Nat. Hazards Earth Syst. Sci., 10, 1725–1737, 2010
www.nat-hazards-earth-syst-sci.net/10/1725/2010/
doi:10.5194/nhess-10-1725-2010

Natural Hazards and Earth System Sciences

Climate change and its effect on agriculture, water resources and human health sectors in Poland

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Received: 16 December 2009 – Revised: 24 June 2010 – Accepted: 5 July 2010 – Published: 19 August 2010

Abstract. Multi-model ensemble climate projections in the ENSEMBLES Project of the EU allowed the authors to quantify selected extreme-weather indices for Poland, of importance to climate impacts on systems and sectors. Among indices were: number of days in a year with high value of the heat index; with high maximum and minimum temperatures; length of vegetation period; and number of consecutive dry days. Agricultural, hydrological, and human health indices were applied to evaluate the changing risk of weather extremes in Poland in three sectors. To achieve this, model-based simulations were compared for two time horizons, a century apart, i.e., 1961–1990 and 2061–2090. Climate changes, and in particular increases in temperature and changes in rainfall, have strong impacts on agriculture via weather extremes – droughts and heat waves. The crop yield depends particularly on water availability in the plant development phase. To estimate the changes in present and future yield of two crops important for Polish agriculture i.e., potatoes and wheat, some simple empirical models were used. For these crops, decrease of yield is projected for most of the country, with national means of yield change being: −2.175 t/ha for potatoes and –0.539 t/ha for wheat. Already now, in most of Poland, evapotranspiration exceeds precipitation during summer, hence the water storage (in surface water bodies, soil and ground) decreases. Summer precipitation deficit is projected to increase considerably in the future. The additional water supplies (above precipitation) needed to use the agro-potential of the environment would increase by half. Analysis of water balance components (now and in the projected future) can corroborate such conclusions. As regards climate and health, a composite index, proposed in this paper, is a product of the number of senior discomfort days and the number of seniors (aged 65+). The value of this index is projected to increase over 8-fold during 100 years. This is an effect of both increase in the number of seniors (over twofold) and the number of senior-discomfort days (nearly fourfold).

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1 Introduction

The Fourth Assessment Report, AR4, of the Intergovernmental Panel on Climate Change (IPCC, 2007) concludes that warming of the global climate system is unequivocal and that "most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* [this likelihood statement can be interpreted as probability in excess of 90%; comment added] due to the observed increase in anthropogenic greenhouse gas concentrations". This means that this most essential IPCC statement has got stronger with every consecutive number of IPCC assessment reports (first, second, third, and fourth reports published in 1990, 1995, 2001, and 2007, respectively).

Europe has already warmed by almost 1 °C over the past century, faster than the global average. Model-based climate projections indicate considerable further warming. In the future, warmer climate, many weather-related extremes are expected to get more frequent and/or more severe. Hence, risks related to climate extremes in many sectors and regions are likely to increase.

In the present paper, projections of climate change impacts on selected sectors and systems, such as agriculture, water resources, and human health are studied at the national level. Even if some impacts are projected to be advantageous, and others – disadvantageous, in balance, these sectors are likely to be adversely affected in Poland. There is a scarcity of studies that include advanced ensembles-type simulations identifying the range of uncertainty, hence getting improved

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insight into the possible impacts at the national and sub-national scale is of considerable importance. Changes in sector-related impacts of climate extremes in Poland are evaluated, based on multi-model ensemble climate projections, obtained within the ENSEMBLES Project of the 6th Framework Programme of the European Union. The novelty is the use of most recent results of ensemble projections and innovative impact assessment methodologies.

2 Projections of climate change

According to IPCC (2007), for the next two decades, a global warming of about 0.2 °C per decade, i.e., similar to the rate observed since 1990, is projected for a range of emission scenarios. The rate of further warming strongly depends on such uncertain factors as population growth and socio-economic development, changes in the energy and land-use systems (largely responsible for emission and sequestration of carbon dioxide), and global architecture of the climate change mitigation policy and efficiency of its implementation. While a full likely range of (unmitigated) global warming for the time horizon of the year 2100 may go from 1.1 to 6.4 °C above the pre-industrial level, the "best" estimate of the temperature increase in the end of the 21st century would be around 4 °C (IPCC, 2007). The objective of the European Union, seconded by more than 100 countries, is to limit the mean global warming in such a way that by the end of the 21st century it will be no more than 2 °C above the pre-industrial level (Commission of the European Communities, 2007).

Projections of precipitation change in Europe showed a marked contrast between winter and summer. Wetter winters are predicted throughout the continent, but in summer, there is a strong difference in projected precipitation change between the northern Europe getting wetter and the southern Europe becoming drier. Less summer precipitation, accompanied by growing temperatures, inevitably leads to more frequent and more intense droughts.

Changes in extreme weather and climate events, based on observations and projections until the mid to late 21st century were summarized in IPCC (2007). Observations show that over most land areas, cold days and nights have got warmer and fewer, while hot days and nights have got warmer and more frequent. Continuation of this trend is *virtually certain* [probability of occurrence in excess of 99%] in the future. Over most areas, frequency of warm spells/heat waves has increased and continuation of this trend is *very likely* in the future. Increase of area affected by drought has been observed and continuation of this trend is *likely* [probability of occurrence in excess of 66%] in the future.

Simulations made with the help of regional climate models in the ENSEMBLES Project allowed us to quantify selected extreme-weather indices, of importance to climate impacts on systems and sectors. Six regional models from the ENSEMBLES Project were used in this study: C4IRCA3 from the Rossby Centre (Norrköping, Sweden); CLM from ETH (Zurich, Switzerland); KNMI – RACMO2 from the Royal National Meteorological Institute (de Bilt, the Netherlands); MPI-M-REMO from the Max Planck Institute (Hamburg, Germany); METO-HC from the Met Office's Hadley Centre (Exeter, UK), and SMHI RCA from the Swedish Meteorological and Hydrological Institute (Norrköping, Sweden). The selected regional climate models were forced by two different global circulation models (GCM). METO-HC, ETHZ-CLM and C4IRCA3 regional models were constructed based on METO-HC GCM, whereas MPI-M-REMO, KNMI–RACMO2 and SMHI RCA were driven on the 5th generation of the ECHAM GCM. For the sake of the present study we selected model-based simulations for two time horizons, a century apart, i.e., 1961–1990 and 2061–2090 (for SRES A2 scenario). For the time horizon 1961–1990, model-based simulations can be compared with reanalysis information and with data from observing stations on the ground.

Validation (verification) of models for the time period 1961–1990 is presented in Appendix A. The degree of consistency between modelled and observed values varies between models and is location-specific. Generally, agreement between models for the common, past, control period, 1961–1990 is not satisfactory, in particular for extreme values. However, comparison of observations (or re-analysis) from 1961–1990 and model-based projections for 2061–2090 would have less sense than comparison of model-based simulations for two time horizons of interest, so that the latter option is selected.

