TECHNISCHE UNIVERSITÄT MÜNCHEN
Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt
Fachgebiet für Ökoklimatologie

Detection of the impacts of climate change on plants from novel unexploited long-term datasets

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Vollständiger Abdruck der von der Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften

genehmigten Dissertation.

Vorsitzender: Univ.-Prof. Dr. A. Göttlein

Prüfer der Dissertation: 1. Univ.-Prof. Dr. A. Menzel
2. Univ.-Prof. Dr. T. H. Sparks

Die Dissertation wurde am 03.02.2014 bei der Technischen Universität München eingereicht und durch die Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt am 14.04.2014 angenommen.

ABSTRACT

Background and aims

Analysing phenological records is a useful way to detect climate change. Examining how species have responded to temperature in the past gives insights into how they may respond in a warmer future climate. In the last decades, considerable research effort has been directed at tracking climate change impacts in physical and biological systems. Changes in plants' life cycle were marked to earlier phenological onset dates and a lengthening of the plant growing season. Phenological response, in turn, can *inter alia* also affect natural ecosystems, human health and the productivity of agricultural systems. However, consistent and detailed long-term phenological datasets are rare for numerous regions and species and – if existing – difficult to locate. Novel long-term and therefore yet unexploited datasets may provide unique or unconventional information on climate change. Such long-term records may consist of unusual phenological observations, human induced activities or measures which are associated to phenological events. Such datasets can be used as indicators of environmental change and may consequently act as proxies for temperature reconstruction.

The major focus of the PhD thesis was to locate, generate and analyse unique long-term (>20 years) datasets suitable for the detection of climate change impacts. Thus, the thesis comprised research work to identify datasets that provide additional information on climate change. By processing and analysing the data, environmental change and the causes of change are then identified. In the course of the analysis, abiotic drivers were disentangled from anthropogenic drivers and therefore the impacts of climatic factors, especially temperature, affecting ecosystems could be evaluated. The additional information and insights, as well as the applicability of these previously unexploited phenological observations were discussed. Consequences of shifting phenological events and phases were evaluated and potential conflicts *inter alia* in terms of ecology, economics and human health were elaborated. Therefore, the findings may help to inform policy-makers of the necessary steps to minimize adverse consequences in an uncertain future.

This thesis is divided into three leading questions: (1) What are the anthropogenic and abiotic drivers influencing the phenological signal of the novel datasets? How can we distinguish natural climatic from anthropogenic influences? (2) What criteria have to be met by novel datasets to qualify as indicators for climate change impact? (3) What is the informative value and applicability of novel datasets and what kind of insights in terms of ecology, economics and applied conservation can be achieved?

Material and Methods

Data acquisition was carried out in numerous research libraries and archives of the *Landesanstalt für Weinbau und Gartenbau* (LWG) in Veitshöchheim, at the wineries *Bürgerspital zum Heiligen Geist* and at the *Staatlicher Hofkeller* in Würzburg. A spatio-temporal dataset for Germany was provided by the *Deutscher Wetterdienst* (DWD) and one last dataset was the result of personal investigations on the island of Guernsey in the English Channel.

The assembled data consist of (1) 60 to 205 years of phenological and other observations on viticulture in Lower Franconia, Germany, (2) a spatio-temporal dataset of first hay cutting records covering 60 years, as well as flowering dates of a grassland species covering 20 years across Germany and (3) a unique dataset of weekly flowering observations over 27 years of over 400 plant species within a single locality on the island of Guernsey.

Furthermore, temperature, precipitation sums and sunshine duration time series in the proximity of the locations of recording were also analysed. In two studies, German national mean temperature data were used. Correlation, multiple and linear regression techniques were used to relate the observations to the climate variables; long-term trends and responses were then calculated.

Results and Discussion

Unique long-term datasets dating back to 1805 were retrieved, providing new insights into the behaviour of numerous natural and agricultural species and practices. Anthropogenic and climatic drivers influencing the signal of novel datasets were identified by distinguishing between the characteristics of the individual observations. Criteria that have to be met by novel datasets to be suitable as indicators for climate change were discussed and confounding features of the datasets were identified.

The most important findings of this thesis can be summarised as:

(1) In Franconia, viticultural true and false phases, as well as observations associated with phenology primarily responded to climate variables, predominantly to temperature. The observed warmer seasons resulted in greater ripening potential in grapes; therefore, must sugar content increased, while the acid component stagnated, implying an altered wine typicity and quality. This, in turn, may result in a loss of the traditional character of Franconian wine. Grape harvest dates, even though a false phase that is influenced by

human decisions, still responded to temperature variables, since human decisions in turn depend, to a certain degree, on phenological observations. Increasing temperatures were related with increases in yield, yet, potential increases in yields are limited by current legislation, thus yield may not reach full potential in the future.

(2) The dataset on the agricultural false phase of hay cutting revealed significant advances in the majority of German federal states, with variations according to geographic patterns. However, during the last two decades, despite continuous warming, hay cutting dates were rather constant. The response of hay cutting dates to temperature decreased and was no longer significant. In contrast, flowering dates of an observed common grass species did advance in the manner expected from past sensitivity to temperature. Thus, differences in agricultural land use as well as agri-environment schemes most likely have confounded the overall trends in hay cutting.

(3) Regarding phenology of natural vegetation (trees, shrubs, perennials and annuals), we found significant overall advances in first flowering dates as well as an overall significant shortening of flowering duration. First flowering primarily responded to temperature variables. The drivers of flowering duration, however, appeared to be more complex. Earlier and shorter flowering seasons for the island of Guernsey may lead to a threat to biodiversity. Human health in regard to pollen allergenicity, on the other hand, might benefit. Additionally, a large variety of cultivars of the genus *Narcissus* was analysed. Earlier flowering cultivars advanced most, were more variable and had longer flowering durations than later flowering *Narcissus*. First flowering and flowering duration were highly sensitive to temperature; however, no significant advancing trend in first flowering could be detected over the study period. Anthropogenic influences were narrowed down to regular pruning practices and non-climatic influences could be neglected. Thus, additional climatic factors, were considered as influential, especially regarding flowering duration.

Conclusions

The studies presented in this thesis provide a cross-section of novel datasets: It examined long-term time series of unexploited and unique observations that provide information on phenology or additional information on climate change. The characteristics of these datasets were either their originality in terms of phenological observation, location, distribution and/or their observation length. The retrieved datasets provided new insights into the behaviour of numerous natural and agricultural species and/or practices. Anthropogenic and climatic drivers influencing the signal of novel datasets were identified by distinguishing between the characteristics of the individual observations. Novel datasets can act as climate proxies and consequently improve our knowledge of how climate change has influenced and will continue to influence ecological and agricultural aspects, as well as human health in the future.

KURZFASSUNG

Hintergrund und Zielsetzung

Der Klimawandel zeigt sich am unmittelbarsten durch phänologische Veränderungen im Jahreszyklus. In den letzten Jahrzehnten wurden bereits umfangreiche Forschungen über die Auswirkungen des Klimawandels auf physikalische und biologische Systeme betrieben. Die im Jahresverlauf periodisch wiederkehrenden Entwicklungserscheinungen der Natur deuten nicht nur auf ein zeitlich früheres Eintreten phänologischer Ereignisse, sondern auch auf eine Verlängerung der Vegetationsperiode der Pflanzen hin. Als wichtigste Ursache gilt hierbei die Erderwärmung. Diese phänologischen Veränderungen beeinflussen wiederum unser Ökosystem, die menschliche Gesundheit sowie die landwirtschaftliche Produktivität. Jedoch sind für eine Vielzahl von Regionen und Arten, zusammenhängende und differenzierte phänologische Langzeitdatensätzen - wenn überhaupt - nur spärlich vorhanden und dadurch schwer zu ermitteln.

Neuartige oder bislang nicht berücksichtigte Langzeitdatenreihen können hingegen einzigartige oder zusätzliche Informationen über den Klimawandel liefern. Solche Zeitreihen, die sich über mindestens 20 Jahre erstrecken, können entweder aus außergewöhnlichen phänologischen Beobachtungen oder aus, auf phänologischen Ereignissen basierenden Tätigkeiten oder Ereignissen bestehen. Diese Datensätze können als Bio-Indikatoren für den Klimawandel und dessen Auswirkungen auf Ökosysteme verwendet werden und somit als Proxy für Temperaturrekonstruktion agieren.

Der Schwerpunkt dieser Doktorarbeit besteht darin, gezielt einzigartige langjährige (> 20 Jahre) Aufzeichnungen zusammenzutragen und auszuwerten, die Rückschlüsse auf Klimaänderungen zulassen.

Der erste Teil dieser Doktorarbeit besteht aus Recherchearbeit zur Ermittlung potentieller außergewöhnlicher Langzeitdatenreihen. Durch die anschließende Aufbereitung und Analyse der ermittelten Daten werden Klimaveränderungen und deren Auswirkungen erfasst. Im Zuge dieser Analyse werden die klimatischen Einflussfaktoren von anthropogenen Einflüssen unterschieden. Somit werden gezielt die klimatischen Einflüsse, insbesondere Temperatur, auf das Ökosystem ermittelt. Die neuen Erkenntnisse, der Mehrwert an Information sowie die Aussagekraft dieser neuartigen Beobachtungen werden in einem letzten Schritt zusammengefasst und diskutiert. Dabei wird u.a. auch auf Konflikte und Probleme im Bezug auf Ökologie, Wirtschaft und menschliche Gesundheit

eingegangen. Je nach Bedarf können hierbei Informationen für politische Entscheidungen über mögliche Anpassungsmaßnahmen an die Folgen des Klimawandels abgeleitet werden.

Drei Forschungsfragen ergeben sich in dieser Arbeit: (1) Welche abiotischen und anthropogenen Faktoren beeinflussen die Aussagekraft neuartiger Datensätze sowie deren Informationsgehalt bezüglich phänologischer Ereignisse? Wie können wir die anthropogenen Einflüsse von natürlichen Faktoren unterscheiden? (2) Welche Kriterien müssen neuartige Datensätze erfüllen, um als Bio-Indikatoren für die Auswirkungen des Klimawandels einsetzbar zu sein? (3) Wie groß ist der Informationsgehalt und die Eignung der neuartigen Datensätze? Welche neuen Erkenntnisse in Bezug auf Ökologie, Wirtschaft und angewandten Naturschutz können gewonnen werden?

Material und Methoden

Die Recherche erfolgte u.a. in den Bibliotheken und Archiven der *Landesanstalt für Weinbau und Gartenbau* (LWG) in Veitshöchheim sowie der *Weingüter Bürgerspital zum Heiligen Geist* und am *Staatlichen Hofkeller* in Würzburg. Ein Datensatz wurde aus Daten des phänologischen Netzwerkes des *Deutschen Wetterdienstes* (DWD) zusammengesetzt, ein weiterer wurde durch persönliche Recherche und Digitalisierungsarbeit auf der Insel Guernsey erfasst.

Die zusammengetragenen Daten bestehen aus (1) phänologischen und weinbaurelevanten Beobachtungen (60 bis 205 Jahre) zum Weinbau in Unterfranken in Deutschland, (2) einem flächendeckenden deutschlandweiten Datensatz (60 Jahre) über den ersten Heuschnitt und Blühzeitpunkt einer Grünlandzeigerpflanze (20 Jahre), (3) einem Datensatz von wöchentlichen Blüteaufzeichnungen (27 Jahre) von über 400 Pflanzenarten innerhalb eines einzigen Standorts auf der Insel Guernsey.

Des Weiteren wurden Zeitreihen von Monats- und/oder Tageswerten von Lufttemperatur, Niederschlagsmengen und Sonnenscheindauer in der unmittelbaren Nähe der jeweiligen Aufnahmeorte ausgewertet. In zwei Studien wurde die gesamtdeutsche mittlere Temperatur herangezogen. Die Auswertung der Datensätze erfolgte durch Korrelations-, lineare- und multiple Regressionsanalysen. Die Daten wurden mit den entsprechenden Klimavariablen in Verhältnis gesetzt und langfristige Entwicklungen und Abhängigkeiten wurden berechnet.

Ergebnisse und Diskussion

Im Zuge dieser Arbeit wurden einzigartige Aufzeichnungen zusammengetragen, die teilweise bis 1805 zurückreichen. Diese Datensätze bieten einen neuen, bisher wenig beachteten Blickwinkel auf das Verhalten und die Veränderung einer Vielzahl von Pflanzen, landwirtschaftlichen und weinbaulichen Erzeugnissen sowie Tätigkeiten. Durch eine gezielte Unterscheidung der verschiedenen Beobachtungen wurden die anthropogenen und klimatischen Einflüsse unterschieden. Merkmale und Kriterien, die für eine Eignung als Bio-Indikatoren der Datensätze notwendig sind, werden aufgelistet. Desweiteren wird der Einfluss verzerrender Faktoren diskutiert.

