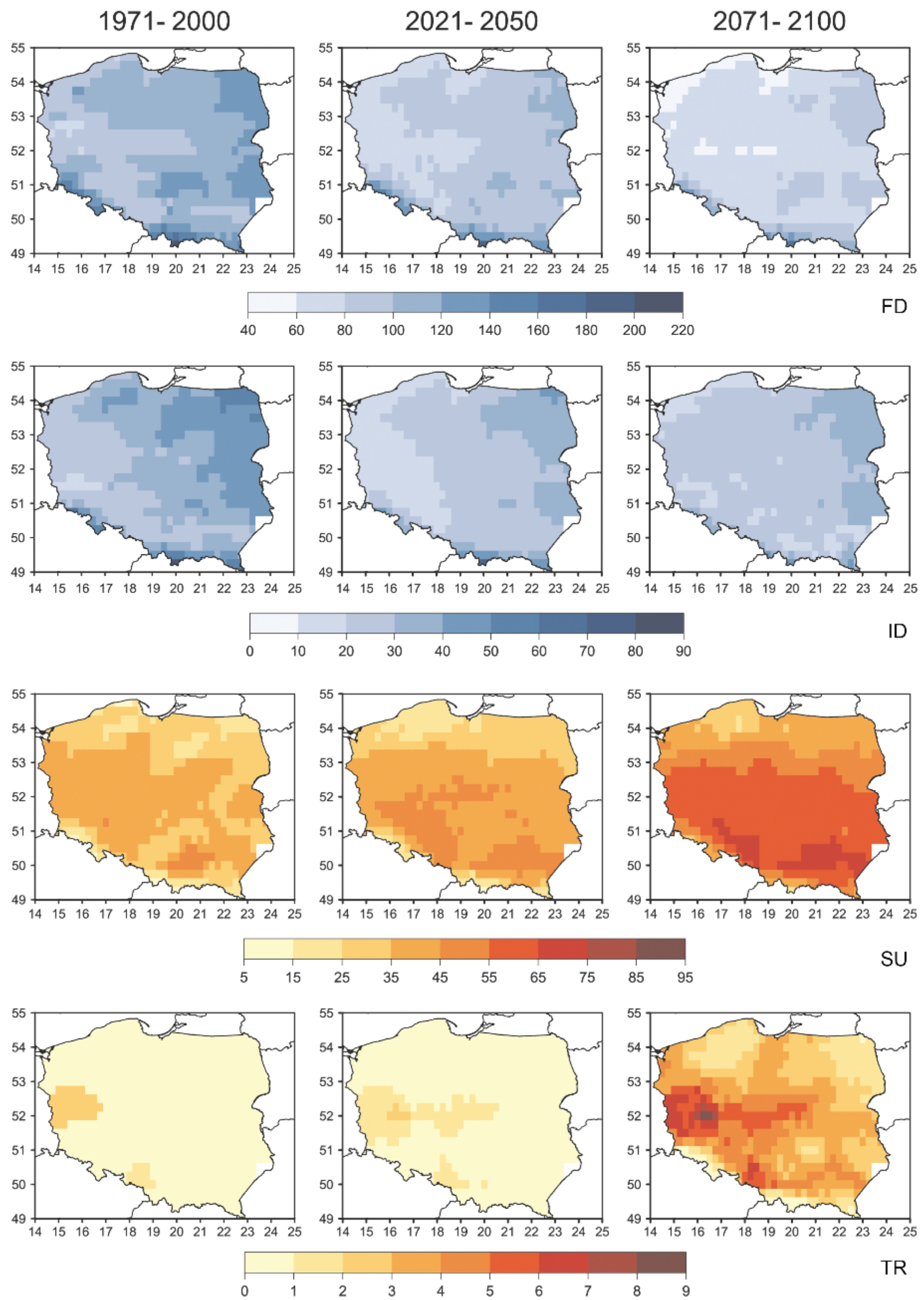


Figure 3. The number of frost days (*FD*), ice days (*ID*), summer days (*SU*) and tropical nights (*TR*) in 1971–2000, 2021–2050 and 2071–2100.

around the middle of the century). Thus, by the end of the 21st century in the prevailing part of Poland there will be 60–80 frost days and less than one month of ice days (twice as less as in the reference period).