Among indices analysed in this paper, that are of particular importance from the viewpoint of impacts on systems and sectors of relevance to this study are the following characteristics referring to a 30-year (climatic) interval:

- number of consecutive days in a year (from the 30-year interval of interest) with the maximum temperature in excess of 35 °C and the minimum temperature in excess of 25 °C;
- number of consecutive days in a year (from the 30-year interval of interest) with the value of heat index above 36 (this value corresponds to maximum temperature in excess of 35 °C and relative humidity in excess of 30%);
- maximum temperature in the 30-year interval;
- length of vegetation period defined as the number of consecutive days in the year with mean temperature in excess of 5 °C;
- number of consecutive days with no, or little (<0.1 mm/day or <0.5 mm/day) daily precipitation.

It is important to comment on the accuracy of the models/projections, or rather on the uncertainty associated with them. Different climate variables are simulated with different levels of success by different models and no one model is "best" for all variables or for all areas. This is especially important for the territory of Poland because of its location – in an "in-between area" in the temperate climatic zone (Szwed, 2010). The country is "between" polar and tropical air masses as well as maritime and continental ones. Hence impact studies using modeled temperature data for Poland should be based on a larger number of models, to assure that the range of simulations will represent the fullest possible range.

As an example, Fig. 1 illustrates six-model mean changes in maximum number of consecutive days with the maximum temperature in excess of 35 °C and the minimum temperature in excess of 25 °C. Despite all the differences between model-based results, there is a commonality of simulations by all the models: greater increases in the value of this indicator are projected in south-east of Poland, with largest changes in the ETHZ model and smallest changes in the SMHI RCA model (Fig. 1a–f).

Table 1 illustrates uncertainty in projections of indices related to weather extremes. An example selected for illustration is the mean number of "hot day and tropical night" events in a year of the 30-year interval of interest, i.e. the mean number of days with the maximum temperature in excess of 35 °C and the minimum temperature in excess of 25 °C, in Poland. Table 1 presents the nation-wide means for six regional models, and a six-model mean, for two time horizons. According to three of the six models compared (KNMI, MPI-M-REMO, and SMHI RCA), such a situation did not arise at all in Poland in 1961–1990, but is projected to occur (albeit not very frequently) a century after (2061–2090). For three remaining models (C4IRCA3, ETHZ, and METO-HC), frequency of such days was greater than zero in 1961–1990 (from 0.003 to 0.16 such days per year) and largely increased for 2061–2090.

Unfortunately, climate models largely disagree on precipitation projections. Moreover, in most cases the agreement between climate models and real data for the control period is not satisfactory. The very high monthly or seasonal differences of predicted precipitation values from the climatological mean and ineffective annual precipitation distributions seem to negate the usefulness of certain models.

After a short review of climate change projections in the present section, next section will deal with impacts on selected sectors and systems.

3 Impacts on sectors and systems

3.1 Agriculture

In the present climate, agriculture in the northern Europe has been temperature-restricted, while in the south it has been water-restricted (Maracchi et al., 2005). Polish agriculture is partly temperature-restricted and partly water-restricted. Climatic projections for the future are good news for the northern Europe, where increase of temperature relaxes the former restriction, but are not good news for the south, where decrease in available water (due to both decrease in precipitation and increase in temperature) is likely and exacerbates the existing restrictions. Countries of Central Europe, such as Poland, are in-between.

Table 1. Average number of days, in a year, with the maximum temperature in excess of 35 °C and the minimum temperature in excess of 25 °C, for two time horizons (1961–190 and 2061–2090); mean for the whole of Poland, for six regional climate models.

Model	Time horizon	
	1961–1990	2061–2090
C4IRCA3	0.003	1.042
ETHZ	0.007	1.509
METO-HC	0.016	1.639
KNMI	0	0.231
MPI-M-REMO	0	0.03
SMHI RCA	0	0.034
Mean across all six models	0.004	0.94

For the territory of Poland the increase in the length of vegetation period, between 30 and 40 days, for nearly all of the country is projected (Fig. 2). The exceptions are: the northern part of the country, where the increase is higher, and a few isolated "islands" in the south, where the increase is lower (20–30 days). Figure 2 presents six-model mean changes in the length of vegetation period between two time horizons, 2061–2090 and 1961–1990.

The mean number of dry days is projected to decrease (wetter conditions) in the northern part of Poland and to increase (drier conditions) in the rest of the country. This resembles the general European divide in precipitation change, with the North getting wetter and the South getting drier. Figure 3 shows six-model mean changes of the maximum number of consecutive dry days with no, or little (<0.1 mm/day or <0.5 mm/day) daily precipitation.

Climate changes, and in particular increases in temperature and changes in rainfall, have strong impacts on agriculture via weather extremes – droughts and heat waves.

Climate changes (in mean values as well as in climate variability) significantly affect crop growth. In general, (cf. Moriondo et al., 2010), both winter and summer crops feature an advanced emergence, anthesis and maturation stages in response to higher temperatures and the duration of the crop-growth cycle is projected to decrease. However, winter crops may escape the higher drought and heat stress frequency which are projected in the summer period.

Figure 4a and b presents projections of changes of crop yields for potatoes and wheat in Poland. The crop models for potatoes and wheat stem from Górski and Doroszewski (1986) and Doroszewski et al. (1997), respectively. The precipitation-yield models used in this paper are

