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ORIGINAL PAPER

Twentieth century variability of surface humidity as the climate change indicator in Kraków (Southern Poland)

Agnieszka Wypych

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Abstract Air humidity is an element that plays an important role among meteorological processes within the atmosphere; however, the variety of humidity indices makes the global view of air moisture changes difficult. Long-term variability of air humidity in Kraków was examined by time-series (1901–2000) analysis of vapour pressure and saturation deficit values and their characteristic days with the background of temperature and saturated vapour pressure changes. Long-term variability of air humidity in Kraków has been visible above all in variations of saturation deficit. It should be connected with the contemporary temperature growth and the city development as the atmospheric water vapour content (described by vapour pressure) becomes relatively stable (with no significant tendencies). The parameter showed well-marked trends over the examined period. The growth of saturation deficit values predominated in the warm half of a year (above all in August: an increase in SD value by 3.0 hPa per century). Apart from atmospheric circulation variability, gradual rise in the number of inhabitants and higher development density contributed to the decline in the city's air humidity; however, the causes of changes in air humidity should be also attributed to natural factors, mainly to variation of air circulation reinforced by the operation of anthropogenic factors. Using air humidity as the indicator, the results that confirm climatic fluctuations in central Europe in the twentieth century obtained earlier were verified and some new aspects of present climate change were given.

A. Wypych (✉)
Department of Climatology, Jagiellonian University, Poland,
7 Gronostajowa Str., 30-387 Kraków, Poland
e-mail: awypych@geo.uj.edu.pl

1 Introduction

Since the last decades of the twentieth century, because of climatic anomalies (heavy rainfall, droughts, hurricanes, etc.) that occur more and more often in different parts of the world, the social interest on climate change phenomena has grown up. Global environmental transformations as well as air temperature increase are connected mainly with intensive anthropopression. The Intergovernmental Panel on Climate Change (IPCC) created in the late 1980s has predicated after worldwide research analyses that observed climate change is the result of both natural and anthropogenic factors (IPCC 2007).

Climatologists' attention is concentrated mainly on temporal and spatial variability of temperature and precipitation as the principal indicators of contemporary climate change (Frich et al. 2002; Klein Tank and Können 2003).

Long-term variability of temperature and precipitation has been the subject of detailed research also in Kraków. Constant increase in the annual mean temperature value has been observed; however, periods with opposite tendency can also be distinguished especially in different seasons (Trepińska and Kowanetz 1997; Kożuchowski et al. 1994). The observed increase reaches 1.5°C/100 years (annual value) and varies from 1.0°C/100 years in July to 2.0°C/100 years in February and April. Although winter months' temperature is characterised by larger increase, the statistically significant (at the 0.05 significance level) upward tendency regards the warm half of the year (Piotrowicz 2007). Precipitation in Kraków is characterised by rather irregular long-term annual patterns. Although distinct dry and wet periods can be easily traced (e.g. at the beginning of twentieth century values considerably higher than the average were recorded) according to IPCC report (2007) generally no trends was found in precipitation in Kraków (Niedźwiedź et al. 2009; Twardosz and Niedźwiedź 2001).

Air humidity, describing the amount of water vapour in the atmosphere, is a meteorological element which is highly related to air temperature with a significant impact on weather conditions. It plays important roles among the meteorological processes which are taking place within the atmosphere i.e. transferring energy (Unger 1993). Although air humidity influences primarily cloudiness and subsequently the radiation transmission as well as precipitation occurrence, some climate change impact models, e.g. the crop models require humidity variables as an input (Huth 2005), the body of research examining its course and variability is lacking. The principal causes of the relatively small number of published papers on air humidity are the lack of long-term hygrometric or psychrometric measurements as well as the methodical difficulties related to the data analysis (Wang and Gaffen 2001; Gaffen and Ross 1999; Heino 1994). The authors stressed unanimously that, mainly because of the scarcity of material, the results obtained to this point did not give an unequivocal answer to the question of air humidity variability and its causes, thus confirming the necessity of further detailed studies and analyses.

