THE INCREASE IN THE PROPORTION OF IMPERVIOUS SURFACES AND CHANGES IN AIR TEMPERATURE, RELATIVE HUMIDITY AND CLOUD COVER IN POLAND

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Abstract: The aim of the study is to characterise the changes in the proportion of impervious surfaces (ISs) in Poland and their impact on changes in temperature, air humidity, and cloud cover. The results of satellite image classification from 1990, 2000, 2010 and 2020, as well as meteorological data from the period 1981–2020 for the warm half of the year, were used. An analysis was performed making it possible to compare the changes in the proportion of ISs in 3 decades, i.e. 1991–2000, 2001–2010 and 2011–2020. In Poland, in the years 1991–2020, the total area of ISs increased by approximately 30%. At the same time, statistically significant positive trends in maximum temperature are visible throughout Poland, ranging from 0.48°C per 10 years to >0.90°C per 10 years. Trends in the magnitude of low-level cloud cover are negative throughout Poland and range from −2.7% to −2.3% per 10 years. The frequency of stratiform clouds is decreasing, while that of mid-level *Cirrus* and *Cumulus* clouds is increasing. The results show a relationship between the increase in ISs in Polish cities and changes in meteorological elements in their area and in the immediate vicinity, which were most pronounced in the first decade of the 21st century.

Key words: impervious surfaces, urban climate, air temperature, humidity, cloud cover, Poland

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Introduction

The increase in air temperature in the world is a fact. Starting from the 1960s, each subsequent decade has been warmer than the previous one. The main cause of contemporary warming is human activity, mainly greenhouse gas emissions (IPCC 2021) and the emission of anthropogenic heat caused by urbanisation and land cover change (Souleymane, Quesada 2020, Wang et al. 2021). The spatial development of urbanised areas causes continuous loss of natural surfaces and an increase in the proportion of the transformed impervious surfaces (ISs) that make up cities. The presence of ISs is evidence of human activity (Arnold, Gibbons 1996). The indication of the increase in the proportion of ISs in relation to pervious surfaces (PSs) makes it possible to determine the directions of human spatial expansion (Jat et al. 2008). Artificial urban surfaces (e.g. asphalt, concrete, brick, steel, aluminium, etc.) are characterised by an increased capacity

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and thermal conductivity compared to natural surfaces outside the city. An increase in the temperature in urbanised areas (urban heat island) favours the intensification of evaporation, but this natural cooling process is less effective than in undeveloped areas. Owing to the high proportion of ISs that limit the infiltration of water into the substrate, there are no humidity resources that could evaporate. The complex geometry of buildings in the city makes it difficult for energy to radiate efficiently through the streets and walls of buildings, because a significant part of it is absorbed by the surrounding buildings. The spatial development of cities causes a change in the values of the basic components of the heat and water balance, which have a direct impact on the formation of cloud cover over urban areas.

The effect of intense urbanisation on increases in air temperature in the context of the occurrence of urban heat islands, both surface urban heat islands and atmospheric urban heat islands, is well documented in the scientific literature (e.g. Oke 1973, Landsberg 1981, Arnfield 2003, Akbari, Rose 2008, Kaplan et al. 2018). There are also studies on the influence of the urban area on humidity, convection and the occurrence of precipitation (e.g. Zhu et al. 2017). The interrelationships between cloud cover and urbanisation, on the other hand, have been poorly researched, and the results are questionable. According to some authors, the city causes an increase in cloud cover (e.g. Abakumova et al. 1996), while, according to others, the agglomeration contributes to its decrease (e.g. Kuczmarski 1982). Kossowska-Cezak (1978) believes that the urban complex affects cloud cover in mechanical and thermal ways and that it usually increases cloud cover over this area, but under certain conditions, it may contribute to the reduction of cloud cover (in the evening, with generally high cloudiness). The explanation of this issue seems to be of particular importance in terms of the effects of contemporary climate change, i.e. heat, drought and flash floods, which particularly affect city dwellers.

The aim of the study is to analyse the characteristics of changes in the share of ISs in Poland and their impact on changes in air temperature, humidity and cloudiness. ISs include all areas that cannot be seeped into by water, i.e. man-made artificial areas identified on the basis of the analysis of satellite images. Low-level clouds are considered to be the visual, comprehensive indicator of changes taking place in the atmosphere, caused by thermodynamic processes related to the change in albedo and the latent heat of the active surface. They are most dependent on local conditions and have the strongest impact on the air temperature at the Earth's surface. By absorbing short-wave solar radiation and the Earth's long-wave radiation, clouds retain heat and cause an increase in temperature, which was called cloud greenhouse forcing.

This study is part of the current research on urban climatology explaining the causes of climate change, which uses modern methods to determine the magnitude of the changes in the Earth's surface transformed by man. The analysis of the increase in the proportion of ISs in Poland and their relationship with selected elements of the climate may help understand the mechanism of anthropogenic causes of contemporary warming.

Source materials and methods

The study uses meteorological data from ground stations and the results of satellite image classification containing information on the imperviousness index for the years 1991–2020. Only the data from the warm half of the year (April–September) were taken into account, because IS extraction is characterised by the highest accuracy in the period of increased vegetation, defined for instance based on the normalised difference

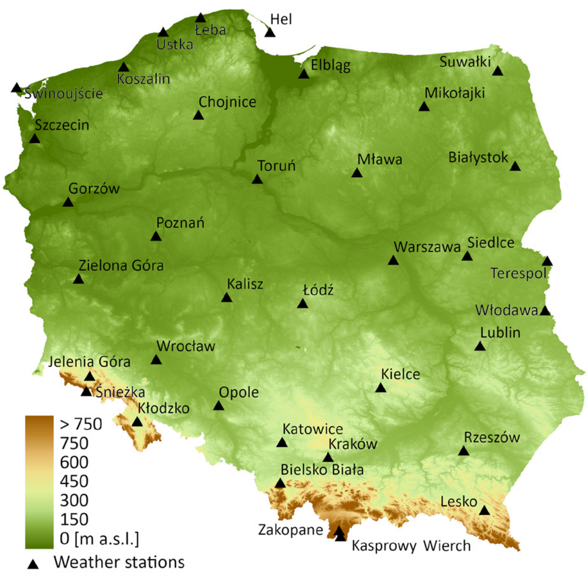

Fig. 1. Location of the weather stations.

Table 1. Cities included in the study, their geographic location, area and population in 2019 (GUS 2020).

City	Altitude	Latitude	Longitude	Area	Population
	[m a.s.l.]	[degree]		[km²]	x 10³
Białystok	148	53°06'26"	23°09'44"	102	297.6
Gorzów	72	52°44'28"	15°16'38"	86	123.6
Katowice	278	50°14'26"	19°01'58"	165	292.8
Kielce	260	50°48'38"	20°41'32"	110	194.9
Kraków	237	50°04'40"	19°47'42"	327	779.1
Lublin	193	51°13'00"	22°23'35"	148	339.8
Łódź	180	51°43'06"	19°23'14"	293	679.9
Poznań	88	52°25'00"	16°50'05"	262	534.8
Toruń	69	53°02'31"	18°35'44"	116	201.4
Warszawa	106	52°09'46"	20°57'40"	517	1790.7
Lesko	420	49°27'59"	22°20'30"	15	5.4

vegetation index (NDVI) (Soltani, Sharifi 2017, Sun et al. 2017). Moreover, the highest air temperatures in Poland occur precisely at this time of the year (Ustrnul et al. 2021). Data from 36 weather stations (Fig. 1) were used to characterise the spatial diversity of selected climate elements for the whole of Poland, while the data from weather stations located in 10 large cities in Poland were selected for a detailed analysis of the relationship between the proportion of ISs and the maximum air temperature, relative humidity, and low-level cloudiness (Table 1); the analysis also included the small town of Lesko, which constituted the background for comparative research. The stations from which meteorological data (i.e. daily values of maximum air temperature, relative humidity and low-level cloudiness) were collected belong to the state meteorological service and operate as part of the Polish Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI). The research included stations that met the criterion of continuity of the data series, without breaks or with slight gaps that could be supplemented on the basis of data from neighbouring stations.