Die wichtigsten Ergebnisse dieser Arbeit lassen sich wie folgt zusammenfassen:

(1) Phänophasen der Weinrebe sowie Arbeitsschritte im Bereich Weinbau in Unterfranken zeigten sich abhängig von Klimavariablen, insbesondere von der Lufttemperatur. Durch die beobachtete Klimaerwärmung verfrühen sich die Phänophasen und das Reifepotential der Weintrauben steigt an. Dadurch erhöht sich das Mostgewicht, der Säuregehalt des Weinmosts hingegen stagniert. In Folge verändert sich die Qualität des Weins und die Produktion des traditionellen "Frankenweins" gerät in Gefahr. Weinlesedaten sind bekannt als "falsche, vom Menschen beeinflusste Phänophasen". Da die Zeitpunkte der Lese jedoch auf phänologischen Beobachtungen und Messungen beruhen, zeigen diese Daten eine starke Abhängigkeit von Temperatur. Eine Erhöhung der Temperatur führt desweiteren zu einer Steigerung des Weinertrags. Um jedoch übermäßige Weinerträge zu unterbinden, gelten in Deutschland sogenannte Hektarertragsregelungen. Der Weinertrag wird, trotz steigender Temperatur, in Zukunft nicht sein volles Potential ausschöpfen können.

(2) Der Heuschnitt in Deutschland gilt ebenfalls als "falsche, vom Menschen beeinflusste Phänophase". Während der letzten 60 Jahre hat sich der erste Heuschnitt in einem Großteil der deutschen Bundesländer signifikant verfrüht. Die Zeitpunkte konnten zudem durch geographische Strukturen erklärt werden. In den letzten zwei Dekaden ist der Zeitpunkt des ersten Heuschnitts, trotz steigender Durchschnittstemperaturen, konstant geblieben. Zur gleichen Zeit ist die Temperaturabhängigkeit der Heuschnittdaten schwächer geworden. Im Vergleich dazu hat sich der Blühzeitpunkt eines gewöhnlichen Grünlandgrases bei gleichbleibender Temperaturabhängigkeit, in der erwarteten Art und Weise nach vorne verlagert. Die sich ändernden Landnutzungen sowie die sich immer

mehr durchsetzenden Agar-Umweltmaßnahmen wurden als verzerrende Faktoren ermittelt.

(3) Eine signifikante Verfrühung des Blühbeginns und der Blühdauer von Pflanzen (Gehölze, Sträucher, Stauden oder Einjährige) wurde festgestellt. Diese Verfrühung des Blühbeginns steht in einer engen Beziehung zur Temperatur. Die Gründe für die Verkürzung der Blühdauer sind hingegeben komplexer. Ein früherer Blühbeginn gekoppelt mit einer kürzeren Blühdauer kann die biologische Vielfalt auf Guernsey beeinträchtigen. Die menschliche Gesundheit könnte hingegen einen Vorteil daraus ziehen. Des Weiteren wurden unterschiedliche *Narcissus*-Kultivare untersucht. Frühblühende Sorten zeigten sich variabler in ihren Blühzeiten und wiesen längere Blühlängen auf als spätblühende Narzissen. Zwar waren Blühbeginn und Blühdauer abhängig von der Temperatur, es wurden jedoch keine signifikanten Trends während des Beobachtungszeitraumes ermittelt. Der anthropogene Einfluss auf diese phänologischen Beobachtungen bestand überwiegend aus alljährlichen Schnitt- und Pflanzarbeiten und werden somit als vernachlässigbar betrachtet. Weitere klimatische Faktoren wurden als mögliche Einflussfaktoren, speziell bezüglich der Blühdauer, erwogen.

Zusammenfassung

Die in dieser Doktorarbeit vorgestellten Studien stellen einen Querschnitt möglicher neuartiger Datensätze dar. Langzeitdatenreihen von einmaligen oder ungewöhnlichen Beobachtungen ermöglichen es, neue oder zusätzliche Informationen über die Auswirkungen des Klimawandels zu erhalten. Die hier zusammengetragenen Daten ermöglichen neue Erkenntnisse über die sich verschiebenden phänologischen Ereignisse sowie über die vom Menschen beeinflussten Tätigkeiten oder Vorkommnisse. Durch eine Einteilung der Datensätze entsprechend ihrer jeweiligen Beobachtungen wurden die anthropogenen und die klimatischen Einflussfaktoren voneinander unterschieden. Neuartige Langzeitdatenreihen können somit Bio-Indikatoren darstellen und dadurch unsere Kenntnisse über vergangene und zukünftige Auswirkungen des Klimawandels verbessern. Hierbei werden u.a. Aussagen über die Konsequenzen für Ökologie, landwirtschaftliche Produktion oder menschliche Gesundheit gemacht.

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1 OUTLINE OF THESIS

The core of this PhD thesis consists of three published and two submitted first author peer-reviewed scientific papers. The publications are briefly summarised and arranged with regard to content in the Chapters 3.1 to 3.5. They are shown in detail in the Appendix.

The **General introduction** (Chapter 2) briefly describes the relevance, impact and current state of research of climate change and phenology. It describes phenological plant responses to changed environmental conditions, as well as types and range of uses of phenological datasets. This leads to a statement of the importance of unconventional datasets and motivation of this research, which is followed by the study design and leading research questions.

The **Summaries** of the candidate's **individual contributions** are listed in Chapter 3.

The first publication in Chapter 3.1 **"Changes in the phenology and composition of wine from Franconia, Germany"** (Bock *et al.* 2011, *Climate Research 50: 69–81*) is based on vineyard observations derived from the *Landesanstalt für Weinbau und Gartenbau* and the winery *Bürgerspital zum Heiligen Geist*. This paper focuses on a broad range of phenological and other properties, such as flowering dates, must sugar content (°Oe), acid content ($g\ l^{-1}$) and harvest dates. Multiple regression analysis was applied to show how phenophases and their temporal trends are influenced by climate variables. We identified whether the cultivars as well as the phenophases and other properties showed distinctive differences and explored their suitability to detect temperature variations. In addition, the impact of future global warming and its effect on the Franconian wine industry was discussed.

The second publication **"Climate-induced changes in grapevine yield and must sugar content in Franconia (Germany) between 1805 and 2010"** (Bock *et al.* 2013, *PLoS ONE 8(7):e69015*) in Chapter 3.2 is based on records from the winery *Staatlicher Hofkeller Würzburg*. The study describes trends in yield and sugar content of grapes over an unusually long period of 206 years. Concerning trends in yield, this is a subject poorly investigated in literature so far. Using multiple regression analysis, this paper illustrates how yield and must sugar content (°Oe) and their temporal trends were influenced by anthropogenic and biotic factors (e.g. pests) and estimates how much of the variability could be explained by climate variables. The future impacts of climate change on viticulture and management of vineyards were discussed.

The third publication (Chapter 3.3) **"Changes in the timing of hay cutting in Germany do not keep pace with climate warming"** (Bock *et al.* 2013, *Global Change Biology* 19(10): 3123–3132) is a spatio-temporal investigation of whether farmers' activities keep up with climate change. The study is based on phenological observations provided by the *Deutscher Wetterdienst* and analyses phenological onset dates of the first hay cut in Germany in terms of spatial and temporal variation. We compared hay cutting trends with trends of a grassland species to test for similarities and whether these trends can be related to increased warming. Furthermore, the effect of agri-environmental schemes were discussed and sensitive regions in terms of grassland ecology were identified.

The fourth publication (Chapter 3.4) **"Changes in first flowering dates and flowering duration of 232 plant species on the island of Guernsey"** (Bock *et al.*, submitted to *Global Change Biology*) allows insights into the phenological behaviour of a large number of species in terms of beginning of flowering and flowering duration over time and their temperature influences. The observations were made by a single observer in a single locality on the island of Guernsey, covering 27 years. Flowering duration is a phenological observation that has rarely been studied so far, especially in such a large number and variety of species. The aim was to investigate variation in trends and to explore how different species and plant traits respond to climate variables by using multiple regression procedures.

The fifth publication **"Climate sensitivity and variation in first flowering and flowering duration of 26 Narcissus cultivars"** (Bock *et al.*, submitted to International Journal of Biometeorology) in Chapter 3.5 was developed from the preceding publication (Chapter 3.4) and singles out a unique long-term time series of 26 *Narcissus* cultivars. Unlike other studies on *Narcissus*, these cultivars in this study were growing wild and were thus recently not affected by cultivation or breeding techniques. With *Narcissus* being one of the most important geophytes for the global ornamental flower industry, the aim of this study was to explore variation in temperature sensitivity between cultivars and relationships between first flowering dates, flowering duration and climate variables.

The **General and summarising discussion** (Chapter 4) highlights the significance of the results according to the emerging research questions and places them in the context of other studies.

The PhD thesis is then summarised and further research perspectives are described in the **General conclusion and outlook in** Chapter 5.

All **References** are summarised in Chapter 6.

In the Appendix, **time-series** that had been **additionally acquired** in the course of this project, but were not included in the thesis, are briefly summarised. In the second part, the individual **Publications** are attached.

2 GENERAL INTRODUCTION

2.1 Climate Change

Climate is the statistical description of the mean and the variability of the climate system over a defined period in a given region. The classical period is 30 years, as defined by the World Meteorological Organisation (WMO), with the period 1961-1990 being the standard WMO reference period for the current climate (WMO 1996).

Climate is always subject to fluctuations. Internal forcing such as ocean variability and external forcing such as orbital variations, solar output and volcanism – which act at different time scales – are important drivers of the climate system. Paleoclimatological reconstructions go back hundreds to millions of years and offer a broad view of the variability and long-term changes in the atmosphere, ocean, cryosphere and land surface (IPCC 2013). The central aim of climate reconstructions dating back a few hundreds of years is to verify the significance of variability simulated by climate models and to detect and quantify anthropogenic effects (IPCC 2007). Proxies such as tree rings, ice cores and documentary records were used to gain information about temperature conditions prior to the instrumental period (Briffa *et al.* 2001; Cuffey & Clow 1997; Cuffey *et al.* 1995). A prominent example is the study of Guiot *et al.* (2005) who presented a multiproxy approach to reconstruct millennium long western European summer temperatures. That study used proxies such as tree-ring widths series, grape harvest dates, ice oxygen isotopes and temperature indices based on historical documents.

Since the beginning of the industrial revolution, human influence resulted in an additional forcing on the climate system. During the last century, the atmosphere and ocean have warmed, the quantity of snow and ice have declined and the sea level has risen (IPCC 2007; IPCC 2013). It is generally accepted that the anthropogenic increase of greenhouse gas concentration and other anthropogenic forcings have been the dominant cause of the observed warming (IPCC 2007; IPCC 2013). Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the dominant anthropogenic greenhouse gases, exceeding the range of concentrations recorded in ice cores during the past 650,000 years (IPCC 2007; IPCC 2013). CO_2 which is regarded as the most important driver of climate change, results mainly from fossil fuel use, deforestation and land use change (Hofmann *et al.* 2006; IPCC 2007). The CO_2 concentration has risen from approximately 280 ppm in preindustrial times to an annual maximum of 393.8 ppm in 2012. A maximum concentration of 399.8 ppm was reached in May 2013 (IPCC 2007; NOAA 2013).

A warming of 0.85 (0.65 to 1.06)°C of the mean global surface temperature over the period 1880 to 2012 has been observed (IPCC 2013). The global warming trend was estimated as 0.15 to 0.20°C per decade (Hansen *et al.* 2010). Thus, the previous decades have been warmer than all the previous decades in the instrumental era, with the 2000s being the warmest (Hansen *et al.* 2010; Hansen *et al.* 2006; Luterbacher *et al.* 2004).

By the end of the 21st century, global surface temperature is expected to exceed 1.5°C relative to 1850 to 1900, depending on the underlying scenario (IPCC 2013). With increasing global mean temperatures, there will be more frequent and longer heat waves and fewer cold temperature events (IPCC 2007). Projections for the future predict that global warming will continue. Based on different scenarios of radiative forcing, global surface temperature is likely to further increase until a stable level is reached (IPCC 2007).

2.2 Responses of plant species

Responses of plant populations range from tolerance, migration to extinction, depending on magnitudes and rates of environmental change (Jackson & Overpeck 2000). Over the past decades, climate change has resulted in numerous shifts in the distribution and abundance of species (Parmesan & Yohe 2003; Root *et al.* 2003). This leads to a major turnover of ecosystems. Migration processes vary according to habitat sizes, ecosystem or number and diversity of species. Migration generally follows either latitudinal or altitudinal gradients (Parmesan & Yohe 2003; Pauli *et al.* 2007), with woody species invading into tundra and alpine vegetation (Hallinger *et al.* 2010).

Nevertheless, not all species will be able to keep pace with future climate change (Jump & Peñuelas 2005). In a study using different projections of climate warming, an extinction across species of 15 to 37% by 2050 was estimated (Thomas *et al.* 2004). While the boreal region was projected to lose few species, the greatest turnover is expected in the transition between Mediterranean and Euro-Siberian regions. Risks of extinction, especially for European regions, are expected to be large, even in moderate scenarios (Thuiller *et al.* 2005). Herbaceous life-forms were found to have stronger temperature responses than woody forms (Arft *et al.* 1999). A recent study discovered, that pioneer and invasive species might profit from warming winters, if late spring frost events would in parallel occur earlier (Laube *et al.* 2013). Thus, biological invasions are becoming another important element of climate change (Vitousek *et al.* 1997). There have been studies suggesting that invasive species respond positively to increases of atmospheric CO_2 or to increases in nitrogen deposition (Dukes & Mooney 1999; Ziska 2003). A recent study discovered that invasive species that occupy unique phenological niches respond more closely to climate change than native species. The study therefore assumed that invasive species may be essential drivers for the extended growing seasons observed with climate change in North America (Wolkovich *et al.* 2013).

