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RESEARCH

Recent seasonally contrasting and persistent warming trends in Latvia

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Abstract

The Baltics is one of the European regions facing the most rapidly increasing air temperatures – a clear signal of climate change. This article comprises an analysis of the spatial distribution and variability of air temperature in Latvia, in the Baltics, comparing the most recent climate normal (1991–2020) with the previous two climate normals (1971–2000; 1981–2010), as well as with a reference period (1961–1990). Compared to the reference period, the annual mean temperature in the last climate normal was 1.2 °C higher across Latvia, corresponding to a warming rate of +0.4 °C decade^{-1}, which is greater than the European average (between 0.17 and 0.22 °C decade^{-1}). Compared to the reference period, a persistent rise of winter (DJF) temperatures by around 2 °C and a rapid increase in the easternmost locations (distant from the sea) were found. Summer (JJA) and spring (MAM) temperatures rose by around 1 °C. The autumn (SON) temperature increase was less pronounced and was only evident during the last two climate normals. Since the reference period, the minimal mean daily air temperatures (5th quantile) in winter, autumn and, especially, spring months have increased at a rate almost double that of the average (50th quantile) temperature (0.72 to 0.39 °C decade^{-1}, respectively). We note that May or June and October experienced little to no average temperature increase, reported elsewhere in the Baltic region. We have confirmed the presence of two seasons in the spatial pattern of air temperature: one from April to July dominated by an N–S gradient and the other from August to March dominated by a W–E gradient. Furthermore, the possible mechanisms and implications of the observed seasonal pattern of the temperature increase are discussed, particularly considering land–atmosphere water and energy flux feedback.

1 Introduction

Globally observed increases in air temperature (IPCC 2013, 2021) are one of the most important characteristics of climate change (Krauskopf and Huth 2020). The most recent World Meteorological Organization (WMO) climatological standard normal (hereafter ‘climate normal’) can be considered the warmest period since the beginning of observations in Europe and globally.

It has been shown that the increase in air temperature in Europe is more pronounced than the global average (Luterbacher et al. 2004; Van Der Schrier et al. 2013; Lakson et al. 2019; Twardosz et al. 2021; EEA 2022). Compared to the pre-industrial period, during the most recent climate normal (1991–2020), the air temperature in Europe has increased on average by 1.7–1.9 °C (EEA 2022). Considering five different data sets covering the entirety of Europe, Krauskopf and Huth (2020) found that from 1957 to 2002, Europe warmed by between 0.17 and 0.22 °C decade^{-1}, depending on the data set. Twardosz et al. (2021) found that since 1985, air temperatures in Europe have increased linearly.

Although increasing temperatures have been observed across Europe (Luterbacher et al. 2004), not all regions have experienced the same rate of increase – there is considerable spatial variability (Krauskopf and Huth 2020; Twardosz et al. 2021). In addition, air temperature increases are more significant over landmasses than over the sea (Trenberth et al. 2007; Meier et al. 2022). Seasonal air temperature patterns are also shifting (Schär et al. 2004; Jaagus 2006; Samset et al. 2019; Krauskopf and Huth 2020; Kjellström et al. 2022), highlighting the importance of local and regional research. In addition, regions with higher rates of temperature increase are also expected to experience elevated rates of change in the future (Frame et al. 2017), which needs to be considered when considering adaptation and mitigation endeavours.

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In line with the global pattern, the Baltic region has also experienced increasing air temperatures (Jaagus et al. 2014; Tomczyk and Bednorz 2014). The Baltic Sea region has been noted as having experienced one of the largest temperature increases across Europe (Serreze et al. 2000; Jaagus et al. 2003; Krauskopf and Huth 2020; Twardosz et al. 2021; Kjellström et al. 2022; Meier et al. 2022). Linear trends in the Baltic Sea region of annual mean temperature anomalies during 1878–2020 were 0.10 °C per decade greater than the global mean (BACC II Author Team 2015; Meier et al. 2022). Giorgi (2006) showed that the most responsive region in Europe to climatic change is the Mediterranean, followed by the north-eastern European region.

Noticeable seasonal air temperature changes in the Baltic region have been observed (Kjellström et al. 2022) and have been found to be particularly pronounced during the winter (DJF) (Bukantis and Rimkus 2005; Jaagus 2006; Krauskopf and Huth 2020). Daily minimum and maximum temperatures have increased (Jaagus et al. 2014), in addition to decreases in daily temperature variability (Avotniece et al. 2010; Kjellström et al. 2022).

In the Baltic region, the air temperature pattern is determined by both large- and small-scale factors. On a large scale, particularly during the cold season, the distance from the Baltic Sea leads to differences in both daily and yearly temperature patterns in coastal and continental areas (Jaagus et al. 2003). On finer spatial scales, factors such as terrain, land cover and land use type and the distance from other water bodies and their size influence temperature patterns (Jaagus et al. 2014).

The Baltics, located on the eastern coast of the Baltic Sea, lie in a transition zone between maritime and continental climates. Atmospheric circulation is a principal factor determining climate variability here (Jaagus 2006; Keevallik 2011; Rutgersson et al. 2014). Any changes in atmospheric circulation in this region result in considerable variability in weather and climate conditions (Kejna and Rudzki 2021). Some climate models indicate particularly high climate change rates in the Baltic region, particularly for its northern and central parts and during the winter season (EEA 2021).

The aim of this study is to characterise annual and seasonal air temperature patterns and trends in Latvia, located in the middle of the Baltic countries, for the most recent climate normal from 1991 to 2020 in comparison to previous climate normals. We document trends in the air temperature during the most recent climate normal, how air temperature changes compared to the reference period (1961 to 1990) and seasonal and regional air temperature differences and related trends. The results show a continuing warming trend and additional spatial and seasonal changes in the studied area, which indicate greater warming patterns at higher elevations and during the winter.

Climate change is a key challenge for Europe and specifically the Baltic Sea region (Lakson et al. 2019), and it is a complex and spatially diverse process (Bukantis and Rimkus 2005; Hegerl et al. 2018; Krauskopf and Huth 2020) that needs to be monitored (Twardosz et al. 2021). Regional studies, such as this one on the national level, are of great importance, essential to understanding overall climate uncertainty in small regions (Kjellström et al. 2022). In the context of increasing interest in evaluating the regional impacts of climate change and to understand how these may vary for different levels of global warming (Hulme 2016), our study plays an important role in exploring local and regional patterns.

2 Location, data and methods

2.1 Meteorological data

Daily mean air temperature measurements from 25 meteorological observation stations of the Latvian Environment, Geology and Meteorology Centre (LEGMC) for the period of 1961–2020 (Fig. 1) have been used in this study. Measurement methods, station locations and instrumentation have significantly changed over this time period, affecting the data quality, availability and homogeneity. Taking this into account, air temperature measurement homogenisation was performed according to the guidelines of the WMO (Venema et al. 2020). Data pre-processing followed the following steps.

1. Time series of relocated meteorological stations (Rīga, Dagda, Jelgava, Madona and Rezekne stations; see Fig. 2) were unified.
2. Time series were merged considering changes in the observation frequency: Until around 1966, there was only one observation per day for many stations, and until 2004, there were eight observations per day (see Fig. 2).
3. The largest gaps of missing observations (see Fig. 2) were imputed using either minimum and maximum temperature time series or linear regression of the nearest observing station data, modelling a regression coefficient every 10 days. The methods used were checked for accuracy by removing a single year of observations from each of the stations, imputing the data and afterwards comparing them with the removed measurements (not shown). For each of the following stations, the best-performing method was found.
    a. Rīga station was modelled by linear regression from multiple Rīga time series, previously mentioned, using a brief period of overlapping observations in 1995–1996;

