Abstract  The rise of air temperature as one result of climate change affects the developmental stages of plants. In Germany, systematic observation of plant phenology development is established by help of International Phenological Gardens (IPGs) and by the phenological network of the German Meteorological Service (DWD) with up to 6500 observation sites for 270 phenological plant phases. Case study 1 aims at quantifying the statistical association between distinct plant phenological phases (‘phenophases’) and measured air temperatures in Germany. This should help in future projections on possible impacts of climate change on plant development and distribution. Accordingly, data on mean annual air temperatures and country-wide observations on 6 phases indicating different plant phenological seasons were analysed by means of regression analysis. Within a Geographic Information System (GIS), Regression Kriging was applied for mapping the development of plant phenology in the past and also in future by using projected temperature data for the climate reference periods 1991–2020, 2021–2050, and 2051–2080 derived from two different climate models (REMO, WettReg) and two emission scenarios (A1B, B1). The results showed already for the comparison of the past climate periods 1961–1990 and 1991–2005 a distinct shift of phenological onset towards the beginning of the year by about 9 days in average for all 6 phases investigated. The strongest shift was observed for hazel bloom advancing 13 days to the beginning of the year. In future, a shift of up to 33 days was calculated comparing data of 1961–1990 and 2051–2080. Since WettReg projections assume a moderate temperature rise, the projected phenological shifts were not that pronounced compared to REMO scenarios. Hence for WettReg B1, a shift by only 17 days was calculated for the beginning of hazel bloom. The strongest relationship between annual air temperatures and phase onset was found for phenophases in spring and, accordingly, the shifts in the beginning of phenophases indicating the spring season were most intense. The algorithms describing the statistical relation between temperature rise and phenology development were integrated into the “Technical Information System on Climate Change and Adaptation Strategies” (Fachinformationssystem Klimawandel und Anpassung, FISKA) which was initiated by the Federal Environment Agency and administered by the Competence Centre on Climate Impacts and Adaptation (KomPass). For implementation, so called ‘calculation engines’ were developed for all 6 indicator phases, each calculating the beginning of the respective phenological phase in days after New Year based on the respective mean annual air temperatures. That allows for future assessments when improved
emission scenarios or climate models are available in order to develop well adapted mitigation measures considering environmental, agricultural and economic issues emerging from changes in plant growth and distribution.

**Keywords** German adaptation action plan · Phenological monitoring · Climate change impacts · Mitigation measures · Expert knowledge system

### 2.1 Background and Goals

According to the recently published Summary for Policymakers (SPM)\(^1\), condensing the most important findings of the latest IPCC report in 2013, it can be stated that “each of the last three decades has been successively warmer at the Earth’s surface than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years” (IPCC 2013, p. 3). Even in 2005, the German government claimed to limit the global temperature increase to +2 °C compared to the pre-industrial state\(^2\). This statement, in fact, relies on recommendations of the German Advisory Council on Global Change (Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU) released already in 1995\(^3\) (Jaeger and Jaeger 2011).

However, even a rise of +2 °C will induce various impacts on environment, economy, and society. Hence, the German adaptation strategy on climate change (Deutsche Anpassungsstrategie—DAS)\(^4\) describes potential impacts, goals, possible conflicts, and adaptation measures including climate risk assessment and management as well as disaster risk reduction strategies for national policies and programmes. For putting this into action, 13 fields of investigation were defined comprising environmental impacts as well as socio-economic issues. However, in contrast to a report published by the European Environmental Agency (EEA 2008), the DAS provides no spatial differentiation of climate change induced observed or projected environmental impacts in Germany. Thus, the implementation of the “Expert Information System on Climate Change and Adaption” (FISKA) was initiated by the German Federal Environment Agency and administered by the Competence Centre on Climate Impacts and Adaptation (KomPass)\(^5\). FISKA shall provide the governmental institutions with basic information and models on climate change impacts for the development and accomplishment of adaption and mitigation strategies. A main objective was to implement an information system providing certain impact models that make it possible to provide spatially differentiated data and models to enable preventive assessment of possible impacts of climate change (Schröder et al. 2010). Accordingly, the approach based on a Geographic

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2 [http://www.bmu.de/N35742](http://www.bmu.de/N35742).
4 [http://www.bmu.de/N42783](http://www.bmu.de/N42783).
Information System (GIS). The GIS prototype was provided with exemplary data and calculation kernels that enable modelling certain impacts of climate change for different spatial extents and periods (Schmidt et al. 2010). One of these kernels allows projection of plant phenology development (Sect. 2.1) by example of six different phenophases (Sect. 2.2.1). For mapping spatial patterns of phenology development (Sect. 2.4), Regression Kriging (Sect. 2.3) was applied within a GIS environment relying on the statistical association between air temperatures and phenophases’ onset. Accordingly, the derived regression functions were applied for different temperature grids based on two climate models (REMO, WettReg) regarding two IPCC emission scenarios (B1, A1B) and covering climate periods in the past (1961–1990, 1991–2005) and in the future (1991–2020, 2021–2050, 2051–2080) (Sect. 2.2.2).