On the other hand, due to relocation of the stations and errors associated with dynamic changes in local conditions (Aguilar et al. 2003) more extensive urban climate studies, including humid island (Lee 1991; Unger 1999; Holmer and Eliasson 1999), were possible. It has been demonstrated that the city centres are usually drier than the suburbs (Robaa 2003); however, Unger (1999) emphasises the considerable variances in research and study results. The scale of differences could be cause partly by the different city structures and the different extent of urbanisation (Unger 1999). The distribution of urban humidity is affected by mixing influences of surface roughness, moisture sources and thermal fields (Robaa 2003). Urban climate studies including urban humid island enable to determine the impact of urbanised areas, which are characterised by specific types of development and urban land uses, on climate conditions and to isolate the anthropogenic factor influencing changes in global climate.

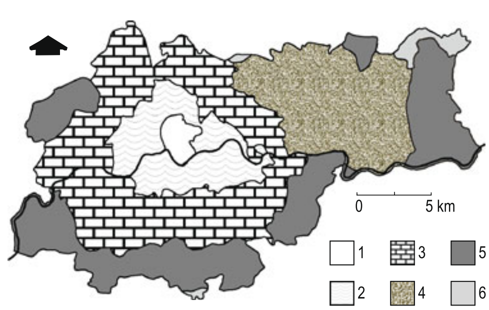
The variety of humidity parameters, some of which describe physical properties of water vapour as a gaseous component of atmospheric air (e.g. vapour pressure, specific humidity) while others characterise the level of air saturation with water vapour (e.g. relative air humidity, saturation deficit) makes the unequivocal answer to the question of air humidity very difficult. Furthermore, as they are functions of different elements their long-term trends vary and a global view of air humidity changes has been unavailable (Dai 2006)

The main objectives of this study are (1) to present the variability of air humidity in Kraków over the twentieth century, (2) to evaluate using air humidity as the indicator of climate change on the basis of detected fluctuations and their intensity, (3) to estimate the role of both atmospheric circulation and local conditions (the developing city) in forming contemporary climatic fluctuations.

2 Study area

Kraków is placed in the Vistula River basin with the neighbourhood of the Wieliczka Foothills (Pogórze Wielickie) and the Kraków Upland (Wyżyna Krakowska) located about 200–250 m higher. It, together with the various relief within the city area and the hydrography, results in modification of many climate features. An important role is played also by urban and industrial land development.

At the beginning of twentieth century, the area of the city included the terrains surrounding the old town (Fig. 1). The dynamic city spreading and the considerable growth of the number of inhabitants as the results of the rapidly developing industry caused the increase of street network with streets and squares paved with concrete and asphalt and the city's growing buildings' density and subsequently serious reduction of the acreage of city green areas. Because of the abovementioned factors: city location and the anthropopression the climate of Kraków is considered to be rather unfavourable.



year	area (km^2)	inhabitants
1900	6.9	85 300
1921	46.9	221 300
1946	165.3	299 400
1951	230.0	357 900
1970	230.0	584 900
1990	326.8	750 500

Fig. 1 Development of the city of Kraków in twentieth century. *1* before 1901, *2* in 1915, *3* in 1941, *4* in 1951, *5* in 1976, *6* in 1986, (source: Mydel 1994)

3 Source material and methods

The research was conducted on the basis of the data for the period 1901–2000 acquired from archival materials of the Climatological Station of the Department of Climatology of the Institute of Geography and Spatial Management, Jagiellonian University (50°04′ N, 19°58′ E, h=220 m a.s.l.) Kraków, Poland. Within that time all observations of water vapour content in the air have been uninterruptedly performed in the same location and using consistently the same method: August psychrometer placed in a thermometer shelter 12 m above the ground level. Although measurements were taken within the existing detailed instruction all the data were thoroughly examined. The identified uncertain values were subjected to further verification. They were compared with the values read from hygrograms and the readings of the hair hygrometer. Extreme cases, which gave rise to doubts, were analysed with regard to the records about the state of the atmosphere: circulation conditions, the occurrence of foehn and some atmospheric phenomena. Subsequently, all the missing data concerning the state of the cambric during the measurements (water/ice) were completed. The presence of ice/water on the cambric has a significant influence on measurement results. It is also related to using an appropriate psychrometric constant. Absence of such information means that the resulting humidity parameters would be subject to excessive error. All the integrated data were verified by modified form of Standard Normal Homogeneity Test by Alexandersson (1986) using AnClim software for time-series analysis (Štepanek 2007). The performed tests did not find any inhomogeneities; however, the content of water vapour in the air is a result of the interaction of numerous factors and processes, which need to be taken into account before analysing the values so the results of any air humidity data studies should be interpreted with great care.