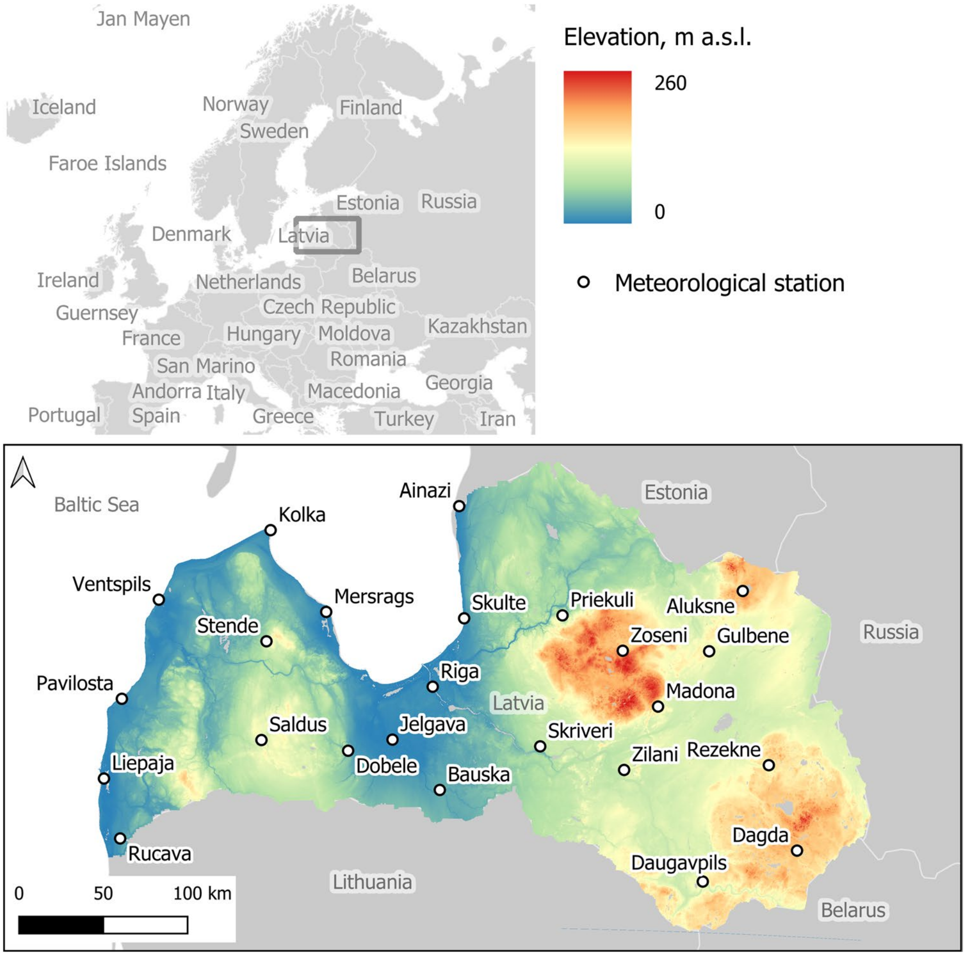


Fig. 1 Location of the study region in Europe (top left) and of the meteorological observation stations in Latvia

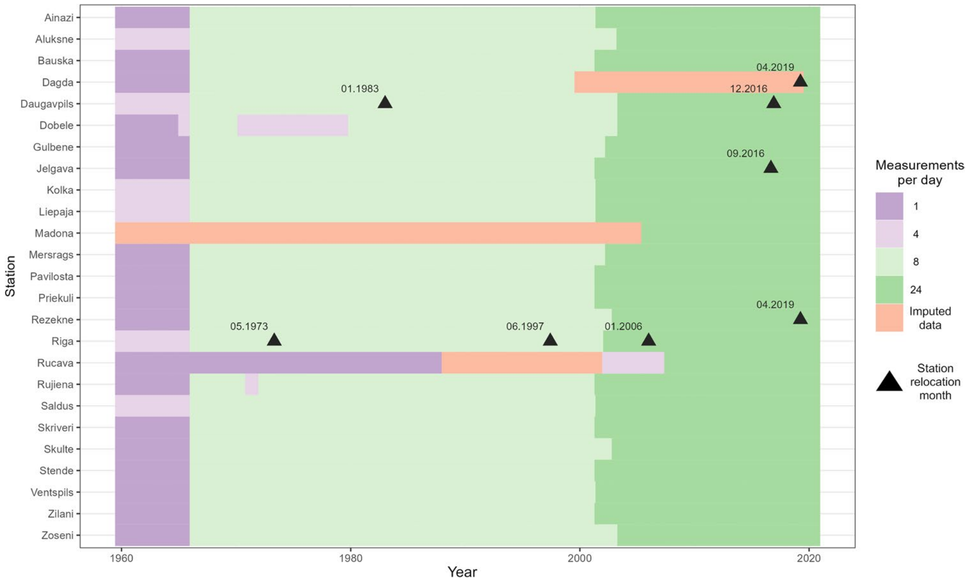


Fig. 2 Air temperature observation frequency and station relocation: colour scale represents measurement frequency, with orange representing periods of missing observations where data were imputed; and meteorological station relocation dates are represented with the black triangles, including month and year of the relocation

b. Dagda and Madona station data were calculated using maximum and minimum temperature data sets as well as modelled with linear regression using the neighbouring stations, respectively Rezekne and Gulbene;

    c. Rucava station was modelled using the linear regression method and data from the neighbouring Liepāja observation station.

4. As a last step, data homogenisation of daily mean temperature measurements was performed using the CLIMATOL homogenisation algorithm (Guijarro 2018), which has shown satisfactory performance for air temperature data (Domonkos et al. 2021). We used two standard normal homogeneity test (SNHT) (Alexandersson 1986) threshold values – 25 for most stations and 20 for Rīga and Priekuli, where the time series were found to be less homogeneous. We also used 8 standard deviations as a threshold for outlier detection – data found to be over these margins were removed and later replaced with data imputed by the CLIMATOL algorithm. All detected inhomogeneities were compared with station metadata to cross-reference the detection results.

The data then were analysed and compared between different climate normals: the most recent climate normal (1991–2020), previous climate normals (1981–2010; 1971–2000) and climate reference period (1961–1990). The WMO has described climatological standard normals as the averages of climatological data computed for the following periods of 30 years for a uniform and extended period (Venema et al. 2020).

Following the recommendations of Krauskopf and Huth (2020) for using multiple types of data sources, as well as for describing spatial differences, E-OBS (Cornes et al. 2018) data have been used. A time series of daily average air temperatures from 1961 to 2020 of gridded E-OBS meteorological data in Latvia with a normal resolution of 0.1° from the Copernicus Climate Data Service has been extracted. The gridded E-OBS meteorological data set provides a means of visualising the mean air temperature spatial patterns in the study area, while observations at meteorological stations provided the most accurate homogeneous time series.

2.2 Statistical methods

2.2.1 Multivariate statistical analysis of seasonal and regional air temperature pattern

Regional characteristics of the seasonal air temperature pattern were explored with multivariate statistical analysis. Regional patterns can be uncovered by using clustering methods, principal component analysis (PCA) and other methods. Most clustering methods provide groupings of observation points into discrete sets of clusters, but additional analysis is needed to gain insight into which parameters determine the clustering results and which determine the similarity between observation points. In contrast, PCA provides continuous variables along an orthogonal axis of maximum variance for each observation point and each variable; thus, it is easy to identify the most extreme observation points and the associations between variables. Therefore, we chose to take this approach. PCA has been previously performed on meteorological parameters, indicating that the first two to three principal components can adequately explain more than 80% of the variance (Estrada et al. 2009; Bethere et al. 2017; Pogumirskis et al. 2021).

PCA is a dimension reduction technique (Davis 2002) that projects multivariate observations to a new set of orthogonal uncorrelated coordinate space – principal components – maximising the variance between samples when projected onto a component (Ringnér 2008). In this study, the long-term mean air temperature for each station and each month were considered as the variable; thus, there were 12 variables for each observation station. A similar approach was used by Pogumirskis et al. (2021) for the analysis of a wind direction data set; however, data points in that study were treated as a probability distribution of the long-term mean monthly wind direction. A singular value decomposition method with the *prcomp* function of the R *stats* package (R Core Team 2021) was used. Scaled and centred (zero mean and unit standard deviation) monthly mean temperatures for a predefined reference period from meteorological station observations were defined as variables and observation points as cases. PCA was useful for identifying six meteorological stations that well represented the diversity of the yearly temperature patterns in the study region.

2.2.2 Quantile regression

Quantile regression, which was developed by Koenker and Bassett (1978), is a statistical method used to estimate the conditional quantiles of a response variable distribution in the linear model, providing a more complete view of relationships between variables. In climatic trend analysis, this technique allows us to simultaneously identify trends in specific portions of the distribution of the dependent variable, independent of the variability experienced by the rest of the distribution. In particular, it is useful for detecting trends in extremes hidden in non-significant mean effects or changes in median conditions in extreme stochastic environments (Koenker and Schorfheide 1994; Chamaillé-Jammes et al. 2007).

In this study, we use quantile regression for the mean air temperature to consider changes not only in the mean values but also in the tail ends of the distribution. Quantile regression was applied to each season and observation station separately using previously homogenised daily mean air temperature data from 1961 until 2020. Quantile regression was also performed on each of the climate normal time periods, distinguishing how the quantiles change between different overlapping time periods. We separately analysed the 5th (0.05), 50th (0.5) and 95th (0.95) quantiles, highlighting changes in the median and extreme parts of the distributions.

