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Spatial and temporal changes of spring temperature, thermal growing season and spring phenology in Germany 1951–2015

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Abstract

Climate change has a strong impact on vegetation dynamics and the relationship between temperature changes and shifts in plant development is well known. However, temperature does not change homogeneously and high spatial and temporal variabilities are possible. For a 65-year period from 1951–2015, we examined trends of mean air temperatures and bioclimatic parameters such as the onset of thermal growing season and two relevant phenological stages in Germany. We focused our analysis only on statistical significant trends. In order to compare them for the same spatial and temporal resolution, gridded datasets were used. From 1951–2015 spring air temperature (March-May) increased by 1.9 K. In the same time the average onset of thermal growing season started 20 days earlier and the beginning of cherry flowering and leaf unfolding of silver birch was advanced by 11 and 13 days, respectively. Nevertheless, a high spatial variability of trends was detected for all parameters. Strongest shifts were more pronounced in coastal areas of Germany and the regional investigation showed significantly stronger trends for North Germany than for South Germany. The study confirmed a strong synchronisation of the temporal and spatial changes in air temperature and the investigated bioclimatic parameters.

Keywords: spring temperature, phenology, thermal growing season, trend, spatial distribution, Germany

1 Introduction

Various studies detected a worldwide temperature rise over the past decades (Werner et al., 2000; Hansen et al., 2006, 2010), with a high impact on temperature-driven environmental processes (Clark et al., 2010; Chmielewski and Rötzer, 2001). Temperature change does not run homogeneously and high spatial and temporal variabilities are possible. Several authors confirm this fact for different countries and regions, e.g. Japan (Schaefer and Domroes, 2009), the southwest karst area of China (Liu et al., 2015), Spain (Del Río et al., 2011) or the Murmansk Region of Russia (Blinova and Chmielewski, 2015). Also in Germany, the average temperature of the troposphere rose significantly from 1950s to 2013 by 0.2 ± 0.1 K per decade (Pattantyús-Ábrahám and Steinbrecht, 2015). The effect of this warming has been proven by Rapp (2000), who showed the existence of temporal and spatial variations of air temperature trends in Germany. Schönwiese and Janoschitz (2008) also demonstrated different temperature trends for Germany and concluded that the spatial variability and intensity of the trends is not only affected by the individual month or season, but also by the length of the observed time period. Small scale studies also showed local variations of temperature trends for different parts of Germany, e.g. in Northern Germany (Arora et al., 2016) and Western Germany (Hundecha and Bárdossy, 2005). Contemporaneously, an earlier timing of phenological events in Germany was observed (Chmielewski et al., 2004; Menzel, 2003), because plant phenology is a suitable and sensitive indicator to evaluate changes in ecosystems and shows a strong response to temperature changes (Cleland et al., 2007; Defila and Clot, 2001; Menzel et al., 2006). Rising spring temperatures in particular cause an earlier onset of phenological stages (Chmielewski et al., 2004) (e.g. leaf unfolding or flowering). Similarity of temperature and phenological changes in Germany was investigated for Baden-Württemberg and Hessen (Schröder et al., 2006, 2014). A high variability of spatial distribution in phenological events was examined for Germany (Scheifinger et al., 2002). However, a temperature change in spring not only affects the onset of individual phenological stages, but has also an impact to the whole growing season. Over the past decades warmer temperatures in the northern hemisphere led to an earlier onset and shift in the length of the growing season (Jeong et al., 2011; Park et al., 2016), which also was observed in Germany (Menzel et al., 2003). For an appropriate assessment of climate change and its impact on ecosystems, long-term data are absolutely necessary. Information about changes of climate conditions and its impacts in ecosystems can be derived from national meteorological observation networks, like the climate and phenological database of Germany's National Meteoro-

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logical Service (Deutscher Wetterdienst, DWD, Kaspar et al., 2014). Unfortunately, monitoring networks are usually inconsistent among themselves, because of the spatial and temporal distribution of data time series and the individual duration of the observation periods. A meaningful alternative are interpolated data, because they have the advantage to fill possible gaps in time and space. Furthermore, by choosing the same spatial resolution for different parameters, a uniform comparison of their changes and trends is possible.

The aim of the study was to investigate changes of three relevant parameters in spring: air temperature, phenology and onset of thermal growing season, in order to identify significant temporal and spatial trends of these parameters for Germany in the period 1951–2015. Additionally, we identified regional similarities and differences between them.

