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ORIGINAL PAPER

Long-term trend of surface relative humidity in Hungary

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Abstract

The long-term trends of relative humidity and its relationship with the long-term change of temperature are some of the unsolved problems of climate research. In this paper, the results of the analysis of long-term changes (1961–2020) in relative humidity and temperature in Hungary are presented. Homogenized station data series were used to perform the analyses. While warming was significant in each season, a significant reduction of relative humidity was observed only in spring and summer. The seasonal variability in the dependence of the change of relative humidity on the change of temperature indicates that the change of temperature directly impacts the change of relative humidity in summer, and the enhancement of evaporation due to the increase of temperature may mitigate the impact of warming in other seasons. Homogenized datasets were used to study the daily variation of the long-term trend of relative humidity. Significant reduction was found at noon in each season, except for autumn. However, the reduction was more scattered during the night, depending on the season and/or the geographical location of the station. The relationship between the surface data and data observed by radio sounding (00 UTC and 12 UTC in time period of 2007–2018) was studied to predict the long-term trends of relative humidity in the lower, 100-m deep layer of planetary boundary layer from the trend of surface relative humidity. The results suggest that this prediction can be reasonable only if daytime trends are considered.

1 Introduction

Water vapour is one of the most important components of the atmosphere. It impacts the hydrological cycle and the radiation budget of the atmosphere of Earth as well. Water vapour influences the global mean temperature because it is an infrared absorber and plays important role in cloud formation as well. Additionally, the latent heat released during condensation provides energy for the global circulation and mesoscale weather phenomenon.

Among earlier studies, the Third Assessment of the Intergovernmental Panel on Climate Change reported that the global average surface temperature rose by 0.6 ± 0.2 °C in the twentieth century (Daniel et al. 2001). Moreover, the warming in the Arctic region is being measured at two or three times higher than the global annual average of the warming (Masson-Delmotte et al. 2018). Results of climate model simulations suggest that the surface temperature increases more quickly over the land than over the oceans, and that the degree of warming is not uniform globally (Sutton et al. 2007). The moisture content of the atmosphere is significantly impacted by the climate change. The long-term characteristics of the moisture content like specific or relative humidity have been also studied. It has been assumed often that the relative humidity of the atmosphere has remained near-constant during global warming. Willett et al. (2008) asserted that if the relative humidity of the atmosphere remained quasi-constant and the temperature of the atmosphere increased, the moisture content of the atmosphere should be increased. They found that the largest increase of the moisture content likely occurred over warmer regions, especially where significant moisture supply was available. The long-term change of specific and relative humidity in the troposphere has also been studied. Peixoto and Oort (1996) analysed radiosonde dataset from the global network to study the pattern of relative humidity in the atmosphere. The highest and lowest relative humidity values were found near the equator and in the subtropical

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areas, respectively. Inhomogeneity of the relative humidity observed at the surface decreases with the increasing altitude. Water vapour in upper troposphere was found to play an important role in the longwave radiation budget of the Earth (Held and Soden 2000). Minschwaner and Dessler (2004) investigated the impact of surface temperature on vapour content in the tropical upper troposphere. They asserted that the increase of both moisture and temperature at the surface resulted in a decrease of relative humidity in the upper troposphere. Dai (2006) and Willett et al. (2008) found that the specific humidity of the atmosphere had increased over the studied period. Dai (2006) asserted that during the periods of 1976−2004, the global average of relative humidity changed by a few per cents near the surface; however, relative humidity decreased significantly over oceans and increased remarkably over the central and eastern part of the USA, India, and western China. Willett et al. (2008) assessed that during the periods of 1973–2003, the global average of relative humidity had not changed significantly; only some seasonal variation had occurred over the region of 60°N–40°S. Simmons et al. (2010) published a decreasing trend of relative humidity over low-latitude and mid-latitude continental areas during the period of 1998–2008. Their results based on the reanalyses of monthly anomalies of air temperature and humidity of European Centre for Medium-Range Weather Forecasts and on the analyses of monthly mean temperature and humidity observed by the Climatic Research Unit and Hadley Centre. They also found that changes in near-surface specific humidity over land and ocean were similar. Furthermore, they concluded that relative humidity over land should have decreased because the moisture supply from the ocean has become limited. This stems from the fact that evaporation from the ocean driven by the sea surface temperature is not followed in line with the increase of temperature over the continent.

Sherwood et al. (2010) asserted that forecasts of changes in relative humidity by general circulation models (GCMs) were in line with the world-wide temperature trend. Changes in relative humidity in the output of GCMs implied a decline in midlatitudes and tropical upper troposphere, and an increase around the tropopause. The authors suggested that the changes of relative humidity may be impacted by the changes in the climate features.

The AR5 of the IPCC presented the increasing trend of specific humidity near the surface and in the troposphere since 1970s (Stocker et al. 2013). However, it was also found that in the last several decades, the relative humidity has decreased significantly near the surface over the continents. Simmons et al. (2010) also emphasized the impact of relative humidity on the formation of precipitation. The relationship between air temperature anomalies and water vapour content for summer and winter seasons over northern Eurasia between 2003 and 2010 was studied by Ye et al. (2014). The authors asserted that the relationship between the precipitable water content and the amount of precipitation could be described by the prevailing positive correlation for winter: an increase in the precipitable water content by 1 kg m^{-2} results in a 26% increase in the average amount of winter precipitation. However, in summer, the relative humidity was found to have a significant influence on the amount of precipitation. They also found that 1% change of the relative humidity anomaly resulted in 8.9% change of the summer precipitation.

Analysis of the climate model simulations by Byrne and O'Gorman (2016) revealed a decreasing trend in relative humidity over continents, and a modest increasing trend over oceans. The authors ran a box model involving atmospheric moisture transport from the ocean to the land and surface evapotranspiration to explain the feature of relative humidity over land. They concluded that in the case of a significant positive temperature anomaly over the continents, the relative humidity decreased over land and changed only slightly over the ocean. Model simulations indicated that the evapotranspiration might play an important role in the change of relative humidity over the continents.

Numerous studies have been published to evaluate the changes of relative humidity due to climate change. The lack of the consensus about the long-term variation of relative humidity is well represented by the content of Table 1, which summarizes the conclusions of a number of reports.

The focus of this study is to determine the changes of humidity in the last decades in Hungary from various databases, and to reveal the differences between the tendencies. Furthermore, correlation between humidity at the surface and lower parts of the planetary boundary layer are also studied. The structure of the paper is as follows: Section 2 introduces the description of the dataset investigated and the methods applied. The results are presented in Section 3, and our conclusions are provided in Section 4.

2 Data and methods

The analysis of long-term relative humidity (hereafter RH) tendencies in Hungary is accomplished by using three different databases: (i) the station homogenized database (SHD_1) of daily average RH and daily average temperature are used to study the long-term changes; (ii) the station homogenized database (SHD_2) for RH observed at noon (12 UTC) and at midnight (00 UTC) is used to reveal the difference between nocturnal and daylight tendencies; (iii) the station raw database (SRD) is used to compare two different methods used for the evaluation of the daily average RH; (iv) the raw radiosonde database (RRD) is used to find the relationship between the RH at the surface and the RH at higher altitudes in the planetary boundary layer (hereafter

Table 1 Short summary of the assessments about the relative humidity

Name of the author(s)	Year of publication	Method of investigation	Long-term trend of relative humidity	Comment on the method
Gaffen and Ross[1]	1999.	Observation data	Increased (winter and spring)	Dataset: 1961–1995 for USA
Ingram[2]	2002.	Model simulation	Increased in the lower and decreased in the upper troposphere	General circulation model
Minschwaner and Dessler[3]	2004	Model simulation	Decreased in the upper troposphere	Single-column, radiative-convective model
Colman[4]	2004.	Model simulation for analysis of the water vapour feedback	Fixed and varying	Bureau of Meteorology Research Centre (BMRC model)
Soden and Held[5]	2006.	Model simulation	Constant	14 coupled ocean-atmosphere models with dataset based on the IPCC SRES A1B[a]
Vincent et al.[6]	2007.	Observation data	Decreased (winter and spring)	Dataset: 1953–2005 for Canada
Ajileye[7]	2016.	Observation data	Negative trend	Dataset: 1983–2005 to compare with 2008–2013 data for Nigeria
Byrne and O'Gorman[8]	2018.	Observation data	Decreased over continents (between 40° S and 40°N)	Dataset: HadISDH
Liu et al.[9]	2018.	Observation data	Decreased	Dataset: 1970–2010 for Yangtze River Delta (China)
Tzanis et al.[10]	2019.	Reanalysis	Depending on seasons and locations	Dataset: 1979–2017 ERA-Interim reanalysis

[a]Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC), IPCC Special Report on Emissions Scenarios (SRES) A1B scenario

[1]Gaffen and Ross (1999)

[2]Ingram (2002)

[3]Minschwaner and Dessler (2004)

[4]Colman (2004)

[5]Soden and Held (2006)

[6]Vincent et al. (2007)

[7]Ajileye et al. (2016)

[8]Byrne and O'Gorman (2018)

[9]Liu et al. (2018)

[10]Tzanis et al. (2019)

PBL). All the data was provided by the Hungarian Meteorological Service (HMS).