Landsat 5–8 satellite imagery provided by the United States Geological Survey (USGS) was used to determine the changes in the proportion of ISs in Poland. In the research, analysis was performed for three moments in time, which facilitated the comparison of changes in the imperviousness index in 3 decades, i.e. the years 1991–2000, 2001–2010 and 2011–2020. For the same periods, the trends of maximum air temperature, relative humidity and the degree of sky coverage by low-level clouds were calculated for the aforementioned cities in Poland.

In the case of satellite data, they were characterised by the same spatial resolution of 30 m for red, green and blue (RGB) bands, as well as near-infrared (NIR) and short-wave IR (SWIR) bands. For each time period, several satellite images from the warm half of the year (April–September) were acquired. The data obtained from the Copernicus programme were also helpful in the analysis. The resources of High Resolution Layers Imperviousness were used to generate the classification pattern of the Support Vector Machine (SVM) algorithm (Langanke 2016).

The analysis of satellite images was carried out in several stages. The first was data pre-processing, in which the areas covered with clouds were removed from the analysis. The next step was to normalise the data by processing images into 16-bit rasters. Performing this operation made it possible to reduce the deviations resulting from the penetration of the atmosphere by electromagnetic radiation (Ban 2016). The last element of pre-processing was the preparation of four-band composites (three bands of RGB + NIR), which—in the next stage—were subjected to the operation of the SVM algorithm.

The second stage of the IS extraction was to calculate the spectral indices and to exclude, on their basis, areas that can be considered pervious with high probability. First, the NDVI (Friedl et al. 1995) was calculated, as a result of which biologically active areas were excluded. In the next step, the normalised difference water index (NDWI) was calculated and thresholded. This index makes it possible to extract and eliminate water features from the analysis (Gao 1996). The last-calculated index was the dry bare-soil index

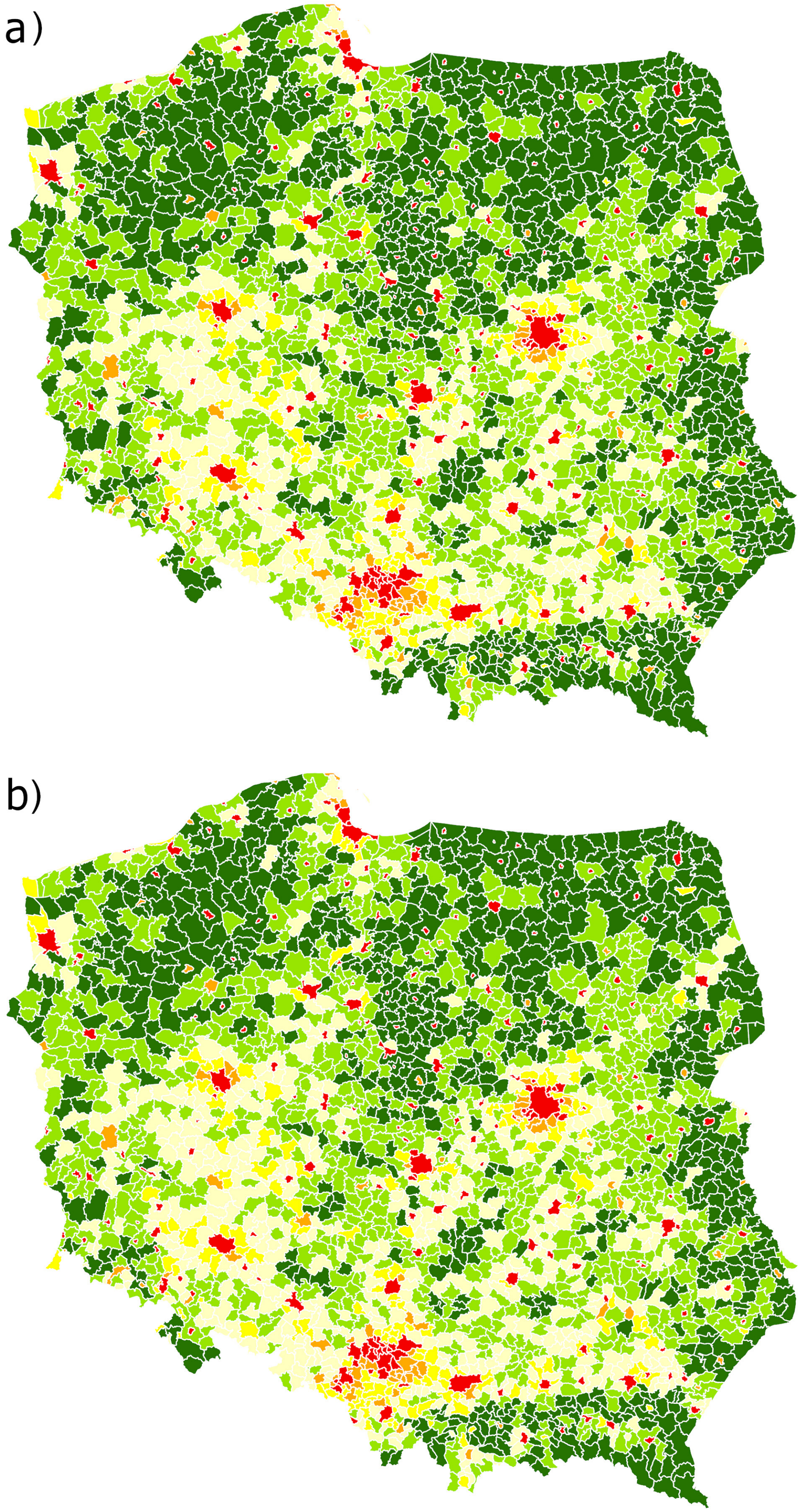

Fig. 2. Proportion of impervious surfaces in Poland by communes in (A) 1990, (B) 2000.

