Lehrstuhl für Ökoklimatologie

Räumliche und zeitliche Variabilität von phänologischen Phasen und Reaktionen im Zuge von Klimaveränderungen

(*Spatial and temporal variability of phenological events and responses due to climate change*)

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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 (Dr. rer. nat.) genehmigten Dissertation.

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Vorwort

Die hier vorgestellte, am Lehrstuhl für Ökoklimatologie der TU München entstandene Arbeit entwickelte sich aus verschiedenen Studien. Im Rahmen des EU Projektes POSITIVE sollte zunächst die Herbstphänologie von Laubbäumen in Mitteleuropa modelliert werden. Im Laufe des Projektes stellte sich jedoch heraus, dass sich mit den vorhandenen Informationen keine befriedigenden Modellansätze finden ließen. Eine Auswahl der zahlreichen getesteten Ansätze ist im Artikel ‚Responses of leaf colouring of four deciduous tree species to climate and weather in Germany' dokumentiert worden.

Während dieses Projektes gewann die Phänologie in der internationalen Forschung jedoch immer mehr an Bedeutung. Dies gab mir die Möglichkeit (basierend auf den im Projekt POSITIVE resultierenden Erfahrungen), im Rahmen weiterer Forschungsvorhaben mit unterschiedlichen Fragestellungen zum Themengebiet Phänologie am Lehrstuhl zu forschen und erfolgreich zu publizieren. Die in der hier vorliegenden kumulativen Dissertation diskutierten Ergebnisse basieren auf den in reviewten Zeitschriften bereits erschienenen bzw. akzeptierten Veröffentlichungen.

Da eine solch umfangreiche Arbeit überhaupt erst durch die Unterstützung und Hilfestellung Anderer möglich wird, möchte ich mich für die Zusammenarbeit bei allen direkt und indirekt Beteiligten recht herzlich bedanken.

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1. Einleitung

1.1 Phänologie

Phänologie ist die Wissenschaft von im Jahreszyklus wiederkehrenden Erscheinungen von Pflanzen oder Tieren; inzwischen werden auch abiotische saisonale Prozesse, wie Eisdauer auf Flüssen oder Seen, dazu gerechnet. Beobachtungen von phänologischen Phasen, wie Austrieb und Blühzeitpunkt, stellen vermutlich die einfachste Methode dar, Veränderungen in verschiedenen Ökosystemen zu verfolgen. Phänologische Erhebungen lassen sich leicht durchführen und bieten eine geeignete Methode, um die breite Öffentlichkeit für die Veränderungen „vor ihrer Haustür“ zu interessieren. So bietet die Phänologie sich als „integratives Messinstrument“ an, um Klimaänderungen aufzuzeigen. Unter anderem aus diesem Grund hat die Phänologie im letzten Jahrzehnt stark an Bedeutung hinzugewonnen (Sparks et al. 2000, Sparks & Menzel 2002).

Um Prognosen über Auswirkungen zukünftiger Klimaveränderungen machen zu können, ist das Wissen über die Reaktionen der Organismen auf die Umweltbedingungen der Vergangenheit wichtig (Sparks & Carey 1995). Als Informationsquelle können langjährige, phänologische Beobachtungen dienen. Die möglicherweise älteste bekannte phänologische Beobachtungsreihe stammt aus Japan, wo seit 705 n. Chr. am Kaiserlichen Hof in Kyoto der Beginn der Kirschblüte notiert wird. Eine der ältesten phänologischen Zeitreihen in Europa umfasst die Beobachtungen in Stratton, Norwich, der Familie Marsham zwischen 1736-1958 (Sparks & Carey 1995).

In Deutschland existieren zwei phänologische Netzwerke. Um regionale und globale vergleichende Untersuchungen betreiben zu können, wurden in den sechziger Jahren des letzten Jahrhunderts von Dr. Schnelle und Prof. Volkert das Netzwerk der Internationalen Phänologischen Gärten gegründet. In ihnen wurden geklonte Pflanzen in Europa ausgebracht und verschiedene Phasen werden bis heute beobachtet (http://www.agrar.hu-berlin.de/struktur/institute/pfb/-struktur/agrarmet/phaenologie/ipg). Das zweite Netzwerk betreibt der Deutsche Wetterdienst (DWD), der seit 1951 phänologische Beobachtungen in seinem Netzwerk sammelt. Freiwillige interessierte Naturbeobachter melden dabei Phasen von wildwachsenden und landwirtschaftlichen Pflanzen nach den vorgegebenen Kriterien der „Anleitung für die phänologischen Beobachter/innen“ (Deutscher Wetterdienst 1991). Die „Hochphase“ der phänologischen Beobachtungen lag in den 1970er Jahren, damals gab es bis zu 4000 ehrenamtliche Melder; momentan umfasst das Netzwerk ca. 1600 Beobachter (http://www.dwd.de/de/FundE/Klima/KLIS/daten/-nkdz/fachdatenbank/datenkollektive/phaenologie/index.htm).

Phänologische Beobachtungen sind keine absoluten Messwerte, sie sind immer subjektive Beurteilungen. Da das Eintreten von phänologischen Phasen vor allem in Frühjahr und Sommer eng an Klima und Witterung gebunden ist, eignet sich die Pflanzenphänologie dennoch sehr gut, um in der Global-Change-Problematik verschiedene Fragestellungen zu Auswirkungen der Klimaänderungen auf die Vegetation zu bearbeiten.

1.2 Klimaänderungen

Klima ist der mittlere Zustand und der gewöhnliche Verlauf der Witterung an einem gegebenen Ort über einen definierten Zeitraum. Es gibt, außer dem Alter der Erde, keine obere zeitliche Grenze; als untere zeitliche Grenze gelten i. d. R. 30 Jahre. So wurden für Beobachtungszeit und Dauer von der World Meteorological Organisation (WMO) die Zeitspannen von 1931-1960 bzw. 1961-1990 als Klimanormalperioden definiert. Wetterschwankungen umfassen dagegen den Bereich von 1 Stunde bis zu einem Tag; Witterungsschwankungen sind in der zeitlichen Auflösung von 1 Tag bis zu einem Jahr zu beobachten. Ausreichende Messdaten der Temperatur liegen erst seit ca. 150 Jahren vor, wohingegen einzelne Messreihen bis ins 17. Jahrhundert zurück gehen. Die Klimageschichte der Erde lässt sich anhand verschiedener Proxy-Daten ermitteln (z.B. Baumringe, Eisbohrkerne, Meeresbodensedimente, Korallen). Verschiedene Isotopenverhältnisse lassen dabei einen Rückschluss auf die regional vorherrschenden klimatischen Verhältnisse zu. So können z.B. über das Verhältnis der Sauerstoffisotope von ^{18}O zu ^{16}O Aussagen über die Temperatur gemacht werden. Die Sonnenaktivität lässt sich beispielsweise über die Beryllium (^{10}Be) Konzentration in Eisbohrkernen abschätzen. Eine weitere Möglichkeit bietet die Untersuchung von Meeresbodensedimenten: hier ergeben sich aus der Artenverteilung der Überreste von Foramiferen (Kalkschalern) sowie wieder über das Verhältnis von Sauerstoffisotopen die Klimainformationen. Abbildung 1 zeigt den rekonstruierten und gemessenen Temperaturverlauf des letzten Jahrtausends. Die obere Grafik zeigt die Abweichung der Oberflächentemperatur der Erde vom Mittelwert des Zeitraums 1961 – 1990 basierend auf Temperaturmessungen zwischen 1860-2000. Die untere Abbildung zeigt die rekonstruierte Temperaturanomalie der Nordhemisphäre der letzten 1000 Jahre. Deutlich zu erkennen ist der steile Anstieg seit dem Beginn des 20. Jahrhundert. Von den letzten zwölf Jahren waren elf unter den wärmsten zwölf Jahren seit dem Beginn der Messung der globalen Oberflächentemperatur (1850). Der neueste 100-jährige lineare Temperaturtrend für den Zeitraum 1906-2005 ist mit 0,75 °C höher als die 0,6 °C für den Zeitraum 1901-2000, die noch im vorigen IPCC Bericht genannt wurde (IPCC 2007). In Deutschland beträgt die Zunahme für den Zeitraum 1901-2000 1°C (Schönwiese et al. 2005).

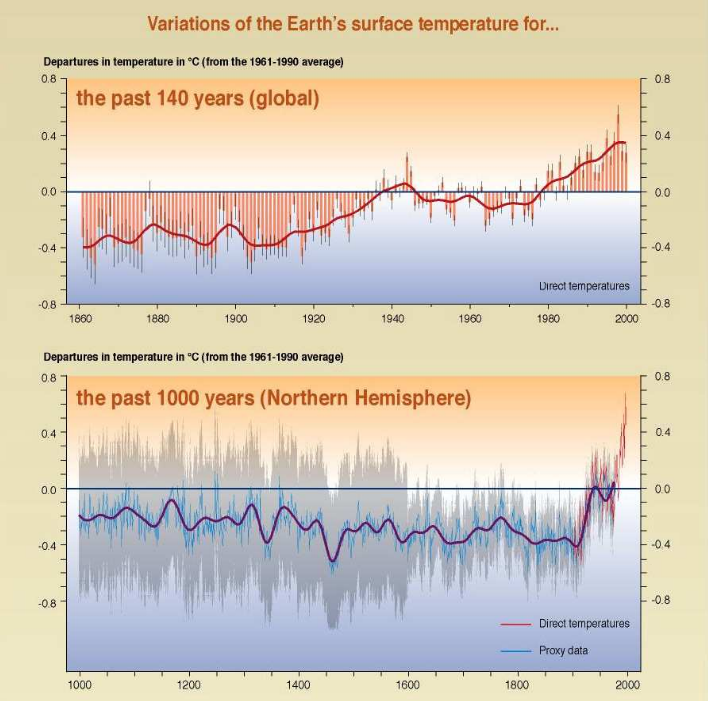

Abbildung 1: *Temperaturanomalie der Erdoberfläche (Abweichungen vom Mittelwert zwischen 1961-1990). Oben: Berechnet aus Temperaturmessungen zwischen 1860-2000, die roten Säulen stehen für Jahreswerte mit wahrscheinlicher Abweichung (schwarze Whisker); die rote Line zeigt das gleitende 10jahres Mittel. Untere Grafik: Rekonstruierte Temperaturanomalie basierend auf Proxydaten der Nordhalbkugel über die letzten 1000 Jahre (blaue Linie: Jahreswerte aus Proxies; rote Line: aus Temperaturmessungen; graues Band: sehr wahrscheinliche Spannweite der Temperaturanomalien; violette Line: 50 Jahre gleitendes Mittel (IPCC 2001b).*

Diese Erhöhung lässt sich zum großen Teil eindeutig menschlicher Aktivität zuschreiben. So ist seit der Industrialisierung vor ca. 150 Jahren die CO_2-Konzentration in der Atmosphäre von 280 ppm auf ca. 380 ppm angestiegen. Durch die Verbrennung fossiler Energieträger werden große Mengen an CO_2 freigesetzt. Weitere anthropogen erzeugte bzw. verstärkt durch anthropogene Einflüsse freigesetzte klimarelevante Spurengase, wie z.B. CH_4, N_2O, FCKWs und bodennahes Ozon, werden ständig in die Atmosphäre eingetragen. So stammen Ammoniak, Lachgas und Methanemissionen vor allem aus der Landwirtschaft und Tierhaltung. Die sehr stabilen, leicht flüchtigen Fluorchlorkohlenwasserstoffe dienen als Kühlmittel oder Treibgase. Sie gelangen bis in die Stratosphäre und zerstören dort die Ozonschicht, in der Troposphäre absorbieren sie Strahlung im Infrarotbereich und tragen so zur globalen Erwärmung bei (IPCC 2007). Man geht davon aus, dass sich die globale Mitteltemperatur in den nächsten 100 Jahren wahrscheinlich zwischen 1.8-4°C erhöhen wird (IPCC 2007).

1.3 Beobachtete Veränderungen im Zuge der rezenten Klimaänderungen

Veränderte klimatische Verhältnisse führen zu Reaktionen und Veränderungen sowohl in biotischen als auch in physikalischen Systemen. So lassen sich Einflüsse der Klimaveränderung bereits an vielen biologischen und physikalischen Systemen nachweisen (IPCC 2001a). Die Kryosphäre beispielsweise reagiert sehr sensibel auf die Klimaerwärmung. Infolgedessen werden die Veränderungen der verschiedenen Elemente der Kryosphäre (Gletscher, Permafrost, Meer- und Seeeis, Eisbohrkerne) verwendet, um vergangene und rezente Klimaveränderungen aufzuzeigen (Bradley & Jones 1995, Everett & Fitzharris 1998).

Pflanzen und Tiere können unterschiedlich auf ein sich veränderndes Klima reagieren. Sie benötigen bestimmte klimatische und ökologische Bedingungen, um sich reproduzieren und entwickeln zu können. Wenn sich die Umweltbedingungen so verändern, dass die Abweichung für die Art zu groß wird, kann sie folgendermaßen reagieren: 1) zeitliche Verschiebung der Lebenszyklen, 2) geographische Verschiebung der Areale oder Veränderung der Populationsdichte innerhalb der Habitatgrenzen, 3) Veränderung der Morphologie (z.B. Körper- oder Eigröße), der Reproduktion oder der Genetik oder 4) Ausrottung bzw. Aussterben. Hinzu kommt, dass jede Art ihre eigenen Anforderungen an klimatische und ökologische Bedingungen hat, somit können Veränderungen zu Störungen von biotischen Interaktionen führen (z.B. Nahrungsnetze, Bestäubung).

Da Artenveränderungen mit unterschiedlicher Geschwindigkeit und in verschiedene Richtungen stattfinden, beispielsweise reagieren die Insekten vor Ort schneller auf warme Frühjahrstemperaturen als Zugvögel, die in Afrika überwintern, kann es zu einem zeitlichen Versatz bei Räuber-Beute-Beziehungen kommen (Stenseth & Mysterud 2002).

Viele Studien zeigen, dass Pflanzen und Tiere auf das sich verändernde Klima reagieren, auch die Anzahl von Reviews über diese Thematik hat in den letzten Jahren zugenommen (z.B. Hughes 2000, Menzel & Estrella 2001, Sparks & Menzel 2002, Walther et al. 2002, Parmesan & Galbraith 2004, Walther 2004, Linderholm 2006, Parmesan 2006).

Abgesehen vom Klima wirken noch viele weitere Faktoren, wie invasive Arten, natürliche Beeinträchtigungen wie Feuer, Schädlinge, Krankheiten und Schadstoffemissionen auf die Arten ein und können auch alle beobachtete Veränderungen der Arten beeinflusst haben. Zahlreiche Tier- und Pflanzenpopulationen werden durch die landwirtschaftliche Intensivierung und Landnutzungsänderungen der letzten 50 Jahre bedroht, viele Arten gehen schon zurück. Habitatzerstückelung (Hill et al. 1999, Warren et al. 2001) oder einfach das Fehlen geeigneter Gebiete zur Besiedelung, z.B. in höheren Lagen, spielen hierbei auch eine große Rolle, besonders beim Aussterben von Arten (Williams et al. 2003, Pounds et al. 2006).

Viele der bereits beobachteten Änderungen können jedoch der rezenten Temperaturerhöhung aufgrund von Treibhausgasemissionen zugeordnet werden. Zu diesen mit großer Wahrscheinlichkeit auf die Klimaerwärmung zurückzuführenden Auswirkungen zählen in physikalischen Systemen z.B. die Abnahme der arktischen Meereisbedeckung um ca. 10-15% seit den 50er Jahren des letzten Jahrhunderts (Comiso et al. 2003) oder der Rückgang von Gletschern und Permafrost auf der Nordhemisphäre (IPCC 2001a). Dort hat sich in den hohen und mittleren Breiten auch die jährliche Dauer der Bedeckung mit See- und Flusseis um ca. zwei Wochen verkürzt (Magnuson et al. 2000).

Die Biosphäre verändert sich ebenso nachweislich aufgrund von klimatischen Veränderungen. Verbreitungsgebiete von Pflanzen und Tieren verlagern sich polwärts (EEA 2004, Walther et al. 2005) sowie in höhere Lagen (Penuelas & Boada 2003). Tier- und Pflanzengesellschaften verändern ihre Zusammensetzung (EEA 2004, Walther 2004), teils durch Invasion anderer Arten, teils durch Verschiebungen in ihrer Zusammensetzung. So wurden z.B. bereits einige arktische und tundrische Pflanzengesellschaften durch Bäume und Zwergsträucher beeinflusst bzw. vollständig ersetzt (Molau & Alatalo 1998, ACIA 2004). Auch Eintrittstermine von phänologischen Ereignissen haben sich verschoben: sie verfrühen sich im Frühling und verspäten sich im Herbst (Menzel & Estrella 2001, Sparks & Menzel 2002, Walther et al. 2002).

1.4 Phänologie als Bio-Indikator für Klimaänderungen

Da die Phänologie bereits nachweisbar auf die Temperaturerhöhung reagiert, eignen sich Zeitreihen von phänologischen Eintrittsterminen sehr gut um Klimaveränderungen zu bestätigen. Die Vegetationszeit, hier definiert als Zeitraum zwischen Blattaustrieb und Laubverfärbung, hat sich in den letzten 30 Jahren um etwa 10 Tage verlängert (Menzel & Fabian 1999, Menzel & Estrella 2001, Chmielewski et al. 2004), wobei sich der Beginn im Frühjahr stärker verschiebt als das Ende im Herbst. Über das Jahr betrachtet zeigt es sich, dass sich frühe Phasen (z.B. Blüte von Schneeglöckchen, Hasel und Forsythie) durch einen größeren Trend zu einem früheren Beginn auszeichnen als Sommerphasen (z.B. Fruchtreife Johannisbeere) bzw. Herbstphasen (z.B. Laubverfärbung von Bäumen). Obwohl phänologische Eintrittstermine von landwirtschaftlichen Pflanzen von wesentlich mehr Faktoren gesteuert werden als wildwachsende Pflanzen, zeigen sich auch hier deutliche Veränderungen. Diese Verschiebungen lassen sich auf die regionale Temperaturerhöhung zurückführen (Chmielewski et al. 2004, **Artikel GCB 2007**).

Auch das Verhalten vieler Tierarten wird von der Temperatur beeinflusst. Verschiedene Zugvogelarten kommen eher in ihre Sommerquartiere zurück bzw. ziehen gar nicht mehr in den

Süden (Sparks et al. 1999, Huppop & Huppop 2003, Jenni & Kery 2003, Sparks et al. 2005a). Der Termin der Eiablage hat sich bei einigen Vogel- und Amphibienarten nachweislich verfrüht (Crick et al. 1997, Beebee 2002).

Da viele phänologische Ereignisse eng an die Temperatur gekoppelt sind (Chmielewski & Roetzer 2001, Fitter & Fitter 2002, Sparks & Menzel 2002, Menzel 2005, Menzel et al. 2005a, Menzel et al. 2006b), können sie als Proxy für die Lufttemperatur dienen. Somit lassen sich aus sehr langen phänologischen Beobachtungsreihen Temperaturzeitreihen rekonstruieren (Chuine et al. 2004, Menzel 2005).

1.5 Weitere Indikatoren für die Länge der Vegetationsperiode

Oft wird die Vegetationsperiode auch mit Klimaindices definiert. Üblich ist z.B. die Dauer der Vegetationsperiode als Zeitraum zwischen dem Über- bzw. Unterschreiten der 5°C oder 8°C Schwelle der Tagesmitteltemperatur festzulegen (Schnelle 1955, Hartmann & Schnelle 1970); manchmal muss die Temperaturschwelle über einen bestimmten Zeitraum, z.B. 7 Tage, überschritten werden (z.B. Primault 1992, Schwartz et al. 2006). Diese Klimaindices werden teilweise auch in globalen Biosphärenmodellen eingesetzt, um den Zeitpunkt des Blattaustrieb oder der Laubverfärbung von Laubbäumen festzustellen (z.B. Kaduk & Heimann 1996).

Da aber gerade bei Biosphärenmodellen vor allem die Zeit der pflanzlichen Aktivität von Bedeutung ist, versucht man diese mit anderen Mitteln, wie z.B. über die berechnete Nettoprimärproduktion (NPP), zu bestimmen.

Zudem zeigen Untersuchungen, dass der Beginn des Frühlings in gemäßigten Breiten zu einer abrupten Veränderung des Verhältnisses von fühlbarer und latenter Wärme in der Energiebilanz führt (Bowen-Ratio) (Schwartz 1992, Schwartz & Crawford 2001). Die Vegetation beeinflusst diese Bowen-Ratio beim Blattaustrieb durch die erhöhte Evapotranspiration und einen Rückgang der latenten Wärme, dies führt zu einem raschen Abfall der Bowen Ratio (Fitzjarrald et al. 2001).

Eine großflächige Erfassung der Pflanzenaktivität lässt sich durch die Auswertung von Satellitenbeobachtungen erzielen, da pflanzenphänologische Informationen auch über die Reflexion in verschiedenen Kanälen von Satellitenbildern abgeleitet werden können. Eine Möglichkeit bietet der Normalized Difference Vegetation Index (NDVI). Dabei kann über das Verhältnis zwischen Rot und dem nahen Infrarot (NIR) die Pflanzenaktivität als NDVI=(NIR-Rot)/(NIR+Rot) abgeschätzt werden. Hier liegen keine artspezifischen Eintrittstermine vor, sondern es werden Angaben über die photosynthetische Aktivität der auf dem Pixel zugehörigen Bodenoberfläche wachsenden Pflanzengesellschaft gemacht (Myneni et al. 1997, Chen & Pan

2002). Die Genauigkeit der Ergebnisse der pflanzlichen Aktivität wird vor allem durch die räumliche und zeitliche Auflösung des Satellitenbildes vorgegeben. Oft werden zweiwöchige Komposite mit 8 km Kantenlänge verwendet, in dicht besiedelten Regionen ergeben sich vor allem Mischpixel aus Vegetation, Wasseroberflächen und Bebauung. Die Auswertung und Interpretation dieser Satellitenbilder ist dementsprechend oft unpräzise. Ein weiterer Nachteil von Satellitenbildern liegt in der Kürze der Zeitreihen, erst seit ca. Mitte der 1980iger Jahre liegen NDVI Messungen vor. Trotzdem bestätigt die Analyse von NDVI Daten, die aus Satellitenbeobachtungen generiert worden sind, die Ergebnisse von Trendanalysen von phänologischen Beobachtungen (Badeck et al. 2004).

Noch großräumigere Aussagen zur Veränderung der Vegetationsperiode können über atmosphärische CO_2-Messungen gemacht werden. Seit 1958 misst man am Observatorium auf Mauna Loa (Hawaii) die CO_2-Konzentration der Luft. In der Nordhemisphäre steigt die Konzentration im Winter an und sinkt im Sommer wieder etwas ab. Die Ursache für den jahreszeitlichen, oszillierenden Verlauf der Kurve liegt hauptsächlich am saisonalen Wachstum der Landvegetation. Die Abnahme des CO_2-Gehaltes nach dem winterlichen Maximum tritt heute ca. 7 Tage früher ein als noch im Jahr 1960 (Keeling et al. 1996). Satelliteninformationen und die Auswertungen von CO_2- Kurven geben zwar einen Überblick über Änderungen der Vegetationsaktivität, es lassen sich jedoch weder artspezifische noch kleinräumige Aussagen über die Veränderungen treffen.

1.6 Blühzeitpunkte, Pollen und menschliche Gesundheit

Phänologische Beobachtungen von Blühterminen allergener Blühpflanzen können auch verwendet werden, um Allergiker über den Pollenflug zu informieren. Mit ihnen lassen sich auch Modelle für Pollenprognosen unterstützen, denn der Betrieb von Pollenfallen ist aufwändig und teuer. Deshalb hat im Jahr 1991 der Deutsche Wetterdienst das Phänologische Beobachtungsprogramm um sechs allergologisch wichtige Blühpflanzen erweitert (Hasel, Erle, Birke, Süßgräser, Roggen, Beifuß). Pollen stellen eine große Belastung für die menschliche Gesundheit dar, gelten sie doch als Auslöser von Allergien (Traidl-Hoffmann et al. 2003). Der Anteil der Bevölkerung in Europa, der sensitiv auf Pflanzenpollen reagiert, hat in den letzten Jahren zugenommen (Huynen et al. 2003). Für diese Pollenallergiker sind gute Pollenflugprognosen wichtig, um eine optimale Prophylaxe durchführen zu können. Bisher werden Pollenflugprognosen vor allem aus Pollenbeobachtungen aus Fallen und Wettervorhersagen erstellt.

1.7 Zielsetzung der Arbeit

In dieser Arbeit werden, aufbauend auf den kurzen Überblick über den Forschungsstand der Phänologie, die räumliche und die zeitliche Variabilität phänologischer Daten ausführlich analysiert (Kap.2: **Artikel GCB 2007, Artikel GCB 2005, Artikel GCB 2001, Artikel GCB 2006**). Im Anschluss daran wird die Variabilität der Temperaturabhängigkeit von phänologischen Eintrittsterminen dargelegt (Kap. 3: **Artikel GCB 2007, Artikel GCB 2006, Artikel Clim Res 2005**). Auf diese Weise soll nachgeprüft werden, ob regionale Unterschiede der Klimaänderung zu regionalen Unterschieden in der Phänologie führen. Statistische Methoden, wie Berechnung von Regressionen und Korrelationen, zeigen die Temperaturabhängigkeit von phänologischen Phasen. Durch lineare Regressionsgleichungen kann der quantitative Einfluss der Temperatur angegeben werden. Doch nicht immer liegt ein linearer Zusammenhang zwischen der Temperatur und dem Einsetzen der phänologischen Phase vor. So können zeitliche Verzögerungen zwischen warmen Temperaturen und der Pflanzenreaktion auftreten. Im Gegensatz dazu könnte auch eine Verstärkung des Temperaturanstiegs zu einer beschleunigten Reaktion in der Phänologie führen.

Zusätzlich wird ausführlich auf die in der Literatur bisher vernachlässigte Laubverfärbung von vier Laubbaumarten Rosskastanie, Hängebirke, Rotbuche und Stieleiche (*Aesculus hippocastanum L., Betula pendula* Roth*, Fagus sylvatica L., Quercus robur L.*) in den gemäßigten Breiten eingegangen. Hier werden übliche Literaturhypothesen auf den Eintrittstermin der Laubverfärbung und weitere klimatologische Einflussfaktoren in ihrer Raumzeitvariabilität untersucht (**Artikel Clim Res 2006**). Die Einsatzmöglichkeit von phänologischen Beobachtungen zur Pollenvorhersage wird im **Artikel Int J Biometeor 2006** dargestellt. Dabei wird der Zusammenhang von phänologischen Blühterminen allergener Pflanzen und Pollenmessungen aus Fallen dargestellt und die raum-zeitliche Variation dieses Zusammenhangs analysiert.

2. Räumliche und zeitliche Variabilität der Phänologie

Phänologische Beobachtungen bieten die Möglichkeit sowohl räumliche, als auch zeitliche Variabilitäten aufzudecken. Man kann anhand von phänologischen Zeitreihen statistische Berechnungen durchführen. Die Beobachtungsdaten innerhalb eines Jahres zeigen an verschiedenen Beobachtungsstationen das regional variable Verhalten von Pflanzen an. Der zeitliche Trend von phänologischen Zeitreihen gibt die Verschiebung des Eintrittstermins über einen bestimmten Zeitraum an. Zuerst allerdings muss man einen genauen Blick auf das phänologische Datenmaterial werfen, da es sich um manuell erfasste subjektive Beobachtungen handelt.

2.1 Problematik von phänologischen Daten

Phänologische Eintrittstermine sind keine physikalischen Messungen, sondern standardisierte Beobachtungen von mehr oder weniger geschulten Personen. In unseren Analysen wurden u.a. phänologische Daten des Deutschen Wetterdienstes (DWD) verwendet. Die ehrenamtlichen Beobachter richten sich dabei nach der ‚Anleitung für den Phänologischen Beobachter' (Deutscher Wetterdienst 1991). Teilweise wurden auch phänologische Eintrittstermine der Internationalen Phänologischen Gärten (IPG) verwendet. In den IPGs wachsen geklonte Pflanzen, um genetische pflanzenindividuelle Unterschiede auszuschließen. Die Beobachtungen werden hier von angeleitetem, wissenschaftlichem Personal durchgeführt. Bei Daten, die uns digital vorliegen, können sich auf unterschiedliche Weise Fehler eingeschlichen haben. Der Beobachter kann z.B. beim Notieren des Datums Tag und Monat vertauschen bzw. den Termin auf dem Beobachterformular im falschen Feld (für andere Phase oder Pflanze) notieren, oder bei der Digitalisierung der Daten können Tippfehler auftreten. Zudem können systematische Fehler auftreten, z.B. wenn ein Beobachter die Phase zu früh oder zu spät erkennt. Auch kleinräumige Variabilität kann im Datensatz eine Rolle spielen, da standortspezifische (wie Boden, Exposition, Wasserverfügbarkeit) oder mikroklimatische Besonderheiten Einfluss auf den phänologischen Eintrittstermin haben. Diese Informationen standen uns jedoch nicht zur Verfügung, so dass soll in dieser Arbeit jedoch nicht weiter darauf eingegangen werden soll.

Diese potentiellen Fehlerquellen führen zu Unsicherheiten in den Daten. Es ist somit nur sinnvoll, einen möglichst großen Datensatz zur Auswertung zu verwenden, denn dann lässt sich eine Fehlerkorrektur relativ sicher durchführen. Abbildung 2 zeigt exemplarisch unkorrigierte Eintrittstermine der Laubverfärbung der Hängebirke in Deutschland (1953-2003). Einige Termine liegen im Frühjahr, andere um Weihnachten. Damit nicht eindeutig falsche Werte die Analysen verfälschen, wurden diese aus dem Datensatz eliminiert. Für die Analysen wurden grundsätzlich kontrollierte phänologische Daten verwendet. Zur Datenkontrolle wurden für alle Stationen die Residuen einer multiplen Regression über geographische Länge, Breite und Höhe für jedes Jahr berechnet. Zusätzlich wurde für jedes Jahr die Standardabweichung der Residuen bestimmt. Beobachtungen, deren Residuum außerhalb der 1,5-fachen Standardabweichung lag, wurden gelöscht (siehe Scheifinger et al. 2002).

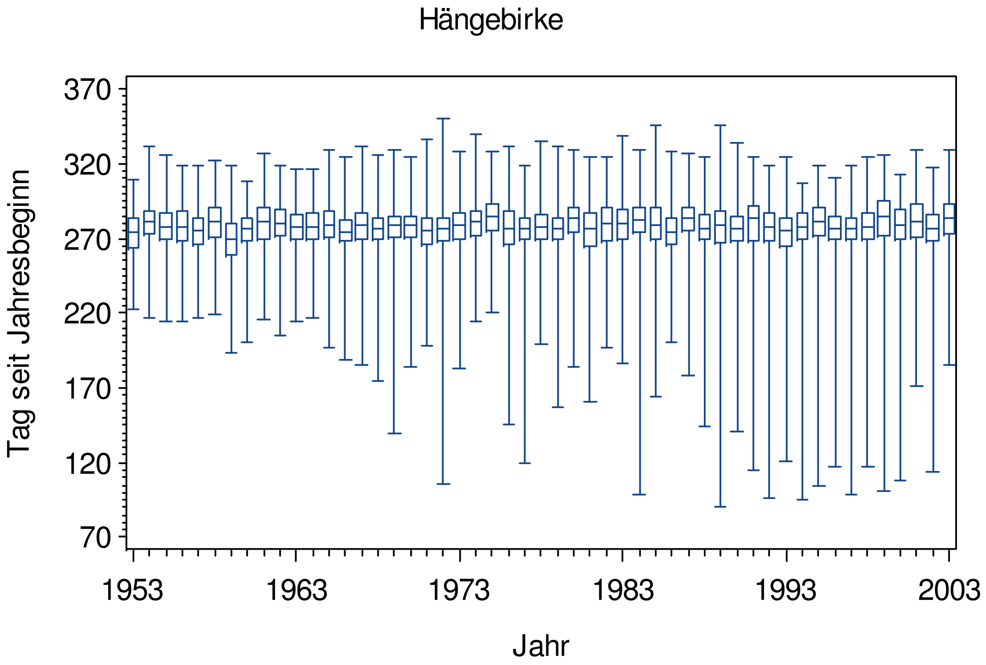

Abbildung 2: *Eintrittstermine der Laubverfärbung Hängebirke (Betula pendula* Roth*) in Deutschland (Tag seit Jahresbeginn). Unkorrigierte Originaldaten des DWD, die Ober- und Unterkante der Box liegen bei den 75ten und 25ten Perzentilen, die Enden der Whiskers markieren die früheste (unten) und die späteste (oben) Beobachtung, die horizontale Linie innerhalb der Box markiert den Median.*

2.2 Auswertungen der räumlichen und zeitlichen Variabilität in phänologischen Beobachtungen

Phänologische Daten liegen einerseits als lokale Zeitreihe vor, andererseits kann man die Phänologie innerhalb eines Jahres an verschiedenen Orten untersuchen bzw. regionale Mittelwerte berechnen und diese wiederum zeitlich untersuchen. Abbildung 3 zeigt die verschiedenen Ebenen, in denen phänologische Daten vorliegen, und die Ansätze, mit denen man sie analysieren kann.

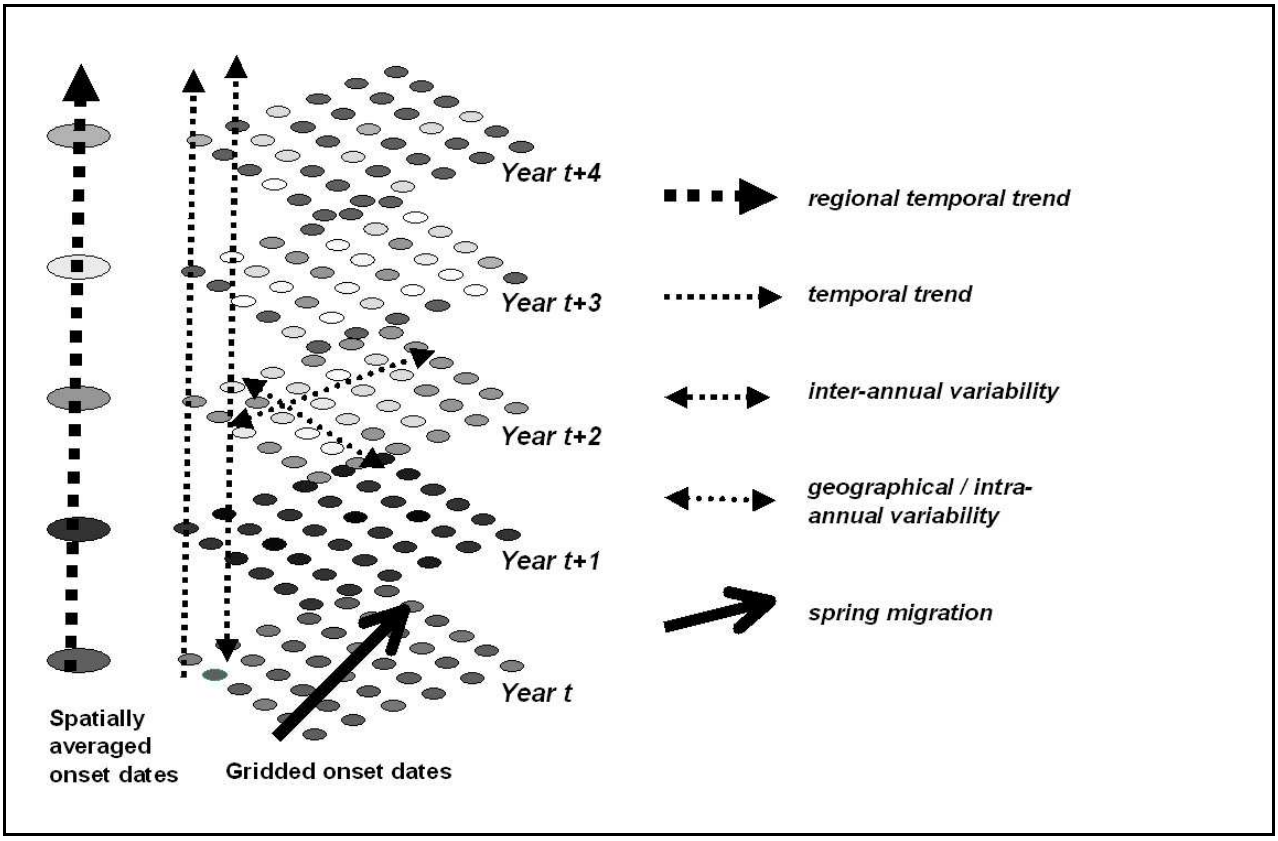

Abbildung 3*: Messungen von räumlichen und zeitlichen Variabilitäten. Das Schema zeigt hypothetische Eintrittstermine an Gridpunkten in einzelnen Jahren. Untersuchungen der Inter-annuellen Variabilität von Eintrittsterminen, sowie die Richtung und die Geschwindigkeit des Frühjahrseinzugs sind nur für einzelne Jahre oder Mittelwerte möglich. Die Berechnung von zeitlichen Trends erfordert längere Zeitreihen an der jeweiligen Station. Regionale Mittel von Trends können von räumlich gemittelten Eintrittsterminen abgeleitet werden. (Menzel et al. 2007)*

Bei der Analyse von phänologischen Daten werden eine Vielzahl statistischer Methoden verwendet. So gibt die Ausgleichsgrade der linearen Regressionsgleichung zwischen dem Eintrittstermin und dem Jahr mit ihrer Steigung den zeitlichen Trend an. Dieser gibt Auskunft über das Verhalten der entsprechenden phänologischen Phase über den Beobachtungszeitraum. Ein negativer Trend steht für eine zeitliche Verschiebung nach vorne, d.h. die Phase tritt am Ende des beobachteten Zeitraumes früher ein als zu Beginn. Ein positiver Trend bedeutet, dass die Phase im Durchschnitt später eintritt. Verschiedene Untersuchungen haben gezeigt, dass die Länge der Zeitreihe eine wichtige Rolle spielt: So bleibt erst bei Beobachtungsreihen mit mindestens 30 Jahren das Vorzeichen des Trends stabil (Dose & Menzel 2004, Sparks & Tryjanowski 2005). Der Trend einer Beobachtungsreihe gibt Auskunft über die zeitliche Veränderung der phänologischen Beobachtungen während des untersuchten Zeitraumes. Vergleicht man die Trends von zeitgleichen Reihen verschiedener Regionen kann man Aussagen über die räumliche Variabilität dieser Änderungen machen (siehe 2.2.2).

2.2.1 Zeitliche Variabilität

Die Analyse aller phänologischen Beobachtungen der Internationalen Phänologischen Gärten (IPG) in Europa gibt eine Übersicht über die zeitliche Veränderung der Vegetationsperiode. Hier haben sich der Beginn von Frühjahrsphasen wie Laubentfaltung im Mittel um 0,20 Tage / Jahr, d.h. 6 Tage in 30 Jahren, verfrüht. Herbstphasen wie Blattverfärbung waren im Durchschnitt 0,16 Tage/Jahr oder 4,8 Tage in 30 Jahren später zu beobachten. Damit verlängerte sich die Vegetationsperiode bis zum Jahr 1993 im Schnitt um fast 11 Tage (Menzel & Fabian 1999). Fortgeführt wird diese Art von Analyse im **Artikel GCB 2001**. Hier wird der lineare Trend von 16 phänologischen Phasen (11 Pflanzenarten) des DWD-Datensatzes, die den ganzen Jahreszyklus abdecken, von 1951 bis 1996 näher untersucht. Im Mittel haben sich Vor- und Frühfrühling um -0,18 bzw. -0,23 Tage/Jahr im Beobachtungszeitraum nach vorne verschoben. Die Blattentfaltung von Laubbäumen tritt zwischen -0,16 und -0,08 Tage / Jahr früher ein. Im Herbst ist die Veränderung der Phänologie nicht so auffällig, die Laubverfärbung von Laubbäumen findet im Durchschnitt um 0,03 bis 0,1 Tage/Jahr später statt. Insgesamt hat sich die Vegetationsperiode bei vier Laubbaumarten (hier definiert als Zeitraum zwischen Blattentfaltung und Laubverfärbung) um 0,2 Tage/Jahr verlängert. Beim Vergleich der Ergebnisse einzelner Beobachtungsstationen von Zeitreihen mit mindestens 20 Beobachtungen bzw. mit mindestens 30 Beobachtungen zwischen 1951-1996 stellt sich heraus, dass frühe Phänophasen wie Blüte von Schneeglöckchen oder Forsythie, die eine große Variabilität (Standardabweichung) aufweisen, weniger signifikante Trends zeigen als Phasen, die im Spätfrühling und Sommer eintreten. Hier zeigen 25-33% der Zeitreihen signifikante Trends (Ausnahmen sind Blüte von Kirsche und Apfel). Der Datensatz mit den längeren Zeitreihen weist einen prozentual höheren Anteil von signifikanten Trends auf als der mit nur mind. 20 Beobachtungen.

Zeitliche Trends von gemittelten Anomalien landwirtschaftlicher Kulturpflanzen und Obst für 78 phänologische Phasen von 20 landwirtschaftlichen Kulturen und Obst (siehe http://www.-dwd.de/de/FundE/Klima/KLIS/daten/nkdz/fachdatenbank/datenkollektive/phaenologie/beob-_programm/) für den Zeitraum zwischen 1951 und 2004 in Deutschland wurden für **Artikel GCB 2007** berechnet. Die Mehrheit der Phasen tritt jetzt signifikant früher ein als vor 53 Jahren, im Mittel um 1,1 Tage pro Dekade. Dabei ist die Verfrühung von phänologischen Phasen einjähriger Feldpflanzen etwas größer (der Mittelwert beträgt –1,3 Tage pro Dekade) als die von mehrjährigen Pflanzen (im Mittel –0,85 Tage pro Dekade) (vgl. Abbildung 4). Zudem sind die Trends der Phasen von einjährigen Pflanzen häufiger signifikant als von mehrjährigen Pflanzen. Bei landwirtschaftlichen Phasen ist zu beachten, dass es sogenannte „falsche Phasen“ gibt, die stark vom Verhalten des Landwirts abhängen, wie Aussaat oder Ernte. Auch die direkt auf eine

„falsche Phase“ folgenden Phasen, die zu den „echten Phasen“ zählen, können noch vom Eintrittstermin der „falschen Phase“ beeinflusst worden sein.

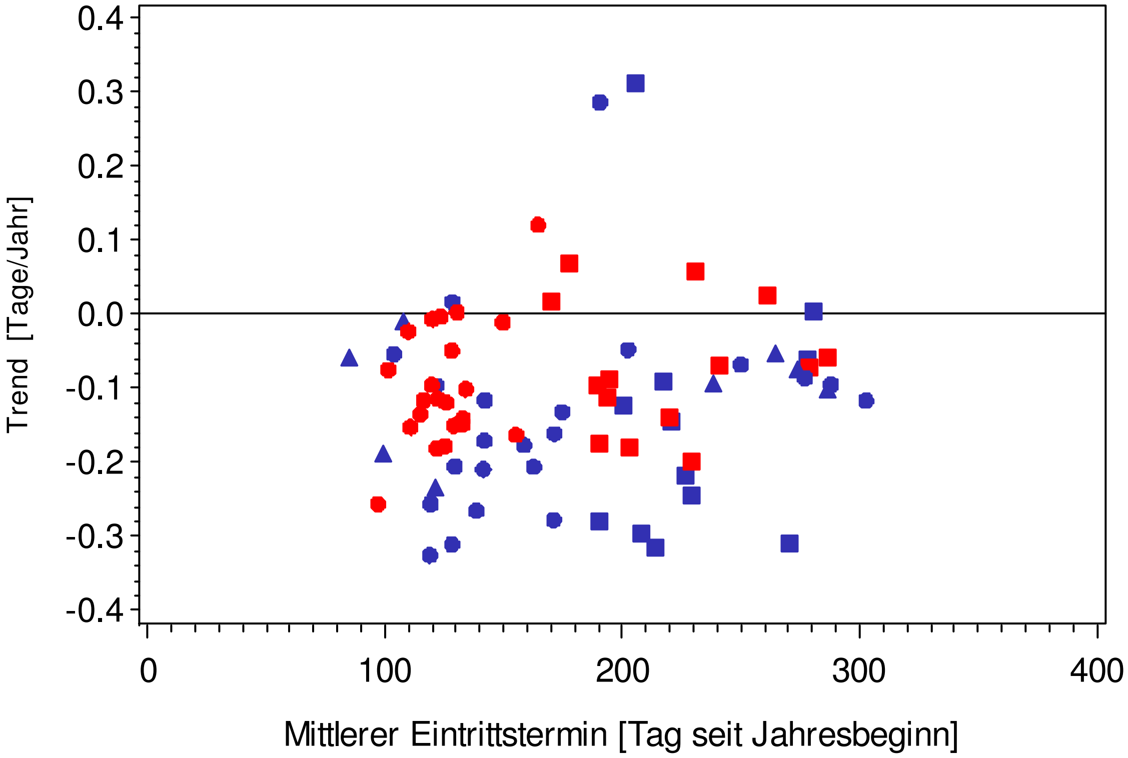

Abbildung 4: *Trends von landwirtschaftlichen phänologischen Phasen in Deutschland (1951-2004). Dreiecke repräsentieren Aussaattermine, Kreise echte Phasen (wie Blüte oder Schossen) und Quadrate stehen für Reife- oder Erntephasen. Einjährige Pflanzen sind blau, mehrjährige Pflanzen rot dargestellt.*

Zeitliche lineare Trends phänologischer Beobachtungen aus 21 Ländern Europas werden in **Artikel GCB 2006** präsentiert. **Artikel GCB 2006** entstand im Rahmen der COST725 Aktion ‚Establishing a European Phenological Data Platform for Climatological Applications’ (www.cost725.org). Es wurden sämtliche verfügbare phänologische Zeitreihen aus Europa verwendet. Dies ist die wohl bisher umfangreichste phänologische Analyse, denn sie enthält die Ergebnisse von rund 125000 Beobachtungsreihen von 542 Pflanzen- und 19 Tierarten aus 21 Ländern (1971-2000). Ziel der Studie war es, einen gesamten Kontinent systematisch auf phänologische Veränderungen hin zu untersuchen. Wichtig war, dass dabei gezeigt werden konnte, dass bisherige Studien nicht selektiv waren, indem etwa überwiegend solche Studien veröffentlicht wurden, die von starken Verschiebungen berichten.

Die linearen Trends aller Zeitreihen zwischen 1971-2000 mit mindestens 20 Beobachtungsjahren in der COST725 Studie zeigen, das 78% der Phasen, die den Blattaustrieb, die Blüte sowie die Fruchtreife umfassen, eine Verfrühung aufweisen (30% davon sind signifikant) und nur 3% dieser Phasen zeigte eine signifikante Verspätung. Laubverfärbung / Laubfall reagieren hingegen wieder nicht so einheitlich und deutlich. In Tabelle 1 sind die Anzahl der Zeitreihen und ihre prozentuale Verteilung in Richtung früherer oder späterer Phaseneintritt dargestellt. Im Mittel tritt der Frühling / Sommer in Europa nun um ca.7,5 Tage früher ein als vor 30 Jahren. Die Laubverfärbung / der Blattfall verspätet sich um ca. 3 Tage in diesem Zeitraum in Europa. Landwirtschaftliche Phasen, wie Aussaat und Ernte zeigen keine so starken linearen Trends (-0,04 Tage / Jahr).

Tabelle 1: *Zusammenfassung aller phänologischen Trends in Europa (lineare Regressionen, 1971-2000) (nach Menzel et al. 2006a)*

	Landwirtschaftliche Phasen	Blattentfaltung und Blüte	Fruchtreife	Laubverfärbung
Anzahl der Reihen	22338	64027	11191	5643
früher	57 %	78 %	75 %	48 %
signifikant früher	13 %	31 %	25 %	12 %
später	43 %	22 %	25 %	52 %
signifikant später	6 %	3 %	3 %	15 %

Allen Studien gemeinsam ist, dass frühe phänologische Phasen (z.B. Schneeglöckchenblüte, Haselblüte) eine größere zeitliche und räumliche Variabilität aufweisen als Sommerphasen. Herbstphasen weisen eine hohe intra-anulle Variabilität auf, zeigen jedoch keine einheitlichen zeitlichen Trends. Eine Übersicht der zeitlichen Trends für Deutschland und der Vergleich mit den Ergebnissen von Trendanalysen anderer Studien wird in Tabelle 3 gegeben.