The SRD contains data (air temperature, RH, and pressure without homogenization) in a time period from 1956 to 2019 with 6-h time resolution, and they are available at 8 meteorological stations (Fig. 1). The SHD_1 and SHD_2 covers a time period from 1961 to 2020. These databases include daily average RH and daily average temperature data, in addition to data concerning RH observed at 00 and at 12 UTC, respectively. The SHD_1 and SHD_2 are available at 9 stations (Fig. 1).

The locations of meteorological stations represent different geographical landforms (Cséplő et al. 2019). The stations in Budapest, Debrecen, Keszthely, Nyíregyháza, Szeged, and Túrkeve are located in the plains. Stations in Szombathely, Pécs, and Miskolc represent hilly areas. The data observed at Keszthely must have been affected by the nearby lake Balaton.

Homogenization method (Szentimrey 2013) is used to eliminate the potential error caused by the different locations of the stations in addition to the measurement frequency, methods, or instruments. The long-term changing of humidity and temperature is studied for seasons such as winter (DJF), spring (MAM), summer (JJA), and autumn (SON) using the daily mean values; furthermore, the trends of RH observed 00 and 12 UTC are analysed. This analysis is performed by using homogenized data of RH for 00 and 12 UTC. The reference period for the assessment of the long-term climatic anomaly is 1961–1990 (World Meteorological Organization 2017).

Long-term tendency of the relative humidity in the lower region of the boundary layer was also studied for a 10-year

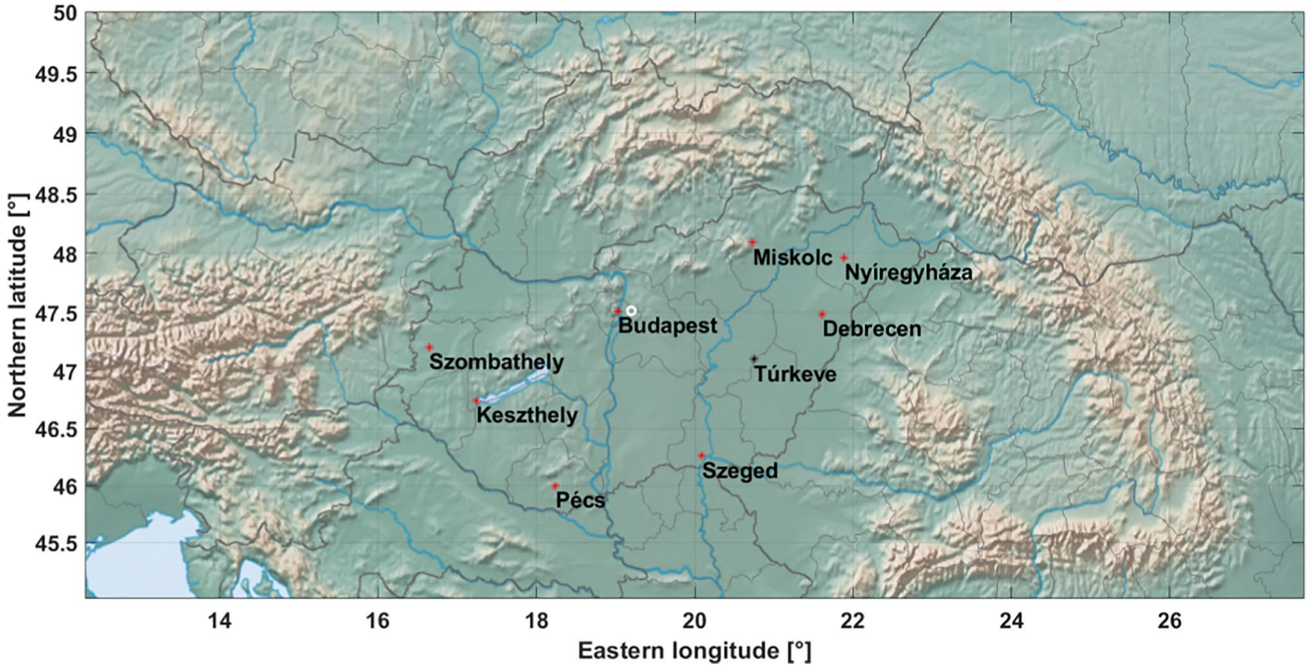


Fig. 1 Location of the meteorological stations. Red asterisks denote stations where both SHD and SRD are available. Only SHD is available for the station at Túrkeve denoted by black asterisk. The sounding station is denoted by an open circle

period (2007–2018). Temperature, pressure, and dew point temperature data at 00 and 12 UTC over Budapest were retrieved from the radio sounding database (RRD). The RH was evaluated at two different altitudes above the surface (50 m and 100 m). The reason for the selection of a shorter time period is that no homogenization method is available for the sounding data, and the type of instruments used for radio sounding had been changed many times in the past. However, since 2007, the same type of instrument (Vaisala AS41, Vaisala Oy, Vantaa, Finnland) has been used. We hypothesize that strong correlation between the RH observed at the surface and at higher elevations allows to extend the time period for the trends of the RH in the lower level of the PBL.

3 Results

3.1 The impact of data averaging techniques

For the climate reports, the daily mean RH has been evaluated by averaging the RH data observed four times a day (hereafter AV1 method):

$$\overline{RH_1} = \frac{1}{4}\sum_{i=1}^{4} RH_i \qquad (1)$$

where RH_i is RH observed at 00:00, 06:00, 12:00, and 18:00 UTC. The issue with this method is that the RH is not a conservative variable, so it is not easy to interpret the physical meaning of this arithmetic average value. Peixoto and Oort (1996) asserted that the evaluation of the daily mean RH using daily average vapour content and daily average temperature (Eq. 2) was more reasonable (hereafter AV2 method):

$$\overline{RH_2} = \frac{\overline{q}}{q_s\left(\overline{T},\overline{P}\right)} \qquad (2)$$

where $\overline{q} = \frac{1}{4}\sum_{i=1}^{4} q_i\left(RH_i, T_i, P_i\right), \overline{T} = \frac{1}{4}\sum_{i=1}^{4} T_i$ and $\overline{P} = \frac{1}{4}\sum_{i=1}^{4} P_i$.

q_i is the specific humidity evaluated from the observed RH, temperature, and pressure. T_i and P_i are the observed temperature and pressure, respectively. q_s means the calculated value of the daily average saturation specific humidity.

In the next part of this section, the comparison of the results calculated by these two methods is presented. Both of the above mentioned daily average RH-s were calculated using SRD for the four different seasons and at each meteorological station. The uncertainty of the evaluation of the long-term changes of the RH is determined by comparing the two different daily averages. The histograms in Fig. 2 depict the relative frequency of differences in the RH calculated by the two methods:

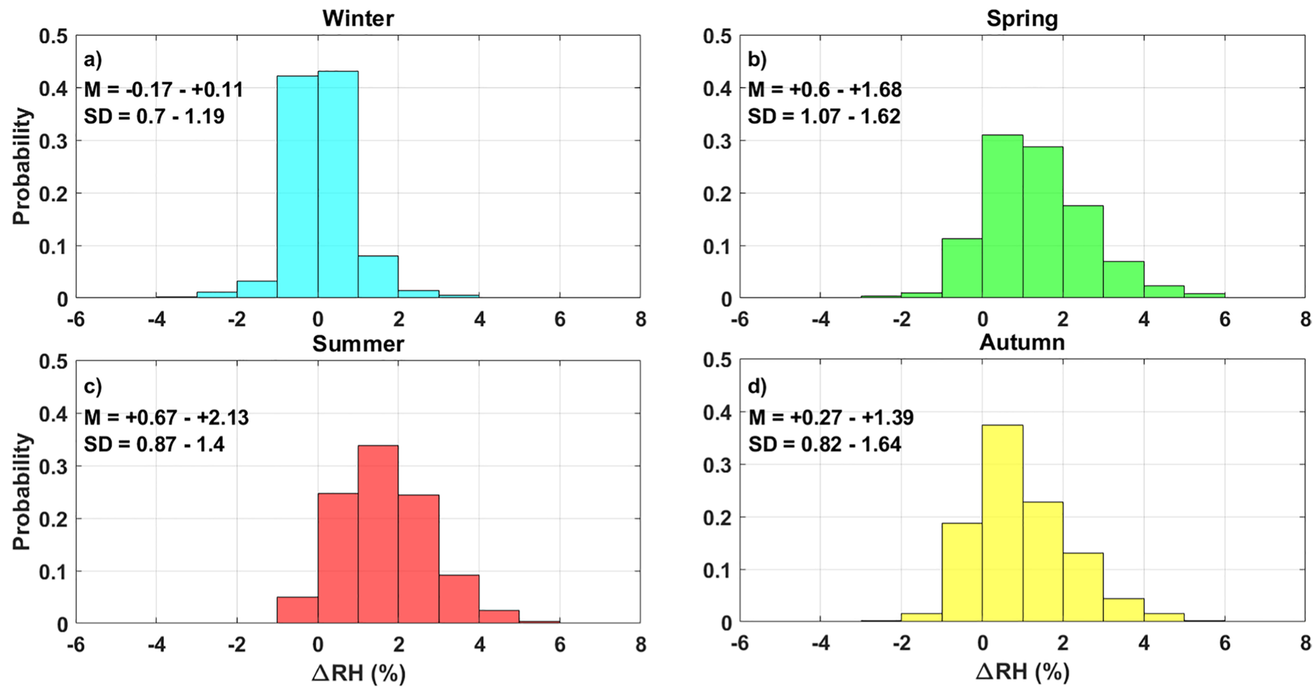


Fig. 2 The empirical probability density functions for difference between relative humidities (ΔRH) calculated by the two different averaging techniques of AV1 and AV2. The histograms reveal the results by analysing the data observed at the Budapest station in the time period of 1961 – 2020. The panels indicate the different seasons: winter (**a**), spring (**b**), summer (**c**) and autumn (**d**). The bin width is 1%

$$\Delta RH = \overline{RH}_1 - \overline{RH}_2 \tag{3}$$

In the case of the Budapest station, the mean and the standard deviation of ΔRH are 0.106, 1.34, 1.666, 0.974 and 0.842, 1.275, 1.124, 1.205, respectively for winter (panel a), spring (panel b), summer (panel c), and autumn (panel d). The plots are similar for other stations. In the case of winter, the daily average of RH depends only slightly on the applied averaging method. (The mean values of ΔRH are in a narrow range around zero, and the standard deviations for ΔRH are less than 1% in this season.) In the other seasons, the difference between the two methods is systematic. The AV1 method gives systematically larger daily average RH than the AV2 one does. (The mean values of ΔRH are between 0.2 and 3.0.) The relative frequency of the ΔRH in the interval of 3–4% is still significant in these seasons. The reason why the bias depends on the season is not clear. We presume that the smaller daily variability of both the specific humidity and the temperature during the winter may explain the smaller bias in this season.

3.2 Daily average relative humidity trend for the time period of 1961–2020

The anomalies of the seasonally averaged daily average RH and the daily average temperature for the Budapest station are plotted in Figs. 3 and 4, respectively. SHD_1 is used to predict the long-term deviation from the average value in the reference period. (In this database, the daily average RH is calculated by the AV1 method discussed in the previous section.) The reference period of 1961–1990 is chosen to evaluate anomalies. While the frequency and magnitude of the positive anomaly in the case of temperature are rather unambiguous in the last decades (except autumn), the tendency of the RH is not as straightforward. Larger fluctuations in both the positive and negative directions occur in winter (Fig. 3a) and autumn (Fig. 3d). Significant negative anomalies for RH happen in spring (Fig. 3b) and summer (Fig. 3c). While long-term trends of the temperature anomaly are similar at the different stations, the long-term trends of RH show larger diversity, mostly in winter and autumn.

Figures 5 and 6 depict the predicted long-term changes (60 years) in RH and temperature. These anomalies are evaluated using linear regression on seasonally averaged daily average temperature and RH. Hypothesis testing of z-probe is used to calculate the significance of the long-terms changes. The null-hypothesis in this test is that the deviation of the calculated anomaly from the values representing the reference time period is equal to zero. The symbols *, **, and *** in Figs. 5 and 6 mean 1, 5, and 10% of significance level, respectively. The null-hypothesis can

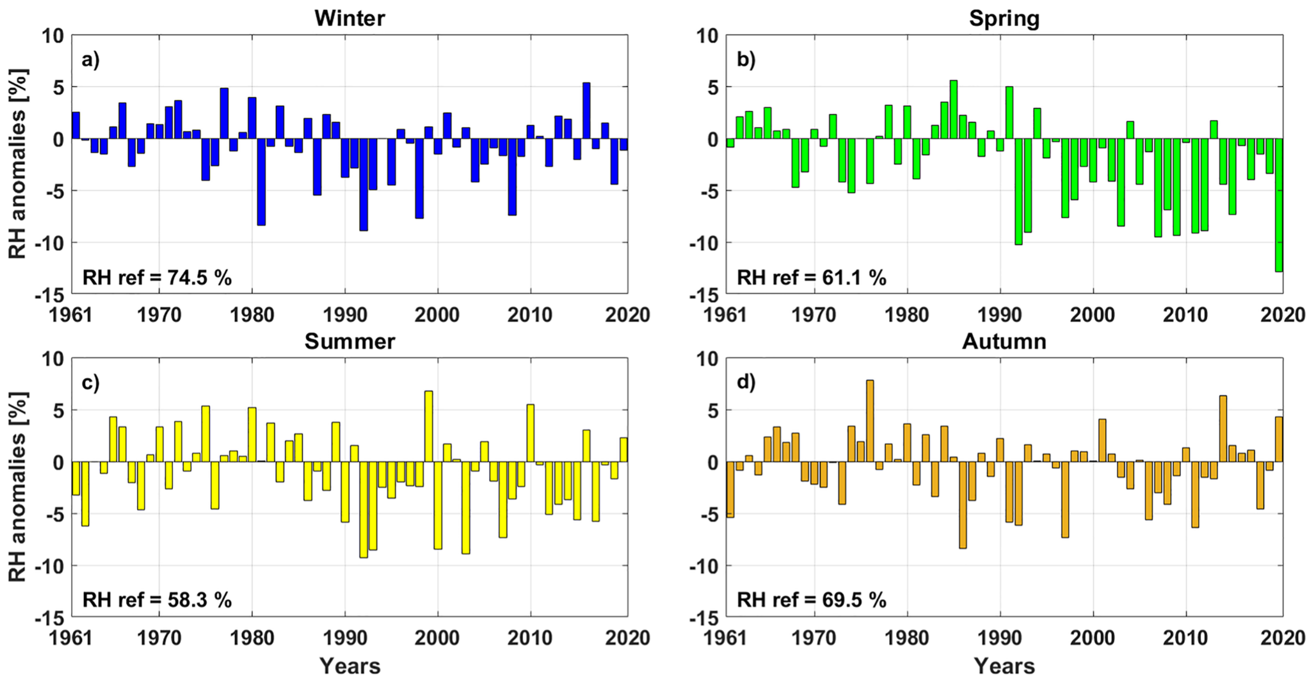


Fig. 3 The anomalies of the RH values in the time period of 1961-2020 compared to the reference period of 1961-1990 in different seasons of: winter (**a**), spring (**b**), summer (**c**) and autumn (**d**) at the Budapest station. RH ref means the average value corresponding to the reference period