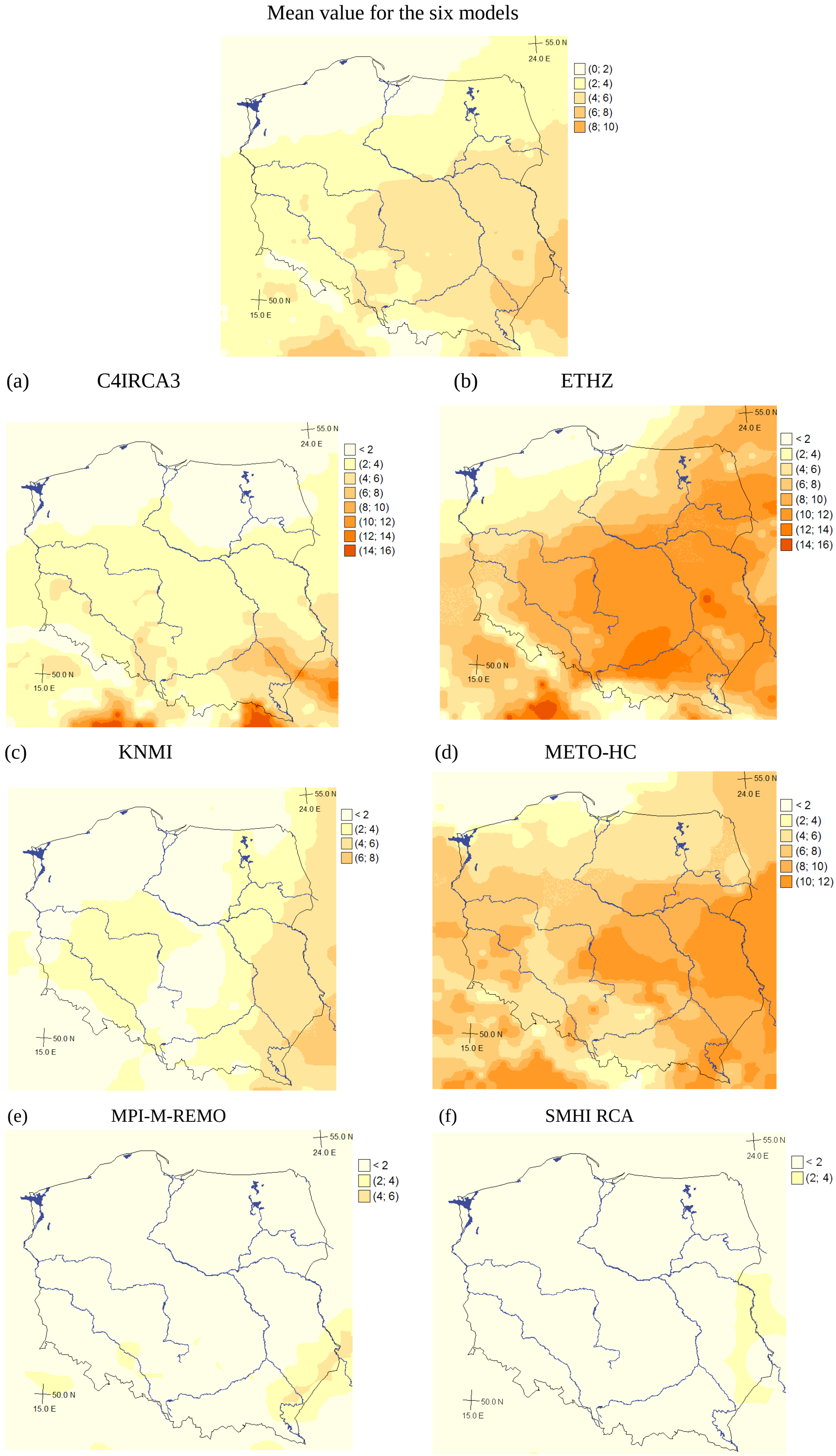


Fig. 1. Six-model mean changes in maximum number of consecutive days with the maximum temperature in excess of 35 °C and the minimum temperature in excess of 25 °C as well as changes for the six individual models **(a)** C4IRCA3, **(b)** ETHZ, **(c)** KNMI, **(d)** METO-HC, **(e)** MPI-M-REMO, and **(f)** SMHI RCA.

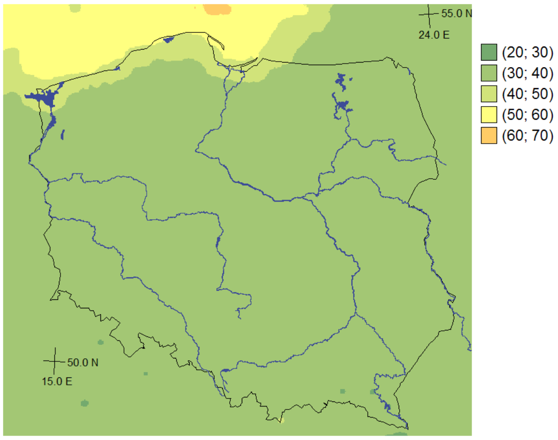


Fig. 2. Six-model mean changes in the length of vegetation period.

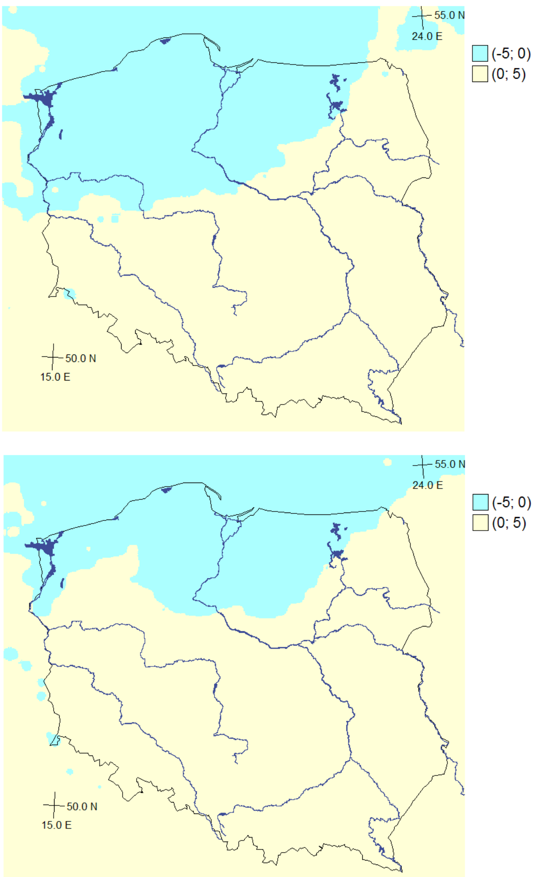


Fig. 3. Six-model mean changes of the maximum number of consecutive days with daily precipitation **(a)** below 0.1 mm/day or **(b)** below 0.5 mm/day.

empirical, rather than physical. They assume, for the Polish conditions, the average soil conditions, the standard (small) fertilizing, no irrigation, etc. They are based primarily on an extensive and multi-year field experience of the authors, supported by empirical data. Based on both real values of rainfall and the value of yield as well, the authors determined rainfall-yield relationship. They stated that the crop yield depends on water availability in the plant development phase (in case of wheat – during 30 days before emergence of ears, while for potato the effectiveness of rain in July and August is most important). The results of studies by Górski and Doroszewski (1986) and Doroszewski et al. (1997) were developed in graphical form (precipitation-yield diagrams).

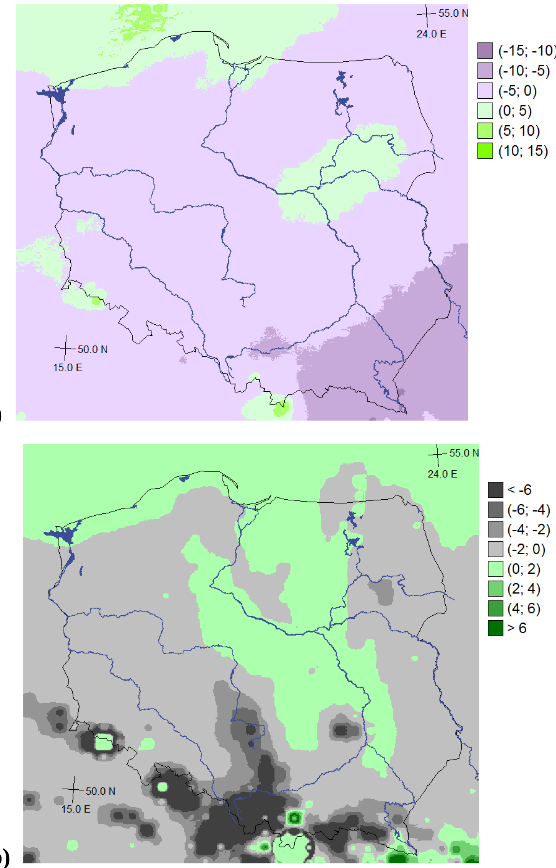


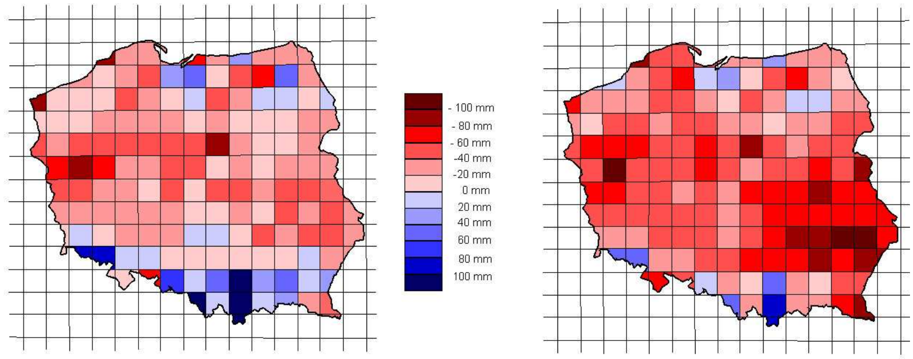
Fig. 4. Projections of climate-triggered changes of crop yields for **(a)** potatoes and **(b)** wheat [in t/ha].