2.2.3 Mann–Kendall test and Sen's slope

The multivariate, non-parametric Mann–Kendall test (Libiseller and Grimvall 2002) was used to identify long-term trends. The Mann–Kendall test is based on the rank or pairwise principle, which compares two observational values. The test can be used for data series with seasonal or serial variability, as it allows test values to be calculated separately for each month. The trend in the parameter under study was considered significant if the p value was less than 0.05, i.e. the probability of the result being due to chance was less than 5%. The Mann–Kendall trend test values and confidence level were calculated with the R *trend* package (Pohlert 2020).

Trend values were calculated using Sen's slope approach (Sen 1968), which is often used in climate data analysis (Atta-ur-Rahman 2017; Alemu and Dioha 2020; Jaagus et al. 2022) as it is more robust than regular linear regression. In essence, Sen's slope is a median of the trend between every two consecutive observations in a time series. The R *trend* package was also used here (Pohlert 2020). Meteorological and climatic data were analysed in the open access data processing and R analysis environment (R Core Team 2021) for data processing using the *tidyverse* ecosystem of packages (Wickham et al. 2019).

3 Results

3.1 Spatial distribution of air temperature

PCA of the mean monthly air temperature during the most recent climate normal (1991–2020) revealed two dominant seasonal components: distance from the Baltic Sea or west–east position (PC1) and latitude in combination with elevation above sea level (PC2; Fig. 3). PC1 explained 59% of the variation, while PC2 explained 26%. The city of Rīga is an obvious outlier, with far higher air temperatures than other observation stations due to the urban heat island effect. Similar results were obtained by Bethere et al. (2017), who examined monthly mean temperature and precipitation in the Baltic region. Furthermore, PC1 strongly correlated with mean monthly temperatures from observation stations from August to March, while PC2 had a strong correlation with temperatures from April to July (Fig. 3).

The PCA results were used to select six meteorological stations that describe the range of conditions observed in the study region (Figs. 1 and 3): two seaside locations, Liepāja and Kolka; two continental stations, Daugavpils and Alūksne; one central location, Saldus; and that in Rīga as an extreme case of the urban climate experienced by more than one-third of Latvia's population.

3.2 Mean annual temperature changes: rate of warming

Latvia's location on the coast of the Baltic Sea, in addition to its hilly terrain and hydrological network, determines

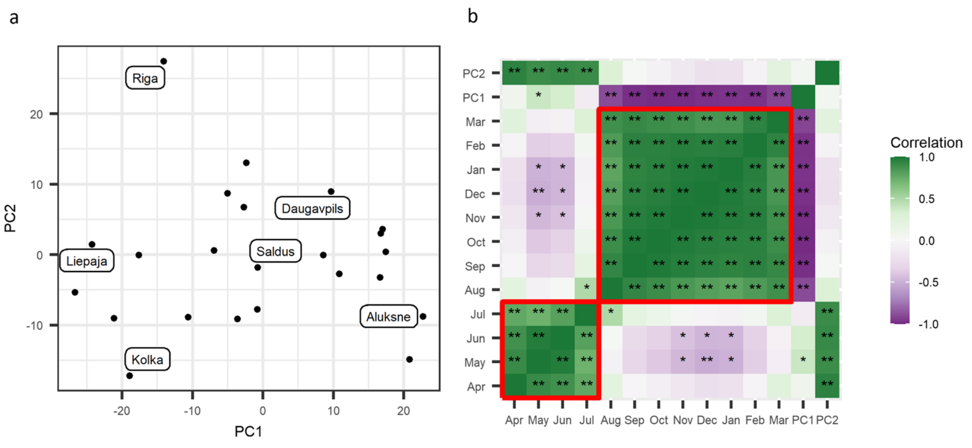


Fig. 3 PCA results of the monthly mean air temperature: **a** – a scatterplot of the first two principal components (PC1 and PC2), with the names of the six meteorological stations selected for detailed analysis shown (see Fig. 1 for locations); **b** a correlation matrix between long-term monthly mean air temperature (1991–2020) at the meteorological stations and principal component values for the respective stations (* – significant at 5% and ** – at 1% level, Pearson correlation). The red square on the bottom left highlights the high correlation of late spring and early summer temperatures with the N–S gradient represented by PC2; the red square on the top right highlights the high correlation of late summer, autumn, winter and early spring temperatures with the W–E gradient represented by the PC1

its relatively unequal air temperature distribution. The average annual temperature gradually decreases from west to east (Fig. 4). Compared to the reference period of 1961–1990, where the average temperature was 5.6 °C, the average annual air temperature in the climate normal 1991–2020 in Latvia was 6.8 °C. This recent climate normal varied regionally from 7.9 °C in Liepāja (coastal) to 5.7 °C in Alūksne (continental). In general, the average annual air temperature in Latvia varied by 4 °C over this period – from 5.0 °C in 1996 to 8.7 °C in 2020. It should be noted that 2020 was the warmest year since 1961. The coldest year during 1991–2020 was 1987, when the annual average temperature was 4.0 °C, almost 3 °C below the norm. In general, over the last 60 years (since 1961), the mean annual temperature increase (1.2 °C) has been steady (Fig. 5, Appendix Fig. 8).

The mean annual temperature shows an upward trend (pronounced and statistically reliable –*p* value of <0.05 for all stations) both in the Baltic Sea coastal areas and in continental locations. In the data from the six examined stations, the annual mean air temperature during the last normal (1991–2020) compared to the 1981–2010 period increased by 0.5 °C, more than the increase between previous climate normals.

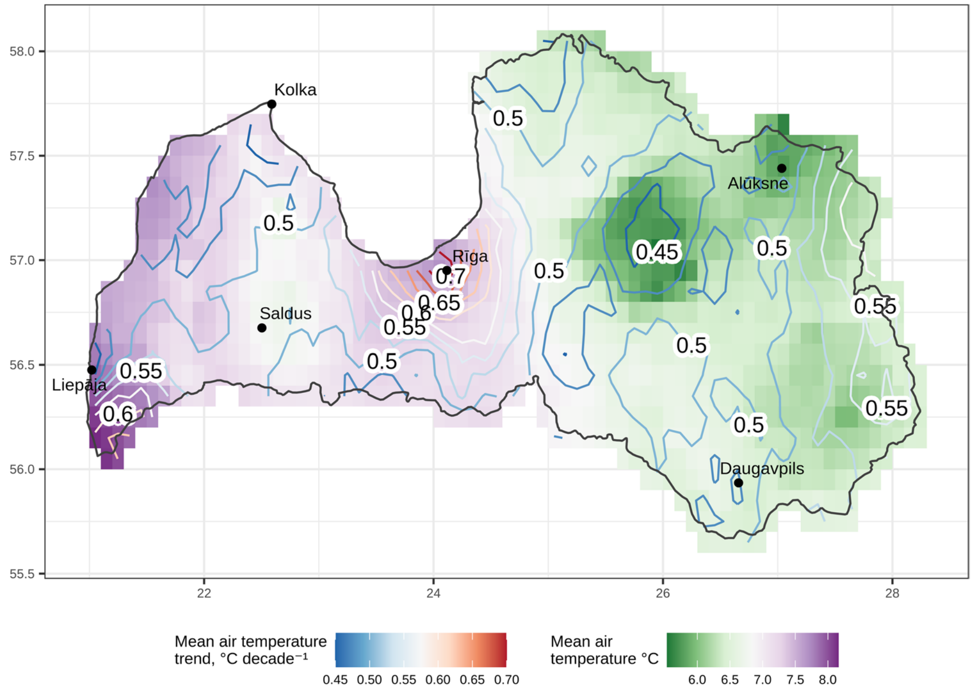


Fig. 4 Annual mean air temperature (background colour, °C) and mean air temperature trend (isolines) in Latvia for the period 1991 to 2020 (°C decade^{-1}, Sen's slope, $p < 0.05$; E-OBS data, Cornes et al. 2018)