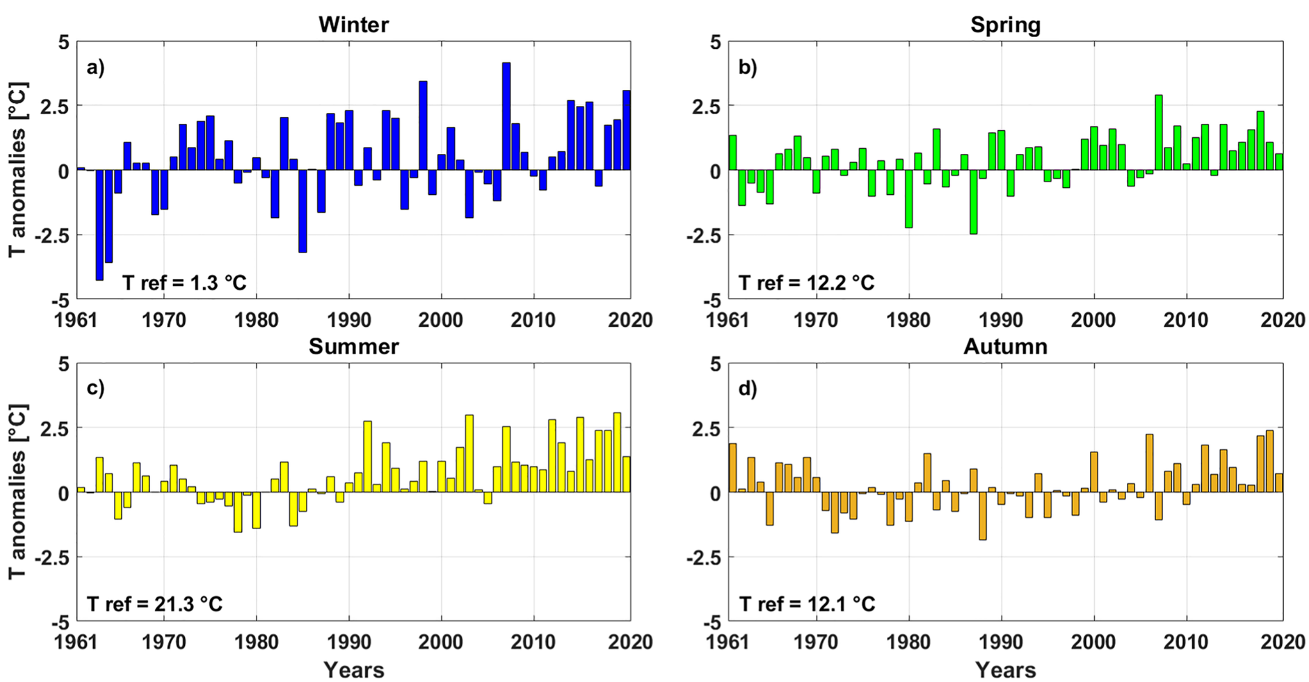


Fig. 4 The anomalies of the temperature values in the time period of 1961-2020 compared to the reference period 1961-1990 for different seasons of: winter (**a**), spring (**b**), summer (**c**) and autumn (**d**) at Budapest station. T ref means the average value corresponding to the reference period

Fig. 5 The long-term predicted anomaly of the RH by seasons for different meteorological stations by the end of the time period of 1961–2020. The symbols above each column denote the significant levels evaluated by z-probe. The data from different surface stations are depicted by columns with different colours

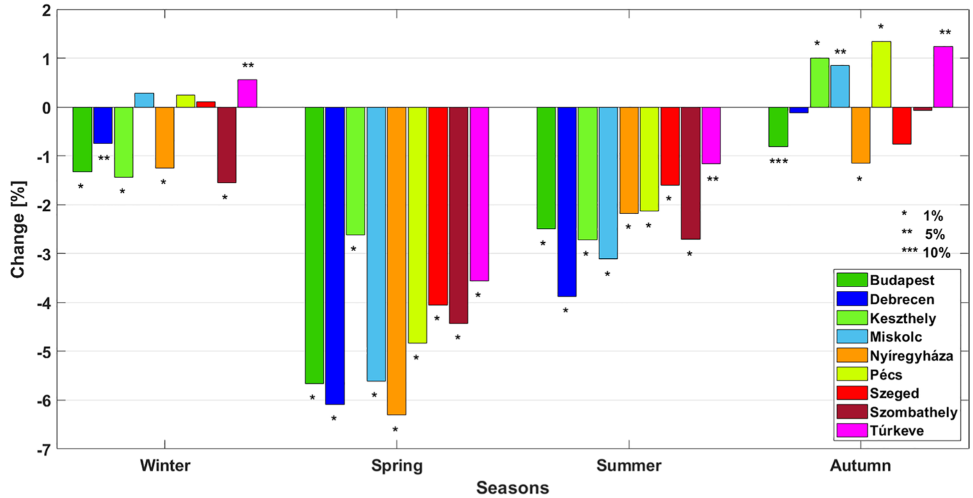
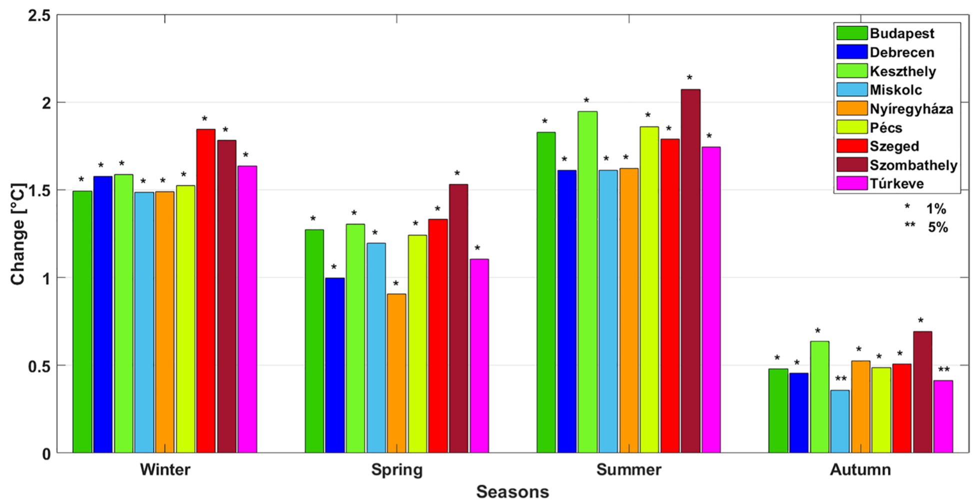


Fig. 6 The long-term predicted anomaly of temperature by seasons at different meteorological stations by the end of time period of 1961–2020. The symbols above each column denote the significant levels evaluated by z-probe. The data from different surface stations are depicted by columns with different colours



be accepted with a significance level larger than 10% in the case of the columns without symbols. If a significance level of 5% is chosen to accept the null-hypothesis, the following characteristics are revealed by the histograms:

(i) The decrease of RH is significant in spring and summer at each station. During the autumn and winter, there are no obvious trends about the changes of RH, even the signs of the changes can be different at different stations.
(ii) Significant warming has been occurred at every station in each season. The magnitude of the changes in temperature is almost the same at each station in winter, spring, and summer. Notable relative difference among the stations is revealed only in autumn.
(iii) The change of RH is more dependent on the location of the station, and the seasonal variability is also apparent. Although the sign of changes is negative in spring and summer at each of station, the magnitudes of the change are more scattered. The ratio of the smallest and largest values is larger than 2 and 3 in spring and summer, respectively. In winter and autumn not only does the magnitude of the predicted anomaly vary significantly from station to station, but both the negative and positive signs of the changes are equally frequent. In these two seasons, the null-hypothesis cannot be rejected at several stations.
(iv) Comparing the predicted seasonal anomaly of RH and temperature, it is not self-evident that the change of RH near the surface can be explained only by the warming of the atmosphere.

The value of the RH is impacted by a number of different atmospheric processes. However, these processes can have an influence on the vapour content, the temperature, or both. Using the definition of RH the time derivative of the relative humidity can be written as follows:

$$\frac{1}{RH}\frac{\Delta RH}{\Delta t} = \frac{1}{q_v}\frac{\Delta q_v}{\Delta t} - \frac{L_v}{R_v T^2}\frac{\Delta T}{\Delta t} \quad (4)$$

where ΔRH, Δq_v, and ΔT are the changing of the seasonal average RH, specific humidity, and temperature between the two subsequent years, respectively. ($\Delta t = 1$ year) RH, q_v, and T are the seasonal average RH, specific humidity, and temperature, respectively. L_v and R_v are the latent heat of condensation and the gas constant for vapour, respectively.

The term on the lhs of Eq. 4 means the relative change of RH. The first and second terms on the rhs of Eq. 4 describe the impact of the change of specific humidity and the change of temperature, respectively. The relationship between the change of RH and the change of temperature is studied by using the SHD_1 for all stations and for each season (Fig. 7). The x and y variables in Fig. 7 are as follows:

$$x = \frac{1}{T^2}\frac{\Delta T}{\Delta t} \text{ and } y = \frac{1}{RH}\frac{\Delta RH}{\Delta t}$$

We hypothesize that a change of temperature results in the change of RH, and the first term on the rhs of Eq. 4 does not depend on the change of temperature. Eq. 4 suggests that the slope of the fitted linear equation should be close to −5500 (the ratio of L_v and R_v). The analysis of the data about the linear regressions indicates that the correlation is highest and the slope of the fitted line is nearest the theoretical value in summer (Fig. 7c). This means that the change of temperature not only explicitly impacts the change of RH, but the first term on rhs of Eq. 4 implicitly depends on the change of temperature due to the temperature dependence of evaporation from the surface. The weak correlation and the significant deviation of the value of slopes from the theoretical value occur in the seasons of winter and autumn (Fig. 7a and d).