2.3 Phenological observations

Phenology is the science of natural recurring plant and animal life cycle events and how these are influenced by seasonal and interannual climate variations. Such periodic life cycles include *inter alia* the emergence of leaves and flowers, egg-laying of birds or amphibia or the first flight of insects (e.g. Menzel 2002). Phenological observations have a long history. Prominent examples of this long tradition of phenological observations are the 1300 year long records of the traditional cherry blossom festivals in Japan (Aono & Kazui 2008), grape harvest records, which have been recorded by wine-growers in France since medieval times (Chuine *et al.* 2004) and the outbreaks of locusts in China that have been written down for at least 3500 years (Tian *et al.* 2011).

Phenological phases reflect *inter alia* the characteristics of the climate in the region where they occur. Temperature is the most important factor influencing phenology of plants in temperate regions. In particular plant phenology takes a key role in the detection of shifts in ecosystem functions due to recent global climate change (Menzel 2002; Menzel & Fabian 1999; Sparks & Carey 1995). The advantages of working with phenology include that it is relatively easy and cost effective to observe (Sparks *et al.* 2009b). Studies dealing with phenological data mainly focus on the timing and duration of recurring phenophases. They furthermore analyse the influence of biotic and abiotic forces on timing and the interaction between phases of the same or different species (Post *et al.* 2008; Schwartz 2003; Webb *et al.* 2012). Different species show divergent rates of advance (Root *et al.* 2003), making species interactions particularly vulnerable due to potential phenological mismatch (Bartomeus *et al.* 2013; Rafferty & Ives 2011; Visser & Both 2005).

Drawing conclusions from phenological observations are relevant for every part of the world. In practice, however, detailed long-term phenological data are predominantly limited to the Northern Hemisphere. In a recent meta-analysis of trends among Southern

Hemisphere species, dominant patterns were found to be consistent with findings from the Northern Hemisphere. However, large data deficiencies and biases, e.g. in terms of data availability were acknowledged (Chambers *et al.* 2013). To gain detailed continuous and standardised long-term data of phenological events, phenological networks have been established. There exist numerous European phenological networks, which are summarised by Nekovar *et al.* (2008), Tooke & Battey (2010) and Menzel (2013). The phenological network of the German Meteorological Service (DWD, Deutscher Wetterdienst) has existed since 1951, collecting phenological observations of wild and agricultural plant species. Volunteers record different phenological phases using specific guidelines (Deutscher Wetterdienst 1991). Networks record phenological observations of wild plant species, of agricultural practices, timing of migration of species or measure the pollen concentrations in the air. The initial use of phenological observations ranged from documenting nature's patterns to giving information for agricultural practices. Nowadays, the networks are predominantly used for information on disease forecasting for agriculture (Hopp 1974), for human health in terms of pollen allergies (Jochner *et al.* 2012) and to study climate change impacts (Koch *et al.* 2006; Menzel 2002). Another approach to gather information on entire regions instead of individual species, is remote sensing phenology which has become an important tool. Using satellites to track phenological events is used for documenting phenological trends and various assessments concerning crop condition, drought, wildfire risks or invasive species (Chapman 2013; Reed *et al.* 1994; White *et al.* 2009).

2.4 Observed changes in phenology and climate research

Changes in phenological events are among the most sensitive of all biological responses to warming and can be used to track changes associated with climate change (e.g. Badeck *et al.* 2004; Cleland *et al.* 2007; Menzel *et al.* 2006a; Parmesan & Yohe 2003; Rosenzweig *et al.* 2008; Walther *et al.* 2002). While plant phenology is highly responsive to air temperature (Arft *et al.* 1999; Dunne *et al.* 2003; Parmesan 2007), other climate variables need to be considered as well. Plant phenology may also be closely related to photoperiod (Caffarra & Donnelly 2011; Jeong & Clark 2005) and chilling (Hanninen & Tanino 2011; Polgar & Primack 2011). However, it was discovered that the effect of chilling might exceed the effect of photoperiod (Laube *et al.* 2013). Moreover, some species are also highly responsive to precipitation, especially in dry or seasonally dry habits (Keatley *et al.* 2002; Peñuelas *et al.* 2002). Nevertheless, temperature is generally accepted as the major climate driver since it represents a strong and widespread documented signal of climate warming in recent decades and has an important direct influence, not only on phenology, but also on many other physical and biological processes. Thus, numerous studies have examined the relationship between phenological events and temperature to obtain predictive relationships between temperature and the timing of a phenophase (e.g. Root *et al.* 2003; Parmesan & Yohe 2003; Menzel *et al.* 2006; Menzel 2000).

To predict future responses of ecosystems to a changed climate it is important to learn how species have responded to climate in the past (Sparks & Carey 1995). There have been changes in onset dates for numerous regions across the globe as well as for various phenophases in plants and animals. The meta-analyses of Parmesan & Yohe (2003) and Root *et al.* (2003) displayed a global mean advance of spring phases by 2.3 and 5.1 days per decade. A broad scale study using satellite imagery detected an earlier onset of spring by 1 day per decade across most temperate regions of the Northern Hemisphere (Schwartz *et al.* 2006). The years 2010 and 2012 were detected as the earliest flowering times for spring phases in the Eastern United States since the 1850s (Ellwood *et al.* 2013).

Earlier phases tend to show greater advances than later phases (Chmielewski *et al.* 2004; Fitter & Fitter 2002; Pau *et al.* 2011; Wolkovich *et al.* 2013). For Europe, Menzel *et al.* (2006a) revealed that leaf unfolding, flowering and fruiting observations advanced by up to 2.5 days per decade, while the trend for leaf colouring was ambiguous. Temperature relationships were generally more pronounced for spring and summer phenophases (advance of 4.6 days per 1°C warming), while autumn phases such as leaf colouring were delayed by only 2.4 days per 1°C warming (Menzel *et al.* 2006a). For example, earlier flowering cherry trees (*Rosaceae*) were more responsive to increasing temperatures, flowering up to 9 days earlier for each 1°C increase, than later flowering species (3-5 days earlier for each 1°C increase) (Miller-Rushing *et al.* 2007). Thus, earlier species appear to be more sensitive to temperature since early species are adapted to higher temperature variability and therefore are more responsive to changes. Regarding grapevine phenology, however, earlier phases (budburst, flowering) generally advanced, although less than later phases such as véraison and harvest (Duchêne & Schneider 2005; Jones & Davis 2000). The growing season, often defined as the time span between leaf unfolding and leaf colouring, has been extended over recent decades, especially due to the earlier onset in spring (e.g. Gunderson *et al.* 2012; Jeong *et al.* 2011; Menzel & Fabian 1999; Richardson *et al.* 2010; Vitasse *et al.* 2009; Zeng *et al.* 2011). At the same time, Jones & Davis (2000) discovered decreasing trends over time for phase intervals of grapevine phenology (flowering to véraison, flowering to harvest, véraison to harvest). Thus, phenological responses are far from being uniform (Parmesan 2007). While phenology in general shows a clear temperature relationship, responses differ with regard to regions, species, events observed and applied methods (Rosenzweig *et al.* 2007). In a multi-species analysis of spatial variability in plants in Germany, the spatial variability of plant responses appeared to increase with warming (Menzel *et al.* 2006b). Another study on flowering phenology of apple trees in Western Europe, however, revealed a decrease in the spatial variability of flowering dates (Legave *et al.* 2013). Such apparently contradictory observations indicated that further investigations are necessary. A lengthening of the growing season due to climate change may have an impact on energy and moisture exchange, seasonal carbon cycle and aerosol formation between land surface and atmosphere. Thus, spatiotemporal patterns of the growing season at regional scales may help to detect responses of climate-induced vegetation dynamics (Chen & Xu 2012). Because of their short generation time, annual plant species are expected to adapt faster to a changing climate than species with a long generation time and lifespan (Jump & Peñuelas 2005). Fitter & Fitter (2002) confirmed that annuals appeared to be more responsive to increased temperature than perennials, Bolmgren *et al.* (2013) and Peñuelas *et al.* (2002), on the other hand, did not find any differences. The effect between insect and wind pollinated plants were also not consistent. While Fitter & Fitter (2002) found insect pollinated species to be more sensitive to temperature than wind pollinated species, Ziello *et al.* (2012a) revealed that the beginning of flowering of wind-pollinated species advanced more strongly than for insect-pollinated species. Additionally, Jochner *et al.* (2013b) furthermore discovered an influence of nutritional status on phenology and pollen production.

2.4.1 Importance for human health

Plant pollen present a major strain for human health since they can trigger allergies. In particular, grasses (e.g. *Alopecurus pratensis, Phleum pratense*) and birch trees (*Betula* ssp.) are the most common cause of hay fever in Europe (D'Amato *et al.* 2007; Emberlin 2008). Phenological observations of plant species are therefore important for information on aeroallergens and human health (Beggs 2004; Traidl-Hoffmann *et al.* 2003). Effects on pollen amount, pollen allergenicity, timing and duration of the pollen season, and plant and pollen distribution can be related to climate change (Beck *et al.* 2013; Beggs 2004; Ziello *et al.* 2012b). The beginning and length of the pollen seasons have already changed. With increasing temperatures an early start of the pollen season has been reported (Emberlin *et* *al.* 1997; Jochner *et al.* 2012; Ziska *et al.* 2003). An analysis of a continental-scale pollen data set furthermore revealed an increasing trend in the amount of airborne pollen in Europe (Ziello *et al.* 2012b). Moreover, a lengthening of the pollen season was found, especially for summer and late flowering grass species (Emberlin 1994). In turn, the extended growing season is likely being influenced by introduced exotic species (Wolkovich *et al.* 2013) such as *Ambrosia artemisiifolia*, which had increased the pollen season in recent decades (Ziska *et al.* 2011).

2.4.2 Importance for agriculture

Not only the natural vegetation, but also agricultural and horticultural operations have responded to distinct climate changes, though, usually showing lower trends. A comparison with historical farming records revealed that many of the current farming events appear as responsive to temperature now as they were 200 years ago (Sparks *et al.* 2005). Studies using long-term records of agricultural species and grapevine have revealed advances in flowering, cropping and harvest (e.g. Chmielewski *et al.* 2004; Estrella *et al.* 2007; Hanks 1996; Jorquera-Fontena & Orrego-Verdugo 2010; Malheiro *et al.* 2010; Williams & Abberton 2004).

Moreover, global warming may result in a shift in the distribution of land suitable for cropping towards the northern boundary. Regions which used to be unsuitable or marginal for crop-growing might benefit (Lisek 2008), while formerly arable land suffers from increasing temperatures (Jones *et al.* 2005; Olesen & Bindi 2002).

However, farming related phenology has to be considered with caution since it also reflects ecological, agricultural and socioeconomic consequences (e.g. Amano *et al.* 2010; Estrella *et al.* 2007; Peñuelas & Filella 2001). Rapid turnovers in cultivars and the technological improvements in production may confound the temperature signal (Sparks *et al.* 2005). Thus, it furthermore has to be kept in mind that the sources of such records should be verified by comparison with other historical and climate evidence (Pfister 1981).

Despite technological improvements in agriculture resulting in overall yield gains, a clearly negative response of average global yields in wheat, maize and barley was found due to increased temperature. From 1981 onwards, the annual combined losses of yield due to climate warming represent roughly 40 Mt per year. These impacts are small relative to the technological yield gains over the same period, nevertheless the study revealed already occurring negative impacts of climate change on crop yields at the global scale (Lobell & Field 2007).

In Germany, increasing temperatures resulted in an overall advance of farming phases such as sowing, subsequent emergence of spring and winter crops and harvest by about two days per decade (Estrella *et al.* 2007; Menzel *et al.* 2006c; Siebert & Ewert 2012). A study on plant pests in Great Britain discovered that a 1°C increase in average winter temperature advanced the emergence of aphid species by four to 19 days depending on the species (Zhou *et al.* 1995). The impact of climate change on spring frost events affecting agriculture has been more contradictory. In Finland and east Canada, the risk of spring frost damage has been found to decrease slightly (Laapas *et al.* 2012; Rochette *et al.* 2004). On the other hand, warmer temperatures can lead to lower levels of freeze tolerance and make plants more vulnerable to freezing injury at different times of the year in frost climate vegetation (Ball *et al.* 2012). Another factor to consider is the increase in temperature variability and extremes. Previously rare frost damage events are likely to increase (Augspurger 2013; Gu *et al.* 2008; Hufkens *et al.* 2012). Thus, climate change might represent a serious constraint on agriculture and horticulture in some areas.

2.4.3 Cultural importance

Another aspect of phenological observations that has only marginally been studied is the aspect of cultural ecosystem services. Cultural events that are based on phenological events are also affected by recent climate change. The cherry flower in Japan (Aono & Kazui 2008) is the most famous example. Flowering of tulips *(Tulipa)* in the Netherlands, snowdrop (*Galanthus nivalis*), bluebell (*Hyacinthoides nonscripta*) or daffodil (*Narcissus*) in the UK, Crocus *(Crocus napolitanus)* in Husum, Germany as well as the almond *(Prunus dulcis)* blossom on the island of Mallorca are regarded as landmark events for the arrival of spring. Thus, they are of cultural, touristic and therefore economic importance (Sparks *et al.* 2012).