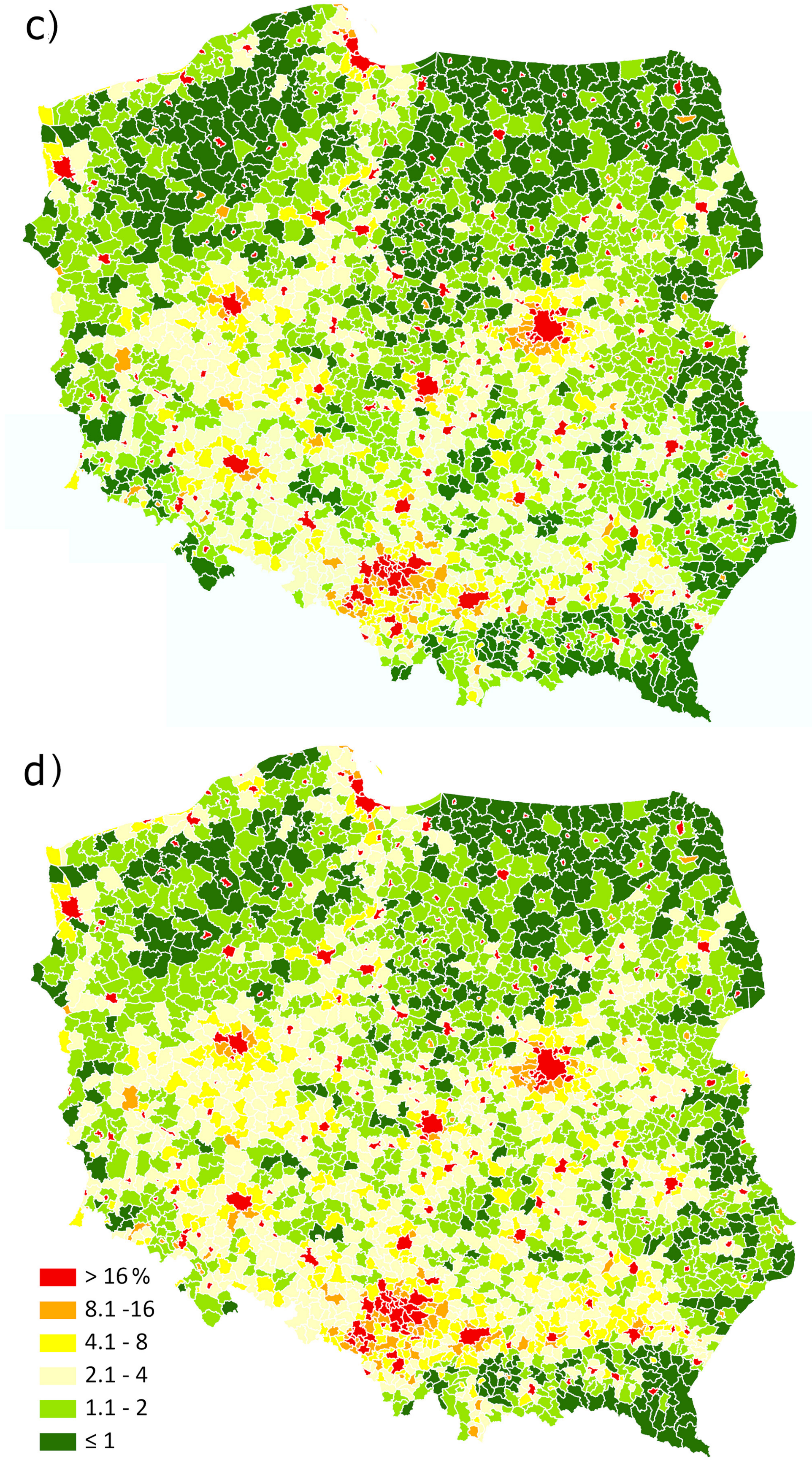

Fig. 2. Proportion of impervious surfaces in Poland by communes in (C) 2010 and (D) 2020.

(DBSI), which made it possible to exclude large areas of exposed soil from the analysis (Rasul et al. 2018). For the classes of the areas excluded from further analyses, i.e. biologically active areas, water features and exposed soils, the classification accuracy was 100%, i.e. each pixel classified as one of the above classes was correctly marked.

The third stage of satellite image analysis was to separate PSs from ISs. Several classification algorithms were tested in the study. The best results were obtained for the SVM, which made it possible to determine the following classes: 1) ISs, 2) arable land, 3) meadows and other vegetation and 4) exposed soils. Classes such as forests and water features were successfully eliminated at an earlier stage of the analysis. The designated areas were aggregated into two main classes to form the final IS/PS map. The obtained IS/PS map was subjected to further analysis. First, the data were aggregated to the administrative borders of the cities. The purpose of this operation was to calculate the area and percentage of IS in each administrative unit, thus obtaining the value of the total imperviousness index of a given urban area.

In the last stage of the analysis, the results presenting the proportion of ISs for three time periods were compared, which made it possible to prepare maps of changes in the value of the area's imperviousness index in individual decades.

High-resolution digital orthophotomaps were used as reference data for the analysis of the accuracy of the IS classification made. In the case of absence of data in the GUGiK's resources, images published via the Google Earth service were used.

Results

The diversity and changes of ISs in Poland

In 2020, the area of ISs in Poland amounted to 9954 km^2, which is 3.2% of the country's area. ISs are unevenly distributed, with a greater share in the south-western and central parts of Poland than in other parts of the country (Fig. 2). Most of them, i.e. as much as 37% of ISs, are located in municipalities (local government units with municipal rights). Among the large cities (>100,000 inhabitants), the following are characterised by the largest proportion of ISs: Chorzów (51.8%), Warszawa (47.5%), Białystok (47.2%), Sosnowiec (41.8%), Poznań (41.3%), Kraków (36.5%), Łódź (36.2%) and Wrocław (35.5%). Interestingly, the highest imperviousness index is found in small towns: Piastów (86.0%), Legionowo (75.6%), Pruszków (63.6%), Mińsk Mazowiecki (62.7%), Kościan (60.6%), Luboń (60.0%), Ząbki (58.0%) and Świętochłowice (55.0%). The above-mentioned cities are part of large, highly urbanised agglomerations. Piastów, Legionowo, Ząbki and Pruszków are the satellite towns of Warszawa, which have been intensively suburbanising in the past 30 years. Luboń plays a similar role for Poznań. Mińsk Mazowiecki and Kościan are more-distant towns, but they are well connected with the core city. For this reason, the population, and thus the IS area, also increased there. Świętochłowice, on the other hand, is a compact town in the centre of the Silesian Metropolis, with a dominant proportion of tenement houses in residential buildings. For comparison, Lesko, located in the south-eastern less-urbanised part of Poland (Fig. 2), is characterised by a share of IS at the level of 1.5%.

In the years 1991–2020, the total area of ISs in Poland increased by approximately 30% (Table 2). This means that new ISs took up almost 2454 km^2, which is almost five times more than the area of Warszawa (517 km^2), the capital of the state and the largest city in Poland. Most ISs emerged outside city centres, which include mainly new road infrastructure investments. The construction of highways, including the A1, A2 and A4 highways, together with numerous interchanges, constituted a significant part of the areas created after 1991 that cannot be infiltrated by water. The construction and hardening of lower-class roads also had a great impact on the increase in ISs. Another factor affecting the growth of ISs in Poland was the widely understood process of urbanisation. It was observed that the increase in the proportion of ISs took place in practically every part of the cities studied (Fig. 3). This means that even in areas of relatively dense development, i.e. in city centres, there were fragments of previously undeveloped space, or as part of the so-called revitalisation, green areas, squares and parks were turned into squares or parking lots covered with impervious paving, concrete or asphalt (Fig. 4).

Table 2. Changes in impervious surface (IS) in Poland in the years 1991–2020.