2.2.2 Räumliche Variabilität von Trends

Die regionale Verteilung der Trends von phänologischen Phasen zeigt, dass innerhalb Europas die Verschiebung von Eintrittsterminen nicht einheitlich ist, sondern deutliche regionale Unterschiede bestehen. Gemittelte Trends von verschiedenen Phasengruppen werden in **Artikel GCB 2006** dargestellt. So hat sich der Einzug des Frühlings im Laufe der letzten 30 Jahre in der Slowakei und in Griechenland sogar verspätet. In Ungarn und Tschechien ist der Zeitpunkt des Frühlingsbeginn fast gleich geblieben und in Belgien und Spanien hat sich der Beginn des Frühlings am stärksten nach vorne verschoben.

Der Trend der Phasengruppe von Fruchtreife weist für die Slowakei und Österreich die stärkste Verfrühung auf. In Belgien und Estland zeigen die Trends dieser Gruppe kaum eine Verschiebung. Für Herbstphasen wird in Europa überwiegend ein positiver Trend berechnet, d.h. die Phasen treten nun meist später ein als zu Beginn der 1970er Jahren. Die größten Trends und damit die stärkste Verspätung findet man in Polen, Dänemark und Spanien. In Deutschland und der Schweiz liegt der gemittelte Trend der Gruppe der Herbstphasen nahe bei Null. In Norwegen und in Russland sind die Herbstphasen nun im Mittel früher zu beobachten als zu Beginn der 1960er Jahre.

Interpolierte Karten zum Frühlingseinzug in Europa zeigen, dass der Beginn des Frühlings sich im Zeitraum zwischen 1958-1998 in West- und Mitteleuropa um vier Wochen verfrüht hat, in Osteuropa jedoch um bis zu zwei Wochen später einsetzt (Ahas et al. 2002).

Für kleinräumigere Untersuchungen von zeitlichen phänologischen Trends auf Landesebene werden die Zeitreihen von einzelnen Stationen betrachtet. Es gibt z.B. eine Studie von Defila und Clot (2005) über zeitliche phänologische Trends in verschiedenen Höhenlagen der Schweiz. So weisen 42 % der Stationen, die in den Alpen in Lagen über 1000 m ü. NN liegen, einen signifikanten Trend auf, jedoch nur 33% der Stationen die unter 600m ü. NN liegen. Der Betrag des Trends ist im Tiefland jedoch größer, d.h. die Verfrühung ist stärker in flacheren Lagen. Der Frühjahrsphasen treten dort 20 Tage, in den Alpen jedoch nur 15 Tage eher ein (Defila & Clot 2005).

Auch für Deutschland wurde nach einem die räumliche Zusammenhang von zeitlichen, phänologischen Trends wildwachsender Pflanzen von einzelnen Stationen gesucht. Es zeigt sich, dass die Verteilung der Trends im allgemeinen chaotisch ist. Deutlich wird dies bei der Darstellung von zeitlichen Trends von 16 phänologischen Phasen (11 Pflanzenarten) des DWD-Datensatzes in Karten, es ist kein regionales Muster zu erkennen (siehe **Artikel GCB 2001** Abb.2). Die Analyse der Karten zeigt keine geographische Abhängigkeit. Die räumliche Streuung der Trends lässt sich nicht zufriedenstellend erklären.

2.2.3 Räumlicher Verlauf von phänologischen Jahreszeiten

Für das EU-Projekt POSITIVE wurde ein Datensatz erstellt, der phänologische Informationen aus verschiedenen Ländern und Netzwerken kombiniert. Erweitert wurde dieser Datensatz mit den Daten aus der historischen Phänologischen Datenbank und den IPGs. Dieser kombinierte Datensatz umfasst 100 Jahre für Zentral- und Osteuropa. Verwendet wurde dieser Datensatz für die Analysen im **Artikel GCB 2005.** Mit Hilfe dieses Datensatzes werden mittlere saisonale Eintrittstermine und der Verlauf des Frühjahrseinzugs auf dem Europäischen Kontinent untersucht. Frühe Frühjahrsphasen beginnen in Westsüdwest Europa und rücken nach Ostnordost vor. Die Phänophasen des mittleren Frühjahrs erscheinen zuerst in Südwesteuropa und „ziehen“ nach Nordosten. Die Phasen des späten Frühjahrs starten in Südsüdwest Europa und wandern nach

Nordnordost (Abbildung 5). Das Voranschreiten des Sommers ist mehr von Süd nach Nord gerichtet, der Herbst setzt von Nordosten her ein und wandert dann Richtung Südwesten.

Der kombinierte Datensatz zeigt bei der Analyse der Variabilität der phänologischen Jahreszeiten ferner, dass frühe phänologische Phasen eine höhere zeitliche Variabilität aufweisen als spätere Ereignisse.

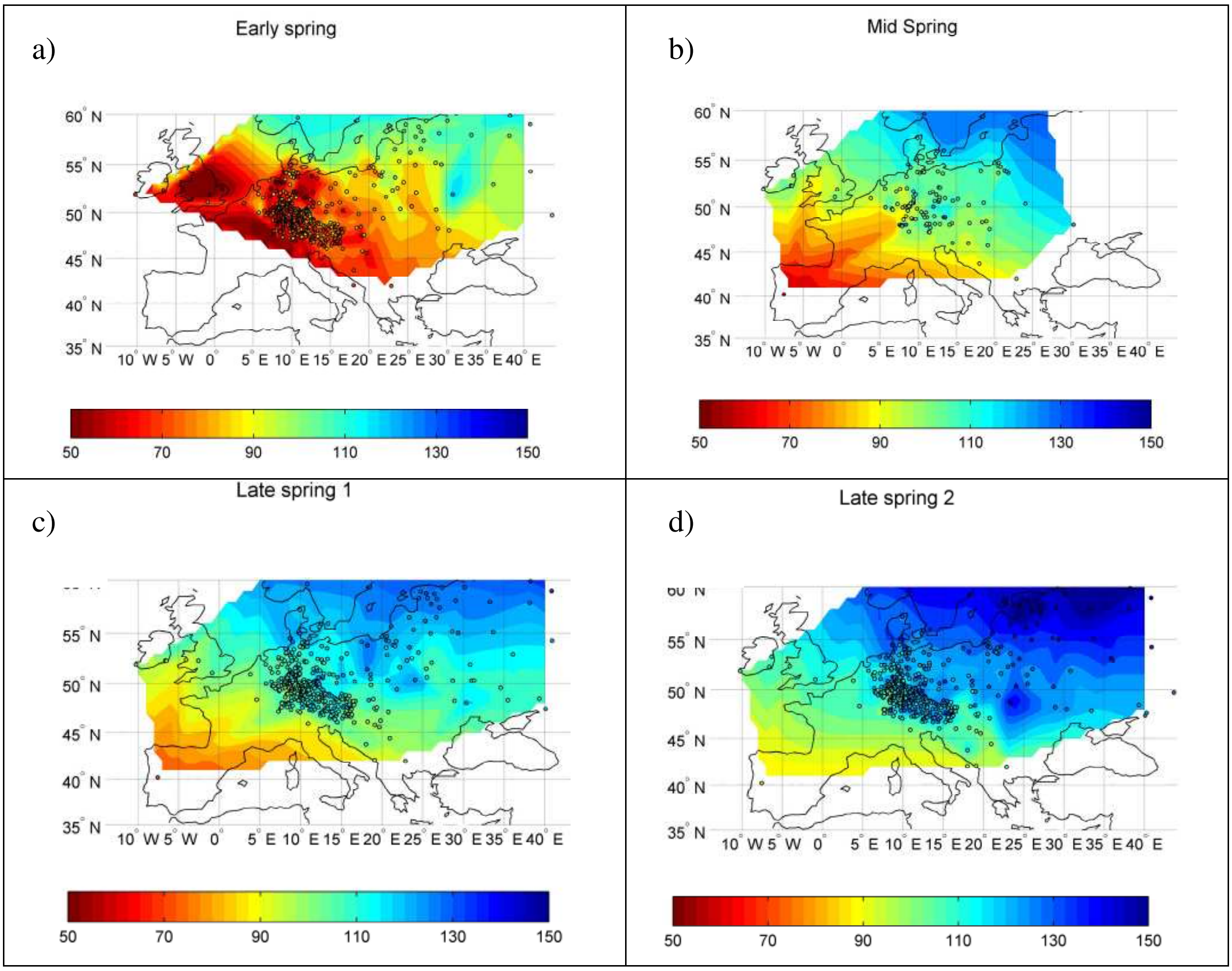

Abbildung 5: *Einzug des Frühjahrs in Europa. Mittlerer Eintrittstermin vom phänologischen Frühjahr in Europa, a) Vorfrühling; b) Hochfrühling; c) Spätfrühling 1; d) Spätfrühling 2 (für Phasenaufteilung siehe Tabelle 1 in Menzel et al. 2005b). Die Achsen geben die geographischen Koordinaten wieder, die Farbskala den Eintritt in Tagen seit Jahresbeginn.*

3. Die „Response to Temperature“ und ihre Auswirkung auf die Variabilität der Phänologie

3.1 Temperaturreaktionen von phänologischen Phasen

Pflanzenreaktionen lassen sich vor allem mit Klimaparametern, die Auskunft über die Temperatur geben, in Zusammenhang stellen. So lässt sich ein Einfluss der Nordatlantik Oszillation (NAO) auf das räumliche Verhalten von phänologischen Phasen feststellen. Der NAO Index stellt den Druckunterschied zwischen dem Azorenhoch und dem Islandtief dar. Über seinen Betrag lassen sich die Strömungsverhältnisse bestimmen und damit die Winterwitterung von Europa herleiten. Ein positiver NAO Index ist gegeben, wenn ein starkes subtropisches Hochdruckzentrum und ein tieferer Druck als üblich über Island herrscht. Durch die erhöhte Druckdifferenz kommt es zu einer starken westlichen Strömung feuchter Luftmassen nach Zentraleuropa, der Winter ist dort relativ warm und feucht. Das Azorenhoch bildet eine Barriere für das Mittelmeergebiet, hier sind die Winter trockener. Bei negativem NAO Index sind beide Drucksysteme nur gering ausgeprägt, die Bedingungen sind nicht stabil und der Mittelmeerraum erhält mehr Regen und feuchte Luftmassen. In Zentraleuropa kommt es eher zu Schneefällen und Kaltlufteinbrüchen.

Der NAO Index stellt also ein Maß für die Witterung im Winter und frühen Frühling dar. Man kann deshalb den NAO Index verwenden, um das jährliche Voranschreiten von phänologischen Phasen zu erklären. So zeigt sich, dass hohe NAO Indices ein anderes Muster des Frühlingseinzugs ergeben als niedrige NAO Indices (**Artikel GCB 2005**). Bei einem hohen NAO Index breitet sich der Frühling von Südwest nach Nordost aus, d.h. der Breitengradient wird kleiner. Abbildung 6 zeigt die Ausbreitung des Hochfrühlings sowohl in Jahren mit hohen (oben rechts) als auch mit niedrigen (oben links) NAO Index. Deutlich ist zu sehen, dass kühle Frühjahrswitterung (NAO low) zu einer Verschiebung der Ausbreitungsrichtung führt. Der Eintritt der Phasen erfolgt insgesamt später und ist dann eher von Süd nach Nord zu beobachten, nicht wie sonst üblich von SW nach NO.

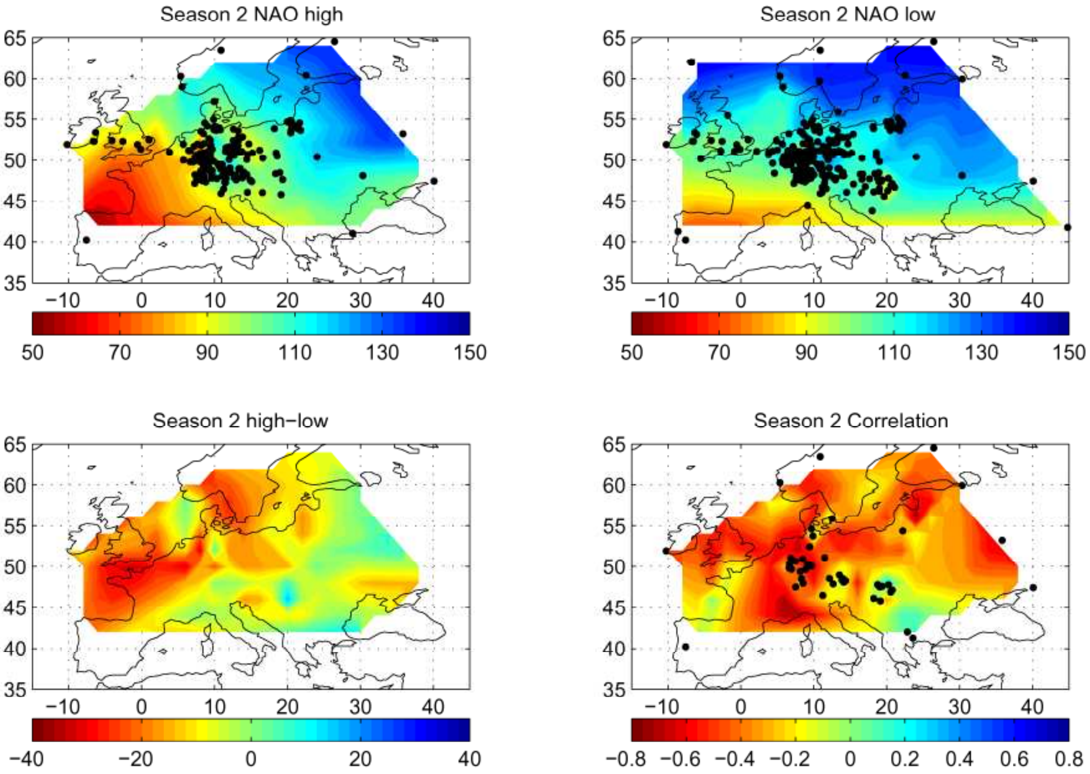

Abbildung 6: *Obere Grafiken: Mittlerer Beginn des Hochfrühlings (Tag seit Jahresbeginn) in Europa für die 10 Jahre mit dem höchsten (1990, 1882, 1928, 1903, 1993, 1910, 1880, 1997, 1989, 1992) und den 10 Jahren mit dem niedrigsten (1969, 1936, 1900, 1996, 1960, 1932, 1886, 1924, 1941, 1895) NAO Winter- und Frühlingsindex. Linke untere Grafik: Differenz zwischen mittlerem Beginn des Hochfrühlings (Tage) in Jahren mit hohem bzw. niedrigem NAO Index. Untere Grafik rechts: Korrelationskoeffizienten zwischen jährlichem Beginn des Hochfrühlings und NAO Index (1879-1998). Achsen in geographische Koordinaten (Menzel et al. 2005b).*

Eine punktuellere Studie befasst sich mit dem Einfluss der Monatsmitteltemperatur auf den Eintrittstermin von phänologischen Phasen (Blüte von Rosskastanie, Flieder und Roter Johannisbeere) in Deutschland (**Artikel Clim Res 2005**) (Menzel et al. 2005a). Hierbei wurden von acht einzelnen Stationen lange Zeitreihen (1900-2000) in Verbindung mit zwei Temperaturdatensätzen untersucht. Pro Grad höherer Monatsmitteltemperatur wurde eine Verfrühung zwischen 2,6 und 6,9 Tagen festgestellt.

Die Temperaturreaktionen von landwirtschaftlichen Kulturpflanzen und Obst in Deutschland wurden mit zwei verschieden Methoden in dem **Artikel GCB 2007** beschrieben. Für beide Vergleiche wurden Regressionen mit Monatsmitteltemperaturen der vor dem Eintrittstermin liegenden Monate berechnet. Außerdem wurden als weitere Parameter noch für den Frühling die

Mitteltemperatur von März, April und Mai und für die Sommertemperatur die Monatsmitteltemperatur von Juni, Juli und August gemittelt.

Die phänologischen Beobachtungen wurden folgendermaßen vorbereitet: (1) Anomalien wurden als Abweichung der Eintrittstermine vom Mittel zwischen 1971 und 1985 berechnet. (2) Aus den Anomaliezeitreihen wurde der lineare zeitliche Trend herausgerechnet und die verbleibende „detrendete“ Zeitreihe verwendet. Denn es ist wahrscheinlich, dass innovative Bewirtschaftungsmethoden und die Verwendung von neuen Technologien auch durch die Klimaveränderung beeinflusst werden, allerdings nicht überall gleichzeitig. Einige Landwirte werden sofort neue Methoden anwenden, die Mehrheit wird erst mal auf die Reaktionen der anderen warten, bevor sie ihre Gewohnheiten ändern, und einige wenige werden der Anpassung auf die Klimaveränderung hinterherhinken (Easterling et al. 2003). Zusätzlich wirken sich noch Neuzüchtungen, Marktpreise und Subventionen auf landwirtschaftliche phänologische Phasen aus. Deshalb vermuten wir, dass der Einfluss von nichtthermalen Störfaktoren auf eine landesweite mittlere Zeitreihe linear ist. Durch das Detrenden der Zeitreihe sollen diese Störfaktoren herausgerechnet werden. In den Abweichungen der detrendeten Zeitreihe verbleiben nur noch die kurzfristigen Fluktuationen. Diese Fluktuationen sollen dann zeigen, inwiefern ein Zusammenhang mit der Temperaturzeitreihe vorliegt und welche Unterschiede die Fluktuationen im Vergleich zu den regulären Anomalien in der Temperaturreaktion aufweisen. Für beide Varianten wurden zwischen den Eintrittsterminen und den Temperaturen Korrelationen und Regressionen durchgeführt.

Fast alle Korrelationskoeffizienten sind negativ (97%). Der Regressionskoeffizient bei der Schätzung der mittleren Temperaturreaktion gegen die März-Mai Temperatur ist bei den detrendeten Zeitreihen signifikant geringer (-3,73 Tage pro °C) als bei den unveränderten Zeitreihen (-4,31 Tage pro °C). Die „wahre“ Größe der Temperaturreaktion wird dazwischen liegen. Mehrjährige Pflanzen weisen einen signifikant höheren Temperaturzusammenhang zu Frühlingstemperaturen auf als einjährige Feldfrüchte.

Länderübergreifend werden die Temperaturreaktionen von Pflanzen auf Monatsmitteltemperaturen in **Artikel GCB 2006** behandelt. Untersucht werden 254 nationale Zeitreihen aus 9 Ländern (1951-1999) die Eintrittstermine von Frühjahrs und Sommerphasen, wie z.B. Blattentfaltung, Blüte und Fruchtreife. Die der Phase vorangegangenen Mitteltemperatur korreliert mit dem Phaseneintritt. Die untersuchten Phasen zeigen eine Verfrühung um 1 bis 5 Tage pro °C Temperaturerhöhung. Zudem stimmt das Muster der beobachteten Veränderung im Frühling mit der nationalen Erwärmung überein (Korrelationskoeffizient $r=-0{,}69$, $P<0{,}001$) (siehe Abb. 7). Deutlich ist zu sehen, dass in Ländern mit einem starken positiven Temperaturtrend auch die

Phänologie einen stärkeren Trend zur Verfrühung (wie Belgien, Dänemark, Deutschland, Spanien) aufweist als in Ländern, in denen nur ein geringerer positiver oder gar negativer Temperaturtrend (Slowakei, Griechenland) vorliegt. Die herbstliche Laubverfärbung wird nicht so stark von der Temperatur beeinflusst. Im Durchschnitt verspätet sie sich um bis zu 2 Tage pro °C (Korrelationskoeffizient r=0,003 P=0,99 für 14 Länder).

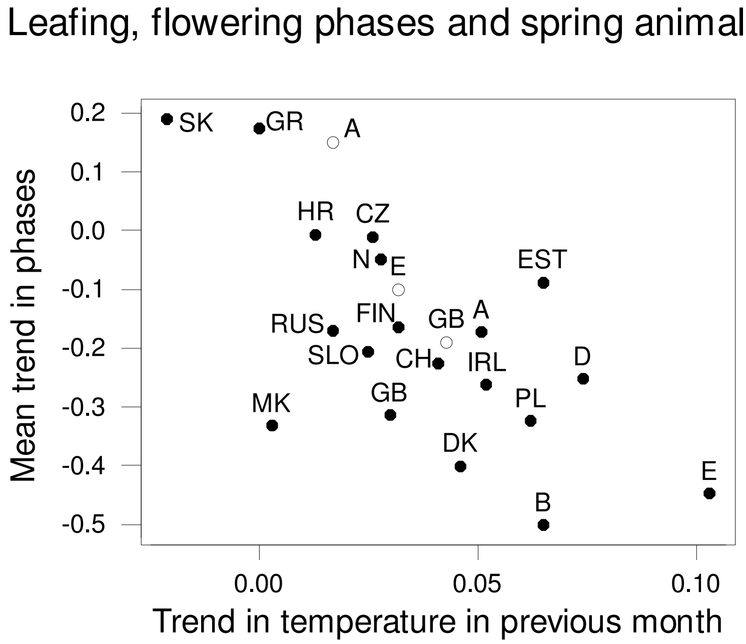

Abbildung 7: *Trends der nationalen Temperatur im Frühjahr [°C/a] gegen die mittleren nationalen Phänologietrends von Frühjahrs- und Sommerphasen (Blattentfaltung, Blüte - geschlossene Kreise; Tierphasen - offene Kreise) [Tage/a]. Länderkürzel nach dem Internationalen Ländercode (Menzel et al 2006).*

Insgesamt zeigt sich in allen vorgestellten Studien, dass vor allem die frühen und mittleren Frühjahrsphasen einen engen Zusammenhang zur Monatsmitteltemperatur des vor dem Phaseneintritt liegenden Monats aufweisen. Herbstphasen hingegen lassen sich meist nicht so gut mit der Lufttemperatur vorheriger Monate korrelieren. Auf die Laubverfärbung in Deutschland wird in Kapitel 3.3 noch im Detail eingegangen.

3.2 Anwendungen von Temperaturabhängigkeiten

Ergänzend zum eigentlichen Thema meiner wissenschaftlichen Arbeit, soll zur Vollständigkeit der Betrachtung hier noch der Aspekt von Anwendungsmöglichkeiten von phänologischen Eintrittsterminen und ihrer Temperaturabhängigkeit erörtert werden.

3.2.1 Temperaturrekonstruktionen mit Hilfe von phänologischen Informationen

Prinzipiell eignen sich phänologische Eintrittstermine von Phasen, die ja einen engen Temperaturzusammenhang aufweisen, auch zur Rekonstruktion von Temperaturzeitreihen. Gemacht wurde dies z.B. anhand von Terminen der Weinlese in Deutschland (Menzel 2005) bzw. Frankreich (Chuine et al. 2004) und der Kirschblüte in Kioto (Aono & Omoto 1993). Für diese Arbeit ist diese Fragestellung jedoch nicht weiter relevant.

3.2.2 Modellierung von phänologischen Eintrittsterminen

Wie bereits erwähnt kann man die Phänologie als Bio-Indikator für Klimaänderungen verwenden. Aufgrund dieses statistischen und kausalen Zusammenhangs lassen sich Eintrittstermine vor allem von Blattaustrieb, Blüte und Fruchtreife relativ gut allein aufgrund von Temperaturinformationen modellieren (z.B. Hänninen 1990, Kramer 1995, von Wuehlisch et al. 1995, Sykes et al. 1996, Menzel 1997, Chuine et al. 1999, Schaber 2002, Chuine et al. 2003). Die erste Verknüpfung von Temperatursummen und Pflanzenreaktionen wurden von Réaumur 1730 (Hunter & Lechowicz 1992) beschrieben. Réaumur zeigte, dass spätere Erntetermine bei Getreide und Wein im Jahre 1735 mit geringeren Temperatursummen im April, Mai und Juni verbunden waren als im Jahr 1734, in dem früher geerntet worden war. So erkannte er den Zusammenhang zwischen Temperaturen und Entwicklungsgeschwindigkeit. Temperatursummenmodelle werden auch heute noch oft verwendet. Vor allem seit dem Ende des 20. Jahrhunderts entstanden eine Vielzahl von phänologischen Modellen, einerseits aufgrund der Entwicklung im Computerbereich, andererseits wegen der fortschreitenden Klimaerwärmung, die in der Gesellschaft inzwischen Anlass zu wachsender Besorgnis für die menschliche Gesundheit und die Umwelt gibt. Anwendung finden phänologische Modelle u.a. in Biosphärenmodellen, die globale C-Kreisläufe modellieren (z.B. White et al. 1999). Ein wichtiger Eingangsparameter hier ist die Länge der Vegetationsperiode, denn Photosynthese bei Laubbäumen kann erst dann stattfinden, wenn die Blätter schon ausgetrieben sind.

Herbstphasen, wie Laubverfärbung, können immer noch nicht zufriedenstellend modelliert werden. Über die Suche nach Einflussfaktoren und der (Un-)Möglichkeit der Modellierung von der Laubverfärbung in Deutschland befasst sich **Artikel Clim Res 2006** (siehe Kap. 3.3).

3.3 Mögliche andere Einflussfaktoren auf den Eintrittszeitpunkt von phänologischen Phasen im Herbst

Lufttemperaturen zeigen also einen starken Einfluss auf phänologische Phasen, vor allem Frühjahres- und Sommerphasen. Im Herbst fallen jedoch die Korrelationskoeffizienten zwischen

Monatsmitteltemperaturen und dem Eintrittstermin der phänologischen Phase wesentlich geringer aus. Diese spezielle Problematik der Laubverfärbung von Hängebirke, Rosskastanie, Rotbuche und Stieleiche in Mitteleuropa wird in **Artikel Clim Res 2006** behandelt. Verschiedene Hypothesen über auslösende Faktoren auf den Zeitpunkt der Laubverfärbung werden an drei Datensätzen untersucht. Zuerst werden Beobachtungsreihen, die im Umkreis von maximal 25 km um eine Klimastation liegen, untersucht, dann werden die phänologischen Beobachtungen für jede Klimastation gemittelt, anschließend werden sowohl die phänologischen Beobachtungen als auch die meteorologischen Parameter über Deutschland gemittelt analysiert. In Tabelle 2 sind einige gängige Literaturhypothesen sowie zusätzliche Parameter aufgelistet, die in **Artikel Clim Res 2006** untersucht werden.

Tabelle 2: *Hypothesen zu möglichen Faktoren, die den Beginn der Laubverfärbung auslösen*

Tagesmitteltemperatur < 11 bzw. 10°C (Auslösetemperatur / sichtbare Laubverfärbung)	Schnelle (1952)
Tagesminimumtemperatur < 7 bzw. 6°C (Auslösetemperatur / sichtbare Laubverfärbung)	Schnelle (1952)
Warmes herbstliches Wetter und ausreichende Wasserversorgung verlängern die Vegetationsperiode	Seyfert (1955, 1966)
Hohe Herbsttemperaturen beschleunigen die Laubverfärbung	Schulze (1970)
Warmer Juni führt zu früher Laubverfärbung	Freitag (1987)
Warmer August / September führt zu später Laubverfärbung	Freitag (1987)
Ende der Vegetationsperiode, wenn Tagesmitteltemperatur unter 8°C nach 1. August in einem Klimadiagramm fällt (verändert: Folge von 5 Tagen < 8°C)	Hartmann & Schnelle (1970)
Monatsmitteltemperaturen des betrachteten Jahres, sowie des Vorjahres	neue Hypothesen: **Artikel Clim Res 2006**
Tag an dem folgende Grenzwerte unterschritten wurde: Mitteltemperatur< 11, 9, 8, 7, 5°C Minimumtemperatur < 7, 5°C	
Monatssumme des Niederschlags des betrachteten Jahres, sowie des Vorjahres	
Anzahl der trockenen Tage pro Monat des betrachteten Jahres, sowie des Vorjahres	

In der Studie **Artikel Clim Res 2006** wurden sowohl thermische, als auch hydrologische Parameter entwickelt und getestet. Die Zusammenhänge zwischen Monatsmitteltemperaturen, Tage, an denen der Grenzwert unterschritten wurde, monatliche Niederschlagssummen bzw. der Anzahl von trockenen Tagen pro Monat wurden mit dem Eintrittsdatum der Laubverfärbung korreliert. Gerade bei Laubbäumen ist davon auszugehen, dass Trockenheit einen Einfluss auf das Ende der Vegetationszeit hat. Die Länge der thermischen Vegetationszeit wurde in Anlehnung an Hartmann & Schnelle 1970 berechnet. Da erste Ergebnisse des stationsweisen Datensatzes zeigten, dass die Spannweite der Korrelationskoeffizienten sehr groß ist (zwischen r=–0,77 Buche und Tag an dem Mitteltemperatur<8°C und r=0,82 für Birke und Septembermitteltemperatur) und alle Parameter Korrelationskoeffizienten mit sowohl positiven als auch negativen Vorzeichen aufweisen, wurde der erste Datensatz nochmals unterteilt. Stationen, die einen signifikant positiven bzw. negativen zeitlichen Trend aufwiesen, wurden gesondert betrachtet. Doch auch diese Unterteilung vereinheitlichte das Bild nicht (Abbildung 8).

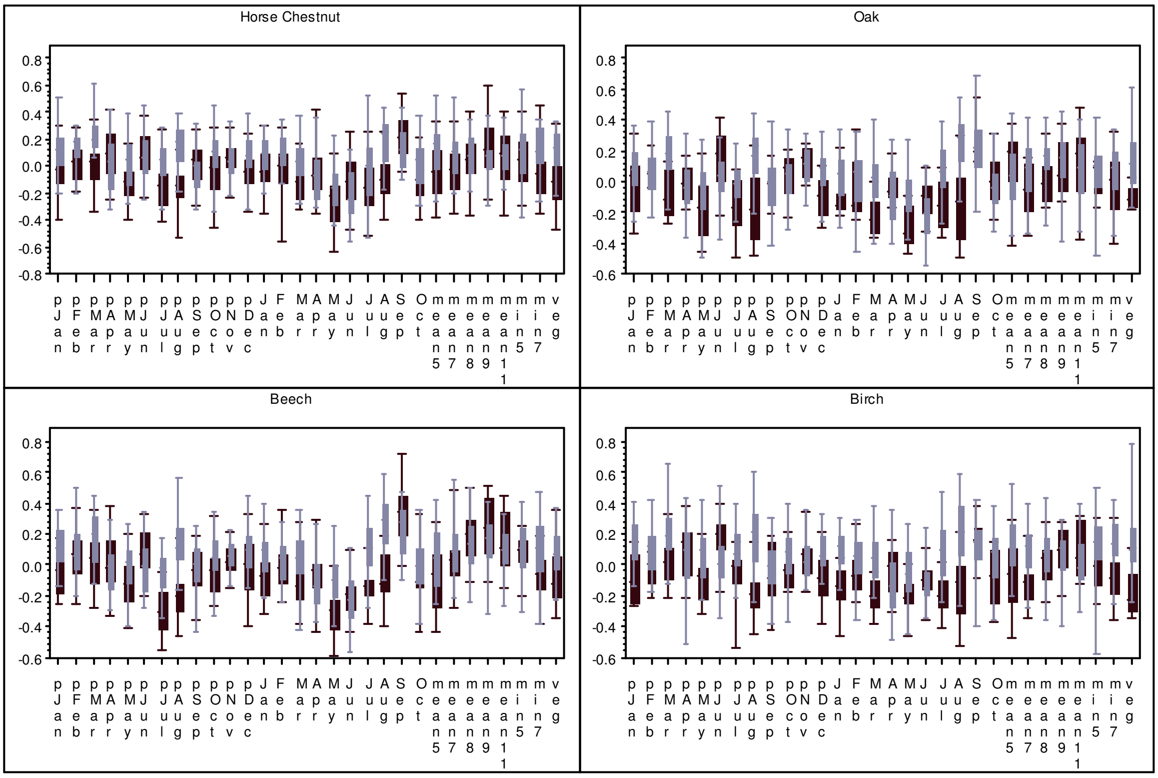

Abbildung 8: *Pearsons Korrelationskoeffizienten (r) zwischen den Eintrittsterminen der Laubverfärbung und allen verwendeten Parameter (vgl.* ***Artikel Clim Res 2006*** *Abb. 2, 3 & 6), unterteilt nach Stationen mit positiven (grau) und negativen (schwarz) signifikanten Trend in Zeitreihen mit mind. 30 Jahren an Beobachtungen (p= vorangegangenes Jahr, mean11= Tag an dem Mitteltemperatur* FD_{mean} *< 11°C; mean9=* FD_{mean} *<9°C, mean8=*FD_{mean} *<8°C; mean7=* FD_{mean} *<7°C; mean5=* FD_{mean} *<5°C; min5= Tag an dem Minimumtemperatur (*$FD_{min)}$ *<5°C; min7=* FD_{min} *<7°C; veg: Ende der Vegetationsperiode, Abgeändert nach Hoffmann und Schnelle 1970).*

Durch gemittelte Eintrittstermine für Deutschland lassen sich zumindest Aussagen darüber treffen, welche Parameter einen relevanten Einfluss auf den Termin der Laubverfärbung nehmen könnte. Das Ergebnis dieser Studie zeigt, dass meteorologische Parameter den Termin der Laubverfärbung kaum bestimmen. Die Monatsmitteltemperatur des Septembers zeigt am ehesten auf alle vier Baumarten einen leichten positiven Einfluss auf den Beginn der Laubverfärbung. Die Monatsmitteltemperatur des Augusts wirkt sich leicht positiv auf Eiche und Birke aus, während ein warmer Juni nur bei Rosskastanie und Eiche und ein warmer Mai nur bei Rosskastanie zu früherer Laubverfärbung führt. Man kann also sagen, dass Herbstphasen, zumindest in Deutschland, nicht sehr gut geeignet sind, um als Bioindikator der Klimaerwärmung verwendet zu werden. Ihre räumliche inter-annuelle Variabilität ist größer als die gemittelte zeitliche. Dies ist wohl auch ein Grund dafür, dass sich bisher sehr wenige Arbeiten mit diesen Phasen beschäftigt haben.

Interessant ist, dass Daten anderer Länder in Europa bei den Herbstphasen sehr wohl eine Verlängerung der Vegetationsperiode nahe legen. In der Metaanalyse (**Artikel GCB 2006**) weisen 10 Länder einen positiven Trend auf, drei Länder (Norwegen, Russland und Schweiz) zeigen einen Trend zu einem früheren Eintritt von Herbstphasen, nur Deutschland zeigt nur einen sehr geringen positiven Trend (vgl. Kap. 2.2). Allerdings sind die Anzahl der beobachteten Phasen und Stationen sehr unterschiedlich. In einigen Länder wird der Mittelwert nur aus wenigen Beobachtungen berechnet, in Deutschlands Mittelwert gehen jedoch sehr viele Stationen und Phasen ein.

4. Auswirkungen der beobachteten Veränderungen

Der Deutsche Wetterdienst (DWD) hat in den 90iger Jahren das phänologische Beobachtungsprogramm an die Erfordernisse der Zeit angepasst und verstärkt Blühphasen von allergenen Pflanzen hinzugenommen, da der Anteil der Bevölkerung, der allergische Reaktionen zeigt, in den letzten Dekaden gestiegen ist (Aberg et al. 1996, Beggs & Bambrick 2005). So sind z.B. 20% der Deutschen auf Birkenpollen sensibilisiert. Die Untersuchungen zu den zeitlichen Trends von Blühphasen weisen darauf hin, dass sich auch die Leidenszeit von Allergikern entsprechend verändert hat. So zeigen Studien, dass sich nicht nur die Blühtermine verfrühen (Menzel & Estrella 2001, Walther et al. 2002), sondern auch, dass der Beginn der Pollensaison sich verfrüht (Frei 1998, Emberlin et al. 2002) bzw. ihre Dauer und Intensität oft zugenommen hat (Jäger et al. 1996, Emberlin et al. 2002, Spieksma et al. 2003).

Die Ergebnisse der Trenduntersuchungen von phänologischen Blühphasen sollten nun verwendet werden, um die Pollensaison zu charakterisieren und um Einflüsse auf die menschliche Gesundheit zu prognostizieren. Hierfür sollten die phänologischen Beobachtungen von allergenen Blühphasen mit Pollenfunden aus Fallen integriert werden (**Artikel Int J Biometeor 2006**). Die Pollenfunde von drei Pollenarten (Betula, Poaceae, Artemisia) von 51 Pollenfallen in Deutschland wurden mit den phänologischen Blühterminen von ca. 400 Phänostationen, die sich im Umkreis von maximal 25 km um die Pollenfallen befinden, verglichen. Die Pollendaten lagen für die Jahre 1992-1993 sowie 1997-1999 vor. Sie enthalten Informationen über den Beginn und den Höhepunkt (Peak) der Pollensaison. Als Beginn der Pollensaison wird im nachhinein der Tag festgesetzt, an dem 1% der gesamten gemessenen Pollen des Jahres erreicht wird, vorrausgesetzt innerhalb der folgenden sechs Tage werden nochmals Pollen gefunden. In der Studie werden dann die Termine der Pollenfunde mit den frühesten Beobachtungen von Blühterminen von angrenzenden DWD Stationen sowie den Mittelwerten dieser Stationen verglichen. Die Studie zeigt, dass der Beginn der Birkenpollensaison im Durchschnitt 5,7 Tage vor dem lokalen Blühtermin beginnt. Der Saisonbeginn von Gräserpollen stimmt gut mit der beobachteten Blüte von Wiesenfuchsschwanz überein (im Mittel werden die Pollen um 0,6 Tage später beobachtet). Der Beginn von Beifußpollen verspätet sich hinter den Blühterminen um ca. 4,8 Tage. Der Höhepunkt der Birkenpollen traf mit dem mittleren Blühtermin zusammen, beide andere Pollenarten hatten ihren Höhepunkt jedoch um einiges später als dem mittleren beobachteten Blühtermin. Das Maximum der Beifußpollen wird im Schnitt mehr als zwei Wochen später erreicht, die meisten Graspollen werden sogar drei Wochen nach dem Blühen gezählt. Bei genauerer Betrachtung stellt sich heraus, dass es große lokale und zeitliche Unterschiede gibt. Vor allem bei Birkenpollen gibt es große Abweichungen in beide Richtungen. So begann die Pollensaison in Norderney im Jahr 1997 57 Tage vor der beobachteten Blüte, im Jahr 1992 erfolgte in Münnerstadt der Pollenpeak 63 Tage nach der Blüte. Somit können nicht alle Funde in Pollenfallen mit den beobachteten Blühterminen erklärt werden. Ferntransport von Pollen sind gerade bei den sehr kleinen Birkenpollen mögliche Ursachen für den vorgefundenen zeitlichen Versatz. Die normale Transportentfernung von anemophilen Pollen beträgt ca. 500 km (Rousseau et al. 2003, Van de Water et al. 2003). Man hat Pollen aber auch schon 3000 km entfernt von seinem Herkunftsort gefunden (Campbell et al. 1999). Außerdem ist zu beachten, dass Funde in Pollenfallen nicht artspezifisch aufgeschlüsselt werden können.

Die Studie stellt einen ersten Ansatz dar, die vorhandenen phänologischen Daten und Pollenfunde in Zusammenhang zu bringen, aber dies gelingt nur teilweise. Weitere Untersuchungen auf diesem Gebiet, z.B. in Verbindung mit Transportmodellen, sind nötig, um aus phänologischen Beobachtungen für Pollenallergiker Nutzen ziehen zu können.

5. Vergleich mit anderen „Fingerprints of Climate Change“

Quantitative Vergleiche verschiedener phänologischer Studien sind nur bedingt möglich. Meist werden unterschiedliche Zeiträume untersucht und die Daten werden unterschiedlich vorbereitet (einzelne Stationen, Mittelwerte oder Anomalien; korrigiert - unkorrigiert). Außerdem gibt es erst seit kurzen Ansätze, verschiedene nationale phänologische Phasen auf die gleiche Art und Weise zu beschreiben und beobachten. Bei der Verwendung von gleichen Datensätzen kann es durch entsprechende Selektionen zu zeitlichen und räumlichen Unterschieden und somit auch leicht unterschiedlichen Ergebnissen bei zeitlichen Trends und Temperaturreaktionen kommen. Die berechneten linearen Trends von Phasen landwirtschaftlicher Pflanzen in **Artikel GCB 2007** weisen über die letzten 53 Jahre im Mittel eine Verfrühung um 1,1 – 1,3 Tage pro Dekade auf. Damit zeigen diese Phasen einen deutlich geringeren Trend zur Verfrühung, als wildwachsende Pflanzen in Europa (-2,5 Tage pro Dekade, **Artikel GCB 2006**). Andere Studien, die sich mit landwirtschaftlichen Phasen beschäftigt haben, bestätigen die Ergebnisse unserer Studie. In den Great Plains, USA, ist der Trend für den Beginn des Ährenschiebens zwischen 1948-2004 für sechs Stationen fast identisch (Hu et al. 2005). Eine weitere Arbeit über 15 landwirtschaftlichen Phasen in Deutschland (1961-2000) kommt zu Verfrühungen im Bereich zwischen 0,6 und 2,9 Tagen pro Dekade (Chmielewski et al. 2004). In Großbritannien zeigte sich, dass 25 von 29 Phasen zwischen 1990-2000 früher erschienen als zwischen 1980-1989 (Sparks et al. 2005b). Zwei weitere Studien unterstreichen die starken regionalen Unterschiede bei landwirtschaftlichen phänologischen Trends in Europa. In Finnland gibt es im Zeitraum zwischen 1965-1999 keine Veränderung bei der Aussaat von Frühlingsgetreide, die Kartoffelaussaat hat sich um ca. 5 Tage verfrüht (Hilden et al. 2005). In Frankreich hingegen findet die Aussaat von Feldfrüchten nun früher statt als noch vor 30 Jahren (bis zu einem Monat bei Mais und Winterweizen) (De La Torre & Benoit 2004). Die Anzahl der Studien, die sich mit landwirtschaftlichen Phasen und ihrer Veränderung durch den Klimawandel beschäftigen, ist wesentlich geringer, als die der Studien, die sich mit wildwachsenden Pflanzen beschäftigen. Denn landwirtschaftliche Phasen werden zusätzlich von nicht-klimatischen Faktoren beeinflusst, sowohl Bewirtschaftungsmethoden und technologische Entwicklungen als auch politische Steuerungen durch Subventionen (Easterling et al. 2003) nehmen Einfluss auf die Bewirtschaftungsmethoden der Landwirte.

Bei Vergleichen von vielen verschiedenen Phasen und Arten ist ein methodischer Ansatz, die zu erwartende Richtung der beobachteten Veränderung gegenüberzustellen. Diese Methode wurde in den globalen Metaanalysen von Root et al. (2003) und Parmesan und Yohe (2003) angewendet. Beide globale Studien unterscheiden nicht nach dem jahreszeitlichen Eintritt der Phase.

Unterteilungen werden nach Speziesgruppen bzw. bei Parmesan und Yohe (2003) auch nach polaren und äquatorialen Zonierungen vorgenommen.

Vergleicht man diese Ergebnisse mit der Studie aus **Artikel GCB 2006,** so zeigt sich, dass der Anteil der Frühjahrsphasen, die sich in die erwartete Richtung verschoben haben, mit ca. 80% fast identisch ist mit dem Ergebnis von Root et al. (2003), die für 81% der untersuchten Reihen eine Verschiebung in die erwartete Richtung feststellt. Die Studie von Parmesan und Yohe (2003) leitet sogar für 87% der untersuchten Beobachtungen eine Veränderung in die erwartete Richtung ab.

In den zwei Meta-Analysen ergeben sich mittlere Verfrühungen von Frühjahrsphasen um 2,3 und 5 Tage pro Dekade, wobei der erste Wert auch Arten beinhaltet, die keine Veränderungen aufweisen (Parmesan & Yohe 2003), während der zweite Wert nur solche Arten enthält, die sich tatsächlich zeitliche verändern (Root et al. 2003). Verschiedene weitere Studien zeigen ähnliche Veränderungen auch für kleinräumigere und artspezifischere Unterteilungen (Menzel & Estrella 2001, Sparks & Menzel 2002, Walther et al. 2002, Walther 2004).

Obwohl sich Studien von phänologischen Netzwerken oft stark unterscheiden in den untersuchten Regionen, Arten, Phasen und angewendeten Methoden, weisen die meisten eine deutliche Verlängerung der Vegetationsperiode um bis zu 2 Wochen in der zweiten Hälfte des 20. Jahrhunderts in mittleren und hohen Breiten der Nordhemisphäre auf.

Die Analyse von Vegetationsindices aus Satellitendaten kommt großräumig zu ähnlichen Ergebnissen: Fast überall auf der Nordhalbkugel ist die Vegetationsperiode länger geworden, 18 Tage im Zeitraum von 1981-1999 in Eurasien und 12 Tage in den USA (Zhou et al. 2001). Einige Einzelstationen können dabei wesentlich stärkere Veränderungen aufweisen (z.B. Verlängerung der Vegetationsperiode um 32 Tage in Spanien zwischen 1952 und 2000 , Penuelas et al. 2002).

Eine Übersicht über die wichtigsten bisher beobachteten Veränderungen von phänologischen Eintrittsterminen im Tier und Pflanzenreich gibt Tabelle 3.

Tabelle 3: Übersicht über die beobachteten phänologischen Veränderungen in der Tier- und Pflanzenwelt; linearer Trend gibt die Richtung der Veränderung an (- Verfrühung, + Verspätung)

Ort	**Zeitraum**	**Art / Phase / Jahreszeit**	**linearer Trend, in Tage / Dekade**	**Autor**
Frühjahrsphasen				
Deutschland	1951-2000	Kirschblüte und Apfelblüte	-0,9 und -1,1	Menzel 2003
Deutschland	1961-1990	Beginn der Vegetationsperiode von Obstbäumen, Kirschblüte und Apfelblüte	-2,3; -2,0; -2,2	Chmielewski et al. 2004
Westen der USA	1957-1994	Flieder und Geißblatt, Blüte	-1,5; -3,5	Cayan et al. 2001
Nordosten der USA	1965-2001	Flieder, Blüte und Laubentfaltung	-3,4 / –2,6	Wolfe et al. 2005
	1959-1993	Flieder, Blüte	-1,7	Schwartz & Reiter 2000
Washington, DC	1970-1999	Blüte von 100 Pflanzenarten	-0,8	Abu-Asab et al. 2001
Deutschland	1951-2000	Blüte und Laubentfaltung von10 Frühlingsphasen	-1,6	Menzel et al. 2003
Schweiz	1951-1998	Blüte und Laubentfaltung von 9 Frühlingsphasen	-1,9	Defila & Clot 2001
Europa (Int. Phänol. Gärten)	1959-1996	Verschiedene Frühlingsphasen (Blüte, Laubentfaltung)	-2,1	Menzel & Fabian 1999
Europa (Int. Phänol. Gärten)	1969-1998	Index verschiedener Frühlingsphasen	-2,7	Chmielewski & Roetzer 2002
21 Europäische Länder	1971-2000	Blüte und Laubentfaltung von verschiedenen Pflanzen	-2,0 (aus den Ländermitteln berechnet)	Menzel et al. 2006a
Japan	1953-2000	Gingko biloba (Laubentfaltung)	-0,9	Matsumoto et al. 2003
Großbritannien	vergangene 23 Jahre	Erscheinen von 18 Schmetterlingsarten	-2,8 bis –3,2	Roy & Sparks 2000
Europa, Nordamerika	vergangene 30-60 Jahre	Zahlreiche Vogelarten, Frühlingswanderung, Schwalbenrückkehr in der Slowakei	-1,3 bis -4,4	Crick et al. 1997, Crick & Sparks 1999, Dunn & Winkler 1999, Inouye et al. 2000, Bairlein & Winkel 2001, Sparks & Braslavska 2001, Lehikoinen et al. 2004
Australien	??	11 Zugvogelarten, Ankunft	Frühere Ankunft	Green & Pickering 2002
Europe, Nordamerika	vergangene 30-60 Jahre	Zahlreiche Vogelarten, Brüten	-1,9 bis -4,8	Dunn 2004
UK, Polen	vergangene 25 Jahre	Amphibien, Eiablage	Frühere Eiablage	Beebee 1995, Tryjanowski et al. 2003

Vegetationsperiode				
Deutschland	1951 bis 2000	4 Laubbaumarten (Laubentfaltung bis Laubverfärbung)	1,1 bis 2,3 (alle Stationen, alle Reihen)	Menzel et al. 2001, Menzel et al. 2003
Schweiz	1951-2000	9 Frühlingsphasen, 6 Herbstphasen	2.7 (nur sign. Veränderungen)	Defila & Clot 2001
Europa (Int. Phänol. Gärten)	1959-1996	Verschiedene Frühlings- / Herbstphasen (Laubentfaltung bis Laubverfärbung, Laubfall)	3.5 (alle Stationen)	Menzel & Fabian 1999, Menzel 2000
Japan	1953-2000	Gingko biloba (Laubentfaltung bis Laubverfärbung)	2.6	Matsumoto et al. 2003
Nordhemisphäre	Jul 1981 – Dez 1999	Vegetationsperiode über NDVI	1 (Eurasien), 0.7 (Nordamerika)	Zhou et al. 2001
Landwirtschaftliche Phasen				
Deutschland	1961-2000	15 landwirtschaftliche Phasen	-0,6 bis -2,9	Chmielewski et al. 2004
Deutschland	1951-2004	78 landwirtschaftliche Phasen Landesmittel	-1,1 - -1,3	Estrella et al. (accepted)
Südfrankreich	1970-2001	Aprikosen- und Pfirsichblüte	1 bis 3 Wochen früher	Seguin 2004
Deutschland	1961-2000	Aussaat von Mais und Zuckerrübe	10 Tage früher	Chmielewski et al. 2004
Frankreich	vergangene 30 Jahre	Aussaat von Mais in 4 INRA Versuchsstationen	20 Tage früher	De La Torre & Benoit 2004
Finnland	1965-1999	Kartoffelaussaat, Frühlingsgetreide	5 Tage früher, keine Veränderung	Hilden et al. 2005
Europäische Union	1975-2001	Weizenblüte, berechnet mit CGMS Model	3 Wochen früher	Genovese et al. 2004
Südfrankreich	Letzten 20 Jahre	Teilweise Verschiebung von zwei auf drei Generationen beim Apfelwickler		Sauphanor (2004) (http://www.international.inra.fr/press/global_warming_increases_codling_moth_damage_to_apple_trees)

In unserer COST725 Studie konnten wir nachweisen, dass es in Europa keinen „Veröffentlichungsfehler“ gibt. Diese Fragestellung war sehr wichtig, da die Ergebnisse einzelner Studien möglicherweise verzerrt sein könnten, insbesondere in Richtung auf besonders drastische Beispiele und Veränderungen, einerseits verursacht durch die Auswahl der Studienorte und Zeiträume durch die Wissenschaftler selbst, andererseits durch das peer-review Veröffentlichungsverfahren, indem ausgefallene oder die Erwartungen widerspiegelnden Ergebnisse leichter den Weg in die internationalen Zeitschriften finden (z.B. Kozlov & Berlina 2002). Daher sollten besonders auch Studien beachtet werden, die Regionen oder phänologische Phasen untersuchen in denen keine Veränderungen beobachtet worden sind, bzw. entgegen der erwarteten Richtung ausfällt. Die folgenden Studien beinhalten auch Regionen, die keine bzw. kaum Veränderung aufweisen: geringe bzw. keine Veränderung des Frühlingsbeginns im kontinentalen Osteuropa (Ahas et al. 2002, Schleip et al. 2005) oder Untergruppen von Arten, die keine Veränderung aufweisen (z.B. spät wiederkehrende Langstrecken-Zugvögel kommen nicht früher, sondern teilweise sogar später zurück (Butler 2003, Strode 2003)). Insgesamt zeigen die Studien jedoch eine überwältigende Anzahl von Pflanzen und Tieren, die sich in die erwartete Richtung verschieben Die Größe der Verschiebung stimmt sehr oft auch mit der Temperaturveränderung vor Ort überein (siehe COST725 Studie).