Long-term changes of the RH observed at 00 UTC and at 12 UTC are depicted in Figs. 8 and 9, respectively. A linear regression method was used to predict the RH anomaly representing nocturnal and daylight time periods. (The SHD_2 was used for this analysis.) The decreasing trend is significant in spring and summer at most of the stations; furthermore, the sign and the magnitude of the anomaly are ambiguous in autumn and winter at night. The trends of the RH anomaly at 12 UTC are regressive in each season, except for autumn. These changes are more evident than changes in the nocturnal period. The decline of RH is significant in spring both at 00 and 12 UTC. The plots in Fig. 8 suggest that the topography and the type of land use can significantly impact the trend of nocturnal RH. An obvious example for this impact is the exceptionally small value of the anomaly in spring at Keszthely, while at other stations, significant reduction occurs in this season. The plots for summer also reveal the inconsistency among the predicted anomalies belonging to different geographical locations. The reason for this variability is not clear. The RH may be impacted by the nearby lake Balaton in the case of Keszthely. The wide scatter of the predicted

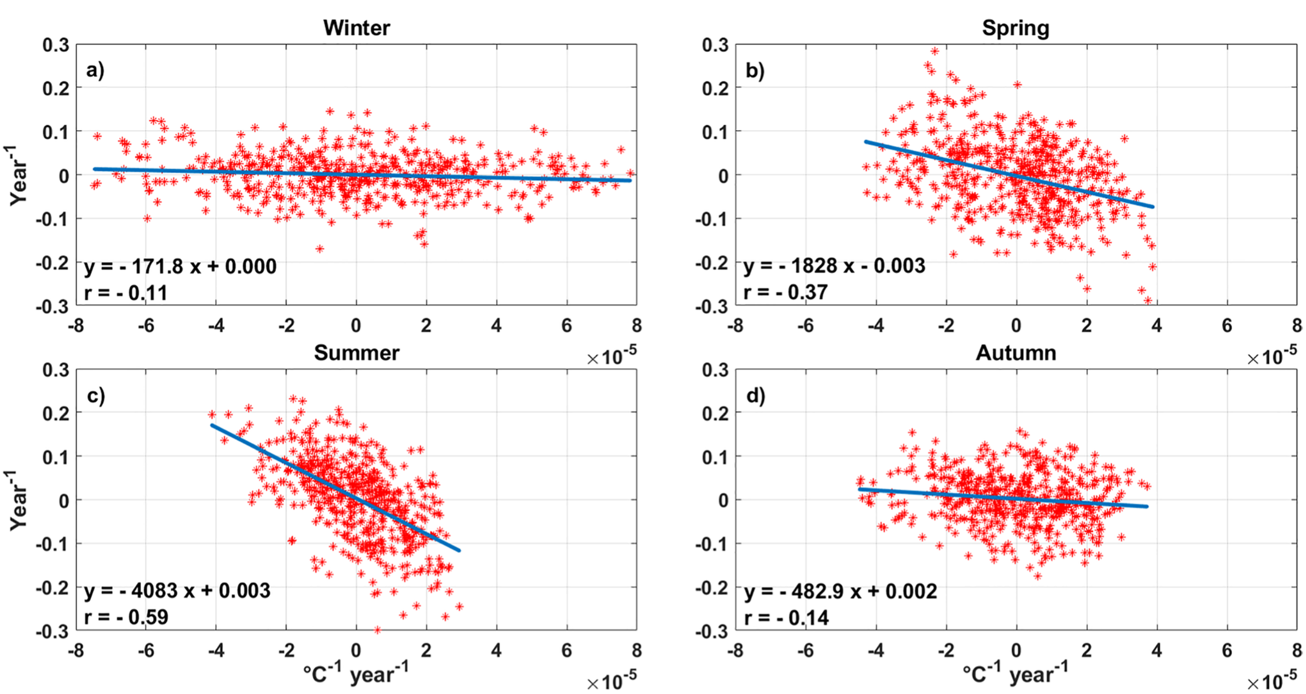


Fig. 7 The correlation between the change of RH and the change of temperature by seasons of winter (**a**), spring (**b**), summer (**c**) and autumn (**d**). The regression lines are plotted (blue, solid lines), along with the equation of regression lines and correlation coefficients provided in each panel

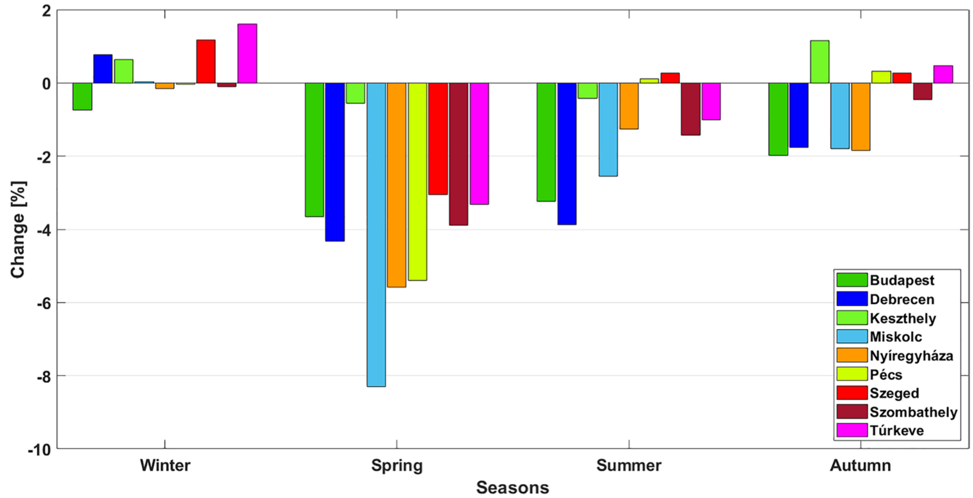


Fig. 8 The long-term predicted anomaly of RH at 00 UTC by seasons at different meteorological stations by the end of the time period of 1961–2020. The data for different surface stations are depicted by columns with different colours

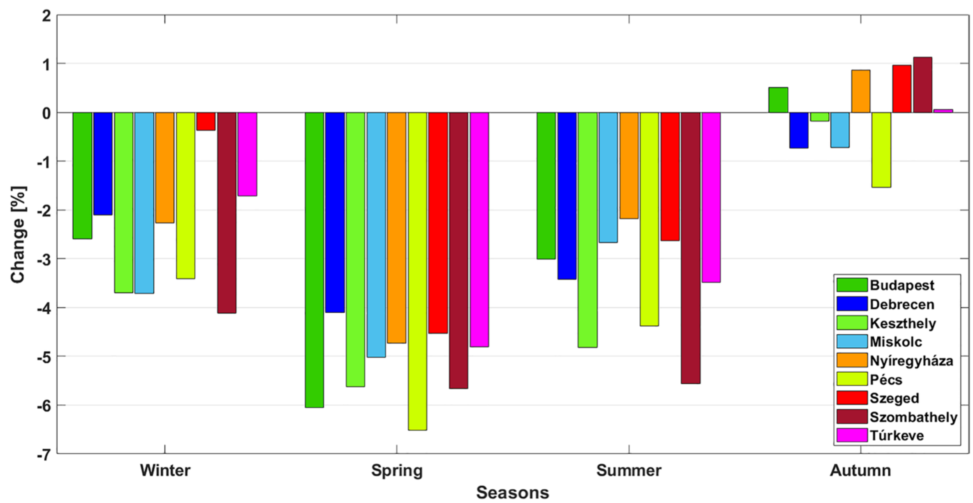


Fig. 9 The long-term predicted anomaly of RH at 12 UTC by seasons at different meteorological stations by the end of time period of 1961–2020. The data for different surface stations are depicted by columns with different colours

anomalies during the night in summer can be related to the impact of urban heat islands at some of the stations. The role of the urban heat island in the change of relative humidity anomaly at night needs further study.

3.3 Trends of relative humidity at levels near the surface

The cloud or fog formation is impacted by the moisture content and temperature of the atmosphere near the surface. Clouds form due to the vertical transportation of moisture from this layer, and the fog forms due to the condensation of vapour. Unfortunately, there is no available homogenized radio sounding data to predict the tendencies over a longer time period in the atmosphere. In this section, the correlation between the surface RH and RH at 100 m and at 50 m above the surface is evaluated. If strong correlation is found between the surface RH and RH observed at the different altitudes of 50 and 100 m, the results about the long-term changes for the surface RH can be generalized to predict the long-term change of RH in the atmosphere in the layer near the surface. The predicted changes at surface and at the two different altitudes are retrieved from SRD and RRD fitting linear equations on the data, respectively (Note that no reference period is defined for this short time period.). The lack of homogenization may not result in false conclusions in this case, because both the location of the observations and the type of the instruments for sounding and surface observation have remained unchanged in the time period of 2007–2018.