For both crops, decrease of yield is projected for most of the country, and increase in some areas. The national means of decrease in yield are: –2.175 t/ha for potatoes and –0.539 t/ha for wheat, whereas the mean yield for the control period 1961–1990 are 19.18 t/ha and 3.53 t/ha, respectively.

3.2 Water resources

A useful index measuring changes in the water budget, in particular for the summer months (June, July, August) is the difference between precipitation and evapotranspiration:

$$P\text{-}E = \Delta S/\Delta t + R \quad (1)$$



(a) (b)

Fig. 5. Changes of climatic water balance in summer in Poland. Period **(a)** 1961–1990 versus **(b)** 2061–2090.

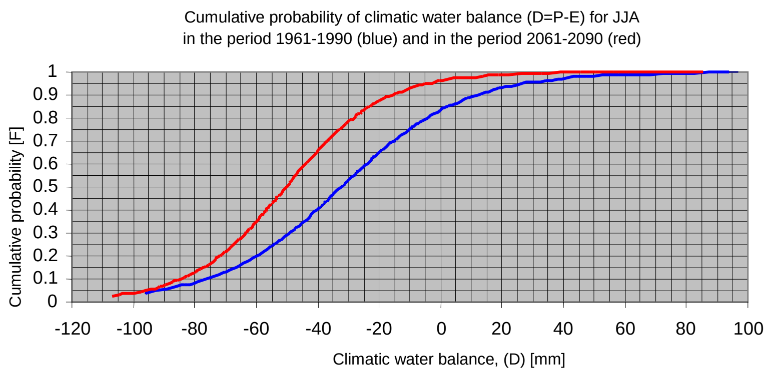


Fig. 6. Cumulative probability curves of water deficit in Poland.

where P is the precipitation; E is the evapotranspiration; S is the water storage in the catchment; and R is the runoff; all components expressed in mm.

Already now, in most of Poland, evapotranspiration exceeds precipitation during summer, hence the water storage (in surface water bodies, soil and ground) decreases. The values of the index P-E are projected to change in adverse way in the future, leading to more frequent and more severe summer water stress.

Evapotranspiration is the most vulnerable component of water balance with respect to climate change. It depends mainly on energy available for changing water into vapor, atmospheric water vapor demand characterizing the water absorption potential of the atmosphere and on plant cover abundance being a function of land use and plant development stage. We will use a model developed by Olejnik and Kędziora (1991), taking into consideration all factors mentioned above, used for estimation of evapotranspiration of six categories of land-use: water, forest, meadow, winter crop, row crop and urban area. Percentage of each type of land-use were taken from CORINE database.

The calculations were carried out for the summer (JJA) for the reference period 1961–1990 and for the projection period 2061–2090.

The meteorological information (precipitation, wind speed, and relative humidity) were taken from simulations by the model MPI-M-REMO which provided the best fit to observed values in the period of 1961–1990.

Figure 5 illustrates the climatic water balance, P-E, for the summer period, weighted according to formula:

$$\mathrm{DEF} = \sum_{k=1}^{k=n} p_k \cdot (P_k\text{-}E_k) \qquad (2)$$

where n is the number of land-use categories; k is the ordinal number of a given land-use category; P_k-E_k is the water deficit for a land-use category k; and p_k is the share of land-use category k in total areas of grid. It is clearly seen that the climatic water balance for the whole country will attain more negative values, indicating increasing water deficit. Especially high changes are projected to appear in south-eastern part of the country.

The cumulative probability curves for the whole country were calculated to indicate the probability of exceedence of particular values of the climatic water balance (water deficit), cf. Fig. 6. Median values of (P-E) will decrease from –32 mm for reference period to –50 mm in the future. Probability of negative water balance will increase from 0.84 to 0.96.

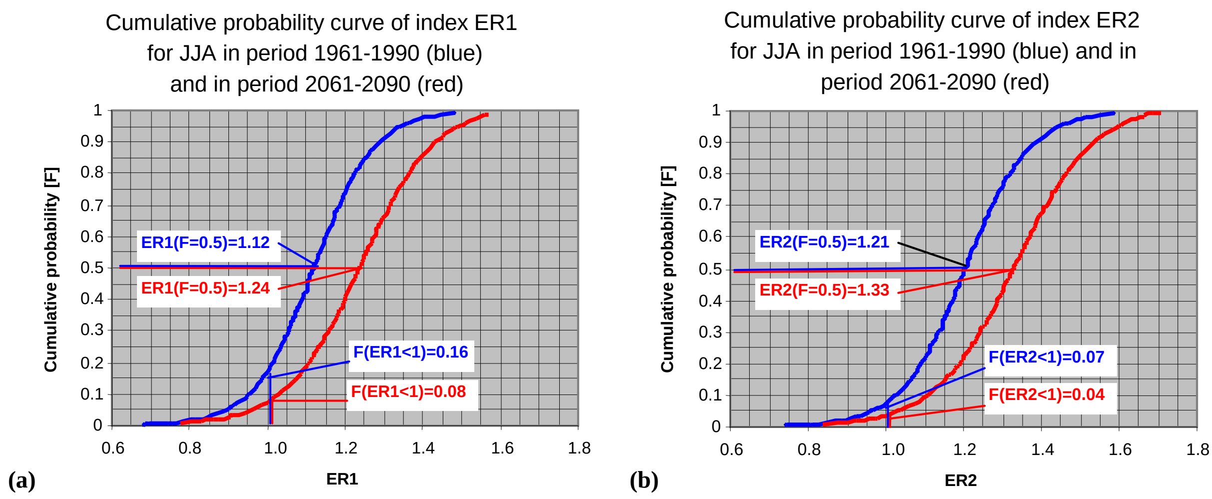


Fig. 7. Cumulative probability curves for indices **(a)** ER1, and **(b)** ER2, defined by Eqs. (3) and (4) in Poland.

Two indices describing climatic impact on water balance, ER1 (Energy Ratio1) and ER2 (Energy Ratio2), proposed by Kędziora (Kundzewicz et al., 1996), were used in the sequel,

$$\mathrm{ER1} = \frac{-\mathrm{LE} \cdot N}{P \cdot \lambda} \tag{3}$$

$$\mathrm{ER2} = \frac{R_\mathrm{n} \cdot N}{P \cdot \lambda} \tag{4}$$

where LE is the latent heat flux, N is the number of seconds in the period, λ is the latent heat of evaporation and R_n is the net radiation. Explanation of the background of indices ER1 and ER2 is presented in Appendix B.