In the warm half of the year, the warmest conditions are observed in the central zone (lowland areas of Poland) (Fig. 3). In these regions, 35–45 summer days occur per year (> 45 days in the Sandomierz Basin). For the near future, warming is hardly visible and refers to no more than 5 additional summer days in the Odra Valley, central Poland and the Sandomierz Basin. A considerable warming is projected only for the end of the century and mostly in central and southern Poland (except mountain ranges). There will be more than 55 summer days in lowland areas (> 65 days in the upper Odra Valley and the Sandomierz Basin). It is hard to talk about tropical nights in Poland due to their rare occurrence even in the near future (< 2 nights / year). However, this situation will likely change significantly in the far future. According to the models, the number of tropical nights will increase in lowland and valley areas (even up to 6–8 nights in the middle west, the central and Silesia Lowland regions). The connection of summer/hot days or heat waves with tropical nights will be the most extreme experience for people living in the largest, densely built-up urban agglomerations in central and southern Poland (*e.g.*: Łódź, Wrocław, Kraków, Katowice) where new extreme events (tropical nights) will be more common. The projected significant warming in summer at the end of the 21st century may lead to high temperature contrasts between the north and the rest of the country, whereas the west-east temperature contrasts in winter will be to some extent blurred.

From the point of view of human health and wellbeing, the most dangerous are long-lasting periods of extreme warm and cold weather (heat and cold waves). Human body has a limited ability to adopt to extreme high or low temperatures. Furthermore, people differ in their vulnerability to such conditions depending on age, gender, type of work, etc. In Poland, we usually observe 1–2 heat waves per year which last 4–10 days (depending on the region) (Fig. 4). In the near future, a slight change in the number and duration of heat waves is projected (increase in southern and decrease in western Poland). Considerable changes are expected at the end of the century when the number of heat waves will double in northern and central Poland and triple in the southern parts. In the far future, heat wave events are expected to occur 2–3 times per year and last annually 11–13 days in northern Poland, and about 4–5 times with a total annual duration of 18–24 days in central and southern Poland. Lhotka et al. (2018) found nearly twice as many heat waves in the Central Europe for the 2020–2049 which is more than in this study. It is explained by the changes in autocorrelation and scale parameter of maximum temperature which has increased in the RCPs scenarios. It might be a real challenge for the public health service to deal with more intense and longer-lasting extreme warm events in a future (especially considering the ageing society). But even now, we experience warmer and warmer summer conditions (heat waves in Poland: 2003, 2006, 2010, 2015). The