The data used included monthly and daily mean values of vapour pressure (VP) and saturation deficit (SD) derived from August psychrometer measurements taken at standard observation times and calculated with identical formulas (Robitzsch 1949; Rojecki 1959). To give the research background one also used daily values of air temperature and saturated vapour pressure (derived from temperature using modified Magnus formulas). To characterise the long-term variations one calculated linear trends of particular parameters. They were compared with atmospheric circulation variability described by simple circulation indices by Niedźwiedź (1981) inspired by earlier Murray and Lewis studies (1966). They describe predominant advection characteristics: progression index—P to define westerly zonal circulation intensity, meridional index—S to determine meridional advection and cyclonicity index—C to indicate prevalence of particular baric situation by using the abstract numbers that were sums of points assigned to each synoptic situation (Niedźwiedź 2007) in an analysed period. The relationships strength was defined by Pearson's correlation coefficient as well as coefficients of determination.

Although archival materials preserved in Kraków meteorological station are considered to be homogenous, measurements taken in the station are burdened with the rapid growth of the city. It makes possible to try to determine the impact of urbanised areas, which are characterised by specific types of development and urban land uses, on humidity conditions and thus to isolate the anthropogenic factor influencing changes in global climate. However, according to many researchers, this is not possible, since natural and anthropogenic influences overlap.

4 Results

4.1 Air humidity secular variability

The Clausius–Clapeyron relation explains exponential increase of the atmosphere water holding capacity with increasing temperature. For rising temperature and in the presence of limited water supplies (e.g. urbanised areas) specific humidity and vapour pressure will not increase much whereas an apparent decrease in relative air humidity as well as saturation deficit growth will be observed.

Rapidly increasing temperatures for the last 30 years of the twentieth century are the large-scale phenomena (Moberg et al. 2006) and one of the factors causing the warming effect is said to be urbanisation. In absolute terms (i.e. specific humidity) the significant global increase of atmospheric moisture has also been recorded since the 1970s (Willett et al. 2008). Although due to the surface warming the increasing moisture trends should also be detected, the constant growth of the city has contributed to the observed variability of locally dependent air humidity.

The temperature growth in twentieth century in Kraków reaches 1.5°C per 100 years; however, it is not a constant increase (Fig. 2). It needs to be emphasised that the last decades (from about 1971) were characterised by the growth of about 1.2°C per 30 years (3.9°C/100 years if maintained; Fig. 2). The tendency refers to both summer (JJA) and winter (DJF) temperatures. The long-term temperature variability implies, according to Clausiuis–Clapeyron relation, the significant increase of saturated vapour pressure (E). In the twentieth century in Kraków, together with the temperature growth, the 1.7 hPa/100 years increase of saturated vapour pressure value was marked (Fig. 2). In spite of the positive temperature tendency for all the seasons E demonstrated statistically significant variability only in summer (JJA) when high temperatures intensify the increase of the atmosphere water holding capacity. The observed extensure achieved in summer was 2.5 hPa/