The index ER1 expresses the ratio of energy used for actual evapotranspiration to energy needed to evaporate precipitation, while the index ER2 expresses the ratio of net radiation to energy needed to evaporate precipitation. So, the index ER1 indicates the real degree of drought. Value of ER1 equal to 1 means that the flux of evapotranspiration is in equilibrium with the flux of precipitation. The higher value of ER1 the worse water conditions of the region. The index ER2 indicates potential degree of drought. It describes the volume of water that would use total energy available for evapotranspiration. In other words, it describes the water needs to fully use the agro-potential of the agricultural environment (e.g. by increase of irrigation). The cumulative probability curves of these two indices calculated for the whole country (Fig. 7) show that probability of equilibrium between evapotranspiration and precipitation (ER1=1) will decrease twofold – from 0.16 in the reference period to 0.08 in the future. The median value will increase from 1.12 to 1.24. So precipitation deficit will increase by 100%, i.e. (1.24–1.12)/(1.12–1). The additional water supplies (above precipitation) which should be available to use the agro-potential of environment (ER2) will increase by about 50%, i.e. (1.33–1.21)/(1.21–1).

The map of spatial distribution of indices ER1 and ER2 (Figs. 8 and 9) show that only in northern and southern parts of the country there are grid cells with ER1 value less than 1 (blue grids). But the number of these grids will decrease from 27 in reference period to 10 in the future horizon of interest. The largest water shortage is in central part of the country, and is projected to grow in severity in the future. In some places it will exceed the value of 1.5 what means that precipitation will cover only the half of evapotranspiration needs.

A similar situation is observed in relation to index ER2 (Fig. 9). Only about 10% of the country area has sufficient water availability in summer (13 grid cells out of 144). In the future horizon, only 5% of the country area will keep positive climatic water balance while over 10% of the area the water shortage will be as much as 50% of precipitation (ER2 value greater than 1.5).

3.3 Human health and well-being

There is empirical evidence that high and prolonged period of raised temperature may have a dramatic impact on different fields on human activity, in particular on human health and well-being. In the present paper, we focus our attention on heat waves. Studies have shown that a significant rise in heat-related illnesses occurs when excessive heat lasts more than two days. Heat waves often turn fatal when the nighttime temperature does not drop very much below the high daytime temperature. In consequence, heat waves have a large impact on mortality (Koppe et al., 2004).

From the human health perspective, it is important how the body really feels the heat. In extreme heat paralleled by high humidity, evaporation is slower and the body must work extra hard to maintain a normal temperature. When heat exceeds the level the body can remove, the body temperature begins to rise and heat-related illnesses and disorders may develop. The heat index HI describes how heat is really felt when air temperature and relative humidity are combined (Stull, 2004).

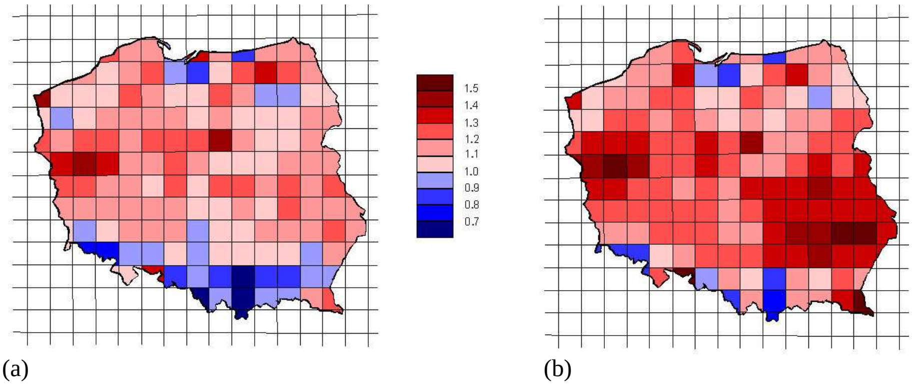


Fig. 8. Index ER1 for summer (JJA) in Poland. **(a)** 1961–1990; **(b)** 2061–2090.

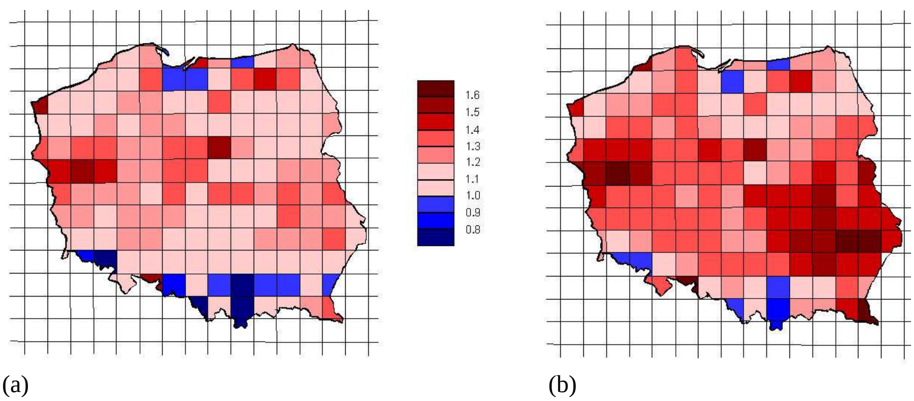


Fig. 9. Index ER2 for summer (JJA) in Poland, **(a)** 1961–1990, **(b)** 2061–2090.

Heat waves have already become increasingly frequent in summer in most of Europe and have affected the, increasingly ageing, European society. A particular, severe case of health effect of a heat wave was noted in the summer of 2003 over much of the continent. A rapid, violent increase of daily mortality during a heat wave was observed in Paris, France, in August of 2003 (Cohen et al., 2005). Due to high night time temperature, in addition to very hot days, the daily mean exceeded 32 °C and coincided with "explosion" of mortality, being over six time higher than a mean from 1999–2002.

Even if the dominating climate of Poland is moderate and sub-humid, at times high temperatures, and heat waves, have been recorded in the summer. The highest air temperature ever observed in the territory of present Poland was 40.2 °C recorded in Prószków near Opole on 28 July 1921 (Lorenc, 2005). In June 2006, a long spell of hot (and dry) weather was recorded in much of the country.

The projections of the number of consecutive days in a year (from the 30-year interval of interest) with the maximum temperature in excess of 35 °C and the minimum temperature in excess of 25 °C for time horizon 2061–2090 point at extension of such periods in the changing climate. Despite all the differences between model-based results, there is a commonality of simulations by all the models: greater increases in the value of this indicator are projected in south-east of Poland, with largest changes in the ETHZ model (more than 15 days) and smallest changes in the SMHI RCA model (up to 2 days) (see Fig. 1). Similarly, the number of days with high values of the heat index are projected to increase in the future.