Index	1991	2001	2011	2020
ISs in km² – municipalities	3093	3199	3445	3475
ISs in km² – rural communes	2479	2652	2976	3517
ISs in km² – municipal–rural communes	2109	2218	2445	2762
ISs in km² – total	7682	8069	8866	9954
ISs share in % – total	2.46	2.58	2.84	3.2
Average annual growth in % – total		0.51	0.99	1.63
Increase in % – total		5.1	9.9	16.3
	Total for the years 1991–2020	29.9		

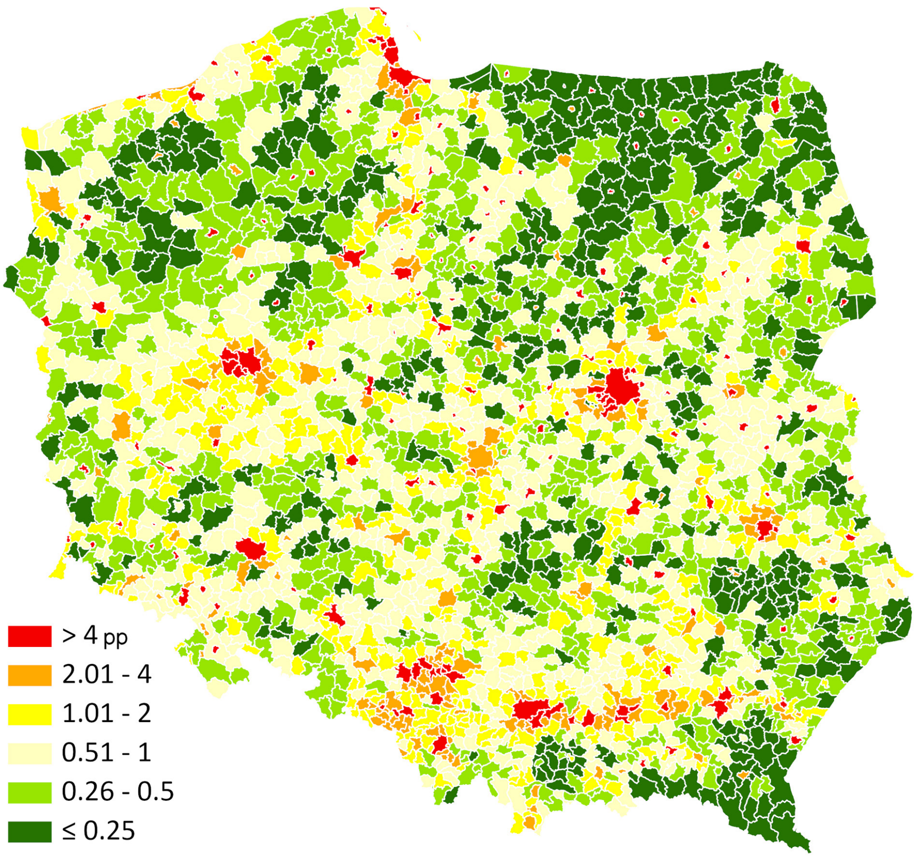

Fig. 3. Changes in the imperviousness index in Poland in percentage points (pp) by communes in 1990–2020.

Fig. 4. Bartoszyce – before and after revitalisation.

Table 3. Proportion (%) of changes in impervious surface in selected cities in Poland in the years 1991–2020 in percentage points.

City	Imperviousness index				Change [%]		
	1991	2001	2011	2020	1991–2000	2001–2010	2011–2020
Białystok	38.1	40.4	43.5	47.2	2.3	3.1	3.7
Gorzów	25.5	26.1	29.4	31.4	0.6	3.3	2.0
Katowice	32.2	32.3	34.1	34.9	0.1	1.8	0.8
Kielce	28.6	29.0	31.2	32.3	0.4	2.2	1.1
Kraków	32.3	32.7	36.6	37.5	0.4	3.9	0.9
Lublin	29.4	31.5	34.4	37.6	2.1	2.9	3.2
Łódź	32.4	32.7	34.4	36.2	0.3	1.7	1.8
Poznań	35.4	36.3	38.8	41.3	0.9	2.5	2.5
Toruń	28.0	29.3	32.9	34.8	1.3	3.6	1.9
Warszawa	41.9	43.2	46.7	47.5	1.3	3.5	0.9
Lesko	1.1	1.2	1.3	1.5	0.1	0.1	0.2

In large cities, the increase in ISs is also related to the occurrence of office buildings and service centres on previously undeveloped properties or on sites of less-intensive development.

Ten large cities were selected for detailed analysis (Table 3), in which the proportion of ISs constitutes >30% of the city's area and there is a weather station in their area from which data are available. To compare the trends of maximum air temperature, relative humidity and low-level cloudiness, Lesko—a small town with a relatively small share of IS (1.5%)—which also has a weather station, was additionally selected.

At the beginning of the analysed multi-year period (1991), the imperviousness index in the analysed cities ranged from 25.5% in Gorzów to 41.9% in Warszawa (Table 3). The greatest increase in proportion of ISs occurred in most of the analysed cities in the years 2001–2010. It was a very dynamic period in Poland's economic development owing to its accession to the European Union in 2004. The obtained EU funds were used for projects related to the development of the national infrastructure, including the construction of roads, highways, city ring roads, bridges, sports centres, etc., which contributed to the growth in IS area. In the years 2001–2010, the largest increase of imperviousness index occurred in Kraków (3.9 pp), and the lowest in Łódź and Katowice (1.7 and 1.8 pp, respectively). In the past decade, the area of ISs in all cities exceeded 30%, and the greatest increase of the imperviousness index was recorded in Białystok (3.7 pp), while the smallest (0.8 pp) increase was in Katowice. The cities with the highest increase in the imperviousness index in the years 1991–2020 were Lublin and Białystok (8.3 and 9.1 pp, respectively), while the smallest increase (2.8 pp) was recorded in Katowice, which had already been highly urbanised since the beginning of the analysed multi-year period.

The spatial and temporal variability of the maximum air temperature, low-level cloud cover and relative humidity in Poland

In the warm half of the year (April–September), the spatial variability of the average maximum temperature of an area in Poland (except for mountain areas) does not exceed 4°C. The area with the highest values (>22°C) is the south-western part of Poland, including the most urbanised areas of the country associated with coal mining and heavy industry. High values (>20°C) are recorded in a wide belt of central Poland, which then gradually decrease to the north (towards the Baltic Sea) and to the south (towards the mountains, the Carpathians and the Sudetes) (Fig. 5A). The increase in the maximum air temperature in south-eastern Poland could be additionally influenced by the greater frequency of the influx of tropical air masses in the warm half of the year (Bartoszek, Kaszewski 2022).

Low-level cloud cover is the lowest in the central belt of Poland with a minimum (40%) near Wrocław and in the coastal belt. The areas with the largest cloud cover (>60%) are the mountains (the region of the southern border of the country) and the lake districts in northern Poland (Fig. 5B).