6. Wissenschaftliche Bedeutung der Arbeit

Im Rahmen dieser Arbeit wurde die zeitliche und räumliche Variabilität von phänologischen Zeitreihen untersucht. Dabei wurde vor allem die umfassende phänologische Datengrundlage des Deutschen Wetterdienstes verwendet, aber auch Beobachtungen anderer Netzwerke integriert. Die phänologischen Daten wurden mit Klimadaten verknüpft, um Zusammenhänge zwischen Klima und Phänologie zu analysieren und ihre qualitativen sowie quantitativen Einflüsse aufzuzeigen. Die phänologische Datenmenge und ihre Verknüpfung zu Klimaparametern, die in der vorliegenden Arbeit in kondensierter Form vorgestellt worden ist, ist in diesem Umfang sicher einmalig.

Es ist wichtig, die Pflanzenphänologie sowie die Zusammenhänge zwischen Temperaturveränderungen und Eintrittsterminen von phänologischen Phasen zu kennen, um die Ergebnisse von Modellierungen des zukünftigen Klimas mit phänologischen Schlüsselparametern, wie die Länge der Vegetationsperiode, verbinden und eventuelle Auswirkungen auf unsere Umwelt abschätzen zu können.

Analysen von einzelnen Beobachtungsreihen zeigen, dass es kleinräumige Unterschiede gibt. Diese lassen sich jedoch nicht immer erklären. So zeigen kartographische Darstellungen von zeitlichen phänologischen Trends in Deutschland keinen Zusammenhang zur geographischen Lage. Die europäischen Ländermittel der zeitlichen Trends korrelieren jedoch gut mit der Größe des nationalen Temperaturtrends.

Der größte Teil der verfügbaren landwirtschaftlichen Beobachtungen des Deutschen Wetterdienstes wurde auf ihre zeitlichen Trends und ihre Temperaturreaktionen hin untersucht und dabei wesentliche Unterschiede zum phänologischen Verhalten von wildwachsenden Pflanzen festgestellt. Diese Differenzierung ist extrem wichtig, da Veränderung der Länge der Vegetationsperiode, die mit Satellitendaten erfasst werden, sowohl wildwachsende als auch landwirtschaftlichen Phasen umfassen, die aber auf Artenebene nicht getrennt werden können.

Auch eine ausführliche Abhandlung und Prüfung von Hypothesen zum Eintritt der Laubverfärbung in Mitteleuropa gab es bisher nicht. Ihre Ergebnisse unterstreichen, dass eine im Zuge der rezenten Klimaerwärmung beobachtete Verlängerung der Vegetationsperiode im wesentlichen auf Verschiebungen im Frühjahr zurückzuführen ist, die wiederum ein deutliches Temperatursignal darstellen. Veränderungen im Herbst, dagegen, wie Laubverfärbung und Blattfall, sind einerseits europaweit sehr inhomogen, andererseits lassen sich ihre Verschiebungen auf keine Witterungszusammenhänge zurückführen.

Den Nutzen der Phänologie für die Pollenvorhersage wurde über den Zusammenhang zwischen phänologischen Beobachtungen allergener Blühpflanzen des Deutschen Wetterdienstes und Funden aus Pollenfallen untersucht. Langjährige phänologische Beobachtungsreihen von Blühterminen haben sicherlich eine entscheidende Funktion, die erst kurzen Messreihen von Pollen in der Luft zu verlängern, um langfristige Veränderungen zu beschreiben. Die immer wieder in vielen wissenschaftlichen Veröffentlichungen erwähnte Funktion der Verbesserung der Pollenvorhersage lässt sich jedoch nicht so einfach darstellen: Die Integration von Pollentransportmodellen erscheint hier unerlässlich.

Die Ergebnisse der hier vorgestellten Untersuchungen vertiefen die Kenntnis der Pflanzenphänologie und zeigen die nontrivialen Zusammenhänge zwischen Temperaturveränderungen und Eintrittsterminen von phänologischen Phasen auf. Die Ergebnisse der publizierten Studien liefern einen wichtigen Beitrag für die Climate-Change-Forschung.

7. Zusammenfassung

Im Lauf der letzten Jahre erlangte die Phänologie einen wichtigen Stellenwert in der Climate Change Forschung. Die umfangreichen Einsatzmöglichkeiten von phänologischen Eintrittsterminen werden in dieser Arbeit komprimiert vorgestellt. Phänologische Eintrittstermine von biotischen und nicht-biotischen Systemen spiegeln Veränderungen im Klima wider. Es besteht ein enger Zusammenhang zwischen der Lufttemperatur und den Eintrittstermine von phänologischen Phasen von Pflanzen. Die Klimaänderungen lassen sich deshalb auch in phänologischen Zeitreihen beobachten. Ein verändertes Klima resultiert in Verschiebungen der Eintrittstermine beispielsweise Austrieb oder Blüte. Die Jahresmitteltemperatur ist in Deutschland im Zeitraum zwischen 1901-2000 um 1°C gestiegen. Dieser zeitliche Trend der Temperatur lässt sich auch in vielen phänologischen Zeitreihen nachweisen. So treten Frühlingsphasen in Deutschland heute im Mittel 8 Tage früher ein als noch vor 50 Jahren. Die Vegetationsperiode, bezogen auf den Zeitraum zwischen Blattaustrieb und Laubverfärbung, hat sich in diesem Zeitraum um 5,5 bis 11,5 Tage verlängert. Landwirtschaftliche Phasen haben sich im Mittel zwischen 1951-2004 um 5,9 - 7 Tage verfrüht. Auch bei Tieren zeigen sich temperaturbedingte Veränderungen im Verhalten. So bleiben einige Zugvogelarten im Winter hier und ziehen nicht mehr in südlichere Regionen. Auch beginnen viele Vogelarten nun früher mit der Eiablage als vor 30 Jahren.

Unterschiede gibt es jedoch in der räumlichen und zeitlichen Variabilität von phänologischen Phasen, d.h. Unterschiede in Eintrittsterminen oder Trends zwischen Regionen und Zeiträumen. Wildwachsende Pflanzen zeigen im allgemeinen einen stärkeren Trend zur Verfrühung als landwirtschaftliche Pflanzen. Betrachtet man die kleinräumige Verteilung von zeitlichen Trends wildwachsender Pflanzen in Deutschland, so zeigt sich allerdings kein Muster. Weder Vorzeichen noch Betrag der Trends sind von der geographischen Lage der Beobachtungsstation abhängig.

Der quantitative Einfluss der Temperatur und ihre Auswirkung auf die Variabilität der Phänologie wurden sowohl bei wildwachsenden als auch bei landwirtschaftlichen Pflanzen und Phasen untersucht. Vor allem die Mitteltemperaturen der Monate, die kurz vor dem Eintrittstermin liegen, korrelieren mit dem Eintrittstermin der Phase. Die Korrelationskoeffizienten erreichen vor allem bei Frühjahresphasen hohe Beträge (bis zu $r>0.8$). Landwirtschaftliche Phasen in Deutschland reagieren im Mittel mit einer Verfrühung um 4,31 Tage/°C, bezogen auf die Mitteltemperatur von März-April-Mai. Europaweit läst sich der Trend der Temperatur gut mit dem Trend von phänologischen Frühjahrsphasen in Zusammenhang bringen.

Die Laubverfärbung von Bäumen in Deutschland hingegen zeigt keinen so engen Zusammenhang mit den Temperaturen der Vormonate. Allein die Septembermitteltemperatur hat auf alle vier untersuchten Laubbaumarten einen leichten positiven Einfluss.

Die Pollensaison hat sich aufgrund der wärmeren Temperaturen verlängert; die Pollenemission ist zudem intensiver geworden. Damit hat sich auch die Leidenszeit der Allergiker verstärkt. Phänologische Eintrittstermine allergener Blühpflanzen bieten eigentlich eine günstige Möglichkeit, Pollenvorhersagemodelle zu optimieren. Unsere Untersuchungen haben jedoch gezeigt, dass die Verknüpfung von Pollenmessungen mit Fallen und phänologische Beobachtungsdaten sich nur bedingt in Beziehung setzen lassen. Ein nicht unbeträchtlicher Anteil der Pollen scheint aus Ferntransport zu stammen.

Wie wertvoll phänologische Beobachtungen für die Climate Change Forschung sind, kann man auch daran erkennen, dass es im neuen IPCC Bericht (AR4) der Working Group II, der im April dieses Jahres erscheint, nun ein eigenes Kapitel über beobachtete Veränderungen in natürlichen und bewirtschaften Systemen gibt.

8. Summary

There is now stronger evidence that recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems. In particular, phenological events - the timing of seasonal activities of animals and plants - offer a simple method to detect ecological changes in response to climate change. Recorded changes in spring and summer events of plants and animals include predominantly earlier leaf unfolding, flowering, fruit ripening, arrival of migrant birds, chorusing of amphibians, and appearance / emergence of butterflies. Phenological changes in autumn often include later leaf colouring, leaf fall, and later or lack of migration of some birds. Spring events are significantly earlier now in Germany, with a mean advance of 1.6 days / decade between 1951-2000. During this time the vegetation period, defined as the time span between leaf unfolding and leaf colouring, has lengthened by between 1.1 and 2.3 days / decade in Germany. Agricultural phases are observed on average 1.1 to 1.3 days / decade earlier than 1951.

Analyses of the spatial distribution of temporal phenological trends in Germany reveal that neither the sign nor the size of the trend is triggered by the geographical position of the respective recording sites.

The quantitative influence of temperature changes on phenological trends varies between species and phases. On a larger scale in Europe, however, national mean temperature trends are quantitatively mirrored by national spring phenological trends.

Changes in the timing of leaf colouring of deciduous trees in Germany are completely different from the observed patterns for onset dates and trends in spring. The onset date of leaf colouring is hardly affected by temperature. Only the mean temperature of September shows a slightly positive influence on the onset of autumnal colouring for all four deciduous tree species analysed.

The pollen season has lengthened as a response to climate warming, too. At first glance, the observed phenological onset dates of the flowering of allergic wind-pollinated plants could provide a cheap means to optimise the pollen forecast. However, our analyses showed that the integration of pollen data and phenological observations cannot easily be implemented. It seems that a significant proportion of the pollen originates from long distance transport.

To conclude, phenology has gained new importance in global climate research, firstly as a temperature proxy in recent centuries, secondly as an easily observed climate change response in nature. The increasing importance of phenological observations can be demonstrated by the fact that the latest IPCC report (AR4) of Working Group II, which will be released in April 2007, starts with a chapter on observed changes in natural and managed systems.

9. Darstellung der Einzelleistungen der Kandidatin

Artikel Int J Biometeor 2006: Von der Kandidatin wurden die Polleninformationen überprüft, die Möglichkeit der Vergleichbarkeit von familienspezifischen Pollenfunden mit artspezifischen Blühbeobachtungen wurde auf verschiedene Arten getestet. Die phänologischen Beobachtungen wurden entsprechend ausgewählt und angepasst. Die Berechnung und Interpretation der Ergebnisse sowie die Erstellung der Abbildungen wurden von der Kandidatin selbstständig durchgeführt. Insgesamt leistete die Kandidatin ca. 80% zur Fertigstellung des gesamten Artikels.

Artikel Clim Res 2006: Die Kandidatin hat sämtliche Datenbearbeitungen, Statistiken und Interpretationen selbstständig erstellt. Die Auswahl der getesteten Parameter, die Analysen und Weiterentwicklungen der Hypothesen und die Planung des Artikels wurden selbständig von der Kandidatin durchgeführt. Der von ihr eingebrachte Arbeitsaufwand liegt bei ca. 85%.

Für **den Artikel GCB 2007** bearbeitete die Kandidatin die phänologischen und klimatologischen Daten, erstellte die Statistiken und hatte maßgeblichen Anteil bei der Interpretation der Ergebnisse. An dem gesamten Artikel hat sie zu ca. 70% beigetragen.

Artikel GCB 2001: Für diese Artikel bereitete die Kandidatin die Daten auf, berechnete Statistiken, erstellte die Karten Abbildung 2 und Abbildung 4 und beteiligte sich an der Interpretation der Ergebnisse. Ihre Beteiligung an diesem Artikel liegt bei ca. 30%.

Artikel GCB 2006: Die Kandidatin bereite Module vor, um die Daten auswerten zu können, berechnete alle Trends für die Daten aus Deutschland, die den größten Anteil an der europaweiten Studie ausmachen, bearbeitete die Klimadaten und erstellte die Verknüpfung zwischen Länderphänologien und Temperaturdaten. Ca. 25% des Artikels wurden von der Kandidatin erbracht.

Artikel Clim Res 2005: Der Artikel entstand aus den Daten einer Diplomarbeit. Die Kandidatin wies die Diplomandin in SAS ein, betreute und unterstützte sie mit. Ca. 25% des Artikels gehen auf die Arbeit der Kandidatin zurück.

Artikel GCB 2005: Für diesen Artikel half die Kandidatin bei der Bearbeitung der phänologischen Daten, der Statistiken und der Interpolation sowie der Interpretation der Ergebnisse. Die Kandidatin trug zu ca. 20 % zur Fertigstellung des Artikels bei.

10. Veröffentlichungen

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11. Estrella N, Sparks T, Menzel A: Trends and temperature response in the phenology of crops in Germany (*accepted by GCB*)

12. Menzel A, Estrella N, Heitland W, Susnik A, Dose V: Species-specific effects on the lengthening of the growing season in two European countries. *(under review by International Journal of Biometeorology)*

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14. Menzel A, Estrella N, Fabian P (2004) Phänologie - Pflanzen in einer wärmeren Welt. In: MunichRe „Naturkatastrophen und Klimawandel – sind wir noch zu retten?“, 144-155.

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12. Appendix

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Estrella N, Menzel A, Kramer U, Behrendt H (2006) Integration of flowering dates in phenology and pollen counts in aerobiology: analysis of their spatial and temporal coherence in Germany (1992-1999). *International Journal of Biometeorology* 51, 49-59.

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Integration of flowering dates in phenology and pollen counts in aerobiology – Analysis of their spatial and temporal coherence in Germany (1992-1999)

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Abstract

We studied the possibility of integrating flowering dates in phenology and pollen counts in aerobiology in Germany. Data were analyzed for three pollen types (*Betula*, *Poaceae, Artemisia*) at 51 stations with pollen traps and corresponding phenological flowering dates for 400 adjacent stations (<25km) for the years 1992-1993 and 1997-1999. The spatial and temporal coherence of these data sets was investigated by comparing start and peak of the pollen season with local minima and means of plant flowering. Our study revealed that start of birch pollen season occurred on average 5.7 days earlier than local birch flowering. For mugwort and grass the pollen season started on average after local flowering was observed; mugwort pollen was found 4.8 days later and grass pollen season started almost on the same day (0.6 days later) as local flowering. Whereas the peak of the birch pollen season coincided with the mean flowering dates (0.4 days later), the pollen peaks of the other two species took place much later. On average, the peak of mugwort pollen occurred 15.4 days later than mean local flowering, the peak of grass pollen catches followed 22.6 days after local flowering. The study revealed a great temporal divergence between pollen and flowering dates with an irregular spatial pattern across Germany. Not all pollen catches could be explained by local vegetation flowering. Possible reasons include long-distance transport, pollen contributions of other than phenologically observed species and methodological constraints. The results suggest that further research is needed before using flowering dates in phenology to extrapolate pollen counts.

Keywords Pollen, flowering, phenology, spatial variability, long-range transport, Germany

Introduction

The impact of climate change on aeroallergens and related allergic diseases, although of enormous importance, has been somewhat neglected (Beggs 2004). Allergies have become more and more frequent in the Western world, especially pollen related allergies. Many studies report that prevalence to pollen related allergic diseases has risen in recent decades (e.g. Haahtela et al. 1990; Aberg et al. 1996; Beggs and Bambrick 2005). Major aeroallergens in Europe comprise pollen of the genus / family *Alnus, Corylus, Betula, Poaceae, Artemisia and Ambrosia*. Especially birch pollen is very common in temperate and northern regions and can cause severe allergic reactions. Almost 20% of the German population is sensitised to birch pollen (Nowak et al. 1996).

The impacts of climate change on aeroallergens include changes in the amount of pollen, the pollen allergenicity, the pollen season, and the plant and pollen distribution (Beggs 2004). In particular, there is strong evidence from various studies that observed higher temperatures due to climate change are associated with an earlier start of plant flowering in spring and summer (e.g. reviews by Menzel and Estrella 2001; Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003; Traidl-Hoffmann et al. 2003) and an earlier onset of the pollen season in the northern hemisphere (Frei 1998; Emberlin et al. 2002; Rasmussen 2002; Beggs 2004). However, not only have trends to an earlier, but also longer and more intense pollen season for various species been reported (e.g. Spieksma et al. 1995, 2003; Jager et al. 1996; Emberlin et al. 2002), as well as a higher allergenicity of pollen (Beggs and Bambrick 2005; Beggs 2004).

Compared to the relatively short history of pollen measurement in pollen traps, phenological observations of starting dates of flowering provide a higher station density and longer records, sometimes covering the entire last century. Thus, a spatial and temporal integration of both phenological and pollen records would constitute a convenient enlargement of the pollen data base, especially for climate impact and epidemiological studies.

Allergic disorders constitute an important public health problem of ethic and economic dimensions, as airway diseases, i.e. hay fever and asthma, reduce well-being and ability to work, finally leading to higher expenses in the health sector. Thus, methods to forecast pollen flight periods and their intensities are necessary to help the sufferers, affected people, and physicians to optimise medication and behaviour. Several systems of pollen forecasts have been installed in different European countries, e.g. in Germany by the German Meteorological Service (DWD) and the Polleninformationsdienst (PID). These institutions forecast the start of the pollen season as well as the day to day variation of its intensity for different pollen types (http://www.pollenstiftung.de/index.php?inhalt=pollenvorhersage, Huynen et al. 2003).

Chuine and Belmonte (2004) published a first pollen prediction model based only on daily mean temperatures. However the obligatory parameterisation was only available for regions in Spain and France. In contrast, most methods used to forecast pollen flight are based on semi-empiric methods, i.e. integration of flowering observations, weather forecast and information on pollen counts in pollen traps. The system installed by the German Meteorological Service, for example, incorporates daily observations of the start of the flowering period at around 400 stations in Germany. Thus, for the application and improvement of pollen forecasts, an integration of flowering and pollen records is also most beneficial.

Airborne pollen, with its aerodynamic diameter of c. 10 µm, contributes to the organic, solid components in the coarse particulate matter (PM10). Pollen is, due to its size, very mobile. Therefore, all efforts to forecast the pollen season via daily temperature data and / or phenological (flowering) observations may emerge as obsolete if most of the pollen found in traps does not originate from the studied surroundings. If the spatial dispersal of pollen on a larger scale is of importance, the models would need to account for this and incorporate variables such as large-scale weather patterns. There are first indications that long-range transport of pollen might be significant. Kasprzyk (2003) reported for a station in Poland that sometimes flowering of the local trees cannot be the source of the pollen found in the traps. Pollen of exotic taxa that originated at least 1000 km away was detected in Canada (Cambon et al. 1992) and in Greenland (Rousseau et al. 2003). Faced with these possibilities of long-range transport, there is a need to clarify to what spatial and temporal extent local pollen production (defined by phenology) is not the source for pollen found in the neighbouring traps.

The overall goal of this paper is to analyse the spatial and temporal coherence between locally observed flowering dates and pollen counts in pollen traps. Although the causal relationship (flowering = production of pollen) seems to be clear, there exists an enormous lack of knowledge in this field. As a study area we chose Germany because it provides an extremely dense network of phenological observers and sufficient number of pollen records by traps. The primary goal of the integration of flowering and pollen data further offers the possibilities (1) to enlarge and reconstruct spatially and temporally the pollen records for climate change impact and epidemiological studies, (2) to improve and optimise the model framework for pollen forecasting, especially as phenological observations are cheaper and might allow earlier warnings, and (3) to quantify the occurrences of local / long-range transport.

Materials and methods

Pollen data

The German pollen monitoring network, run by the Polleninformationsdienst (PID, www.pollenstiftung.de) comprises 51 stations with pollen traps (Burkard type) across Germany (see Fig. 1), predominantely at lower altitudes hower few also at 600- 800 m a.s.l.. The traps are positioned at 10 to 12 m above ground in order to measure regional pollen distribution, and to reduce the influence of plants in direct neighbourhood.

At each station, daily averages of pollen numbers per cubic meter ambient air are counted and, as a minimum, the pollen for 6 groups (*Corylus, Alnus, Betula, Artemisia, Poaceae*, and *Secale*) are identified. For our analyses we had pollen data for birch (*Betula*), grass (*Poaceae*) and mugwort (*Artemisia*) for the years 1992/1993 and 1997-1999 available. For each pollen type, the annual start day of pollen flight (start), and the day of the maximum pollen count (peak) was determined. The start of pollen season was defined as the date when 1% of the total number of pollen grains of the year has been reached, provided that one of the following six days shows another pollen count (Krämer et al. 2001). Table 1 summarises the number of pollen stations for each year and pollen type.

Phenological data

Phenological data were provided by the German Meteorological Service (DWD). In the DWD phenological network volunteers at around 1600 stations observe defined plant development stages. The following three phases were selected for our study: beginning of flowering of birch (*Betula pendula* L.), of meadow foxtail (*Alopecurus pratensis L.*) and of mugwort (*Artemisia vulgaris L.*). Flowering of orchardgrass (*Dactylis glomerata L.*) was not included in the analysis as its onset dates were much later than the start of the grass pollen flight period. The guidelines for phenological observers (Deutscher Wetterdienst 1991) specify that observations should be made at normal sites with average microclimatic conditions, and the observation sites should be within 50 m of a fixed elevation range. Beginning of flowering is defined as the day on which the first blossoms are fully open on at least three spots on the observed object. In addition, the observer has to check if wind pollinated plants emit pollen. For our investigation, we selected a subset comprising those stations within 25 km distance around the pollen traps (Fig.1). Due to the dense phenological network, records of more than 400 phenological stations were available for each species and year.

Methods of analysis

All observed dates within the pollen and the phenological data set were converted to Julian date. For each pollen station and species, we determined the first observed phenological flowering date (min) and the mean of all observed flowering dates (mean) at the surrounding phenological stations (≤ 25 km). These two phenological variables were subtracted from the respective dates of the start and peak of the pollen flight period in order to investigate the temporal differences between pollen and phenological measures. A negative deviation signified an earlier occurrence of pollen in the ambient air as detected by the pollen traps than flowering of the respective species observed in the local surrounding. Special emphasis was given to the spatial variability and regional pattern of these time spans. In addition, to analyse the geographic influence, a regression of the difference between pollen season (start / peak) and first flowering (min) and the geographic co-ordinates, latitude and longitude was calculated.

Results

The average annual dates of the start of the pollen season of birch, mugwort and grass compared to the observed start of flowering dates suggested a close connection between these records (see Fig. 2). However, a closer look revealed that, e.g. for birch the start of the pollen season at the pollen stations occurred earlier than the average local minima of the start of flowering. For mugwort and grass, this relationship is only true in few years. Whereas the peak of the birch pollen season coincides with the mean flowering dates, the pollen peaks of the other two species took place much later. Thus, for birch pollen, all comparisons of flowering dates (min, mean) with measures of the pollen season (start, peak) are presented, but for mugwort and grass the graphs are restricted to comparisons with min flowering dates.

In Table 2, the remarkable results for the birch pollen season are further examined for the different years. At 56 % (1998) to 79 % (1997) of the pollen stations, the start of the pollen season was observed earlier than the first flowering in the surroundings. The time span between these events was up to 57 days. However, in fewer cases, the start of pollen season was much later than the first flowering (up to 34 days). In very rare cases, even the peak of the pollen season was noted before the first flowering dates. On the other hand, it could take several weeks until the peak followed the first observed phenological flowering, e.g. in the year 1992 at Münnerstadt, the pollen peak was 63 days after the onset of flowering. In all other years, the pollen peak followed the phenological observation by about 1 month (e.g. 38 days in 1998).

The skewness of the difference between start of pollen flight and flowering is not consistent; the years 1992, 1998 and 1999 have a negative skewness, 1997 is flat and 1993 has a positive skewness. The difference between the peak of pollen season and flowering the skewness in all years is >0. In all years the deviation is higher for the difference of the start of pollen season and flowering than for the difference the peak of pollen season and flowering. 1992 has the highest value (16.69 days for start, 15.64 days for peak), and the smallest standard deviation is in 1993 (7.87 days for start, 7.07 days for peak).

The spatial analyses of the time spans between the pollen count (start, peak) and the respective flowering dates (min, for birch also mean) around the pollen stations are presented in Figs. 3, 4,5 and 6.

For birch (Fig. 3), the time span between first pollen observations and the phenological onset of flowering varied strongly. Sites where the start or the peak of the pollen season was observed before the local flowering dates have negative values as equivalent for differences in days. Only at sites with positive values was the phenological observation noted before the pollen was caught in the trap, thus phenological monitoring would support regional pollen forecast. It is obvious that, when comparing start of the pollen season and first flowering, more stations exhibited negative values (=not explained by local flowering) than when comparing pollen peak and first flowering.

There was no regional pattern apparent. For a statistical justification a regression of the differences between start / peak of pollen season and flowering against latitudeand longitude of the pollen station as well as mean altitude of the respective surrounding pheno stations (≤25 km) was calculated. For both cases the results showed that there is no geographic dependence (start: P>F 0.2 and R^2=0.067; peak: P>F 0.001 and R^2=0.07).

Stations with strong negative values are located close to the northern coast in 1997 and 1999, e.g. in 1997 the start of the pollen season in Norderney was 57 days before birch flowering occurred on local plants. But in 1992 and 1993, the stations with the largest negative values were situated in the south and east, while in 1998 the greatest difference emerged in central and southern Germany.

The day of the peak pollen observation compared to the first flowering at neighbouring stations for birch displayed a more uniform pattern. For the years 1993, 1997 and 1999, the difference between observed local flowering and peak of pollen was negative only at a few stations. Larger deviations were found in 1992 at Dresden, where the pollen peak was noted 36 days before the first locally observed flowering of birch, and in 1998 at Westerland, where there was a difference of 13 days between the peak of pollen and the first locally observed flowering.

When comparing the measures of the birch pollen season (start, peak) to the mean (mean) of the flowering dates for each pollen station (Fig. 4), these differences shift, as anticipated, to higher negative values, especially for the start of the pollen season. Only at very few stations was the start of the pollen season measured after the phenological event was noted. In 1997 and 1999, even for the peak of the pollen season, more stations had negative values than positive ones. In the other years the distribution was almost even. Within the 5 years analysed, we identified occurrences with a reported peak of pollen season more than 30 days later than mean flowering: in 1992 in Münnerstadt, the peak of pollen season occurred 58 days after mean flowering, in 1998 a time gap of 33 days appeared in Berlin-West and one of 31 days in Homburg.

The spatial distribution of the time spans between the start and the peak of the pollen season for mugwort and the first observed flowering displayed a very heterogeneous pattern (Fig. 5). Some stations showed a great discrepancy between pollen counts and flowering, e.g. in 1992 the first pollen was measured 132 days before first flowering at Borkum, while in all other years early pollen observations were made around 50 days before flowering occurred. But at most stations pollen findings were later than the observed flowering. Here, the difference reached up to 45 days in 1999. The peak of mugwort pollen found in the traps was, with the exception of a very few stations, later than the observed flowering. These stations exhibiting earlier pollen than flowering were not consistent over the years, including seaside, alpine, and Rhine rift stations. The majority of the stations had dates of peak of the pollen flight around 10-50 days after onset of flowering.

For the grass pollen flight period (Fig. 6), the time span between start of the pollen season and flowering of *Alopecurus pratensis* at neighbouring stations varied. In 1992, the maximum time span occurred at Homburg where pollen was found 50 days before flowering started. In all following years (1993, 1997-1999) there were smaller differences between pollen and flowering dates. The largest positive deviation was found at Freiburg in 1998, where the grass pollen season started 28 days later than the observed flowering. For the clear majority of the stations, the start of the pollen season was a week before or after flowering was observed. In nearly all cases (stations and years), the peak of the pollen season was detected later than onset of flowering, with the exception of two stations at a time in 1993, 1998 and 1999, which were not identical.

Discussion

Our results clearly demonstrate that *Betula* exhibited the greatest temporal divergences between pollen caught in pollen traps and observed onset of flowering in Germany. These time spans were by far too large to assume pollen dispersal exclusively from local plants. The phenological observations used in this analysis stem from various stations located within 25 km around the traps, and thus their data should represent the regional vegetation’s behaviour. From publications by Rapiejko (1995) we know that first pollen grains at ground level might be up to 2 weeks earlier than at roof level. Thus it can be assumed that the temporal mismatch observed in our study would even be larger if the pollen traps were situated at ground level. Of course for some offsets between pollen findings and local flowering there may be simpler explanations such as mistakes within the pollen data, or the flowering data. For example, if the exact onset date of flowering is not identified correctly, pollen might have been emitted before the noted date. Another reason could be associated with the definition of the start and peak of the pollen season, due to the fact that both are dependent on total pollen load of the year (Krämer et al. 2001). In addition. the weather conditions at the site might influence the distribution of pollen, because no or reduced pollen flight will occur when it is rainy or calm, but this hardly explains the compelling differences between local flowering and pollen findings over all observed years, especially not pollen catches before local flowering.

Therefore, due to size of *Betula* pollen (c. 10 µm aerodynamic diameter), the most likely explanation for the long time span between observed local flowering and observed pollen is long-range transport. Different studies have confirmed that the regular maximum distance of anemophilous pollen transport is around 500 km (Van de Water et al. 2003; Rousseau et al. 2003). But some weather conditions can lead to far longer transport, e.g. in Greenland, different pollen types had been found travelling at least 1000 km (e.g. Cambon et al. 1992; Rousseau et al. 2003) and in the arctic, pollen was identified originating from approximately 3000 km away (Campbell et al. 1999). This fact might be the reason for our findings that the start of the pollen season was not well explained by local phenology. Even the peak of the pollen concentration was mainly found before local vegetation started flowering.

The peak concentration depended more on local plants' flowering; only at few stations did we observe that local plants' average flowering was before the start of the pollen season.

Grass pollen appeared not as mobile; fewer stations exhibited first pollen observations before flowering. The peak strongly depended on local flowering of grass. The differences between start of pollen and of flowering season of *Artemisia* was very irregular; some events could stem from long-distance transport. Especially in 1992, we identified several such events. Further research is planned to investigate where the pollen found in Borkum, an island in the North sea, originated from (e.g. by backwards trajectories). The prevailing wind direction there is west, so pollen could have originated from far away.

In general, observations of flowering in phenological networks might help to explain pollen catch in traps, but our analysis points out that phenological observations with the current methodology are not nearly sufficient. First, pollen transport over various distances might lead to pollen findings before or after local vegetation starts flowering (Kasprzyk 2003). Other possibilities to explain this temporal mismatch comprise a noteworthy contribution of other than the phenologically observed species to the pollen loads in the traps (e.g. other species of the genus *Betula*, such as *Betula pubescens*, and of the family Poaceae, such as *Dactylis glomerata*) and difficulties in identifying the first flowering specimens in a larger surrounding. Thus, information on flowering is of tremendous importance, not only for single specimens at average microclimatic sites, but also at population or ecosystem levels.

Pollen catches and phenological data displayed a wide range between their events (start, peak, min, mean), thus further research is needed before using flowering dates in phenology to extrapolate pollen counts. The fact that the pollen peak of *Betula* occurred before local flowering started raises further unanswered questions concerning the distribution of pollen in central Europe. Further research is required into long-distance transport as well as regional dispersal of pollen, because it is still unknown how strongly these events influence pollen concentrations. First attempts have been made with trajectories (e.g. Smith et al. 2005; Jarosz et al. 2004; Rousseau et al. 2004; Bourgeois et al. 2001; Cabezudo et al. 1997; Cambon et al.

1992). Smith et al. (2005) tried to locate the regional origin within the UK, whereas Jarosz et al. (2004) calculated forward trajectories from the source to find the area of deposition. The studies by Rousseau et al. (2003, 2004), Bourgeois et al. (2001) and Cambon et al. (1992) discussed the origins of pollen from almost vegetation-free regions in the far north. There might be a high potential to support and develop new pollen forecast practices by modelling air mass / pollen transport via trajectories, finally reducing the impact of pollen induced allergies on suffering individuals and optimising their medication.

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Tables

Table 1: Number of pollen observation stations with different pollen records in Germany

Year	*Betula*	*Poaceae*	*Artemisia*
1992	39	43	40
1993	44	45	38
1997	48	51	44
1998	46	49	35
1999	47	48	38

Table 2: Differences between start (Start) and peak (Peak) of the birch pollen season and the respective earliest starting dates of flowering (Min), n (neg) number of stations where flowering is observed later than the pollen measures, n (pos) number of stations where flowering is observed earlier than the pollen measures

Year	Start – Min						
	n (neg)	n (pos)	Min	Max	Mean	Median	SD
1992	29	10	-54	34	-4.95	-4.0	16.69
1993	25	19	-26	26	-1.57	-2.0	7.87
1997	38	10	-57	21	-9.5	-9.5	12.26
1998	26	20	-39	13	-5.91	-1.5	11.68
1999	36	11	-31	18	-6.21	-4.0	10.93
Year	Peak – Min						
	n (neg)	n (pos)	Min	Max	Mean	Median	SD
1992	3	36	-36	63	10.38	9.0	15.65

1993	4	40	-2	36	7.7	7.0	7.07
1997	4	44	-5	37	9.96	8.5	9.28
1998	3	43	-13	38	11.54	10.0	9.28
1999	5	42	-6	28	6.51	5.0	7.66

Figure legends

Figure 1

Distribution of pollen traps (large dots) and corresponding phenological stations (small dots) at ≤ 25 km distance in Germany

Figure 2

Annual mean onset dates of the start (Start) and peak (Peak) of the pollen season at the pollen stations in Germany and of the earliest and mean flowering dates of the respective phenological stations (see Fig. 1)

Figure 3

Difference in days between start (Start) of the birch pollen season (upper row) / peak (Peak) of the pollen season (lower row) and earliest flowering (Min) at pollen stations in Germany (1992-1993, 1997-1999). Circle / negative value: Start / Peak of pollen season before start of flowering, square / positive value: Start of flowering before Start / Peak of the pollen season

Figure 4

Difference in days between start (Start) of the birch pollen season (upper row) / peak (Peak) of the pollen season (lower row) and mean flowering dates (Mean) at pollen stations in Germany (1992-1993, 1997-1999). Circle / negative value: Start / Peak of pollen season before mean flowering, square / positive value: Mean flowering before Start / Peak of the pollen season

Figure 5

Difference in days between start (Start) of the mugwort pollen season (upper row) / peak (Peak) of the pollen season (lower row) and earliest flowering (Min) at pollen stations in Germany (1992-1993, 1997-1999). Circle / negative value: Start / Peak of pollen season before start of flowering, square / positive value: Start of flowering before Start / Peak of the pollen season

Figure 6

Difference in days between start (Start) of the grass pollen season (upper row) / peak (Peak) of the pollen season (lower row) and earliest flowering (Min) at pollen stations in Germany (1992-1993, 1997-1999). Circle / negative value: Start / Peak of pollen season before start of flowering, square / positive value: Start of flowering before Start / Peak of the pollen season

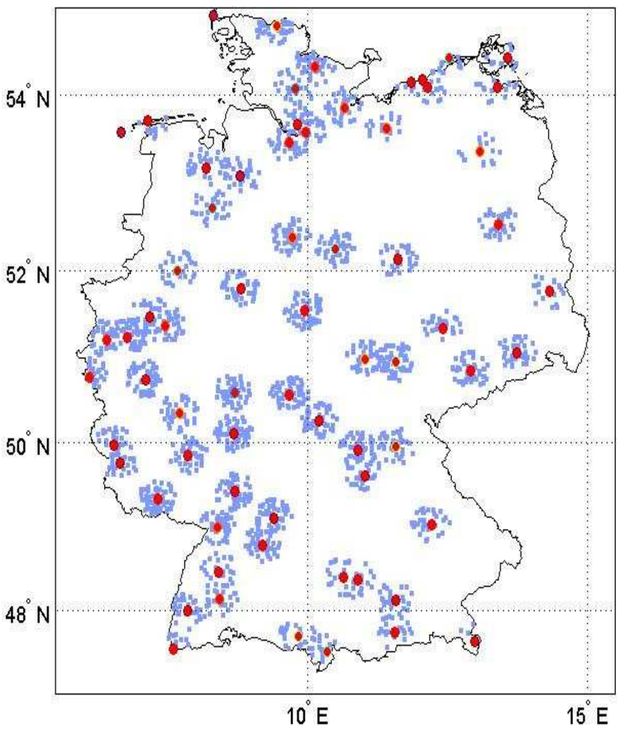


Figure 1

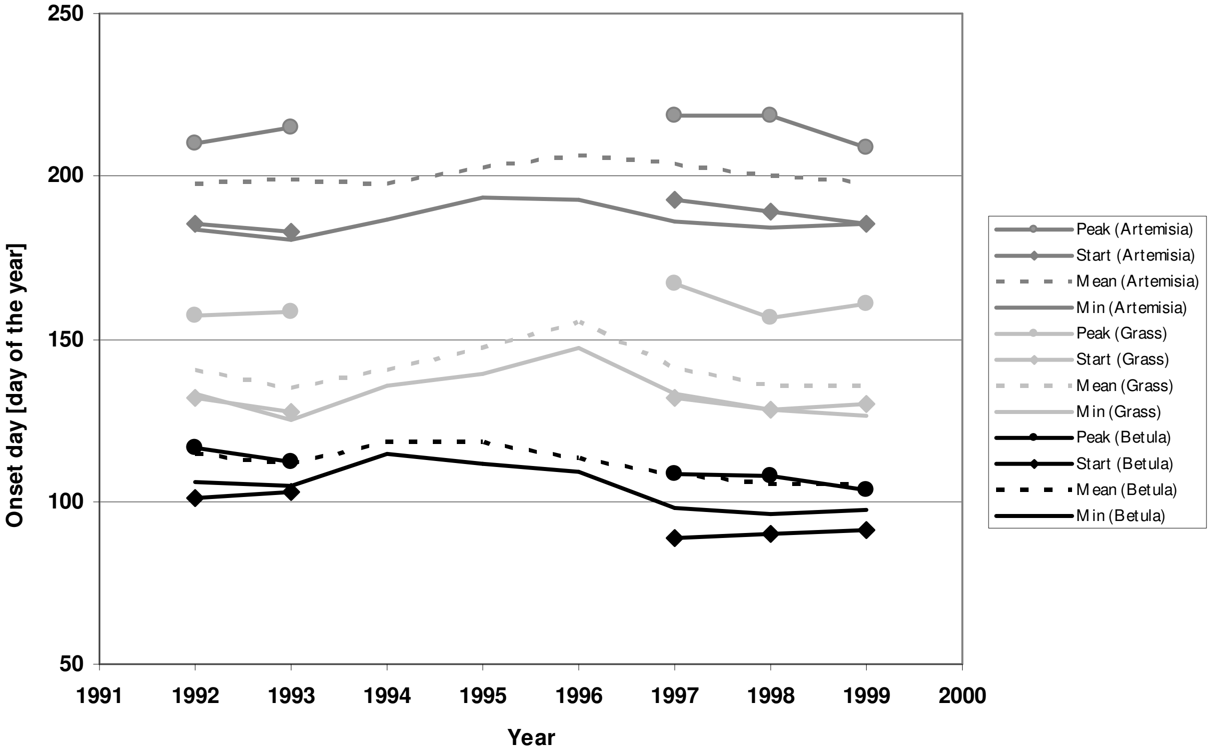
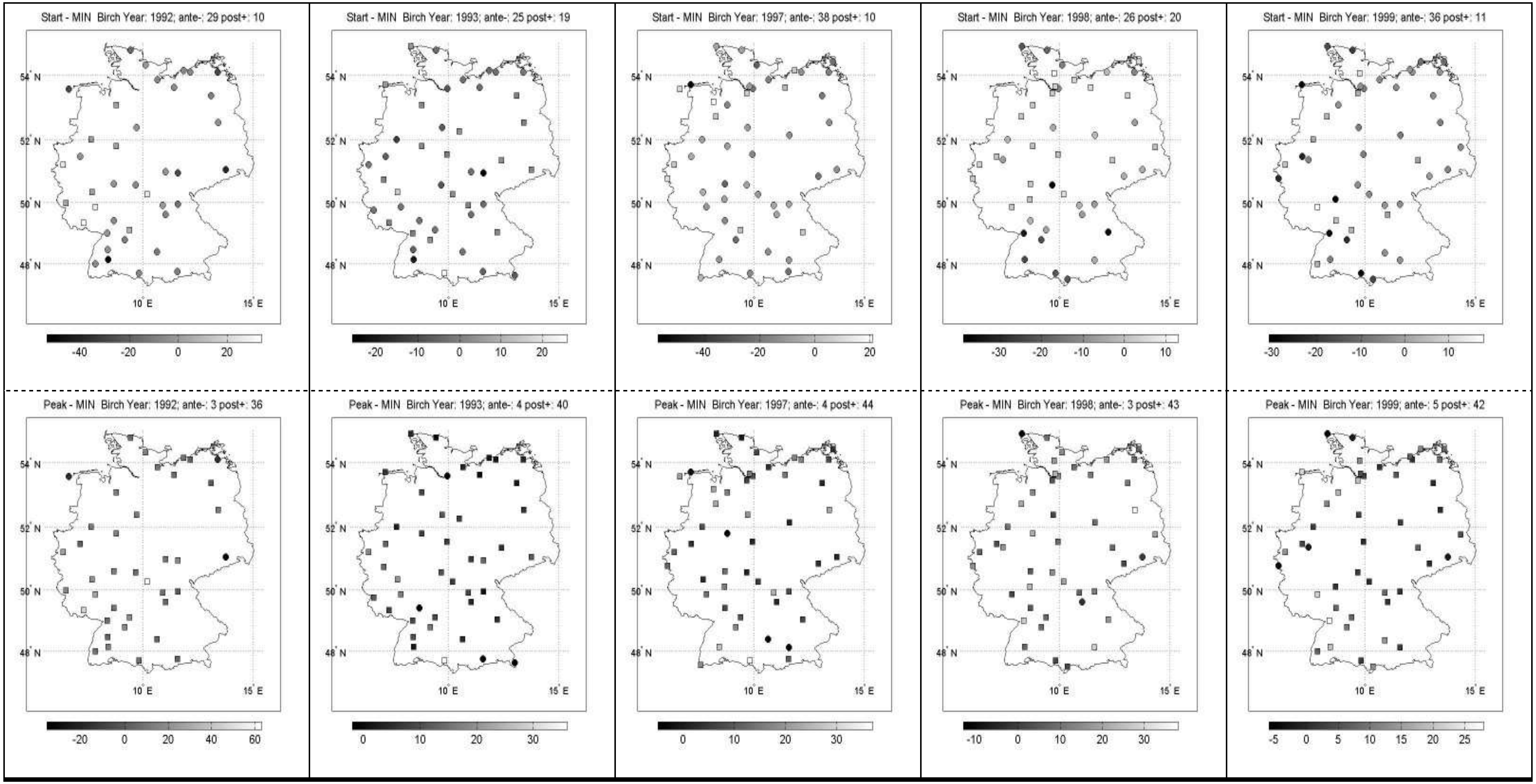

250
200
150
100
50
Onset day [day of the year]
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Year
Peak (Artemisia)
Start (Artemisia)
Mean (Artemisia)
Min (Artemisia)
Peak (Grass)
Start (Grass)
Mean (Grass)
Min (Grass)
Peak (Betula)
Start (Betula)
Mean (Betula)
Min (Betula)