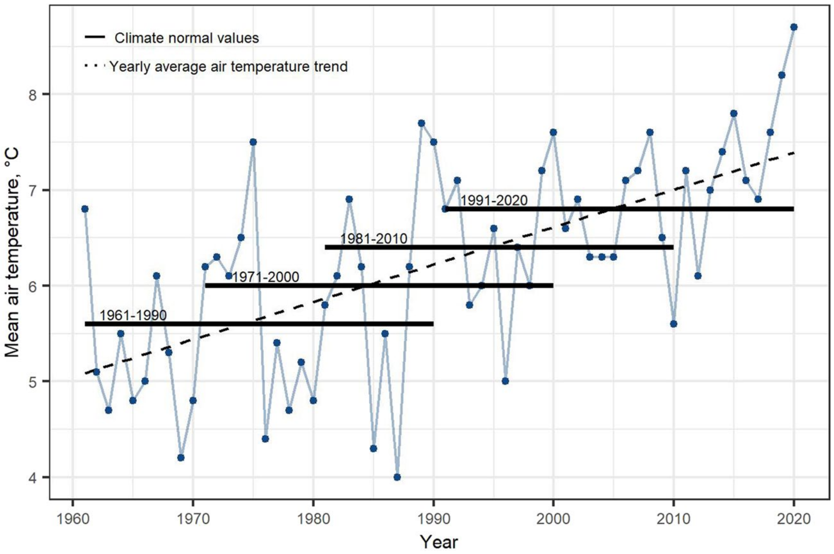


Fig. 5 Annual mean air temperature for the period 1961–2020: mean value for Latvia (blue dots and solid line), its corresponding linear trend (dashed line) and the mean air temperature of four consecutive climate normals (thick black lines) ($n = 25$). Using Sen's slope, statistically significant ($p < 0.001$) with a rate of change of 0.4 °C decade^{-1}

The Sen’s slope value for the long-term data (1961–2020) is +0.4 °C decade^{-1}. The warming rate in the most recent climate normal was +0.5 °C decade^{-1}, showing accelerated warming compared to the reference period (when the warming rate was +0.3 °C decade^{-1}).

3.3 Seasonal changes

The summer season (JJA) average air temperature in Latvia is 16.2 °C (long-term data, 1961–2020). The average air temperature in winter (DJF) is −3.4 °C, with relatively large regional differences: At coastal stations such as Liepāja and Kolka, average winter temperatures over the long-term period were −1.2 °C and −1.4 °C, respectively, i.e. on average warmer than in the continental part, where winter temperatures fall to −5.4 °C in Alūksne and −4.5 °C in Daugavpils (Table 1). These are significant differences considering that the distance along the meridional section between the coastal stations and the continental stations does not exceed 500 km and the difference in altitude is less than 200 m.

Seasonal changes in air temperature have been recorded for all climate normals and for the reference period. The winter season, excluding the climate normal 1981–2010, shows the most pronounced changes. It is notable that the most significant changes in winter season temperatures are characteristic of the reference period (1961–1990): Winter season temperatures were more than 1 °C higher at all six stations compared to the 1971–2000 climate normal. It should be noted that over 1971–2000, autumn air temperatures showed a negative trend.

In the most recent climate normal (1991–2020; Table 1), increases equal to the reference period were found for both spring and summer air temperatures – on average for Latvia +1.1 °C, with a more explicit warming pattern during spring in coastal areas. Over the long term, compared to the reference period and the most recent climate normal, winter air temperatures have increased by 2 °C, with more pronounced changes at continental stations (2.2 °C at Alūksne to 1.8 °C at the coast). The autumn season has the least pronounced increase, with an overall autumn air temperature increase of 0.6 °C in Latvia as whole and regional differences of 0.9 °C in Rīga (urban area) and 0.4 °C in Liepāja (coastal). Autumn air temperature changes are not characterised by a continentality effect like that affecting spring and summer temperature changes.

The mean air temperature difference in January between the reference period (1961–1990) and the most recent climate normal (1991–2020) is more significant: +2.4 °C for Latvia as a whole, with larger increases for the continental stations Alūksne and Daugavpils (+2.7 °C and +2.6 °C, respectively) and less pronounced increases for the coastal stations, Liepāja and Kolka (+2.1 °C) (Table 1). It is notable that in June, May and October, the mean air temperature changed very little (Fig. 6).

The Sen slope data (Fig. 6) show a significant increase in air temperature for all months except October, June and, for most stations, May. However, at the coastal stations Kolka and Liepāja, May temperatures also increased significantly between the reference period and the most recent climate normal. Interestingly, despite the large average January temperature changes, long-term Sen’s slope values for Latvia in January are not statistically significant, except for the continental stations Alūksne and Daugavpils.

Larger variability of average monthly air temperature data is characteristic of the winter months, especially February. Smaller temperature fluctuations are recorded for April and May and for August and September air temperatures

Table 1 Seasonal mean air temperatures in Latvia (mean spatial value) and in the selected meteorological stations during the reference period (1961–1990) and the most recent climatological standard normal period (1991–2020); corresponding air temperature differences (diff.) between the climate normals are also given (all units in °C)

Station	Time	Winter	Spring	Summer	Autumn	Year	Winter diff.	Spring diff.	Summer diff.	Autumn diff.	Year diff.
Aluksne	1961–1990	−6,5	4,2	15,3	5,0	4,5	2,2	1,1	0,9	0,6	1,2
	1991–2020	−4,3	5,3	16,2	5,6	5,7					
Daugavpils	1961–1990	−5,5	5,0	15,9	5,9	5,3	2,0	1,3	1,0	0,7	1,3
	1991–2020	−3,5	6,3	16,9	6,6	6,6					
Kolka	1961–1990	−2,3	3,5	15,3	7,7	6,1	1,8	1,4	1,0	0,7	1,2
	1991–2020	−0,5	4,9	16,3	8,4	7,3					
Liepaja	1961–1990	−2,1	4,9	15,7	8,3	6,7	1,8	1,3	1,1	0,4	1,2
	1991–2020	−0,3	6,2	16,8	8,7	7,9					
Riga	1961–1990	−3,4	6,3	17,0	7,2	6,8	1,9	1,0	1,1	0,9	1,2
	1991–2020	−1,5	7,3	18,1	8,0	8,0					
Saldus	1961–1990	−4,0	4,9	15,4	6,6	5,7	1,9	1,1	1,0	0,5	1,2
	1991–2020	−2,1	6,0	16,4	7,1	6,9					
Latvia, country mean	1961–1990 1991–2020	−4,4 −2,4	4,8 5,9	15,6 16,7	6,5 7,1	5,6 6,8	2,0	1,1	1,1	0,6	1,2

(Fig. 7). In general, continental stations such as Daugavpils and Alūksne have greater temperature amplitudes in the winter season. In the spring and autumn, there are no regional changes in the amplitude size. In the summer months, the influence of the urban heat island effect is clearly visible in the example of the Rīga station – The average temperature is, on average, higher than at other stations (Fig. 7), and the temperature amplitude is more significant.

In the most recent climate normal, February was the only month where the long-term median of average temperatures was sub-zero for all stations (Fig. 7). Conversely, during the reference period, this was also the case in December (Fig. 7). In the recent climate normal, the median of average temperatures in March was below 0 °C only at Alūksne station, while in the reference period, this was the case for most observation stations; thus, we observe a noticeable shortening of the period with mostly sub-zero temperature. Compared to the reference period, January air temperatures significantly decreased in the most recent climate normal – The air temperature at the continental stations was, on average, higher and ranged less, whereas the temperature amplitude of February, November and December at these stations increased.

The minimum average temperature increased as well: In the reference period, the minimum average monthly temperature was below −10 °C for all stations. For the most recent climate normal, this was not the case for any of the six stations. In February, for the recent climate normals period, a minimum average air temperature of −10 °C or less was only found in the continental stations (Fig. 7, Alūksne, Daugavpils). The maximum average temperatures for the winter months did not change significantly, except for December, which is generally characterised by a significant broadening of the temperature range. Summer average maximum monthly temperatures increased, especially in July and August, and especially in Rīga and at the continental stations.

3.4 Seasonal temperature distribution trends: quantile regression analysis

In all seasons, the meteorological stations showed generally positive air temperature trends (Appendix Fig. 9). Data from many, but not all, of the stations showed a statistically significant increasing trend among the 30-year periods. Comparing climate normals, the autumn quantiles of 1961–1990 were the only ones that were uniformly negative (decreasing air temperature) among the six meteorological stations. Specifically, the 95th quantile of 1961–1990, approximately describing the maximum average air temperature, showed a significant downward trend. There is a shift in the observed autumn climate; however, as within the latest normal (1991–2020), all autumn quantiles show significantly significant positive trends, with the largest increases observed in the 5th quantile (representing the minimum average air temperature), between approximately 1.3 and 2.1 °C decade^{-1}. In fact, such large increases are not observed in any other quantiles for any season, showing that specifically during the last normal period, significantly less cold autumn days were observed.

Opposite tendencies can be observed in the spring and winter months – While generally, an air temperature increase is observed, over the last three climate normal periods, this increase seems to have somewhat slowed down or stayed relatively unchanged in all the considered quantiles. Winter shows the only one statistically significant negative trend over all observation stations, which is in Liepāja – The 5th quantile for the 1991–2020 period has decreased by 0.72 °C decade^{-1}. It is important to note that the 50th and 95th quantiles in winter remain significantly positive, showing different trends in maximum, mean and minimum quantiles. This shows that, especially at coastal stations, the quantiles show larger differences in various parts of the distribution, curiously increasing the observed air temperature spread.