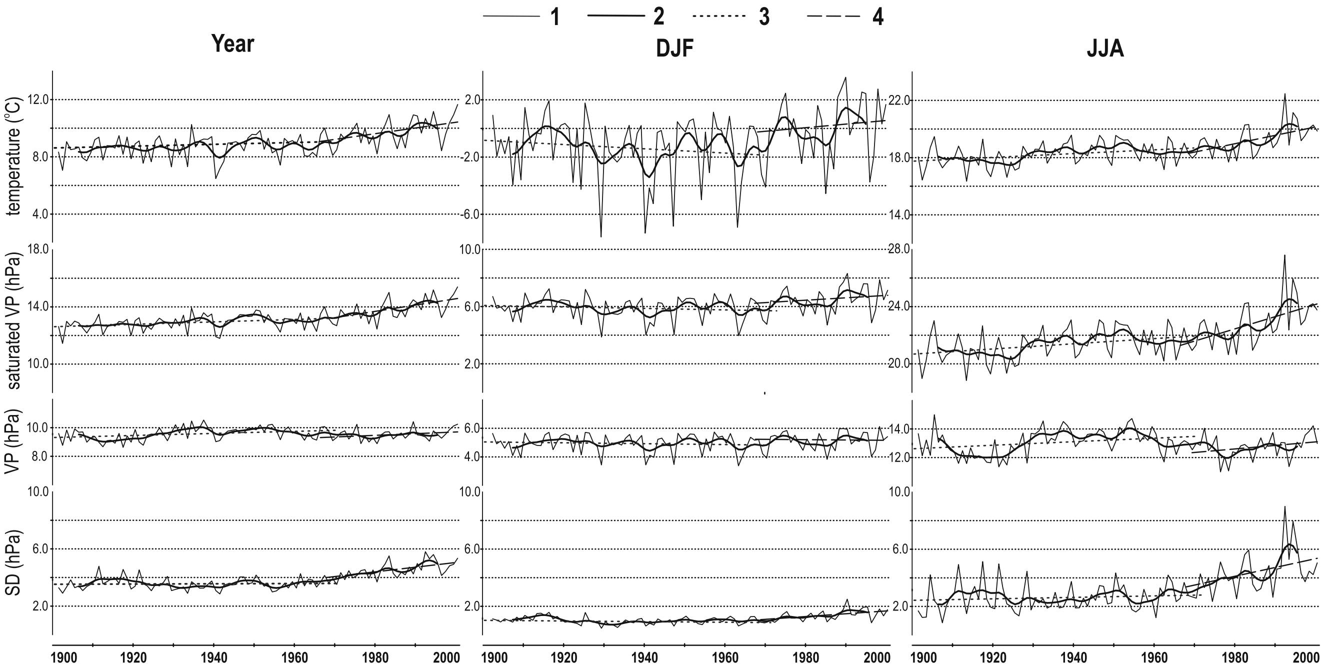


Fig. 2 Variability of selected climatological elements in Kraków (1901–2000). *1* element course, *2* 11-year Gauss pass-filter, *3* linear trend 1901–1970, *4* linear trend 1971–2000

30 years (for the period 1971–2000) with the after-effect of 8.5 hPa/100 years if maintained.

Limited water supplies connected with the progressive urbanisation in Kraków make surface evaporation constrained by reduced acreage of green as well as extended artificial areas might restrain the moisture complementation. To describe the amount of water vapour in the atmosphere and estimate the probable saturation shortage, vapour pressure as well as saturation deficit variability was carefully examined.

Long-term variation of vapour pressure in Kraków (1901–2000) corresponded with air temperature variation—r^2= 0.856 (Fig. 2); however, the observed increase was not statistically significant for α=0.05. The only more significant increase in values occurred in the period 1912–1937. Long-term variation lacked any well-defined periods with vapour pressure values significantly higher or lower than the mean (Wypych 2003). Values higher than the long-term mean were recorded in the middle of the century (1930–1960), while the lower ones occurred at the beginning of the century and in its last decades (Fig. 2).

The observed increase in temperature particularly in the last decades of the twentieth century is unfortunately not matched by the vapour pressure variability. There are no statistically significant changes for the period 1971–2000 (Fig. 2) neither for the summer (JJA) nor for winter (DJF) values. Moreover the decrease of the atmospheric water vapour content in Kraków is marked in winter months.

The described vapour pressure tendency together with growing temperature and consequently saturated vapour pressure values brings the apparent decrease in relative air humidity as well as saturation deficit growth.

The level of air saturation with water vapour is described by saturation deficit. It has been widely used especially in agrometeorology since the introduction of evapotranspiration indices. Long-term variation of air saturation deficit in Kraków showed a significant (at the level of α=0.05) upward trend. The increase in value over a multi-annual period amounted to 1.4 hPa per century (Fig. 2). A steady growth of saturation deficit has happened since the second half of the twentieth century. Annual means have exceeded the long-term mean (SDav=3.7 hPa) since 1971. The exception was 1980, when a slight decrease in saturation deficit occurred. The highest values (up to 6.0 hPa) were recorded in the last three decades (5.8 hPa in 1992) and departures from the mean reached +2.0 hPa. A considerable increase in saturation deficit in the period under discussion could be observed in summer (up to 3.0 hPa per century in August). In winter, long-term variations of saturation deficit had very low fluctuations (Wypych 2004).

Long-term humidity changes might be described also by frequency of particular saturation deficit values in distinguished (every 4.0 hPa) intervals (Fig. 3). The decrease in number of days with the lowest SD (≤4.0 hPa) as well as the increase of the highest values (>12.0 hPa) are statistically significant. Both tendencies are evident in the second half of the twentieth century (especially the last decades).