Figure 2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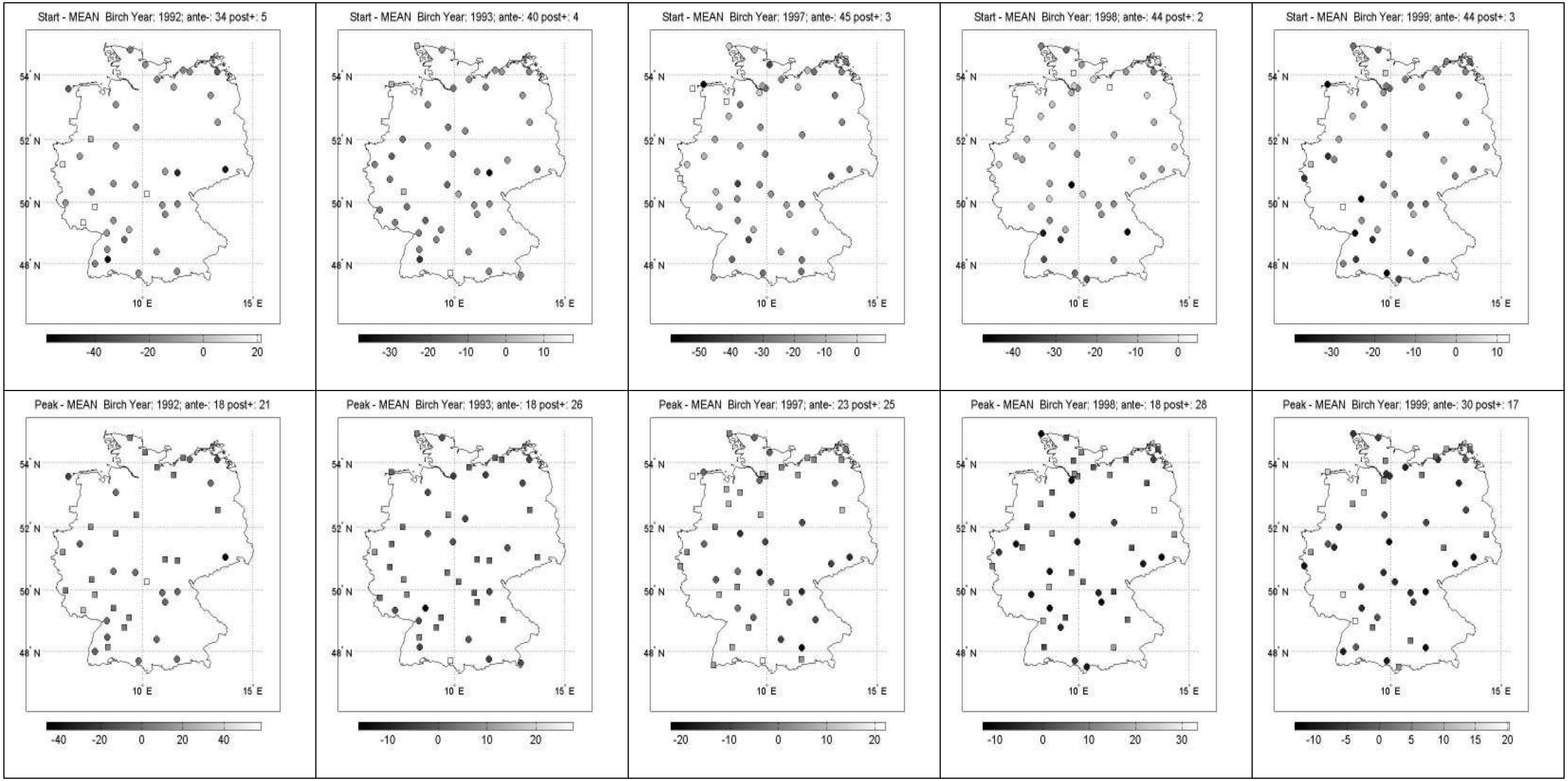
Start - MIN Birch Year: 1993; ante-: 25 post+: 19
Start - MIN Birch Year: 1997; ante-: 38 post+: 10
Start - MIN Birch Year: 1998; ante-: 26 post+: 20
Start - MIN Birch Year: 1999; ante-: 36 post+: 11
54° N
52° N
50° N
48° N
10° E
15° E
-40 -20 0 20
-20 -10 0 10 20
-40 -20 0 20
-30 -20 -10 0 10
-30 -20 -10 0 10
Peak - MIN Birch Year: 1992; ante-: 3 post+: 36
Peak - MIN Birch Year: 1993; ante-: 4 post+: 40
Peak - MIN Birch Year: 1997; ante-: 4 post+: 44
Peak - MIN Birch Year: 1998; ante-: 3 post+: 43
Peak - MIN Birch Year: 1999; ante-: 5 post+: 42
-20 0 20 40 60
0 10 20 30
0 10 20 30
-10 0 10 20 30
-5 0 5 10 15 20 25

Figure 3


Start - MEAN Birch Year: 1992; ante-: 34 post+: 5
Start - MEAN Birch Year: 1993; ante-: 40 post+: 4
Start - MEAN Birch Year: 1997; ante-: 45 post+: 3
Start - MEAN Birch Year: 1998; ante-: 44 post+: 2
Start - MEAN Birch Year: 1999; ante-: 44 post+: 3
54° N
52° N
50° N
48° N
10° E
15° E
-40 -20 0 20
-30 -20 -10 0 10
-50 -40 -30 -20 -10 0
-40 -30 -20 -10 0
-30 -20 -10 0 10
Peak - MEAN Birch Year: 1992; ante-: 18 post+: 21
Peak - MEAN Birch Year: 1993; ante-: 18 post+: 26
Peak - MEAN Birch Year: 1997; ante-: 23 post+: 25
Peak - MEAN Birch Year: 1998; ante-: 18 post+: 28
Peak - MEAN Birch Year: 1999; ante-: 30 post+: 17
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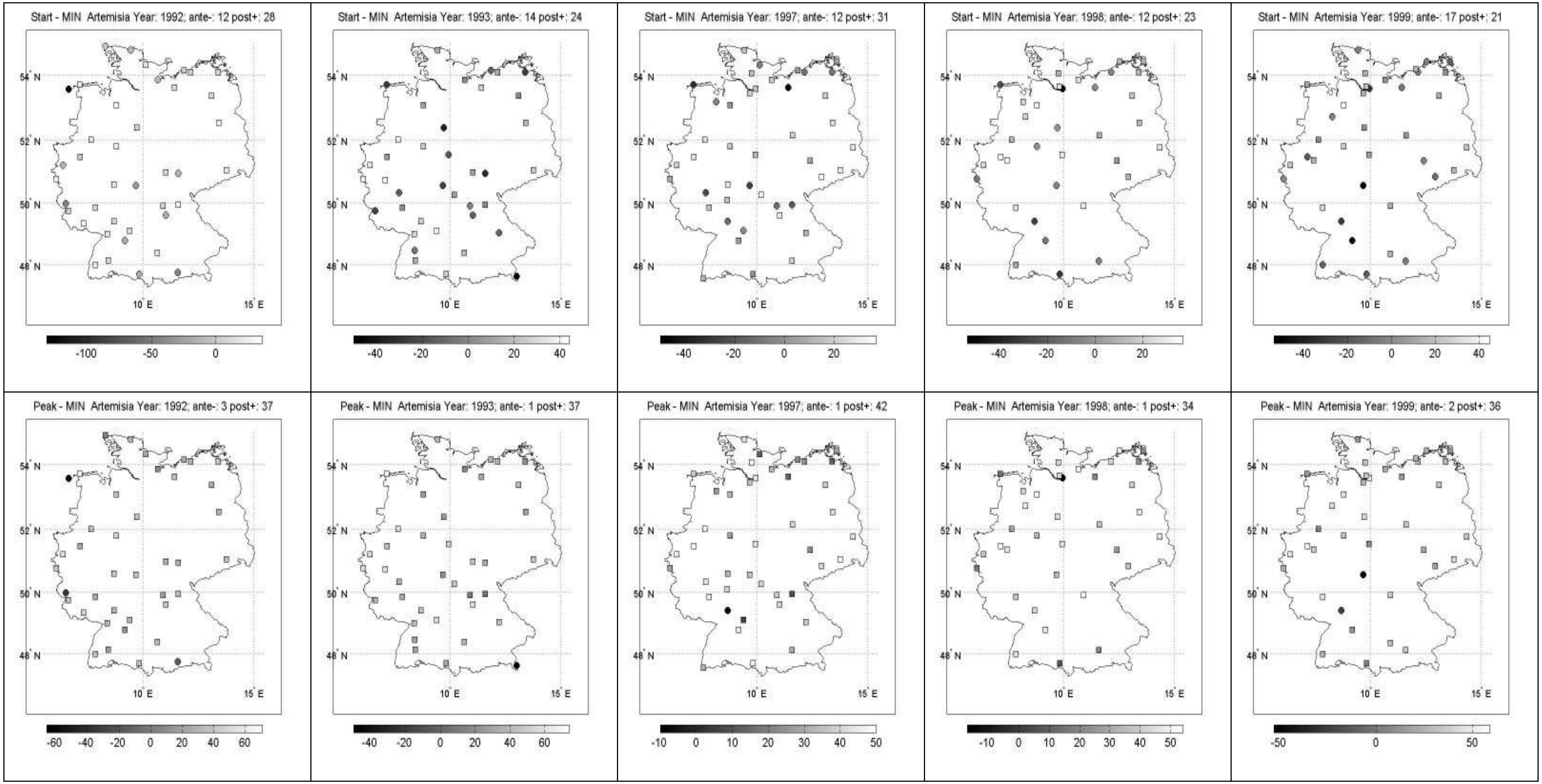
-10 0 10 20
-20 -10 0 10 20
-10 0 10 20 30
-10 -5 0 5 10 15 20

Figure 4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Start - MIN Artemisia Year: 1993; ante-: 14 post+: 24
Start - MIN Artemisia Year: 1997; ante-: 12 post+: 31
Start - MIN Artemisia Year: 1998; ante-: 12 post+: 23
Start - MIN Artemisia Year: 1999; ante-: 17 post+: 21
Peak - MIN Artemisia Year: 1992; ante-: 3 post+: 37
Peak - MIN Artemisia Year: 1993; ante-: 1 post+: 37
Peak - MIN Artemisia Year: 1997; ante-: 1 post+: 42
Peak - MIN Artemisia Year: 1998; ante-: 1 post+: 34
Peak - MIN Artemisia Year: 1999; ante-: 2 post+: 36
54° N
52° N
50° N
48° N
10° E
15° E
-100 -50 0
-40 -20 0 20 40
-40 -20 0 20
-40 -20 0 20
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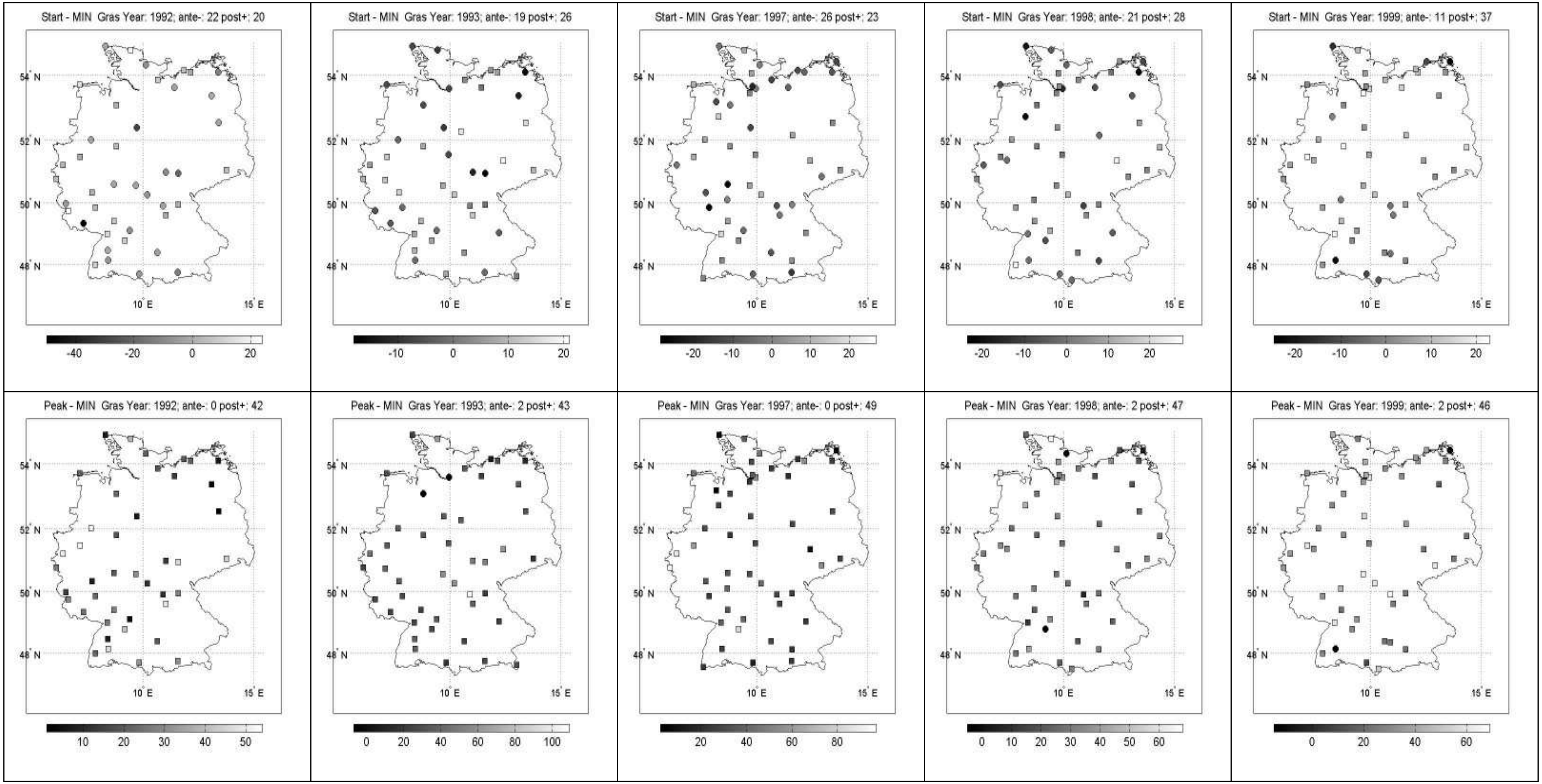
-50 0 50

Figure 5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-10 0 10 20
Start - MIN Gras Year: 1997; ante-: 26 post+: 23
-20 -10 0 10 20
Start - MIN Gras Year: 1998; ante-: 21 post+: 28
-20 -10 0 10 20
Start - MIN Gras Year: 1999; ante-: 11 post+: 37
-20 -10 0 10 20
Peak - MIN Gras Year: 1992; ante-: 0 post+: 42
10 20 30 40 50
Peak - MIN Gras Year: 1993; ante-: 2 post+: 43
0 20 40 60 80 100
Peak - MIN Gras Year: 1997; ante-: 0 post+: 49
20 40 60 80
Peak - MIN Gras Year: 1998; ante-: 2 post+: 47
0 10 20 30 40 50 60
Peak - MIN Gras Year: 1999; ante-: 2 post+: 46
0 20 40 60
54° N
52° N
50° N
48° N
10° E
15° E

Figure 6

Artikel Clim Res 2006

Estrella N & Menzel A (2006) Responses of leaf colouring in four deciduous tree species to climate and weather in Germany. *Climate Research* 32, 253-267.

Climate Research

Responses of leaf colouring of four deciduous tree species to climate and weather in Germany

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RPH: Estrella & Menzel: Responses of leaf colouring to climate and weather

ABSTRACT: The annual timing of leaf colouring of deciduous trees in temperate regions is not predictable using phenological models. In this analysis we show that commonly applied hypotheses of leaf colouring triggers have neither satisfactory explanatory power nor significant statistical proof. We tested meteorological parameters, such as monthly mean temperatures, threshold temperatures, monthly sums of precipitation and number of dry days per month of the year of the phenological event and of the previous year and the length of the vegetation period. Their influence on leaf colouring dates for 4 deciduous tree species (horse chestnut, beech, birch, oak) in Germany (1951–2003) was tested by Pearson's correlations. We created 3 different datasets: (A) phenological observations for single stations within 25 km of meteorological stations, (B) means of phenological observations around (<25 km) meteorological stations, and (C) phenological means for Germany. Only the mean temperature of September had a slight influence on the onset of leaf colouring (mean: rchestnut = 0.45; rbeech = 0.56; roak = 0.51; rbirch = 0.45). Taking all correlation coefficients r > |0.3| into account, we can deduce that a warm September (all species) and August (oak, birch) delayed leaf colouring while a warm June (horse chestnut, oak) and May (horse chestnut) advanced leaf colouring.

KEY WORDS: Response · Leaf colouring · Autumn phenology · Growing season · Vegetation period · Germany · Climate change

1. INTRODUCTION

There is an abundance of evidence that the global climate has changed in recent decades and that this change has had an influence on natural resources (IPCC 2001). Among the biological systems affected, phenologyis one of the prominent bio-indicators of climate change, since the timing of recurring phenological events is altered by changed weather conditions. Significant correlations exist between winter/spring temperatures and spring phenological phases, such as bud burst, leaf unfolding or flowering in mid and higher latitudes (Menzel & Estrella 2001, Sparks & Menzel 2002, Walther et al. 2002, Menzel 2003, Root et al. 2003). Due to this statistical and causal relationship, it is possible to model the onset of these spring events, e.g. leaf unfolding (e.g. Hänninen 1990, Kramer 1995, Menzel 1997, Schaber 2002) or flowering (e.g. Chuine et al. 1999, 2003), based exclusively on temperature information as input.

In contrast, the causes of the timing of phenological events of deciduous plants in autumn, such as leaf colouring or leaf fall, are less understood. Theoretical knowledge exists about the triggering factors for leaf colouring and leaf fall of deciduous tree species. Trees shed their leaves in fall in order to reduce the evaporative surface area in winter and to avoid frost damage to leaves. The responsible chemical reactions are largely known: abscisic acid (ABA) and ethylene (as phytohormones) promote leaf fall by building the abscission zone at the base of the petiole. During the formation of the abscission zone, substances within the leaf which are useful for the plant are broken down and transferred to the woody parts of the tree (e.g. Koike 1990, Sitte et al. 2002).

There is some evidence that autumn phenological events may have been delayed in recent decades (e.g. Menzel & Fabian 1999, Chmielewski & Rötzer 2001), but these changes are less clearcut than their equivalents in spring and their pattern is far less homogenous (Menzel 2002, Sparks & Menzel 2002). So far, no model framework exists to predict them. Some older studies even demonstrated that autumn phenological events were difficult to interpolate and map, as no consistent relationship with altitude, latitude and longitude existed (Schnelle 1979).

A few studies also report an observed lengthening of the growing season, defined as the time span between leaf unfolding and leaf colouring (e.g. Defila & Clot 2001, Matsumoto et al. 2003). However, in order to interpret changes in the timing of autumn events or changes in the length of the growing season as effects of climate change and attribute them to explicit factors, it is necessary to develop a framework of how their timing is triggered, modified or altered by weather and climate conditions.

There are numerous hypotheses about weather or climate conditions modifying the onset of leaf colouring in temperate regions. In Table 1, common hypotheses are summarised. Some are vague and imprecise: Baumgartner (1950) stated that leaf colouring was induced by minimum temperatures, but he did not state the threshold temperature. Seyfert (1955, 1966) claimed that the timing of leaf colouring started later when there were warm temperatures and sufficient water supply in autumn. High radiation in autumn has been quoted as one of the causes of early leaf colouring; it might stimulate the production of assimilates, which cannot drain off and support the decomposition of chlorophyll (Seyfert 1970). Schulze (1970) argued in the same direction with high autumn temperatures quickening leaf colouring. Freitag (1987) tested mean June air temperatures and concluded that a warm June advanced, whereas a warm August and September temperatures delayed, the onset of leaf colouring, which is in contrast to Seyfert (1970) and Schulze (1970). Pfau (1964) postulated a constant length of the growing season which is defined as the period between the start of leaf unfolding until the onset of leaf colouring. Schnelle (1952) listed different threshold temperatures: as soon as the mean temperature in autumn dropped below 11°C leaf colouring was induced, after a drop below 10°C leaf colouring could be observed. The same stimulating effect would have minimum temperatures below 7 or 6°C, where leaf colouring is again observable when the minimum temperature declines another degree. Hartmann & Schnelle (1970) defined the vegetation period as the period when the mean temperature exceeded 8°C in a climate diagram. These and other more agriculturally based definitions (e.g. mean air temperature permanently above 5°C) are only rough approximations, which do not consider the annual weather conditions. Therefore, we modified these hypotheses: the end of the vegetation period is induced when the daily mean temperature falls below the threshold temperature for a sequence of 5 d. Further hypotheses about the influence of water availability were included in our analysis. Maede (1952) suggested that the soil water balance was influencing the onset of leaf colouring. By analysing different extended-range (general) weather situations (Grosswetterlagen), Seyfert (1955) stated that particularly synoptic types which led to declining soil water potential were responsible for an earlier onset of leaf colouring.

Most of the hypotheses described above (Table 1) have their origin in theoretical considerations or analyses of short time series of a few observed trees. In addition, most of them have never been verified on a statistically relevant dataset. Thus, the primary goal of this study was to test both the listed and some new hypotheses using a comprehensive meteorological and phenological dataset provided by the German Meteorological Service (DWD) before developing a model framework for autumn phenological events. The main aim was to identify meteorological parameters which trigger the onset of leaf colouring of deciduous trees and which might later be used in a statistical model. This is a major question, since the currently changing length of the growing season in temperate and boreal regions is mainly attributed to global warming and is used as a high-quality indicator to track changes in the biosphere (EEA Report 2004). However, the length of the growing season depends not only on its wellunderstood start in spring, but also on its less understood end in autumn.

2. MATERIALS AND METHODS

2.1. Climate data

Meteorological data were provided by the German Meteorological Service (DWD). The data covered the time period from 1951 to 2003 and contained daily mean (Tm), maximum (Tmax) and minimum air temperature (Tmin) as well as daily precipitation at 54 stations (Fig. 1). Monthly mean temperatures, monthly sums of precipitation and the number of dry days per month were calculated for each climate station and year. In addition, national means for Germany of all variables were generated using data from all stations. As derived climatological variables, we determined for each meteorological station the first date (entry day) after 1 August with values below certain threshold temperatures: daily mean temperature of 11°C (FDmean < 11), 9°C (FDmean < 9), 8°C (FDmean < 8), 7°C (FDmean < 7) and 5°C (FDmean < 5) and minimum temperature below 7°C (FDmin < 7) and 5°C (FDmin < 5). As such dates are strongly correlated, there was no need to test all other workable threshold temperatures.

2.2. Phenological data

Out of the considerable dataset of phenological time series covering the time span from 1951 to 2003 in Germany, we selected the onset of leaf colouring in 4 deciduous tree species: horse chestnut Aesculus hippocastanum L., silver birch Betula pendula L., common oak Quercus robur L. and European beech Fagus sylvatica L. These phases are recorded throughout Germany by volunteers (ca. 1550 stations in 2004, maximum number of ca. 2500). Autumn colouring has to be recorded when 50% of all leaves (still on the tree or already fallen to the ground) show autumnal colouring (DWD 1991). The data were collected and qualitychecked by the German Meteorological Service. Three subsets were generated from the total phenological dataset. First, Set A contained phenological observations from single stations which were (1) situated within 25 km, (2) within 50 m altitude of the meteorological stations (see 2.1, Fig. 1), and (3) whose phenological time series had to contain at least 15 yr of observations. For a second dataset (Set B) a phenological mean for each meteorological station was calculated from the surrounding phenological stations satisfying the first 2 criteria used in Set A (here even shorter time series of phenological observations were accepted). The third dataset (Set C) consisted of annual average phenological data of the 4 deciduous tree species for Germany. The number of phenological and climate stations used in each dataset is listed in Table 2. For a further detailed analysis of the plant responses to temperature, we selected long-term time series (>30 yr) of Set A and divided them into 2 groups: stations with a positive significant (5% level) trend in the observation period (A+, equivalent to an observed delay in leaf colouring) and stations with a significant negative trend (A–). Fig. 2a shows the geographical variability of the mean onset of leaf colouring between 1951 to 2003 for Set B, Fig. 2b demonstrates an example of the interanual variations of birch for Set A and the year 1995.

2.3. Methods

For all 3 subsets, Pearson correlation coefficients (r) were calculated between the observed onset dates of leaf colouring and each meteorological parameter as well as derived variables (e.g. crossing of temperature thresholds) to test the hypotheses of Table 1 marked with an asterisk. For monthly mean temperatures we calculated correlations with leaf colouring both for the ‘current’ year, i.e. the year of observation, (e.g. mo_1 = January) and for the previous year (e.g. p_8 = August). Correlation coefficients were only calculated when $n > 16$.

3. RESULTS

3.1. Effects of monthly mean temperature

Correlation coefficients (r) between the onset of leaf colouring and monthly mean temperatures for all 3 datasets are shown in Fig. 3.

When analysing all phenological stations assigned to climate stations (Fig. 3a, Set A), the respective correlation coefficients of leaf colouring dates with mean monthly temperatures did not reveal consistent signs for single months. In contrast, they spread from large negative to large positive values for almost every month. Some single stations reached values up to –0.75 (birch mo_3) or 0.82 (birch mo_9); however, these were outliers.

Only the mean temperatures of September of the current year were predominantly positively correlated with leaf colouring dates. Thus, a warm September was associated with later leaf colouring. If only the 5th to 95th percentile range is considered, r varied between 0.48 and –0.17 (birch), 0.51 and–0.13 (horse chestnut), 0.56 and –0.08 (oak) and 0.58 and –0.10 (beech). August temperatures had a similar, but weaker influence; both warm August and September tended to delay leaf colouring.

For all species, predominantly negative correlations with mean temperatures for May of the current year existed, but there was a high variability among stations, even regarding the sign of the correlation. A similar effect of mean June temperatures with warm temperatures advancing leaf colouring dates was strongest for horse chestnut. Therefore, a temperature relationship with leaf colouring dates was apparent for the months of May, June, August and September. For all other months of the current and previous year, the correlation coefficients revealed a stochastic pattern of the influence of monthly mean temperatures.

In the next step, we reduced the spatial phenological variability by calculating annual means of the onset dates of leaf colouring for all phenological stations near a meteorological station (Set B, Fig. 3b). In the respective scatterplots, it is quite obvious that the range and the absolute values of r were lower than for Set A. Extreme values for r were reached in oak ($r = 0.74$, mo_8 and $r = –0.67$, mo_10). As for Set A, August and September monthly mean temperatures showed a positive influence on the onset of leaf colouring for all species; the September effect was stronger. For horse chestnut and beech, all stations had positive correlation coefficients for August and September. Mean temperatures of May and June were mainly negatively correlated with leaf colouring dates; for horse chestnut this was true for all meteorological stations. The influence of the mean temperatures in May was stronger for horse chestnut, beech and birch, whereas oak reacted more to mean June temperatures.

In Set C, we used monthly mean temperature anomalies for Germany to calculate correlations between annual monthly temperatures and a national mean of leaf colouring for each species. Mean anomalies in May were negatively correlated with the onset of leaf colouring in horse chestnut ($r = –0.60$), this was the highest value of r for all species and months. Horse chestnut was further correlated with mean June ($r = –0.54$) and September ($r = 0.45$) temperature anomalies. For the 3 other species, mean September anomalies had the strongest influence on leaf colouring, ranging from 0.45 (birch) to 0.56 (beech). Birch ($r = 0.45$) and oak ($r = 0.39$) leaf colouring dates also exhibited a positive relationship to March temperature anomalies of the previous year, which is difficult to interpret.

In general, the results of all 3 analyses concerning the influence of monthly temperature were comparable. Single station analysis (Set A) showed a vast range of r and no consistency concerning the sign. Spatial averaging of the phenological response (Set B) led to a more regular pattern of the influence of the mean monthly temperature than for the single phenological stations, although the maximum values of r were lower. However, there were still outliers in both directions, and, at most stations, the correlation coefficients between the onset of leaf colouring and the monthly mean temperature were often inconclusive ($r < |0.2|$). In the analysis of national phenological and climatological means, the influence of single months was reduced for all species. Taking all correlation coefficients r > |0.3| into account, we can deduce that a warm September (all species) and August (oak, birch, beech) delayed leaf colouring, whereas a warm June (horse chestnut, beech, oak), May (horse chestnut, beech) and March of the previous year (horse chestnut, birch, oak) advanced leaf colouring.

3.3. Effects of drought

The impact of threshold temperatures on leaf colouring dates was tested for the 3 phenological Sets A–C. Fig. 4 displays the respective correlation coefficients between leaf colouring dates and the first day (FD) on which the air (mean or minimum) temperature falls below a defined threshold. These FDs can only have a triggering effect on leaf colouring if they occur earlier than autumnal colouring. This is true for all thresholds tested except FDmean <5°C, which occurs, on average, later than the mean onset of leaf colouring, but this threshold was retained as it is very commonly used to define the end of the vegetation period.

For Set A, it was quite apparent that even the signs of the correlation coefficients for single months were not identical at the various stations analysed. This was true for all species and months. The correlation coefficients ranged between 0.79 (FDmean <11°C, beech) and –0.77 (FDmean <8°C, beech). The 5th percentile values of r varied between –0.36 (FDmean <5°C, horse chestnut) and –0.18 (FDmin <5°C, oak), the 95th percentile values between 0.51 (FDmean <9°C, beech) and 0.35 (FDmean <7°C, horse chestnut). The results for the different thresholds were similar for all phases: there was hardly any relationship between the dates of crossing threshold temperatures and leaf colouring dates, only for beech and oak FDmean <9°C is the interquartile range box clear of zero.

This pattern was similar in Set B: for all phases and thresholds the range of r comprised positive as well as negative values. Oak and beech reached higher r values than horse chestnut and birch (e.g. beech maximum r = 0.63, FDmean <8°C). FDs and leaf colouring dates were predominantly positively correlated with leaf colouring dates, especially for FDmean <7 to 9°C (beech, oak) and FDmean <9°C (horse chestnut, birch). This means that longer warm periods in summer and autumn delayed leaf colouring.

Set C revealed that most of the leaf colouring dates of oak and beech reacted to threshold temperatures. Oak reached the highest value with r = 0.51, followed by beech with r = 0.46 for FDmin <5°C. Birch reacted strongest on FDmin <5°C, but with r = 0.40 it was less significant than beech and oak. Leaf colouring of horse chestnut was least correlated to threshold temperatures (maximum r = 0.39 for FDmean <9°C).

3.3. Effects of drought

Soil water balance is thought to have an influence on the timing of leaf colouring (see Table 1). But the amount of water available to plants is also dependent on factors other than precipitation, such as soil type, slope and exposure. However, these important auxiliary data were not available for our phenological dataset, and they could not be deduced from other datasets, mainly because the exact location of the observed trees was unknown. Therefore we decided to use precipitation data in order to avoid unjustified assumptions about soil type or depth.

We tested monthly total precipitation and the number of dry days per month of both the current and the previous year. The coarse temporal resolution of monthly sums may lead to biased results. For example, storm rainfall events that can elevate monthly sums are predominantly direct runoff. As we wanted to treat precipitation and temperature effects separately, we did not create a humidity index to combine temperature and precipitation.

Neither of the hydrological parameters tested revealed meaningful correlations with onset dates of leaf colouring. For both Sets A and B, there was a wide range of positive and negative values of r. For example, for the monthly sums of precipitation (Set A, Fig. 5a) the range of r for horse chestnut was always >1 (all mo), the smallest range of r (0.88) was for oak leaf colouring and monthly sums of precipitation in April of the current year.

For all 4 species and all months, the correlation coefficients displayed not only a large variability, but their means were also always <|0.1|. This indicates that the influence of monthly precipitation sums was negligible. For single phenological stations, there were very few significant correlation coefficients >–0.7: e.g. for horse chestnut (January and May of the previous year, January, June, September and October of the current year), for beech (October of the previous year and July of the current year) and for oak (September of the previous year). The drier these months were, often in autumn of the previous year, the earlier leaf colouring took place at these particular stations. High correlation coefficients for birch leaf colouring and October and November precipitation sums of the current year (0.72) at single stations demonstrate the problem of correlations tested on hundreds of time series; just by chance some are large even if the corresponding months clearly occur after leaf colouring.

Set B (Fig. 5b) displayed smaller ranges in r (mean range for all species and months 0.66). Only in 7 mo did we find a station with a correlation coefficient >|0.5|, the highest value (–0.63) was for birch leaf colouring and March precipitation of the previous year.

Using Set C (Fig. 5c), only very small correlation coefficients were revealed: e.g. for horse chestnut (r < |0.2|), for beech the largest r were 0.29 (October of previous year) and –0.26 (August of the current year), similarly for oak 0.25 (June of previous year) and –0.29 (August of the current year) and for birch –0.30 (August of the current year). Thus, the only consistent trait in these scatterplots was a small indication that drier Augusts were related to later leaf colouring. This can be ascribed to the fact that a dry August is a proxy for a warm August (see Section 3.1).

The second indicator, number of dry days, exhibited slightly higher correlation coefficients than the monthly sums of precipitation (Fig. 6). Number of dry days were mainly negatively correlated to leaf colouring dates, which means that longer dry periods led to earlier leaf colouring. The most decisive months, identified in Set A (Fig. 6a), were June and July (horse chestnut) and April and May (beech) and, for Set B (Fig. 6b), June (all 4 species). This relatively strong influence of dry days in June on leaf colouring dates was also revealed in Set C: horse chestnut (r = –0.33), beech (–0.24), oak (–0.23) and birch (–0.16). The drier the August the later leaf colouring took place for all species except horse chestnut (number of dry days: $r_{beech} = 0.23$, $r_{oak} = 0.26$, $r_{birch} = 0.20$).

3.4. Length and End of vegetation period

Various definitions of the end of the vegetation period exist, both meteorological as well as phenological. Common meteorological definitions are based on threshold temperatures, e.g. ongoing or temporary drop of mean air temperature below 5 or 10°C in the second half of the year. Biosphere models, which need the end of the vegetation period for deciduous trees in temperate regions as one parameter, generally apply a threshold temperature (e.g. IBIS 5°C threshold temperature; Foley et al. 1996), others use a combination of temperature and day length (e.g. BIOME BGC; White et al. 1997). The common simple definition of the length of the growing season by a specific time span, e.g. from 1 March until the end of October (Kärpäti & Varga 1964) or, as used in forestry in Germany, from 1 May until the end of September (Hartmann & Schnelle 1970) is not suitable for modelling purposes, as it does not allow for spatial or annual variability of leaf colouring dates. Hartmann & Schnelle (1970) suggested a threshold temperature of 8°C for trees; however, they used the smoothed temperature curves in climate diagrams to define the start and the end of the vegetation period, which does not allow for interannual variations.

In order to reduce the influence of single extreme events, and to take yearly variations into account, we used a method where the vegetation period started when daily mean temperatures exceed 5°C for 7 consecutive days and ends as soon as the daily mean temperature fell below 5°C for 5 consecutive days (Arora & Boer 2005). We examined whether these indices matched with observed leaf colouring dates. The results of the threshold approach (first drop below thresholds of 5 and 8°C) are summarised in Fig. 4 (FDmean5 and FDmean8). We enlarged the definition to a drop below these threshold temperatures for 5 consecutive days, which corresponds to the 5°C agricultural (FAO 1978–1981) and 8°C forestry definitions (Hartmann & Schnelle 1970). The results were quite similar, and the results for a threshold of 8°C are displayed in Fig. 7. Leaf colouring dates were not strongly related to these vegetation end dates. In the single station analyses (Fig. 6a), the lowest correlations coefficients were r = –0.71 for birch, –0.66 for beech, –0.59 for oak and –0.54 for horse chestnut; the highest were 0.63 (birch), 0.62 (horse chestnut), 0.62 (beech) and 0.57 (oak). In the climate station analyses (Fig. 7b), the extreme values of r were lower ($r < |0.4|$). The values of r for the German mean of leaf colouring and end of vegetation period were $<|0.1|$ for all species; therefore we conclude that there is hardly any correlation between the parameters tested and leaf colouring.

3.5 Differentiation by the sign of leaf colouring trend

Our last approach was to divide Set A into phenological stations where leaf colouring time series exhibited a significant positive trend, which corresponds to delayed leaf colouring, and those stations with a significant negative trend. Here we examined whether explicit trends were related to higher explanatory values of the triggering variables tested. Only phenological stations with at least 30 yr of leaf colouring observations and a significant (positive or negative) trend were correlated with the same meteorological parameters as before. We included 31 stations with a positive trend (A+) and 28 stations with a negative trend (A–) for horse chestnut, 36 stations A+ and 18 stations A– for beech, 48 stations A+ and 8 stations A– for oak, and 37 stations A+ and 12 stations A– for birch.

In Fig. 8, the correlation coefficients between leaf colouring dates and all the meteorological factors, except drought, are plotted. Neither stations with positive leaf colouring trends nor stations with negative trends showed a specific pattern. In order to verify this finding, we systematically checked, for all parameters, whether the mean correlation coefficients of the 2 groups differed from each other using 2 sample *t*-tests. Out of 22 monthly temperatures tested for 4 species, 32 comparisons of mean correlation coefficients did not show any difference between the 2 groups. However, in 56 cases, the mean correlation coefficients for stations with positive and negative trends displayed significant differences. These results are most difficult to interpret as there is almost no consistency between the 4 species studied (e.g. September of the current year displayed significantly different correlation coefficients for horse chestnut and beech whereas there were no significant differences for oak and birch). Only the months of January, March, May and August displayed significant differences in their correlation coefficients between stations with positive and negative trends for all species.

4. DISCUSSION AND CONCLUSIONS

There is no complete and coherent model for the timing of observed leaf colouring of deciduous trees in temperate zones. Some biosphere models have a procedure to end the vegetation period of deciduous broadleaf trees in temperate regions: The IBIS biosphere model, for example, uses the common hypothesis that mean daily temperature <5°C leads to leaf shedding (Foley et al. 1996); more complex modules use a combination of soil and air temperature to calculate the annual course of the leaf area index (LAI) Knorr 2000); the BIOME BGC applies an 11 d mean of daily mean temperature, and leaf shedding is initiated when the temperature drops below 11°C with a day length <10.92 h or when the smoothed temperature falls <2°C (White et al. 1997). These biosphere models determine the day on which leaves are shed, but none them is designed to predict the onset of leaf colouring of a specific deciduous tree species in temperate regions.

On the other hand, numerous hypotheses exist in the literature; a fact that might reflect the complexity of the problem. No test has ever systematically checked the statistical relationship to leaf colouring dates on a national scale. We tested all those hypotheses listed in Table 1, except constant day length. With a constant day length, leaf colouring should always occur at the same day of the year in defined latitudinal bands, which is obviously not the case.

There are some possible reasons why triggers of autumn colouring, contrary to leaf unfolding, are generally difficult to identify. (1) The phenological phase ‘leaf colouring’ is obviously less easy to recognise than the first 3 green leaves in spring, because the phase definition refers to 50% of all leaves coloured, including leaves both on branches and on the ground. The variation among individual trees at comparable or identical sites is much higher than in spring (Baumgartner 1952). (2) There is always the possibility of green leaf fall’, if temperatures and water supply in autumn do not lead to a visible change in leaf colour, and then observers can hardly note the date for the end of the vegetation period. The age of the tree and internal influences are more important for the timing leaf colouring than external influences (e.g. Baumgartner 1952, Junges 1962, Brügger 1998).

Our analyses underline that leaf colouring might be triggered by factors other than temperature alone. However, none of the factors tested exhibited explanatory power. Results show a vast station-to-station variability, therefore they do not ‘prove’ any of the hypotheses concerning warm autumn weather and sufficient water supply (Seyfert 1955, 1966) or accelerated leaf colouring through high autumn temperatures (Schulze 1970). The hypotheses related to the crossing of certain threshold temperatures cannot be confirmed by our dataset on leaf colouring dates, thus rebutting the hypotheses of Baumgartner (1959) and Schnelle (1952). Modified threshold temperatures describing the end of the vegetation period show hardly any correlation with leaf colouring, therefore we can reject the hypothesis of Hartmann & Schnelle (1970). In addition, none of the monthly sums of precipitation nor the number of dry days per month produced meaningful correlations; these proxies for soil moisture did not offer a convincing trigger for leaf colouring. This may be because they are an inadequate proxy or because water supply is not a trigger in these climatic conditions.

We conclude that, for mid latitudes, the triggers of leaf colouring are a complex mixture of several interacting factors. Only the hypothesis of Freitag (1987) is partially supported, because among the factors of slightly higher influence are: (1) mean monthly August to September temperature ($r > 0.4$ for all species in Set C) and (2) mean monthly May/June temperatures. However, due to the vast station-to-station variability, these results do not ‘prove’ any of the hypotheses between monthly temperature and onset of leaf colouring.

Further methodological issues concerning hypotheses related to e.g. soil properties and radiation were not undertaken due to the lack of relevant auxiliary data (radiation, soil type, exposure or slope). These differences in local conditions may be a reason for the lack of significant results. However, we know from analyses of spring phenology that it is possible to compare heterogeneous sites and genetically non-identical plants, especially if using a large number of stations. Thus site differences alone should not cause the level of ‘white noise’ found in autumn phenology. Another problem in our analyses is that while monthly mean temperatures are a commonly used explanatory variable in phenology they do not represent a physiological period.

Further studies on possible triggering factors could include experimental approaches to supply auxiliary data and to scale down the time-span of influencing factors (e.g. monthly to weekly data). Additional studies on our datasets (not shown) suggest that there was no regional pattern in the correlation coefficients of the different analyses. Moreover, we tested temperature sums (starting in March, with thresholds of either 8 or 5°C) and the number of days above thresholds, but these did not produce meaningful results.

Building a multiple linear model for leaf colouring is hampered by the lack of significant and relevant parameters and the strong interrelation of those parameters that have some importance (e.g. dates when different threshold temperatures are crossed and mean monthly temperatures, temperature and precipitation).

Although the correlations did not reveal triggers for leaf colouring, the best ones can be integrated in a multiple linear regression model with 3 parameters; this constitutes a good compromise between including relevant factors and avoiding ‘statistical’ ballast.

In a best R^2 procedure, the mean onset of leaf colouring in Germany was explained by 3 parameters which were selected out of all available parameters.

For 3 phases, only mean monthly temperatures were used: for beech ($R^2 = 0.56$) and oak ($R^2 = 0.56$), June, August and September monthly mean temperatures were included, for horse chestnut ($R^2 = 0.68$), May, June and September mean temperatures. For birch $R^2 = 0.49$), the number of dry days in September were incorporated alongside August and September mean temperatures. Regressions were:

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- Horse chestnut leaf colouring [day of the year] = 289.16 + (–1.03 × mo_5 [°C]) + (–0.96 × mo_6 [°C]) + (1.14 × mo_9 [°C]) •
- Beech leaf colouring [day of the year] = 264.86 + (–1.30 × mo_6 [°C]) + (1.04 × mo_8 [°C]) + (1.56 × mo_9 [°C]) •

- Oak leaf colouring [day of the year] = 269.06 + (–1.34 mo_6 [°C]) + (1.33 mo_8 [°C]) + (1.31 mo_9 [°C]) •
- Birch leaf colouring [day of the year] = 254 + (0.68 mo_8 [°C]) + (1.45 mo_9 [°C]) + (–0.35 ndry_9 [no. of days])

In general, monthly mean temperature for May and June, as well as the number of dry days in September, had negative regression coefficients, whereas monthly mean temperature in August and September had positive coefficients. This means that a warm August and September delayed leaf colouring, but a dry September as well as warm May and June led to an advanced leaf colouring. Our results show that it is, in principle, possible to build a model for a whole region, or even on a national scale, but due to the white noise in the datasets containing single stations as well as climate station information, it is not possible to design a valid overall model that is site-specific.