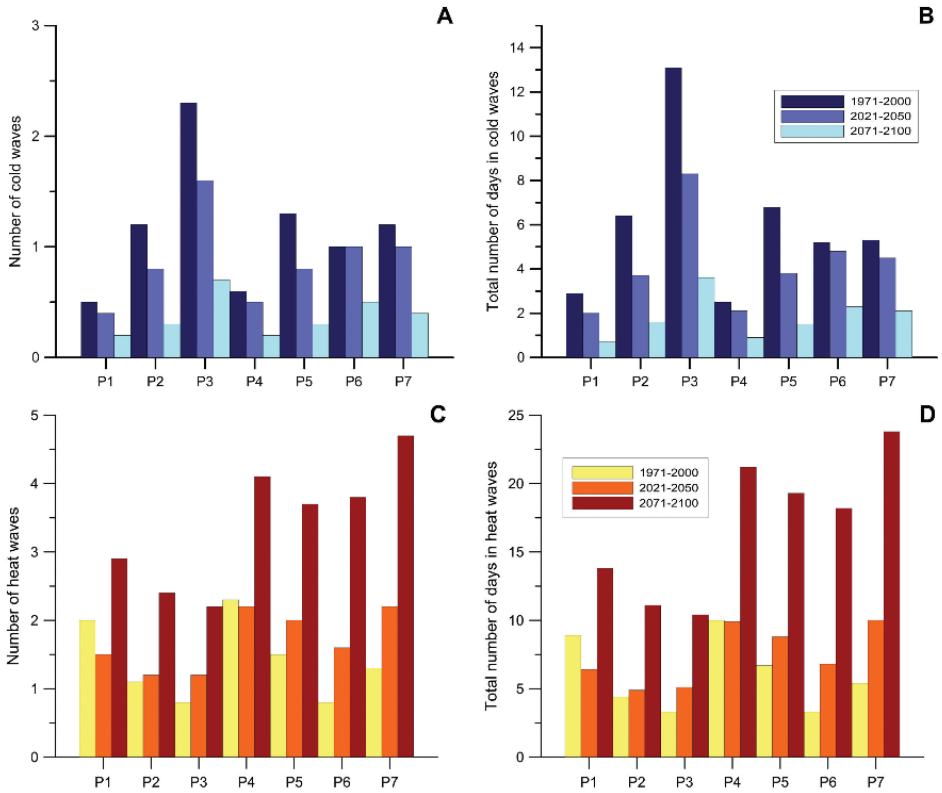


Figure 4. The annual number of cold waves (*A*), heat waves (*C*), and the annual total number of days in the cold waves (*B*), heat waves (*D*) for the selected points (see Tab. 1) in 1971–2000, 2021–2050 and 2071–2100.

heat wave in 2015 was one of the most striking in whole Europe (Hoy et al., 2017). According to European Climate Assessment and Dataset in the last decades (1976–2010), the duration of the warm spell has increased in Poland up to 10 days (Pasqui and Giuseppe, 2019). McMichael et al. (2004) estimate that the risk of various health outcomes will be more than double by the year 2030.

It is worth mentioning that the 2071–2100 period is associated not only with more and longer-lasting heat waves but also with the fact that these events will be much more intense (not shown). At the same time, the number and duration of cold waves will be gradually reduced (Fig. 4). The most remarkable changes are presented for the coldest regions of Poland (except for mountains) – the north eastern area of Poland, where the number of cold waves decreases from 2.5 to less than 2 and finally to less than 1 per year, and their total duration from 13 to 3–4 days at the end of the century. According to the models, in the remaining area of Poland cold waves will occur very rarely (once per 2–5 years) and will last shortly. It should be emphasized that a significant decrease in extreme cold conditions will be already noticed in the near future with a further decrease in the subsequent decades, whilst a distinct increase in extreme warm conditions should be expected mostly by the end of the 21st century. The fact that the climate in Poland moves toward warming does not mean that people should neglect cold conditions and believe that every winter will be warmer than the previous one. This situation is even more dangerous because in the last decades we have become used to warm winters and we have lost alertness. But even in the far future extreme cold conditions can appear and a lot of people may lose their lives. According to Cheshire (2016) twice as many people have died from hypothermia than from hyperthermia.