As it was mentioned the summer temperature did not show any well-marked trends in changes. However, a growing trend in the number of hot (t≥25°C) and very hot days was visible

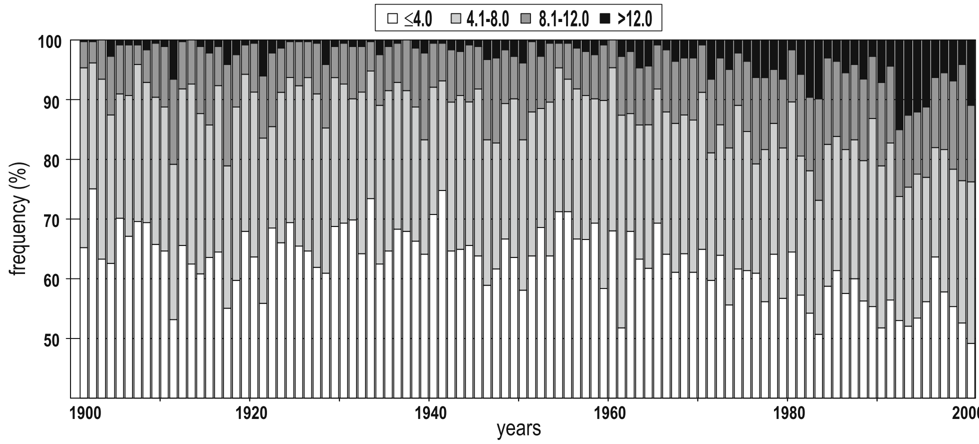


Fig. 3 Variability of annual frequency (%) of saturation deficit (SD) in defined intervals (hPa) in Kraków (1901–2000)

in Kraków and was statistically significant at the level of α= 0.05 what signified a growing dynamics of changes in air temperature during summer (Piotrowicz and Wypych 2006).

High humidity events described herein by vapour pressure values higher or equal than 18.8 hPa at least in one of the observation times—so called: sultry days according to Scharlau criteria (1950) are characterised by a significant year-by-year variability; however, there is no clear tendency in the long-term course (Fig. 4). The highest frequency characterised summer months: of all occurrences, more than 30% happened both in July and in August (with the increase of sultriness in August) and 18% in June. The days when sultriness persisted for the whole day are worth the special attention as they are considerably more taxing for human body. They do not occur in Kraków every year, however, during the last 30 years of the twentieth century their frequency increased and they appeared every summer, except for 3 years: 1976, 1983 and 1993.

To describe low humidity incidents saturation deficit values not lower than 10.0 hPa measured at midday observation time were espoused as high SD values are accompanied by intensive transpiration. The number of mentioned days shows year-by-year variability and the tendency of slight growth (17 days yearly per 100 years; Fig. 4). There are about 95 such days each year on average, however, the number balanced from 63 in 1941 up to 134 in 1983. The largest increasing tendency in air dryness has taken place in April and August since 1980.

4.2 Air humidity variability factors

Most of the recent climate change works confirmed the correlation between global circulation indices above Europe and the Atlantic and the air temperature and also between regional circulation and the air temperature (Kyselý 2008; Huang et al. 2006; Degirmendžić et al. 2004; Domonkos et al. 2003; Niedźwiedź 1993) and precipitation (Niedźwiedź et al. 2009; Huang et al. 2006; Degirmendžić et al. 2004; Trigo and DaCamara, 2000). The abovementioned results allow expecting that the variability of circulation indices had also an influence on humidity conditions.

The most intensive zonal westerly circulation marked at the beginning and on the turn of 1920s and 1930s. Visible density has been observed also since 1970s of twentieth century. Meridional circulation pattern was characterised by minor fluctuations. The highest indexes were recorded in second decade while at the end of previous century the more intensive northern advection was noticed.

The most evident changes of air humidity took place in summer when the circulation dynamics reaches definitely the minimum (Jacobeit et al. 2003; Ustrnul 1997; Bárdossy and Caspary 1990) and in spring. Although in winter, when