All observed summer quantile trends over all observed 30-year periods show an increase, especially the 95th quantile. It is worth noting that the largest increasing summer trend was found for the 1981–2010 period, where the average summer 95th quantile trend in Latvia is almost +0.9 °C decade^{-1}. However, during the most recent normal period, large increasing trends of the 95th quantile are seen in winter and autumn, as previously mentioned.

When analysing the changes spatially during the most recent climate normal, from 1991 to 2020, it is interesting to note that, specifically in the autumn months, the continental stations (Alūksne and Daugavpils) show a more pronounced increasing trend in the 5th quantile (2.0 °C decade^{-1}) than do the stations close to the sea, such as Liepāja (1.6 °C decade^{-1}) and Kolka (1.3 °C decade^{-1}).

Both Alūksne and Daugavpils also show no significant trends in the spring quantiles, as opposed to Kolka, Liepāja, Saldus and Rīga, where at least one of the quantile trends is statistically significant. Alūksne and Daugavpils also show more pronounced winter trends in the 50th quantile compared to other stations (comparing, for example, Daugavpils with 0.9 °C decade^{-1} and Kolka with 0.3 °C decade^{-1}). This indicates shifting climate tendencies in the stations. In the continental areas, the largest contributions to the warming trend are found in the winter and late autumn months, while temperature increases for other stations are spread out more evenly throughout the year (and are not as large). This effect is consistent across all the observed quantiles.

4 Discussion

We observe significant long-term temporal and spatial changes in the annual mean, seasonal and monthly air temperatures in the study area of Latvia. In the time period

1961–2020, the average annual temperature in Latvia increased by 1.2 °C. In the most recent climate normal (1991 to 2020), the tendency towards climate warming, especially in the winter season, accelerated. This has a large potential impact on both the economy and the ecosystems of the region (Tingley and Huybers 2013). In general, the annual mean temperature in coastal areas in Latvia is 2.2 °C higher compared to continental territories, and spatial differences are more pronounced during the winter season. The warming rate differs depending on the location (Fig. 4). In particular, the winter temperature increase is more pronounced in eastern continental locations (Alūksne, Daugavpils) compared to coastal stations (Kolka, Liepāja). This corresponds with the Europe-wide analysis of Twardosz et al. (2021).

4.1 Warming rate

The warming rate since 1961 has mostly been linear, with a slight acceleration during the recent climate normal (1991–2020; Appendix Fig. 8), when the mean air temperature was 0.4 °C higher than during the previous period (1981–2010); however, the difference is smaller than the rounding error. Twardosz et al. (2021) observed a considerable acceleration of warming since 1985. Similar breakpoints during the late 1980s have been found in phenological (Kalvāne and Kalvāns 2021) and hydrological (Apsīte et al. 2013; Jaagus et al. 2017) data sets. It is likely that the acceleration of winter and spring warming, and the increasing minimum temperatures (Appendix Fig. 9), have had relatively little influence on the annual mean temperature, but have significantly affected spring phenology and hydrology. Observations are in line with findings from elsewhere in the region. The air temperature in Estonia has risen by about 2 °C during the second half of the 20th century (Jaagus 2006; Jaagus et al. 2014), even more rapidly than what we have observed in Latvia.

Linear trends of annual mean temperature anomalies in the Baltic Sea region over 1878–2020 were 0.10 °C decade^{-1}, which is greater than the global mean temperature trend and slightly greater than that found in earlier studies made by Meier et al. (2022). In the area studied here, the temperature change was found to be 0.4 °C decade^{-1} during the last 60 years (1961 to 2020). A slight increase in the warming rate can be noted during the most recent climate normal, although it is smaller than the rounding error (Appendix Fig. 8). Climate warming generally manifests as a rise in maximum temperature and in minimum temperature (Jaagus et al. 2014), including a growth in the frequency of tropical nights (Kažys et al. 2011), which has also been found in Latvia (Avotniece et al. 2010).

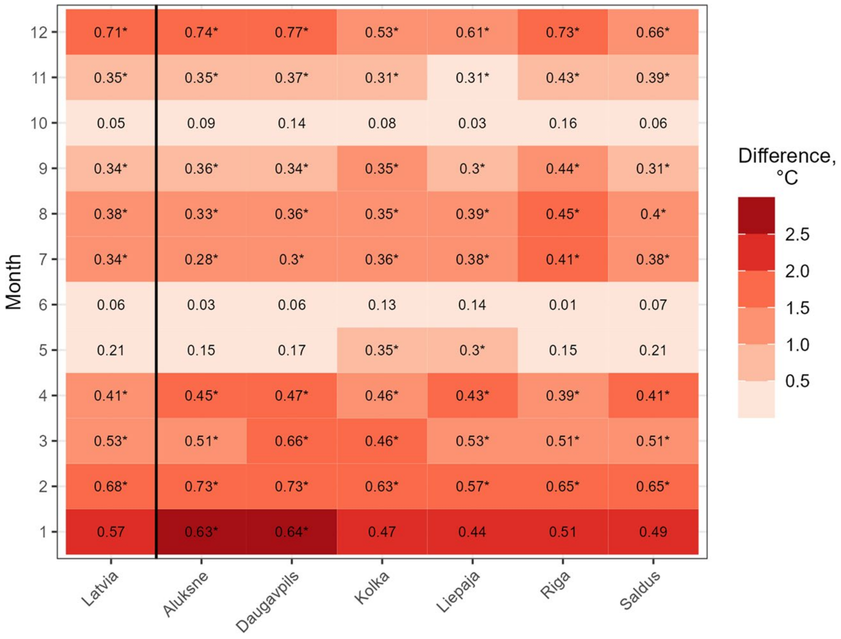
4.2 Season-specific temperature trends

A pattern of two spatial thermal seasons can be identified (Fig. 3): one is W–E dominated and the other S–N dominated. These can be considered as an advection thermal season (August to March) and a radiative thermal season (April to July), reflecting the two apparently dominant mechanisms shaping the spatial distribution of mean air temperature. In fact, August is in a transitional position between the two seasons. Such seasonal weather condition patterns have been noted before in Latvia, found by comparing large-scale atmospheric circulation data to long-term observations of air temperature, precipitation and river discharge (Klavins and Rodinov 2010). These authors found that meridional circulation prevailed during spring and summer, while zonal circulation dominated in winter. Bethere et al. (2017) explored the climate of the Baltic region – through the monthly mean air temperature and precipitation sum – using principal component analysis. They found that the distance from the Baltic Sea, in combination with latitude (distance from the Equator) and elevation above sea level, plays a crucial role in shaping climatic signatures in the region. A similar two-season pattern was also observed, analysing the wind direction patterns in the region (Pogumirskis et al. 2021), with a sharp seasonal transition in April and a more gradual transition in August and September. Thus, our results confirm these previous findings.

On the seasonal level of aggregation, during the most recent climate normal (1991 to 2020) in Latvia, the strongest air temperature increase was observed in winter (DJF; Appendix Fig. 8). Despite the increasing number and duration of hot days (Avotniece et al. 2010), the summer (JJA) mean temperature increased less significantly. An autumn (SON) mean air temperature shift was also observed during the studied periods. More granularities emerge when considering monthly mean temperature – June, October and, to a lesser extent, May stand out in particular – No or very little warming was observed in these months. Similar patterns have been previously observed (Jaagus et al. 2014) and elsewhere in the Baltic Sea region (Kjellström et al. 2022), indicating that this pattern has some physical causes related to large atmospheric circulation patterns as well as local factors rather than being just a statistical coincidence. Kjellström et al. (2022), examining atmospheric circulation data from the Stockholm area, suggested that this might be explained by the nature of the North Atlantic Oscillation (NAO): More negative NAO values are observed specifically during June and October. Studies in Poland (e.g. Kejna and Rudzki 2021) also highlighted that the role of meridional flow is particularly important in autumn.

Upon analysing data from meteorological stations across Europe in the period from 1951 to 2020, it can be concluded that the most significant increase in temperature is in the period of spring, while the lowest increase is in autumn (Twardosz et al. 2021). Summer can be defined as a relatively stable season. That study emphasises that there is a significant increase in winter temperatures in the northern part of the Baltic region, which is consistent with our study.