At the same time, according to projections until 2035 delivered by the Polish Statistical Office (GUS, 2009), the number of aged inhabitants of Poland is expected to increase, continuing the already observed trend (Table 2). The number of aged people (65+) in absolute numbers and in relative terms (% of the total Polish population) have been on gradual increase in Poland: from 3.305 million (9.67% of the total population) in 1975, to 5.131 million (13.46% of the total population) in 2007. Projections for 2035 (after GUS, 2009) read: 8.358 million (23.22% of the total population), cf. Fig. 10.

The population projections indicate that the percentage of inhabitants of Poland older than 65 years is likely to increase further beyond 2035. Extrapolation of the GUS population

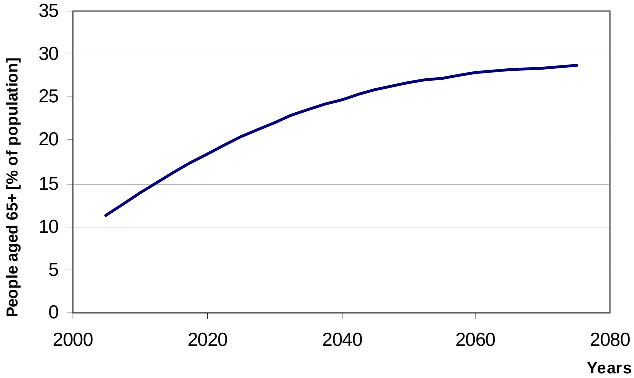


Fig. 10. Relative growth of the number of seniors (aged 65+) in Poland, as % of the total population. Until 2035 – projections by GUS. From 2035 to 2075 – polynomial extrapolation of projections.

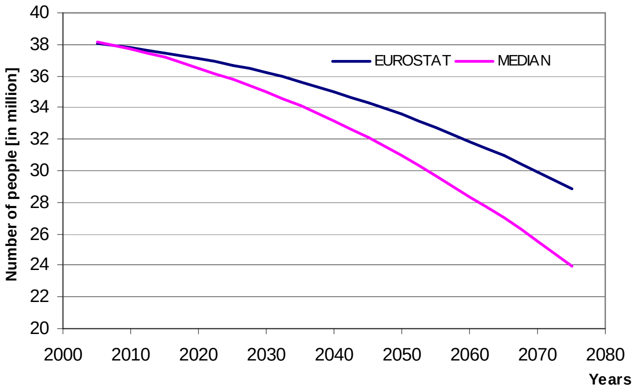


Fig. 11. Changes of population of Poland until 2075 based on projections by Eurostat and median by Matysiak and Nowok (2006) until 2050 and extrapolation for further 25 years.

Table 2. Population projections for Poland until 2035 by age groups (in thousands). Source of data: GUS (different years).

Year/ Age	Total (thous.)	65+ (thous.)	65+ (%)	80+ (thous.)	80+ (%)
1975	34 186	3305	9.67	418	1.22
2007	38 116	5131	13.46	1140	2.99
2010	38 092	5153	13.52	1314	3.44
2015	38 016	5929	15.60	1488	3.91
2020	37 830	6954	18.38	1566	4.14
2025	37 438	7844	20.73	1537*	4.11*
2030	36 796	8195	22.27	2005	5.45
2035	35 993	8358	23.22	2574	7.15

* The numbers for 2025 are lower than for 2020. This can be interpreted by the drop of birth numbers during the World War Two (1939–1945).

Table 3. Change in the number of senior-discomfort days, number of seniors, and value of the composite index between 1975 and 2075.

Year Year	Number of senior discomfort days	Number of seniors (65+) in Poland (in million)	Value of composite index (in million)
1975	1.336*	3.305	4.415
2075	5.085**	6.861–8.279***	34.888–42.099

* This value refers to average conditions in the period 1961–1990.
** This value refers to average conditions in the period 2061–2090.
*** Two values for 2075 (extrapolation of projection by Matysiak and Nowok, 2006, and Eurostat, respectively).

projection, for the age class of 65+ up to the year 2075, is presented in Fig. 10. However, the total population of Poland is likely to decrease in the future (Fig. 11).

In the present article, the value of the heat index (cf. Stull, 2004), HI=36 °C, corresponding to a value of maximum daily temperature in excess of 35 °C and humidity in excess of 30%, is arbitrarily assumed as a critical threshold for people in the age equal to or greater than 65 years ($HI_{crit65+}$). We are aware that adequate determination of such a threshold should be on the one hand supported by insightful medical research, on the other hand, this is an individual-specific value. However, the proposed HI value seems to make sense on the basis of literature data and personal consultations with medical scientists.

According to National Weather Service information on Heat index/Heat disorders, which relates ranges of heat index with specific heat disorders particularly for people in higher risk groups (seniors and children) fatigue is possible when HI index varies from 27 °C to 30 °C. For heat index of 32–40.5 °C sunstroke, heat cramps and heat exhaustion are possible in result of prolonged exposure and/or physical activity (NOAA, 2007). Thus, it seems that the HI index about 40 °C represents dangerous and not only discomfort days for seniors. This statement was confirmed indirectly by Diaz, who, basing on research study in Madrid, stated that the daily maximum temperature at which the slope of the relationship between mortality and temperature becomes steeper is 36.5 °C (Díaz et al., 2002).

In search for a health-related index, we tried to propose something simple that works. We do not wish to deal with highly uncertain nation-wide estimates of mortality or morbidity, because there are too many complicating factors – reasons for uncertainty. Instead, we propose a composite index, being a product of the number of population aged 65+ for the whole of Poland and the annual mean number of days with HI in excess of $HI_{crit65+}$, for the time horizons 1961–1990 and 2061–2090. Spatial distribution of projections of climatic indices is available, but spatial disaggregation of population projection in the age class 65+ would be very problematic. Hence national aggregates were used.

Extrapolating the projections, one gets the estimates of the number of people in the age of 65+ in Poland in 2075 as: 6.861 and 8.279 million, for two sources considered (Matysiak and Nowok, 2006, and Eurostat, respectively).

Table 3 presents the change in the number of senior-discomfort days, between 1975 (mid-point of the control period 1961–1990) and 2075 (mid-point of the future horizon of interest, 2061–2090). Senior-discomfort days are defined as days with the value of Heat Index in excess of $HI_{crit65+}$=32 (corresponding to maximum temperature in excess of 35 °C and relative humidity in excess of 30%). Composite index, proposed in this paper is a product of the number of senior-discomfort days and the number of seniors (65+).

As shown in Table 3, the average annual number of the composite index is projected to increase over 8-fold during 100 years. This is an effect of both increase in the number of seniors (over twofold) and the number of senior-discomfort days (nearly fourfold). There are no data to test the relevance of this, somewhat arbitrary and common-sense threshold. However, similar approach could be repeated for any other numerical threshold that may replace our proposal.

4 Discussion and concluding remarks

Multi-model ensemble climate projections in the ENSEMBLES Project of the EU were used to evaluate the changing risk of weather extremes in Poland in three sectors: agriculture, water resources, and human health. Changes in risk were evaluated by comparison of model-based simulations for two 30-year (climatological standard normal) periods, a century apart, i.e. 1961–1990 and 2061–2090.