2 Material and methods

2.1 Air temperature data

Two datasets with different spatial and temporal resolutions were used to investigate significant changes of mean air temperature in Germany. The first dataset (E-OBS, Version 14.0) was provided by the EU-FP6 project ENSEMBLES (Haylock et al., 2008) and contains interpolated daily values of mean air temperature from 1951–2015. It has a gridded resolution of 0.25°, or about 25 × 25 km. In this resolution, Germany is represented by 731 grid cells.

The 'CDC' dataset was provided by the German National Meteorological Service (DWD) with a finer spatial resolution of 1 × 1 km, but only contains monthly mean air temperature from 1951–2015 (Kaspar et al., 2013) This dataset was used to validate the results of the E-OBS data.

2.2 Phenological data

In this study, phenological observations from the German phenological monitoring network of DWD from 1951–2015 were used. The network currently consists of about 1.100 volunteers who have been observing phenological data from several plant species since 1950. For this study we used the leaf unfolding dates (UL, BBCH 11) of silver birch (*Betula pendula L.*) and dates for the beginning of sweet cherry (*Prunus avium L.*) flowering (BF, BBCH 60). Both plant species are widespread in Germany and good representatives of phenological spring stages.

3 Method

To investigate spatial trends of mean air temperature in meteorological spring, we examined the average mean air temperature of March, April, May and the whole spring season (March-April-May, MAM) for the period of 1951–2015. Further we calculated the monthly and spring temperature average for every grid cell (731 in total). In order to calculate linear trends of air temperature, the method of least square regression was used with the *'year'* as independent variable. If the estimator was significantly different from zero ($\alpha < 0.05$), it was assumed that the trend is significant. The level of significance was determined by student's t-test.

3.1 Determination of onset of thermal growing season

In this study we used the method of Chmielewski (2013) to obtain the onset of thermal growing season. As data basis we used the E-OBS dataset, as daily values are required for the computation of growing season. Results of the onset dates are represented in day of year (DOY). The onset was defined by a base temperature of 5 °C. From 1951–2015 mean and annual onset per grid cell was calculated and tested for linear trends, including the significance level. We used least square regression to calculate the trends and determined the statistical significance with student's t-test

3.2 Interpolation of phenological data

Because of the irregular temporal and spatial distribution of phenological data, no consistent observation dataset was available. In order to analyse trends in the phenological data nevertheless we interpolated the two phenological stages (UL, BF) from 1951–2015 to a regular grid in the same spatial resolution as the E-OBS dataset (0.25°). In the first step we checked the phenological observations for plausibility and outliers, by using DWD quality criteria (better than '*dubious*') (Kaspar et al., 2013). Afterwards observations were removed, if they differed more than 30 days from the average of each phenological stage. At last we calculated a phenological grid dataset by using a combination of a distance-weighted-interpolation and geo-regression for elevation correction. In order to do this, for every single year between 1951 and 2015 a geo-regression (longitude, latitude, altitude) was calculated, based on the timing of phenological stages in Germany. Then, for every year and every grid cell the timing of the phenological stage and the altitude of the grid cell was estimated by distance-weighted-interpolation, using at least 10 surrounding stations. Finally, the timing of the phenological stage was adjusted at each grid cell to the altitude of the E-OBS dataset, using the previous altitude-regression of the interesting phenological stage. For instance, the mean altitude gradient (1951–2015) for UL was 3.1±1 and for BF 3.7±1 days per 100 meter of elevation.

At all gird cells linear trends and significance levels were also examined for the two interpolated phenological stages.

3.3 Regional analysis

To identify different regional trends of air temperature, onset of growing season and phenology, Germany was divided in a northern and southern part at midpoint altitude (~51.250° N). For both parts (N-Germany, S-Germany) the regional average of the significance level of the trend was calculated and compared. Differences in mean were checked with the Wilcoxon-Mann-Whitney-test (U-Test, $\alpha < 0.05$). Additional for a better identification of the regional trends, the upper and lower quartile of all significant trends were calculated and marked.

4 Results

4.1 Changes of air temperature

The annual mean air temperature for Germany from 1951–2015 was 8.60±1.17 °C. The temperature significantly increased by 0.25 K per decade and the mean annual temperature rise achieved 1.60 K over the 65-year period. The strongest increase of air temperature in all seasons occurred in spring with 0.30 K per decade (Table 1), which was highly significant.