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Table 1. Hypotheses of possible factors triggering the onset of leaf colouring (* re-examined in this paper)

Minimum temperature dropping below a certain, not defined threshold	Baumgartner (1950)
Daily mean temperature <11/10°C (trigger/observed event)*	Schnelle (1952)
Minimum temperature <7/6°C (trigger/observed event)*	Schnelle (1952)
Warm autumn weather and sufficient water supply lengthen the growing season*	Seyfert (1955, 1966)
High autumn temperatures accelerate leaf colouring*	Schulze (1970)
Warm June leads to early leaf colouring*	Freitag (1987)
Warm August/September leads to later leaf colouring*	Freitag (1987)
High radiation in autumn induces early leaf colouring	Seyfert (1970)
Constant length of the growing season	Pfau (1964)
End of vegetation period when daily mean temperature (T_{mean} < 8°C (after 1 August) in a climate diagram (modified to sequence of days below 8°C)*	Hartmann & Schnelle (1970)

Table 2. Number of phenological (Phen) and climate (Clim) stations for each species and dataset (A–C)

		Dataset A		Dataset B		Dataset C	
Species	Common name	Phen	Clim	Phen	Clim	Phen	Clim
Aesculus hippocastanum	Horse chestnut	330	54	636	54	665	54
Fagus sylvatica	European birch	292	53	604	53	629	53
Quercus robur	Common oak	289	53	612	53	640	53
Betula pendula	Silver birch	325	54	635	54	663	54

Fig. 1. Map of Germany with meteorological stations (squares) and phenological stations (circles) within 25 km distance (here for leaf colouring data of birch)

Fig. 2. (a) Mean onset (days of the year) of leaf colouring (1951–2003) for dataset B, and (b) onset (days of the year) of leaf colouring for birch in 1995 for dataset A

Fig. 3. Pearson correlation coefficients (r) of monthly mean temperatures (months with leading p = previous year) and the onset dates of leaf colouring. Within the boxs the dot represents the mean and the horizontal line the median. (a) dataset A: data of single phenological stations near meteorological stations, (b) dataset B: spatially averaged phenological means near meteorological stations, and (c) dataset C: national phenological means and national temperature anomalies

Fig. 4. Pearson correlation coefficients (r) of the first days (FD) on which the temperature drops below a threshold (mean11: $FD_{mean} < 11°C$, mean9: $FD_{mean} < 9°C$, mean8: $FD_{mean} < 8°C$, mean7: $FD_{mean} < 7°C$, mean5: $FD_{mean} < 5°C$, min7= $FD_{min} < 7°C$, min5: $FD_{min} < 5°C$) and the onset dates of leaf colouring. Within the boxs the dot represents the mean and the horizontal line the median. (a) dataset A: data of single phenological stations near meteorological stations, (b) dataset B: spatially averaged phenological means near meteorological stations , and (c) dataset C: national phenological means and national meteorological means

Fig. 5. Pearson correlation coefficients (r) of monthly sums of precipitation (months with leading p = previous year) and the onset dates of leaf colouring. Within the boxs the dot represents the mean and the horizontal line the median. (a) dataset A: data of single phenological stations near meteorological stations, (b) dataset B: spatially averaged phenological means near meteorological stations , and (c) dataset C: national phenological means and national meteorological means

Fig. 6. Pearson correlation coefficients (r) of monthly number of dry days (months with leading p = previous year) and the onset dates of leaf colouring. Within the boxs the dot represents the mean and the horizontal line the median. (a) dataset A: data of single phenological stations near meteorological stations, (b) dataset B: spatially averaged phenological means near meteorological stations and (c) dataset C: national phenological means and national mean of number of dry days

Fig. 7. Pearson correlation coefficients (r) of the end of vegetation period in forestry (drop of mean air temperature below 8°C on 5 subsequent days, modified Hoffmann & Schnelle 1970) and onset dates of leaf colouring. (a) dataset A: data of single phenological stations near meteorological stations, (b) dataset B: spatially averaged phenological means near meteorological stations, and (c) dataset C: national phenological means and national mean of end of vegetation period

Fig. 8. Pearson correlation coefficients (r) of onset dates of leaf colouring and parameters of Fig. 2, 3 &6, divided up for stations with positive (grey) and negative (black) significant trends in time series longer than 30 yr (monthly mean temperatures, months with leading p = previous year; mean11 = $FD_{mean} < 11°C$; mean9 = $FD_{mean} < 9°C$, mean8 = $FD_{mean} < 8°C$; mean7 = $FD_{mean} < 7°C$; mean5 = $FD_{mean} < 5°C$; min5 = $FD_{min} < 5°C$; min7 = $FD_{min} < 7°C$; veg: end of vegetation period modified after Hoffmann and Schnelle 1970)

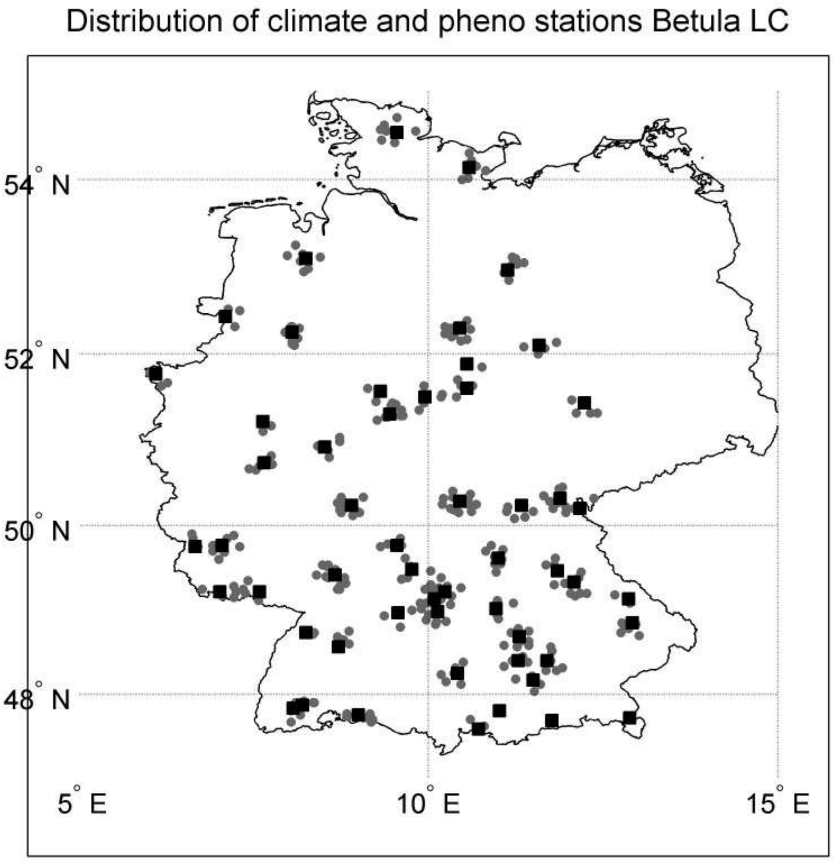

Distribution of climate and pheno stations Betula LC
54° N
52° N
50° N
48° N
5° E
10° E
15° E

Fig. 1

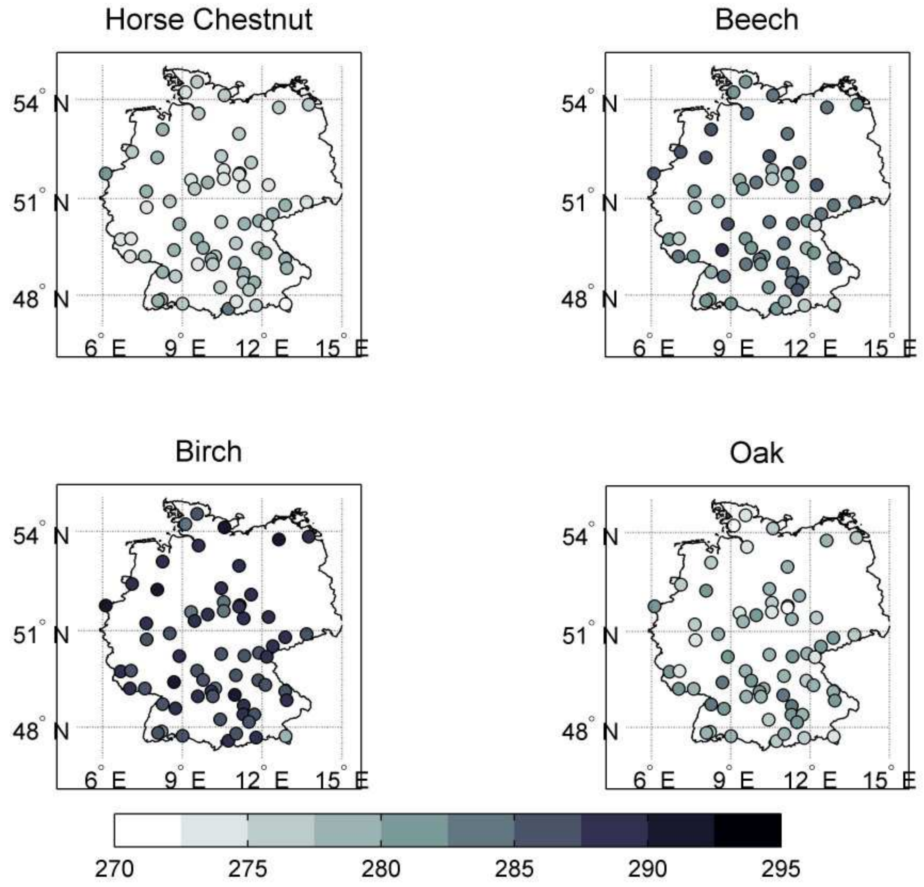


Figure 2 a

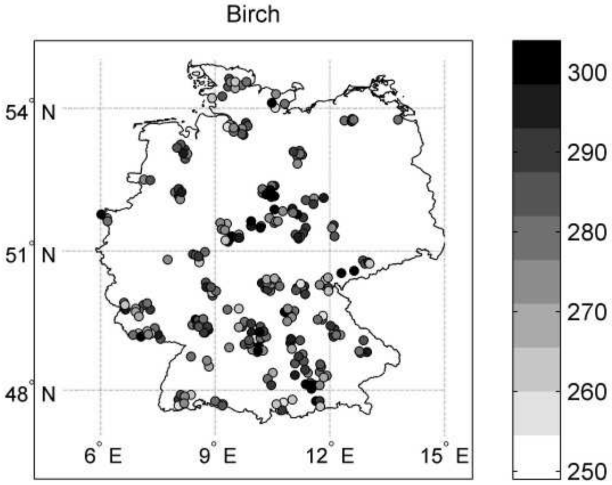


Figure 2 b

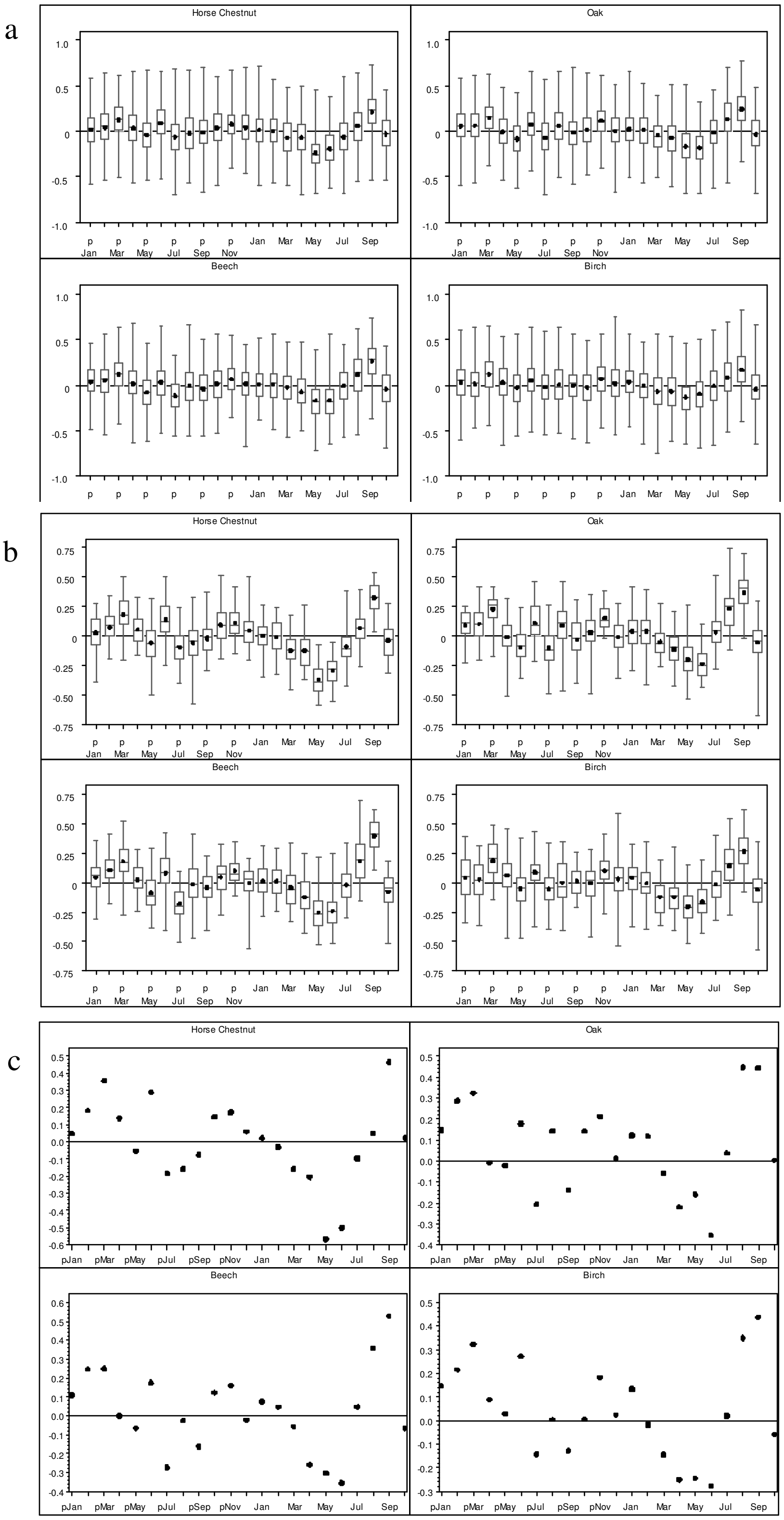

a
Horse Chestnut
Oak
Beech
Birch
1.0
0.5
0
-0.5
-1.0
p Jan
p Mar
p May
p Jul
p Sep
p Nov
Jan
Mar
May
Jul
Sep
b
Horse Chestnut
Oak
Beech
Birch
0.75
0.50
0.25
0
-0.25
-0.50
-0.75
c
Horse Chestnut
Oak
Beech
Birch
pJan
pMar
pMay
pJul
pSep
pNov
Jan
Mar
May
Jul
Sep

Figure 3

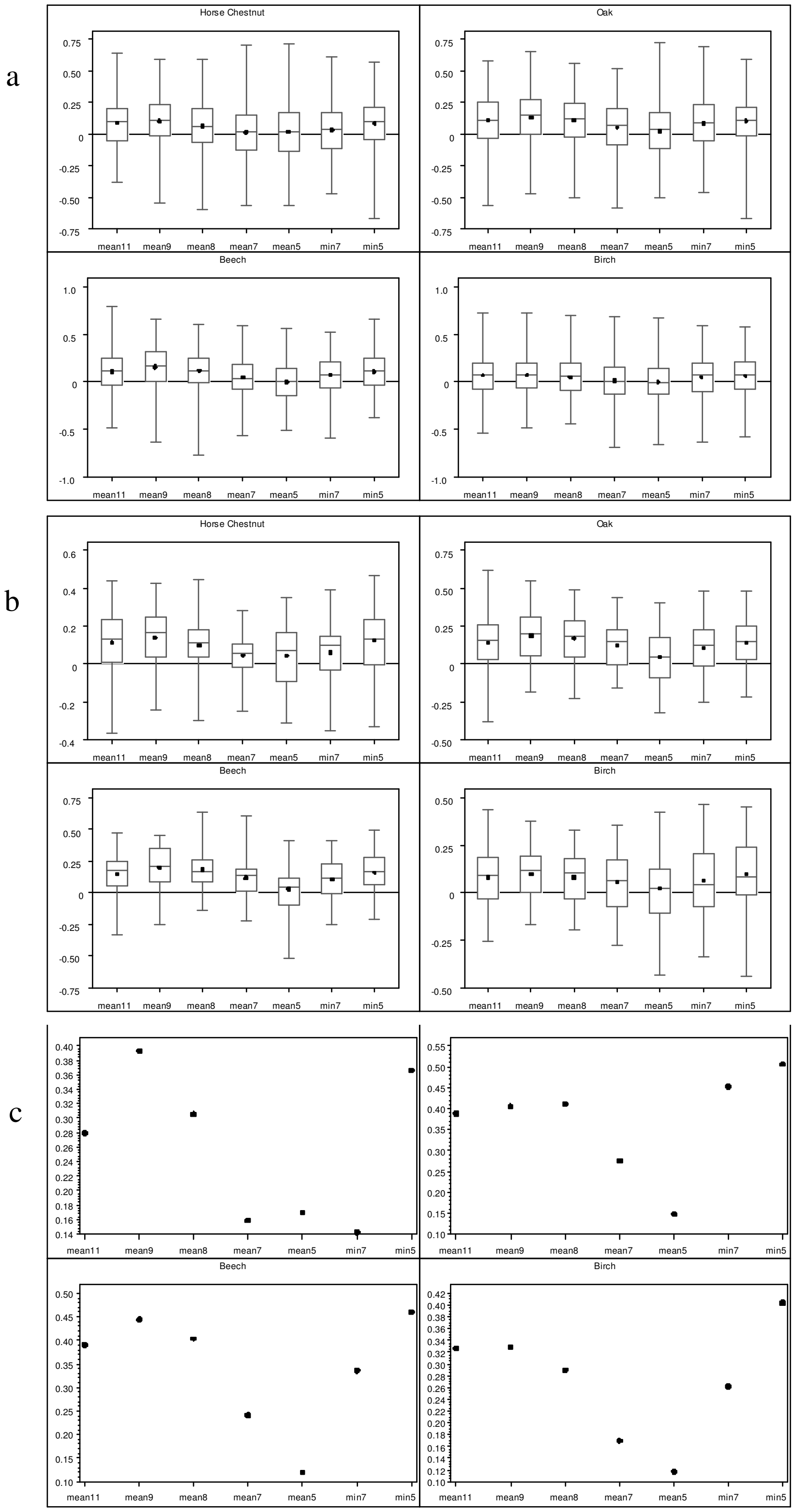

a
Horse Chestnut
Oak
0.75
0.50
0.25
0
-0.25
-0.50
-0.75
mean11
mean9
mean8
mean7
mean5
min7
min5
Beech
Birch
1.0
0.5
0
-0.5
-1.0
b
Horse Chestnut
Oak
0.6
0.4
0.2
0
-0.2
-0.4
Beech
Birch
c
Beech
Birch

Figure 4

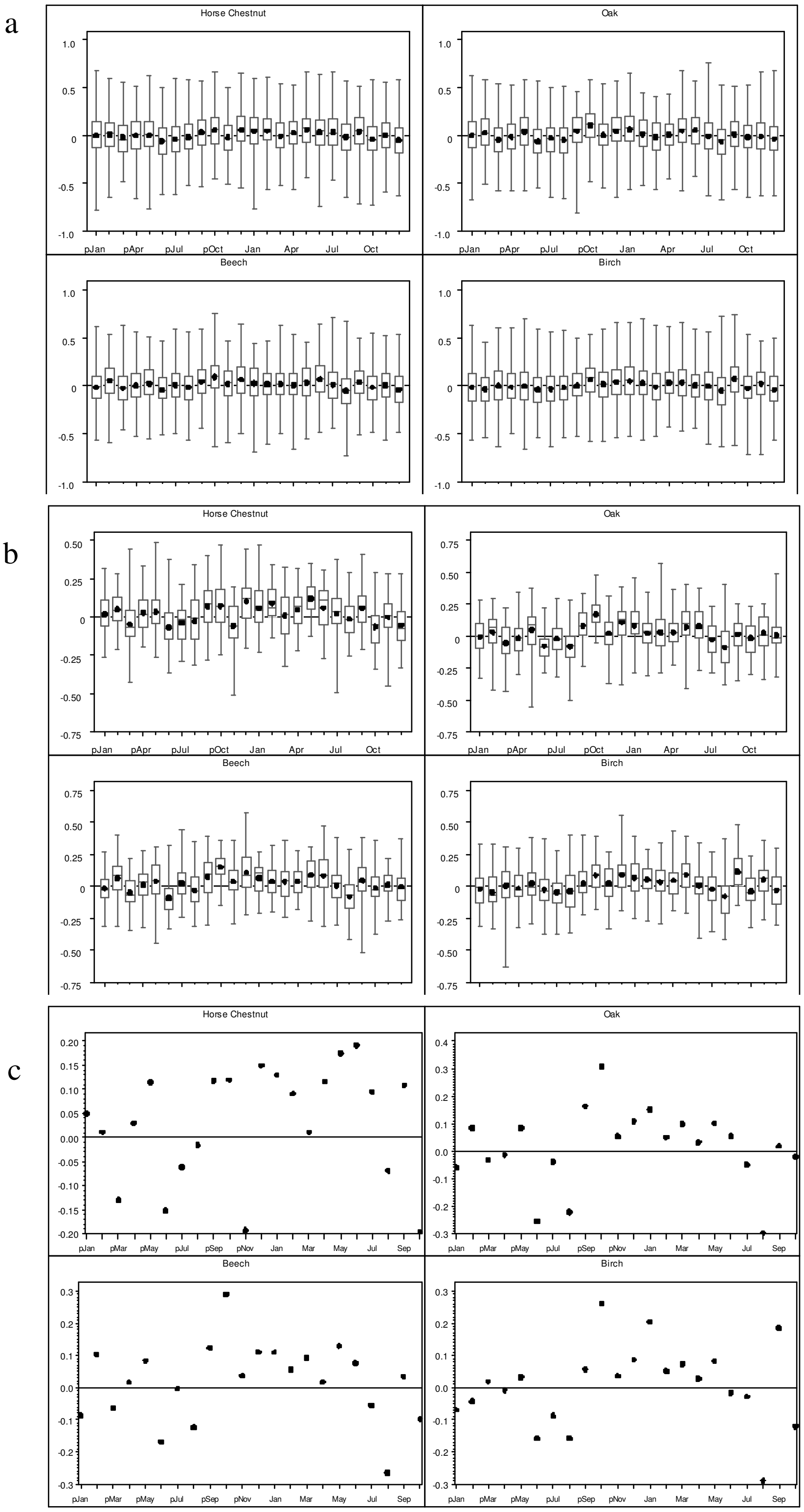

a
Horse Chestnut
Oak
Beech
Birch
1.0
0.5
0
-0.5
-1.0
pJan
pApr
pJul
pOct
Jan
Apr
Jul
Oct
b
Horse Chestnut
Oak
Beech
Birch
0.75
0.50
0.25
0
-0.25
-0.50
-0.75
pJan
pApr
pJul
pOct
Jan
Apr
Jul
Oct
c
Horse Chestnut
Oak
Beech
Birch
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
pJan
pMar
pMay
pJul
pSep
pNov
Jan
Mar
May
Jul
Sep

Figure 5

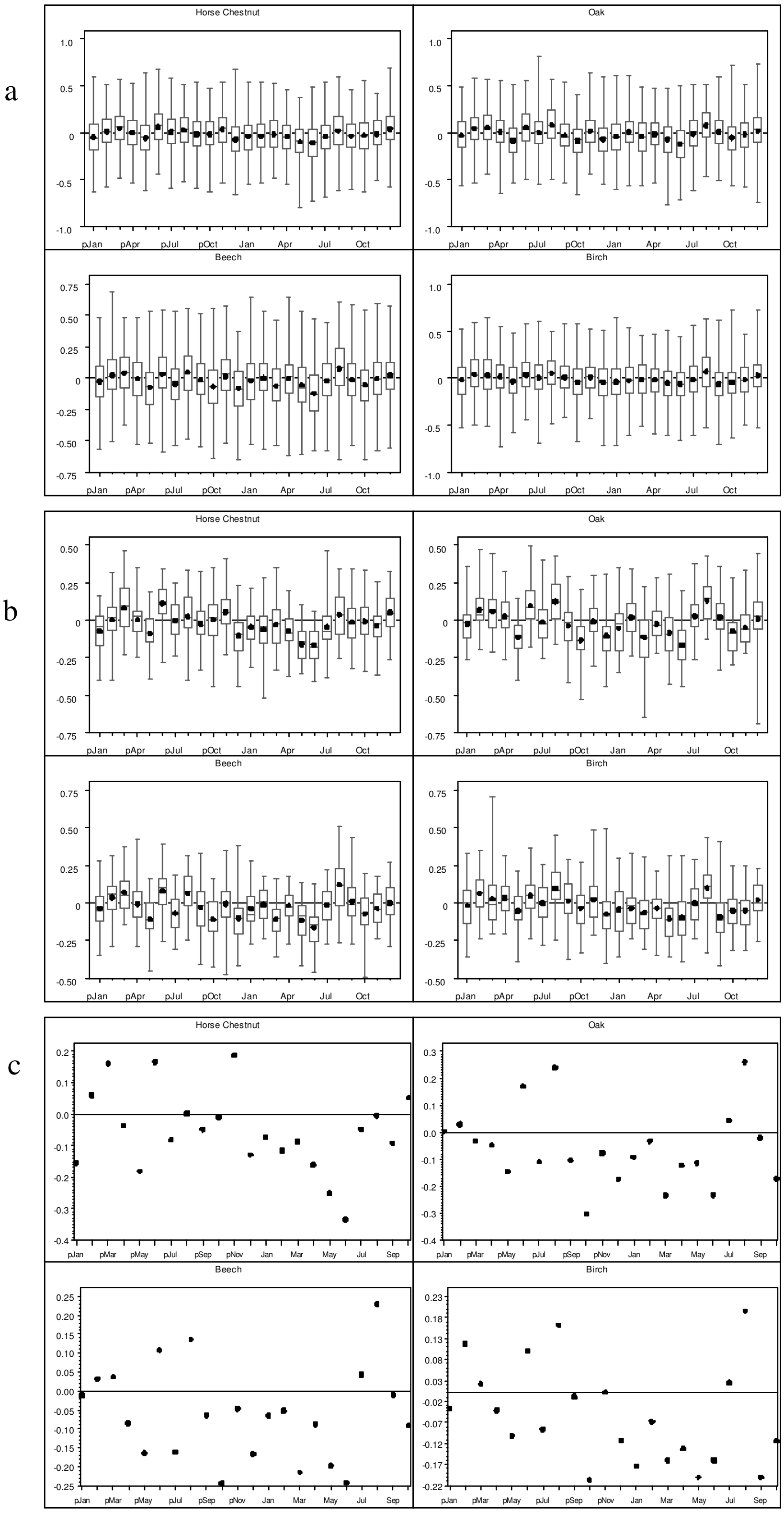
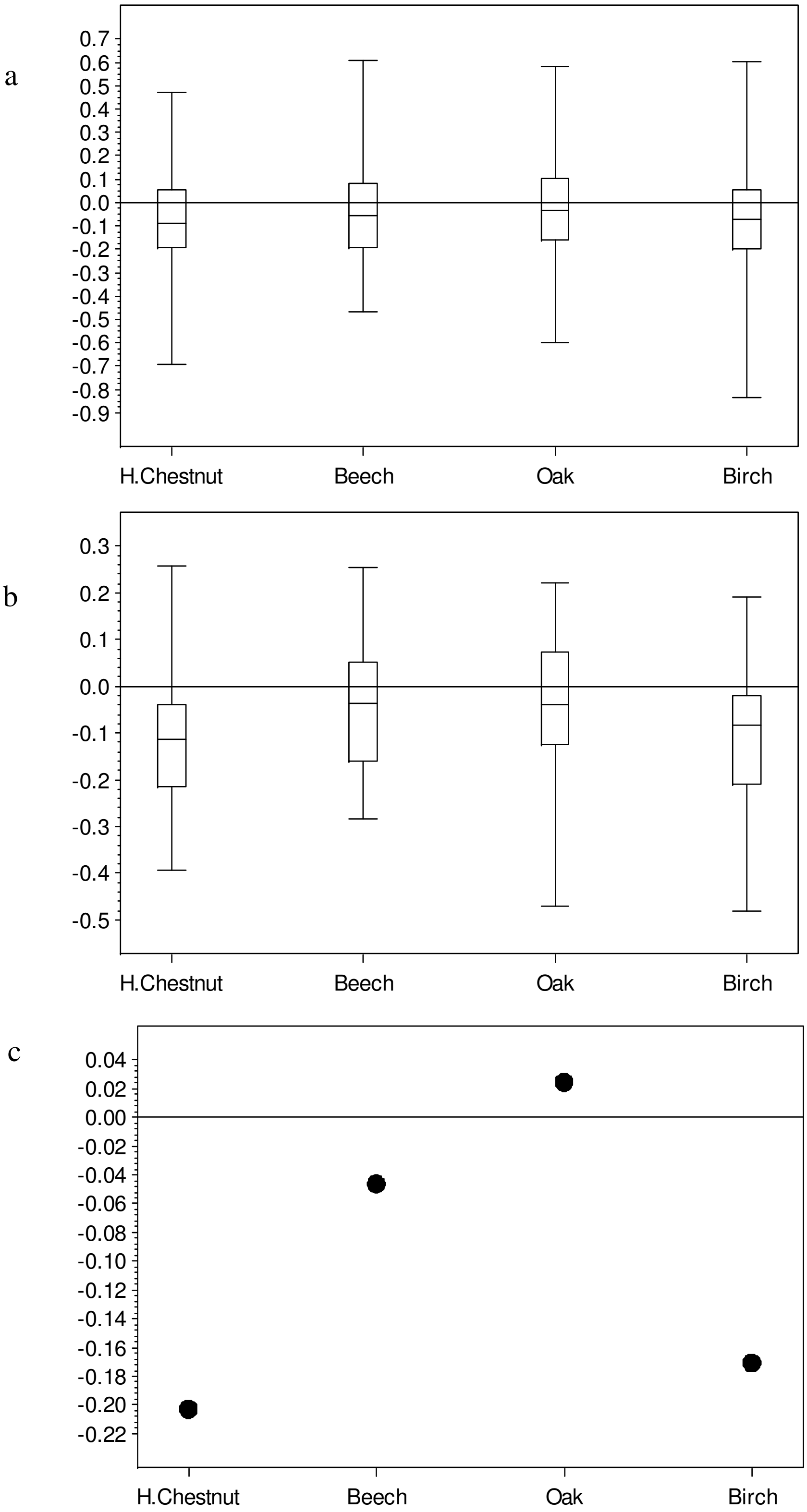

a
b
c
Horse Chestnut
Oak
Beech
Birch
1.0
0.5
0
-0.5
-1.0
0.75
0.50
0.25
-0.25
-0.50
-0.75
pJan
pApr
pJul
pOct
Jan
Apr
Jul
Oct
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0.3
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
0.23
0.18
0.13
0.08
0.03
-0.02
-0.07
-0.12
-0.17
-0.22
pMar
pMay
pSep
pNov
Mar
May
Sep

Figure 6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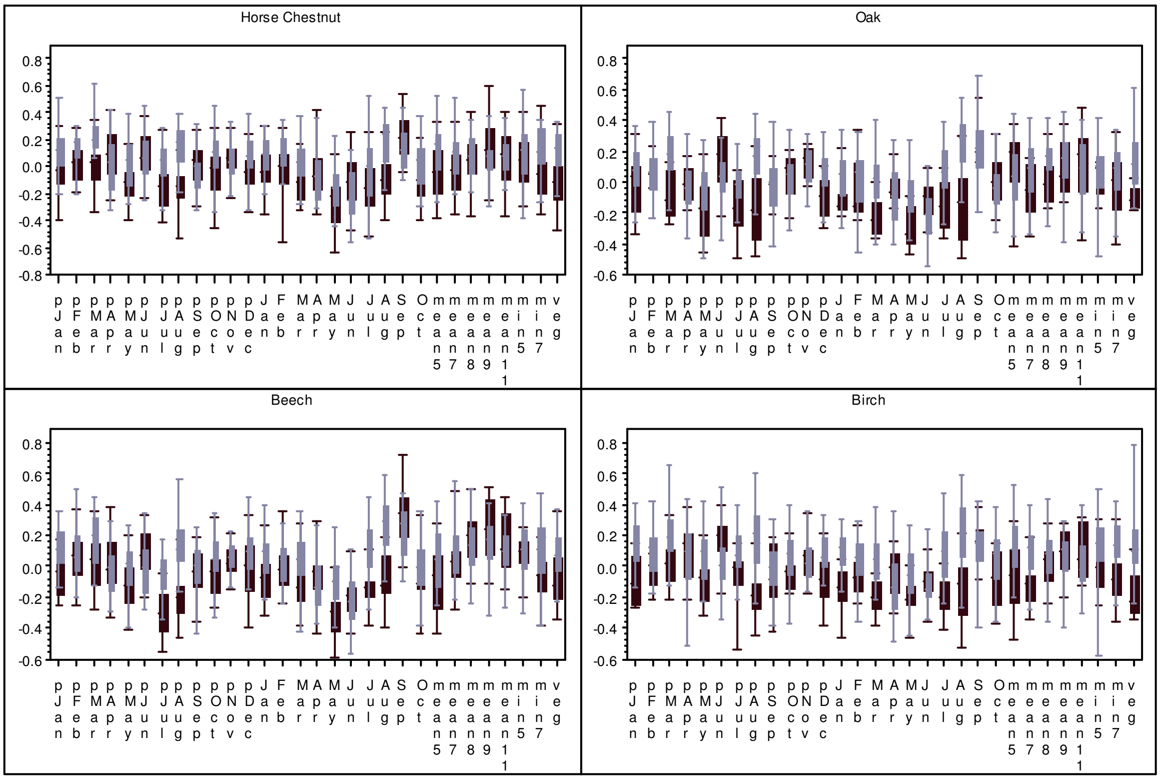
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
H.Chestnut
Beech
Oak
Birch
b
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
H.Chestnut
Beech
Oak
Birch
c
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.20
-0.22
H.Chestnut
Beech
Oak
Birch

Figure 7


Horse Chestnut
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
pJan
pFeb
pMar
pApr
pMay
pJun
pJul
pAug
pSep
pOct
pNov
pDec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
mean5
mean7
mean8
mean9
mean11
min5
min7
veg
Oak
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
pJan
pFeb
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mean5
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min5
min7
veg
Beech
0.8
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0.2
0.0
-0.2
-0.4
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pJan
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mean5
mean7
mean8
mean9
mean11
min5
min7
veg
Birch
0.8
0.6
0.4
0.2
0.0
-0.2
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pJan
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pMay
pJun
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pOct
pNov
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Jan
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Mar
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May
Jun
Jul
Aug
Sep
Oct
mean5
mean7
mean8
mean9
mean11
min5
min7
veg

Figure 8

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Global Change Biology

Trends and temperature response in the phenology of crops in Germany

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Keywords: agriculture, horticulture, climate change, temperature, phenology, response

Abstract: The phenology of 78 agricultural and horticultural events from a national survey in Germany spanning the years 1951 to 2004 is examined. The majority of events are significantly earlier now than 53 years ago, with a mean advance of 1.1 to 1.3 days / decade. Mean trends for 'true phases', such as emergence and flowering, of annual and perennial crops are not significantly different, although more trends (78% vs 46%) are significant for annual crops. We attempt to remove the influence of technological advance or altered farming practices on phenology by detrending the respective time series by linear regression of date (day number) on year. Subsequently, we estimate responses to mean monthly and seasonal temperature by correlation and regression in two ways; with and without removing the year trend first. Nearly all (97%) correlation coefficients are negative, suggesting earlier events in warmer years. Between 82% and 94% of the coefficients with seasonal spring and summer temperatures are significant. The conservative estimate (detrended) of mean temperature response against mean March-May temperature (-3.73 days/°C) is significantly less than the full estimate (-4.31 days/°C), the 'true' size of phenological temperature response may lie in between. Perennial crops exhibited a significantly higher temperature response to mean spring temperature than the annual crops.

Introduction

There is a growing body of evidence of phenological advance across the northern hemisphere as a consequence of rising temperatures (e.g. reviews by Hughes 2000, IPCC 2001, Walther et al. 2002, Sparks and Menzel 2002, Root et al. 2003, Parmesan and Yohe 2003). This phenological advance has been demonstrated in the leafing and flowering of plants (e.g. Menzel and Fabian 1999, Abu-Asab et al. 2001, Menzel et al. 2001, Defila and Clot 2001, 2005, Chmielewski and Rötzer 2001, Matsumoto et al. 2003, Menzel et al. 2006), the appearance of insects, e.g. advancement in the phenology of butterflies has been reported from a number of national (Roy and Sparks 2000) and local studies (e.g. Forister and Shapiro 2003, Stefanescu et al. 2003), and nesting and migration of birds (e.g. Crick et al. 1997, Crick and Sparks 1999, Dunn and Winkler 1999, Inouye et al. 2000, Bairlein and Winkler 2001, Sparks et al. 2004) amongst others. It is likely that phenological shifts are much more widespread than have been reported but that limited data, for example from the southern hemisphere and on mammals, have not allowed a comprehensive picture to be put together. The bulk of data has so far come from native plants and animals, with much less from activities heavily influenced by human activities, such as agriculture and horticulture. Only very few studies have looked at shifts in agricultural phases so far (e.g. Chmielewski et al. 2004, Hu et al. 2005).

Although the timing of farming operations is controlled (to some extent) by man, he cannot operate completely independently of the weather. For the purpose of this paper we use the phrase “annual” for those crops with a cultivation period less than one year. Some phases of annual crops, such as sowing or harvest, depend on farmers’ decisions and are thus called ‘false phases’ (Schnelle 1955). Subsequent phases, such as emergence, may partly depend on these sowing dates. Human decisions on irrigation, fertilisers, weed control and varietal choice (for example plant breeding producing earlier maturing varieties) may also influence phenology to a small extent. However it is also expected that the phenology of perennial crops cannot be manipulated to the same extent by farmers' decisions. There is concern that changes to farming practices, such as technological advance and rapid turnover in cultivars in annual crops (e.g. as reported by Hildén et al. 2005), will make time series of their phenology less informative as to the influence of weather and climate on farming. However, there have been a number of papers reporting changes to phenology of cultivated plants (Hildén et al. 2005 for Finland, De LaTorre and Benoit 2004 for France, Chmielewski et al. 2004 for Germany, Hu et al. 2005 for U.S. Great Plains).

In this paper we examine the agricultural and horticultural records across Germany to see how climate has influenced the timing of 78 different phenological events. We attempt to remove the influence of technological advance on phenology in order to estimate the changes taking place as a consequence of climate warming. Finally, we examine whether differences exist in the phenological sensitivity of annual and perennial crops.

Materials and Methods

Phenological Data

The German Meteorological Service (DWD – Deutscher Wetterdienst) has been running a large scale phenological network since 1951. The current network of c.1550 recorders (in the mid 1970s up to 4000) collects phenological data on cultivated (agricultural and horticultural) and native plants following a fixed recording scheme (for details see http://www.dwd.de/en/FundE/Klima/KLIS/daten/nkdz/fachdatenbank/ datenkollektive/phaenologie/beob_programm/index.htm). Annual dates for each of the 78 phenological events on 20 cultivated plants plus permanent grassland (see list in Table 1) were converted to day number post-December 31 prior to calculations. National time series for the period 1951-2004 were created as the annual mean of anomalies. For each station a mean onset date for the period 1971-1986 (if number of years >11) was calculated; then annual deviations of the observed dates from this station mean were determined and finally, the annual mean anomalies were computed for Germany for each of the phases (Menzel 2003). For 13 events (1 annual, 12 perennial, marked with an asterisk in Table 1) recording ceased in 1990/91 and these events have been treated differently in the trend summary since their trend coefficient is likely to be reduced as they did not experience the warmer 1990s. All events were categorised by plant type (a: annual, p: perennial) and phase (s: sowing as ‘false’ phase; h: maturity / harvest as autumn phases; t: all other ‘true’ phases predominantly in spring and summer (see Table 1)).

Temperature Data

The temperature data set TYN CY 1.1, created by Mitchell et al. (2002) for Germany, was downloaded from the Tyndall Centre for Climate Change Research (www.cru.uae.ac.uk/~timm/climate/index.html). The data set comprises monthly mean temperatures from 1951 to 2000.

Analysis

Trends in the national time series were examined by linear regression of date (day number) on year. It is likely that changes in management practice and use of new technology may also respond to climate change, but will not be realised at all sites at once. Some farmers will implement changes as soon as possible, the majority might wait for the reaction of others before they change their habits, and a few will delay adapting to climate change. Therefore, the shape of the curve between the number of farmers adapting and time is assumed to be s-shaped or logistic (Easterling et al. 2003) with a near linear increase in the middle period. Taking into account that changes in plant breeding, technological advances, farmers' reaction to climate change, as well as market prices and policies related to subsidies are mixed up in the phenological signal, we propose that the nonthermal influence of disturbing factors on a countrywide mean time series is approximately linear (Menzel et al 2006). In addition, we suggest that the above mentioned effects of changes in management practice and technology will be reliased more quickly in annual plants than in perennials, such as fruit trees. Therefore, we examined the responses to temperatures in two ways. The first was via correlation and regression with monthly temperatures. The second was similar but sequentially after fitting a year term to remove any linear trend in the series. The former may exaggerate the temperature response if there has been a non-temperature related response through time, whereas the latter would underestimate it. We believe the true figure to lie in between.

Results

Trends

Table 1 displays mean dates and trends through time for each of the events. 68 of the 78 events returned a negative regression coefficient against year of which 44 were statistically significantly earlier ($p<0.05$). Of the 10 events that returned a positive coefficient, two (maize heading and winter rape harvest, both annual) were significantly later ($p<0.05$). The mean trend coefficient was -0.111 days/year. The 13 events for which recording ended in 1990/91 have been omitted from the remaining analysis in this section. The overall trend on their omission becomes -0.129 days/year. The mean trend for the 41 annual crop events (-0.136) was not significantly different from the mean trend of the 24 perennial crop events (-0.118) ($p=0.57$ from ANOVA). The comparisons between annual and perennial crops for true events (-0.143 vs -0.136 $p=0.83$) and harvest/maturity events (-0.145 vs -0.090 $p=0.39$) were also not significant. 32 (78%) of the annual crop events produced significant negative trends while only 11 (46%) of the trends in perennial crops events were significant; these differences are significant (Chi- squared contingency table $\chi^2_1=7.02$, $p=0.008$). Figure 1 displays a scatterplot of the trends against the mean date of the event.

Temperature relationships

Correlation coefficients of detrended national anomalies (i.e. after removing a year trend) with mean monthly temperatures, up to and including the month in which the mean event of the event occurred, are shown in Table 2. These correlations are heavily dominated by negative coefficients, suggesting earlier events in warmer years. Indeed of the 496 correlations, 479 (97%) were negative and 309 (62%) were significantly negative. There were no significant positive correlations. Correlation coefficients with temperatures of the last three months of the previous year (October-December) had a much lower level of significance (7% positive, 4% negative) and are not shown here. The temperatures of the three months leading up to the mean event date seem to be particularly important; some 72% of these correlations are significantly negative. However, events with a mean date in October (not included in table 2) appeared to much less influenced by temperature with only one (Winter wheat, emergence) of the 27 correlations being significant.

After fitting a year trend, the regression coefficients ('detrended') with mean March-May (MAM) temperature and with mean June-August (JJA) temperatures (for events with a mean date after July 1) are shown in Table 2. Coefficients were significant for 68 of the 78 regressions with MAM temperatures (87%) and 28 of the 34 with JJA temperatures (82%). All coefficients were negative. The equivalent 'ordinary' regression coefficients (i.e. not taking into account any trend over time) are also shown in Table 2. A slightly higher level of significance was achieved; 70 out of 78 regressions with MAM temperature (90%) and 32 out of 34 regressions with JJA temperature (94%) were significant. Again, all coefficients were negative. The mean regression coefficient of detrended time series (-3.73 days/°C) with MAM temperature was significantly smaller than the ordinary regression coefficient (-4.31 days/°C , paired t-test $t_{77}=8.51$ $p<0.001$). This was also true for regressions with JJA temperature (detrended -3.57 days/°C, ordinary -3.97 days/°C, paired t-test $t_{33}=4.22$ $p<0.001$). There was a high degree of correlation between detrended and ordinary regression coefficients ($r=0.95$ for MAM and $r=0.97$ for JJA, both $p<0.001$).

A comparison of the temperature regression coefficients between annual and perennial crops is summarised in Table 3. In all but one of the harvest comparisons (regression on JJA), perennial crops had a greater response to temperature than annual crops. In particular, for regression on MAM mean temperature, perennial crops revealed a significantly higher temperature response than annuals.

Discussion

We present here a condensation of some 4.9 million observational records from 78 phenological phases of agricultural and horticultural species across Germany over more than 50 years.

The classification of annual and perennial crops followed the observational program of the DWD, with field crops as annuals and fruits and permanent grassland as perennial crops (DWD 1991). Most of the cultivated strawberries are biennial, and were grouped into perennials here. Annual plants are sown in late summer (winter rape), autumn (all other winter crops) and spring at a time considered by farmers to be optimum (considering soil and weather conditions). Similarly harvest dates of field crops do not only depend on the ripeness of the crops but also on the farmers' decision, thus these phases are also 'false' phases (*sensu* Schnelle 1955). Even the phase following directly after a 'false' phase, such as emergence, partly depends on the farmers' earlier decision on sowing date. They are still strongly influenced by temperature, and these phases are not considered as 'false' phases by definition (Menzel et al. 2006). The false phases may be altered by technical advances in agricultural machinery, because timing of sowing and harvest depends on being able to get machinery safely onto fields. Phenological phases of perennial plants are not considered as 'false' phases; human influence perhaps most noticeable in breeding efforts which occur over much longer cycles than in annual crops

Our trend analyses reveal that the majority of events are significantly earlier now than 53 years ago with an mean advance of 1.1 to 1.3 days / decade. This average advance is clearly below means for spring and summer events of wild plants in Europe (-2.5

days / decade, Menzel et al. 2006) and also less than results of a global assessment (-2.3 days / decade, Parmesan & Yohe 2003).

However, the mean trends in German agricultural and horticultural phenology (1951-2004), revealed by our study, are almost identical to wheat heading trends in the U.S. Great Plains (1948-2004, 6 stations) (Hu et al. 2005) and other results from Germany for 15 agricultural phases of apple, cherry, winter rye, sugar beet and maize (1961-2000) advancing between 0.6 and 2.9 days / decade (Chmielewski et al. 2004). In contrast, a strongly advancing trend was reported by Williams and Abberton (2004) for the UK where the flowering dates of the same varieties of white clover had become significantly earlier (1962-2002) with an advance of approximately 7.5 days per decade since 1978. Similarly, for a large number of agricultural records kept by a farmer in Sussex, UK, Sparks et al. (2005) found that 25 of the 29 events were earlier in 1990-2000 than in 1980-1989. Another two examples underline a strong regional variation of agricultural phenological trends in Europe: In Finland (1965-1999), sowing dates of spring cereals have not become earlier and potato sowing dates have advanced by c.5 days in the last four decades (Hildén et al. 2005), whereas in France, sowing dates of cereals are now earlier than 30 years ago (up to one month for maize and winter wheat) (De La Torre and Benoit 2004).

Since the magnitude of trends is dependent on the underlying time frame (see Sparks and Menzel 2002, Dose and Menzel 2004, Sparks and Tryjanowski 2005), our comparison of trends in annual and perennial crops could have been hampered by the reorganisation of the network in 1990/91 when 13 events ceased. However these events were not included in trend comparisons thus restricting events to those covering the full 1951-2004 period. Here we found more significant trends in annual crops than in perennial crops, but not a significant difference in magnitude of change. The first fact suggests that phenological variability may be lower in annual crops. Therefore, our results are only partly in accordance with results of the broad study by Fitter and Fitter (2002) who found that in wild plants, annuals are likely to advance flowering more than congeneric perennials. We assume that a likely greater turnover in technology and plant breeding in annual crops (e.g. wheat) than in perennial crops (e.g. apples) and possibly stronger modified (adaptive) behaviour of the farmer in cropping of annuals may have masked differences. In addition, in contrast to Fitter and Fitter (2002), most perennial crops in our study (except strawberries and permanent grassland) are woody trees and shrubs (phanerophytes) with resting buds more than 25 cm above soil level, thus they can not be regarded as congeneric to annuals.

There were strong negative links between temperature and phenology, with the vast bulk of tabulated correlations being negative of which more than 60% were significant. This means that in general, despite common analyses of annual and perennials, true and false agricultural phases, the vast majority of phases is advanced by higher spring and summer temperatures.

We estimated responses to temperature in two ways; with and without removing a year trend first. These estimates will probably underestimate and overestimate respectively the temperature effects since there has been a gradual rise in temperature during the study period. The linear trend of March-May (MAM) temperature is 0.25 °C / decade, and of July-August (JJA) 0.11 °C / decade. The coefficients against detrended time series concentrate only on the inter-annual fluctuations in temperature ignoring the long-term trend. The ordinary coefficients include the temperature trend but may also contain some element of advance caused by cultivar changes or changed farming practices.All of the coefficients we calculated were negative and between 82% and 94% of the seasonal correlations were significant. The conservative estimate of mean temperature response against mean March-May (MAM) temperature (-3.73 days/°C) was significantly less than the full estimate (-4.31 days/°C). If the mean advance of phenology shown here (-1.1 to -1.3 days / decade) was only influenced by temperature, we would expect a theoretical temperature response of between -4.4 and -5.2 days / °C, which is close to our full estimate.

As expected, overall, and particularly for true events, the perennial crops showed higher temperature responses than the annual crops, probably because these phases are less influenced by human decisions and / or breeding. So, assuming that more events in cropping of annuals than perennials (sowing and subsequent emergence, harvest) are triggered by farmers' decisions, this difference suggests conservative working practices.

Our findings are generally in accordance with earlier studies: Williams and Abberton (2004) found for the UK that first flowering dates of the same varieties of white clover were significantly negatively correlated with minimum and maximum temperatures during February and March and soil temperatures between January and April. Another analysis of a large number of agricultural records kept by a farmer in Sussex, UK (Sparks et al. 2005) found that 18 of 29 events were significantly negatively related to temperatures of the three calendar months preceding the mean event date. The response rates to temperature varied between 4 and 12 days earlier for each 1°C warmer which is clearly above the values we determined for Germany. An earlier study for Germany, however, reported quite similar temperature responses to February – April temperature, ranging between 3.8 and 4.7 days / °C for the beginning of the growing season, stem elongation of winter rye, cherry tree blossom and apple tree blossom (Chmielewski et al. 2004). Their values slightly differ from those in our study due to different time spans and methods.

Our study period of 54 years is too short to analyse whether the temperature response of phenological phases varies over time. Sparks et al. (2005) report that 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. Similar results have been found by Menzel et al. (2005) for the last 100 years.

To summarise, we suggest that the detrended temperature response of phenological phases in agriculture and horticulture exhibits the real nature of those changes. Our analyses clearly demonstrate that perennial crops reveal a stronger temperature response than annual crops. This finding suggests that further study of the reactions of farmers to changing temperature conditions by varying their dates of sowing, harvesting and in the selection of varieties would help to separate the impacts of recent temperature change from adaptation measures. However, our comprehensive results reported here clearly demonstrate that agricultural and horticultural phenology has advanced in Germany in recent decades and that rising temperature is influencing these events by advancing phenology on average by some 4 days/°C.

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Table 1. Definitions of the 78 phenological events, sorted by their mean dates and classification by type of phase (s sowing, t true, h harvest or maturity) and as annual or perennial crop. The final column indicates the per annum trend in the event in Germany in the period 1951-2004 (or 1951-1990/91 for events marked*), trends in bold are statistically significant (p<0.05).