Figure 10 reveals the predicted changes of RH at different altitudes at the Budapest meteorological station. The positive sign of the predicted change of RH at the surface in the time period of 2007–2018 seems to contradict the long-term predicted changes (Figs. 5, 8, and 9). (Note that the data analysed here is only a subset of the data analyzed in the previous section.) While the trend for the surface RH is rather obvious and does not depend on the time of day and the seasons, at altitudes of 50 and 100 m the

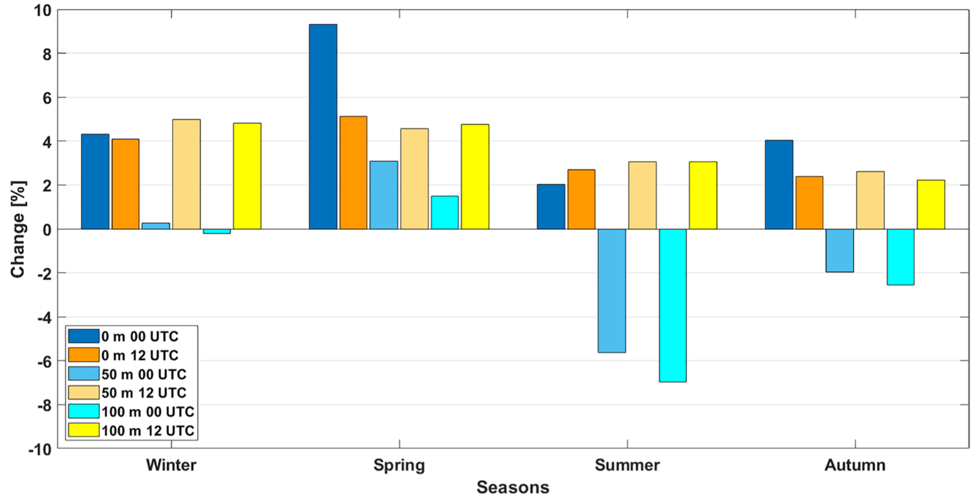


Fig. 10 The predicted changes of RH at different levels by seasons at the Budapest meteorological station between 2007 and 2018. The data for different surface altitudes of 50 and 100 m are depicted by columns with different colours

pattern is not so evident. While the trends at these altitudes at 12 UTC are the same as at the surface, at midnight, the magnitudes and/or the sign of trends are significantly different from the corresponding values at the surface.

Scatter plots with linear regression in Figs. 11 and 12 depict the correlation between the observed data (temperature and RH) measured at surface and the altitudes of 50 and 100 m for the time period of 2007–2018. The specific humidity (Fig. 13) was evaluated from data about the temperature and RH. The plots are in line with the theory of the daily evolution of the PBL (Stull 1988):

(i) The temperature profile close to the surface is near dry adiabatic at noon (see the interception parameters of the linear equations in panels b and d in Fig. 11). The frequency of the occurrence of temperature inversion near the surface is high at midnight. The temperature gradient is predominantly between +1 and +5 °C/100 m.

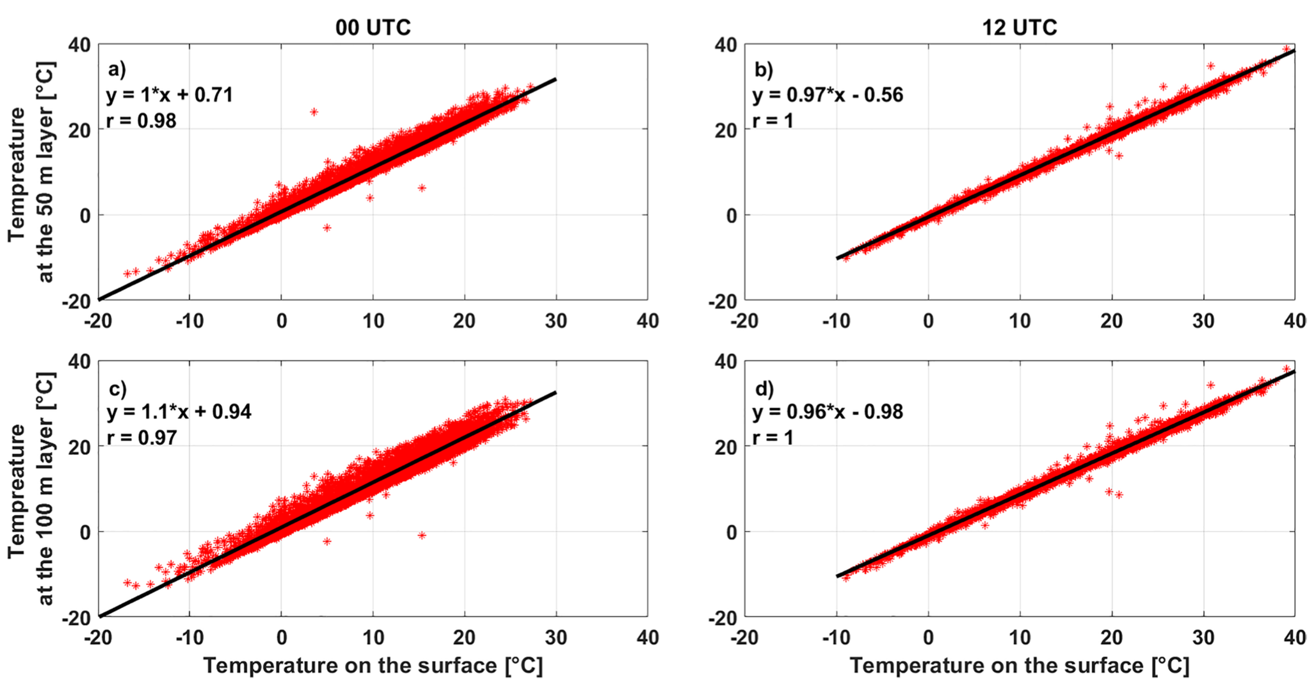


Fig. 11 Scatter plots about the relation between the surface temperature values and temperatures observed at altitudes of 50 and 100 m at 00 and 12 UTC. The panels depict the temperature data at different time of a day (in columns) at different altitudes (in rows). The data was measured at the Budapest meteorological station in the time period of 2007 - 2018. The regression lines are plotted (black, solid lines), and the equation of regression lines and correlation coefficients are given in each panel as well

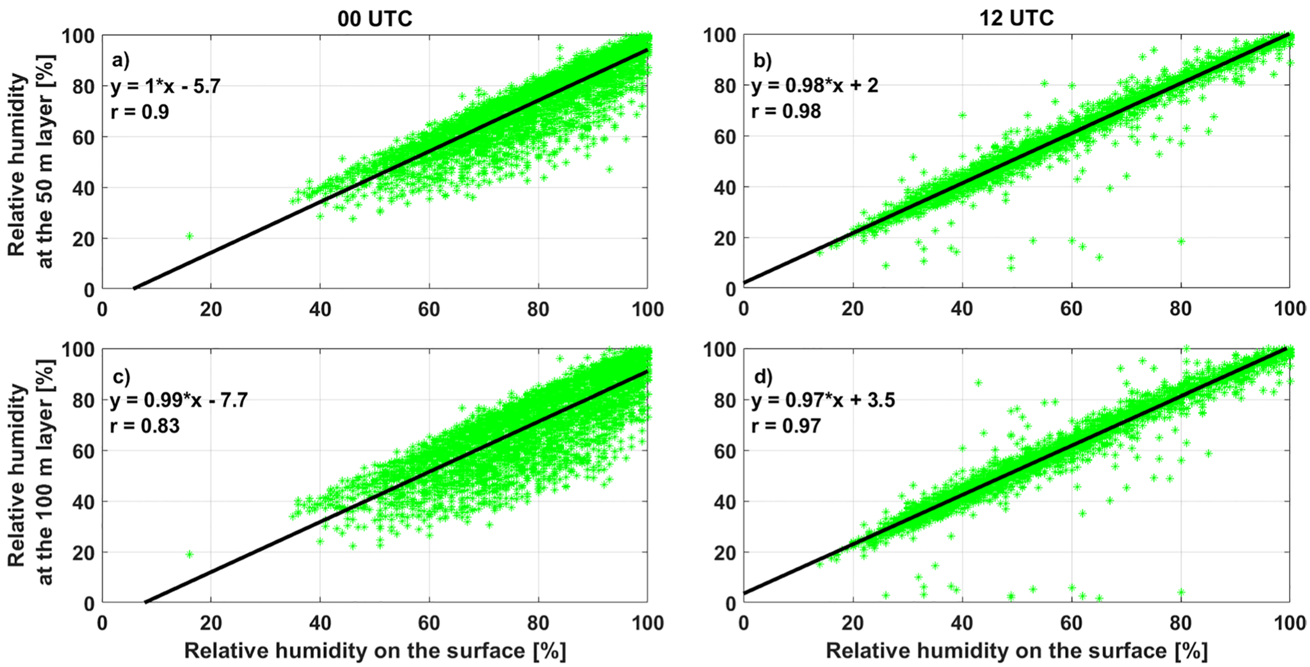


Fig. 12 Scatter plots about the relation between the surface RH and RH observed at altitudes of 50 and 100 m at 00 and 12 UTC. The panels depict the relative humidity data at different time of a day (in columns) at different altitudes (in rows). The data was measured at the Budapest meteorological station in the time period of 2007 - 2018. The regression lines are plotted (black, solid lines), and the equation of regression lines and correlation coefficients are given in each panel as well