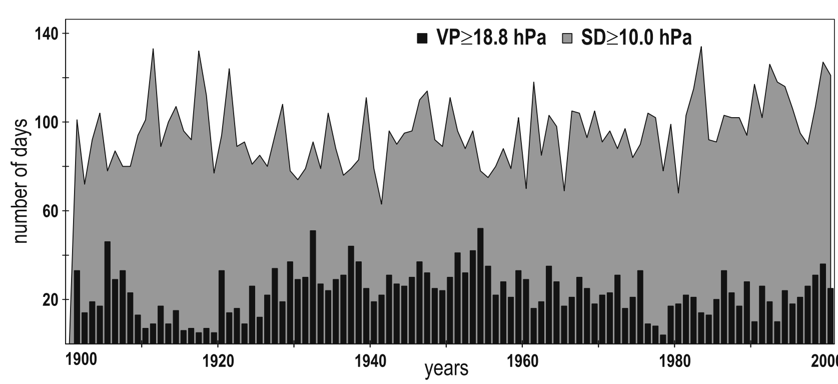


Fig. 4 Variability of annual number of sultry days (VP≥18.8 hPa) and days with SD≥10.0 hPa measured at midday observation time in Kraków (1901–2000)

the tendency in zonal westerly circulation intensity is the most noticeable—increase, no statistically significant trends in air humidity are observed.

The analysis of air humidity parameters variability and atmospheric circulation intensity relations (Table 1) proves the most significant correlation within the cold season of the year. Statistically significant, however weak, coherences between circulation types (both zonal and meridional) and air humidity in Kraków are observed in autumn (Table 1). Humidity conditions in winter months (December–February) are definitely under the influence of zonal westerly air mass advection what induces the increase of vapour pressure. Simultaneously the saturation deficit values increase as the warm Atlantic air masses make the air temperature and consequently the air capacity of water vapour increase. Regarding analysed classification calendar, correlation coefficients are statistically significant (α=0.05) but they do not achieve any high absolute values (Table 1).

5 Conclusions

Humidity has a reference for climate impact studies, i.e. bioclimatology and agrometeorology. At the surface water vapour is a climate variable that affects human comfort and health, surface evaporation and plants' transpiration (Dai 2006) especially in summer. Growing number of inhabitants in Kraków enforces studies connected with thermal and humid conditions to estimate the living comfort. High humidity (high air saturation) inhibits evaporation of perspiration and consequently body's ability to keep cool what may contribute to higher heat stress. However, low humidity (low air saturation) can also be a source of heat stress since dryness enhances the lung and upper air passage transpiration that makes the air even more dry as well as increases the effect of air pollution.

Air humidity is a meteorological element dependent on many factors, both atmospheric circulation and local. Analysis conducted to confirm the impact of global atmospheric circulation (zonal circulation above all) and the regional circulation over Southern Poland showed the significant but not very strong relation. They confirm 8% (on average) of air humidity changes in Kraków in the twentieth century and are strongly seasonally dependent: specified synoptic situations affect both low and high air humidity conditions. In the light of the described connections or even their deficiency while the air humidity characterised by the parameters describing air saturation (SD) shows the visible variability, it can be presumed that the probable causes of increasing dryness of the air in Kraków may have originated in the dynamic development of the city.

High air humidity at the beginning of the twentieth century was a result of the global circulation intensification

Table 1 Determination coefficients (r^2) of selected air humidity parameters and regional circulation indices by T. Niedźwiedź in Kraków (1901–2000)

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year	MAM	JJA	SON	DJF
VP	P	**0.49**	**0.44**	**0.13**	0.00	0.02	**0.19**	**0.14**	**0.16**	0.01	0.02	**0.06**	**0.35**	0.01	0.00	**0.10**	0.01	**0.48**
	S	0.00	0.02	**0.05**	**0.37**	**0.31**	**0.12**	0.02	0.03	**0.32**	**0.30**	**0.10**	0.01	**0.08**	**0.18**	0.03	**0.29**	0.01
	C	**0.05**	**0.06**	0.01	**0.05**	0.02	0.00	0.00	0.00	0.00	0.02	**0.17**	**0.13**	0.01	0.00	0.02	**0.07**	**0.05**
SD	P	**0.42**	**0.44**	**0.08**	0.00	0.00	0.02	**0.11**	0.02	0.04	**0.10**	**0.36**	**0.43**	0.01	0.00	**0.06**	**0.08**	**0.42**
	S	0.03	0.00	0.01	**0.12**	**0.12**	**0.06**	0.01	**0.11**	**0.08**	**0.09**	0.02	0.04	0.02	0.02	0.02	0.01	0.02
	C	0.02	0.00	0.02	0.01	0.04	**0.13**	**0.34**	0.02	**0.06**	0.01	0.10	**0.15**	0.00	0.00	**0.11**	0.01	0.00