Scientific name	**English name**	**Phase**	Mean day number	Mean date (1970-1986)	Type of phase	annual/ perennial	Trend
Avena sativa	Oats	Sowing	85.2	26-Mar	s	a	-0.057
Ribes uva-crispa	Gooseberry	First leaves	97.2	07-Apr	t	p	**-0.256**
Beta vulgaris	Sugar beet	Sowing	100.1	10-Apr	s	a	**-0.187**
Prunus armeniaca	Apricot	First flowers open	101.6	11-Apr	t	p	-0.074
Avena sativa	Oats	Emergence	103.9	13-Apr	t	a	-0.053
Beta vulgaris var. *crassa*	Fodder beet	Sowing	108.2	18-Apr	s	a	-0.009
*Prunus persica**	Peach	First flowers open	109.9	19-Apr	t	p	-0.022
Ribes uva-crispa	Gooseberry	First flowers open	110.9	20-Apr	t	p	**-0.152**
*Ribes rubrum**	Red currant	First flowers open	115.1	25-Apr	t	p	-0.134
Prunus avium	Sweet cherry	First flowers open	116.4	26-Apr	t	p	-0.116
Hordeum vulgare	Winter barley	Beginning of shooting	119.0	29-Apr	t	a	**-0.325**
Secale cereale	Winter rye	Beginning of shooting	119.5	29-Apr	t	a	**-0.255**
Prunus avium	Sweet cherry	Full flowering	119.9	29-Apr	t	p	-0.095
*Prunus domestica**	Plum	First flowers open	120.1	30-Apr	t	p	-0.006
Zea mays	Maize	Sowing	121.6	01-May	s	a	**-0.232**
Beta vulgaris	Sugar beet	Emergence	121.9	01-May	t	a	**-0.095**
Pyrus communis	Pear	First flowers open	122.0	02-May	t	p	**-0.180**
Prunus cerasus	Sour cherry	First flowers open	122.5	02-May	t	p	-0.114
*Prunus domestica**	Plum	Full flowering	123.6	03-May	t	p	-0.003
Pyrus communis	Pear	Full flowering	125.5	05-May	t	p	**-0.177**
Prunus cerasus	Sour cherry	Full flowering	126.1	06-May	t	p	-0.119
Prunus avium	Sweet cherry	End of flowering	128.2	08-May	t	p	-0.049

Triticum aestivum	Winter wheat	Beginning of shooting	128.4	08-May	t	a	**-0.310**
Beta vulgaris var. *crassa*	Fodder beet	Emergence	128.6	08-May	t	a	0.017
Malus domestica	Apple (early varieties)	First flowers open	129.2	09-May	t	p	**-0.150**
Brassica napus var. *napus*	Winter rape	First flowers open	129.6	09-May	t	a	**-0.205**
*Prunus domestica**	Plum	End of flowering	130.6	10-May	t	p	0.003
Malus domestica	Apple (early varieties)	Full flowering	133.0	13-May	t	p	**-0.147**
Pyrus communis	Pear	End of flowering	133.1	13-May	t	p	**-0.140**
Prunus cerasus	Sour cherry	End of flowering	134.2	14-May	t	p	-0.101
Zea mays	Maize	Emergence	138.6	18-May	t	a	**-0.265**
Avena sativa	Oats	Beginning of shooting	141.6	21-May	t	a	**-0.209**
Hordeum vulgare	Winter barley	Beginning of heading	142.0	21-May	t	a	**-0.170**
Secale cereale	Winter rye	Beginning of heading	142.3	22-May	t	a	**-0.115**
*Rubus idaeus**	Raspberry	First flowers open	149.9	29-May	t	p	-0.010
	Permanent grass	First silage cut	155.3	04-Jun	t	p	**-0.163**
Secale cereale	Winter rye	Full flowering	158.7	07-Jun	t	a	**-0.176**
Triticum aestivum	Winter wheat	Beginning of heading	162.8	11-Jun	t	a	**-0.206**
*Rubus fruticosus**	Blackberry	First flowers open	164.6	13-Jun	t	p	0.121
*Fragaria × ananassa**	Strawberry (early varieties)	Fruit ripe for picking	170.6	19-Jun	h	p	0.019
Beta vulgaris	Sugar beet	Closed stand	171.2	20-Jun	t	a	**-0.277**
Avena sativa	Oats	Beginning of heading	171.6	20-Jun	t	a	**-0.160**
Beta vulgaris var. *crassa*	Fodder beet	Closed stand	174.9	23-Jun	t	a	**-0.131**
Prunus avium	Sweet cherry (early varieties)	Fruit ripe for picking	178.1	27-Jun	h	p	0.070
*Rubus idaeus**	Raspberry	Fruit ripe for picking	189.8	08-Jul	h	p	-0.094
Ribes rubrum	Red currant	Fruit ripe for picking	190.5	09-Jul	h	p	**-0.173**
Hordeum vulgare	Winter barley	Beginning of hard dough/yellow ripeness	190.6	09-Jul	h	a	**-0.278**
Zea mays	Maize	Beginning of heading	190.8	09-Jul	t	a	**0.287**
Prunus avium	Sweet cherry (late varieties)	Fruit ripe for picking	194.3	13-Jul	h	p	-0.109
Ribes uva-crispa	Gooseberry	Fruit ripe for picking	194.8	13-Jul	h	p	-0.087

Hordeum vulgare	Winter barley	Harvest	201.4	20-Jul	h	a	-0.120
*Zea mays**	Maize	Full flowering	202.5	21-Jul	t	a	-0.047
Prunus cerasus	Sour cherry	Fruit ripe for picking	203.8	22-Jul	h	p	**-0.177**
Brassica napus var. *napus*	Winter rape	Harvest	206.4	25-Jul	h	a	**0.315**
Secale cereale	Winter rye	Beginning of hard dough/yellow ripeness	208.7	27-Jul	h	a	**-0.293**
Triticum aestivum	Winter wheat	Beginning of hard dough/yellow ripeness	214.7	02-Aug	h	a	**-0.313**
Avena sativa	Oats	Beginning of hard dough/yellow ripeness	217.9	05-Aug	h	a	-0.089
Malus domestica	Apple (early varieties)	Fruit ripe for picking	220.7	08-Aug	h	p	**-0.136**
Secale cereale	Winter rye	Harvest	221.0	09-Aug	h	a	**-0.143**
Triticum aestivum	Winter wheat	Harvest	227.3	15-Aug	h	a	**-0.217**
*Prunus domestica**	Plum (early varieties)	Fruit ripe for picking	229.8	17-Aug	h	p	**-0.197**
Avena sativa	Oats	Harvest	230.0	17-Aug	h	a	**-0.243**
*Rubus fruticosus**	Blackberry	Fruit ripe for picking	231.2	19-Aug	h	p	0.060
Brassica napus var. *napus*	Winter rape	Sowing	238.9	26-Aug	s	a	**-0.091**
Pyrus communis	Pear (early varieties)	Fruit ripe for picking	241.4	29-Aug	h	p	-0.067
Brassica napus var. *napus*	Winter rape	Emergence	250.2	07-Sep	t	a	**-0.068**
*Prunus domestica**	Plum (late varieties)	Fruit ripe for picking	261.6	18-Sep	h	p	0.028
Hordeum vulgare	Winter barley	Sowing	265.1	22-Sep	s	a	**-0.051**
Zea mays	Maize	Harvest	271.0	27-Sep	h	a	**-0.308**
Secale cereale	Winter rye	Sowing	274.8	01-Oct	s	a	**-0.074**
Hordeum vulgare	Winter barley	Emergence	277.3	04-Oct	t	a	**-0.085**
Beta vulgaris	Sugar beet	Harvest	278.8	05-Oct	h	a	**-0.059**
Pyrus communis	Pear (late varieties)	Fruit ripe for picking	279.8	06-Oct	h	p	-0.071
Beta vulgaris var. *crassa*	Fodder beet	Harvest	280.8	07-Oct	h	a	0.005
Malus domestica	Apple (late varieties)	Fruit ripe for picking	286.7	13-Oct	h	p	-0.056
Triticum aestivum	Winter wheat	Sowing	287.0	13-Oct	s	a	**-0.099**
Secale cereale	Winter rye	Emergence	288.2	15-Oct	t	a	**-0.094**

Triticum aestivum	Winter wheat	Emergence	302.9	29-Oct	t	a	**-0.116**

Table 2. Correlation coefficients of detrended national anomalies (after removing year trend) of the 78 phenological events on mean monthly temperatures from January through to the month in which the mean date of the event occurred. The final columns summarise four separate regression models per event: regression coefficients of detrended time series (after removing year trend) on March-May (MAM) and June-August (JJA) mean temperature, and ordinary regression coefficients against March-May and June-August mean temperatures. Regressions on June-August temperatures are only summarised for events with a mean date from July 1 onwards. All coefficients in bold are statistically significant (p<0.05).

			Correlation coefficients (detrended) with temperature in:									Regression coefficients of phase date on			
												detrended		ordinary	
Crop	**Phase**	Mean date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	MAM	JJA	MAM	JJA
Oat	Sowing	26-Mar	-0.24	**-0.50**	**-0.69**							**-4.15**		**-4.46**	
Gooseberry	First leaves	07-Apr	**-0.30**	**-0.63**	**-0.81**	**-0.31**						**-6.02**		**-7.41**	
Sugar-beet	Sowing	10-Apr	-0.13	**-0.39**	**-0.52**	-0.16						**-2.66**		**-3.68**	
Apricot	First flowers open	11-Apr	**-0.41**	**-0.73**	**-0.77**	**-0.35**						**-8.36**		**-8.52**	
Oat	Emergence	13-Apr	-0.22	**-0.51**	**-0.70**	**-0.30**						**-4.30**		**-4.59**	
Fodder beet	Sowing	18-Apr	-0.10	**-0.38**	**-0.50**	**-0.32**						**-2.22**		**-2.27**	
Peach	First flowers open	19-Apr	**-0.42**	**-0.74**	**-0.74**	**-0.43**						**-8.25**		**-8.30**	
Gooseberry	First flowers open	20-Apr	**-0.29**	**-0.63**	**-0.74**	**-0.46**						**-5.66**		**-6.49**	
Red currant	First flowers open	25-Apr	-0.25	**-0.58**	**-0.70**	**-0.49**						**-5.26**		**-5.99**	
Sweet cherry	First flowers open	26-Apr	**-0.35**	**-0.60**	**-0.67**	**-0.56**						**-5.49**		**-6.12**	
Winter barley	Beginning of shooting	29-Apr	**-0.40**	**-0.64**	**-0.66**	**-0.57**						**-4.12**		**-5.89**	
Winter rye	Beginning of shooting	29-Apr	**-0.37**	**-0.60**	**-0.59**	**-0.61**						**-3.80**		**-5.19**	
Sweet cherry	Full flowering	29-Apr	**-0.33**	**-0.59**	**-0.65**	**-0.57**						**-5.19**		**-5.71**	
Plum	First flowers open	30-Apr	**-0.41**	**-0.70**	**-0.69**	**-0.59**						**-7.82**		**-7.83**	
Maize	Sowing	01-May	-0.13	-0.24	-0.08	**-0.29**	-0.06					-0.60		**-1.86**	
Sugar-beet	Emergence	01-May	-0.19	**-0.42**	**-0.48**	**-0.52**	-0.16					**-3.07**		**-3.59**	
Pear	First flowers open	02-May	**-0.44**	**-0.62**	**-0.65**	**-0.57**	-0.11					**-5.83**		**-6.81**	
Sour cherry	First flowers open	02-May	**-0.35**	**-0.57**	**-0.62**	**-0.62**	-0.08					**-5.03**		**-5.65**	

Plum	Full flowering	03-May	**-0.41**	**-0.69**	**-0.68**	**-0.61**	-0.09			**-7.51**		**-7.51**	
Pear	Full flowering	05-May	**-0.42**	**-0.62**	**-0.62**	**-0.58**	-0.11			**-5.51**		**-6.47**	
Sour cherry	Full flowering	06-May	**-0.35**	**-0.57**	**-0.60**	**-0.63**	-0.10			**-4.82**		**-5.47**	
Sweet cherry	End of flowering	08-May	**-0.33**	**-0.57**	**-0.62**	**-0.61**	-0.12			**-4.88**		**-5.14**	
Winter wheat	Beginning of shooting	08-May	**-0.37**	**-0.61**	**-0.58**	**-0.60**	-0.24			**-3.78**		**-5.47**	
Fodder beet	Emergence	08-May	-0.18	**-0.39**	**-0.41**	**-0.59**	-0.22			**-2.57**		**-2.48**	
Apple (early ripening varieties)	First flowers open	09-May	**-0.38**	**-0.55**	**-0.58**	**-0.67**	-0.20			**-5.25**		**-6.06**	
Winter rape	First flowers open	09-May	**-0.48**	**-0.62**	**-0.60**	**-0.61**	-0.20			**-5.29**		**-6.40**	
Plum	End of flowering	10-May	**-0.40**	**-0.69**	**-0.66**	**-0.63**	-0.12			**-7.02**		**-7.01**	
Apple (early ripening varieties)	Full flowering	13-May	**-0.36**	**-0.53**	**-0.55**	**-0.67**	-0.22			**-5.01**		**-5.82**	
Pear	End of flowering	13-May	**-0.41**	**-0.60**	**-0.59**	**-0.61**	-0.16			**-5.21**		**-5.97**	
Sour cherry	End of flowering	14-May	**-0.36**	**-0.56**	**-0.57**	**-0.65**	-0.19			**-4.74**		**-5.29**	
Maize	Emergence	18-May	-0.22	-0.23	-0.01	**-0.37**	**-0.56**			**-1.44**		**-2.88**	
Oat	Beginning of shooting	21-May	-0.22	**-0.48**	**-0.49**	**-0.49**	**-0.39**			**-3.12**		**-4.26**	
Winter barley	Beginning of heading	21-May	**-0.39**	**-0.54**	**-0.48**	**-0.63**	**-0.42**			**-3.68**		**-4.61**	
Winter rye	Beginning of heading	22-May	**-0.36**	**-0.52**	**-0.45**	**-0.65**	**-0.43**			**-3.41**		**-4.03**	
Raspberry	First flowers open	29-May	-0.26	**-0.55**	**-0.60**	**-0.55**	**-0.48**			**-5.82**		**-5.84**	
Permanent grassland	First silage cut	04-Jun	-0.24	**-0.32**	**-0.49**	-0.20	**-0.53**	**-0.47**		**-3.17**		**-4.05**	
Winter rye	Full flowering	07-Jun	-0.19	**-0.39**	**-0.38**	**-0.38**	**-0.72**	**-0.39**		**-3.38**		**-4.51**	
Winter wheat	Beginning of heading	11-Jun	-0.27	**-0.43**	**-0.35**	**-0.53**	**-0.60**	**-0.46**		**-3.66**		**-4.78**	
Blackberry	First flowers open	13-Jun	-0.27	**-0.50**	**-0.57**	**-0.47**	**-0.57**	**-0.34**		**-5.18**		**-4.92**	
Strawberry (early ripening varieties)	Fruit ripe for picking	19-Jun	-0.13	**-0.42**	**-0.48**	**-0.41**	**-0.61**	**-0.52**		**-4.12**		**-4.08**	
Sugar-beet	Closed stand	20-Jun	-0.06	-0.23	**-0.31**	-0.11	**-0.58**	**-0.40**		**-2.40**		**-3.82**	
Oat	Beginning of heading	20-Jun	-0.19	**-0.38**	**-0.36**	**-0.47**	**-0.60**	**-0.52**		**-3.08**		**-3.95**	
Fodder beet	Closed stand	23-Jun	-0.10	-0.27	**-0.32**	**-0.30**	**-0.66**	**-0.44**		**-2.17**		**-2.86**	
Sweet cherry (early ripening varieties)	Fruit ripe for picking	27-Jun	-0.20	**-0.34**	**-0.35**	**-0.57**	**-0.63**	**-0.59**		**-3.94**		**-3.56**	
Raspberry	Fruit ripe for picking	08-Jul	-0.21	**-0.50**	**-0.55**	**-0.49**	**-0.53**	**-0.52**	-0.29	**-5.18**	**-4.23**	**-5.38**	**-4.26**

Red currant	Fruit ripe for picking	09-Jul	-0.19	**-0.39**	**-0.43**	**-0.56**	**-0.59**	**-0.59**	-0.19			**-4.33**	**-2.99**	**-5.27**	**-3.79**
Winter barley	Beginning of hard dough/yellow ripeness	09-Jul	**-0.30**	-0.27	-0.24	**-0.48**	**-0.50**	**-0.38**	**-0.35**			**-3.70**	**-4.15**	**-5.04**	**-5.18**
Maize	Beginning of heading	09-Jul	-0.17	-0.18	-0.16	-0.21	**-0.53**	**-0.52**	0.04			**-2.30**	-1.17	-0.84	**-0.31**
Sweet cherry (late ripening varieties)	Fruit ripe for picking	13-Jul	-0.21	**-0.33**	**-0.31**	**-0.54**	**-0.53**	**-0.61**	-0.21			**-4.17**	**-3.45**	**-4.76**	**-3.95**
Gooseberry	Fruit ripe for picking	13-Jul	-0.21	**-0.41**	**-0.47**	**-0.56**	**-0.57**	**-0.61**	-0.21			**-4.37**	**-3.08**	**-4.85**	**-3.48**
Winter barley	Harvest	20-Jul	**-0.33**	**-0.32**	**-0.48**	**-0.35**	**-0.49**	**-0.59**	**-0.42**			**-4.24**	**-4.42**	**-4.83**	**-4.91**
Maize	Full flowering	21-Jul	-0.40	-0.06	**-0.44**	0.24	-0.35	**-0.61**	**-0.45**			-2.63	**-5.40**	-2.76	**-5.39**
Sour cherry	Fruit ripe for picking	22-Jul	-0.22	**-0.36**	**-0.38**	**-0.47**	**-0.64**	**-0.61**	-0.22			**-4.29**	**-3.50**	**-5.26**	**-4.32**
Winter rape	Harvest	25-Jul	**-0.38**	**-0.41**	**-0.46**	**-0.41**	**-0.49**	**-0.55**	**-0.41**			**-4.23**	**-4.65**	**-2.51**	**-3.21**
Winter rye	Beginning of hard dough/yellow ripeness	27-Jul	**-0.30**	-0.28	-0.17	**-0.50**	**-0.50**	**-0.39**	**-0.54**			**-4.06**	**-5.99**	**-5.34**	**-7.05**
Winter wheat	Beginning of hard dough/yellow ripeness	02-Aug	**-0.34**	-0.29	-0.24	**-0.48**	**-0.54**	**-0.47**	**-0.58**	**-0.38**		**-4.14**	**-6.09**	**-5.49**	**-7.26**
Oat	Beginning of hard dough/yellow ripeness	05-Aug	-0.26	-0.24	-0.23	-0.28	-0.16	**-0.35**	**-0.50**	-0.20		**-3.68**	**-7.23**	**-4.11**	**-7.56**
Apple (early ripening varieties)	Fruit ripe for picking	08-Aug	-0.24	**-0.38**	**-0.35**	**-0.51**	**-0.60**	**-0.62**	-0.24	-0.21		**-3.82**	**-3.39**	**-4.57**	**-4.02**
Winter rye	Harvest	09-Aug	-0.27	-0.20	-0.25	**-0.30**	**-0.54**	**-0.53**	**-0.61**	**-0.36**		**-3.16**	**-5.67**	**-3.98**	**-6.37**
Winter wheat	Harvest	15-Aug	**-0.35**	-0.16	-0.27-	-0.21	**-0.53**	**-0.46**	**-0.61**	**-0.34**		**-3.24**	**-5.58**	**-4.42**	**-6.74**
Plum (early ripening varieties)	Fruit ripe for picking	17-Aug	-0.30	**-0.46**	**-0.45**	-0.29	**-0.46**	**-0.45**	**-0.40**	**-0.50**		**-3.82**	**-4.99**	**-4.23**	**-5.05**
Oat	Harvest	17-Aug	**-0.32**	-0.17	-0.25	-0.29	**-0.47**	**-0.45**	**-0.70**	**-0.41**		**-3.39**	**-6.91**	**-4.59**	**-7.93**
Blackberry	Fruit ripe for picking	19-Aug	-0.31	**-0.43**	**-0.42**	**-0.41**	**-0.54**	**-0.57**	**-0.56**	**-0.47**		**-4.93**	**-7.03**	**-4.80**	**-7.01**
Winter rape	Sowing	26-Aug	-0.24	-0.10	-0.26	-0.20	**-0.44**	**-0.28**	**-0.47**	**-0.34**		**-1.06**	**-1.66**	**-1.56**	**-2.08**
Pear (early ripening varieties)	Fruit ripe for picking	29-Aug	-0.26	**-0.41**	**-0.30**	**-0.30**	**-0.51**	**-0.49**	-0.28	-0.25		**-2.83**	**-3.21**	**-3.20**	**-3.51**
Winter rape	Emergence	07-Sep	-0.12	-0.17	-0.24	-0.14	**-0.45**	**-0.31**	**-0.35**	**-0.28**	-0.18	**-0.93**	**-1.34**	**-1.30**	**-1.65**
Plum (late ripening	Fruit ripe for picking	18-Sep	-0.28	**-0.44**	**-0.44**	**-0.38**	**-0.58**	**-0.49**	**-0.53**	**-0.45**	-0.05	**-4.20**	**-5.40**	**-4.14**	**-5.39**

varieties)															
Winter barley	Sowing	22-Sep	-0.12	-0.11	0.08	-0.15	**-0.39**	-0.20	**-0.37**	**-0.32**	-0.18	-0.37	**-1.19**	**-0.64**	**-1.42**
Maize	Harvest	27-Sep	-0.25	-0.13	-0.15	0.03	**-0.41**	**-0.29**	**-0.55**	**-0.50**	-0.19	-1.87	**-6.36**	**-3.55**	**-7.77**
Winter rye	Sowing	01-Oct	-0.10	-0.11	0.16	-0.10	**-0.38**	-0.18	-0.26	-0.19	-0.06	-0.24	**-1.00**	-0.64	**-1.34**
Winter barley	Emergence	04-Oct	-0.07	-0.03	0.17	-0.05	**-0.30**	-0.15	-0.23	-0.16	-0.23	-0.11	-1.07	-0.58	**-1.46**
Sugar-beet	Harvest	05-Oct	0.15	-0.12	-0.23	0.17	**-0.30**	-0.22	0.04	-0.01	-0.12	-0.57	-0.22	**-0.89**	-0.50
Pear (late ripening varieties)	Fruit ripe for picking	06-Oct	-0.24	**-0.29**	-0.22	**-0.51**	**-0.38**	**-0.46**	**-0.35**	-0.14	0.01	**-2.82**	**-3.13**	**-3.21**	**-3.46**
Fodder beet	Harvest	07-Oct	0.13	-0.18	-0.23	0.06	**-0.39**	-0.17	-0.09	-0.13	-0.09	**-0.62**	-0.48	-0.59	-0.45
Apple (late ripening varieties)	Fruit ripe for picking	13-Oct	-0.24	**-0.31**	**-0.30**	**-0.57**	**-0.48**	**-0.52**	**-0.41**	-0.23	0.02	**-2.63**	**-2.86**	**-2.93**	**-3.11**
Winter wheat	Sowing	13-Oct	-0.04	0.00	0.16	-0.16	-0.26	-0.18	**-0.32**	-0.17	-0.02	-0.23	**-1.37**	-0.77	**-1.82**
Winter rye	Emergence	15-Oct	-0.06	-0.07	0.19	-0.06	**-0.32**	-0.17	-0.18	-0.10	-0.06	-0.10	-0.92	-0.62	**-1.36**
Winter wheat	Emergence	29-Oct	-0.05	-0.01	0.10	-0.16	-0.25	-0.15	-0.26	-0.08	0.00	-0.45	-1.31	-1.09	**-1.85**

Table 3. A comparison of mean regression coefficients for annual and perennial crops. Regressions were either based on detrended series (after fitting a year trend) or calculated on ordinary series, and against mean March-May (MAM) temperature or mean June-August (JJA) temperature. Significance of differences between annual and perennial crops was determined by ANOVA. There were too few true phases of perennial crops late in the year to permit a reliable comparison with annual crops on the effects of JJA temperatures.

			Annual		Perennial		
Events	Detrended or Ordinary	Period	mean	SE	mean	SE	P
All	Detrended	MAM	-2.58	0.23	-5.07	0.24	<0.001
All	Ordinary	MAM	-3.28	0.27	-5.52	0.23	<0.001
All	Detrended	JJA	-3.37	0.53	-3.94	0.36	0.46
All	Ordinary	JJA	-3.80	0.60	-4.28	0.31	0.57
True	Detrended	MAM	-2.72	0.30	-5.77	0.27	<0.001
True	Ordinary	MAM	-3.48	0.37	-6.29	0.24	<0.001
Harvest/maturity	Detrended	MAM	-3.07	0.38	-3.96	0.20	0.043
Harvest/maturity	Ordinary	MAM	-3.78	0.47	-4.30	0.22	0.30
Harvest/maturity	Detrended	JJA	-4.81	0.66	-3.94	0.36	0.26
Harvest/maturity	Ordinary	JJA	-5.41	0.78	-4.28	0.31	0.19

Figure Legend

Figure 1. Trends in German agricultural and horticultural phenology (1951-2004). Triangles represent sowing dates, circles true events (such as emergence or flowering) and squares represent maturity or harvest events. Annually sown crops are shown as open symbols, perennial crops as solid symbols.

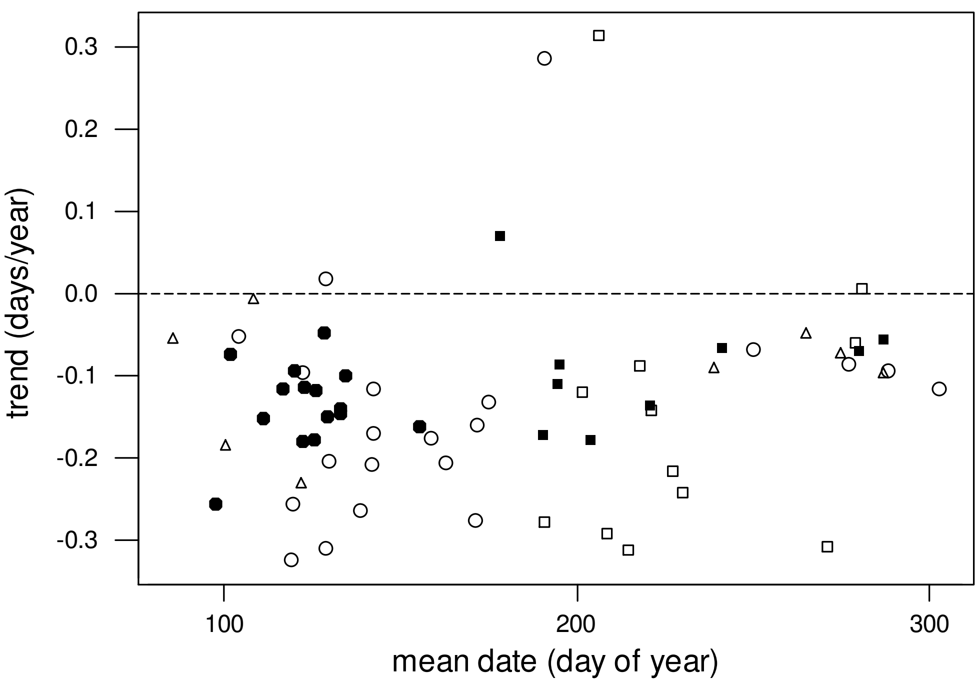
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
trend (days/year)
100
200
300
mean date (day of year)

Figure 1

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Global Change Biology

Spatial and temporal variability of the phenological seasons in Germany from 1951 to 1996

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Abstract

Various indications for shifts in plant and animal phenology resulting from climate change have been observed in Europe. This analysis of phenological seasons in Germany of more than four decades (1951-96) has several major advantages: (i) a wide and dense geographical coverage of data from the phenological network of the German Weather Service, (ii) the 16 phenophases analysed cover the whole annual cycle and, moreover, give a direct estimate of the length of the growing season for four deciduous tree species. After intensive data quality checks, two different methods - linear trend analyses and comparison of averages of subintervals - were applied in order to determine shifts in phenological seasons in the last 46 years. Results from both methods were similar and reveal a strong seasonal variation. There are clear advances in the key indicators of earliest and early spring (-0.18 to -0.23 d y-1) and notable advances in the succeeding spring phenophases such as leaf unfolding of deciduous trees (-0.16 to -0.08 d y-1). However, phenological changes are less strong during autumn (delayed by + 0.03 to + 0.10 d y-1 on average). In general, the growing season has been lengthened by up to -0.2 d y-1 (mean linear trends) and the mean 1974-96 growing season was up to 5 days longer than in the 1951-73 period. The spatial variability of trends was analysed by statistical means and shown in maps, but these did not reveal any substantial regional differences. Although there is a high spatial variability, trends of phenological phases at single locations are mirrored by subsequent phases, but they are not necessarily identical. Results for changes in the biosphere with such a high resolution with respect to time and space can rarely be obtained by other methods such as analyses of satellite data.

Keywords: climate change, Germany, growing season, phenology, season, trend, vegetation Period

Introduction

During recent years, phenology, the science of the timing of seasonal plant and animal activity, has had increasing attention in the context of climate change. Climate change may alter the onset of phenological phases such as the arrival of migrant birds or the length of the growing season, and affect the distribution and fitness of plants and animals. On the other hand, phenological changes in plants and animals, as well as shifting species ranges (e.g. Parmesan et al. 1999) or ice cover (Magnuson et al. 2000), are discussed as `fingerprints' for climate change. Whereas in high and mid-latitudes phenological spring phases were found to depend strongly on temperature conditions during winter and spring, the most important factors causing changes in autumn phases are not as clear.

Various indications for shifts in plant and animal phenology have been observed in Europe and the cool and temperate zones of the northern hemisphere (summarized, e.g. by Menzel 1999, Ahas 1999, Crick & Sparke 1999, Crick et al. 1997, Defila 2000). New results have been published recently by Jaagus & Ahas (2000), Roy & Sparks (2000), Schwartz & Reiter (2000), Sparks (1999), Sparks et al. (2000), Thomas & Lennon (1999), Beaubien & Freeland (2000) and Roetzer et al. (2000), covering leaf unfolding, flowering and leaf colouring of plants as well as the arrival dates of migrant birds, dates of egg laying of birds or spawning of fish and the timing of first appearance of butterflies. In general, only a few locations show records covering a century, while most of the data are from the last four to five decades only. Wide geographical coverage is available only for a very few species and phases. While some of these studies describe qualitative changes only (e.g. number of species with tendencies towards earliness), results of other studies can be quantified into trends in days/year. However, results of studies should be compared with caution, as the underlying time periods differ and strong regional differences are described. Almost all studies analyse one or a few different spring phases only. On average, spring has advanced by up to 0.3 d y-1 over the last three to four decades. Only a few studies deal with autumn phases whose shifts seem to be less pronounced and smaller.

In this study, the phenological database of the German Weather Service is used as direct biomonitoring data in order to analyse shifts in the phenological seasons over the last five decades. Compared to analyses of satellite data (Myneni et al. 1997) or CO2 records (Keeling et al. 1996), covering larger areas, the phenological dataset comprises longer time periods (starting in 1951). Moreover, the time-step of satellite observation (minimum of 7 days) is greater than the changes in phenology observed so far. Another advantage of this immense and comprehensive phenological network of more than 2000 volunteer observers is that the spatial variability of trends can be analysed. Phenological phases covering the whole vegetation period from very early spring to late autumn allow an assessment of the seasonal differences as well as the stability of trends of succeeding phases. Moreover, the growing season of different deciduous trees can be determined directly.

Materials and methods

Phenological observations

Since 1951, the German Weather Service has been operating a very dense phenological network with more than 2000 stations. Out of this huge observational programme (167 phenological phases of wild plants, agricultural crops, fruit trees and grapes) 16 phases of wild plants representing major phenological seasons were selected in order to cover the whole growing season. In Table 1 they are arranged in order of their seasonal development. For four deciduous tree species, the length of the growing season was defined directly as the time span between leaf colouring and leaf unfolding. Station information includes the geographical coordinates and altitude as well as the natural region.

Data quality check

As phenological observations for the German Weather Service are almost entirely made by volunteers, it may be that some of these prefer monitoring on weekends, thus causing a temporal bias in the data. Therefore, as a general quality check, the days of the week were calculated for all dates (see Table 2). Given an equal occurrence, every weekday should be represented by 14.29% of all days. It turns out that observations on Sundays are more frequent, whereas Thursdays are under-represented. For all five examples in Table 2, the H0 hypothesis of an equal distribution can be rejected at the 0.1% level.

Because all observations are stored in the database without any further quality checks, it is important to eliminate incorrectly recorded single values which may have resulted from errors in recording dates, from transferring and digitizing data or from misunderstandings of phase definitions. By means of a semi-automatic procedure, an intensive data-quality check was made (for further details see Menzel 1998; Estrella 1999), and obvious errors, such as records below or above a certain limit, were omitted. Records with less than 20 years of observation were discarded also, because analyses of trends and mean values for such short records are not useful (Rapp & Schönwiese 1995; Gornik 1994). For every phenological phase all records were plotted on the screen region-by-region, and records with excessive standard deviations were marked and checked for extreme values. Inhomogeneous records and those with many or longer gaps were omitted. No data were interpolated in order to prevent trends of adjacent stations being applied to the records. Finally, records significantly exceeding the existing variation within the bulk of data were discarded. After this data-quality check, about 1000 records with 30 years of observations remained (Table 3), for almost every phenological phase. Data from the former German Democratic Republic from 1951 to 1960 had not been digitized in the phenological database of the German Weather Service and were thus unavailable. Moreover, from 1982 to 1991, there were no observations of Fagus sylvatica in this part of Germany. Therefore, the density of stations with records of more than 20 or 30 years is reduced accordingly.

Methods of trend analysis

Phenological observations show, like other climate parameters, spatial and temporal variation. The trend is an indicator of a change in the onset of a phenological phase over a certain time period. Rapp & Schönwiese (1995) describe several methods for deriving a temporal trend from a time series. As phenological records have different lengths and include different years, it is not recommended to compare first and last values of the time series, or first and last values of a linear regression, but rather normalize the trend to one year.

For all 20 phenological phases in Table 1 the data on onset of phenophases have been related to the year by means of linear regression analysis. For a positive correlation between the onset and the year, i.e. a positive trend, the dates of onset are delayed over time, whereas a negative trend describes advancing onset. The F-test for the significance of the linear regressions requires a normal Gaussian distribution of the data. Because many phenological data are not normally distributed (Runge & Schönwiese 1986; Hechler 1990; Menzel 1997), the trend noise ratio and the Mann- Kendall-trend test should be calculated too (see Rapp & Schönwiese 1995). However, trends which are significant following the F-test ($P < 0.05$) are often significant following the two other tests too (Menzel 1997, 1998; Estrella 1999), and therefore the F-test was generally used.

Figure 1 shows the average curve of all springtime phenological series of the International Phenological Gardens in Europe. The years 1974 as well as 1989 and 1990 can clearly be recognized as years with early plant development. Linear trends calculated for records with varying starting years and the constant end year 1996 reveal that the trend is not independent of the time period analysed. For longer periods starting in 1986 and earlier the trends are always negative. Therefore, as a second method, mean phases averaged over different subintervals were compared in order to verify the results of the linear trend analysis. For this purpose, the whole period was both divided into two subintervals of equal length (1951-73 and 1974-96), and also split into two overlapping 30-y periods (1951-80 and 1967-96), in order to reduce the strong influence of the extreme year 1974. This method of comparing means of subintervals mostly results in weaker trends than linear regression analyses (Rapp & Schönwiese 1995).

Results of trend analyses

Significance

Only 5-33% of the normalized linear trends of records spanning 20 or more years (hereafter referred as records 20 +) and 6-38% of records with 30 or more years (hereafter referred as records 30 +) are significant (see Table 3). The first phenophases of the growing season, such as Galanthus nivalis and Forsythia suspensa flowering, which have a high variability, show less significant trends than phenophases occurring in the later spring, summer and autumn which have 25-33% of significant records (exceptions are flowering of Prunus avium and Malus domestica). For records 30 + the percentage of significant trends rises. Similar percentages have been reported by Menzel (1997, Menzel 2000) for the International Phenological Gardens and by Bradley et al. (1999) for 55 different phases observed in Wisconsin.

Sign

Both positive and negative trends can be found for the same phase (see Table 3). All spring phenophases have up to 22% significant negative trends. Following the seasonal order, flowering of Tilia platyphyllos and fruit ripening of Sambucus nigra mostly reveal negative trends as well, whereas leaf colouring of A. hippocastanum, B. pendula and F. sylvatica shows almost the same percentage of negative and positive trends. For leaf colouring of Quercus robur the trends are mostly positive and indicate a later onset of fall. The annual growing season clearly indicates a gradual lengthening over the years.

Mean values

Analyses of mean values also indicate an earlier onset of spring phenophases and a later onset of autumn phases. In detail, all spring phenophases as well as the midsummer phase of flowering of T. platyphyllos and the early autumn phase of fruit ripening of S. nigra have mean negative trends (see Table 4). The strength of these negative trends clearly decreases from very early spring to the beginning of summer, with the exception of flowering of G. nivalis, M. domestica and P. avium. The mean trend of the mid-autumn phase of fruit ripening of Aesculus hippocastanum is almost zero, whereas all late autumn phases show mean positive trends. Compared to analyses of all data, mean trends become higher when only significant records are considered.

For the four deciduous tree species the mean trends of the growing season are positive indicating a lengthening over the last decades. They range between 0.11 (F. sylvatica) to 0.22 (Q. robur) d y-1 (records 20 +) and between 0.10 (F. sylvatica) to 0.18 (B. pendula) d y-1 (records 30 +). Thus, over a 30-y period the growing season would have been extended by 3.3-5.6 d.

Spatial distribution

Eight examples of spatial distribution of trends in Germany of all records 20 + are shown on maps (Fig. 2). For every phenological station the normalized trend is characterized by its sign (black = negative trend or earlier onset, grey = positive trend or later onset) and its significance (not significant or $P > 0.05$, significant or $P < 0.05$ and highly significant or $P < 0.01$) indicated by the size of the dot. Generally, neither the sign of the trend nor the significance level seem to be dependent on geography.

In most cases, spring phenophases are earlier, even though both positive and negative trends can be found all over Germany. However, different spatial patterns can be identified according to species (Fig. 2).

Flowering of G. nivalis, the key phase of the earliest spring, mostly shows tendencies towards an earlier onset in Germany, with significant negative trends being more frequent in southern

Germany. Flowering of F. suspensa, a key indicator of the early spring, has almost exclusively negative trends, significant ones being more frequent in northern Germany. Maps of leaf unfolding of B. pendula (not shown here) and A. hippocastanum are quite similar, with predominantly negative trends - there are just a few positive trends which appear to be concentrated in the low mountain range of central Germany. In contrast, late spring phases, such as leaf unfolding of F. sylvatica and Q. robur (not shown here) as well as May shooting of P. abies, show several positive trends across Germany, but negative trends are clearly predominant. Flowering of M. domestica (not included) and P. avium are interesting in that their trends are largely insignificant. The midsummer flowering phase of T. platyphyllos (not shown) as well as fruit ripening of S. nigra, which occur in early autumn, have some positive trends which seem to be concentrated both in the low mountain range and in the eastern parts of Germany. Negative and positive trends of both fruit ripening and leaf colouring of A. hippocastanum (mid and late autumn) balance each other equally. In contrast, leaf colouring of Q. robur (shown in Fig. 2) and B. pendula clearly have predominantly positive trends with occasional negative trends distributed equally over Germany.

Correlation with geographical parameters

The linear trends have been related to geographical longitude, latitude and altitude by means of linear regression and multiple linear regression in order to give exact figures for the spatial distribution. Flowering of T. platyphyllos, fruiting and leaf colouring of A. hippocastanum revealed no significant correlation either with altitude, latitude or with longitude. All other regressions on altitude were significant, but the percentage variation accounted for by the regression model (R^2) was always lower than 4%. About half of the regressions on latitude and longitude were significant, but the influence of these two variables is also very weak ($R^2 < 6\%$). For spring phases, with the exception of flowering of G. nivalis, there is a positive correlation between altitude and trend (in lower altitudes more negative trends, R^2_{max} 3%), a negative correlation between latitude and trend (in northern parts more negative trends, R^2_{max} 5%) and almost no significant correlation with longitude. For autumn phases, the trend decreases with altitude and longitude (higher altitudes and eastern parts with weaker positive or more negative trends, R^2_{max} 1%) and has no significant correlation with latitude. For the trends of the length of growing season there are significant negative correlations with altitude (higher trends in lower altitudes, R^2_{max} 2%). Therefore, correlations of trends with geographical parameters may be significant, but not relevant.

Further information including slope, exposure and soil properties is not available.

In order to illustrate this relationship between strength of trend and station altitude, the frequency of positive and negative trends were compared within specified elevation ranges (Fig. 3): spring phenophases, such as flowering of F. suspensa (b) and leaf unfolding of B. pendula (a), have a higher percentage of negative trends at lower elevations, whereas for the autumn phase of leaf colouring of B. pendula (c) the proportion of positive trends does not differ much over the altitude range. Tendencies towards a lengthening of the growing season of B. pendula (d) are most pronounced at lower altitudes.

Reproducibility of trends in phenological seasons

The trends obtained for the different phenophases show a characteristic seasonal variation: high negative trends in early spring with decreasing strength of trend to low values in early autumn, then positive trends in late autumn. However, high spatial variability demands the comparison of succeeding phenological events observed at the same station in order to study the reproducibility of trends. Figure 4 gives an example of such an analysis showing the trends of two succeeding phenophases in spring, leaf unfolding of A. hippocastanum and B. pendula. The overall correlation is quite good (r = 0.60). However, the majority of trends is located in the 3rd quadrant, indicating an earlier onset of leaf unfolding both of A. hippocastanum and B. pendula. Only a few stations reveal a later onset of both phenophases (1st quadrant). There are many stations with no significant trend for either phenophases and a few stations where only one of them is significant. But phenological stations with significant trends of both phenophases mostly fall into the 3rd quadrant. Therefore, trends are mirrored by subsequent phenophases, although they are not necessarily identical with respect to strength and significance.

Comparison of mean values of different subintervals

A second verification of trend results was carried out by comparing phenological phases averaged over different subintervals (1951-73 to 1974-96 and 1951-80 to 1967-96) (Table 4). A positive difference suggests an earlier onsetin the second period, while a negative difference suggests a later onset. As mean values depend strongly on the number of observations (Schnelle 1955; Gornik 1994), only records with more than 20 observations in the two periods of 23 years or more than 27 observations in the two periods of 30 years were used. This precondition reduced the number of records considerably, especially in the eastern parts of Germany.

Early spring phenophases (such as flowering of G. nivalis and F. suspensa) were observed 6 days earlier during the period 1974-96 than during the 1951-73 period. Leaf unfolding of A. hippocastanum and B. pendula has advanced by 3 days, May shoot of P. abies, leaf unfolding of Q. robur and flowering of P. avium by only 1 day, whereas leaf unfolding of F. sylvatica and flowering of M. domestica have not changed at all. Fruit ripening of S. nigra occurs about 3 days earlier during the second subinterval, while the date of fruit ripening of A. hippocastanum has not changed on average.

The onset of autumn phases is generally observed later in the second subinterval; by half a day for leaf colouring of A. hippocastanum and almost 3 days for leaf colouring of Q. robur. Overall, the growing season has lengthened by up to 5 days.

The latter period includes the very early years 1974, 1989 and 1990, thus resulting in a large difference between subintervals. The comparison was repeated for a second pair of 30 years subintervals (1951-80 to 1967- 96). Compared to the first analysis the mean differences are smaller, but the tendency is the same: an earlier onset of spring, a later onset of autumn and a lengthening of the growing season, up to 1.5 days for F. sylvatica and 3.3 days for Q. robur.

Discussion

The most important first step before calculating trends in phenological records is a careful quality control (Rötzer 1996; Menzel 1997). Nevertheless, extreme values still escape a first control run and can lead to dubious high trends.

For the present study, two different methods of trend analysis were chosen: normalized linear trends of records with 20 or 30 years of observations and comparisons of mean values for different subintervals (1951-73 and 1974-96 as well as 1951-80 and 1967-96). The results obtained with both methods were similar and the shifts of phenological records during the last 4-5 decades reveal a very strong seasonal variation. This was reported for the February to June months by Bradley et al. (1999) as well. This seasonal variation consists of clear advances of flowering of G. nivalis (by -0.18 d y-1 for records with 30 y and more) and of flowering of F. suspensa (by -0.23 d y-1) and notable advances of the succeeding spring phenophases such as May shoot of P. abies and leaf unfolding of deciduous trees.

Continuing in the annual sequence key phases of midsummer and early autumn, flowering of T. platyphyllos and fruit ripening of S. nigra, advance slightly by -0.10 and -0.13 d y-1, respectively, whereas the key phases of full autumn, fruit ripening and leaf colouring of A. hippocastanum, show almost no change. Phases occurring in late autumn, such as leaf colouring of Q. robur,

F. sylvatica and B. pendula, are delayed (+ 0.03 to + 0.10 d y-1).

Only the phenophases of flowering of M. domestica and P. avium and leaf unfolding of F. sylvatica, deviate from this seasonal behaviour because of weaker tendencies. The smaller reaction of F. sylvatica to changes in winter and spring temperatures is already described in the literature (Kramer 1995; Menzel 1997). The smaller trend in flowering phases suggests that flowering of M. domestica and P. avium is triggered more by photoperiod than by air temperature or that shifts in cultivars planted may have caused this smaller changes in flowering.

The analyses of spatial variability of the trends, as shown in maps and analysed by linear and multiple linear regressions, did not reveal any substantial regional differences although the influence of the independent variable `elevation above sea level' was found to be significant for most of the phenophases studied here. It is the intention of the present authors to investigate whether this is caused by different temperature changes or by other factors that vary with altitude, such as exposure and slope, or that are more frequent in the low mountain range (e.g. soil factors). The high spatial variability of trends is not caused by the different record lengths because maps of the mean differences between the 1951-73 and 1974-96 subintervals showed the same spatial variability of changes.

In general, over the last 4-5 decades, the growing season has been lengthened, by up to 0.2 d y-1 (0.11 for F. sylvatica, 0.17 for A. hippocastanum, 0.18 for B. pendula and0.22 Q. robur, records 20 +). The second method of trend analysis revealed a lengthening of 3 (F. sylvatica) to 5 days (B. pendula) between the 1951-73 and 1974-96 subintervals. Relating these changes of 3-5 days to the 23 years spanning from 1962 (centre of the 1951-73 period) and 1985 (centre of the 1974-96 period), also gave advances ranging from 0.13 to 0.23 d y-1. Thus, the results using the two different methods are nearly identical. In general, advances of spring phases are more pronounced than delays of autumn phases. Compared to results of other studies (e.g. Rapp & Schönwiese 1994; Kramer 1995; Menzel 1999; 2000) these reported changes are slightly smaller. This may result from differences in the periods analysed. Kramer (1995) suggested that the reaction of the cloned plants in the International Phenological Gardens to rising air temperature is equal or higher than that of native and site-adapted plants. In the present study the length of growing season is directly calculated for four deciduous tree species, whereas in the analysis of the data of the International Phenological Gardens (Menzel & Fabian 1999; Menzel 2000) the lengthening was determined based on the advance of spring (mean value of trends of all phenophases from earliest spring to late spring) and the delay of autumn (mean value of trends of leaf colouring).

This lengthening of the growing season up to 5 days (direct comparison of 1951-73 and 1974-96 subintervals) or up to 6.6 days, respectively (linear trend of 0.22 d y-1 projected for a 30-y period) seems small. However, given a total length of the growing season of 160-165 d for F. sylvatica, Q. robur and B. pendula, this lengthening amounts to about 5% and thus may be important.

By means of trend analysis of phenological phases, changes in the biosphere can be detected for the whole seasonal cycle and for large regions (Menzel 1999). Such data are at much higher resolution in time and space than those that can be obtained generally by other methods, such as those from remote sensing. For example, both negative and positive trends can be found even at adjacent stations, a sensitivity that is beyond the lower resolution capabilities of satellite data.

Therefore, phenology is an important instrument for biomontitoring.