2.2 Materials

For mapping the developmental stages of plants in Germany certain phenophases were correlated with air temperature measurements for two observation periods in the past (1961–1990, 1991–2005). The resulting regression equations were also used for depicting possible future development of phenophase onset regarding the respective climate projections.

2.2.1 Phenology Data

In Germany, systematic observation of plant phenology is established by international phenological gardens and by the phenological network of the German Meteorological Service (DWD) with up to 6500 observation sites (Fig. 2.1, right). For case study 1, phenological observations on 6 phases indicating different plant phenological seasons were analysed by means of regression analysis (Sect. 2.3): hazel (beginning of flowering pre-spring), forsythia (beginning of flowering, first spring), apple (beginning of flowering, full spring), elder (first bloom, early summer), large-leaved lime (first bloom, midsummer), and apple (fruit maturity, late summer) (Table 2.1). Data on phenology observations were available from 1961 to 2005.

The phenological observations at each site were conducted two or three times a week within a defined area with a radius of 5 km by volunteers according to a guideline published by the German Weather Service (DWD 1991). Phenological data were provided as vector data sets (point layer) and were processed within a GIS environment. For analysis, all those observation sites were considered where for at

least 80% of the years within an observation period records were available. Accordingly, for the climate reference period 1961–1990 there had to be at least 24 observations at a particular site and for the period 1991–2005 at least 12 observations. By performing T-tests and by comparing descriptive statistical measures it could be assured that there were no significant differences between both data cohorts comparing sites with a complete temporal coverage and sites with an 80% coverage.

### 2.2.2 Data on Air Temperatures

Data on mean monthly air temperatures were provided by the German Meteorological Service (DWD) for the climate reference period 1961–1990 and the period
2.2 Materials

1991–2009. The data are based on about 670 measurement stations spread across Germany (Fig. 2.1, left). These local measurements were transformed to surface maps (Fig. 2.2) by means of Regression Kriging (Sect. 2.3). This was performed by correlating temperature values and altitudes of the respective measurement sites. The correlation coefficients indicated high \( r = 0.75–0.83 \) and significant relationships. In the GIS, the regression model was used to calculate high resolution long-term annual temperature maps for both periods based on the global digital elevation model GLOBE\(^8\) (spatial resolution = 1 × 1 km\(^2\)).

Temperature data for future climate reference periods 1991–2020, 2021–2050, and 2051–2080 were derived from the climate projections REMO (Regional Model; Max Planck Institute for Meteorology) (Jacob et al. 2008) and WetReg (Weather Condition-based Regionalisation Method; Climate & Environment Consulting Potsdam) (Spekat et al. 2006) which are based on the global ECHAM5 climate model. ECHAM5 is the 5th generation of the ECHAM general circulation model. Depending on the configuration, the model resolves the atmosphere up to 10 hPa for tropospheric studies or up to 0.01 hPa for middle atmosphere studies (often referred to as MAECHAM5) (Roeckner et al. 2006). Both REMO and WetReg projections were applied considering two emission scenarios: Scenario A1B assumes a rapid economic growth, a global population reaching a number of 9 billion in 2050 and then showing a gradual decline, the quick spread of new and efficient technologies and a balanced use of all energy sources. Scenario B1 assumes a more integrated and more ecologically healthy world with rapid economic growth as in A1. Further assumptions include, rapid changes towards a service and information economy, a population increasing up to 9 billion in 2050 and then declining as in scenario A1B, although with reductions in material intensity and the introduction of clean and resource efficient technologies as well as an emphasis on global solutions to economic, social and environmental stability (IPCC 2007). The spatial resolution of both REMO and WetReg grids was 12 × 12 km\(^2\).