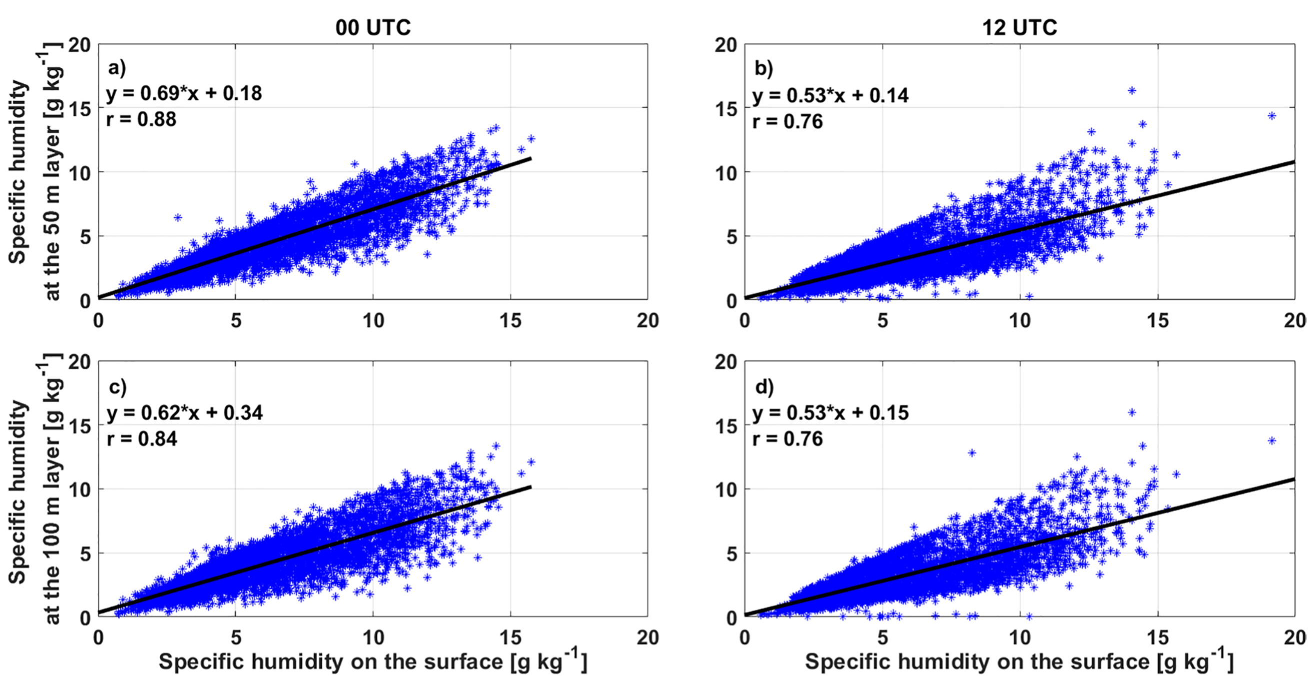


Fig. 13 Scatter plots about the relation between the surface specific humidity values and specific humidity at altitudes of 50 and 100 m at 00 and 12 UTC. The panels depict the specific humidity data at different time of a day (in columns) at different altitudes (in rows). The specific humidity values were evaluated from the temperature and RH measured at the Budapest meteorological station in the time period of 2007 - 2018. The regression lines are plotted (black, solid lines), and the equation of regression lines and correlation coefficients are given in each panel as well

The correlation is weaker in the case of specific humidity compared to temperature data, but it is still significant in the range of 0.76–0.88 (Fig. 13). The specific humidity is higher at the surface than above both at noon and midnight. However, above the surface, the vertical profile of specific humidity depends on the time of day. During the daytime, the atmosphere seems to be well mixed with respect to vapour content between altitudes of 50 and 100 m. (The equations of the fitted lines are almost the same in Fig. 13b and d.) As a result of the less efficient mixing (or because the top of the PBL can be lower than 100 m during the night), the specific humidity is slightly smaller at the level of 100 m than at the level of 50 m. The RH is determined by the temperature and the specific humidity, so its profile is impacted by these two parameters. At noon, the magnitude of RH is approximately the same at each investigated level from the surface to the altitude of 100 m. This stems from the fact that the decrease of the specific humidity is compensated for by the decrease of temperature. At night, the decrease of the RH with altitude is conspicuous. The increase of temperature and the decrease of specific humidity together result in significant decrease of RH with the increasing altitude. The correlation between RH at the surface and RH at two different altitudes is rather strong at noon and weaker, but still strong at midnight.

(ii) The scatter plots of the dots around regression lines (residuals) suggest that the temperature and RH vertical gradients vary in wider interval at 00 UTC than at 12 UTC. This is confirmed by preparing histograms to reveal the relative frequency of the gradients (not shown). While the frequency of the values near the dry adiabatic gradient is dominant in the case of temperature data at noon, the gradients at midnight scatter in a significantly wider range (the mode of the distribution is around 0 to −1 °C, the average value is 1.5–2 °C, and the standard deviation is between 2 and 3 °C).

The data about RH is separated into seasonal subsets. The results of the analysis of the scatter plots in Figs. 14 and 15 can be summarized as follows:

(i) The correlations between the RH observed at the surface and at different altitudes are significantly stronger at 12 UTC than at 00 UTC in each season (panel e, f, g, and h in Figs. 14 and 15). As it can be expected, the correlation between the surface RH and RH at 50 m is stronger than between the surface RH and RH at 100 m.

(ii) The seasonal change of correlation coefficients is small in the case of the 12 UTC data, and they show

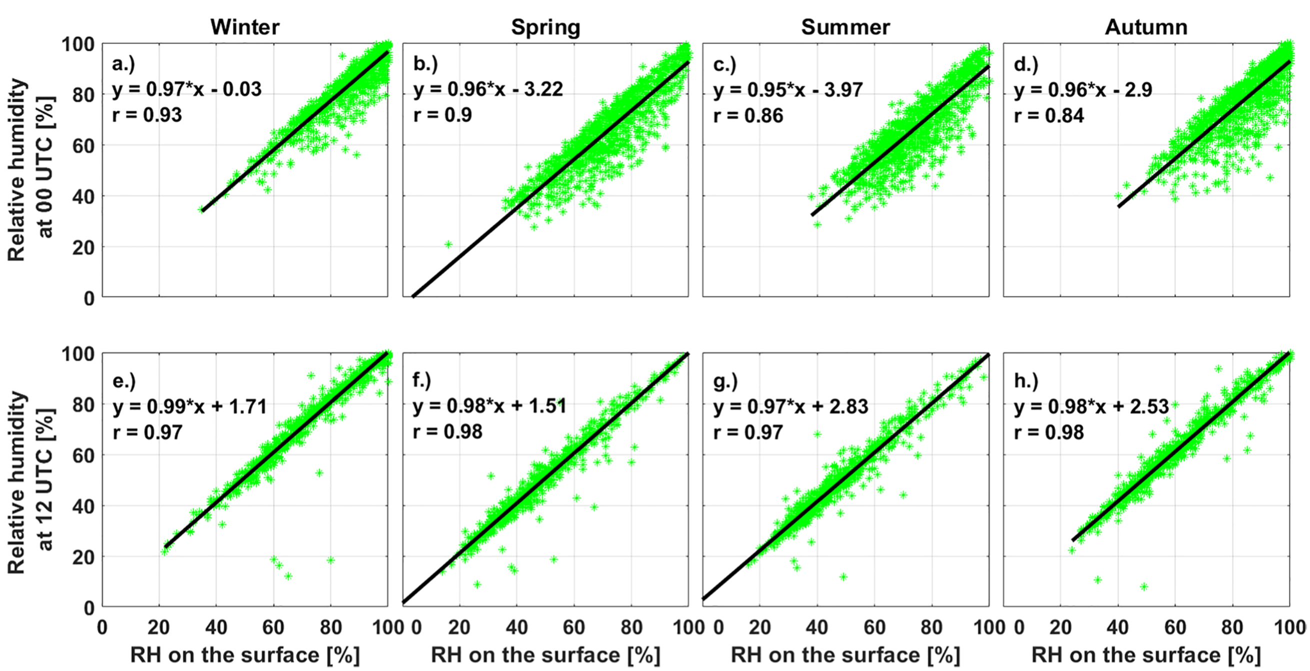


Fig. 14 Scatter plots about the relation between the surface RH and RH observed at altitudes of the 50 m at 00 and 12 UTC in each season, separately. The panels depict the relative humidity data at different time of a day (in rows) in different seasons (in columns). The data was measured at the Budapest meteorological station in the time period of 2007 - 2018. The regression lines are plotted (black, solid lines), and the equation of regression lines and correlation coefficients are given in each panel as well