Statistically significant values (α=0.05) bolded

P zonal circulation index, *S* meridional circulation index, *C* cyclonicity index (westerly circulation) and the local conditions: location in a weakly ventilated, damp Vistula river valley and limited air circulation due to deposition of thermal inversion layers in the concave terrain. Drying-up of the air in Kraków is connected with the temperature growth and proved by the values which occurred in the last 30 years of twentieth century especially in spring (April) and autumn (October). The gradual rise in the number of inhabitants and higher development density contributed to the decline in the city's air humidity (SD). After Second World War land improvement of waterlogged areas and expansion of industrial areas resulted in a significant drying of the city's air. Artificial heat emission into the atmosphere contributed to a rise in the dry day rate. Moreover, the expanding street network with streets and squares paved with concrete and asphalt and the city's growing buildings' density reduced the acreage of green areas in the city. This led to reduction of retention areas causing fast drainage of surface runoff as well as inhibiting evaporation and transpiration processes. The causes of changes in air humidity should be also attributed to natural factors, mainly to variation of air circulation reinforced by the operation of anthropogenic factors.

References

Aguilar E, Auer I, Brunet M, Peterson TC, Wierniga J (2003) Guidelines on climate metadata and homogenization. WMO, Geneva

Alexandersson H (1986) A homogeneity test applied to precipitation data. J Climatol 6:661–675

Bárdossy A, Caspary HJ (1990) Detection of climate change in Europe by analysing European atmospheric circulation patterns from 1881 to 1989. Theor Appl Climatol 42:155–167

Dai A (2006) Recent climatology, variability, and trends in global surface humidity. J Climate 19:3589–3606

Degirmendžić J, Kożuchowski K, Żmudzka E (2004) Changes of air temperature and precipitation in Poland in the period 1951–2000 and their relationship to atmospheric circulation. Int J Climatol 24(3):291–310

Domonkos P, Kyselý J, Piotrowicz K, Petrovic P, Likso T (2003) Variability of extreme temperature events in South-Central Europe during the 20th century and its relationship with large-scale circulation. Int J Climatol 23:987–1010

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson TC (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res 19:193–212

Gaffen DJ, Ross RJ (1999) Climatology and trends of US surface humidity and temperature. J Climate 12:811–828

Heino R (1994) Changes of relative air humidity in Finland. In: Heino R (ed) Climate variations in Central Europe, Proceedings of the European Workshop on Climate Variations, Finland, 314–320

Holmer B, Eliasson I (1999) Urban-rural vapour pressure differences and their role in the development of urban heat island. Int J Climatol 19:989–1009

Huang J, Mingxia JI, Higuchi K, Shabbar A (2006) Temporal structures of the North Atlantic Oscillation and its impact on the regional climate variability. Adv Atmos Sci 23(1):23–32

Huth R (2005) Downscaling of humidity variables: a search for suitable predictors and predictands. Int J Climatol 25:243–250. doi:10.1002/joc.1122

IPCC—Intergovernmental Panel on Climate Change (2007) Climate Change. Cambridge University Press, Cambridge

Jacobeit J, Wanner H, Luterbacher J, Beck C, Philipp A, Sturm K (2003) Atmospheric circulation variability in the North-Atlantic–European area since the mid-seventeenth century. Clim Dyn 20:341–352

Klein Tank AMG, Können GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. J Climate 16:3665–3680

Kożuchowski K, Trepińska J, Wibig J (1994) The air temperature in Cracow from 1926 to 1990: persistence, fluctuations and the urban effect. Int J Climatol 14:1035–1049

Kyselý J (2008) Influence of the persistence of circulation patterns on warm and cold temperature anomalies in Europe: analysis over the 20th century. Glob Planet Change 62:147–163

Lee DO (1991) Urban-rural humidity differences in London. Int J Climatol 11:577–648

Moberg A, Jones PD, Lister D, Walther A, Brunet M, Jacobeit J, Alexander LV, Della-Marta PM, Luterbacher J, Yiou P, Chen D, Klein Tank AMG, Saladié O, Sigró J, Aguilar E, Alexandersson H, Almarza C, Auer I, Barriendos M, Begert M, Bergström H, Böhm R, Butler CJ, Caesar J, Drebs A, Founda D, Gerstengarbe FW, Micela G, Maugeri M, Österle H, Pandzic K, Petrakis M, Srnec L, Tolasz R, Tuomenvirta H, Werner PC, Linderholm H, Philipp A, Wanner H, Xoplaki E (2006) Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. J Geophys Res 111:D22106. doi:10.1029/2006JD007103