The spatial variability of relative humidity is related to the air temperature distribution, with the warmest areas being the least humid and vice

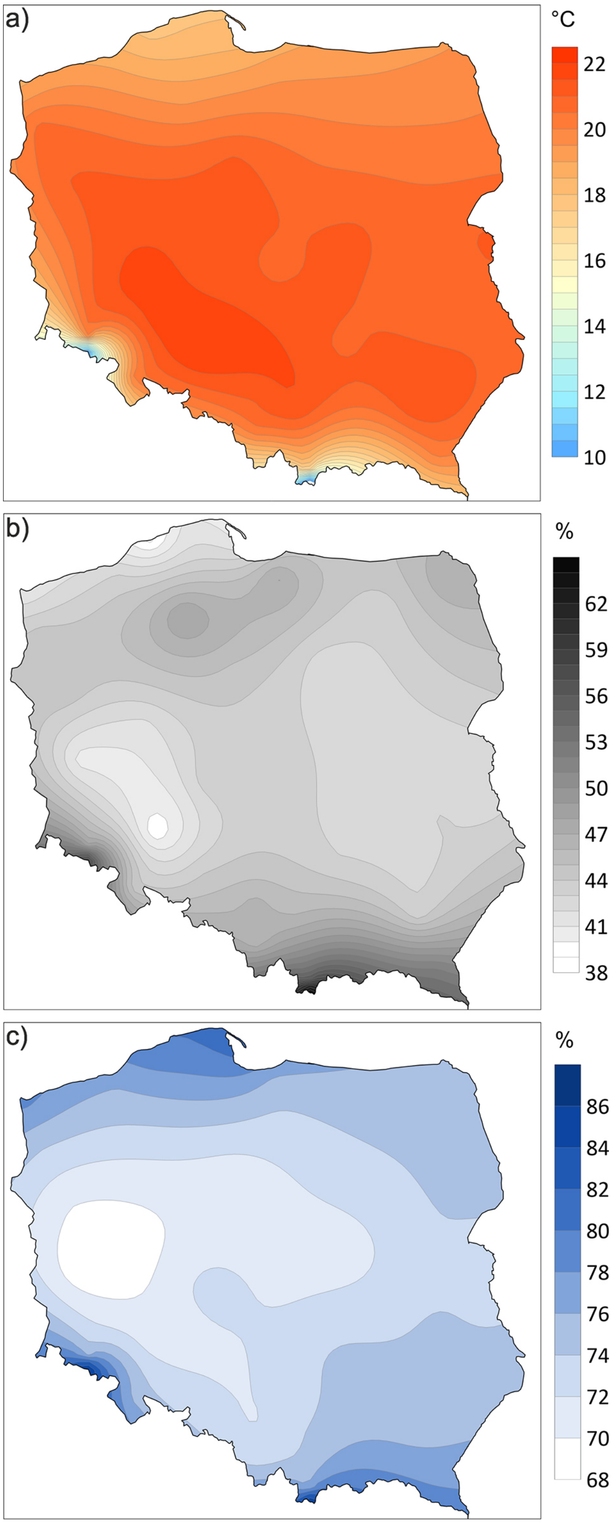

Fig. 5. The average (A) maximum air temperature, (B) low-level cloud cover and (C) relative humidity in the warm part of the year (April–September) in the period 1991–2020.

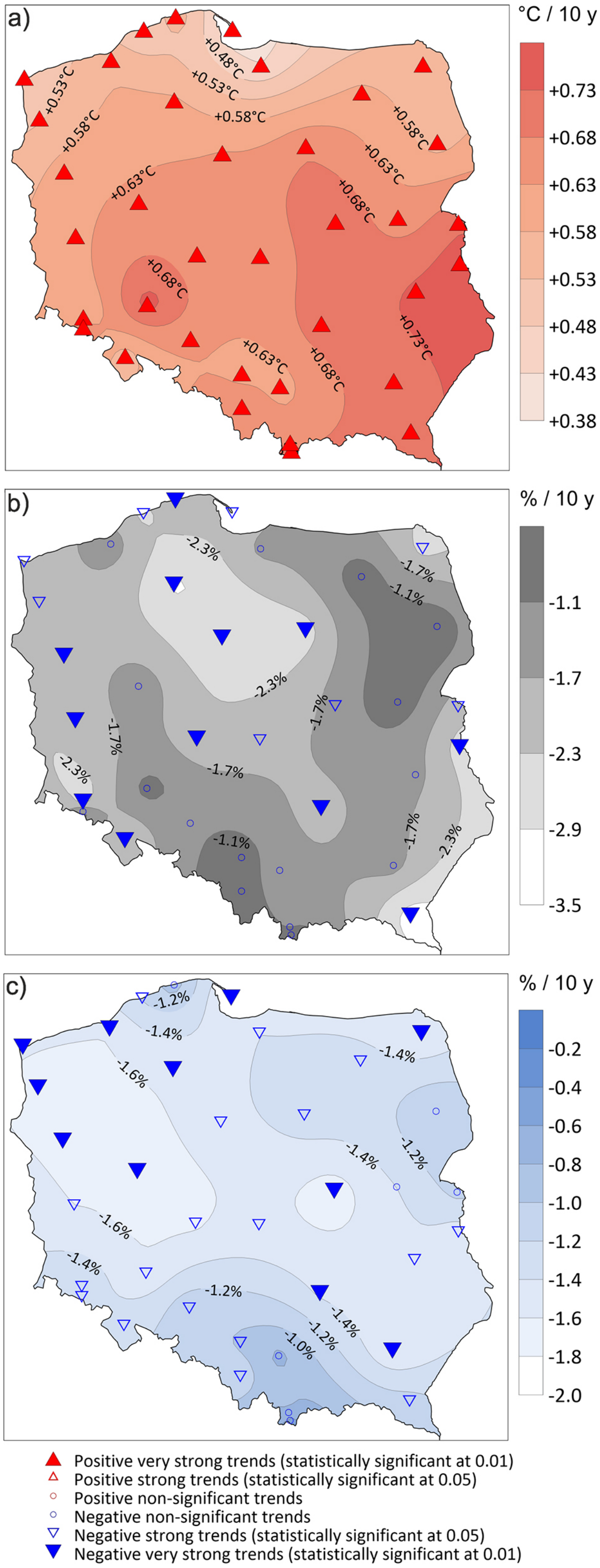

Fig. 6. The magnitude (slope value) and statistical significance of linear trends of (A) maximum air temperature, (B) low-level cloud cover and (C) relative humidity in the warm part of the year (April–September of 1991–2020).

versa, i.e. the coolest being the most humid (Figs 5A, C). The lowest values (approximately 68%) are characteristic for the areas of central-western Poland (near Gorzów and Poznań), and the highest (>80%) are for mountainous and coastal areas (Fig. 5C). The eastern half of Poland, which is dominated by agricultural land, is more humid than the western part, which is more urbanised.

In the analysed years (1991–2020), positive, statistically significant trends in maximum temperature are visible throughout Poland. They range from 0.48°C per 10 years on the central coast to >0.9°C per 10 years in the vicinity of Wrocław. The largest temperature increases are recorded in the central, eastern and south-eastern parts of the country (Fig. 6A), while the smallest values are in the north, which may be caused by the influence of the Baltic Sea.

The trends in the magnitude of low-level cloud cover and relative humidity are negative throughout Poland. The largest statistically significant decrease in cloud cover (Fig. 6B) occurred in the south-east region of Poland, in the vicinity of Lesko (−2.7% per 10 years), in the northern half of the country (in its central part) and in the vicinity of Jelenia Góra in the south-west (−2.3% per 10 years each).

The magnitude of the decreases in the relative humidity values was in the range from −1.0% to −1.6% per 10 years (Fig. 6C). The largest, statistically significant trends occur in the north and in the mid-west of Poland, as well as in the vicinity of Warszawa.