2.5 Unconventional phenological observations

Most studies that have analysed the impact of climate change on phenological events depend on detailed long-term records (e.g. Bradley *et al.* 1999; Fitter & Fitter 2002; Menzel *et al.* 2005; Sparks & Carey 1995) since they provide important contexts for understanding impact of projected climatic changes (Dennis & Sparks 2007). Despite efforts to collect wide-ranging phenological records (Menzel *et al.* 2006a; Parmesan & Yohe 2003; Root *et al.* 2003), systematic long-term records are still rare and unavailable for many regions and species (Amano *et al.* 2010; Chambers & Keatley 2010; Miller-Rushing *et al.* 2006; Primack *et al.* 2004). Therefore, it is necessary to extract phenological information from records of alternative sources to examine the impact of climate change. Examples of such alternatives, i.e. unusual, unique or human induced observations are *inter alia* cryophenological records of freeze and breakup dates of ice (Helama *et al.* 2013), the records of flower festivals (e.g. Aono & Kazui 2008), arrival and departure of migratory birds (e.g. Beaumont *et al.* 2006), the use of herbarium records (e.g. Gallagher *et al.* 2009; Miller-Rushing *et al.* 2006; Robbirt *et al.* 2011), naturalists' diaries (Bolmgren *et al.* 2013; Ledneva *et al.* 2004; Rumpff *et al.* 2010; Sparks & Carey 1995), farmers' diaries (Chuine *et al.* 2004; Sparks *et al.* 2005), grape harvest records (e.g. Chuine *et al.* 2004; Maurer *et al.* 2009) and photographs (e.g. Miller-Rushing *et al.* 2006; Sparks *et al.* 2006). Such datasets, especially at the community level are important to supply sufficient data to answer further questions of how phenological changes may continue as a result of climate change (Amano *et al.* 2010; Miller-Rushing *et al.* 2006).

2.6 Motivation of research

The detection of climatic change is the process of demonstrating that the climate has changed in some defined statistical sense (Le Treut *et al.* 2007). It is essential to understand and predict climate change impacts and their consequences, especially regarding ecosystems and the various arising economic and social consequences. We depend on detailed information to identify current and future problems for production (e.g. in horticulture, agriculture, viticulture and forestry), conservation (e.g. biodiversity) and human health (e.g. pollen release and insect infestations (Sparks 2007; Sparks & Menzel 2002)). Since the number of species and regions for which we have such information is limited, alternative ways and potential sources of data from other fields gain importance. However, experimental warming studies were found to underpredict advances in phenology in comparison to long-term studies. Species' or traits' specific temperature sensitivities do not necessarily match with observational studies (Wolkovich *et al.* 2012). Overcoming data limitations and extending the focus from purely natural phenological observations to other unexploited datasets would improve our understanding of how climate and climate change have and will influence phenological response.

Thus, the topic of this PhD thesis focuses on climate change detection using unique or unconventional long-term observations providing new or additional information on climate change impacts. This work seeks to detect trends over time and relationships with climate variables to improve the understanding of responses to climate change. The aims of this thesis were to examine the factors that have an influence on phenological onset dates. Abiotic drivers, specifically climate were separated from anthropogenic drivers such as technical advance, and thus the impact of climate affecting ecosystems were analysed. The informative value and applicability of datasets of the phenological observations were specified. Consequences of shifting phenological events and phases were discussed and potential conflicts in terms of ecology, economics and conservation were elaborated.

2.7 Data and study design

2.7.1 Data acquisition

The first part of this research comprised the investigation and acquisition of unexploited or unique long-term datasets that may give additional information of climate change.

The requirements for the sought-after data sets were:

- suitability for the detection of climate change impacts,
- revealing changes in phenology or human-induced activities,
- providing new insight in future climate change impacts,
- unique, unconventional or underexploited in terms of
  - location, region or spatial distribution,
  - phenological observation (e.g. species, event),
  - characteristics of observation,
- covering at least 20 years of observation.

Research was *inter alia* carried out in numerous research libraries and archives at the *Landesanstalt für Weinbau und Gartenbau* (LWG) in Veitshöchheim, at the wineries *Bürgerspital zum Heiligen Geist* and at the *Staatlicher Hofkeller* in Würzburg. Furthermore, phenological data were obtained from the *Deutscher Wetterdienst* (DWD) and personal investigations were done on the island of Guernsey (Table 1). Datasets that were retrieved during this project, but were not included in the thesis are briefly summarised in the appendix.

2.7.2 Data preparation

This part involved the digitisation of the records. The relevant information of the records had to be extracted, calculated and summarised in a database. Information from different sources were combined and related to each other. Historical measuring units were converted and observations were verified by comparison with other historical and climate evidence. Spatial datasets were restructured and evaluated using geographic information systems (ArcGIS 10). Calculations were performed with the program R 2.13.1 (R Development Core Team 2011) and Excel 2007.

2.7.3 Analyses

The temporal and spatial variability of these novel phenological observations were analysed. Temperature time series near the respective observation sites or the national mean temperature were analysed. Subsequently, the observations were related to climate variables. Confounding factors within the relationships were identified and the effect of the abiotic drivers (i.e. climate) estimated. Statistical analysis was performed with the program R 2.13.1 (R Development Core Team 2011) and IBM SPSS version 19, GIS-based regionalisation and interpolations were conducted using ArcGIS 10.

Over a large temperature range, the relationship between phenological onset dates and temperature is usually regarded as a linear function (Sparks *et al.* 2000). Thus, the detection of trends in time and climate variables has primarily been made with regression and correlation analyses (e.g. Ahas *et al.* 2002; Bradley *et al.* 1999; Defila & Clot 2001; Menzel & Fabian 1999; Rutishauser *et al.* 2009; Schwartz & Reiter 2000; Sparks & Carey 1995). There has been a discussion on the linearity of temperature relationships not being valid at the cooler and/or warmer temperature edge and that a sigmoid form would be more suitable (Menzel *et al.* 2005; Sparks *et al.* 2000), especially at colder locations (Sparks *et al.* 2009a). However, observational studies could only confirm this for single sites (Newnham *et al.* 2013) and not for a wider geographical region as recently reported by Jochner et al. (2013, personal communication).

Therefore, statistical methods used in this thesis were:

- Correlation techniques,
- Linear regression techniques,
- Multiple linear regression techniques.

2.7.4 Discussion

Trends over time and relationships with potential climate drivers are analysed. The informative value and applicability of the analysed observations are discussed.

Furthermore, the influence of anthropogenic, biotic and abiotic forces on timing, and the interaction between phases and/or traits is discussed. The magnitude and consequences of the observed changes are elaborated, especially in terms of ecology, economics, socioeconomics and applied conservation.

2.8 Research questions

In this PhD thesis, changes in plant phenology and in temperature time series were detected and confirmed, using novel and unexploited datasets. Furthermore, it was tested whether these alternative sources provide new insights and add knowledge to our understanding of climate change impacts. Subsequently, the following research questions were addressed and finally discussed in the **General and summarising discussion** (Chapter 4).

(1) What are the anthropogenic and abiotic drivers influencing the phenological signal of the novel datasets? How can we distinguish natural climatic from anthropogenic influences?

(2) What criteria have to be met by novel datasets to qualify as indicators for climate change impact?

(3) What is the informative value and applicability of novel datasets and what kind of insights in terms of ecology, economics and applied conservation can be achieved?

Table 1. Datasets used in the PhD thesis.

Data	Unit	Period	Observation rhythm	Location/Area	Data type		Source
Phenological observations of grapevine cultivars	date	1968-2010	annual	Veitshöchheim	phenological vineyard observations	excel spread sheet	Landesanstalt für Wein- und Gartenbau
	date	1970-2010	annual	Randersacker	vintage records	tables	Bürgerspital zum Heiligen Geist
Grape harvest dates	date	1968-2010	annual	Veitshöchheim	phenological vineyard observations	excel spread sheet	Landesanstalt für Wein- und Gartenbau
	date	1950-2010	annual	Randersacker	vintage records	tables	Bürgerspital zum Heiligen Geist
Grapevine composition	°Oe	1949-2010	annual	Veitshöchheim	phenological vineyard observations	excel spread sheet	Landesanstalt für Wein- und Gartenbau
	°Oe	1950-2010	annual	Randersacker	vintage records	tables	Bürgerspital zum Heiligen Geist
	$g\ l^{-1}$	1960-2010	annual	Randersacker	vintage records	tables	Bürgerspital zum Heiligen Geist
Grapevine yield	hl/ha kg/ha kg/l	1805-1905	annual	Würzburg	doctoral thesis (Eifler 1908)	book	Staatlicher Hofkeller Würzburg
	hl/ha kg/ha kg/l	1874-1924	annual	Würzburg	doctoral thesis (Weigand 1925)	book	Staatlicher Hofkeller Würzburg
	hl/ha kg/ha	1915-1952	annual	Würzburg	anniversary publication (Bayerisches Staatsministerium für Ernährung 1977)	book	Staatlicher Hofkeller Würzburg
	hl/ha kg/ha	1962-2010	annual	Würzburg	vintage records	handwritten	Staatlicher Hofkeller Würzburg
Grapevine composition	°Oe	1864-1905	annual	Würzburg	doctoral thesis (Eifler 1908)	book	Staatlicher Hofkeller Würzburg
	°Oe	1962-2010	annual	Würzburg	annual vintage records	handwritten records	Staatlicher Hofkeller Würzburg
First hay cut	date	1951-2011	annual	Germany (5973 sites)	phenological observation	text file	Deutscher Wetterdienst
First flowering dates	date	1991-2011	annual	Germany (770 sites)	phenological observation of 1 plant species	text file	Deutscher Wetterdienst
First flowering dates	date	1985-2011	weekly	Guernsey (UK)	phenological observation of 232 plant species	handwritten records	Single observer (Nigel Jee)
Flowering duration	weeks	1985-2011	weekly	Guernsey (UK)	phenological observation of 232 plant species	handwritten records	Single observer (Nigel Jee)

3 SUMMARIES OF INDIVIDUAL CONTRIBUTIONS

3.1 Publication I

CHANGES IN PHENOLOGY AND COMPOSITION OF FRANCONIAN WINE (GERMANY)

Anna Bock ,Tim H. Sparks, Nicole Estrella, Annette Menzel

Published in

Climate Research (2011) 50: 69–81

The majority of the highest quality wine-producing regions in Western and Central Europe have benefitted from an increase in quality ratings due to climate change. Traditional Franconian wine, on the other hand, is in danger of losing its unique characteristics and its traditional spatial distribution. In this long-term study (1949 to 2010), reference vineyard observations in Lower Franconia, Germany were used. This wine region is one of the most northerly in the world. The use of adapted grape cultivars is required, however, recent climate change has an impact on the unique quality of traditional wine. Phenological events and intervals, and composition (acid and must sugar content at harvest) of three white grape cultivars were analysed for trends over time and relationships with potential climate drivers using multiple regression. Overall, the phenology of grapevines in Lower Franconia has tended towards earlier occurrence with a shortening of phenological intervals. The relative amounts of must sugar in the grapes at harvest have tended to increase. The findings confirm a consistent relationship between onset dates of phenological phases and corresponding climate data. The grapevines were most influenced by mean maximum temperatures preceding the event, whereas precipitation and sunshine appeared less important. The observed warmer season results in greater ripening potential in grapes; as a consequence, the sugar content increases, while the acid component decreases, resulting in an altered wine typicity and quality. Thus the balanced ratio of sugar and acid content shifts in favour of the sugar component, which may result in a loss of the traditional character of Franconian wine.

Candidates own contribution:

Data acquisition, data manipulation, statistical analysis and interpretation, as well as writing of the manuscript (90% contribution). Tim Sparks, Nicole Estrella and Annette Menzel contributed with suggestions for statistical analysis, corrections and proof reading.

3.2 Publication II

CLIMATE-INDUCED CHANGES IN GRAPEVINE YIELD AND MUST SUGAR CONTENT IN FRANCONIA (GERMANY) BETWEEN 1805 AND 2010

Anna Bock ,Tim H. Sparks, Nicole Estrella, Annette Menzel

Published in

PLoS ONE (2013) 8(7): e69015

When attempting to estimate the impacts of future climate change it is important to reflect on information gathered during the past. Understanding historical trends may also aid in the assessment of likely future agricultural and horticultural changes. The timing of agricultural activities, such as grape harvest dates, is known to be influenced by climate and weather. However, fewer studies have been carried out on grapevine yield and quality. In this paper an analysis is undertaken of long-term data from the period 1805-2010 on grapevine yield (hl/ha) and must sugar content (°Oe) and their relation to temperature. Monthly mean temperatures were obtained for the same time period. Multiple regression was used to relate the viticulture variables to temperature, and long-term trends were calculated. Overall, the observed trends over time are compatible with results from other long term studies. The findings confirm a relationship between yield, must sugar content and temperature data; increased temperatures were associated with higher yields and higher must sugar content. However, the potential increase in yield is currently limited by legislation, while must sugar content is likely to further increase with rising temperatures.