The mean air temperature in spring (MAM) was 8.12±1.46 °C and increased from 1951–2015 by 1.93 K. Fig. 1 shows the spatial distribution of mean air temperature trends for March, April, May, MAM. Grid cells with a significant trend are coloured and non-significant cells are blank. The trend of MAM temperature varied among the grid cells from 0.17 K to 0.39 K per decade (Table 1). The strongest trends were mostly located in the coastal region of North Germany and in South-East Germany (Fig. 1, MAM). The average trend in N-Germany was 0.30 K per decade and significantly 0.02 K higher than in S-Germany, which had an average positive trend of 0.28 K per decade. The coldest month in spring was as expected March with an average air temperature of 3.90 °C, and only three-quarters of all grid cells had a significant temperature change (Table 1). Average March temperature increased significantly by 0.30 K per decade. Regionally, a high concentration of significantly positive trends was found in the North, especially near the Baltic Sea and along the German Bight (Fig. 1, March). This spatial tendency continues in April (Fig. 1, April), where the mean temperature trend in N-Germany was with a 0.05 K increase per decade significantly higher than in S-Germany (Table 1). In April, 99 % of the German territory showed significant temperature trends with the highest average rate among the spring months of 0.32 K per decade. Additionally, the strongest maximum trend of 0.45 K per decade was also found in April (Table 1). The spatial distribution of the temperature trends in May (Fig. 1, May) was in contrast to the two previous months. It has an opposite tendency, where S-Germany had a significant higher temperature change (0.30 K/10 a) than N-Germany (0.24 K/10 a). The average temperature rise in May was only 0.27 K per decade, but had regionally the widest range from 0.14 K per decade (minimum trend) to 0.44 K per decade (maximum trend, Table 1).

4.2 Changes in timing of phenological stages

In the period 1951–2015, leaf unfolding of silver birch started on 21 April and was followed 3 days later by the beginning of sweet cherry flowering (24 April). The standard deviation of both phenological stages had the same magnitude of about 8 days (Table 2). For both phenological stages a significantly earlier timing was detected, for the beginning of flowering (BF) of the sweet cherry −1.69 days and for the beginning of leaf unfolding (UL) of silver birch even −1.98 days per decade. For the whole 65-year period, BF of sweet cherry starts 11.0 days and UL of silver birch 12.9 days earlier than at the beginning of the period (Table 2). Further, the range and the spatial distribution of the trends were not evenly distributed across Germany and varied between −0.99 and −3.64 days per decade for UL and −1.06 and −2.67 days per decade for BF. Over and above this, a significant difference in the timing of both phenological stages between N- and S-Germany was observed (Table 2). UL of silver birch and BF of sweet cherry had emerged significant earlier in N-Germany (−2.3 d/10 a and −1.8 d/10 a, respectively), mainly at the coastal areas (Fig. 2).

4.3 Changes in onset of thermal growing season

The average onset of thermal growing season in Germany was on 19 March ($s = 16.4$ d). The range between the earliest and latest onset of all significant grid cells reached from 4 February till 15 April (34.5–104.5 DOY). In the period from 1951–2015 the onset date significantly decreased by altogether 20.3 days or 3.1 days per decade, respectively. We only detected negative trends for the onset dates with a range between −1.9 and −5.4 days per decade. The strongest shifts were located along and near the North Sea coast. Comparing N- with S-Germany, not only the occurrence of significant trends was more distinct in the North (Fig. 2, VB), but also the mean trend was significantly higher in N-Germany. The mean trend of the onset of growing season in S-Germany was only −2.8 days per decade and −4.1 days per decade in N-Germany, with a total difference between both regions of 1.25 days per decade (Table 2).

5 Discussion and conclusion

This study has shown that the average spring temperature (MAM) has increased by 0.30 K per decade and this temperature rise had a major impact on the onset of thermal growing season and timing of two relevant phenological spring stages. The total trend of 1.9 K for the spring temperature from 1951–2015 is almost identical with the results of Rapp (2000), where spring