Increases in temperature and changes in rainfall, driving water availability in the plant development phase, were found to have strong impacts on agriculture in Poland, in particular via weather extremes – droughts and heat waves. With the help of simple empirical models, developed for Polish conditions in IUNG (Institute of Soil Science and Plant Cultivation), it was found that for two commonly cultivated crops, i.e. potatoes (specialty of Poland) and wheat, one may expect yield decrease for most of the country. This complements the general findings obtained by Moriondo et al. (2010) for the whole of Europe.

Water-related projections demonstrate that the water budget is likely to become increasingly stressed. Under present climate, evapotranspiration exceeds precipitation in summer, and this leads to depletion of the water storage (on the surface, in the soil and in the ground). This summer water budget (evapotranspiration minus precipitation) deficit is projected to increase further in the future, so that in order to use the agro-potential of the environment, higher additional water supplies would be needed. However, already the present scanty water resources of Poland do not allow massive irrigation and the situation is likely to become more severe in future. The interpretation presented in this contribution makes use of energy ratio indices introduced by Kędziora.

Health-related impacts of climate change embrace, among others, consequences of changes of temperature extremes. Increase in the severity and frequency of heat waves is projected by climate models. This can be regarded in a multi-factor context, together with the increase in the number of seniors in Poland (notwithstanding the decrease in the population total). In result, the value of a composite index, proposed in this paper, being a product of the number of senior discomfort days and the number of seniors (aged 65+) is projected to increase over 8-fold during 100 years. The validity of this index needs to be corroborated. Using maximum temperature and relative humidity is not the only possibility of creating a meaningful index. Some researchers (e.g. Piotrowicz, 2009) use another construct, named Humidex, based on temperature and dewpoint.

There is no doubt that the future changes of impacts of weather extremes and related vulnerability will be complex. Increasing risk of climate extremes and their adverse impacts is driven by climate change (and changing climate variability, in particular) and changes in socio-economy (population, including its age structure, economic development and land use, e.g. urbanization and shrinkage of agriculture).

It is difficult to evaluate the credibility of individual climate scenarios and projections. Multi-model probabilistic approaches are preferable to using the output of only one climate model, when assessing uncertainty in the climate change impacts. Study of a larger range of different climate model-based scenarios, being the core of the ENSEMBLES Project, suggests that adaptive planning should not be based on only one or a few scenarios, since there is no guarantee that the range of simulations represents the full possible range.

Neither a single simulation nor an ensemble (consensus) average of model results are appropriate in extreme event studies, since they may lead to underestimation of extremes. Studying frequency distributions of extreme events among multi-model ensembles is likely to produce more trustworthy results. However, for a national scale, like Poland, there may be a preferred model that performs better than the other models on reconstructing the control period situation.

The climate change impact on sectors depends, in general, not only on changes in the characteristics of climate-related and sector-relevant variables, but also on such system properties, as: pressure (stress) on the system, its management (also organizational and institutional aspects), and adaptive capacity. Climate change is likely to challenge existing management practices by contributing additional uncertainty.

In the three sectors considered in this paper, i.e. agriculture, water resources and human health, it is possible to adapt to climate change in both mean and extreme event contexts, in the sense of reducing adverse effects and enhancing the benefits of advantageous impacts (e.g. longer vegetation period, less frost nights in spring). However, no definitive knowledge of adaptation options is available in Poland.

Among adaptation measures to climate change in the agricultural sector are: changes of agrotechnical practices (e.g., use of crop rotation, advancing sowing dates) and introduction of new cultivars (heat-wave- and drought-tolerant crops). Soil moisture should be conserved e.g. through mulching.

Adaptation to increasing drought in the water sector embraces multiple actions on both supply and demand sides. One can increase the water supply by storing more water in any kind of water retention (in surface water bodies, including man-made reservoirs, in wetlands, in groundwater aquifers, and in the soil) to smooth the temporal water variability. Water transfer from an area of relative abundance to an area of scarcity may smooth the spatial water variability. Water demand management embraces all measures to improve efficiency of water use.

Adaptation to heat waves in the public health system embraces a range of measures, such as heat warning system, air conditioning, heat-relief shelters, awareness raising – urging people to avoid dehydration and to avoid staying outside.

Appendix A

Validation based on observations and re-analysis

To choose the "best" model for projections of meteorological parameters for the horizon 2061–2090, the following procedure was used:

1. On the basis of monthly average temperature and precipitation (observed and predicted by six models) over the control period 1961–1990, values of the following four criteria were calculated:
   - Sum of absolute values of differences between real and predicted values.
   - Sum of squares of these differences.
   - Standard deviation of real and predicted values.
   - t-Student statistic.
2. The rank from 1 to 6 was attributed to each model according to the following rules:
   the smaller the sum of differences, the sum of squared differences, or t-Student value, the lower position of model. In relation to standard deviation, the lower rank was attributed to the model having values that better fit to real values of temperature and precipitation.
3. Then the products of all ranks for temperature and precipitation were calculated (two rows above the next to last row in Table A1).
4. Total products of ranks were calculated by multiplication of product of ranks for temperature by product of ranks for precipitation (the next to last row in Table A1).
5. The final ranks were attributed to each model in the last row of Table A1.

The results in the Table A1 show that the model performing best for the area of Poland is MPI-M-REMO, marked in bold.

Appendix B

ER1 and ER2 indices

In order to determine the values of indices ER1 and ER2 (Kundzewicz et al., 1996), firstly the latent heat flux of evapotranspiration was calculated according to formula

$$\mathrm{LE} = -\frac{(R_\mathrm{n}+G)}{(1+\beta)} \tag{B1}$$

where R_n is the net radiation; G is the ground heat flux; and β is the Bowen ratio.

Based on Eq. (B1), the evapotranspiration [in mm/month] was calculated as $E = n \cdot \mathrm{LE}/28.34$, where n is the number of days in the month.

Net radiation was calculated according to the following formula:

$$R_\mathrm{n} = (1-\alpha)\cdot R_0 \cdot (0.22+0.54\cdot u) - 5.68\times10^{-8}\cdot(t+273)^4 \left(0.56-0.08\cdot e^{0.5}\right)\cdot\left(0.10+0.90\cdot u\right) \tag{B2}$$

where α is the albedo (dimensionless); R_0 is the extra terrestrial solar radiation ($\mathrm{W\,m^{-2}}$); u is the relative sunshine (dimensionless); t is the air temperature (°C); and e is the water vapour pressure (hPa).

Albedo for field crops and meadows (α) was calculated as follows: α = 0.16 + 0.07$\cdot f$, where f is the plant development stage, changing from 0 (bare soil) to 1 (full development plant cover). For water, the value of albedo was taken as 0.10, while for urban areas as 0.30. For forests, albedo was taken as 0.16 (averaged for coniferous and deciduous forests).

Soil sensible heat flux (G) was calculated by use of the following formula:

$$G = -0.2R_n\cdot(1-0.75f)\cdot\sin\left[\frac{\pi}{6}(i-2)\right] \tag{B3}$$

where i denotes the ordinal number of the respective month; and f is the plant development stage (dimensionless), changing from 0 to 1.

Bowen ratio is derived from:

$$\beta = 12.75/(W+3.9) - 0.02 \tag{B4}$$

The factor W in Eq. (B4) is calculated from the formula:

$$W = \frac{100\left(d\cdot v^{0.5}\right)^{\mathrm{art}\left(\frac{\pi}{2}\cdot f\right)}}{t\,(u+0.4)} \tag{B5}$$

where W is an agrometeorological empirical index, expressing the influence of the meteorological conditions and plant

Table A1. Ranking of the models.