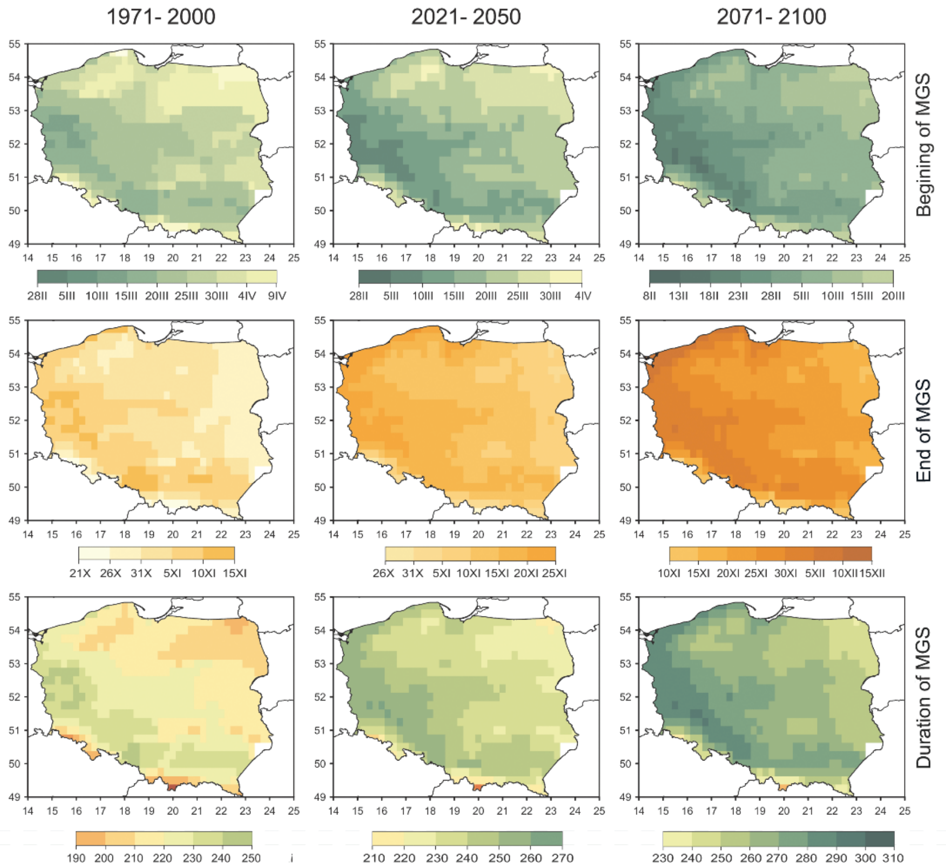


Figure 5. The beginning, end and duration of the meteorological growing season (*MGS*) in 1971–2000, 2021–2050 and 2071–2100.

4.2. Agriculture

Plant growth is primarily determined by temperature. Changes in the mean temperature as well as its extremes have a serious impact on food production. Proper plant development is possible when the daily mean temperature exceeds 5 °C. In Poland, the best temperature conditions for vegetation growth occur in northwestern Poland, along the Odra Valley and in the Sandomierz Basin, where the *MGS* starts at the turn of March and ends in the first half of November, lasting more than 230 days (Fig. 5). The least favourable conditions were found in the northeastern parts of the country and in the mountainous regions, where the *MGS* begins in April or later, ends in the second half of September and lasts less than 190 days. Between 2021 and 2050, the beginning of *MGS* will start earlier by 5 / 10 days (western / eastern part of Poland) and in the 2071–2100 period by another 20 / 15 days, which means significant changes at the end of the century. The end of *MGS* is expected to be moved toward the end of the year. In the near future, it should be delayed by 10 / 5 days, respectively, and in the far future by another 15 days. These changes will lead to the extension of the entire *MGS* by 10 / 20 days in the mid-century to another 40 / 30 days at the end of the century. Similar results for Poland were obtained by Nieróbca et al. (2013). According to the models, at the end of the 21st century the *MGS* will start/end in the first part of February / at the turn of December in western and central Poland, and March / mid-November in north eastern Poland, which will make the *MGS* prolonged by up to two months in some areas of Poland in comparison with the end of the 20th century.

From this point of view, the changes should have only a positive impact on food production, but nothing could be further from the truth. It should be underlined that the extension of growing season is not as important as an increase of heat resources (temperature increase). According to Sadowski et al. (2009), there is a limited variety of crops in Poland that can benefit from warmer climate such as: winter rape, spring barley or sugar beet. Białobrzeska et al. (2010) found good suitability of very warm climate conditions in 2006 for wine growing in the 58% of Poland's area, whilst in the cold year 2004 such conditions did not occur at all. The main problem with high temperature is related to accelerated plant development which leads to reduced plant size, insufficient seed formation, lower yield potential. It is predicted that a temperature increase of 1 °C in Poland accelerates the growth of wheat by one week and maize by two weeks (Górski, 2006), but this also results in wheat yield reduction and maize improvement. Abrupt changes in temperature during critical times of plant development (spring frosts, summer heat waves) might seriously affect the productivity (Hatfield and Prueger, 2011, 2015). Furthermore, an increase of heat resources has a negative impact on agriculture due to the development of pests. Under warmer climate conditions, maize pests (corn borer or corn rootworm) extend from southern Poland to the north (Kundzewicz and Kozyra, 2011) and may compromise maize development. During warm years, insects can have more generations, which increases the risk of crop losses (Walczak and Tratwal, 2009). Warmer conditions will also accelerate the development of weeds. Spring frost poses a serious hazard to the flowering of the fruit trees, while extremely high temperatures affect fruit formation. The May 2017 frost in Poland did massive damage to fruit blossoms and led to high prices of fruit on the market. Furthermore, an increase of temperature in winter is usually followed by the absence of snowfall (water storage problems), and in summer during high extremes by the lack of rainfall, which in turn can lead to water deficit and droughts. This can pose another challenge, *i.e.* of adaptation to crop production requirements.

4.3. Energy

In summer, energy consumption mainly refers to electricity generation. Under very warm atmospheric conditions, part of this energy is used by cooling devices. In "the warmer future", it will have to satisfy a higher energy demand. In the reference period, the number of days with potential use of cooling devices was strictly related to the summer temperature distribution in Poland. The highest number of 30–40 days was found in the central zone of Poland, the Odra Valley and the Sandomierz Basin (Fig. 6). A shorter period of *DNC* of fewer than 15–20 days was observed in northern Poland and the mountain regions. In the near future, the number of DNC will increase only by another 5 days, but in the far future the increase will be remarkable (by up to 40–50 days in the central zone and up to 50–65 days in southern Poland). In northern Poland, the changes will be less significant with up to 10 more *DNC* during the entire 21st century.