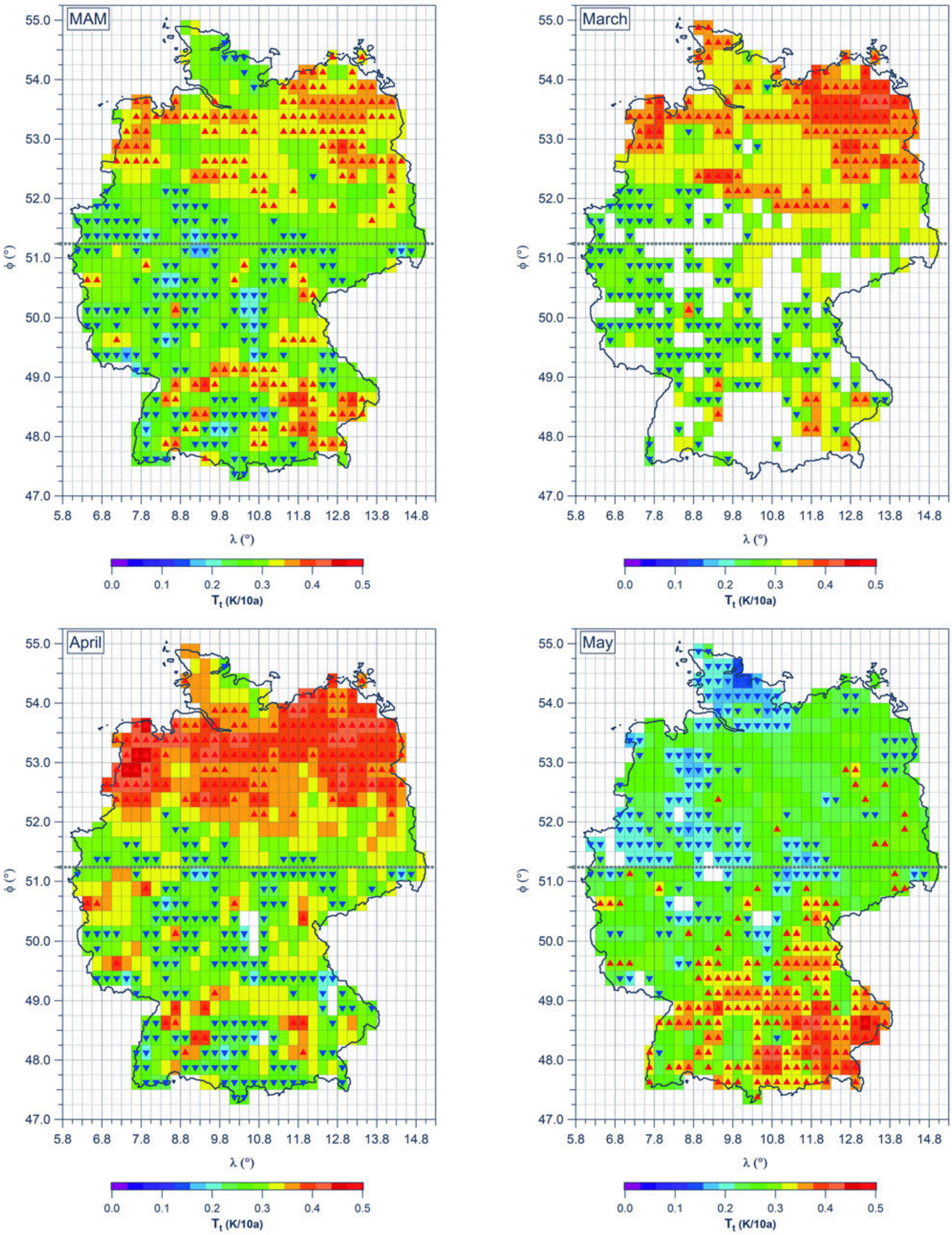

Figure 1: Significant trends (T_t) of mean air temperature in spring (MAM), March, April and May (1951–2015) in Germany, upper (▲) and lower (▼) quantiles of significant trends.