Candidates own contribution:

Data acquisition, digitalisation from original documents, data manipulation, statistical analysis and interpretation, as well as writing of the manuscript (90% contribution).
Tim Sparks, Nicole Estrella and Annette Menzel contributed with suggestions for statistical analysis, corrections and proof reading.

3.3 Publication III

CHANGES IN THE TIMING OF HAY CUTTING IN GERMANY DO NOT KEEP PACE WITH CLIMATE WARMING

Anna Bock ,Tim H. Sparks, Nicole Estrella, Annette Menzel

Published in

Global Change Biology 19(10): 3123–3132

A unique long-term phenological dataset of over 110,000 records of 1st cutting dates for haymaking across Germany, spanning the years 1951-2011 was examined. In addition, we analysed a long-term dataset on the beginning of flowering of meadow foxtail (*Alopecurus pratensis*) covering the last 20 years. We tested whether hay cutting dates (based on a human decision when to cut) showed trends, temperature relationships and spatial distribution similar to the development of this grassland species, and if these trends could be related to climate change. The timing of 1st hay cut was strongly influenced ($p < 0.001$) by altitude, latitude and longitude, revealing in particular an east-west gradient. Over the past 60 years there have been changes in the timing of hay cutting, with the majority of German federal states having significant ($p < 0.05$) advances of ~1 day per decade. Overall, the response to mean March- May temperature was highly significant (-2.87 days°C^{-1}; $p < 0.001$). However, in the last 20 years no federal state experienced a significant advance and 2 were even significantly delayed. The temperature response in this post-1991 period became less or non significant for most of the federal states. We suggest that differences in agricultural land use and unequal uptakes of Agri-Environment Schemes (AES, which encourage later cutting) were likely to be responsible for the regional differences, while the general increase in AES appears to have confounded the overall trend in hay cutting in the last 20 years. Trends over time and responses to temperature were small relative to those associated with the phenology of meadow foxtail. The advance in phenology of this species is greater than the advance in hay cutting, implying that hay cutting may not be keeping pace with a changing climate, which may have a positive effect on grassland ecology.

Candidates own contribution:

Data preparation, statistical analysis, interpretation as well as writing of the manuscript (80% contribution). Tim Sparks, Nicole Estrella and Annette Menzel contributed with suggestions for statistical analysis, corrections and proof reading.

3.4 Publication IV

CHANGES IN FIRST FLOWERING AND FLOWERING DURATION OF 232 PLANT SPECIES ON THE ISLAND OF GUERNSEY

Anna Bock, Tim H. Sparks, Nicole Estrella, Nigel Jee, Andrew Casebow, Christian Schunk, Michael Leuchner, Annette Menzel

Submitted to

Global Change Biology (26 January 2014)

Climate change has affected plant phenology; increasing temperatures are associated with advancing first flowering dates. The impact on flowering duration however, has rarely been studied. We analysed first flowering dates and flowering durations from a 27-year time series of weekly flower observations on 232 plant species from the island of Guernsey, in the English Channel. The aim of this study was to explore variation in trends and relationships between first flowering dates, flowering duration and temperature. We specifically looked for evidence that traits explained variations in sensitivity of first flowering among species. Overall trends revealed significantly earlier flowering over time, by an average of 5.2 days decade^{-1} since 1985. A highly significant shortening of flowering duration was observed, by an average of 10 days decade^{-1}. Correlations between first flowering, flowering duration and year varied between different species, traits and flowering periods. Significant differences among traits were observed for first flowering and to a lesser degree in flowering duration. Overall, in comparison to first flowering, more species had significant trends in flowering duration. Temperature relationships revealed large differences in strength and direction of response. 55% of the species revealed a significant negative relationship of first flowering dates and temperature. In contrast, only 19% of flowering durations had a significant negative temperature relationship. The advance in first flowering date along with a shortening of flowering duration suggests potential serious impacts on pollinators, which might pose a major threat to biodiversity, agriculture and horticulture. Human health, in terms of pollen allergies, however, might benefit from a shortening of specific plant pollen seasons.

Candidates own contribution:

Data acquisition and digitalisation, data preparation, statistical analysis, interpretation as well as writing of the manuscript (75% contribution). Nigel Jee provided the dataset. The other co-authors contributed with suggestions for statistical analysis, corrections and proof reading.

3.5 Publication V

CLIMATE SENSITIVITY AND VARIATION IN FIRST FLOWERING AND FLOWERING DURATION OF 26 NARCISSUS CULTIVARS

Anna Bock, Tim H. Sparks, Nicole Estrella, Nigel Jee, Andrew Casebow, Michael Leuchner, Annette Menzel

Submitted to

International Journal of Biometeorology (20 December 2013)

Changes in first flowering dates over the past century can be linked to climatic change. These alterations reflect the ability of species to react to global warming. Not only natural vegetation, but also commercial crops have been affected. Daffodils (*Narcissus*), a commercially important species of the flower industry, are usually sold at special occasions such as Mother's Day and Easter. Despite the influences of plant breeding and cultivation practices, the timing of flowering of daffodils has been affected by warming in recent years, causing production shortfalls around Mother's Day in the UK. In this study, we analysed weekly flowering observations of 26 *Narcissus* cultivars on the island of Guernsey in the English Channel. First flowering and flowering duration were recorded over a 27 year long period. Analysis focussed on trends over time and relationships with climate variables. The analysis reveals that earlier flowering cultivars advanced most, were more variable and had longer flowering periods than later flowering *Narcissus*. We furthermore discovered a strong relationship of first flowering dates and flowering duration with climate variables, with temperature appearing to be the main driver. While the overall trend did show a significant advance in flowering, this was significant within the study period for only one of the individual cultivars. This reflects that the temperature between December and March during this period had not significantly increased in Guernsey. The results of this study may help to understand whether flowering patterns in *Narcissus* cultivars can adapt to future climate change.

Candidates own contribution:

Data acquisition and digitalisation, data preparation, statistical analysis, interpretation as well as writing of the manuscript (80% contribution). Nigel Jee provided the dataset. The other co-authors contributed with suggestions for statistical analysis, corrections and proof reading.

4 GENERAL AND SUMMARISING DISCUSSION

4.1 Strength and characteristics of the thesis

The aim of this PhD thesis was to assess the use of different novel phenological datasets and their suitability as climate proxies. In the previous chapters, changes in phenology as well as human-induced events associated with phenology were examined at different spatial and temporal scales.

Using these specific datasets, this PhD thesis revealed temperature related changes not only in natural biological systems, but also in specific phenophases heavily influenced by man. The number of data, the spatial coverage and/or the temporal length of the datasets used in the PhD thesis have been unprecedented in this extent. They thus provide additional information on different aspects of environmental change; and therefore act as unconventional indicators of climatic change.

The aspects that have contributed to the novelty and the originality of the datasets were characterised by:

- a multi-phenophase long-term dataset of three grapevine cultivars at the northern boundary of wine-growing in Germany. The dataset covered 61 years and combines true phenophases (e.g. budburst, flowering) as well as human induced activities and measures which are associated to phenological events (e.g. harvest date, must sugar content at harvest; Chapter 3.1),
- a unique long-term dataset on grapevine yield and must sugar content at the northern boundary of wine-growing in Germany, covering 205 years (Chapter 3.2),
- an exceptionally large spatio-temporal long-term dataset of over 110,000 single observations on the timing of first hay cutting at a national scale. This comprehensive dataset on a human induced phenological observation covered 60 years. In addition, over 8,000 records of first flowering of *Alopecurus pratensis* were compared to these hay cutting dates (Chapter 3.3),
- a multi-species and multi-cultivar phenological long-term dataset, recorded on the island of Guernsey. The weekly observations over 27 years consisted of over 160,000 single flowering observations and gave information on first flowering and flowering duration (Chapter 3.4),

- a multi-cultivar dataset of weekly observations on *Narcissus* flowering, recorded on the island of Guernsey. The 27 year long record revealed detailed information on first flowering dates and flowering duration of an important commercial flowering crop (Chapter 3.5).

4.2 Main results

4.2.1 Grapevine phenology

It is generally accepted that the area suitable for agriculture will expand in high and middle latitudes due to global warming. However, in other areas, acreage reduction are expected (Kiselev *et al.* 2013; Ray *et al.* 2012). World-renowned viticultural regions, especially in western and central Europe, might benefit from future climate conditions. Increases in mean temperature may lead to a higher suitability for grapevine growth and higher wine quality (Fraga *et al.* 2013; Moriondo *et al.* 2013). Nevertheless, the impact of shifts in climate varies according to the individual wine-growing region. Therefore, there may be a need to adapt the grapevine cultivars grown in order to still produce the best wine in future climates (Webb *et al.* 2013). So far, analysis of grapevine production and the impact of climate change in Europe has mainly focused on the Mediterranean region, France and the western wine-growing regions (Mosel and Rhine Valley) in Germany (Ashenfelter & Storchmann 2010; Jones *et al.* 2005; Moutinho-Pereira *et al.* 2009; Webb *et al.* 2013). Grapevine phenology in Lower Franconia (Chapter 3.1) has not been examined in detail so far.

We found that the warmer seasons resulted in a greater ripening potential for the cultivars *Müller-Thurgau*, *Riesling* and *Silvaner* between 1949 and 2010. This can be observed through trends towards earlier phenophases, shortening of phase intervals, earlier harvest dates and increases in must sugar content. Harvest models are generally more complex, but the analysis confirmed that advances in harvest dates could be largely explained due to earlier maturity. Concerning the different cultivars, the late maturing *Silvaner* and *Riesling* are likely to benefit more from advancing harvest dates than *Müller-Thurgau*. In this (currently) not water limited region, mean temperature was the most important influencing factor. With temperature no longer being a limiting factor for wine-growing in Franconia, vineyards could expand to other, formerly unsuitable sites. At present, wine growing in Lower Franconia is still benefitting from global warming. With climate change impacts continuing and becoming stronger, however, the cultivation of early maturing cultivars may become difficult in Franconia. Thus, the cultivars currently grown in Franconia may become less suitable. With higher inter-annual variability in the future in terms of climate, irregularities may lead to additional threats to viticulture (Fraga *et al.* 2013). For southern Europe, increased dryness and cumulative thermal effects during the growing season are expected (Malheiro *et al.* 2010). Vineyards in Lower Franconia, as well, are likely to suffer in the future from increased summer dryness. Thus, water supply by irrigation measures will gain more importance in the future. Modelling results furthermore show the potential for a rapid change in the landscape concerning wine grape production (Moriondo *et al.* 2013).

4.2.2 Wine quality

Wine quality is mainly based on the ratio between must sugar (°Oe) and acid levels ($g\ l^{-1}$) of the grapevine must. In Chapter 3.1, no significant trends were found for acid levels. Must sugar content, on the other hand, had a significant upward trend by 2.4°Oe per decade, which is in line with other studies (Duchêne *et al.* 2010). In contrast, in southwest France and Slovenia a reduction of the content of total acidity was revealed as a result of higher temperatures during the growing season (Jones & Davis 2000; Vrsic & Vodovnik 2012).

The measurement of must sugar content is used as an indicator of ripeness and harvest time (Conde *et al.* 2007) and was significantly responsive to temperature in both studies on Franconian viticulture (Chapter 3.1 and 3.2). Approximately 68 to 89% of the variation in must sugar content could be explained by temperature, precipitation and sunshine hours for the period 1950-2010 (Chapter 3.1). For the period of 1864-1905, 28% and, for 1962-2010, 43% of the variation in must sugar content was explained by temperature (Chapter 3.2). These lower values may be explained by sampling effects of the selected cultivars. The differences in must sugar content between the two periods in Chapter 3.2 were *inter alia* explained by the type of wine sought after.

Higher sugar and faster accumulation of must sugar content predominantly leads to higher contents of residual sugar; thus, higher alcohol content and little acidity retained result in a changed wine quality (Duchêne *et al.* 2010; Jones & Davis 2000). While the increase of must sugar content is currently still asked for at the northern boundary of wine-growing, in the long run implementation of measures aimed at mitigating these impacts of climate change are likely to gain importance (Palliotti *et al.* 2013). Viticultural practices usually focus at delaying maturity to offset the effect of high temperature. Practices include post-veráison limitation of canopy photosynthesis by defoliation, cluster thinning and shoot thinning and can hence affect berry weight and other wine characteristics (Kok 2011; Poni *et al.* 2013). Nevertheless, in Chapter 3.1 and 3.2 we proved that the composition of grapevine must provides a valuable proxy for climate change impacts. However, the measurement of sugar content of grapevine must only started in the 19th century; therefore, temperature reconstructions of this variable before the 19th century cannot be achieved.