In the cold half of the year, a large amount of energy is used for heating. Coal combustion is the main energy carrier in Poland which largely contributes to particulate matter emissions in the central and southern parts of the country (Jędruszkiewicz et al., 2017). The spatial distribution of the heating season is the opposite of *MGS*, the shortest in western, southwestern and southern Poland (less than 200 days) and the longest in the northeastern and mountain regions (above 220 days) (Fig. 7). The *HS* begins in mid-October / third week of September (west-

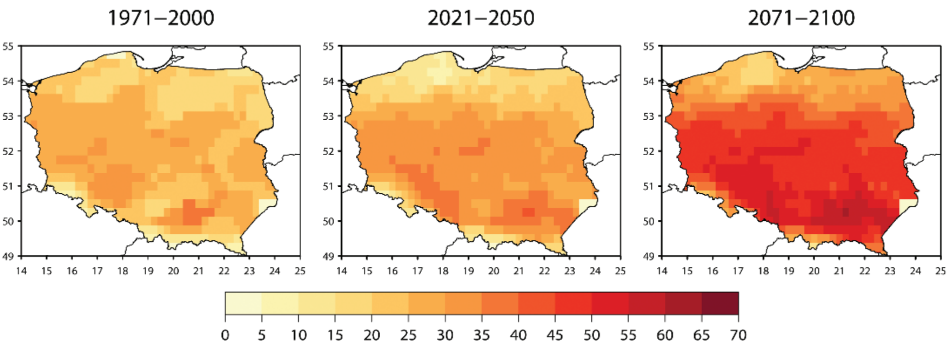


Figure 6. The number of days need cooling (*DNC*) in 1971–2000, 2021–2050 and 2071–2100.