Fig. 6 Monthly mean air temperature Sen's slope (given in values, °C decade^{-1}, * – significant at the 5% level) for the period from 1961 to 2020. The colour shows the difference in the recent climate normal (1991–2020) compared to the reference period (1961–1990) for Latvia overall and for the six selected meteorological observation stations



Month	Latvia	Aluksne	Daugavpils	Kolka	Liepaja	Riga	Saldus
12	0.71*	0.74*	0.77*	0.53*	0.61*	0.73*	0.66*
11	0.35*	0.35*	0.37*	0.31*	0.31*	0.43*	0.39*
10	0.05	0.09	0.14	0.08	0.03	0.16	0.06
9	0.34*	0.36*	0.34*	0.35*	0.3*	0.44*	0.31*
8	0.38*	0.33*	0.36*	0.35*	0.39*	0.45*	0.4*
7	0.34*	0.28*	0.3*	0.36*	0.38*	0.41*	0.38*
6	0.06	0.03	0.06	0.13	0.14	0.01	0.07
5	0.21	0.15	0.17	0.35*	0.3*	0.15	0.21
4	0.41*	0.45*	0.47*	0.46*	0.43*	0.39*	0.41*
3	0.53*	0.51*	0.66*	0.46*	0.53*	0.51*	0.51*
2	0.68*	0.73*	0.73*	0.63*	0.57*	0.65*	0.65*
1	0.57	0.63*	0.64*	0.47	0.44	0.51	0.49

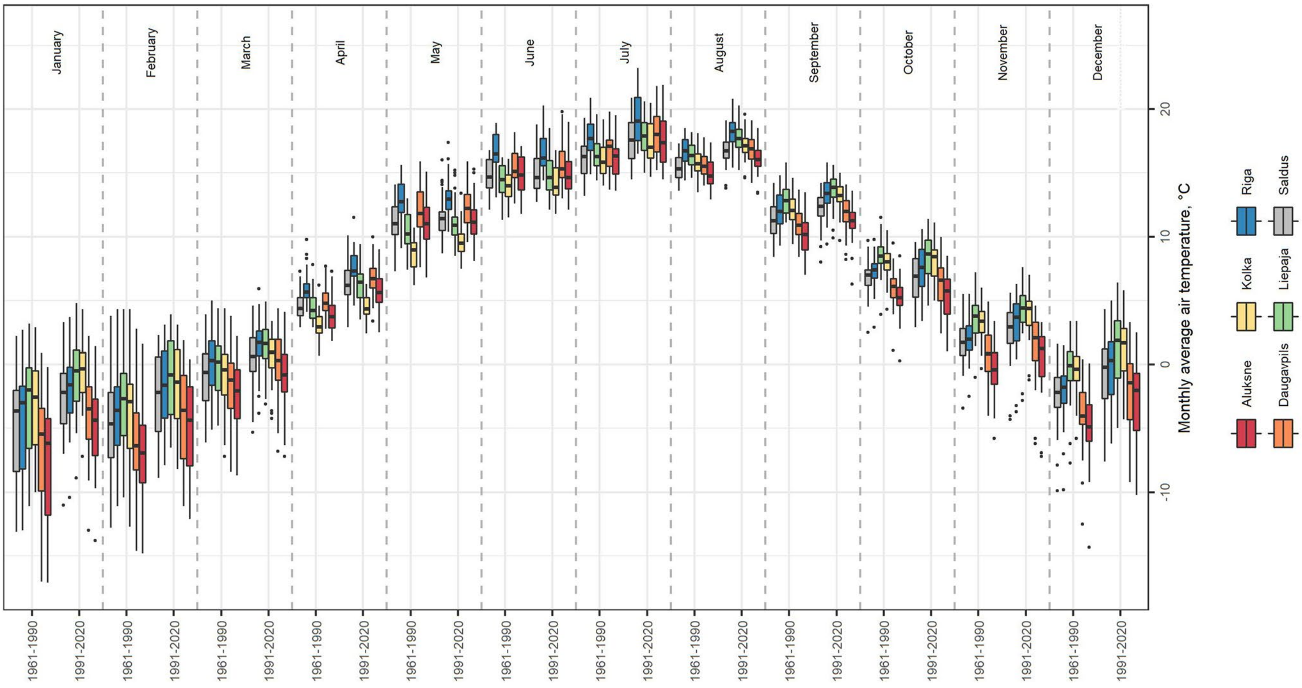


Fig. 7 The variability of mean monthly air temperature at the six selected meteorological stations for the climate normals 1961–1990 and 1991–2020. The thicker black bars denote median air temperatures, the lines represent the 1.5 interquartile range, and the boxes denote the 25th and 75th percentiles. The dots represent outliers

Rapid winter temperature changes throughout the Baltic Sea region have been noted in numerous publications (Bukantis and Rimkus 2005; Jaagus 2006; Christensen and Christensen 2007; Lakson et al. 2019; Krauskopf and Huth 2020; Twardosz et al. 2021). For example, Krauskopf and Huth (2020), analysing five different meteorological data sets in Europe, found that Europe is warming by up to 0.22 °C decade^{-1}, with the most pronounced warming in winter (0.34 °C decade^{-1}; ERA5 and E-OBS, Cornes et al. 2018). Küttel et al. (2011) argued that 70% of the variation in winter temperature in Europe could be explained by changes within the types of circulation. The frequency and magnitude of western circulation changes have also been depicted in other studies (Bukantis and Rimkus 2005; Kejna and Rudzki 2021). Relatively small changes in autumn (SON) temperatures have generally been found for the Baltic Sea region (Pokorná et al. 2018; Krauskopf and Huth 2020; Kejna and Rudzki 2021; Twardosz et al. 2021; Brázdil et al. 2022)

Observing the 5th quantile of winter, autumn and, especially, spring months in Latvia, it can be seen that the warming rate is almost double that of the 50th quantile (0.72 to 0.39 °C decade^{-1}, respectively, Appendix Fig. 9). In summer, however, there are relatively similar warming trends in all observed quantiles. This is in line with previous findings (Avotniece et al. 2010), where it was found that the cold days of the year show a very pronounced warming trend, while a relatively uniform rise of the summer temperatures has been observed.

4.3 Contribution of local factors

We observe overall increasing air temperatures, which is particularly distinct for the 5th quantile. However, the average temperature has changed little for October and May–June – months linked to the intermediate seasons. As discussed before, this pattern of temperature trends is likely shaped by large-scale atmospheric circulation. However, the air temperature can be modulated locally by energy fluxes between large water bodies, the land surface and the atmosphere. In the following paragraphs, we speculate as to what mechanisms could modulate the local air temperature.

It can be speculated that winter warming is amplified due to the loss of snow cover. Decreased snow extent and duration of snow cover has been well documented in the non-Arctic areas of Europe (Groisman et al. 1994; Bednorz and Kossowski 2004; BACC II Author Team 2015; Stonevicius et al. 2018). However, in winter in Latvia, the strongest warming was detected for January and December (Fig. 6) for the easternmost stations, Alūksne and Daugavpils, especially for the smallest quantiles especially (Appendix Fig. 9). However, the average monthly temperature at these stations remains below freezing (Fig. 7), implying little change of snow cover in contrast to coastal stations (Kolka and Liepāja). In addition, incoming solar irradiance is close to its yearly minimum during December and January (on average, about 18 W m^{-2} in January compared to about 230 W m^{-2} in June) (E-OBS data set Cornes et al. 2018). Thus, other mechanisms contributing to winter warming are possible, including warm air mass advection from the increasingly ice-free Baltic Sea (thermal inertia; Jaagus et al. 2003) or the decline of atmospheric aerosols (Hegerl et al. 2018).

Somewhat speculatively, we posit that soil–atmosphere feedback can explain the low warming trend for June–May, depending on the observation station (Fig. 6; Jaagus et al. 2014; Kjellström et al. 2022). The soil moisture regime can have a nonlinear feedback effect on the air temperature, particularly in the interim seasons – spring and autumn (Vecellio and Frauenfeld 2022). Milder winters and warmer springs have resulted in advancing leaf-out dates of major tree species in the region (Kalvāne and Kalvāns 2021). During May and June, the earlier start of the vegetation season has led to earlier attainment of the yearly maximum leaf area index (LAI; time series derived from ESA PROBA-V satellite, Copernicus Global Land Service 2022), which can result in increasing cooling by transpiration during late spring–early summer. Furthermore, cloudiness can increase due to an increase of vegetation-derived aerosols (Paasonen et al. 2013) resulting from the earlier start of the vegetation season. Negative vegetation feedback may contribute to the relatively low rate of warming during the late spring–early summer (Fig. 6).