Compared with WetReg (Fig. 2.3), REMO (Fig. 2.4) estimates higher temperatures and stronger increase. Regarding climate model WetReg and emission scenario B1, which supposes a more moderate rise of greenhouse gases, the overall air temperature mean should increase by 1.0 °C (Fig. 2.3, lower row) comparing the periods 1991–2020 and 2051–2080 whereas for the scenario A1B air temperatures are expected to increase by about 1.7 °C (Fig. 2.3, upper row).

Regarding climate model REMO and emission scenario B1, the overall air temperature mean should increase by 1.2 °C (Fig. 2.4, lower row) comparing the periods 1991–2020 and 2051–2080 whereas for the scenario A1B the modelled temperature increase was 2.2 °C (Fig. 2.4, upper row).

\(^8\) http://www.ngdc.noaa.gov/mgg/topo/globe.html.
Fig. 2.2 Long-term annual means on air temperatures in Germany for the climate reference period 1961–1990 (left) and the period 1991–2009 (centre) as well as according differences between both periods (right).
Fig. 2.3  Projected long-term annual means on air temperatures in Germany for the climate periods 1991–2020 (left), 2021–2050 (centre) and period 2051–2080 (right) according to climate model WettReg and considering emission scenario A1B (upper row) and B1 (lower row)
Fig. 2.4: Projected long-term annual means on air temperatures in Germany for the climate periods 1991–2020 (upper row), 2021–2050 (centre row) and period 2051–2080 (lower row) according to climate model REMO and considering emission scenario A1B (upper row) and B1 (lower row).
2.3 Methods

For a spatially differentiated view on the respective phenological shifts in Germany the mapping results derived by Regression Kriging (Sect. 2.3) were intersected in a GIS with a map on Germany’s ecoregions (Schmidt 2002; Schröder and Schmidt 2001). Ecological land classifications were computed based on data which represent several interacting factors which may be of importance for natural processes such as the developmental stages of plants. The ecological land classification used for case study 1 was calculated from the data listed in Table 2.2 applying Classification and Regression Trees (CART) (Breiman et al. 1984). The respective computations yielded a map (Fig. 2.5) illustrating the patterns of spatially discriminated and ecologically defined land classes which synonymously are called ‘natural land classes’, ‘ecoregions’ or ‘landscapes’ (Schröder 2006, Schröder et al. 2006b). All ecoregions are itemised with regard to the values or the statistical distribution of values of 48 ecological characteristics which were used to generate the land classes by use of CART (Schröder and Schmidt 2001).

2.2.3 Ecological Land Classification

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The following table shows the data used for ecological land classification:

<table>
<thead>
<tr>
<th>Map title</th>
<th>Period/state</th>
<th>GIS layer</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential natural vegetation</td>
<td>1998</td>
<td>1</td>
<td>BfN</td>
</tr>
<tr>
<td>Soil texture</td>
<td>2000</td>
<td>1</td>
<td>BGR</td>
</tr>
<tr>
<td>Altitude above sea level</td>
<td>1996</td>
<td>1</td>
<td>UNEP</td>
</tr>
<tr>
<td>Mean of monthly global radiation March–November</td>
<td>1981–1999</td>
<td>9</td>
<td>DWD</td>
</tr>
<tr>
<td>Mean of monthly evaporation January–December</td>
<td>1961–1990</td>
<td>12</td>
<td>DWD</td>
</tr>
<tr>
<td>Mean of monthly precipitation January–December</td>
<td>1961–1990</td>
<td>12</td>
<td>DWD</td>
</tr>
<tr>
<td>Mean of monthly air temperature January–December</td>
<td>1961–1990</td>
<td>12</td>
<td>DWD</td>
</tr>
</tbody>
</table>


2.3 Methods

For generating maps depicting the mean beginning of certain phenological phases in Germany, Pearson’s correlation coefficients between long-term annual air temperature and each phenological phase were calculated for both periods 1961–1990 and 1991–2005. For each observation site of the phenological network the according temperature value was extracted from the temperature grid (Figs. 2.2, 2.3, 2.4) averaged for each period. Like for processing the air temperature maps for the climate periods in the past (Sect. 2.2.2), Regression Kriging (Hengl et al. 2007; Odeh et al. 1995) was performed to derive maps on the phenological development: Regression functions for both periods in the past (1961–1990, 1991–2005) were applied in the GIS to map the beginning of the respective phenological phase. Residual maps on the differences between measured and modelled temperatures were calculated by
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Fig. 2.5. Ecoregions of Germany calculated by CART (Classification and Regression Trees) from the data in Table 2.1. (According to Schröder and Schmidt 2001)
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