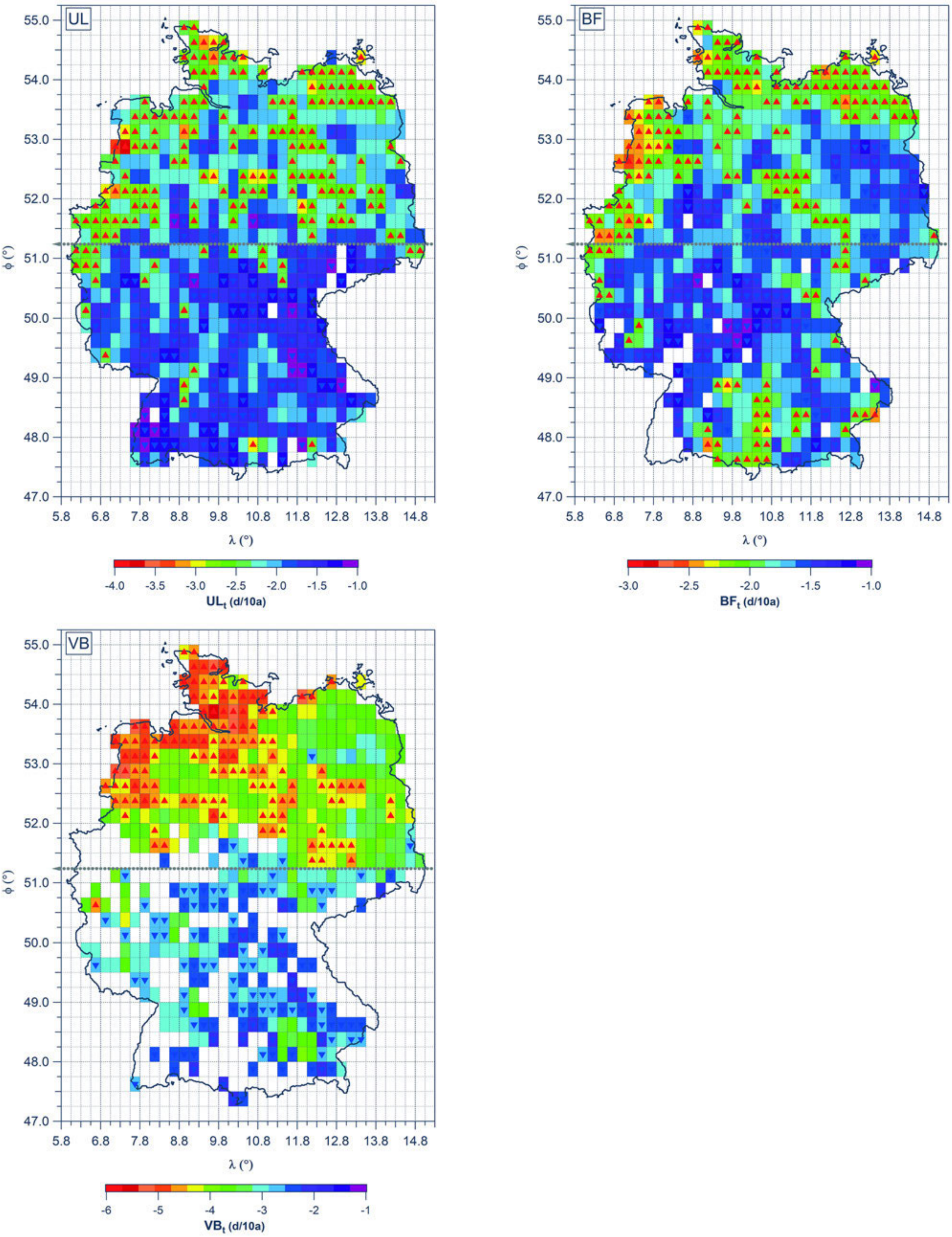

Figure 2: Significant trends of leaf unfolding of silver birch (UL_t), beginning of sweet cherry flowering (BF_t) and onset of thermal growing season (VB_t), 1951–2015 in Germany, upper (▲) and lower (▼) quantiles of significant trends.

Table 1: Statistics of E-OBS data: mean, standard deviation (s), average trend, p-value, percentage of significantly changed area, minimum & maximum trend of significant grid cells and average regional trend in N- and S-Germany, different letters per row indicate significant difference of mean trends (U-Test, $\alpha < 0.05$).

E-OBS	mean (°C)	s (°C)	trend (K/10a)	t-test $\alpha < 0.05$	sig. area (%)	min trend (K/10 a)	max trend (K/10 a)	north (K/10 a)	south (K/ 10a)
March	3.90	2.30	0.30	0.024	76.2	0.24	0.43	0.33^{a}	0.30^{b}
April	7.97	1.85	0.32	0.001	99.0	0.20	0.45	0.35^{a}	0.30^{b}
May	12.50	1.70	0.27	0.003	98.1	0.14	0.44	0.24^{b}	0.30^{a}
MAM	8.12	1.46	0.30	0.000	100.0	0.17	0.39	0.30^{a}	0.28^{b}
Year	8.60	1.17	0.25	0.000	100.0	0.15	0.35	0.24^{a}	0.25^{a}

Table 2: Statistics of phenological data (UL: leaf unfolding, BF: beginning of flowering) and onset of thermal growing season: mean, standard deviation (s), average trend, p-value, total change from 1951–2015, minimum & maximum trend of significant grid cells and average regional trend in N- and S-Germany, different letters per row indicate significant difference of mean trends (U-Test, $\alpha < 0.05$).