Murray R, Lewis RP (1966) Some aspects of the synoptic climatology of the British Isles as measured by simple indices. Meteorol Mag 95:193–203

Mydel R (1994) Rozwój urbanistyczny miasta Krakowa po drugiej wojnie światowej, Kraków, 1–80 (in Polish)

Niedźwiedź T (1981) In: Rozprawy Habilitacyjne UJ (ed) Synoptic situations and its influence on spatial differentiation of selected climatic elements in upper Vistula basin, vol 58. Kraków, in Polish with English summary

Niedźwiedź T (1993) Changes of atmospheric circulation (using the P, S, C, M indices) in the winter season and their influence on air temperature in Cracow. In: Obrębska-Starklowa B (ed) Early meteorological instrumental records in Europe. Zesz. Nauk. UJ, Prace Geogr., 95:107–113

Niedźwiedź T (2007) Catalogue of synoptic situations and circulation indices in the upper Vistula river basin (1873–2007). Computer file available at Department of Climatology, University of Silesia, ul. Będzińska 60, PL 41-200 Sosnowiec, Poland: tadeusz.niedzwiedz@us.edu.pl

Niedźwiedź T, Twardosz R, Walanus A (2009) Long-term variability of precipitation series in east central Europe in relation to circulation patterns. Theor Appl Climatol. doi:10.1007/s00704-009-0122-0

Piotrowicz K (2007) Air temperature. In: Matuszko D (ed) Climate of Kraków. Instytut Geografiii Gospodarki Przestrzennej UJ, Kraków, pp 99–112, in Polish with English summary

Piotrowicz K, Wypych A (2006) Long-term variations in the number of hot, very hot and sultry days in Krakow. Papers on Global Change IGBP 13:43–58

Robaa SM (2003) Urban–suburban/rural differences over Greater Cairo, Egypt. Atmósfera 16:157–171

Robitzsch M (1949) Ausfürlische Tafeln zur Berechnung der Luftfeuchtigkeit, Leipzig

Rojecki A (1959) Psychrometric tables. Wydawnictwa Komunikacyjne, Warszawa (in Polish) Sharlau K (1950) Zur Einführung

eines Schwülemosstabes und Abgrenzung von Schwülezonen durch Isohygrothermen. *Erdkunde IV*
Štepanek P (2007) AnClim-software for time series analysis (for Windows). Dept. of Geography, Fac. of Natural Sciences, Masaryk University, Brno. 1.47 MB
Trepińska J, Kowanetz L (1997) Many years' course of mean monthly values of air temperature in Cracow (1792–1995). In: Trepińska J (ed) Fluctuations of climate in Cracow (1792–1995). Instytut Geografii UJ, Kraków, pp 99–130, in Polish with English summary
Trigo RM, DaCamara CC (2000) Circulation weather types and their influence on the precipitation regime in Portugal. Int J Climatol 20:1559–1581
Twardosz R, Niedźwiedź T (2001) Influence of synoptic situations on the precipitation in Kraków (Poland). Int J Climatol 21:467–481
Unger J (1993) The urban influence on the diurnal and annual patterns of absolute humidity in Szeged, Hungary. Acta Climatologica 27:33–39
Unger J (1999) Urban-rural air humidity differences in Szeged, Hungary. Int J Climatol 19:1509–1515
Ustrnul Z (1997) Variability of the atmospheric circulation on the Northern Hemisphere in the 20th century. Mat Badawcze IMGW Ser Meteorologia 27:1–208 (in Polish with English summary)
Wang JX, Gaffen DJ (2001) Late-twentieth-century climatology and trends of surface humidity and temperature in China. J Climate 14:2833–2845
Willett KM, Jones PD, Gillett NP, Thorne PW (2008) Recent changes in surface humidity: development of the HadCRUH dataset. J Climate 21:5364–5383. doi:10.1175/2008JCLI2274.1
Wypych A (2003) Vapour pressure variability in Cracow in the 20th century. In: Kłysik K, Oke TR (eds) Proceedings of 5th International Conference on Urban Climate, University of Łódź, vol 2, 479–482
Wypych A (2004) Variability of the air humidity in Kraków. PhD Thesis, Jagiellonian University Archives (in Polish)