It is worth emphasising that the changes in air temperature and humidity over Poland occurred not only on the earth's surface, but also at different altitudes in the troposphere (Fig. 7 and Table 4). The difference between the two meteorological elements in this aspect was that the magnitude of the negative humidity trends increased with altitude, while the greatest increase in air temperature occurred in the lower troposphere.

The long-term course of the area average maximum temperature shows a gradual increase in the period 1991–2020 with slight deviations in individual years, with the lowest value (17.8°C) in 1996 and the highest (22.2°C) in 2018 (Fig. 8). The trend of low-level cloud cover throughout

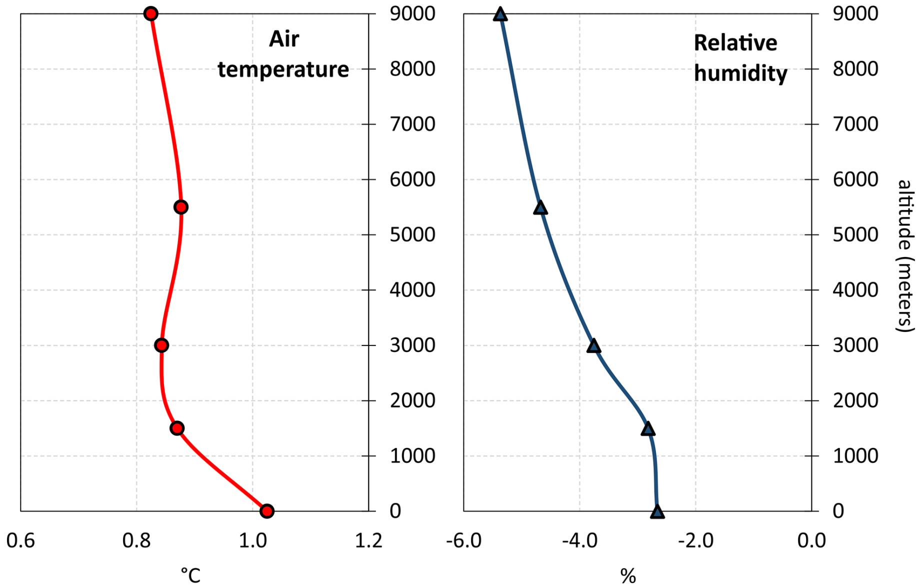

Fig 7. The slope of increase in average air temperature and decrease in relative air humidity in the period 2001–2020 compared to the years 1981–2000 at various altitudes in the troposphere (averaged values for Poland).

Table 4. The linear temporal trend slopes of the average area-wise values of air temperature and relative humidity at 2 m AGL and at different isobaric levels in Poland in the years 1981–2020.

Pressure levels (hPa)	Unit	April–September				
		2 m AGL	850	700	500	300
Air temperature	[°C per 10 years]	0.49*	0.40*	0.38*	0.43*	0.37*
Relative humidity	[% per 10 years]	−1.25*	−1.28*	−1.86*	−2.44*	−2.90*

*Statistically significant at the level of $p<0.01$; AGL, above ground level.

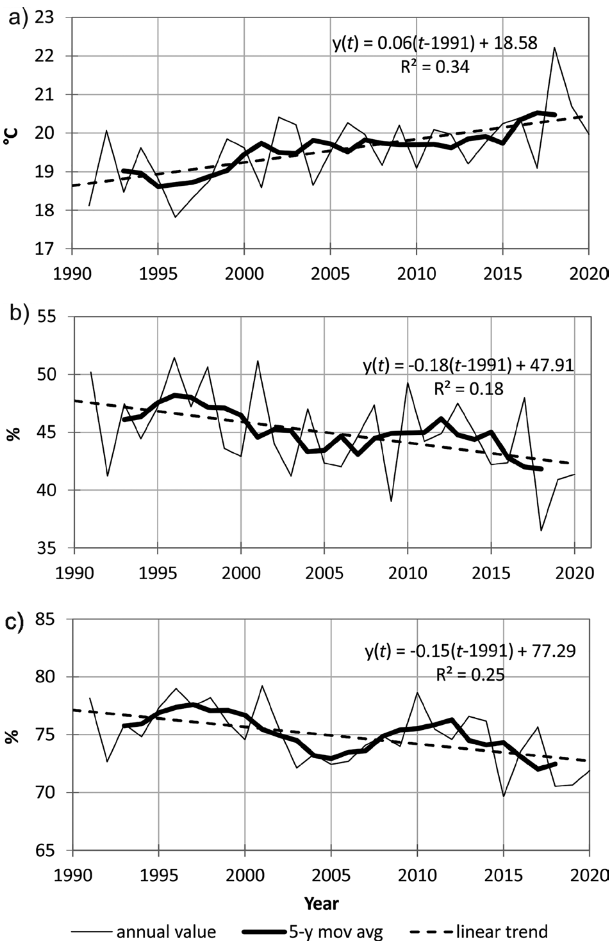

Fig. 8. The multi-annual variability of the average (A) maximum air temperature, (B) low-level cloud cover and (C) relative humidity in the warm part of the year (1991–2020) in the selected areas.

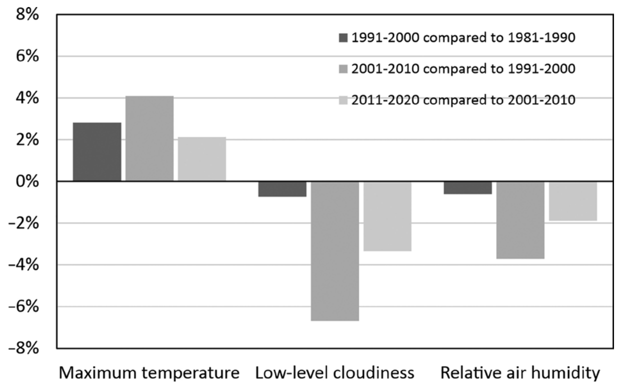

Fig 9. Percentage magnitude of changes in the maximum temperature, low-level cloudiness and relative air humidity between the decades (averaged values for the 10 cities).

the research period is negative, but from 2010 to 2017, higher values were recorded than in several years of the first decade of the 21st century. The long-term course of relative humidity corresponds to the course of cloud cover, and the same year (2010) is also followed by a several-year increase in the value of this characteristic, with a general negative trend over the entire multi-year period.

The relationships between the increase in the proportion of ISs and meteorological conditions in selected cities in Poland

In all 10 analysed cities, the highest increase in the maximum temperature occurred in the second decade of the analysed multi-year period (2001–2010), which ranged from 3.5% in Toruń to 4.5% in Lublin and Warszawa (Table 5). This decade also saw the greatest decrease in low-level cloud cover (Table 6) and relative humidity (Table 7). The cities where the low-level cloud cover decreased the most are Gorzów and Toruń (10.9% and 10.8%, respectively). On the other hand, the decrease in relative humidity was the strongest (6.2%) in Łódź and Warszawa. Averaged values from the 10 cities also show that the most dynamic changes in the values of maximum temperature, cloud cover and relative humidity (Fig. 9) occurred in the years 2001–2010, in which the largest increase took place in sealed surfaces (Table 3). In that decade, the greatest changes related to the amount of low-level cloud cover; in relation to the previous decade, the decrease was >6%.