Likewise, the lack of a significant warming trend in October can speculatively be considered a result of the increasing depletion of soil water reserves during the longer and hotter summers. The decreasing soil moisture reserves due to increasing transpiration (Dezsi et al. 2018) leads to less heat being stored in the soil (given the lower heat capacity of dry soil) and thus a smaller ground heat and latent heat flux into the atmosphere from the soil in autumn. This would counteract the overall warming trend through a mechanism opposite to that proposed by Vecellio and Frauenfeld (2022) for permafrost regions, suggesting that increasing soil moisture leads to a range of feedback contributions to the autumn warming of surface air. We speculate that in a temperate climate setting, dryer soil would lead to an effect counteracting the warming trend.

Here, we have speculatively outlined some feedback mechanisms of land surface–atmosphere energy fluxes that can modulate surface air temperature. The identified mechanisms are based on the scientific literature but need proper validation. Nevertheless, we consider this to be a useful narrative in understanding the complex feedback between the climate and land surface processes, ranging from phenology (Kalvāne and Kalvāns 2021) to potential evapotranspiration (Dezsi et al. 2018), further leading to interactions with the hydrological cycle and to the propagation of droughts caused by climate-change-related atmospheric effects on groundwater (Babre et al. 2022).

5 Conclusions

We have examined observed air temperature data considering the last climate normal period, from 1991 to 2020, in Latvia. It was found that the annual mean air temperature increased by 1.2 °C compared to the reference period (1961 to 1990), indicating a strong warning in the Baltics at a rate of +0.4 °C decade^{-1}. The largest increase in mean air temperature was observed in winter (2.0 °C), followed by summer and spring (1.1 °C), with the least in autumn

(0.6 °C). October and May or June experienced no or only slight warming. Furthermore, we note that the minimal daily mean temperatures in autumn during the last climate normal increased at more than double the rate of the mean temperature increase, which was not the case for other seasons. Additionally, the annual mean temperature in coastal areas in Latvia is 2.2 °C higher compared to continental territories, and spatial differences are more pronounced during the winter season. In line with previous studies, we have identified a two-season spatial pattern for air temperature: one from April to July, dominated by an N–S gradient, and the other from August to March, dominated by a W–E gradient. We argue that the changing seasonal temperature patterns have nonlinear interactions with the soil water regime – A phenomenon that deserves further study to understand its climate change implications.

Appendix

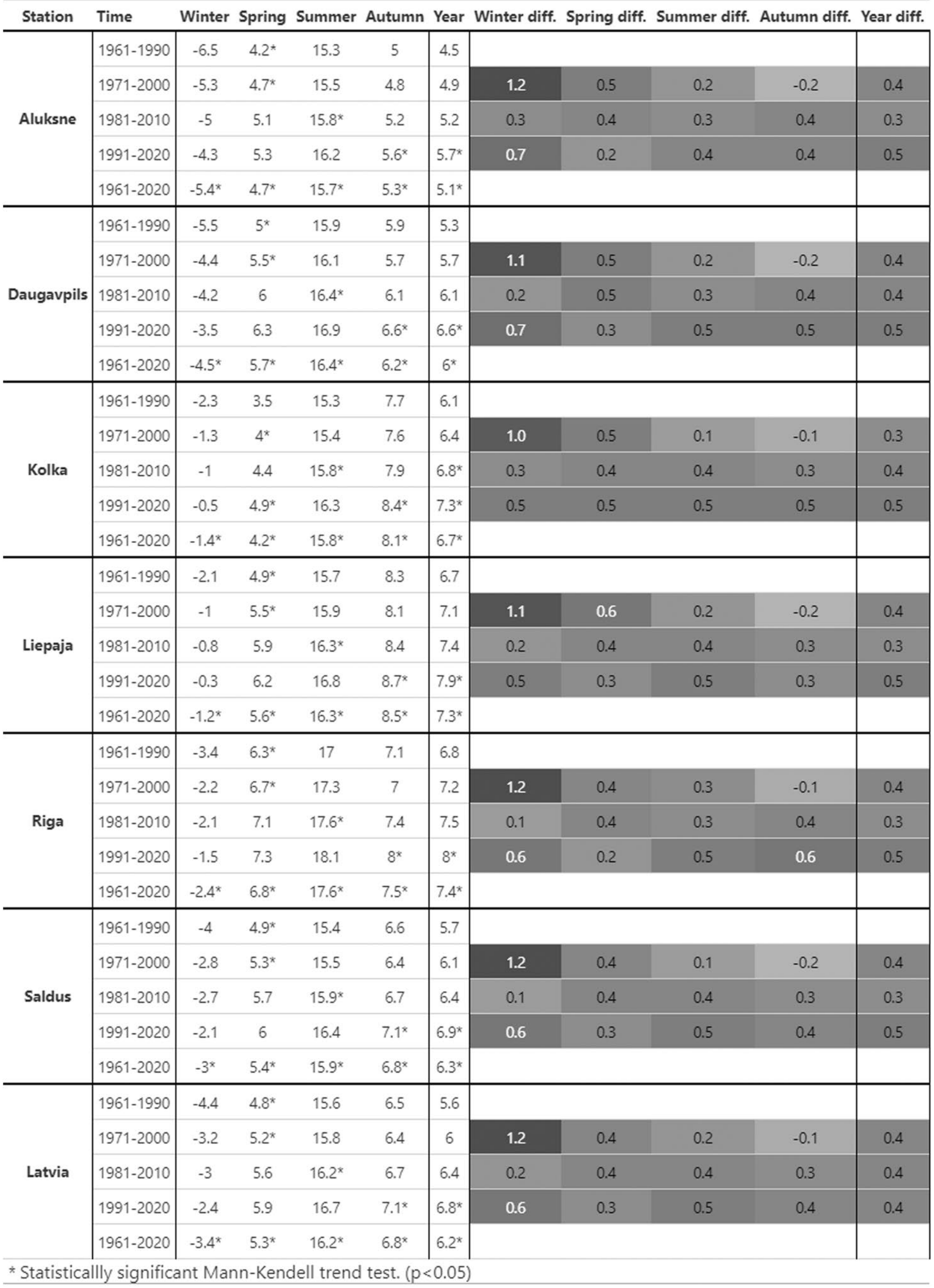


Fig. 8 Seasonal mean temperatures (°C) for the six selected meteorological stations and for Latvia (average of 25 meteorological stations) during the four climate normals and the reference period. On the right, differences in the air temperature during a particular climate normal compared to the previous normal (given as absolute values) are shown. *denotes statistically significant (5% level) using the Mann–Kendall test; the background shades of grey represent the same data as numbers with darker tones indicating stronger warming

Station	Time	Winter	Spring	Summer	Autumn	Year	Winter diff.	Spring diff.	Summer diff.	Autumn diff.	Year diff.
Aluksne	1961-1990	-6.5	4.2*	15.3	5	4.5					
	1971-2000	-5.3	4.7*	15.5	4.8	4.9	1.2	0.5	0.2	-0.2	0.4
	1981-2010	-5	5.1	15.8*	5.2	5.2	0.3	0.4	0.3	0.4	0.3
	1991-2020	-4.3	5.3	16.2	5.6*	5.7*	0.7	0.2	0.4	0.4	0.5
	1961-2020	-5.4*	4.7*	15.7*	5.3*	5.1*					
Daugavpils	1961-1990	-5.5	5*	15.9	5.9	5.3					
	1971-2000	-4.4	5.5*	16.1	5.7	5.7	1.1	0.5	0.2	-0.2	0.4
	1981-2010	-4.2	6	16.4*	6.1	6.1	0.2	0.5	0.3	0.4	0.4
	1991-2020	-3.5	6.3	16.9	6.6*	6.6*	0.7	0.3	0.5	0.5	0.5
	1961-2020	-4.5*	5.7*	16.4*	6.2*	6*					
Kolka	1961-1990	-2.3	3.5	15.3	7.7	6.1					
	1971-2000	-1.3	4*	15.4	7.6	6.4	1.0	0.5	0.1	-0.1	0.3
	1981-2010	-1	4.4	15.8*	7.9	6.8*	0.3	0.4	0.4	0.3	0.4
	1991-2020	-0.5	4.9*	16.3	8.4*	7.3*	0.5	0.5	0.5	0.5	0.5
	1961-2020	-1.4*	4.2*	15.8*	8.1*	6.7*					
Liepaja	1961-1990	-2.1	4.9*	15.7	8.3	6.7					
	1971-2000	-1	5.5*	15.9	8.1	7.1	1.1	0.6	0.2	-0.2	0.4
	1981-2010	-0.8	5.9	16.3*	8.4	7.4	0.2	0.4	0.4	0.3	0.3
	1991-2020	-0.3	6.2	16.8	8.7*	7.9*	0.5	0.3	0.5	0.3	0.5
	1961-2020	-1.2*	5.6*	16.3*	8.5*	7.3*					
Riga	1961-1990	-3.4	6.3*	17	7.1	6.8					
	1971-2000	-2.2	6.7*	17.3	7	7.2	1.2	0.4	0.3	-0.1	0.4
	1981-2010	-2.1	7.1	17.6*	7.4	7.5	0.1	0.4	0.3	0.4	0.3
	1991-2020	-1.5	7.3	18.1	8*	8*	0.6	0.2	0.5	0.6	0.5
	1961-2020	-2.4*	6.8*	17.6*	7.5*	7.4*					
Saldus	1961-1990	-4	4.9*	15.4	6.6	5.7					
	1971-2000	-2.8	5.3*	15.5	6.4	6.1	1.2	0.4	0.1	-0.2	0.4
	1981-2010	-2.7	5.7	15.9*	6.7	6.4	0.1	0.4	0.4	0.3	0.3
	1991-2020	-2.1	6	16.4	7.1*	6.9*	0.6	0.3	0.5	0.4	0.5
	1961-2020	-3*	5.4*	15.9*	6.8*	6.3*					
Latvia	1961-1990	-4.4	4.8*	15.6	6.5	5.6					
	1971-2000	-3.2	5.2*	15.8	6.4	6	1.2	0.4	0.2	-0.1	0.4
	1981-2010	-3	5.6	16.2*	6.7	6.4	0.2	0.4	0.4	0.3	0.4
	1991-2020	-2.4	5.9	16.7	7.1*	6.8*	0.6	0.3	0.5	0.4	0.4
	1961-2020	-3.4*	5.3*	16.2*	6.8*	6.2*					