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Table 1 Phenological phases and corresponding phenological seasons analysed

Phenological season	No.	Phase	Species (Latin)	Species (Engl.)
Earliest spring	1	Flowering	*Galanthus nivalis* L.	Snowdrop
Early spring	2	Flowering	*Forsythia suspensa* (THUNB.) VAHL	Forsythia
	3	Leaf unfolding	*Betula pendula* ROTH	Silver birch
	4	Leaf unfolding	*Aesculus hippocastanum* L.	Horse chestnut
	5	Flowering	*Prunus avium* [L.] MOENCH	Sweet cherry
	6	Leaf unfolding	*Fagus sylvatica* L.	Common beech
Late spring	7	Flowering	*Malus domestica* BORKH.	Apple
	8	Leaf unfolding	*Quercus robur* L.	Common oak
	9	May shoot (first needle emergence)	*Picea abies* (L.) KARST.	Norway spruce
Mid-summer	10	Flowering	*Tilia platyphyllos* SCOP	Large-leafed lime
Early autumn	11	Fruit ripening	*Sambucus nigra* L.	Common elder
Mid autumn	12	Fruit ripening	*Aesculus hippocastanum* L.	Horse chestnut
Late autumn	13	Leaf colouring	*Aesculus hippocastanum* L.	Horse chestnut
	14	Leaf colouring	*Betula pendula* ROTH	Silver birch
	15	Leaf colouring	*Fagus sylvatica* L.	Common beech
	16	Leaf colouring	*Quercus robur* L.	Common oak
	17	Growing season	*Betula pendula* ROTH	Silver birch
	18	Growing season	*Fagus sylvatica* L.	Common beech
	19	Growing season	*Aesculus hippocastanum* L.	Horse chestnut
	20	Growing season	*Quercus robur* L.	Common oak

Table 2 Frequency distribution [%] of the days of the week on which phenological events are recorded (only selected phases)

	Leaf unfolding of *B. pendula*	Leaf unfolding of *F. sylvatica*	May shoot of *P. abies*	Leaf colouring of *B. pendula*	Leaf colouring of *F. sylvatica*
Monday	14.7	14.8	14.5	14.3	14.1
Tuesday	14.0	13.9	14.1	14.4	14.3
Wednesday	14.3	14.1	13.7	14.1	14.1
Thursday	13.8	13.9	14.0	13.8	13.5
Friday	14.0	14.0	14.0	14.3	14.4
Saturday	14.5	14.3	14.7	14.3	14.4
Sunday	14.7	15.1	15.0	14.8	15.2

Table 3 Percentage of records with negative, significant negative (sig. neg.), positive and significant positive (sig. pos.) trends for records with 20 years and more (records 20 +) and 30 years and more, respectively (records 30 +)

		Trend of records 20 +					Trend of records 30 +				
No.	Phenophase	No. in total	% neg.	% sig. neg.	% pos.	% sig. pos.	No. in total	% neg.	% sig. neg.	% pos.	% sig. pos.
1	*G. nivalis* F	2212	72	11	28	1	1180	77	16	23	1
2	*F. suspensa* F	1687	85	11	15	0	865	90	15	10	0
3	*B. pendula* LU	2540	74	17	26	2	1273	77	20	23	2
4	*A. hippocastanum* LU	2442	76	22	24	2	1216	79	26	21	2
5	*P. avium* F	2269	62	4	38	1	1050	61	4	39	2
6	*F. sylvatica* LU	1893	63	19	37	6	874	61	19	39	7
7	*M. domestica* F	2410	59	8	41	4	1142	58	7	42	4
8	*Q. robur* LU	1932	68	22	32	5	888	69	21	31	5
9	*P. abies* M	1926	68	22	32	5	775	67	22	33	6
10	*T. platyphyllos* F	1568	66	15	34	5	679	71	18	29	4
11	*S. nigra* FR	2055	64	23	36	8	928	68	28	32	7
12	*A. hippocastanum* FR	2247	54	14	46	11	1020	56	16	44	12
13	*A. hippocastanum* LC	2086	52	16	48	15	976	53	19	47	18
14	*B. pendula* LC	2298	45	14	55	19	1058	45	15	55	23
15	*F. sylvatica* LC	1781	47	15	53	18	818	45	16	55	22
16	*Q. robur* LC	1670	39	9	61	23	741	36	9	64	29
17	*B. pendula* GS	1044	34	6	66	24	444	31	7	69	28
18	*F. sylvatica* GS	790	39	6	61	19	354	38	6	62	23
19	*A. hippocastanum* GS	1845	33	5	67	22	793	32	7	68	23
20	*Q. robur* GS	1325	27	4	73	28	549	25	4	75	31

Table 4 Mean trends (sig., significant trends only) and mean differences between the subintervals 1951-73/1974-96 and 1951-80/ 1967-96, respectively,

		Mean trends [dy-1]				Difference 1951-73 & 1974-69 mean			Difference 1951-80 & 1967-96 mean		
		Records									
No.	Phenophase	20 +	20 + (sig.)	30 +	30 + (sig.)	No.	mean value [d]	SD	No.	mean value [d]	SD
1	*G. nivalis* F	-0.16	-0.48	-0.18	-0.48	235	6.26	5.28	227	2.46	3.46
2	*F. suspensa* F	-0.24	-0.53	-0.23	-0.48	121	6.03	3.47	115	3.04	2.36
3	*B. pendula* LU	-0.14	-0.37	-0.13	-0.34	179	3.02	3.17	172	1.5	2.05
4	*A. hippocastanum* LU	-0.16	-0.38	-0.15	-0.33	218	3.08	3.95	209	1.75	2.46
5	*P. avium* F	-0.05	-0.18	-0.03	-0.1	166	1.02	2.56	157	0.31	1.63
6	*F. sylvatica* LU	-0.08	-0.23	-0.06	-0.17	156	0.09	3.56	150	0.08	2.41
7	*M. domestica* F	-0.05	-0.21	-0.03	-0.08	178	0.78	2.97	175	0.49	1.94
8	*Q. robur* LU	-0.12	-0.31	-0.09	-0.23	127	0.87	3.24	117	0.85	2.28
9	*P. abies* M	-0.13	-0.31	-0.09	-0.22	94	1.42	4.01	90	0.93	2.73
10	*T. platyphyllos* F	-0.09	-0.24	-0.1	-0.24	78	1.34	4.46	71	1.29	2.66
11	*S. nigra* FR	-0.12	-0.28	-0.13	-0.3	128	2.78	6	121	2.53	3.82
12	*A. hippocastanum* FR	-0.02	-0.06	-0.03	-0.06	145	0.65	5.09	137	0.52	3.29
13	*A. hippocastanum* LC	0	-0.01	-0.01	-0.01	169	-0.33	5.94	163	-0.03	3.8
14	*B. pendula* LC	0.03	0.07	0.04	0.1	167	-2.16	7.16	159	-1.42	4.74
15	*F. sylvatica* LC	0.03	0.06	0.03	0.07	175	-2.3	6.19	168	-1.18	3.96
16	*Q. robur* LC	0.09	0.23	0.1	0.23	119	-3.74	5.61	112	-2.22	3.49
17	*B. pendula* GS	0.18	0.44	0.18	0.39	60	-4.8	7.57	58	-2.92	5.3
18	*F. sylvatica* GS	0.11	0.33	0.1	0.29	58	-2.92	6.64	55	-1.53	3.91
19	*A. hippocastanum* GS	0.17	0.44	0.14	0.31	116	-3.56	7.11	114	-1.89	4.44
20	*Q. robur* GS	0.22	0.49	0.18	0.39	72	-4.61	5.94	66	-3.29	3.9

Figure Legend

Figure 1 Mean onset of spring phenophases in the International Phenological Gardens and dependence of their normalized linear trends on the period analysed (fixed end 1996, variable starting years) (after Menzel 1998)

Figure 2 Linear trend and its significance according to F-test of all records with 20 years of observations and more. Black dot: negative trend, grey dot: positive trend, small sized dot: $P > 0.05$, medium: $P < 0.05$, great: $P < 0.01$)

Figure 3 Frequency [%] of negative (black) and positive (grey) trends in different altitude ranges: a leaf unfolding of B. pendula, b flowering of F. suspensa, c leaf colouring and d growing season of B. pendula

Figure 4 Trends of leaf unfolding of B. pendula (y-axis) compared with those of A. hipocastanum (x-axis) at single stations. Significance is given according to F-test.

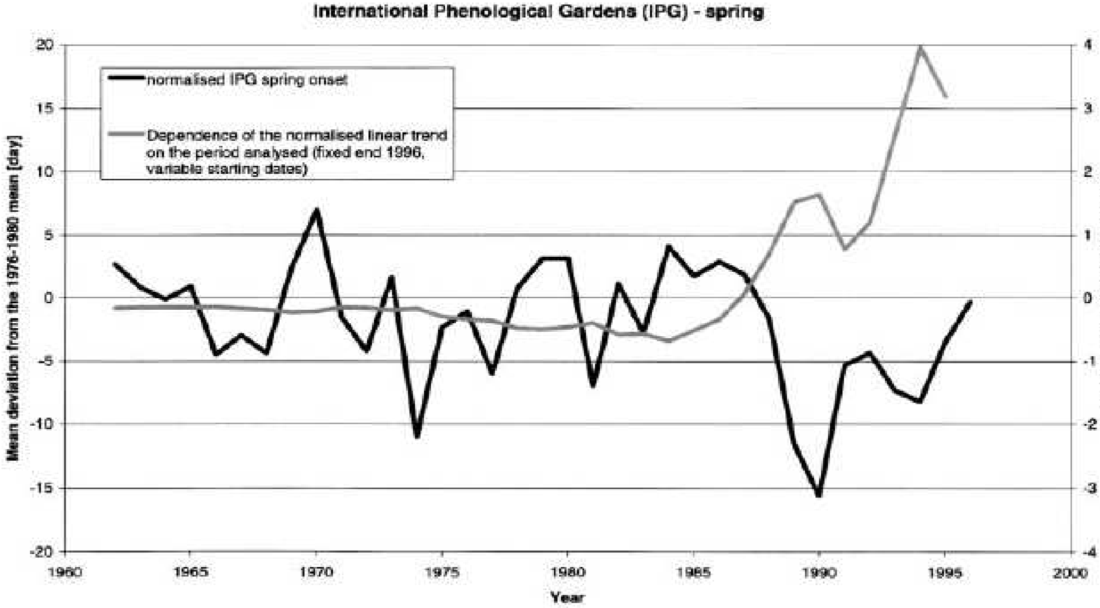
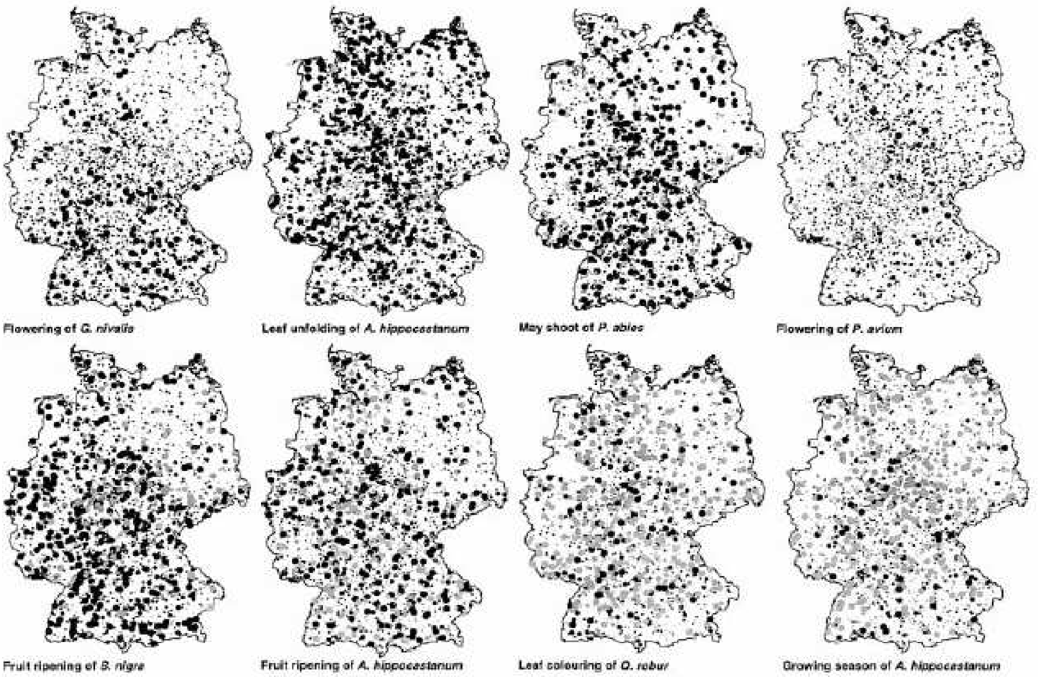


Figure 1



Flowering of *G. nivalis*
Leaf unfolding of *A. hippocastanum*
May shoot of *P. abies*
Flowering of *P. avium*
Fruit ripening of *S. nigra*
Fruit ripening of *A. hippocastanum*
Leaf colouring of *Q. robur*
Growing season of *A. hippocastanum*

Figure 2

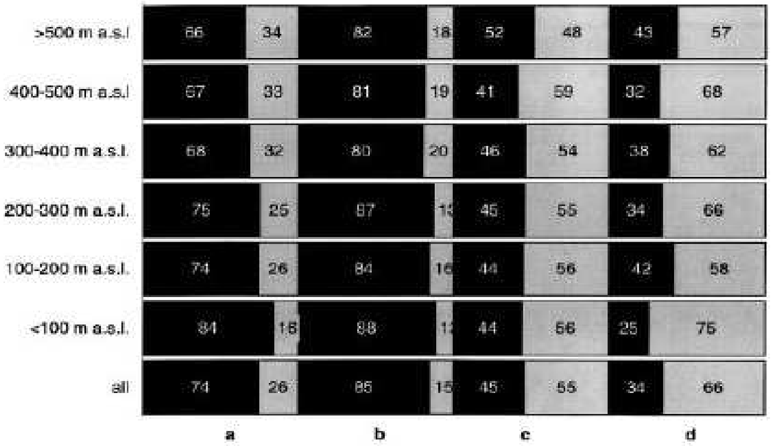


Figure 3

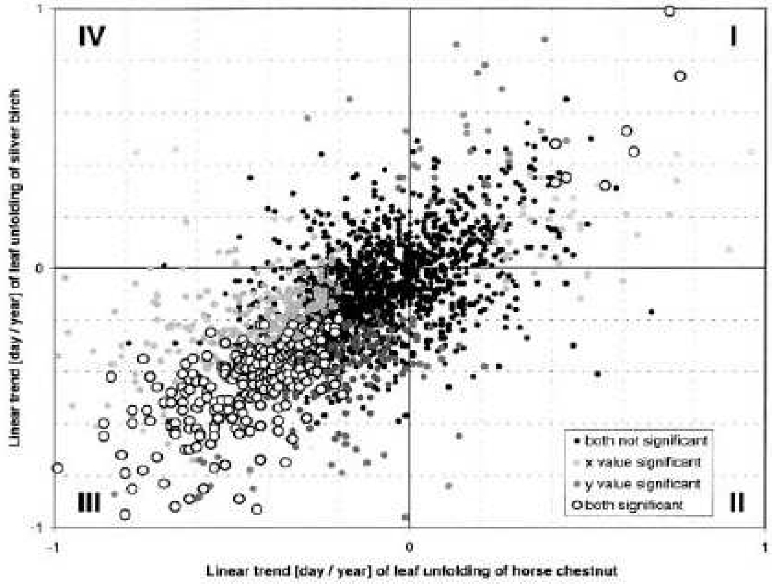


Figure 4

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Global Change Biology

European phenological response to climate change matches the warming pattern

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Abstract

Global climate change impacts can already be tracked in many physical and biological systems; in particular, terrestrial ecosystems provide a consistent picture of observed changes. One of the preferred indicators is phenology, the science of natural recurring events, as their recorded dates provide a high-temporal resolution of ongoing changes. Thus, numerous analyses have demonstrated an earlier onset of spring events for mid and higher latitudes and a lengthening of the growing season. However, published single-site or single-species studies are particularly open to suspicion of being biased towards predominantly reporting climate change-induced impacts. No comprehensive study or meta-analysis has so far examined the possible lack of evidence for changes or shifts at sites where no temperature change is observed.We used an enormous systematic phenological network data set of more than 125 000 observational series of 542 plant and 19 animal species in 21 European countries (1971–2000). Our results showed that 78% of all leafing, flowering and fruiting records advanced (30% significantly) and only 3% were significantly delayed, whereas the signal of leaf colouring/fall is ambiguous. We conclude that previously published results of phenological changes were not biased by reporting or publication predisposition: the average advance of spring/summer was 2.5 days / decade in Europe. Our analysis of 254 mean national time series undoubtedly demonstrates that species' phenology is responsive to temperature of the preceding months (mean advance of spring/summer by 2.5 days / °C, delay of leaf colouring and fall by 1.0 day / °C). The pattern of observed change in spring efficiently matches measured national warming across 19 European countries (correlation coefficient $r=-0.69$, $p<0.001$).

Key words: climate change, Europe, growing season, meta analysis, phenology, season, temperature response, trend

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Introduction

Many studies examining the impacts of global warming on terrestrial ecosystems reveal a consistent pattern of change, the response to warming by phenological change across the northern hemisphere seems to be especially well documented (IPCC, 2001; Sparks & Menzel, 2002; Walther et al., 2002; Parmesan & Yohe, 2003; Root et al., 2003). The majority of the published studies focus on the question of whether changes in systems and sectors relate to changing regional climates. As a consequence of this bulk of studies, further reporting of phenological trends in peer-reviewed journals may become more and more difficult, especially when 'simply' dealing with 'no change' or 'change opposite to the direction expected' (Hughes, 2000; Kozlov & Berlina, 2002; Menzel, 2002). Thus, there exists the danger of reporting or publication bias of these observed impacts. In principle, four combinations of system and climate changes are possible (Fig. 1). 'No change' in the tracking systems seems to be less likely to be reported, especially if it matches with 'no change' in temperatures. However, this combination also emphasises consistency with the functional understanding of the system and predicted climate responses. Within the Intergovernmental Panel on Climate Change (IPCC), Working Group II on Impacts, Adaptation and Vulnerability is involved with an assessment of observed changes for its next report (AR4, April 2007). Here, it is extremely important to keep track of the entirety of changes in order to properly address the questions of evidence of no change, change opposite to the direction expected, change not matching climate/ temperature change, and to discuss the questions of resilience and thresholds.

Two recent meta-analyses have summarized the coherent picture of a global ‘fingerprint’ of climate change. Parmesan & Yohe (2003) included multispecies studies from any location that reported neutral, negative and positive results and analysed a total of 677 species or species functional groups’ phenology. However, the results of one study site in the United Kingdom (Fitter & Fitter, 2002) alone accounted for nearly half of its records. A second meta-analysis was restricted to publications reporting significant changes of one or many species (Root et al., 2003). Consequently, the average spring advance revealed by the latter was higher (5.1 compared with 2.3 days decade^{-1}). Metaanalyses which include reanalyses of network data for all available species do not yet exist. Thus, the goal of the present study was an exhaustive Europe-wide analysis of all observed changes in phenology (plants/ animals) in the period 1971–2000. Owing to the systematic (re-)analysis of all available records, including those from dense phenological networks, this metaanalysis allows, for the first time, a methodical review of absence of evidence and of possible reporting or publication bias. By incorporating monthly temperature series for countries, we were able also to quantify the species’ responsiveness to temperature.

Material and Methods

An extremely abundant data set of trends in European phenological phases was systematically collected within the COST action 725 ‘Establishing a European phenological data platform for climatological applications’ (http://www.cost725.org) comprising all phenological records digitally available at present. It included entire phenological networks of 11 countries (Austria, Belgium, Czech Republic, Estonia, Germany, Latvia, Poland, Slovakia, Slovenia, Switzerland, Russia (provided by the 5FP project POSITIVE)), five specialists networks (Finland, Spain, the Netherlands, Norway, United Kingdom) and the network of the International Phenological Gardens in Europe (http://www.agrar.huberlin. de/pflanzenbau/agrarmet/ipg_en.html), spreading over 14 countries including, in addition to countries named above, Croatia, Denmark, Greece, Ireland and Macedonia. In total, phenological trends of 542 plant species in 21 countries (125 628 time series) and 19 animal species in three countries (301 time series) were analysed. The phenophases of wild plants, fruit trees and agricultural crops were assigned to a BBCH (Biologische Bundesanstalt, Bundessortenamt and CHemical Industry) code (Meier, 1997) and grouped either by BBCH code or BBCH subgroups (principal growth stages). If applicable, agricultural and natural phases were treated separately.

Annual mean onset dates for nine countries (Austria, Belarus/northern Russia, Estonia, Czech Republic, Germany, Poland, Slovenia, Switzerland, Ukraine/ southern Russia), comprising 254 records (phenophases×countries) of 10+ years, however mostly covering the total period 1951–1999, were available for the quantitative assessment of temperature responses. Annual, monthly and seasonal temperature means for all European countries (1901–2000) were used from the Tyndall Centre (Mitchell et al., 2002, 2004). Annual mean onset dates were correlated by Pearson’s product moment correlation with three mean monthly temperatures (the month of mean onset, and the two preceding months) of the respective country. The highest correlation coefficient of these three served as a measure for the temperature responsiveness of the respective phenophase in that country. The slopes of linear regressions of the annual mean dates against the mean temperature of the month before the event provided a measure for the temperature sensitivity. These regression coefficients were analysed in total, by mean onset date, by phenophase group and for selected species×country combinations.

Each of the COST725 team member states contributed a countrywide trend analysis (1971–2000) including mean onset dates and their standard deviation, linear regressions of the onset dates against year including slope of the regression, standard error of the slope and significance of the regression by F-test. In the subsequent meta-analysis (103 199 records of 15+ years) these trends were analysed for Europe by four phenophase groups (b0, farmers' activities; b1, flowering and leaf unfolding; b2, fruiting; b3, leaf colouring), for countries by phenophase groups, and for countries and species.

Results

We found that phenological changes were a clear reaction to temperature. Figure 2a displays all correlation coefficients of 254 mean national records with temperature. Most phases correlated significantly with mean monthly temperatures of the month of onset and the two preceding months. For 19% of the phenophases the highest correlation was with the month of onset, 63% with preceding month and 18% with 2 months earlier. The average correlation coefficients for four groups (farmers' activities, spring and summer phases, fruit ripening, leaf colouring) are given in Table 1; their means all clearly differed from zero (t-tests, b0-b2 $p<0.001$, b3 $p<0.007$). Analysis of Variance followed by Tukey's HSD showed that there were significant differences ($p<0.001$) between the groups in their average correlation with temperature, all of which differed from one another except farmers' activities and fruit ripening.

For spring and summer, and most of the autumn fruit ripening phases, the mean correlation coefficient was negative. Thus, higher temperatures were related to earlier onset dates. The mean value for flowering (Fig. 2a, $\bar{r}=-0.69$) and other spring phases, such as leaf unfolding and budburst of wild plants ($\bar{r}=-0.69$), shooting and closure of the stands ($\bar{r}=-0.62$) as well as ear formation ($\bar{r}=-0.55$) of agricultural crops displayed quite similar temperature sensitivity. Farmers' activities, such as drilling, tilling, harvesting, known as 'false phases', which respond to a lesser degree to climate, also revealed a quite high mean correlation with temperature($\bar{r}=-0.53$). Only the emergence and sprouting of agricultural winter crops in autumn, which is very much related to harvesting and subsequent drilling, were less related to temperature ($\bar{r}=-0.28$). Earlier fruit ripening was connected to warmer summers ($\bar{r}=-0.45$); only for Aesculus hippocastanum in Switzerland and Slovenia was there an opposite relationship. Fruit ripening of agricultural plants was more closely related to temperature ($\bar{r}=-0.57$) than wild plants ($\bar{r}=-0.29$). Delayed leaf colouring was associated with higher temperatures ($\bar{r}=+0.33$); only in eastern Europe (Russia-Belarus, Russia-Ukraine and Czech Republic) did warming result in earlier leaf colouring. There was a clear dependence of the temperature sensitivity on mean timing as earlier phases and very late phases had the highest correlation, negative and positive respectively, with temperature.

The temperature response was assessed by the slope of linear regression of mean date on mean temperature of the month before onset (Fig. 2b). Spring and summer phases advanced by up to 4.6 days / °C warming (two outliers in summer are related to agricultural phases in Germany) and autumn leaf colouring was delayed by up to 2.4 days / °C. Overall, mean onset dates influenced the temperature response, the mean for autumn phases (+0.98 days / °C) did differ significantly from the other three groups' means (-2.10, -2.52, and -2.18 days / °C) (Tab.1). Phases analysed for more than six countries are highlighted in Fig. 2b: All spring phases, except Robinia pseudoacacia flowering, exhibited a stronger response to temperature in warmer than in colder countries. The regression coefficients of the temperature sensitivity against mean onset date of flowering (days °C^{-1} / day of the year) were 0.028 (R^2=0.37) for Corylus avellana, 0.030 (R^2=0.78) for Tussilago farfara, 0.047 (R^2=0.74) for *A.* hippocastanum, 0.049 (R^2=0.21) for Syringa vulgaris, 0.029 (R^2=0.60) for Taraxacum officinalis, and, in contrast, -0.072 (R^2=0.21) for *R.* pseudoacacia. For Betula pendula, both the rate of advance of leaf unfolding and the rate of delay of leaf colouring per °C temperature rise were also higher in (warmer) countries with earlier mean onset (regression coefficients 0.093, R^2=0.54 and –0.062, R^2=0.40, respectively). All observed changes in Europe (1971-2000, 103,199 time series with 15+ years) are summarized in Table 2 by sign, significance, and means of the trends. In general, for farmers' activities and especially spring, summer, as well as fruit ripening phases, there were more negative than positive trends (i.e. more time series revealed advancing onset), in contrast to leaf colouring and leaf fall phases where we had almost the same proportion of negative and positive trends (Fig. 3). Thus, there is a clear signal across Europe of changing spring and summer phenology with 78% of leaf unfolding and flowering records advancing (31% significantly) and only 22% delayed (3% significantly). The signal in farmers' activities was generally smaller (57% advancing, 13% significantly, 43% delayed, 6% significantly). In contrast to spring events, the signal for leaf colouring in fall is quite ambiguous (48% advancing, 52% delayed) and less apparent as there were similar proportions of negative and positive significant trends. It is important to note that fruit ripening of different species was mostly advanced (75% negative, 25% significantly negative; 25% positive, 3% significantly positive trends). The total signal for spring and summer phenology including fruit ripening of wild plants was apparent with almost 80% advancing time series. These results strongly support previous results on a smaller number of sites and species and confirm them as being free from bias towards reporting global change impacts. Average trends in farmers' activities were small (Table 2), while those of leafing, flowering and fruiting show a clear advance of 2.5 days/decade. Leaf colouring and fall trends were close to 0, but suggested more of a delay when the average trend per country is examined (1.3 days/decade). When analysing the country means of the trends we found, for the first time, that phenology is not only a good bio-indicator for temperature changes in general, but also mirrored them quantitatively. Average phenological trends for countries systematically varied with temperature changes of the same country. Thus, for spring, our analysis revealed higher negative (advancing) trends of flowering and leaf unfolding in countries which exhibit a stronger warming in the preceding month (1971-2000) (r=-0.69, $p<0.001$, 19 countries, Fig. 4a). Even the average trends of animal spring phases in three countries fitted perfectly into the relationship between phenological and temperature trends. Mean fruit ripening trends in eight European countries matched national temperature changes of the previous month quite well (r=-0.66, p=0.076, Fig. 4b). For leaf colouring and leaf fall in autumn, there is no clear relationship between national phenological and temperature trends (r=0.003, p=0.99, 14 countries, Fig. 4c). Even for single species, such as leaf unfolding of Fagus sylvatica and flowering of Prunus avium, their mean national trends match the pattern of temperature increase in March (*F. sylvatica* r=-0.86, p=0.003, 9 countries, Fig. 4d; *Prunus avium* r=-0.73, p=0.004, 13 countries, Fig. 4e).

Discussion

Our meta-analysis comprised a huge selection of species and countries, included false phases in farming, and various phases of wild and agricultural plants covering the whole vegetation period. Owing to the enormous number of records included, the results are representative for Europe. The temperature response of spring phenology was unquestionable. We found that the earlier species were more sensitive, probably because of higher temperature variability in spring months, and they better indicated changes in temperature. The autumn signal was vague (delayed leaf colouring, but earlier fruit ripening because of warming, the latter more pronounced in agricultural than wild plants), thus further studies about observed climate change impacts in autumn should clearly differentiate between these phases. The temperature response varied between –4.6 days / °C in spring and +2.4 days / °C in autumn, early spring phases again had the strongest reactions. Our important finding, that all spring phases within European countries, except R. pseudoacacia flowering, exhibited a stronger response to temperature in warmer countries with earlier mean onset dates, may allow future parametrization of simple site-specific phenological models where no data were observed. We would recommend further study to consider some questions arising from this study. Why is responsiveness to temperature greater in warmer countries? Will increased autumn temperatures hinder vernalization and thus delay spring? Will this interfere with spring temperatures advancing spring? To what extent does rainfall and soil moisture influence phenology, particularly of leaf colouration phases? We trust that these, and other questions, can be addressed under COST725 auspices on the European datasets it is assembling. Our first systematic meta-analysis of more than 100 000 phenological time series in Europe clearly confirmed that there was no reporting or publication bias in earlier studies. There is an evident signal of advancing leaf unfolding, flowering and fruiting in wild plants all across Europe apparent in almost 80% of the records. The mean advance of spring in Europe of 2.5 days / decade matches previous results for the continent (Menzel & Fabian, 1999) and is slightly above results for a few countries in Central Europe (Defila & Clot, 2001, 2005; Menzel, 2003), however, in accordance with them, as our study period was restricted to the last three decades characterized by a stronger warming trend. Leaf colouring and leaf fall were less frequently observed; the majority of trends analysed were from Germany where, on average, no trend in leaf colouring was found (Fig. 4c; Menzel, 2003). Thus, our summary of all trends revealed no clear signal of leaf colouring changes in the last three decades, whereas results for other European countries based on fewer records showed delayed autumn (Menzel & Fabian, 1999; Defila & Clot, 2001). Normalized difference vegetation index (NDVI); Myneni et al., 1997; Zhou et al., 2001) and the CO2 signal (Keeling et al., 1996) provide spatially and species-averaged information on the start and end of the growing season. Confined to shorter time spans starting in 1981 (NDVI), their lengthening of the growing season peak at about 10 days / decade for Eurasia (Zhou et al., 2001), probably due to the fact that ground-based visible colouring or leaf fall occurs later than the end of the growing season derived by NDVI or that the magnitudes derived by NDVI data depends on their coarse temporal resolution. The spring phenological signal, however, is a perfect indicator for climate change impacts, as observed advances quantitatively mirror the measured warming.

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Tables

Table 1 Mean temperature sensitivity and response of phenological phases: Correlation and regression coefficients (slopes) of annual mean phenological records for 9 European countries (see ‘Materials and methods’) against mean monthly temperatures of the respective country (the month of mean onset, and the two preceding months) (see ‘Materials and methods’).

Phenophase group		n	Mean ±se of correlation coefficient	Mean ±se of regression coefficient
b0	Farmers activities	54	- 0.53 ± 0.02	- 2.10 ± 0.16
b1	Leaf unfolding, flowering	160	- 0.66 ± 0.01	- 2.52 ± 0.07
b2	Fruit ripening	25	- 0.45 ± 0.05	- 2.18 ± 0.34
b3	Leaf colouring	13	+ 0.33 ± 0.10	+ 0.98 ± 0.37

Table 2 Summary of phenological trends in Europe: All temporal trends (1971-2000, time series of 15+ years) which have been systematically reported to the COST725 meta-analysis (n=103199) for four different groups. Neg_all / Pos_all proportions of negative and positive trends, Neg_sig / Pos_sig proportions of significantly negative and positive trends ($p<0.05$), Tr_{mean} mean slopes for Europe (days $year^{-1}$), $avTr_{mean}$ average of national mean slopes (days $year^{-1}$) to adjust for different station numbers in the different national networks.

Phenophase group		n	Neg_all	Neg_sig	Pos_all	Pos_sig	Tr_{mean}	$avTr_{mean}$
b0	Farmers activities	22338	0.57	0.13	0.43	0.06	-0.041	-0.060
b1	Leaf unfolding, flowering	64027	0.78	0.31	0.22	0.03	-0.250	-0.200
b2	Fruit ripening	11191	0.75	0.25	0.25	0.03	-0.237	-0.190
b3	Leaf colouring	5643	0.48	0.12	0.52	0.15	0.017	0.129
b1 + b2	Leaf unfolding, flowering, fruit ripening	75218	0.78	0.30	0.22	0.03	-0.248	-0.198

Figure legends

Figure 1 Categories of system responses to observed changes and nonchanges in climate and relation to publication biases.

Figure 2 Temperature sensitivity and response across the year. **a**, Maximum correlation coefficients of 254 mean national time series in nine European countries (see 'Material and Methods') with mean temperatures of the previous months. Phenophases groups include farmers' activities (b0), spring and summer with different leafing, shooting and flowering phases (b1), autumn fruit ripening (b2) and leaf colouring of deciduous trees in fall (b3). **b,** Regression coefficients against mean temperature of the previous month. F flowering, LU leaf unfolding, LC leaf colouring. The overall dependence of temperature sensitivity and response on mean date is high (**a**, $R^2=0.59$, $y=0.0000003x^3 - 0.0001204x^2 + 0.0182684x - 1.5823$, $p<0.001$; **b,** $R^2=0.47$, $y=0.0000024x^3 - 0.0011345x^2 + 0.170218x - 10.4650$, $p<0.001$).

Figure 3 Histograms of phenological trends in Europe**.** All temporal trends (1971-2000, time series 15+ years) as linear regression coefficients (days / year) systematically reported to the COST725 meta-analysis (n=103199) for four different groups.

Figure 4 National mean temperature trends against mean phenological trends. **a,** in spring and summer (leaf unfolding, flowering - closed circles, animal phases - open circles). **b,** in summer and early autumn (fruit ripening). **c**, in autumn (leaf colouring and leaf fall). **d**, for leaf unfolding of *Fagus sylvatica* and **e**, for flowering of *Prunus avium.* Country abbreviations follow the international country codes.

		Climate	
		change	no change
System	change	Most likely to be published, especially when as expected	Likely to be published, explained by other drivers
	no change	Unlikely to be published, explained by other drivers	Unlikely to be analysed or reported

Figure 1

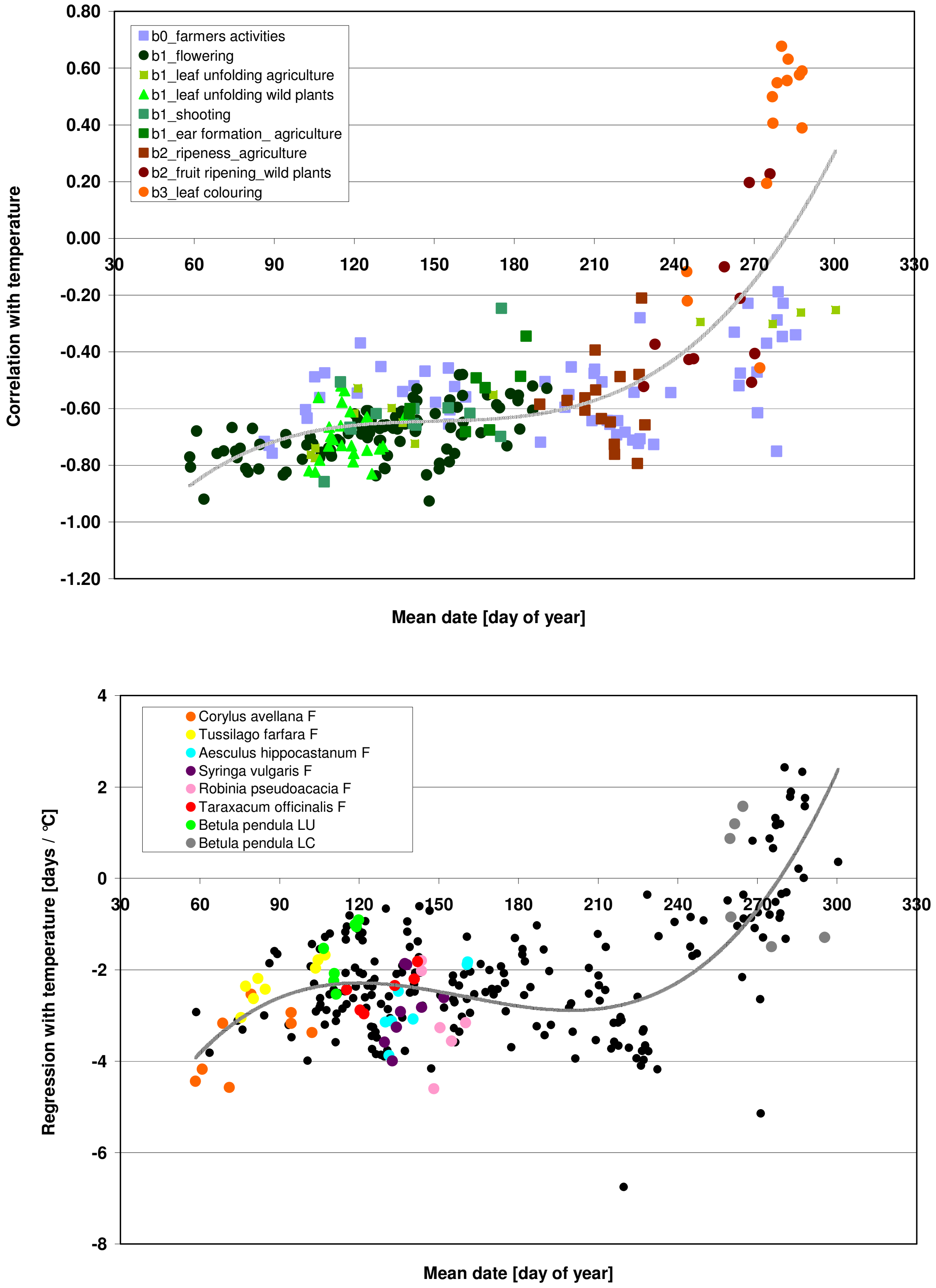
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
Correlation with temperature
30
60
90
120
150
180
210
240
270
300
330
■ b0_farmers activities
● b1_flowering
■ b1_leaf unfolding agriculture
▲ b1_leaf unfolding wild plants
■ b1_shooting
■ b1_ear formation_ agriculture
■ b2_ripeness_agriculture
● b2_fruit ripening_wild plants
● b3_leaf colouring
Mean date [day of year]
4
2
0
-2
-4
-6
-8
Regression with temperature [days / °C]
30
60
90
120
150
180
210
240
270
300
330
● Corylus avellana F
● Tussilago farfara F
● Aesculus hippocastanum F
● Syringa vulgaris F
● Robinia pseudoacacia F
● Taraxacum officinalis F
● Betula pendula LU
● Betula pendula LC
Mean date [day of year]

Figure 2

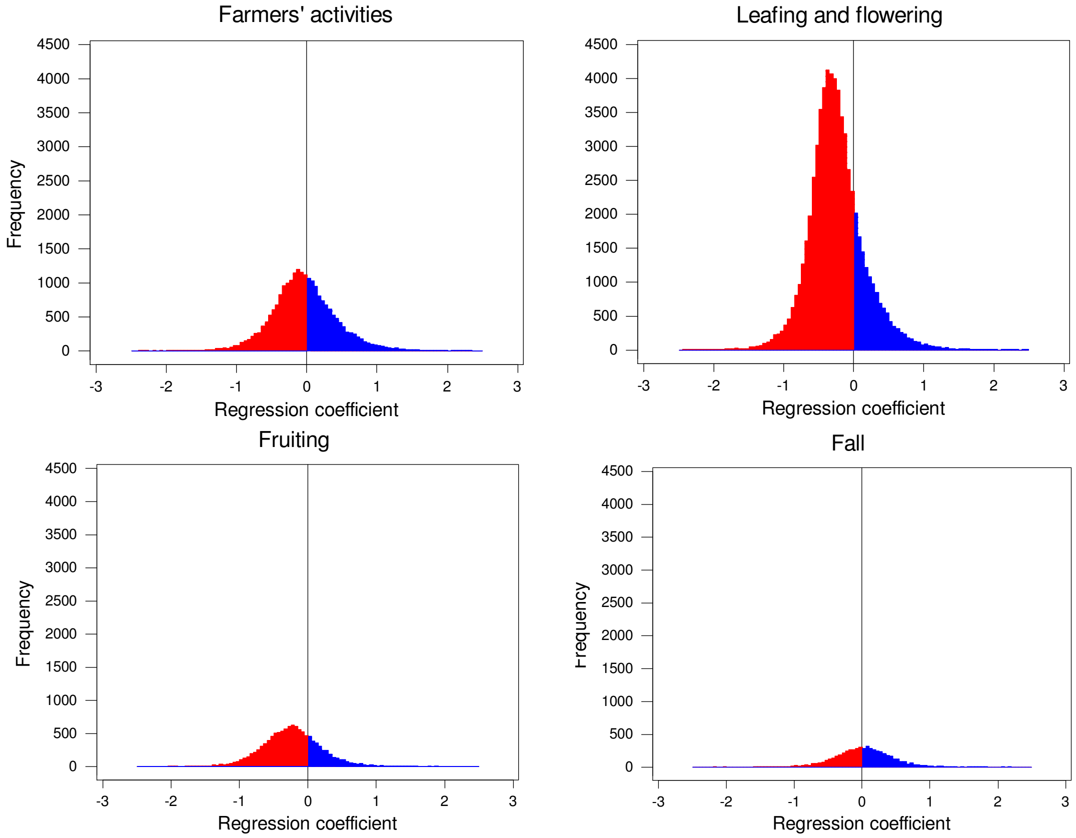
Farmers' activities
Leafing and flowering
Fruiting
Fall
Frequency
0
500
1000
1500
2000
2500
3000
3500
4000
4500
-3
-2
-1
0
1
2
3
Regression coefficient

Figure 3

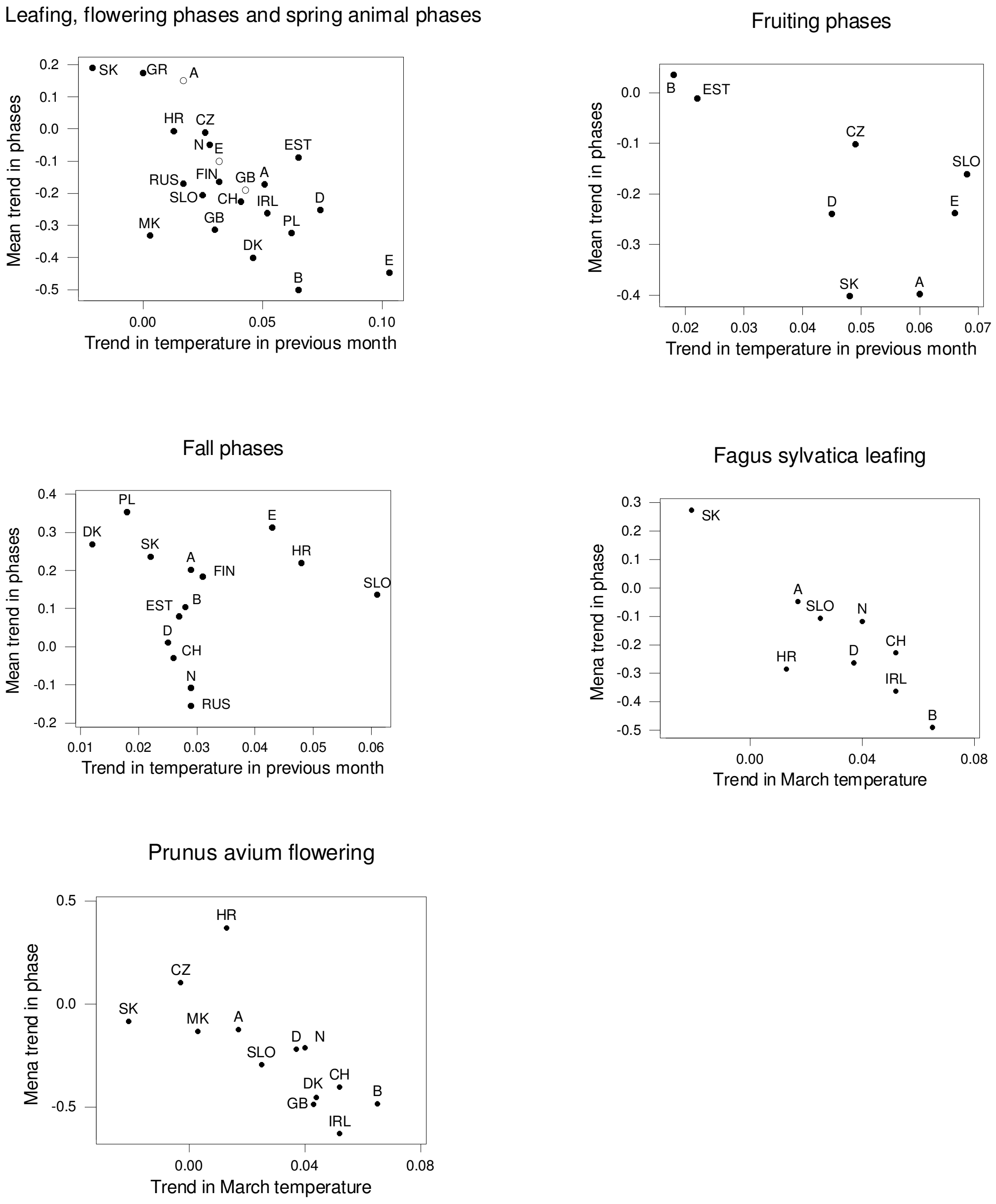
Leafing, flowering phases and spring animal phases
Mean trend in phases
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
SK
GR
A
HR
CZ
N
E
EST
RUS
FIN
GB
A
SLO
CH
IRL
D
MK
GB
PL
DK
E
B
0.00
0.05
0.10
Trend in temperature in previous month
Fruiting phases
Mean trend in phases
0.0
-0.1
-0.2
-0.3
-0.4
B
EST
CZ
SLO
D
E
SK
A
0.02
0.03
0.04
0.05
0.06
0.07
Trend in temperature in previous month
Fall phases
Mean trend in phases
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
PL
E
DK
SK
HR
A
FIN
SLO
EST
B
D
CH
N
RUS
0.01
0.02
0.03
0.04
0.05
0.06
Trend in temperature in previous month
Fagus sylvatica leafing
Mena trend in phase
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
SK
A
SLO
N
CH
HR
D
IRL
B
0.00
0.04
0.08
Trend in March temperature
Prunus avium flowering
Mena trend in phase
0.5
0.0
-0.5
HR
CZ
SK
MK
A
D
N
SLO
CH
DK
GB
B
IRL
0.00
0.04
0.08
Trend in March temperature

Figure 4

Artikel Clim Res 2005

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Climate Reasearch

Changes in the temperature response rates of long-term phenological records in Germany

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ABSTRACT:
The temperature response of long-term phenological records covering the whole 20th century was studied for 8 stations across Germany and for 3 phenophases (beginning of flowering in the horse chestnut *Aesculus hippocastanum* L., lilac *Syringa vulgaris* L., and red currant *Ribes rubrum* L.). Two different climate data sets were used: monthly mean temperatures for the 20th century for Germany from a Tyndall Centre data set (TYN) and a local climate data set from climate stations operated by the Deutscher Wetterdienst (German weather service, DWD) adjacent to the phenological stations. Linear regression of flowering onset and spring temperatures (March, April) revealed that, in general, a 1°C increase in temperature resulted in advances of flowering dates of 2.6 to 6.9 d, with a stronger temperature response rate at climate stations with higher spring temperatures and subsequent earlier spring onset. The effects of choosing local or national mean temperatures were small. Whilst a linear relationship between spring onset dates and temperature is generally indicated, this linearity of response might not be valid over the whole temperature range. The linear response rates at single stations (DWD) decreased towards cooler stations with later onsets, and for almost all stations there was a slightly reduced response at the cooler end of the temperature range (TYN). In most cases, the response rates of flowering onset to variations in temperature (TYN) did not differ significantly between the first and the second half of the 20th century; thus, there are no indications of adaptation processes.

KEY WORDS: Response · Temperature · Temperature response rate · Phenology · Germany · Climate change

1. INTRODUCTION

Numerous studies have concurrently documented a progressively earlier start for vegetation activity in spring and, less comprehensively, a later end in autumn. Therefore, a lengthening of the growing season during the last 2 to 5 decades for the temperate and boreal zone of the northern hemisphere is clearly apparent (e.g. Walther et al. 2002, Root et al. 2003, Walther 2004). Global meta-analysis conclusively reveals a mean advance of spring events by 2.3 d per decade (Parmesan & Yohe 2003). It is well known that the onset of spring and summer events, and consequently the length of the growing season, is very sensitive to climate and weather. In contrast to climatic factors influencing autumn phenology, the climate signal controlling spring and summer phenology is fairly well understood: nearly all phenophases correlate with temperatures in the preceding 1 to 3 mo (Sparks et al. 2000, Sparks & Menzel 2002, Menzel 2003). This relationship can be demonstrated in manipulative experiments (e.g. growth chambers, artificial heating of outdoor plots) or is revealed by phenological models based on temperature. The temperature response of spring and summer phenophases is most common evaluate with statistical methods, such as correlation or regression analyses, or simply by displaying onset dates vs. temperature measures. The changes currently experienced by emergence of vegetation and invertebrates may reach 6 to 8 d per °C (Sparks & Menzel 2002, Walther et al. 2002).

Although there is little doubt that the observed changes in phenology, namely a progressively earlier onset of spring and summer phenophases in the temperate and boreal zone of the northern hemisphere, can be attributed to increasing temperatures, several questions concerning this temperature response arise.

(1) Analyses of the temperature response in phenology often use mean monthly temperature data of adjacent climate stations (e.g. Peñuelas et al. 2002, Matsumoto et al. 2003), regional or national averages (e.g. Sparks & Carey 1995, Sparks et al. 2000, Menzel 2003) or climate reanalysis data (e.g. Chmielewski & Rötzer 2001). However, the temperature response might depend on the spatial resolution of the climate data examined. Thus, we will first analyse whether the temperature response of 3 flowering phases at several long-running stations in Germany is different when climate data of adjacent climate stations or mean national data are utilised.

(2) There have been some indications that although there is an approximate linear relationship between spring onset dates and temperature, this relation might not be true over a wider range of temperatures (Sparks et al. 2000). We assume a broad section of linear response with smaller responses at the ends, resulting in a s-shaped (sigmoid) flowering–temperature relationship. Short records do not provide enough variation in both temperature and phenology to assess this question of linearity. Thus, secondly, by means of long-term phenological records spanning the whole of the last century we will investigate the linearity of temperature responses.

(3) As summarised in the IPCC Working Group II report, temperature changes have already affected many physical and biological systems, and the uncertainty, especially concerning phenology and growing season changes, is relatively low (IPCC 2001). In contrast, major gaps exist about evidence of adaptation processes. Thus, thirdly, we will evaluate whether the temperature response in separated time periods during the 20th century is diverging, which might be a clue for adaptation.