In the reference city (Lesko), with a small proportion of ISs, the magnitude of changes in the analysed meteorological elements fell on other decades than in the 10 large cities (Tables 5–7). The greatest reduction in low-level cloud cover and relative humidity occurred in the last decade (2011–2020), while the air temperature increased in the analysed period at a similar rate (being the highest in the decade 1991–2000).

A more detailed analysis of cloud cover changes showed that in the past 40 years, in the analysed cities, there have been significant changes in the frequency of occurrence of particular types of clouds (Fig. 10). Particularly noticeable is the decrease in the frequency of low- and mid-level stratiform clouds (*Stratus*, *Nimbostratus*, and *Altostratus*), and the increase in the frequency of high-level *Altocumulus* and *Cirrus* clouds.

Table 5. The average maximum temperature T_{max} in individual decades and the magnitude of its changes in the areas of the analysed cities in the warm part of the year (April–September).

City	Average T_{max}				Change		
	1981–1990	1991–2000	2001–2010	2011–2020	1991–2000 compared to 1981–1990	2001–2010 compared to 1991–2000	2011–2020 compared to 2001–2010
	[°C]				[%]		
Białystok	19.8	20.5	21.3	21.6	+3.4	+4.0	+1.6
Gorzów	19.7	20.4	21.2	21.5	+3.1	+3.9	+1.5
Katowice	19.8	20.4	21.2	21.6	+3.1	+3.6	+2.2
Kielce	19.5	20.1	21.1	21.6	+3.0	+4.4	+2.5
Kraków	20.0	20.7	21.5	21.9	+3.5	+3.8	+1.9
Lublin	19.2	19.7	20.6	21.2	+2.7	+4.5	+2.6
Łódź	19.8	20.2	21.0	21.5	+1.8	+4.3	+2.2
Poznań	20.0	20.6	21.5	21.8	+2.9	+4.5	+1.5
Toruń	20.0	20.5	21.2	21.8	+2.8	+3.5	+2.5
Warszawa	20.0	20.3	21.2	21.8	+1.9	+4.4	+2.7
Lesko	18.6	19.3	20.0	20.7	+3.8	+3.6	+3.3

Table 6. Average low-level cloudiness in individual decades and the magnitude of its changes in the analysed cities in the warm part of the year (April–September).

City	Average low-level cloudiness (%)				Change		
	1981–1990	1991–2000	2001–2010	2011–2020	1991–2000 compared to 1981–1990	2001–2010 compared to 1991–2000	2011–2020 compared to 2001–2010
	[%]				[%]		
Białystok	47.6	47.9	46.2	45.6	+0.5	−3.6	−1.2
Gorzów	48.4	49.0	43.9	40.6	+1.2	−10.9	−7.9
Katowice	47.0	47.9	46.2	45.5	+1.8	−3.6	−1.5
Kielce	46.8	46.2	42.4	39.4	−1.3	−8.5	−7.5
Kraków	44.1	42.3	40.0	39.0	−4.3	−5.5	−2.6
Lublin	45.7	44.7	42.6	41.4	−2.1	−4.8	−2.6
Łódź	45.0	46.2	43.1	41.7	+2.6	−7.0	−3.2
Poznań	44.0	43.5	40.7	39.9	−1.0	−6.7	−2.1
Toruń	48.1	47.9	43.0	42.2	−0.5	−10.8	−1.9
Warszawa	48.1	47.9	43.0	42.2	−4.2	−5.5	−2.9
Lesko	54.4	54.6	52.4	48.0	+0.8	−4.0	−8.8

Table 7. Average relative air humidity in individual decades and the magnitude of its changes in the area of the analysed cities in the warm part of the year (April–September).

City	Mean *f*				Change		
	1981–1990	1991–2000	2001–2010	2011–2020	1991–2000 compared to 1981–1990	2001–2010 compared to 1991–2000	2011–2020 compared to 2001–2010
	[%]				[%]		
Białystok	73.7	73.2	71.7	70.5	–0.6	–2.1	–1.6
Gorzów	72.8	72.6	70.1	67.8	–0.2	–3.6	–3.3
Katowice	73.7	73.2	71.7	70.5	–0.6	–2.1	–1.6
Kielce	76.7	76.6	74.0	73.0	–0.1	–3.4	–1.4
Kraków	75.7	74.8	73.4	72.5	–1.2	–1.9	–1.2
Lublin	77.0	76.3	73.7	72.6	–0.9	–3.5	–1.4
Łódź	74.9	74.8	70.3	70.1	–0.1	–6.2	–0.3
Poznań	72.5	72.4	68.6	66.9	–0.2	–5.3	–2.6
Toruń	73.6	72.1	70.1	68.9	–2.0	–2.8	–1.7
Warszawa	74.7	74.6	70.1	67.6	–0.2	–6.2	–3.7
Lesko	78.7	78.2	77.7	76.0	–0.6	–0.6	–2.2