	mean (DOY)	s (d)	trend (d/10 a)	*t*-test $\alpha < 0.05$	trend (d/65 a)	min trend (d/10 a)	max trend (d/10 a)	north (d/10 a)	south (d/10 a)
UL silver birch	21 April (111.1)	7.68	−1.98	0.000	−12.86	−0.99	−3.64	-2.26^{b}	-1.75^{a}
BF sweet cherry	24 April (113.9)	8.29	−1.69	0.001	−11.01	−1.06	−2.67	-1.82^{b}	-1.63^{a}
onset growing season	19 March (77.6)	16.39	−3.13	0.003	−20.34	−1.93	−5.44	-4.06^{b}	-2.81^{a}

temperature in Germany was found to have risen between 0.5 °C and 1.8 °C in the period 1966–1995. Further we found that the increase of spring temperatures is not homogenously distributed across Germany. Mainly the March and April temperature increased stronger in N- than in the S-Germany with significant differences between the two regions (Table 1). In both months, coastal areas always showed the strongest trend. This tendency (Fig. 1, March, April) is in agreement with the spring temperature contour maps from Rapp (2000) for the period 1966–1995. Furthermore, Schönwiese and Janoschitz (2008) also confirmed strong temperature trends in NE-Germany for the period 1971–2000 (cf. Fig. 1, MAM, March, April), but most of them were non-significant. Rapp (2000) supposed that the higher standard deviation in S-Germany makes it more difficult to detect significant trends.

The stronger increase of air temperature in the northern region can be explained by two mechanisms. First, a rather modest warming of the ocean in Western Europe, mainly in the North Sea and Germany Bight (Holt et al., 2012), has a more distinct effect on air temperatures in coastal areas. Contemporaneously, rising temperatures in the Baltic Sea were observed, especially in the end 20th century, which were related to changes in atmospheric circulation (Omstedt et al., 2004). Strongest trends of changing surface temperatures were found in the southern Baltic Sea for spring and summer in the period 1958–2009 (Lehmann et al., 2011). A synchronous ecological regime shift in North Sea and Baltic Sea (Alheit, 2005) supports this hypothesis. Additionally, Rapp (2000) found that the climate of North and Central Germany is becoming more maritime than that of South Germany, which is becoming slightly more continental. He assumed that the temperature change is linked with a more zonal character of the European circulation.

The second reason of a stronger warming in the northern regions of Germany can be explained by the snow albedo feedback mechanism. The decline of snow cover duration in the Baltic region between 1920/1921–1994/1995, was investigated by Jaagus (1997) and could additionally explain the stronger temperature rise in March and April in N-Germany (Fig 1, March, April).

In order to verify our temperature trends in spring we used an alternative dataset for the same period. The ‘CDC’ dataset (cf. Table 1&3) showed nearly the same values for the mean air temperatures and standard deviations in Germany. Small differences only occurred because of a slightly positive temperature bias (higher mean) and over-smoothing (lower SD) in the E-OBS dataset (Hofstra et al., 2009). The magnitude of the calculated temperature trends was identical (cf. Table 1&3) and the significant trends had almost the same spatial distribution (data not shown). The difference in the amount of significant areas between both datasets did only occur because of the different spatial resolution of the two datasets. The results show that the calculated trends in monthly and seasonal air temperature are consistent between both datasets and are not arbitrary.

Rising temperatures, mainly in March and April, had a direct impact on the onset of growing season, which advanced by 20 days in the period 1951–2015. The regional temperature trend between N- and S-Germany in March and April was in accordance with our trends for onset of growing season. The strongest changes in the onset of growing season were also observed in N-Germany, first of all in the North Sea coastal region (Fig. 2, VB), where more significant trends were detected. The difference in the onset dates between N- and S-Germany was 1.25 days (Table 2).

Table 3: Statistics of CDC (temperature dataset from Climate Data Centre of DWD) data: mean, standard deviation (s), average trend, p-value, percentage of significantly changed area, minimum & maximum trend of significant grid cells and average regional trend in N- and S-Germany, different letters per row indicate significant difference of mean trends (U-Test, $\alpha < 0.05$)

CDC	mean (°C)	s (°C)	trend (K/10 a)	t-test $\alpha < 0.05$	sig. area (%)	min trend (K/10 a)	max trend (K/10 a)	north (K/10 a)	south (K/10 a)
March	3.89	2.34	0.30	0.024	76.5	0.23	0.52	0.33^{a}	0.30^{b}
April	7.94	1.92	0.32	0.001	98.7	0.18	0.51	0.35^{a}	0.30^{b}
May	12.48	1.78	0.27	0.003	98.4	0.13	0.53	0.24^{b}	0.30^{a}
MAM	8.11	1.55	0.30	0.000	99.9	0.13	0.52	0.30^{a}	0.29^{b}