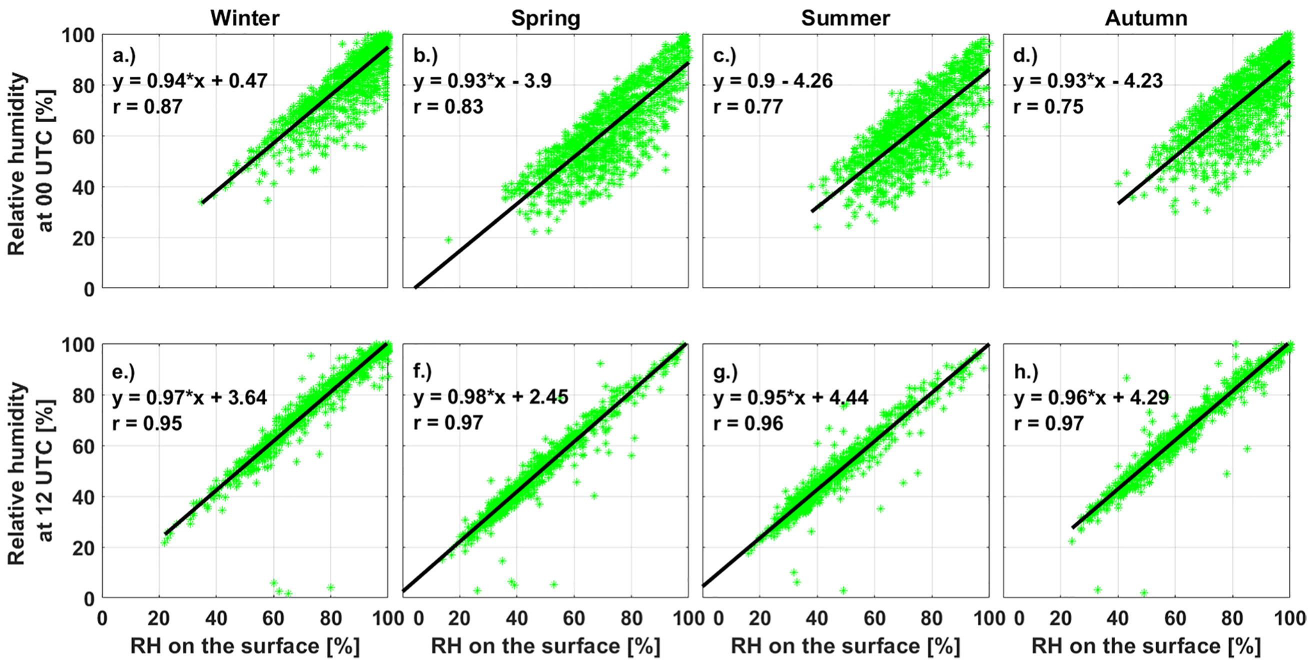


Fig. 15 Scatter plots about the relation between the surface RH and RH observed at altitudes of the 100 m at 00 and 12 UTC in each season, separately. The panels depict the relative humidity data at different time of a day (in rows) in different seasons (in columns). The data was measured at the Budapest meteorological station in the time period of 2007 - 2018. The regression lines are plotted (black, solid lines), and the equation of regression lines and correlation coefficients are given in each panel as well

significantly larger seasonal variability in the case of 00 UTC data.

(iii) Analysis of the residuals around the regression lines shows that while the variance of the residual is small and near constant in the case of 12 UTC data, it is significantly larger and more variable in the case of 00 UTC data.

4 Conclusions

The long-term trend of RH significantly impacts the efficiency of cloud and fog formation. Results published in the last few decades have demonstrated, that global warming can results in significantly different trends for RH in different regions of the Earth. Trends are varying in wide intervals depending on the geographical location, land use, and the season (see Table 1). In this study, the long-term trend of RH in Hungary is evaluated using data for the time period of 1961–2020. To avoid errors caused by the changing of the observation methods and locations of the stations, homogenized data bases were used to evaluate the trends. Although the topography and the land use are relatively homogenous in this country, the dependence of the trend of the RH based on the geographical location can still be demonstrated.

The results of this study are summarized as follows:

(i) The reliability of the available database has been checked by the comparison of two averaging techniques. Theoretically, the different methods used for the evaluation of daily average RH values can provide significantly different averages. Our calculation proves that the two averaging techniques provide close to the same results in the case of winter data. In the case of the other seasons, the differences between results can be significant and commensurable with the expected long-term changes. However, the differences are systematic, which means that the long-term trends must not be impacted.

(ii) The predicted anomalies of daily averaged RH are found to be significantly decreasing during seasons of spring and summer in Hungary. In the other two seasons, the null-hypothesis about the trends (there are no changes) can be accepted at 5 stations during the winter and at 6 stations in autumn at significance level of 5%. The versatility of the sign of changes is apparent in these seasons. However, significant warming has occurred in each season and at every station. Fatichi et al. (2015) concluded similar results analyzing RH and temperature data observed in Switzerland in the time period of 1981–2011. They found that although the temperature trend was positive in

the whole year, RH trend was negative only from January to June. In the other parts of the year, the increase of temperature was modest, and the relative humidity was either constant or rising. The discrepancy between the RH and temperature terms suggests that the change of the temperature can impact the change of RH not only directly but indirectly as well.

(iii) Analysis of the relationship between the change of temperature and of RH reveals that change of the temperature does not influence RH in winter and autumn. In these seasons, the increase/decrease of the temperature can be offset by enhanced/reduced evaporation rate. During spring, this compensation is less efficient, and during the summer, the direct impact of the change of the temperature on the change of the RH is decisive. The seasonal dependence of this effect stems from the fact that in seasons with lower average temperatures, even a small increase of the vapour due to evaporation from the surface results in significant increase of RH. During the summer, when the average temperature is higher, significantly larger evaporation rate can mitigate the impact of the increase of temperature (see the Clausius–Clapeyron equation for vapour). This result is in line with the assertion of Ye et al. (2014). They found that an increase of temperature and as consequence the decrease of RH in summer results in a decrease of precipitation efficiency and precipitation amount in northern Eurasia.

(iv) The trends for the anomaly of RH are found to depend on the time of day. Significant decrease of RH (between 2 and 6%) occurs in daytime in each season, but autumn. During the nocturnal period, even the sign of the anomaly shows large variability. The impact of topography and type of land use on the tendency of RH is more evident in this period of the day.

There is no available long-term homogenized radio sounding data to estimate the trends of the RH near the surface. We hypothesized that the long-term trends at altitudes of 50 and 100 m could be evaluated if the trends at the surface are available. This study proved that the correlation is strong at both altitudes in the case of the 12 UTC data in each season. Correlations are weaker and change in wider intervals depending on the altitude and season in the case of 00 UTC data. We conclude that the trends of the RH near the surface in daytime can be evaluated if the trends at the surface are available. The relationships between the surface trends and the trends at 50 m and 100 m are ambiguous in the nocturnal periods. The significance of the residuals can result in a large error in the evaluation of the long-term trends. In the next part of the research, we intend to compare the RH data calculated by regional climate models with our results.

Author contribution All authors contributed to the study conception and design. Homogenized datasets were generated by Beatrix Izsák; material preparation and analyses were performed by Anikó Cséplő and István Geresdi. The first draft of the manuscript was written by Anikó Cséplő, and all authors commented on the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets analysed during the current study are partly available on the website of https://odp.met.hu/. The part of the datasets that is not available on the above mentioned website because it is originated from the archives of the Hungarian Meteorological Service but is available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval This work is original, and this manuscript is not submitted to other journal even other form or language.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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