4.2.3 Grapevine yield

Technological advance (e.g. new crop varieties and improved cropping practices) were found to be more important than the effects of increased temperature (Ewert *et al.* 2005; Lobell & Asner 2003; Tao *et al.* 2013). On the other hand, yield growth has been slowing in recent years; thus, climate change may have a bigger impact than technological advance in future (Bindi & Olesen 2011; Kristensen *et al.* 2011). Globally, recent climate trends have had a distinct negative impact on production of several major crops (Lobell & Field 2007). However, changes in crop yield due to global warming appear in geographical patterns. Acreages of agricultural crops may expand towards the north; in southern regions a drier climate is expected which may lead to a negative impact on crop yields (Kiselev *et al.* 2013). Thus, yield is expected to decrease in southern central Europe, while in the northern parts yield potential of various crops may increase (Bindi & Olesen 2011; Cho *et al.* 2012; Supit *et al.* 2010). In Canada, yields of cold season vegetables were associated with increasing trends from about 1950 to the 1980s, then yields levelled off or decreased with subsequent high interannual variation. These trends were related to an increase in the number of hot days with maximum temperatures over 30°C (McKeown *et al.* 2005).

To estimate the impacts of future climate change on agriculture, information gathered in the past becomes essential. In Chapter 3.2, a rare historical record on grapevine yield, dating back to 1805, was retrieved. These records are the first long-term dataset of grapevine yield and must sugar content (°Oe) in Germany. After relating the yield data with historical descriptions for validation, part of the variation in yield in the 19th and beginning of the 20th century could be explained by specific historical events. One example was the emergence of grapevine pathogens such as Downy Mildew (*Plamopara viticola*), which contributed to the large variability in grapevine yield around 1900. Overall, Chapter 3.2 confirms an upward trend in yield and must sugar content between 1805 and 2010. Considering the confounding factors influencing yield, approximately 15% of the increase in yield is due to increased temperature. The greatest growth in yield occurred between

1915 and 1952 and was associated with improved viticultural techniques and vineyard management. Since the late 1980s, the increase in yield has been limited, especially due to the introduction of a yield limit in German agricultural policy. In contrast, in an Australian study on wheat yield between 1952 and 1992, which was not affected by limitation measures, 30-50% of the observed yield increase was estimated to be due to climate trends (Nicholls 1997). However, the Australian observation period covered only part of the period of our grapevine yield study (i.e. 1962-1992). Increasing temperatures may also result in threats to viticulture. Climate irregularities such as late frost events may increase (Fraga *et al.* 2013) and more severe epidemics of Downy Mildew are expected. The latter may result in a need for additional viticultural adaption in terms of more intense and frequent uses of fungicide sprays to maintain the present yield and quality (Salinari *et al.* 2006).

The significant relationship between temperature, yield and must sugar content suggests that these variables could be used as climate proxies and support climate reconstructions. Despite recent yields being less reliable because of adapted viticultural practices, this long-term dataset provided a rare opportunity to investigate whether historical relationships between yield and temperatures applied in the course of the previous century.

4.2.4 Agricultural phenology (First hay cut)

When analysing hay cutting practices at a national scale, a larger number of factors had to be considered to identify the impact of climate. Changes and improvements in agricultural techniques, traditional versus fixed dates for agricultural practices and environmental programmes are the most prominent anthropogenic factors influencing temporal trends. In Chapter 3.3, changes in the timing of hay cutting over the past 60 years in Germany were analysed. While changes in crop cultivars in recent decades might have an influence on agricultural crops (Siebert & Ewert 2012), permanent grassland appears not to be affected (Williams & Abberton 2004). The timing of first hay cut was significantly influenced by geographic location. Higher altitude locations were associated with later onset dates. Particularly noteworthy was the east-west gradient of first hay cut, with hay cutting starting earlier in the east. This gradient was contrasted with the findings of the beginning of flowering of the grassland species *Alopecurus pratensis*, which is starting earlier in the west than the east. These results were confirmed by other studies which also found an east to west component for harvest of agricultural crops (Siebert & Ewert 2012), while other natural phenological phases had a west to east component (Estrella *et al.* 2009). While the overall national trend showed a not quite significant advance in hay cutting (regression coefficient = -0.06 days/year, p = 0.07), individual federal states had both significant and not significant trends. Remarkably, the northern states displayed advances up to 1.2 days per decade, while the south did not show any significant trend. Additionally, temperature responses in the northern federal states were higher (30-53% of the variation were explained) than in the south (max. 34% of the variation was explained). These results were explained by the diverse adaption of environmental schemes between the federal states, depending on the land-use and intensity of the agriculture (Kleijn & Sutherland 2003) which is associated with a north to south gradient in Germany. The impact of agri-environmental schemes are generally expected to be higher in rather extensively managed sites (Scheper *et al.* 2013). This hypothesis is furthermore supported by a recent study in the US which found that liquidity and solvency of the farmers have a negative impact on the participation in agri-environmental programs (Mishra & Khanal 2013).

4.2.5 Flowering phenology

The majority of long-term studies focusing on first flowering dates were done for temperate regions in the US and Europe (e.g. Abu-Asab *et al.* 2001; Ellwood *et al.* 2013; Fitter *et al.* 2002). Fewer records have been disclosed in other climates (e.g. Dai *et al.* 2013; Peñuelas *et al.* 2002). The study site of Chapter 3.4 is set on the island of Guernsey and thus focuses on a maritime region characterised by rainfall throughout the year with temperate summers with hardly any frost events in winter due to its maritime climate. The dataset provided a unique insight into flowering phenology of a large number of plant species and cultivars within a single locality. The weekly flowering observations allowed conclusions concerning first flowering and, more importantly, flowering duration. The timing of first flowering is a widely acknowledged phenological event since it is highly responsive to temperature. The behaviour of flowering duration, however, is less studied especially over a longer period. Most studies on flowering season used approximations of flowering duration from either beginning of flowering and full flowering (Miller-Rushing *et al.* 2007; Ziello *et al.* 2012b) or from pollen counts (D'Amato *et al.* 2002; Ziska *et al.* 2011). In this study, we discovered a dataset of over 160,000 phenological observations on beginning of flowering and flowering duration of 470 plant species for the period 1985 to 2011. Of the entire dataset, 232 plant species had over 15 years of data. Thus, the uniqueness of dataset is the fact that not only first flowering dates but also the actual flowering duration from beginning to end of flowering of 232 plant species over a 27 year long period was recorded.

Numerous studies found advances of first flowering dates (e.g. Abu-Asab *et al.* 2001; Amano *et al.* 2010; Ellwood *et al.* 2013; Menzel *et al.* 2006a; Ziello *et al.* 2012a). In a study in the Mediterranean region, plant species were found to have advanced by approximately 2 days per decade from 1952-2000. In Chapter 3.4, we found an average advance by approximately 5 days per decade, but for a shorter and more recent period. 55% of all observed species were significantly related to temperature. In order to find underlying drivers of phenology, relationships were furthermore analysed by traits. Significant differences among traits were observed for first flowering and to a lesser degree in flowering duration. Trends varied greatly among species. The strongest advance in first flowering was found for geophytes, while therophytes did not show any significant trend. A study on divergent responses to spring and winter warming revealed that apparent nonresponding species might be responding to temperature after all. Species either respond to temperature of different months in a contrasting way but at similar magnitude or the inclusion of monthly temperature of much earlier months would significantly improve model predictions (Cook *et al.* 2012b). Furthermore, in warm temperate latitudes, where winter temperatures are scarcely sufficient for satisfying chilling requirements for some species, a delay in phenology may be the result of insufficient chilling (Polgar & Primack 2011; Schwartz & Hanes 2010).

In Chapter 3.4, flowering duration was not mainly driven by temperature since it only affected 19% of all observed species. Hence, the influence on flowering duration appeared to be more complex than for other phenological phases. Other factors such as soil moisture, accumulated heat or chilling units need to be considered.

More specialised climate models and additional climate data, especially related e.g. to soil moisture, soil temperature and winter snowpacks, are likely to be critical for generating more powerful phenological models that can be used for extrapolating future phenological behaviour (Wolkovich *et al.* 2013). A shortening of flowering duration of individual plant species due to warming may result in a reduction of human exposure time to pollen of specific allergenic species. Thus, allergic sufferers might actually benefit from a shorter pollen season. However, additional research to identify further drivers of flowering duration is needed.

In Chapter 3.5, we had the opportunity of analysing 26 subspecies and cultivars of the same genus (*Narcissus*) over a period of 27 years. The observation site was, again, the island of Guernsey in the English Channel. Climate sensitivity and variation of first flowering and flowering duration of 26 *Narcissus* cultivars were analysed. Daffodils (*Narcissus*) are of major importance to the flowering industry and are thus of economic and aesthetic value, especially during the spring season. While numerous studies exist on *Narcissus* breeding and optimum growing conditions (Barkham 1980; Hanks *et al.* 2001; Veatch-Blohm *et al.* 2013), little is known on long-term trends of a larger number of naturalised cultivars. The analysis showed that earlier flowering cultivars advanced most, were more variable and had longer flowering durations than later flowering *Narcissus* cultivars. First flowering and flowering duration were highly sensitive to temperature and to a lesser degree to precipitation; however, no significant advancing trend in first flowering could be detected in our study period. The reason for this lack of advancing trend might be that the temperature between December and March had not significantly increased over the observation period. The only significant increase in temperature of the selected months occurred in November, when the cultivars were either sensitive to forcing or chilling, depending on the respective cultivar; however, the trend is weak. These aspects might explain the lack of strong trends in these phenological observations.

4.3 Key research findings

4.3.1 Confounding factors

What are the anthropogenic and abiotic drivers influencing the phenological signal of the novel datasets? How can we distinguish natural climatic from anthropogenic influences?

True phenological phases are exclusively triggered by environmental factors, predominantly climate (Menzel *et al.* 2006c). Novel datasets, on the other hand, are often influenced by non-climatic drivers. In this thesis, we predominantly examined the abiotic drivers temperature, precipitation and sunshine duration (depending on availability). Although other climate drivers, including photoperiod, chilling and forcing units may affect phenological events, we focused on temperature which it is the most consistent and dominant controller of spring phenology in temperate regions (Chuine *et al.* 2010; Rohde *et al.* 2011) as well as the most reported (Wolkovich *et al.* 2012). To work out the predominantly human induced drivers, especially for historical datasets, additional historical, economic and climate evidence had to be considered to disentangle natural climatic or anthropogenic influences. However, the exact quantitative attribution of these influences remains a challenging task because of their interaction and feedbacks (Kienel *et al.* 2013). To elaborate the interaction of anthropogenic drivers, we have to distinguish between the characteristics of the respective feature of the datasets:

(1) Agricultural/horticultural phenological phases

In this thesis, agricultural (i.e. viticultural) phenological phases include budburst, flowering, véraison and are so-called climate triggered true phases, since they occur as a direct effect of climate (Menzel *et al.* 2006c). In Chapter 3.1, we revealed highly significant climate relationships of phenological onset dates. 49 to 59% of the variation in budburst, 82 to 93% of full flowering and 85 to 87% véraison were explained by regression models. Thus, we confirmed that later phenological phases (i.e. flowering and véraison) primarily responded to climate variables, predominantly to temperature, and that the anthropogenic influence can be regarded as less influential.

(2) Agricultural false phases and observations that are heavily influenced by human decisions

Studies using farming records or farming related phenological data reported that most of these events respond, at least in part, to temperature (Chmielewski *et al.* 2004; Menzel *et al.* 2006c; Sparks *et al.* 2005; Tao *et al.* 2012). Phenological dates in agriculture and their responses to climatic factors are a result of human decisions and may differ from those of wild plants and vary in time. In particular, factors such as change in cultivars, adaptation of crop growing, and management need to be considered (Estrella *et al.* 2007). Viticultural false phases are winegrowers' activities that are climate-triggered only to a certain degree. They thus reflect also viticultural management practices and therefore follow climate warming to a lesser extent than true phases of plant species. Great care should be used to make sure that the same cultivar is being examined (Hanks 1996; Sparks & Carey 1995; Williams & Abberton 2004). In Chapter 3.1, we were able to compare the phenology (budburst, flowering, véraison) of three different cultivars *(Silvaner*, *Riesling* and *Müller-Thurgau)* with a dataset of combined unknown cultivars (must sugar content (°Oe) and harvest date). We revealed that both datasets did show similar significant trends, however, the explanatory power of the dataset of the individual cultivars was greater. Grape harvest dates are a widely accepted proxy for climate reconstructions (e.g. Chuine *et al.* 2004; Maurer *et al.* 2011). Since the 19th century, harvest date is recorded as the point at which, due to the optimum sugar levels, the harvest commences (Jones & Davis 2000). In Chapter 3.1, it was possible to compare grape harvest dates with the phenology of the respective grapevine over a 60 year period. Depending on the cultivar, the correlation between must sugar content and harvest date was highly significant (r = 0.78 to 0.85). The relationship between véraison and harvest dates furthermore revealed a highly significant correlation (r = 0.75 to 0.82). Analysis of equality of slopes moreover confirmed no differences between trends in véraison and harvest. These findings verify that grape harvest dates, despite being a false phase that is influenced by human decisions, still respond to temperature variables, since human decisions, in turn, depend, to a certain degree, on phenological observations (ripeness of grapes, i.e. véraison) and measurements of must sugar content.