Criterion	Parameter	Real values	Models					
			C4IRCA3	ETHZ	KNMI	METO-HC	**MPI-M-REMO**	SMHI RCA
Sum of differences	Temp.		–14.6	–35.6	–5.4	4.3	**–1.2**	–9.5
	Prec.		205.8	158.7	117.7	136.6	**95.1**	109.8
Ranks	Temp.		5	6	3	2	**1**	4
	Prec.		6	5	3	4	**1**	2
Sum of square of differences	Temp.		655.5	703.0	507.7	771.4	**558.3**	419.8
	Prec.		3775	2496	1696	2101	**1152**	1591
Ranks	Temp.		4	5	2	6	**3**	1
	Prec.		6	5	3	4	**1**	2
Standard deviation	Temp.	7.994	7.719	7.994	6.794	8.374	**7.124**	6.177
	Prec.	15.04	6.81	6.65	9.06	14.98	**14.15**	12.43
Ranks	Temp.		2	1	5	3	**4**	6
	Prec.		5	6	4	1	**2**	3
t-Student	Temp.		0.046	0.111	0.018	0.004	**0.004**	0.033
	Prec.		0.121	0.063	0.160	0.070	**0.144**	0.192
Ranks	Temp.		3	6	4	2	**1**	5
	Prec.		3	1	5	2	**4**	6
Product of ranks	Temp.		120	180	120	72	**12**	120
	Prec.		540	150	180	32	**8**	72
Total product of ranks			64 800	27 000	21 600	2304	**96**	8640
Final rank			6	5	4	2	**1**	3

development stage on evapotranspiration. The higher the index value is, the greater the part of net radiation used for evapotranspiration. d is the saturation vapour pressure deficit (hPa); and v is the wind speed ($\mathrm{m\,s^{-1}}$); and t is the air temperature (°C).

Water vapor pressure e, and water vapor pressure deficit d were calculated as follows:

$$e = 5.5\exp(0,05662t) \quad \text{(B6)}$$

$$e_\mathrm{s} = 6.123\exp[17.25t/(t+237.2)] \quad \text{(B7)}$$

$$d = e_\mathrm{s} - e \quad \text{(B8)}$$

where e_s is the saturated water pressure.

Acknowledgements. The reported work is a contribution to the integrated project ENSEMBLES (Ensemble-based predictions of climate changes and their impacts) of the Sixth Framework Programme of the European Union (contract GOCE-CT-2003-505539).

Edited by: G. Leckebusch
Reviewed by: M. Bindi and another anonymous referee

References

Cohen, J.-C., Veysseire, J.-M., and Bessemoulin, P.: Bio-climatological aspects of summer 2003 over France. Chapter 4, in: Extreme Weather Events and Public Health Responses, edited by: Kirch, W., Menne, B., and Bertollini, R., Springer Berlin Heidelberg, 33–46, 2005.

Commission of the European Communities: Adapting to Climate Change in Europe – Options for EU Action, Green Paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions {Sec(2007) 849}, Com(2007) 354 Final, Brussels, 29 June 2007.

Díaz, J., Jordán, A., García, R., et al.: Heat waves in Madrid, 1986–1997: effects on the health of the elderly, Int. Arch. Occ. Env. Hea., 75, 163–170, 2002.

Doroszewski, A., Demidowicz, G., and Górski, T.: Wpływ niedoboru opadów na straty w produkcji zbóż jarych w Polsce, Rocz. AR Pozn., CCXCI, Melior. Inż. Środ., 17, 223–231, 1997 (in Polish).

Górski, T. and Doroszewski, A.: Wpływ opadów atmosferycznych na plonowanie ziemniaków w Polsce, Zeszyty Prob. Post. Nauk Roln., 284, 369-375, 1986 (in Polish).

GUS (Główny Urząd Statystyczny): Population projection for Poland 2008–2035, Warszawa, available at: http://www.stat.gov.pl/cps/rde/xbcr/gus/PUBL_L_prognoza_ludnosci_na_lata2008_2035.pdf (last access: 27 July 2010), 2009.

GUS (Główny Urząd Statystyczny): Roczniki statystyczne Polski, Warszawa, 1976, 2005, 2009.

IPCC (Intergovernmental Panel on Climate Change): Climate Change 2007: The Physical Science Basis. Summary for Policymakers, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, available at: :http://ipcc-wg1.ucar.edu/wg1/wg1-report.html (last access: 16 December 2009), 2007.

Koppe, Ch., Kovats, S., Jendritzky, G., and Menne, B. (Lead authors): Heat-waves: risks and responses, in: Health and Global Environmental Change Series, No. 2, WHO Europe, Copenhagen, 2004.

Kundzewicz, Z. W., Kędziora, A., and Chalupka, M.: Comprehensive assessment of drought risk and characteristics of drought in Wielkopolska region. Summary of research and result form the KBN Research Project no 4 S401 055 04, Research Centre for Agricultural and Forest Environment of the Polish Academy of Sciences, Poznań, Poland, 1996 (in Polish).

Lorenc, H.: Atlas klimatyczny Polski, Wyd. IMGW, Warszawa, 2005.

Maracchi, G., Sirotenko, O., and Bindi, M.: Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe, Climatic Change, 70, 117–135, 2005.

Matysiak, A. and Nowok, B.: Stochastic forecast of the population of Poland, 2005–2050, MPI DR Working Paper 2006-026, Rostock, Germany, 2006.

Moriondo, M., Bindi, M., Kundzewicz, Z. W., Kędziora, A., Szwed, M., Choryński, A., Matczak, P., Radziejewski, M., McEvoy, D., and Wreford, A.: Impact and adaptation opportunities for European agriculture in response to climatic change and variability, Mitigation and Adaptation Strategies for Global Change, published online, doi:10.1007/s11027-010-9219-0, 2010.

NOAA's National Weather Service: Heat Wave: A Major Summer Killer, available at: http://www.nws.noaa.gov/os/brochures/heat_wave.shtml(last access: 27 July 2010), 2007.

Olejnik, J. and Kędziora, A.: A model for heat and water balance estimation and application to land use and climate variation, Earth Surf. Proc. Land., 16, 601–617, 1991.

Olesen, J. E. and Bindi, M.: Consequences of climate change for European agricultural productivity, land use and policy, Eur. J. Agron., 16, 239–262, 2002.

Piotrowicz, K.: The occurrence of unfavorable thermal conditions on human health in Central Europe and potential climate change impacts: an example from Cracow, Poland, Environ. Manage., 44, 766–775, doi:10.1007/s00267-009-9357-x, 2009.

Stull, R. B.: Meteorology for Scientists and Engineers, 2nd edn., Brooks/Cole, Pacific Grove, CA, USA, 502 pp., 2004.

Szwed, M.: Uncertainty of the climate model projections based on the Poland's territory example, Proceedings of the Sixth EGU Alexander von Humboldt Conference on "Climate Change, Natural Hazards, and Societies", Merida, Mexico, 14–19 March 2010.