* Statisticallly significant Mann-Kendell trend test. ($p<0.05$)

Station	Period	Winter			Spring			Summer			Autumn		
		5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
Aluksne	1961-1990	0.062	0.071*	0.058*	0.135*	0.041	0.046	-0.009	-0.007	-0.011	-0.025	-0.018	-0.077*
	1971-2000	0.098*	0.063*	0.063*	0.093*	0.070*	0.004	0.059*	0.005	-0.010	-0.124*	0.036*	-0.032
	1981-2010	0.014	0.042*	0.078*	0.009	0.071*	-0.012	0.038*	0.063*	0.080*	0.088*	-0.022	0.044*
	1991-2020	0.007	0.079*	0.048*	0.019	0.033	0.021	0.037*	0.020	0.051*	0.200*	0.050*	0.075*
	1961-2020	0.060*	0.084*	0.050*	0.064*	0.044*	0.014	0.022*	0.022*	0.031*	0.057*	0.011	0.014*
Daugavpils	1961-1990	0.087*	0.092*	0.079*	0.222*	0.047*	0.024	-0.025*	-0.017*	-0.025	-0.029	-0.015	-0.068*
	1971-2000	0.050	0.056*	0.064*	0.082*	0.089*	0.027	0.046*	0.005	0.006	-0.127*	0.040*	-0.004
	1981-2010	0.039	0.038*	0.071*	0.021	0.067*	0.000	0.036*	0.050*	0.091*	0.108*	-0.007	0.014
	1991-2020	0.062	0.092*	0.040*	0.063	0.035	0.013	0.042*	0.045*	0.026	0.207*	0.067*	0.066*
	1961-2020	0.072*	0.087*	0.058*	0.085*	0.047*	0.020*	0.021*	0.028*	0.035*	0.048*	0.016*	0.024*
Kolka	1961-1990	0.033	0.046*	0.063*	0.105*	0.011	0.041	-0.010	-0.003	-0.016	-0.030	-0.017	-0.047*
	1971-2000	0.099*	0.050*	0.023*	0.110*	0.066*	0.006	0.044*	0.022*	0.008	-0.063*	0.026	0.035*
	1981-2010	0.096*	0.034*	0.053*	0.032	0.055*	0.011	0.041*	0.066*	0.092*	0.044*	0.008	0.073*
	1991-2020	0.036	0.030*	0.043*	0.024	0.041*	0.086*	0.063*	0.037*	0.041*	0.131*	0.052*	0.053*
	1961-2020	0.094*	0.052*	0.042*	0.090*	0.036*	0.045*	0.027*	0.028*	0.038*	0.028*	0.012*	0.025*
Liepaja	1961-1990	0.065	0.064*	0.062*	0.165*	0.026	0.054	0.012	0.014*	-0.045*	0.000	-0.015	-0.050*
	1971-2000	0.094*	0.054*	0.010	0.106*	0.062*	0.036	0.052*	0.022*	-0.009	-0.104*	0.019	-0.004
	1981-2010	0.043	0.019	0.045*	0.005	0.066*	-0.027	0.043*	0.066*	0.089*	0.016	-0.014	0.059*
	1991-2020	-0.072*	0.024*	0.051*	0.041	0.045*	0.044	0.051*	0.033*	0.054*	0.158*	0.050*	0.062*
	1961-2020	0.065*	0.054*	0.038*	0.077*	0.041*	0.050*	0.032*	0.034*	0.036*	0.018*	0.006	0.022*
Riga	1961-1990	0.099*	0.086*	0.096*	0.153*	0.042	0.074*	0.000	0.011	0.011	-0.009	-0.015	-0.052*
	1971-2000	0.073	0.066*	0.056*	0.071*	0.089*	-0.006	0.041*	0.028*	-0.006	-0.078*	0.047*	0.012
	1981-2010	0.000	0.027	0.053*	-0.005	0.060*	-0.057*	0.043*	0.068*	0.065*	0.058	0.013	0.068*
	1991-2020	-0.043	0.053*	0.056*	0.032	0.037	0.062*	0.042*	0.033*	0.066*	0.184*	0.058*	0.086*
	1961-2020	0.059*	0.070*	0.055*	0.059*	0.041*	0.029*	0.031*	0.035*	0.038*	0.048*	0.023*	0.040*
Saldus	1961-1990	0.059	0.082*	0.100*	0.146*	0.025	0.043	0.009	-0.004	-0.005	-0.021	-0.020	-0.081*
	1971-2000	0.117*	0.051*	0.038*	0.089*	0.080*	0.031	0.056*	0.018*	-0.011	-0.084*	0.024	0.011
	1981-2010	0.022	0.020	0.044*	-0.018	0.076*	0.000	0.041*	0.069*	0.066*	0.060*	0.008	0.058*
	1991-2020	-0.074	0.046*	0.041*	0.020	0.038*	0.055*	0.050*	0.039*	0.050*	0.160*	0.055*	0.077*
	1961-2020	0.057*	0.065*	0.051*	0.070*	0.042*	0.039*	0.030*	0.030*	0.035*	0.028*	0.012*	0.019*
Latvia	1961-1990	0.062	0.081*	0.072*	0.152*	0.033	0.052*	0.005	0.000	0.000	0.009	-0.019	-0.070*
	1971-2000	0.106*	0.052*	0.036*	0.090*	0.079*	-0.012	0.041*	0.016*	-0.009	-0.087*	0.031*	0.000
	1981-2010	0.047	0.035*	0.062*	0.021	0.078*	-0.021	0.030*	0.062*	0.087*	0.072*	-0.005	0.045*
	1991-2020	-0.055	0.062*	0.058*	0.035	0.033	0.060*	0.045*	0.039*	0.067*	0.164*	0.054*	0.067*
	1961-2020	0.073*	0.073*	0.051*	0.072*	0.039*	0.029*	0.023*	0.030*	0.041*	0.037*	0.011	0.021*

* Statisticallly significant trend. (p<0.05)

Fig. 9 The 5th, 50th and 95th quantile regression slope (°C decade−1) for the six stations (Alūksne, Daugavpils, Kolka, Liepāja, Rīga, Saldus) and Latvia (average of 25 stations) estimated using the daily average air temperature over four seasons for the four different climate normals and the full 60-year period (respectively 1961–1990, 1971–2000, 1981–2010, 1991–2020 and 1961–2020); *values are statistically significant using the Mann–Kendall trend test (5% significance level); the background colour shows the same data as numbers – reds are positive, blues – negative and white – no trend

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Author contribution All authors contributed to the study conception and design. Data collection and analysis were performed by Andis Kalvāns (spatial data from E-OBS), Viesturs Zandersons (temporal data analyses) and Dace Gaile (quantile regression). The first draft of the manuscript was written by Gunta Kalvāne and Agrita Briede (Introduction) and Andis Kalvāns (Discussion), and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data sets generated during and analysed during the current study are available in the repository of LEGMC Latvian Environment, Geology and Meteorology Centre, [https://www.meteo.lv/meteorologija-datu-meklesana/?nid=461 in Latvian].

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Declarations

Competing Interests The authors declare no competing interests.

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