Farmers cope with climate change based on their perceptions of changing climate patterns. In a case study in Tibet, where farmers still exercise traditional farming methods, farmers acknowledged increasing temperatures and reported earlier sowing and harvest dates (Li *et al.* 2013). In Germany, over the past 60 years, hay cutting dates have advanced (Chapter 3.3). Nevertheless, the dataset on hay cutting in Germany showed that during the last two decades, despite continuous warming, hay cutting dates were rather constant while the response of these dates to temperature decreased and was no longer significant. In contrast, flowering dates of commonly observed grass species did advance in the manner expected from past sensitivity to temperature. Thus, differences in agricultural land use, timing of holidays, as well as agri-environment schemes most likely have confounded the overall trends in hay cutting. Another example for a diverging response was shown in the analysis of long-term data on grape harvest yields and quality, i.e. must sugar content (°Oe) in Chapter 3.2. Must sugar content was highly responsive to temperature, especially in the past 50 years. Yield data (hl/ha), however, is more affected by non-climatic drivers. Long-term yield data may be especially affected by rapid turnovers in cultivars, technological advances in production, improvements in harvesting machinery, timing of holidays, or the need to use labour on particular dates (Sparks *et al.* 2005). The effects of increasing temperatures and increased atmospheric CO_2 are expected to result in an overall increase in European crop productivity (Bindi & Olesen 2011). However, technological advance (e.g. new crop varieties and improved cropping practices) used to be more important than the effects of increased temperature (Ewert *et al.* 2005). On the other hand, yield growth has been slowing in recent years, thus, climate change may have a bigger impact than technological advance in the future (Bindi & Olesen 2011; Kristensen *et al.* 2011). In Chapter 3.2, we discovered that the relationship of temperature with grape yield data is much weaker for yield than for must sugar content. In contrast to other agricultural crops, maximum possible yield is not desired in viticulture, hence, adapted viticultural practices are used to limit yield. Grapevine yield and must sugar content were related to temperature, yet, potential increases in yields are limited by current legislation and, thus, may not reach full potential in the future.

(3) True phenological phases of garden plants and wild plants

In this thesis, true phenological phases include first flowering dates and flowering duration (Chapter 3.4 and 3.5). These are so-called climate triggered true phases (Menzel *et al.* 2006c), since they occur as a direct effect of climate. The observations were conducted within a single location and the species observed were a combination of managed garden plants and wild growing plants. Anthropogenic influences were narrowed down to regular pruning practices and non-climatic influences could thus be neglected. 88% of all species revealed significant temperature relationships of the six months preceding first flowering. Flowering duration, however, did show significant temperature relationships for 19% of all species. We hence confirmed that first flowering primarily responded to temperature variables. The drivers of flowering duration, on the other hand, appeared to be more complex. Additional climatic factors, such as chilling, precipitation or soil temperature may be of greater importance. For Guernsey, which is lying in a region with a long growing season and relatively low interannual variability, biotic forces might be more influential than in other regions (Pau *et al.* 2011). However, the anthropogenic influence on both observations was estimated as negligible.

4.3.2 Criteria

What criteria have to be met by novel datasets to qualify as indicators for climate change impact?

To draw any informative value from datasets regarding recent climate change, they need to meet certain criteria. In this project a wide range of possible datasets was retrieved and edited. Yet, only a part of the acquired data was suitable for further analysis.

Concerning long-term data in agriculture and viticulture, it is necessary to know whether the same cultivar was being examined over the observation period (Sparks & Carey 1995; Williams & Abberton 2004). In Chapter 3.1 and 3.4, we were able to either distinguish between different grapevine cultivars or we were able to confirm that the overall combination of various cultivars remained the same over the observation periods. In a long-term dataset on hop growing in Bavaria (Appendix A), however, research revealed *inter alia* a massive turnover in hop cultivars, resulting in a sudden shift in spring practices and harvest dates. Since there was no information on the actual hop cultivars grown in the respective years, no climate-related results could be drawn from this dataset.

Climate varies among study sites. For vineyard phenology, for example, the mesoclimate depends on the setting of the vineyard (slope, exposition and elevation), resulting in different phenological responses. In Chapter 3.1 and 3.2, we were able to confirm that the observed vineyards were the same over the observation periods. In Appendix B1, on the other hand, we retrieved a long-term dataset on the swarming behaviour of honey bees (*Apis melifera*). The beehives were usually moved to various regions (depending on what kind of honey was sought) during the summer season. Thus, the swarming time-series could not be regarded as homogenous. The same problem occurred for the dataset on bird migration in Hungary (Appendix C) and the dataset on cherry ripening in Australia (Appendix F). While in both cases, unique long-term datasets, dating back to the beginning of the 19th century, were discovered, both datasets revealed a large spatial variability in observation locations. Hence, no homogeneous time-series could be established and analysed.

Continuous observations, covering at least 20 years, are essential to gain climate-related information. While this criteria appeared to be met for all datasets retrieved for this thesis, gaps, incomplete data or unsuitable data within the time-series were discovered (Chapters 3.3, 3.4 and 3.5) and thus reduced the informative value. We were able to eliminate these factors for the hay-cutting dataset (Chapter 3.3) and flowering dataset (Chapter 3.4 and 3.5) by either using the adjusted long-term means from a two way ANOVA, excluding the respective observations, or adjusting the datasets. However, for the datasets on hop-growing (Appendix A), swarming of *Apis melifera* (Appendix B1 and B2), spring-cleansing flights of *Apis melifera* (Appendix B2) and bird migration in Hungary (Appendix D), the gaps in the time-series were regarded as too large and/or frequent.

4.3.3 Informative value and applicability

What is the informative value and applicability of novel datasets and what kind of insights in terms of ecology, economics and applied conservation can be achieved?

It is common knowledge that increased temperatures result in earlier seasonal appearance of phenological events (e.g. Menzel *et al.* 2005; Rosenzweig *et al.* 2007). However, the ecological and species-specific mechanisms and consequences are still unclear. There are two main approaches to predict plant species' responses to global warming. One approach relying on observations over time or space (Fitter *et al.* 2002; Jochner *et al.* 2013a; Menzel *et al.* 2006a; Parmesan 2007), the other one relying on warming experiments on a small scale (Arft *et al.* 1999; Dunne *et al.* 2003; Fu *et al.* 2013; Harte & Shaw 1995). However, Wolkovich *et al.* (2012) demonstrated that phenological responses derived from warming experiments underpredicted advances in the timing of flowering or leafing 8.5-fold and 4.0-fold, respectively. Hence, novel datasets that provide information on other aspects of environmental change may be used as valuable new indicators. Such datasets may be especially valuable in regions and at local scales where long-term phenological records are rare, such as in the Southern Hemisphere (Chambers *et al.* 2013).

In general, this thesis demonstrates that the novel datasets analysed act as indicators for environmental change and thus present a useful and important way to detect the footprint of climate change. Furthermore, novel datasets in this thesis reveal consequences of global warming on our ecosystem, economy and landscape. The cultural landscape in Europe is defined as "combined works of nature and of man" (UNESCO 2014). Cultural landscape is thus influenced by land-use and land-cover, which in turn are closely related to climate. Climate-induced changes in phenology affect species distribution (Thuiller *et al.* 2008). This again may result in shifts in the distribution of land for cropping and viticulture. Hence, land that is currently arable may suffer from global warming (Jones *et al.* 2005). Apart from the economic consequences (e.g. crop failure), a change in land-use also impacts the aesthetic value of characteristic cultural landscapes, which is also an aspect of ecosystem services. In Chapter 3.1 and 3.2, we revealed that the observed warmer season resulted in greater ripening potential in grapes. We found that currently the Franconian wine growers are still benefiting from global warming. Yet, in the long-term, the consequences will be an altered wine typicity which may result in a loss of the traditional Franconian wine. While the temperature related increase in grape yield would result in a price decline, grape yield is already limited by legislation. Must sugar content, however, is likely to further increase. Adapted viticultural practices (e.g. acidification, change of cultivars) or an expansion of the vineyards to formerly unsuitable sites are likely to become necessary in the future. Abandoned or newly cultivated vineyards would not only impact the ecology (Hannah *et al.* 2013) but also affect the characteristic cultural landscape of Franconia. Furthermore, a warming climate influences the vulnerability of crops regarding pests (Sparks *et al.* 2005) such as Downy Mildew *(Plasmopara viticola)*, Powdery Mildew *(Oidium tuckern)* and Grape

Phylloxera *(Viteus vitifoliae)*. In Chapter 3.5, the impact of global warming on the commercial flower crop *Narcissus* was analysed. We revealed that earlier flowering cultivars advanced most, were more variable and had longer flowering periods than later flowering cultivars. The results of this study may help commercial growers to understand which *Narcissus* cultivars are best adapted and suitable for production with future climate change.

The timing of phenological events interacts with herbivores, pollinators, and other ecological mechanisms and may thus lead to ecological mismatches (Both *et al.* 2009; Durant *et al.* 2007; Ellwood *et al.* 2013; Forrest & Thomson 2011; Parmesan 2006). Furthermore, advances in spring phenology are more likely to be impacted by late frost events which have negative effects on plant growth and fruit development (Ellwood *et al.* 2013; Inouye & Mcguire 1991; Nielsen & Rasmussen 2009; Norby *et al.* 2003). In Chapter 3.3, spatial and temporal variation in the timing of hay-cutting and flowering of grassland species were discovered, revealing strong anthropogenic influences on hay-cutting activities. The regional importance of the impact of agri-environmental schemes in Germany was revealed and potential problem areas regarding the conservation of grassland ecology could be identified. In Chapter 3.4, significantly earlier flowering due to increased temperatures was detected among 232 plant species. At the same time, highly significant shortening of flowering duration was observed. This would translate into an earlier and shorter flowering season for the island of Guernsey. Generally, a shorter flowering season may lead to a decline in flower visitor abundance in the future (Høye *et al.* 2013) and thus pose a major threat to biodiversity. However, human health, in terms of pollen allergies, might slightly benefit from a shortening of specific plant pollen seasons.

5 GENERAL CONCLUSION AND OUTLOOK

Recent climate change, particularly increases in temperature, have affected physical and biological systems (e.g. Rosenzweig *et al.* 2008). Therefore, phenological observations are widely used for providing evidence of climate change impacts. In particular, long-term phenological datasets reveal profound insights into life cycle events and how these are influenced by seasonal and interannual climate variation. Thus, systematic phenological data collection is of crucial importance. Nevertheless, uncertainty remains about how climate change will affect specific species, regions and how ecosystems and productivity will be affected (Mazer *et al.* 2013; Moriondo *et al.* 2010; Polgar & Primack 2011).

In this thesis, spatial and temporal variability of unique phenological time-series and as well as time-series of events that are influenced by human decisions were analysed. The central aim was to overcome data limitations and to focus not only on purely natural phenological observations (i.e. true phases), but to include novel and unexploited datasets that may provide additional information on climate change. The importance of long-term phenological records was emphasised, the informative value of a large variety of exceptional datasets regarding the footprint of climate change was stressed.

In the course of this project, large scale spatial and/or temporal observations were acquired and combined to provide novel information on responses to global change. Additional sources and climate variables were used to set the information into context via various statistical analysis. We therefore identified appropriate and unique long-term datasets suitable for the detection of the footprint of climate change for further research. We separated confounding, predominately anthropogenic, factors from the phenological signals to estimate the effect of increased temperatures. Hence, new additions to our knowledge of climate change responses were revealed and possible future impacts on the ecology and economics of the respective regions were assessed.

Therefore, this thesis highlights:

(1) the importance of long-term phenological time-series and offers a comprehensive overview on a variety of datasets providing novel insights on climate change impacts. The originality of datasets is characterised either by

- the type and variety of phenological observation (i.e. common phenological observations vs. must sugar/acid content, grape harvest dates, grape yield and hay cutting dates),

- the unique location or spatial distribution of the observations, where hardly any other research has been done before (i.e. the northern boundary of wine growing in Germany, a large spatial analysis of Germany, the island of Guernsey in the English Channel),
- the temporal extent of the dataset (i.e. 27 to 205 years of observation).

(2) the explanatory power of the novel datasets regarding the, predominantly, anthropogenic confounding factors:

- agricultural phenological phases (e.g. viticultural phenology),
- agricultural false phases, events or measurements that are heavily influenced by human decisions (e.g. grape harvest dates, must sugar content, hay cutting dates),
- true phenological phases (e.g. first flowering dates, flowering duration).

(3) the informative value and applicability of novel datasets, regarding future impacts of climate and environmental change on

- economy (e.g. the wine industry in Franconia, daffodil production),
- ecology (e.g. cultural landscape in Franconia, grassland ecology in Germany),
- conservation measurements (e.g. agri-environmental schemes, potential focus areas in Germany),
- human health (start and duration of pollen season).

There are still numerous specifics in phenological behaviour that are unclear. Some individual species reveal an apparently paradoxical behaviour and either have no significant trends or have delayed their timing (Fitter & Fitter 2002; Wolkovich *et al.* 2013). While Cook *et al.* (2012b) attempted to explain this by the interplay between vernalisation and spring warming sensitivities to temperature, they also pointed out that more studies are needed to understand how these diverse pathways interact to influence flowering in wild communities. Early-flowering species were found to be more responsive to warming than later-flowering species (Cook *et al.* 2012a; Menzel *et al.* 2006a), more recent studies, on the other hand, also found the reverse of this trend (Høye *et al.* 2013; Iler *et al.* 2013). This apparent contradiction may be explained by varying phenological responses among different environments. Phenological research has tended to focus on mesic, temperate sites (Pau *et al.* 2011), where soil moisture is unlikely to limit growth, and phenology is strongly controlled by temperature (Cook *et al.* 2012a; Nemani *et al.* 2001). Thus, it is essential that more research is done for many more species, communities and regions of the globe. Phenological networks at local, regional, or national level provide detailed and standardised phenological observations. For regions, however, where continuous phenological observations are rare or do not extend back very far, unique and unexploited observations may also represent an important tool in future phenological and climate change studies.