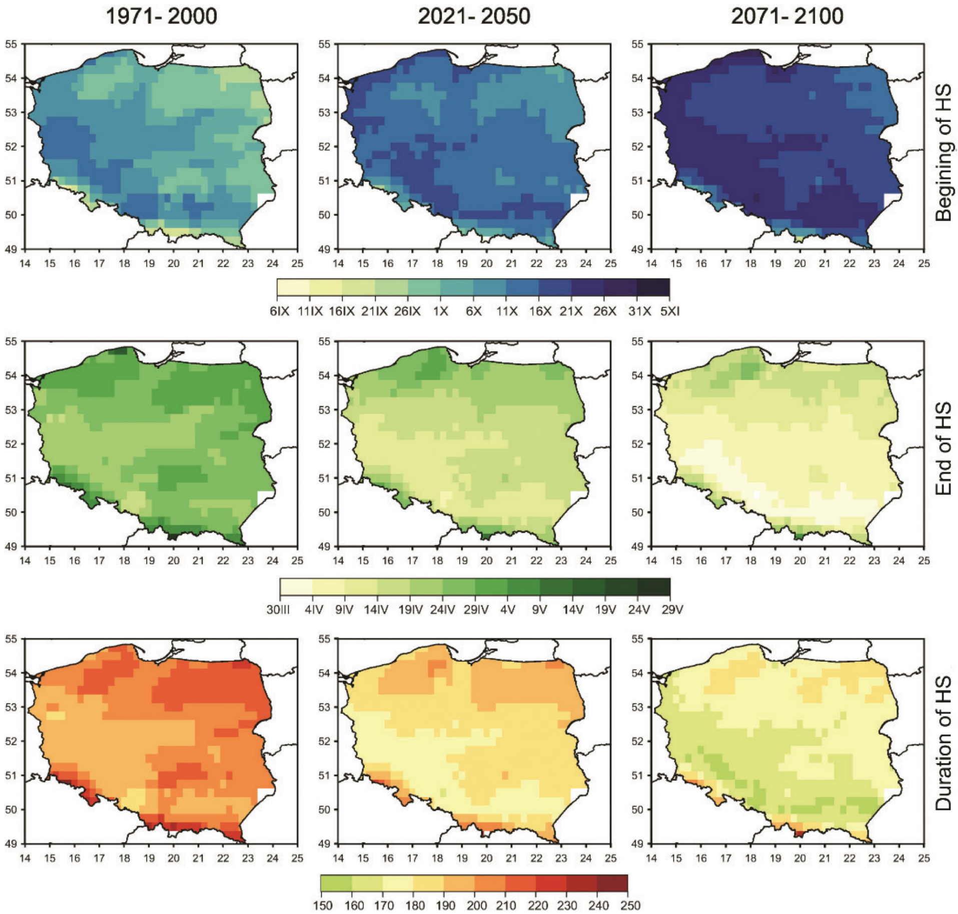


Figure 7. The beginning, end and duration of the heating season (*HS*) in 1971–2000, 2021–2050 and 2071–2100.

ern / eastern part of the country) and ends in second part of April / beginning of May. The regional model climate projections suggest quite even changes in *HS* in the 21st century. The *HS* will start later and finish earlier by 10 days in 2021–2050 and another 10 days in 2071–2100. Slightly higher changes are expected for the first part of the 21st century which might be related to higher warming in the cold part of the year. Generally, the *HS* will last shorter by approximately 30–40 days at the end of the century. Additionally, it might improve the condition of air due to lower emissions from small residential furnaces (mostly in transitional seasons).

Generally, at the end of the 21st century total demand for energy will increase (the production of one unit of cold uses 2–3 times more fossil fuel than one unit of heat) and the differences in energy production between winter and summer will be blurred. But even now (2000–2011), the Polish electricity distributor PSE S.A. finds that demand for energy in summer has increased by about 20%, while in winter it has started to decrease since 2010; the total energy demand has increased since 1992. Higher demand for energy in Poland means higher CO_2 annual emissions, which additionally reinforces the global increasing trend of CO_2 concentration.

4.4. Tourism

In the warm half of the year, by the end of 21st century, the temperature increase should have had mostly positive effect on tourist business. According to regional climate models used in the study, in the near future, we expected warming from 0.5–1°C in the northwestern Poland to 1.5–2.0 °C toward south east (not shown). In the far future, the warming reach 2 °C in the coastline areas, 3.5 °C in Central, Eastern Poland and 4.5 °C in southern parts in the summer months with respect to reference period. These changes should improve temperature comfort in Polish tourist destinations such as: coastline areas, Masurian Lakeland or mountains. In the future, Northern and Central Europe (Poland) might attract and take over more tourists from the southern regions (Mediterranean) where the summer temperature will be too high. The only exception can be summer months (June-September) at the end of 21st century, when the warming of 4.5 °C and more frequent or longer lasting warm spells in Southern Poland might lead to exceedance of the comfort threshold, especially in the urban areas (Kraków, Katowice, etc.). Furthermore, an increase of the water temperature in the summer can trigger excessive algae blooms what reduce attractiveness of water areas.

In the cold half of the year, when the warming is the most pronounced even in the current climate, the thermal comfort will definitely improve. This is presented in Fig. 2 where the lower part of the minimum temperature distribution in winter is significantly shifted. Fig. 3 indicates a prominent decrease of the number of frost and ice days. Except thermal comfort improvement, the skiing areas in Lakeland, Carpathian and Sudeten Mountains might face a real challenge to keep the sufficient amount of snow cover on the slopes. This problem has already happened in Central Poland (*i.e.* Kamieńsk ski arena) where producing the artificial snow cover, in temperature above 0 °C, is pointless and no longer profitable. Nevertheless, the temperature conditions from the tourists perspective will improve and a similar conclusion can be found in the study of Jacob et al. (2018) under the warming of 1.5 °C and 2.0 °C.

5. Conclusion

Since the end of the 20th century, thermal comfort exceedance have prevailed for about a month each year and this situation should not change significantly till the middle of the 21st century. Far more considerable changes are expected at the end of the century. When very warm conditions such as summer days, tropical night or heat waves occur more frequently, they will also be more intense and last longer. The number of such events will be at least double. It needs to be emphasized that thermal conditions for northern Poland will not change considerably. As regards such spatial temperature change diversification, adaptation plans should be implemented mostly in central and southern Poland. It is highly recommended to create new resting points inside the cities (green parks, water curtains, shadowed places), reduce the heat island effect (by implementing green or cool roofs, cool pavements, green car parking lots); public buildings (hospitals, playschools and schools) should be equipped with air conditioning systems. Additional care should be provided for people whose chronical illnesses are somehow related to thermoregulation. Furthermore, local authorities should implement early warning systems and provide education for society. On the other hand, during wintertime people will face more comfortable climate condition because of a significant reduction of frost and ice days in the near future and a further decrease of frost days in the far future.