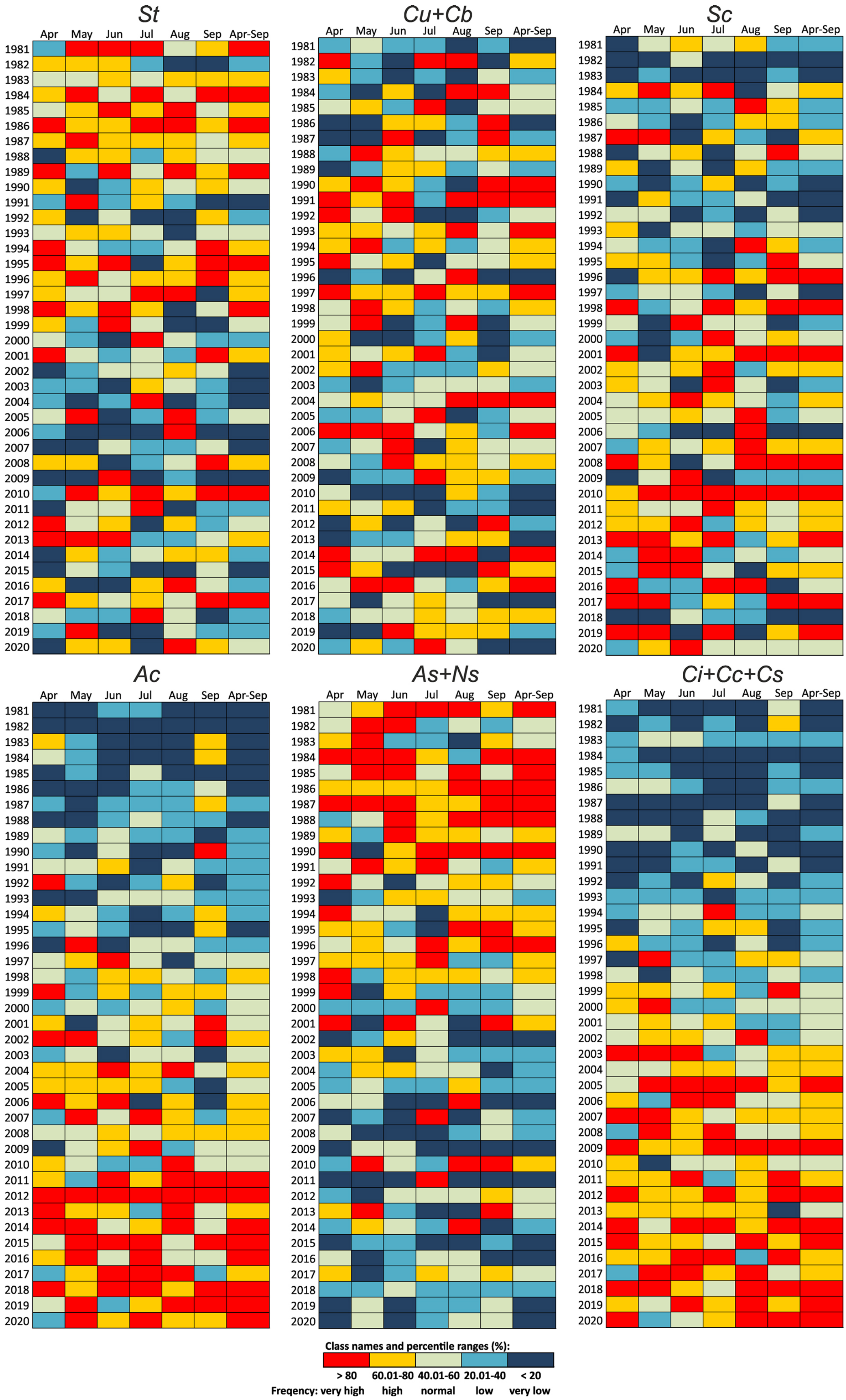

Fig. 10. The quantile classification of the frequency of occurrence of certain types of clouds (averaged values for the 10 cities).

Discussion and conclusions

There is no doubt that the development of civilisation has changed the coverage of the Earth's surface. According to Hurtt et al. (2006), in the years 1700–2000, as a result of human activity, from 42% to 68% of the Earth's surface was transformed. The strongest changes occurred in the moderate latitudes of the Northern Hemisphere. They caused the modification of the radiation balance by affecting the albedo changes and the latent heat flux. They also affected the increase in air temperature, the water cycle, river runoff, surface roughness, dust emission, snow cover and more. The phenomenon of taking up soil for housing development, production of plants, public transport networks, etc. and covering it with impervious material is described in detail in the reports of the European Commission (Prokop et al. 2011). The results of the studies by Gardi et al. (2014) suggest that sealing the substrate is almost irreversible. In already heavily urbanised European countries, such as the Netherlands and Germany, the rate of loss of natural surfaces is high, and there is little room for further urbanisation. In Central and Eastern Europe, the accelerated growth of built-up areas was a consequence of the political and economic changes of the late 1980s, and the expansion of the European Union and the integration of new countries into the common market led to the development of transport infrastructure, urban expansion and further sealing of the surface (Gardi et al. 2014).

The processes of taking up land in other parts of the world are much faster than in Europe, especially in emerging economies. For example, 5.1% of all Chinese territory was converted into land for manufacturing and communal activity between 1996 and 2003 (Chen 2007), and in the Beijing–Tianjin–Hebei region, urban area increased by 71% between 1990 and 2000 (Tan et al. 2005). Similar growth rates were also recorded in India and other rapidly developing countries (Fazal 2000). Worldwide, urban areas are increasing their surface area at twice the rate of their populations (Angel et al. 2011).

In Poland, as in many other countries, intensive urbanisation is taking place and the proportion of ISs is increasing. In 2020, the ISs in this country covered 9954 km^2, which constituted 3.2% of the area. In the years 1991–2020, the total area of ISs increased by approximately 30%. Such a large change in the coverage of the earth's surface in a relatively short time (30 years) and the progressive warming have motivated us to undertake research on the impact of the increase in the share of ISs on thermal conditions, humidity and cloud cover in Poland. Our research showed that in the warm half of the year, in all of the 10 analysed cities, the increase in ISs in recent decades coincided with the decrease in low-level cloudiness. On a local scale, both of these phenomena should strengthen the effect of the albedo decrease and contribute to the heating of the active surface and, thus, to an increase in temperature and a decrease in air humidity. Indeed, the highest rates of air temperature increase and relative air humidity decrease occurred in the years 2001–2010, when the highest IS increase was recorded in most cities. Another important observation is that the significant decrease in low-level cloudiness was also accompanied by a change in the cloud structure. The frequency of low- and mid-level stratiform clouds (*Stratus*, *Nimbostratus*, and *Altostratus*) decreased, while the frequency of high-level *Altocumulus* and *Cirrus* clouds increased. The decrease in the frequency of stratiform clouds may have been affected by processes taking place in recent years on a large spatial scale, i.e. the intensification of air dryness caused by an increase in air temperature in the entire vertical profile of the troposphere over Poland. However, the higher frequency of *Altocumulus* and *Cirrus* clouds could be related to the reduction of low-level cloud cover, which made it possible to see the clouds in the middle and upper troposphere.

This study is, therefore, part of the research on the causes of modern climate warming. According to many scientists (including Tett 2002, Meehl et al. 2004, Lean, Rind 2008, Gillett et al. 2012, Huber, Knutti 2012, Jones et al. 2013, Wigley, Santer 2013), natural factors on a global scale have not had a significant impact on the increase in air temperature in the past few decades and could even cause its decrease (e.g. the weakening of the Sun's activity, volcanic eruptions). Furthermore, the results of the research conducted in Poland (including Kulesza 2020, Bartoszek et al. 2021, Bartoszek, Matuszko 2021) indicate that radiation and circulation factors do not play a major role in the recorded increase in air temperature in this country. On the other hand, there are many arguments that the climate is warming as a result of human activity caused by the increase in greenhouse gas concentrations and the change in the Earth's surface cover as a result of urbanisation, soil transformation, deforestation and changes in the Earth's albedo (IPCC 2021).

Research by Stephens et al. (2015) and Goode et al. (2021) confirmed a decrease in the albedo of the Earth's surface over the past 20 years, which means that our planet absorbs much more solar radiation than it did before the beginning of the 21st century. According to Goode et al. (2021), the main reason for the decline in the Earth's solar reflectivity may be the lower amount of low-level clouds associated with the warming of the Eastern Pacific. The results of modelling studies on the hydrometeorological effects of urbanisation remain ambiguous (Lowry 1998, Shepherd 2005, Mahmood et al. 2014). The major challenges limiting our understanding of urban modification of convection is the difficulty in separating the urban signature from those of topography, land–sea or land–lake boundaries, and the large-scale atmospheric forcing in field experiments or in real-case modelling studies. As a result, studies conducted at different locations, in different seasons, and/or under different synoptic conditions often produce different findings (Zhu et al. 2017).

Unfortunately, the climatological literature lacks current studies on the impact of urbanised areas on the long-term variability of cloud cover and the occurrence of individual types of clouds. The problem of IS's influence on cloud cover was discussed only in the study by Theeuwes et al. (2019), which highlights the increase in cloud cover in the afternoon and evening hours over urban areas in Europe, i.e. in London and Paris. Owing to the still small number of scientific publications in this field, the results of our research constitute an important contribution to the discussion on the consequences of the increase in ISs in cities and contribute to further analyses on a larger spatial scale.

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Author's contribution

Krzysztof Bartoszek: conceptualization, data curation, software, visualization, validation, writing-reviewing and editing, investigation, writing-original draft preparation; Wojciech Łachowski: data curation, resources, writing-original draft preparation, writing-reviewing and editing, visualization; Dorota Matuszko: conceptualization, methodology, writing-original draft preparation, investigation, supervision, writing-reviewing and editing.

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