In this PhD thesis we discovered that novel phenological observations or observations that are associated with phenological events are capable of improving our understanding of current and future climate change impacts and thus have potential for further research. The number of potential datasets retrieved in this project suggests that there exist many other long-term datasets providing insights into impacts of environmental change. More attention should therefore be paid to unexploited phenological observations in future research. Novel datasets can act as unconventional climate proxies and thus improve our understanding of how climate change has influenced and will continue to influence various aspects such as ecology, agriculture, economy and human health in the future. These new indicators of climate change may help to inform policy-makers of the necessary steps to reduce adverse consequences in an uncertain future.

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ACKNOWLEDGEMENTS

For the success of my PhD thesis I would like to thank numerous people for their support and guidance throughout my PhD.

Prof. Dr. Annette Menzel for supervision, encouragement and motivation. For giving me the opportunity to work on this project and for supporting me with her scientific expertise and advice.

Prof. Dr. Tim Sparks for supervision, constant motivation and his time commitment. I am especially grateful for his inspiring comments and insights into "unusual" datasets and statistics, and his endless patience with my manuscripts.

My co-authors Dr. Nicole Estrella, Andrew Casebow, Christian Schunk and Prof. Dr. Michael Leuchner for their encouraging comments and statistical support. Nigel Jee for providing his valuable records.

Dr. Marie Keatley for her warm welcome, hospitality and scientific support during my stay in Melbourne.

My colleagues Dr. Nicole Estrella, Dr. Chiara Ziello, Nik Hofmann, Anton Knötig, Raimund Helm, Dr. Christian Zang, Dr. Isabel Dorado Liñán, Michael Matiu, Steffen Taeger, Dr. Clemens Wastl, Elisabeth Martinez Sancho, Hannes Seidel, Dr. Christine Cornelius, Prof. Dr. Michael Leuchner, Prof. Dr. Susanne Jochner, Julia Laube, Renée Monserrat Capdevielle, Marvin Lüpke, Christian Schunk, Dr. Christina Schuster and Brigitte Fleischner for the help in any technical, scientific or bureaucratic concerns and the good working atmosphere as well as the FBÖK Committee for memorable moments.

Special thanks to Michael, Susi i.K. and Tine for their understanding, constant support and for believing in me. And especially to Prof. Susanne Jochner and Prof. Michael Leuchner for comments and edits to my work.

To my family, friends and flatmates for enduring my mood swings and supporting me throughout my PhD thesis.

This research was funded by Technische Universität München - Institute for Advanced Study, funded by the German Excellence Initiative.

PUBLICATION LIST

Reviewed Publications

Bock A, Sparks TH, Estrella N, Menzel A (2011) Changes in the phenology and composition of Franconian wine (Germany). *Climate Research 50: 69–81*.

Bock A, Sparks TH, Estrella N, Menzel A (2013) Changes in the timing of hay cutting in Germany. *Global Change Biology 19(10): 3123–3132*.

Bock A, Sparks TH, Estrella N, Menzel A (2013) Climate-induced changes in grapevine yield and must sugar content in Franconia (Germany) between 1805 and 2010. *PLoS ONE 8(7): e69015*.

Submitted Publications

Bock A, Sparks TH, Estrella N, Jee N, Casebow A, Leuchner M, Menzel A *(submitted to International Journal of Biometeorology)* Climate sensitivity and variation in first flowering and flowering duration of 26 Narcissus cultivars.

Bock A, Sparks TH, Estrella N, Jee N, Casebow A, Schunk C, Leuchner M, Menzel A *(submitted to Global Change Biology)* Changes in first flowering dates and flowering duration of 232 plant species on the island of Guernsey.

Publications in preparation

Santangeli A, **Bock A**, Sparks TH, Peltonen-Sainio P, Valkama J *(in prep.)* Farmland bird *(Vanellus vanellus and Numenius arquata)* phenology and the impact of agricultural management.

Conference attendance and presentations

Phenology 2012 Conference **Sep 2012**
Milwaukee, USA
Bock A, Sparks TH, Estrella N, Menzel A (2012). Changes in the timing of grass cutting in Germany (1955 to 2011). (oral presentation)

Student Conference on Conservation Science **Mar 2012**
Department of Zoology, University of Cambridge, UK
Bock A, Sparks TH, Estrella N, Menzel A (2012). Changes in the timing of grass cutting in Germany (1955 to 2011) and the effects on grassland ecology. (oral presentation)

19th International Congress of Biometeorology **Dec 2011**
Auckland, New Zealand
Bock A, Sparks TH, Estrella N, Menzel A (2011). Changes in the yield and composition of Franconian wine (Germany) from 1805 to 2010. (oral presentation)

European Geosciences Union General Assembly 2011 **Apr 2011**
Vienna, Austria
Bock A, Sparks TH, Estrella N, Menzel A (2011). Climate Change and its effect on Franconian wine. (poster presentation)

Student Conference on Conservation Science **Mar 2011**
Department of Zoology, University of Cambridge, UK

APPENDIX

Attachment of additionally acquired time-series

A) Diary of hop farming

The dataset is based on multigenerational records on hop growing (*Humulus lupulus*) in Pfaffenhofen (Germany) and derived from three handwritten notebooks. The records were made during the time period 1924 to 1998 and consist of dates and information of various farming practices related to hop growing: planting, cultivating and pruning practices, putting up wire ropes for the hops, tillage, harvest and yield.

The records revealed various missing information and partly inconsistent observations, leading to an overall inconsistent time series. Further analysis of this dataset showed, that in this case, the recorded events were overall driven by non-climatic influences. Cultivating practices and pruning appeared to be highly dependent on the actual weather (dry soil was needed). Furthermore, a massive turnover in hop cultivars in the 1970s resulted in various shifts in the timing of spring practices and harvest dates. Improvements in tillage machinery led to less frequent cultivation practices. Furthermore, traditions and timings of holidays (e.g. Easter) may have had an influence, especially in the earlier years. The records of hop yield was recorded in "metzen" (former measuring unit, equals to 60 l) till 1960. From there on, information of weight units were inconsistent. Due to changing acreages and field names, it was not possible to calculate the respective yield per hectare.

B) Honey bees

1) Diary of a beekeeper

This long-term dataset is based on records of a beekeeper from Franconia (Germany) and derived from three handwritten notebooks. The records covered the period 1942 to 1997 and included yearly information on bees (*Apis melifera*) and beekeeping activities, such as swarming of bee colonies, expenses and returns, number and sizes of bee hives and control measures of the beekeeper.

The dataset revealed numerous missing years as well as an inconsistent way of recording. Missing entries on bee swarming were, furthermore, not possible to equate with the absence of swarming activities. Furthermore, the beehives were not located in only one area, but were moved to various sites and regions according to the maximum possible honey production. Detailed information on the control measures of the beekeeper revealed a persistent aim to prevent any kind of swarming activity (e.g. removing the queen bee). The missing information on the actual location of the beehives made it impossible to relate the bee data to respective climate variables. Overall, the analysis of this dataset showed that the recorded variables were predominantly driven by human influence rather than by climatic variables.

2) LWG

This dataset is based on the performance testing (Leistungsprüfung) of bee colonies (*Apis melifera*) in Bavaria, which are supervised by the "*Landesanstalt für Weinbau und Gartenbau*" (LWG) in Veitshöchheim. The dataset covers the period 1985-2012 and was extracted and digitised from records at the LWG. Bee colonies were tested for performance such as honey yield, population size, spring development, winter hardiness, as well as for characteristics such as gentleness, behaviour on combs, swarming behaviour and hygienic behaviour. The testing was done without employing any kind of control or management measures, therefore depended predominantly on non-human factors.

The performance testing was executed at three different district offices: Acheleschweig in southern Bavaria, Kringell in eastern Bavaria and Schwarzenau in northern Bavaria. The observations of interest were hygienic behaviour (i.e. spring cleansing flight) and the swarming behaviour since they are most likely to be dependent on climatic factors.

The analysis of the datasets revealed large gaps in the observations which could not be filled, despite strong efforts to retrieve the information from the respective district offices. The only consistent time series analysed was on the spring cleansing flight in Kringell. A significant change in first cleansing flight was observed, with spring cleansing advancing by approximately 28 days over the observation period. Moreover, there was a significant relationship between the advance of the first cleansing flight and January to March mean temperature (41 % of the variation being explained by temperature). The findings suggest that climate change has an influence on the behaviour of honeybees and, thus, the use of the honeybee as a bio-indicator of climate changes should be considered.

C) Bird migration

Ottó Herman (1835-1914) was a Hungarian naturalist. His work, especially in ornithology in Hungary is still of great scientific importance. The records were obtained from the Balfour & Newton Libraries at the Department of Zoology of the University of Cambridge, UK.

The information were found in publications, written in German and Hungarian, of the *"Zweiter Internationaler Ornithologischer Congress, Budapest 1891 - Die Elemente des Vogelzuges in Ungarn bis 1891"* (Second International Congress on Ornithology, Budaspest 1891 - The Elements of Bird Migration in Hungary till 1891). The publications included records of first sightings of migrating birds from numerous locations within the former Kingdom of Hungary. This observation area comprised parts of the current Austria, Slovenia, Croatia, Romania and the Ukraine. Sightings observed included a large number of bird species, including barn-swallow (*Hirundo rustica*), white stork (*Ciconia ciconia*) and skylark (*Alauda arvensis*) for the period 1849-1889. The analysis of the dataset revealed large variations in locations and species observed over the recording period. In this context, further journals on ornithology and observations of bird migration in Hungary (Journal Naumannia, Journal für Ornithologie) were retrieved. However, due to the large observation area (former Kingdom of Hungary), it was not possible to either extend the time-series by comparable observations or to fill missing observations.

D) Winegrowing County of Castell

Wine-growing in Castell at the *"Fürstlich Castell'sche Domänenamt"* dates back to the 13th century. Documents on cellar records and vintage records date back till the 16th century. These annual account books (*Rechnungsbücher*) are preserved in the archive of Castell (*Fürstlich Castell'sches Archiv*). The information of interest was the wine tithe and the vineyards that were cultivated in each year.

There exists one account book a year with information on all the accounting regarding the principality of Castell. All account books are handwritten in kurrent (an old form of German language handwriting, based on late medieval cursive writing). The first mention of the wine tithe was in 1470. The first account book with records on the wine tithe was 1569. Since 1578, the wine tithe was recorded annually with varying units (e.g. *Eimer, Fuder, Maß)* and varying vineyard acreages. However, the investigation of the respective information of the account books from 1578 to 1937 (approximately 359 account books) would have been time-consuming and thus not possible within the period of this PhD.

E) Daffodil festivals in the Southern Hemisphere

Phenology has been affected by increasing temperatures in every part of the world. However, detailed long-term phenological data are predominantly limited to the Northern Hemisphere.

Daffodil festivals, for example, are the most commonly held flowering events that can be found in all temperate parts of the word. In this project we attempted to gain information on climate change impacts using such flower shows and flowering festivals to detect impacts of increasing temperature. Early flowering species are known to be most responsive to temperature, and thus flowering is expected to have advanced with increased temperatures over recent decades.

In the course of this project, annual daffodil, lavender as well as wildflower shows were tracked down at several locations on the mainland of Australia, Tasmania and New Zealand. The dates of the shows and festivals were retrieved from archives and daffodil societies of the respective towns in Australia and New Zealand. The shows covered varying time periods with the earliest show having started in 1937. However, we discovered in the course of this project that all retrieved shows have or had stipulated dates, depending either on public holidays, specific weekends (e.g. every 2nd week in November) or were coordinated with other flowering shows in the vicinity. The daffodil festivals were, furthermore, able to react to varying weather conditions by presenting either later or earlier flowering *Narcissus* cultivars. Native flowers for wildflower shows were collected from a larger area, with varying species being presented at the show depending on species flowering at the respective time. Thus, the collected time-series were not suitable for the detection of climate change impacts.

F) Cherries harvest dates in Australia

The arrival of the first box of local cherries into the metropolitan markets of Melbourne has been announced in the Sydney Morning Herald since 1836. In the course of this project we were able to retrieve a nearly complete time-series of dates of the first arrival of cherries at the Sydney markets from 1899 till 2012. This was achieved by going through the local newspaper archive of the town Young, one of the first and most important cherry growing region in New South Wales and the already digitised newspapers of the Sydney Morning Herald (www.trove.nla.com.au).

However, it was not practicable to limit the data to cherries from the same origin (i.e. Young). With the expansion of the Australian cherry production area, improvements in transport systems and storage facilities, the first box of cherries arrived from varying areas and regions, as far as South Australia. Changes in cherry cultivars furthermore affected the time-series. These were confounding factors that we were not able to eliminate during the course of this thesis.