Moreover, for both phenological stages, UL silver birch and BF sweet cherry, the predominate area of strong negative trends are again the coastal regions of Baltic and North Sea (Fig. 2, UL, BF). Except for May temperature, which is usually not relevant for the timing of thermal growing season and the majority of phenological spring events in Germany, trends in all other examined times series (temperature, onset of growing season, phenology) showed a strong synchronisation of temporal and spatial trends. This means that significant changes of air temperature in spring, mainly in March and April, are well linked with bioclimatic parameters, such as the onset of growing season and timing of phenological spring events. This result additionally confirms the worldwide findings of Walther et al. (2002) and Rosenzweig et al. (2007). It showed that even in a small territory like Germany a high spatial heterogeneity in temperature rise can be observed.

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References

Alheit, J., C. Mollmann, J. Dutz, G. Kornilovs, P. Loewe, V. Mohrholz, N. Wasmund, 2005: Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. – ICES J. Marine Sci. **62**, 1205–1215.

Arora, R., K. Tockner, M. Venohr, 2016: Changing river temperatures in northern Germany. Trends and drivers of change. – Hydrol. Process. **30**, 3084–3096.

Blinova, I., F.-M. Chmielewski, 2015: Climatic warming above the Arctic Circle: are there trends in timing and length of the thermal growing season in Murmansk Region (Russia) between 1951 and 2012? – Int. J. Biometeorol. **59**, 693–705.

Chmielewski, F.-M., 2013: Phenology in agriculture and horticulture (chapter 29). – In: Schwartz, M.D. (Ed.): Phenology: an integrative environmental science. – Springer Science+Business Media B.V. Dordrecht, 2nd Edition, 539–561.

Chmielewski, F.-M., T. Rötzer, 2001: Response of tree phenology to climate change across Europe. – Agricult. Forest Meteor. **108**, 101–112.

Chmielewski, F.-M., A. Müller, E. Bruns, 2004: Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. – Agricult. Forest Meteor. **121**, 69–78.

Clark, R.M., R. Thompson, 2010: Predicting the impact of global warming on the timing of spring flowering. – Int. J. Climatol. **30**, 1599–1613.

Cleland, E.E., I. Chuine, A. Menzel, H.A. Mooney, M.D. Schwartz, 2007: Shifting plant phenology in response to global change. – Trends in Ecology & Evolution **22**, 357–365.

Defila, C., B. Clot, 2001: Phytophenological trends in Switzerland. – Int. J. Biometeorol. **45**, 203–207.

del Río, S., L. Herrero, C. Pinto-Gomes, A. Penas, 2011: Spatial analysis of mean temperature trends in Spain over the period 1961–2006. – Global Planetary Change **78**, 65–75.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D.W. Lea, Medina-Elizade, M., 2006: Global temperature change. – PNAS **103**, 14288–14293.

Hansen, J., R. Ruedy, M. Sato, K. Lo, 2010: Global surface temperature change. – Rev. Geophys. **48**, RG4004, DOI: 10.1029/2010RG000345.

Haylock, M.R., N. Hofstra, A.M. Tank, G. Klein, E.J. Klok, P.D. Jones, M. New, 2008: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. – J. Geophys. Res. Atmos. **113**, D20119, DOI: 10.1029/2008JD010201.

Hofstra, N., M.R. Haylock, M. New, P.D. Jones 2009: Testing E-OBS European high-resolution gridded data set of daily precipitation and surface temperature. – J. Geophys. Res. **114**, D21101, DOI:10.1029/2009JD011799.

Holt, J., S. Hughes, J. Hopkins, S.L. Wakelin, N. Penny Holliday, S. Dye, C. González-Pola, S. Hjøllo, K.A. Mork, , G. Nolan, R. Proctor, J. Read, T. Shammon, T. Sherwin, T. Smyth, G. Tattersall, B. Ward, K.H. Wiltshire, 2012: Multi-decadal variability and trends in the temperature of the northwest European continental shelf. A model-data synthesis. – Progress in Oceanography **106**, 96–117.

Hundecha, Y., A. Bárdossy, 2005: Trends in daily precipitation and temperature extremes across western Germany in the second half of the 20th century. – Int. J. Climatol. **25**, 1189–1202.

Jaagus, J., 1997: The impact of climate change on the snow cover pattern in Estonia. – Climatic Change **36**, 65–77.

Jeong, S.-J., C.-H. Ho, H. -J. Gim, M.E. Brown, 2011: Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008. – Global Change Biol. **17** , 2385–2399.