As far as agriculture is concerned, the temperature change will seriously affect vegetation. According to the model projections, by the end of the 21st century the growing season will start earlier by about 25 days and end later by another 25–30 days. In the area of the current most favourable conditions for plant development (western Poland, the Odra Valley and the Sandomierz Basin), the growing season will extend by about two months and in eastern Poland by about 40 days. In a warmer climate probably only the wine grape cultivation might be profitable in most of the area of the country. It is estimated that the majority of crops, *i.e.* wheat, rye or potato will be reduced. Furthermore, for a number of crops the growing season will be shorter due to excessively high temperatures. The early beginning of growing season can expose plants to frost. In order to reduce the negative impact of temperature rise on agriculture, adaptation plans should be prepared and implemented by national and local governments. It is important to educate farmers how to adapt to the changes (*e.g.* introduce new varieties of crops; fruit plants resistant to heat, droughts, pests; increase cultivated areas; grow plants in more efficient ways; use irrigation systems) or to prevent harvest loss (*e.g.* launch new technologies).

Without a doubt, the temperature increase will affect energy systems. On the one hand, a heating season shorter by over one month in Poland will limit energy production and consumption. On the other hand, more extreme days in summer, projected mostly for the end of the 21st century will result in a higher demand for energy necessary for cooling buildings. It is assumed that energy savings in the heating season will not balance demand for energy in summer. In Poland the problem with energy production will grow. The country is still fossil fuel oriented and the changes in policy are slow. In a warmer climate, power plants may face other difficulties, *e.g.* water shortage or too warm water for cooling the power plants blocks. There are many approaches to coping with higher demand for energy (insulating buildings, passive housing, renewable energy, using fewer power consuming devices, innovative technologies, etc.).

Finally, when talking about Polish tourism attractiveness in the future, two approaches should be considered. Warmer atmospheric conditions in the warm half of the year will improve the attractiveness of Polish mountains, coastline and lake areas. Even if Poland enhances its tourism attractiveness in the near future, the highest increase of maximum temperatures projected for the far future will lead to a higher optimum comfort exceedance rate in July and August. Another aspect of temperature change in tourism is warmer winters. The decreasing number of frost and ice days will seriously affect winter sports (skiing).

Although, the study present broaden information about the temperature change and its impact on human wellbeing and economy a further investigation is needed. In the light of a new RCP scenarios and better model resolution, the more detail datasets can be acquire which is desire especially in the mountain areas. Furthermore, it was proved by Lhotka et al. (2018) that the higher resolution models (12.5 km) perform better for the extreme values.

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SAŽETAK

Opći pregled mogućeg utjecaja ekstremnih promjena temperature na društvo i gospodarstvo u Poljskoj u 21. stoljeću

Joanna Jędruszkiewicz i Joanna Wibig

Ovaj rad daje pregled kako projicirane promjene ekstrema u Poljskoj mogu utjecati na ljudsko zdravlje i njezino gospodarstvo. U tu svrhu korišteni su statistički korigirani podaci iz 7 regionalnih klimatskih modela. Za srednju i južnu Poljsku predviđa se za kraj 21. stoljeća značajan porast ekstremnih vrućih događaja (tj. toplinskih valova, tropskih noći), što bi moglo ozbiljno utjecati na društvo koje živi u velikim urbanim područjima. Manje ekstremni hladni događaji poboljšavaju toplinsku ugodnost zimi. Negativni utjecaj zagrijavanja utjecat će na energetske sustave s većom potražnjom električne energije ljeti, a u poljoprivredi: raniji početak vegetacijske sezone i cvjetanje cvijeća povećat će rizik od oštećenja od mraza u rano proljeće, dok će pretjerana vrućina smanjiti prinose ljeti. Poljskom turizmu trebala bi pogodovati veća toplinska ugodnost (osim vrućeg srpnja i kolovoza u dalekoj budućnosti te zagrijavanja tijekom zimske sezone u bliskoj budućnosti, što će dovesti do smanjenja snježnog pokrivača).

Ključne riječi: hladni val, toplinski val, sezona grijanja, meteorološka vegetacijska sezona, Poljska, temperaturni ekstremi

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