Kaspar, F., G. Müller-Westermeier, E. Penda, H. Mächel, K. Zimmermann, A. Kaiser-Weiss, T. Deutschländer, 2013: Monitoring of climate change in Germany – data, products and services of Germany's National Climate Data Centre. – Adv. Sci. Res. **10**, 99–106.

Kaspar, F., K. Zimmermann, C. Polte-Rudolf, 2014: An overview of the phenological observation network and the phenological database of Germany's national meteorological service (Deutscher Wetterdienst). – Adv. Sci. Res. **11**, 93–99.

Lehmann, A., K. Getzlaff, J. Harlass, 2011: Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. – Climate Res. **46**, 185–196.

Liu, B., C. Chen, Y. Lian, J. Chen, X. Chen, 2015: Long-term change of wet and dry climatic conditions in the southwest karst area of China. – Global Planetary Change **127**, 1–11.

Menzel, A., 2003: plant phenological anomalies in Germany and their relation to air temperature and NAO. – Climatic change **57**, 243–263.

Menzel, A., G. Jakobi, R. Ahas, H. Scheifinger, N. Estrella, 2003: Variations of the climatological growing season (1951–2000) in Germany compared with other countries. – Int. J. Climatol. **23**, 793–812.

Menzel, A., T.H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kübler, P. Bissoli, O. Braslavska, A. Briede, F. -M. Chmielewski, Z. Crepinsek, Y. Curnel, Å. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatczak, F. Mage, A. Messtre, Ø. Nordli, J. Peñuelas, P. Pirinen, V. Remi Ova, H. Scheifinger, M. Striz, A. Susnik, A. van Vliet, F. -E. Wielgolaski, S. Zach, A.N. Zust, 2006: European phenological response to climate change matches the warming pattern. – Global Change Biol. **12**, 1969–1976.

Omstedt, A., C. Pettersen, J. Rodhe, P. Winsor, 2004: Baltic Sea climate. 200 yr of data on air temperature, sea level variation, ice cover, and atmospheric circulation. – Climate Res. **25**, 205–216.

Park, T., S. Ganguly, H. Tømmervik, E.S. Euskirchen, K.-A. Høgda, S.R. Karlsen, V. Brovkin, R.R. Nemani, R.B. Myneni, 2016: Changes in growing season duration and productivity of northern vegetation inferred from long-term remote sensing data. – Env. Res. Lett. **11**, 84001.

Pattantyús-Ábrahám, M., W. Steinbrecht, 2015: Temperature trends over Germany from homogenized radiosonde data. – J. Climate **28**, 5699–5715.

Rapp, J., 2000: Problematik und Ergebnisse klimatologischer Trendanalysen für Europa und Deutschland. – Berichte des Deutschen Wetterdienstes **212**, Offenbach am Main: Selbstverlag des Deutschen Wetterdienstes.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, P. Tryjanowski, C.E. Hanson, 2007: Assessment of observed changes and responses in natural and managed systems. – In: Climate Change, 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden (Eds.) – Cambridge University Press, 79–131.

Schaefer, D., M. Domroes, 2009: Recent climate change in Japan – spatial and temporal characteristics of trends of temperature. – Clim. Past **5**, 13–19.

Scheifinger, H., A. Menzel, E. Koch, C. Peter, R. Ahas, 2002: Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in central Europe. – Int. J. Climatol. **22**, 1739–1755.

Schönwiese, C.-D., R. Janoschitz, 2008: Klima-Trendatlas Europa 1901–2000. – Berichte des Instituts für Atmosphäre und Umwelt der Universität Frankfurt, Frankfurt/Main.

Schröder, W., G. Schmidt, J. Hasenclever, 2006: Geostatistical analysis of data on air temperature and plant phenology from Baden-Württemberg (Germany) as a basis for regional scaled models of climate change. – Env. Monitoring Assessment **120**, 27–43.

Schröder, W., G. Schmidt, S. Schönrock, 2014: Modelling and mapping of plant phenological stages as biometeorological indicators for climate change. – Env. Sci Eur **26**, 5. https://doi.org/10.1186/2190-4715-26-5.

Walther, G.-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.-M. Fromentin, O. Hoegh-Guldberg, F. Bairlein, 2002: Ecological responses to recent climate change. – Nature **416**, 389–395.

Werner, P.C., F.-W. Gerstengarbe, K. Fraedrich, H. Oesterle, 2000: Recent climate change in the North Atlantic/European sector. – Int. J. Climatol. **20**, 463–471.