2. MATERIALS AND METHODS

2.1. Phenological data

From the data set of long-term phenological time series covering the 20th century (1900 to 2000) in Germany (A. Testka unpubl. data), we selected 3 phenophases: the beginning of flowering of the horse chestnut *Aesculus hippocastanum* L., lilac *Syringa vulgaris* L., and red currant *Ribes* *rubrum* L. These phases were selected since they were available at a number of stations with long-term data series. The observations were recorded at 8 different sites within the network of the German Weather Service (Deutscher Wetterdienst, DWD) (see Fig. 1). The phenological observations compiled originated from different sources and networks (Menzel & Testka 2002, A. Testka unpubl. data): observations within one of the first (European) phenological networks, published by Ihne (1883 to 1941), were extracted from the historical phenological database of the DWD. Observational records for 1936 to 1944 were digitised from Schnelle & Witterstein (1952). Post World War II data (1945 to 1952) in the former West Germany were extracted from the corresponding meteorological yearbooks (DWD 1949–1952, 1960); 1947 to 1956 data for the former East Germany were taken from Seyfert (1957, 1960, 1961) and some original record sheets. From 1951 onwards, the observations originate from the current phenological network of DWD including 1961 to 1990 data from the Meteorological and Hydrological Service of the former East Germany. All phenological data (whether digital or hard copy) were kindly provided by the DWD. Data were checked for plausibility (correlation with neighbouring phases, appropriate seasonal order), and obvious errors (e.g. wrong month) and were corrected when necessary. Smaller gaps in the records (between 1 and 15% of all records) were filled by correlation with observations at adjacent stations or observations of preceding or following phases at the same station when the correlation coefficient was greater than 0.55. Following this process only a few years (some in the 1920s and 1930s, but mostly after World War II) had missing values. The stations at Geisenheim, Teterow and Lübeck, in particular, provide nearly complete time series of the 20th century.

2.2. Climate data

For some of the phenological stations (see Fig. 1), the temperature data recorded at the adjacent climate stations provided a complete coverage for the 20th century (Karlsruhe; Hamburg Fuhlsbüttel at ca. 50 km distance from the phenological station at Lübeck) or partial coverage (1935 to 2000 Geisenheim; 1936 to 2000 Bad Dürnheim at 10 km from Villingen). The 1900 to 2000 climate data for the phenological station of Eisleben had to be built up from 3 different locations of corresponding climate stations; thus, these temperature time series can not be regarded as homogenous. Further non-homogeneity may stem from change of observing time, change of instruments/exposition or sometimes from observers. Local climate station information is hereinafter referred to as DWD.

Temperature data for the other phenological stations were not suitable either due to a combination of different relocated climate stations (Frankfurt, Veitshöchheim) or due to their distance from the phenological station (Teterow, nearest climate station Schwerin at ca. 70 km distance).

Monthly mean temperatures for each calendar month for the 20th century for Germany (1901 to 2000, country summary) have been taken from the Tyndall Centre (TYN CY 1.1) data set (Mitchell et al. 2004, www.cru.uea.ac.uk/~timm/cty/obs/TYN_CY_1_1_text. html; see also Mitchell & Jones 2005). This data set is hereinafter referred to as TYN.

2.3. Methods

Previous studies have shown that for the onset of spring activity the temperatures of the preceding spring months are decisive (Sparks et al. 2000, Matsumoto et al. 2003, Menzel 2003). For the spring phases analysed in this paper, stepwise linear regressions with mean monthly temperatures (proc stepwise, SAS statistical package) revealed the months March and April, and often February, as months with the highest correlation coefficients. In order to homogenise the analyses here, we always tested the relationships between the onset of the 3 spring flowering phases and mean monthly temperatures of March and April, although a slightly different combination of months could have resulted in a minor increase of variation explained (^{R2}). For all 3 questions (see 'Introduction'), the onset of flowering– spring temperature relationships were assessed by scatter plots, linear regression models and LOWESS smoothing (LOcally-WEighted Scatterplot Smoother).

3. RESULTS

3.1. Variation of temperature response with climate data sets

The responses of the onset of flowering to variations in temperature (both TYN and DWD climate data sets) are displayed in Figs. 2 & 3; the results of fitting linear regressions are summarised in Table 1.

In general, all phases at all stations, regardless of the climate data set used, revealed the well known relationship of higher spring temperature resulting in earlier flowering onset. In the scatter plots of flowering vs. TYN (Fig. 2), the mean spring onset dates of the stations followed the climate differentiation of regions. Mean flowering dates differed by almost 1 mo between the phenological stations with earliest onset dates (Karlsruhe, Geisenheim) and the latest (Villingen). In the scatter plots of onset vs. DWD (Fig. 3), the data points arranged on both the *x*- and the *y*-axis followed the local climate (temperature) conditions and their biological mirror (onset of flowering).

In general, a 1°C increase in temperature resulted in advances of flowering dates of 2.6 (flowering of horse chestnut at Villingen) to 6.9 d (flowering of red currant at Eisleben). The percentage of variation explained by linear regressions covers a large range between 15% (horse chestnut, Villingen) and 67% (lilac, Eisleben) (Table 1). For horse chestnut and lilac, the response to TYN was mostly more pronounced for stations with earlier means (mean date vs. slope: horse chestnut, $r = 0.87$, $R^2 = 76\%$; lilac, $r = 0.68$, $R^2 = 46\%$), this pattern was also visible for the regression with DWD. Response rates of flowering of red currant did not display this stronger temperature response at earlier stations (mean date vs. slope: $r = –0.04$, $R^2 = 0\%$).

There was a maximum of 10% difference between the percentages of variation explained (R^2) for TYN and DWD; often the higher values were reached by TYN. At Eisleben and Lübeck the temperature response determined for DWD was lower than for TYN; for Geisenheim, Karlsruhe and Villingen the response to local climate was more pronounced. However, the maximum difference was 1.2 d per °C. The effect of choosing local or national mean temperatures was small.

3.2. Linearity of temperature response

The LOWESS smoothing (TYN) (Fig. 2) reveals almost linear relationships. At almost all stations the response is slightly flattened at the cooler edge of the temperature range. Out of 24 examples, only 6 do not display this pattern: flowering of horse chestnut at Veitshöchheim, lilac at Teterow and Veitshöchheim, and red currant at Eisleben, Lübeck and Teterow. In particular, for the coldest station in the data set, Villingen, a non-linear relationship is displayed by the LOWESS smoothing.

However, at the warmer end of the temperature range, the hypothesized reduced temperature response, which would finally result in the hypothesised s-shaped (sigmoid) flowering–temperature relationship, is not as expected (e.g. only for horse chestnut at Geisenheim and Lübeck, lilac at Eisleben and Frankfurt, and red currant at Geisenheim and Teterow); for all other cases this pattern is not apparent.

The relationship of onset dates vs. DWD spring temperature is almost linear for each station separately and all stations together (Fig. 3). Here, as for the TYN response discussed above, the linear response rates at single stations are lower in cooler stations with later onsets (see Table 1), but not in warmer stations with earlier onset; thus, an increasing non-linearity of the response is only apparent for the colder end.

3.3. Variation of temperature response with time

In Fig. 4 the LOWESS curves for the responses of the onset of flowering to variations in temperature (TYN) are displayed for 2 different time periods: 1900 to 1950 (I) and 1951 to 2000 (II); the slopes and the standard error of the slopes of the corresponding linear regressions are summarised in Fig. 5. The regressions at all stations and periods are significant ($p < 0.001$) except those in the 1900 to 1950 period at Villingen, which are consequently not further analysed (Fig. 5). In most cases, there are no significant differences between the slopes in the first and the second half of the 20th century. Rare relevant differences show both larger responses in the first half (twice) and in the second half of the century (four times). Slightly smaller, but not significantly different, responses (in days per °C) are often revealed in the second half of the century. The results when comparing the LOWESS fits are quite similar. For flowering of horse chestnut and lilac there are almost no differences. For red currant, it seems that similar mean March/April temperatures have resulted in earlier flowering dates in the first half than in the second half of the 20th century. This might be connected with a possible change in cultivars planted.

4. DISCUSSION AND CONCLUSIONS

Climatological studies have revealed that the spatial correlation of air temperature is relatively high. In Germany, Schönwiese et al. (1998) demonstrated for the reference climate station Frankfurt a. Main that for winter and annual values the correlation coefficients between Frankfurt and 95 other stations were mostly above 0.8, even for stations 800 km distant. As expected, the spatial representativeness of summer temperature was lower (on average 0.9 for 100 km dropping to 0.5 for 800 km distant). This high spatial coherence of temperature might be the reason why the choice of temperature data leads to relatively small differences in the computed temperature responses (for linear regressions a maximum difference in slope of 1.2 d per °C, a maximum difference in R^2 of 10%). This means that the primary relationship between onset of phenological phases and mean spring temperatures is consistent even for different temperature data sets. One has to take into account that the plant observed will be at a certain distance from the local climate station, will most likely experience other microclimates and be exposed to a range of plant body temperature rather than air temperature measured in shade at 2 m. Thus, depending on the phenological station, the temperature response was slightly higher with either the national or the local climate data set. There is a need for further research to determine whether it is really a fact that the responses to local climate station data, compared to national mean temperatures, seem to be more pronounced in warmer regions (e.g. Karlsruhe, Geisenheim) and less so in colder regions (e.g. Eisleben, Lübeck, see Table 1).

The hypothesis that the temperature response of phenological spring phases is not linear over the whole range of spring temperatures is quite reasonable. Relatively cold weather in spring may delay the onset of spring phenophases over a large range of temperatures. Nevertheless, the plant might finally react to day length in order not to ‘miss too much of the growing season’. In addition, temperatures below a certain threshold (e.g. 5°C, depending on the species) may not be effective as forcing temperatures; this might also explain a reduced response rate. There are also good reasons that day length and photoperiod might prohibit a too early start of the growing season, even in very warm springs. The spring temperature level in Germany might still be too low to exhibit this missing non linearity at the warm end. In addition, the necessary winter chilling may not be completely fulfilled under warm spring conditions; thus, plants might need more forcing temperatures (Cannell & Smith 1983), such that the temperature response at the warmer end may not be linear anymore.

However, even analysing the century-long records in our phenological data set comprising high inter annual variation in temperature does not display the suggested non-linearity of the response at both ends of the temperature range. The LOWESS smoothing only displayed a slight reduction of the response towards colder springs, which is especially valid for one station (Fig. 2, Villingen).

Furthermore, the use of local climate station data (Fig. 3) does not produce an overall s-shaped response. As the temperature response at the colder stations is lower (see Table 1), the overall local temperature response curve is flattened at the colder end. For the warmer climates, the local temperature in spring is obviously higher than the German average. Here, the response is very similar to that in other stations. There might exist the key problem that the earlier the onset dates (e.g. the end of March), the less suitable the 2 fixed temperatures of March and April.

Only in animal phenology have T. H. Sparks et al. (unpubl. data) found for 3 long-term records of mean first egg laying dates of pied flycatcher *Ficedula hypoleuca* in Wales (46, 26, and 21 yr), which were remarkably synchronised and had identical temperature response rates, that one of the sites experienced an unexplained additional change in mean laying date (i.e. shift in the intercept on the *y*-axis). This could be due to adaptation to recent advanced spring conditions by a reduced interval between arrival and nesting, due to selection for earlier nesting individuals or caused by other influencing environmental conditions in the wintering grounds and on the migration route.

There are no other findings in the literature so far concerning altered temperature responses in plants over time. Our results also suggest that, despite some variations, there are no systematic differences in the temperature response rates in the first and second half of the last century. Minor, non-significant variations often reveal a smaller response in the second half of the century. However, for red currant only, there seems to be a systematic shift in average flowering dates (compared to mean March/April temperatures) towards later flowering dates in the second half of the 20th century. Any connection that this might have with a possible change in cultivars planted is speculative.

To summarise, our findings suggested a consistent basic linear relationship between onset dates of phenological phases and mean spring temperatures independent of different types of temperature data sets. Even century-long records comprising high inter annual variation in temperature did not display the hypothesized non-linearity of the temperature response at both ends of the temperature range. There was no evidence for systematic adaptation processes as the temperature response seemed to be mostly unaltered over the last century.

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Tables

Table 1. *Aesculus hippocastanum, Syringa vulgaris and Ribes rubrum.* Results of linear regressions between flowering onsets of horse chestnut, lilac and red currant and mean monthly March/April temperatures. TYN: Tyndall Centre (www.cru.uea.ac.uk/~timm/cty/obs/TYN_CY_1_1_text.html, Mitchell et al. 2004); DWD: Deutscher Wetterdienst (German weather service) data taken from climate stations adjacent to phenological stations; DOY: day of the year, mean onset date during 1900 to 2000, (day/°C); n: number of observations; R2: variation explained; TYN-DWD: difference between TYN and DWD. All regressions are significant ($p < 0.0001$)

				TYN				DWD				TYN-DWD	
Species	Station	Date	DOY	Slope	SE	n	R^2	Slope	SE	n	R^2	Slope	R^2
Horse chestnut	Karlsruhe	27.04	117	–4.84	0.59	81	0.45	-5.19	0.66	81	0.46	0.35	-0.01
	Geisenheim	28.04	118	-4.77	0.44	97	0.55	-5.53	0.69	63	0.57	0.76	-0.03
	Frankfurt	29.04	119	-4.81	0.47	86	0.55						
	Veitshöchheim	06.05	126	-4.75	0.58	75	0.47						
	Eisleben	09.05	129	-4.58	0.46	81	0.56	-4.06	0.44	82	0.54	-0.52	0.01
	Lübeck	13.05	133	-3.49	0.49	95	0.35	-3.10	0.49	95	0.32	-0.38	0.02
	Teterow	15.05	135	-4.04	0.50	93	0.42						
	Villingen	21.05	141	-2.55	0.70	78	0.15	-3.12	0.81	52	0.20	0.57	-0.05
Lilac	Karlsruhe	25.04	115	-5.89	0.60	81	0.55	-5.90	0.71	81	0.51	0.01	0.04
	Geisenheim	25.04	115	-5.03	0.63	97	0.40	-5.68	0.94	63	0.45	0.66	-0.06
	Frankfurt	29.04	119	-4.65	0.45	86	0.56						
	Veitshöchheim	01.05	121	-4.57	0.48	75	0.55						
	Eisleben	07.05	127	-5.37	0.43	81	0.67	-4.57	0.44	82	0.58	-0.80	0.08
	Lübeck	15.05	135	-4.58	0.53	95	0.44	-4.46	0.50	95	0.39	-0.12	0.05
	Teterow	16.05	136	-4.72	0.48	93	0.51						
	Villingen	20.05	140	-3.07	0.63	78	0.24	-3.60	0.72	52	0.26	0.53	-0.02
Red currant	Geisenheim	09.04	99	-5.15	0.57	97	0.46	-6.34	0.81	63	0.44	1.18	0.02
	Karlsruhe	09.04	99	-5.04	0.63	81	0.44	-5.21	0.72	81	0.44	0.17	0.00
	Frankfurt	10.04	100	-4.58	0.69	86	0.34						
	Veitshöchheim	11.04	101	-5.08	0.56	75	0.52						
	Eisleben	20.04	110	-6.90	0.62	81	0.61	-6.30	0.57	82	0.51	-0.60	0.09
	Lübeck	24.04	114	-5.13	0.63	95	0.41	-5.02	0.59	95	0.32	-0.11	0.10
	Teterow	26.04	116	-5.38	0.63	93	0.44						
	Villingen	02.05	122	-4.46	0.81	78	0.28	-5.31	0.85	52	0.31	0.85	-0.02

Figure legends

Figure 1
Names and sites of the 8 phenological stations in Germany

Figure 2
Beginning of flowering in horse chestnut, lilac and red currant (008 *Aesculus hipocastanum*, 015 *Syringa vulgaris*, 051 *Ribes rubrum)* (*y*-axis, days since January 1), vs. monthly mean air temperatures in March/April (*t*34, *x*-axis, °C) at 8 different stations in Germany (data taken from TYN CY 1.1 data set, Mitchell et al. 2004, ww.cru.uea.ac.uk/~timm/cty/obs/ TYN_CY_1_1_text.html)

Figure 3
Beginning of flowering in horse chestnut, lilac and red currant (008 *Aesculus hipocastanum*, 015 *Syringa vulgaris*, 051 *Ribes rubrum)* vs. monthly mean air temperatures in March/ April *(t* 34) at 5 different stations in Germany (DWD temperature data from adjacent climate stations of the German Weather Service). DOY: day of the year

Figure 4.
LOWESS fits for beginning of flowering in horse chesnut, lilac and red currant (008 *Aesculus hipocastanum*, 015 *Syringa vulgaris*, 051 *Ribes rubrum)* vs. monthly mean air temperatures in March/April *(t*34 TYN) for 2 different time periods (1900 to 1950 and 1951 to 2000). DOY: day of the year

Figure 5.
Temperature response rates for 2 different time periods (I: 1900 to 1950; II: 1951 to 2000). White and grey bars represent the slopes of linear regressions in March/April (±SE) (*y*-axis, days per °C) (upper panel: horse chestnut; middle panel: lilac; lower panel: red currant). All regressions are significant ($p < 0.001$)

Figure 1


Lübeck
Teterow
Eisleben
Rochlitz
Geisenheim
Frankfurt
Veitshöchheim
Karlsruhe
Villingen

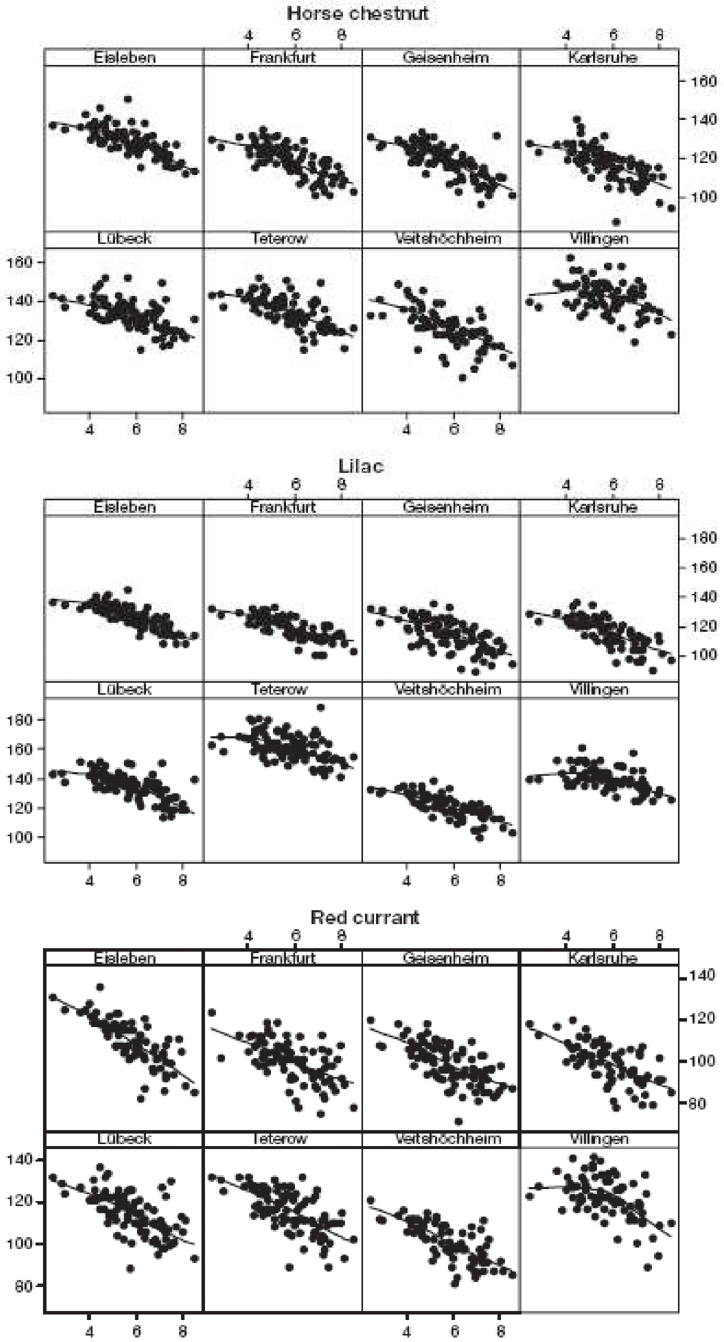
Horse chestnut
Eisleben
Frankfurt
Geisenheim
Karlsruhe
Lübeck
Teterow
Veitshöchheim
Villingen
160
140
120
100
4
6
8
Lilac
Eisleben
Frankfurt
Geisenheim
Karlsruhe
Lübeck
Teterow
Veitshöchheim
Villingen
180
160
140
120
100
4
6
8
Red currant
Eisleben
Frankfurt
Geisenheim
Karlsruhe
Lübeck
Teterow
Veitshöchheim
Villingen
140
120
100
80
4
6
8

Figure 2

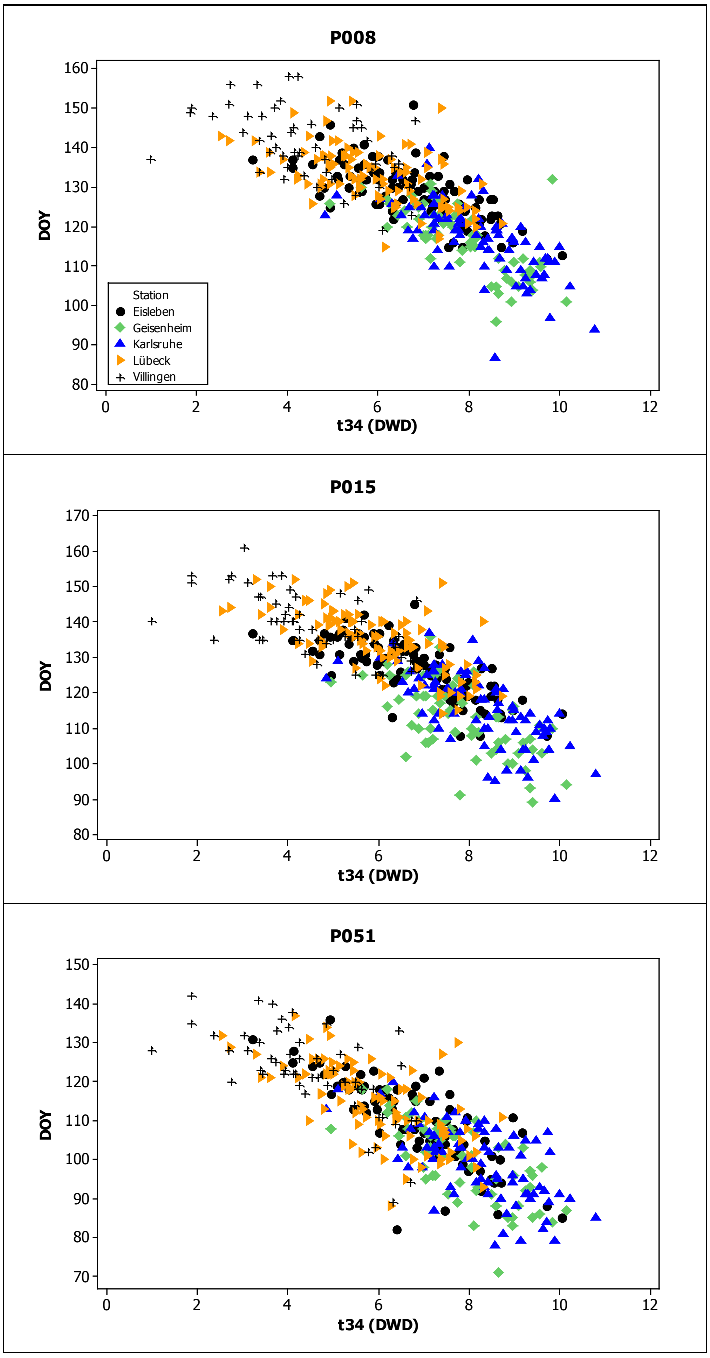
P008
DOY
160
150
140
130
120
110
100
90
80
t34 (DWD)
0
2
4
6
8
10
12
Station
● Eisleben
◆ Geisenheim
▲ Karlsruhe
▶ Lübeck
+ Villingen
P015
DOY
170
160
150
140
130
120
110
100
90
80
t34 (DWD)
P051
DOY
150
140
130
120
110
100
90
80
70
t34 (DWD)

Figure 3

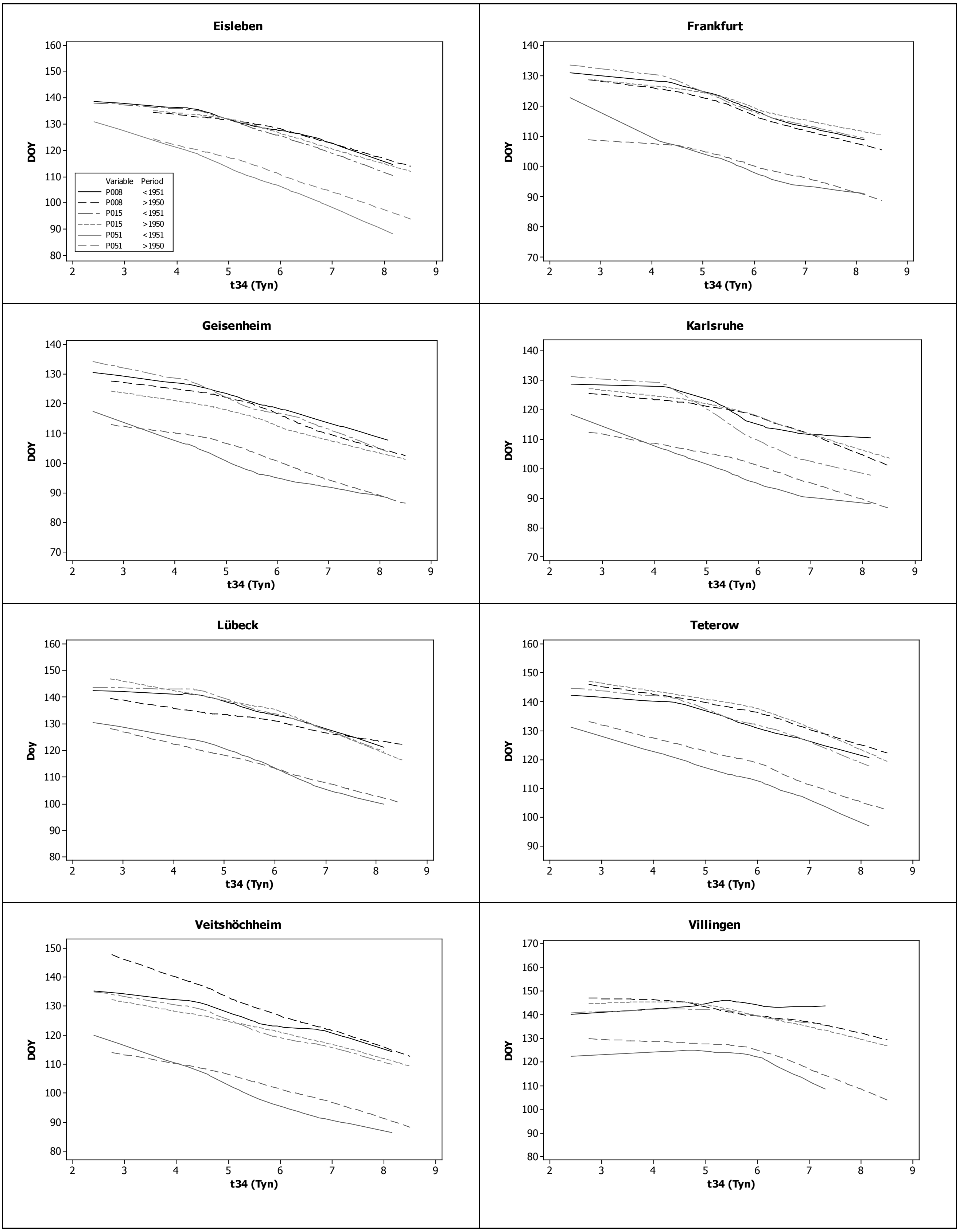
Eisleben
Frankfurt
Geisenheim
Karlsruhe
Lübeck
Teterow
Veitshöchheim
Villingen
DOY
Doy
t34 (Tyn)
Variable Period
P008 <1951
P008 >1950
P015 <1951
P015 >1950
P051 <1951
P051 >1950

Figure 4

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Global Change Biology

‘SSW to NNE’ – North Atlantic Oscillation affects the progress of seasons across Europe

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Abstract

Three European plant phenological network datasets were analysed for latitudinal and longitudinal gradients of nine phenological ‘seasons’ spanning the entire year. The networks were: (1) the historical first European Phenological Network (1882–1941) by Hoffmann & Ihne, (2) the network of the International Phenological Gardens in Europe (1959–1998), founded by Schnelle & Volkert in 1957 and based on cloned plants, and (3) a dataset (1951–1998) that was recently collated during the EU Fifth Framework project POSITIVE, which included network data of seven Central and Eastern European countries. Our study is most likely the first, for over a century, to analyse average onset and year-to-year variability of the progress of seasons across a continent. For early, mid, and late spring seasons we found a marked progress of the seasonal onset from SW to NE throughout Europe, more precisely from WSW to ENE in early spring, then from SW to NE and finally from SSW to NNE in late spring, as exhibited by the relationship between latitudinal and longitudinal gradients. The movement of summer was more south to north directed, as the longitudinal gradient (west–east component) strongly declined or was even of opposite sign. Autumn, as shown by leaf colouring dates, arrived from NE to SW. Possible reasons for the differences among the three datasets are discussed. The annual variability of latitudinal and longitudinal gradients of the seasons across Europe was closely related to the North Atlantic Oscillation (NAO) index; in years with high NAO in both winter and spring, the west–east component of progress was more pronounced; in summer and autumn, the pattern of the seasons may be more uniform.

Keywords: latitudinal gradients, longitudinal gradients, North Atlantic Oscillation, phenology, seasons

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Introduction

The onset of seasons has always been a subject of human interest, mainly because the length of the growing season determines the choice of crops, which can be grown and harvested in a region. The oldest observational record of a phenological event at a single site is probably the record of cherry flowering at the royal court at Kyoto beginning in the seventh century (Menzel, 2002a). One of the earliest phenological networks covering a greater scale is most likely the first European Phenological Network founded by Hoffmann, Professor of Botany at the University of Giessen, and his student Ihne in 1882 (Hoffmann & Ihne, 1882). The observations made in this network were published yearly by Ihne (1883–1941). Their analyses of these data showed that the spring green wave ran through Europe from SSW to NNE, as published on a historical map of the onset dates of apple flowering in Europe by Hoffmann in 1885 (Hoffmann, 1885; Schnelle, 1955). Later on, Schnelle (1965) published maps of mean onset (1930–1939) of five seasons in Europe. In North America, the forest entomologist Hopkins (1938) related phenological measurements to geographical parameters in a law known as Hopkins' 'Bioclimatic Law', in which the delay in phenology in relation to altitude (1 day (100 - ft)$^{-1}$), latitude, and longitude (4 day deg^{-1}) were estimated.

A few studies in Central Europe also provided horizontal velocities of progress (km day^{-1}). For example, Schnelle (1948) determined 28–50kmday^{-1} in a SSW–NNE direction through Central Europe for spring phases, 35kmday^{-1} SE–NW for harvest of winter rye, and 28kmday^{-1} ENE–WSW for sowing of winter rye in autumn. Subsequently, analyses of phenological network data have reported the delay or advance of phenological onset dates per degree of latitude or longitude, hereafter referred to as latitudinal or longitudinal gradients (e.g. for the IPG, Menzel, 1997; Rötzer & Chmielewski, 2001). In more recent times, the spring green wave can easily be followed up by remote-sensed data (e.g. Schwartz & Reed, 1999; Menzel, 2002a; Badeck et al., 2004).

Less is known about the spatial pattern of the onset of summer and autumn phases in Europe. Schnelle (1955) reported that autumn proceeded through Europe from NE to SW. However, the real picture may not be so simple. The studies of Schnelle (1979), which intended to draw maps of leaf colouring and leaf fall in Germany, exhibited that leaf colouring and leaf fall had almost no consistent spatial pattern.

Overwhelming indications have been reported that spring and summer phases tended to occur earlier in recent decades whereas autumn seems to be slightly delayed (e.g. Ahas et al., 2002; Sparks & Menzel, 2002; Walther et al., 2002). However, this does not imply, at the same time, that the pattern of the seasonal progress in Europe remains constant: either the speed and/or the direction of the spring green wave and the succeeding seasons throughout Europe might have also experienced changes.

This pattern of phenological seasons is important to assess the impacts of global change on life cycle events in the biosphere, not only at the level of individual plants and sites, but also at the population level on a broader spatial scale. An altered pattern of seasonal progress, for example, might also influence food chains, animal migration, and cross breeding between populations (Walther et al., 2002). Thus, in this paper, we analyse the patterns of the seasons progressing throughout Europe using data from different phenological networks of distinct time periods and concepts (native vs. cloned plants). This pattern will be linked to the North Atlantic Oscillation (NAO) index. This atmospheric circulation index describes a major driving force of the northern hemisphere climate system, which largely determines the interannual variation of winter temperatures in the northern Atlantic region (Hurrell, 1995). Through its widespread influence, the NAO is linked to manifold ecological processes (Ottersen et al., 2001). Winters with a positive NAO index are characterised by warm wet conditions in Northern and Central Europe.

Phenological phases in these areas respond to higher NAO indices by earlier spring onset (advancing onset of leaf unfolding, flowering, and a lengthening of the growing season) (e.g. Menzel, 1997; Chmielewski & Rötzer, 2002; Menzel, 2003). The first spatial studies for Central (Scheifinger et al., 2002) as well as Central and Eastern Europe (Aasa et al., 2004) indicate a decreasing influence of the NAO with increasing distance to the North Sea.

Data

Three different phenological datasets were analysed for their spatial pattern of the onset of plant phenological seasons in Europe:

(1) The historical dataset of the first European Phenological Network, as reported by Ihne and Hoffmann (mainly based on Ihne (1883–1941)), hereafter referred to as IHNE. This network comprised phenological observations from numerous stations across Europe; in our analysis we included a few earlier observations as reported by Hoffmann and Ihne (e.g. observations at Giessen dating back to 1855), which are also retained in the historical phenological database of the Deutscher Wetterdienst. However, the European network was mainly active during the 1879–1941 period (Schnelle, 1955).

(2) The International Phenological Gardens (IPG), a network of phenological observation sites, where cloned specimens of trees and plants have been observed (Schnelle & Volkert, 1957). Although this network was founded in 1957, its major observational period started in the mid 1960s; thus, the period analysed was restricted to a 34-year period from 1965 to 1998.

(3) A dataset including observations in different European phenological networks, which were gathered by the 5FP EU project POSITIVE (hereafter referred to as POSITIVE) (Ahas et al., 2002; Menzel, 2002b). In contrast to the IPG dataset, records were made on native plants by volunteers, and the networks themselves were mainly operated by National Weather Services. In order to cover the whole study period (1951–1998), the networks were restricted to seven countries in Central and Eastern Europe (Austria, Estonia, Germany, Poland, Russia, Slovenia, Switzerland).

The combined dataset covers the period of 1879–1998 with nine missing years (1942–1950). As the species observed differ among these datasets and even from country to country within the POSITIVE dataset, we analysed phenological 'seasons' instead of single phenological phases. The onset of nine seasons throughout the year was constructed by averaging the selected phenological phases listed in Table 1. All three datasets were checked for extreme outliers (occurring apparently in the wrong season or well outside the 1st– 99th percentile range of the frequency distribution); these values were set as missing. Unfortunately, in the POSITIVE dataset no data from south-west Europe are available, and in the IHNE and IPG dataset only very few stations from Spain and France are included; therefore, results presented later on in Figs 1 and 3 should be viewed with caution for these regions. As auxiliary data we used the monthly means of the NAO index (Jones et al., 1997, http://www.cru.uea.ac.uk/ cru/data/nao.htm), as well as monthly temperature means for Europe (CRUTEM2 land air temperature anomalies on a 51 to 51 grid-box basis, Jones & Moberg 2003, http://www.cru.uea.ac.uk/cru/data/temperature/, here: 10°W 35°N to 35°E 70°N).

Methods

The spatial pattern of phenological seasons across Europe is described by latitudinal and longitudinal gradients. We calculated these by multiple linear regressions of the onset of seasons against latitudinal and longitudinal coordinates. The respective regression coefficients are regarded as gradients indicating the number of days required by the seasons to pass 1° of latitude or longitude. Low gradients in days deg $^{-1}$ correspond to fast progression of the seasons and wide contour lines in a contour plot, respectively. As in Central Europe, regarding distance, 2° latitude corresponds to 3° longitude, and a relationship of latitudinal to longitudinal gradient of 3 : 2 corresponds to a SW– NE direction of progress.

The latitudinal and longitudinal gradients were determined (a) for long-term averages and (b) for annual observations.

To build up long-term seasonal averages (a) of IHNE, all stations were kept for further analysis, if at least 30 observations of phases, as listed in Table 1, were available (equal to at least 10 years when three phases per season are included or at least 15 years for two phases). As the observational period of IPG data is much shorter, seasonal station means were only discarded when less than 16 observations per season were available (equal to or less than 5-year records). Within the POSITIVE dataset, only long-term phenological records (429 years or 444 years in Germany in order to balance the proportion of different countries) were included in the analysis. In addition, only those phases that were also observed in Russia and/or Poland were included in Table 1, in order to provide an equally wide latitudinal and, especially, longitudinal range to all seasons.

In Fig. 1, sites with long-term averages in the three datasets (IHNE, IPG, POSITIVE) are displayed for season 3 (late spring). Interpolated mean onset dates in these maps (Fig. 1) correspond quite well, where data are available for all three datasets. Figure 2 provides a comparison of long-term mean onset dates of all nine seasons for a selected region in western Germany (51°N > LAT > 48.7°N, 6.5°E < LON < 9.3°E (LAT, latitude; LON, longitude)) with up to five IPG, 40 IHNE, and 55 POSITIVE sites, depending on season. Although the phases (Table 1) included in the seasonal averages, the time periods of observation (see data section), and the exact station locations are completely different, in nearly all seasons the mean seasonal onset dates in the three datasets are a reasonable match. Only in season 1, IPG phases (flowering of different Salix clones) seem to occur later than POSITIVE or IHNE phases, and for season 8 (fruit ripening in early autumn) there are some differences between IHNE and POSITIVE data. However, this example by and large supports our assumption that the constructed phenological seasons are comparable in the three datasets.

For both IHNE and IPG data, annual latitudinal and longitudinal gradients (b) were determined for the seasons when at least 20 stations per year and season were available. For the POSITIVE dataset this threshold was set to 30 stations.

In order to account for the annual variability in these latitudinal and longitudinal gradients, the gradients were correlated (Pearson's correlation coefficient) with the NAO index as well as with mean European temperatures (up to five individual monthly means within a season).

Results

Table 2 displays the regression coefficients of the multiple linear regressions of the overall mean onsets in seasons across Europe against LAT and LON, including their significance (P), the degrees of freedom (df), and the corresponding explained variation (R2). Although the magnitude of the latitudinal and longitudinal gradients differs to a certain extent among the three different datasets (see the Discussion), there is apparently a clear pattern of the progress of the seasons through Europe: in all three datasets analysed, the latitudinal and longitudinal regression coefficients are positive for all spring seasons (1 early spring _ first flowering, 2 mid spring, 3 late spring I _ main greening up and leaf unfolding, 4 late spring II _ flowering of fruit trees, and 5 late spring III _ late flowering and leaf unfolding). Thus, spring seasons generally progress from SW to NE through Europe. More precisely, the direction is WSW to

ENE in season 1 as the relationship of latitudinal to longitudinal gradients is less than 3–2 corresponding to SW to NE; in mid spring (season 2) the direction is almost SW–NE, and later on (season 3– 5) SSW to NNE. In the summer seasons (6, 7), the west to east component declines, having different signs between the three datasets and not being significant in all cases. Thus, the movement of summer, comparable with late spring, is apparently more south–north directed with latitudinal coefficients significant in five of six cases. The results for fruit-ripening phases occurring in early and mid autumn (season 8) are not as clear, only for the POSITIVE dataset do we find a negative, significant latitudinal gradient; for the IHNE data, it is positive, but not (quite) significant. In late autumn (season 9), there is a relatively clear turnaround in the pattern with leaf colouring being observed much earlier in the NE than in the SW parts of Europe. However, although all the latitudinal and longitudinal gradients are negative, only half turn out to be significant.

For the respective annual latitudinal and longitudinal gradients of these nine phenological seasons, a high year-to-year variability was apparent. Thus, the annual latitudinal and longitudinal gradients (IHNE) were correlated with mean monthly or combined mean monthly air temperatures in Europe (Table 3). Apart from the longitudinal correlation coefficients for the seasons 3 and 9, all regression coefficients are negative. This result reveals that for the IHNE data, in general, warmer temperatures in the months preceding the onset of the different seasons lower both the latitudinal and longitudinal gradients. Lower gradients indicate fewer days between successive degrees of latitude or longitude, and thus a higher velocity of progression.

However, considering the NAO index as an explanatory variable for the annual variation in latitudinal and longitudinal gradients, the picture is quite different (Table 4). Obviously, high NAO indices in winter and spring do influence the latitudinal gradients of spring phases (1–5) across Europe, making the latitudinal gradients smaller and the pattern more uniform. As the western and maritime parts, especially, of Europe are influenced by western airflow, the longitudinal gradients increase with higher NAO (i.e. the differences between western and eastern parts of Europe are more pronounced and the west–east velocity of progress is lower). Both smaller latitudinal and higher longitudinal gradients influence the pattern and switch the direction of progress to WSW–ENE. For the onset of summer (6, 7) and autumn (8, 9) the results are, when significant and displayed in Table 4, quite contradictory between the three different datasets. For autumn and summer, especially, in the IHNE dataset, high NAO indices in winter and spring are correlated with both smaller latitudinal and longitudinal gradients, rendering Europe both in west–east and in south–north directions more uniform.

Discussion

The POSITIVE dataset has already been analysed for rates and spatial patterns of changes in spring phenology. The study of Ahas et al. (2002) revealed higher advances in Western and Central Europe and a less pronounced delay in the Eastern parts of Europe. There is also plenty of evidence that spring and summer phases, especially, strongly respond to change in air temperature (e.g. IPG data Menzel (1997); Chmielewski & Rötzer (2002), POSITIVE data Ahas et al. (2002); Menzel (2002b); Scheifinger et al. (2002)). In this study, we focused on the pattern of the onset of phenological spring seasons in Europe, which also seem to be closely related to the circulation pattern and warming of the European continent at the end of winter: spring seasons progress from WSW to ENE, from SW to NE, and finally from SSW to NNE, the later ones much faster than those in the early spring. Europe is one of the most maritime continents. At the beginning of spring, eastern Europe might be still under the active influence of the western end of the continental Siberian High with low temperatures, whereas the western maritime parts of Europe might be under strong and persistent westerly circulation. Fronts connected to cyclonic low-pressure systems tend to bring relatively warm maritime air masses. Thus, at this time of the year the south–north gradient in phenological onset dates should logically have a pronounced west–east component. Later on, in early summer, the continental surfaces have warmed considerably. Consequently, a pronounced south–north direction is apparent. In late autumn, as shown by leaf colouring dates, the growing season ends first in the north-east of Europe progressing to the south-west. As we only used temperate deciduous trees to determine the onset of late autumn, an earlier end of the growing season in Mediterranean areas because of lack of soil moisture is not taken into account.

Although the pattern of phenological seasons across Europe described above is consistent within the three datasets analysed, the magnitude of the gradients seems to be quite different: the spring and summer latitudinal and longitudinal gradients in the POSITIVE dataset are the lowest, and the IPG data were in some cases lower than in the IHNE data. There are a lot of hypothetical explanations for this feature. First of all, the three datasets cover different spatial extents (see Fig. 1) and, thus, different ranges of latitude and longitude (e.g. the POSITIVE dataset might stretch furthest to the east into Russia although it has only a moderate north south range). It is likely that this may have an influence on coefficients and regression models. In addition, the density of phenological stations in Germany is much higher in POSITIVE, even though only stations with very long records have been taken into account. Differences between the IPG data and the two other datasets may be because of observations on cloned plant material instead of site-adapted, natural vegetation. Most of the clones are of German origin as the two founders of this network were German. From provenance trials, it is known that specimens brought south suffer from late spring frost, as their respective sums of forcing temperatures (which are required to induce the onset of the seasons) are reached much faster than those of site-adapted plants in warmer regions. In contrast, being planted in the north, they generally start their growing season too late. This might explain why the latitudinal and longitudinal gradients observed for long-term average onset dates of the seasons in the IPG dataset are to a certain degree higher than for the POSITIVE dataset. The IHNE dataset covers the highest latitudinal and longitudinal gradients. During the 1879–1941 period spring temperatures (March–May) in Europe were _0.32 1C colder than in the 1961–1990 standard period, whereas in the 1951–1998 period they were 0.16 1C warmer than 1961–1990 (CRUTEM2 land air temperature anomalies on a 5° to 5°grid-box basis, Jones & Moberg, 2003, http://www.cru.uea.ac.uk/cru/ data/temperature/, here: 10°W 35°N to 35°E 70°N), thus lower temperatures led to steeper phenological gradients and thus lower velocities of progression.

The Icelandic Low and Azores High are two main contributors to climatic controls in Europe with the Icelandic Low strongest in winter and the Azores High weakest in March and strongest in July. The NAO index is simply the pressure difference between Iceland (low) and the Azores (high); thus, a high NAO in winter and early spring is linked to more westerly circulation leading to higher temperatures, at least in western and Central Europe (Hurrell, 1995). The influence of NAO on phenological spring phases at single sites is well known (e.g. Chmielewski & Rötzer, 2002; Menzel, 2003). Scheifinger et al. (2002) showed that in Central Europe the influence of NAO on phenology temporally decreases with increasing day of the year and spatially with increasing distance from the coast. Aasa et al. (2004) studied the correlation between phenological phases and NAO indices of winter months at stations in Central and Eastern Europe and reported that stronger correlations are found for the western stations (Germany, Austria) and the Baltic region, especially in early spring.

Testing the influence of NAO on the latitudinal and longitudinal gradients in our study, we found that high NAO indices in winter and spring decrease the latitudinal gradients of spring phases (1–5) across Europe, making the latitudinal differences smaller and the pattern in the west more uniform. In contrast, longitudinal gradients increase with high NAO indices in winter and spring, and thus a reduced south–north component in progression. Consequently, spring then approaches more from the WSW. The probably more intense reaction within the IPG dataset may be because of the higher proportion of stations in the northwestern parts of Europe that are included.

Combining all three phenological datasets (IHNE, IPG, POS) we calculated the mean onset of the seasons at all stations in 1879–1998 (only 9 years 1942–1950 are missing). In order to demonstrate the influence of NAO index on the pattern of spring progression in Europe, we determined the mean onset of a season in Europe for the 10 years with the highest (1990, 1882, 1928, 1903, 1993, 1910, 1880, 1997, 1989, 1992) and the 10 years with the lowest (1969, 1936, 1900, 1996, 1960, 1932, 1886, 1924, 1941, 1895) NAO winter and spring index (November–March). These two maps are displayed in Fig. 3 (upper two plates) for season 2 (mid spring). The two different patterns of progression are clearly evident SW–NE in years with high NAO index and S–N in years with low NAO index despite the known fact that the onset of spring phases in years with high NAO index is undoubtedly advanced.

The third plate in Fig. 3 (lower left) also shows the differences in onset between the average NAO high and average NAO low years, which are more pronounced in the western (France, Ireland, UK) and north-western (south Scandinavia) parts of Europe and less distinct in the continental part of Europe. A simple correlation between the onset of season 2 and NAO index during the whole 1879–1998 period (plate 4 in Fig. 3) reveals that the remarkable correlation, which can be found in nearly all parts studied, does not necessarily implicate a high relevance of the NAO index in all regions in Europe.

The effects of the NAO on summer phases is generally less pronounced (Table 4) as in not every case is there a significant relationship, and even then their sign might be opposite. For autumn phases (seasons 8 and 9), winter and spring with high NAO index seem to have both lowered latitudinal and longitudinal gradients of the progression of the seasons; thus, the pattern of the onset of fruit ripening and leaf colouring is more uniform in those years.

Europe is also affected by the North Atlantic Drift current, which is an extension of the Gulf stream, and as a result experiences relatively warm sea surfaces temperatures influencing the mid and high latitude area. Thus, there is possibly also a relationship with the North Atlantic Drift and the onset of phenological seasons in Europe, which should be considered in further studies.

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Table 1

Composition of the phenological seasons in the three datasets (see text) (F first flowering, FF full flowering, LU leaf unfolding, M May shoot, FR fruit ripening, LC leaf colouring)

	Season	IHNE data (native plants)	IPG data (clones)	POSITIVE data (nat.)
1	Early spring	F *Corylus avellana* F *Galanthus nivalis* F *Salix caprea*	F *Salix acutifolia* F *Salix viminalis* F *Salix smithiana*	F *Corylus avellana* F *Tussilago farfara*
2	Mid spring	F *Ribes uva-crispa* F *Anemone nemorosa* LU *Aesculus hippocastanum*	F *Ribes alpinum* F *Salix aurita* LU *Ribes alpinum*	
3	Late spring I	F *Prunus spinosa* F *Ribes rubrum* F *Prunus avium*	LU *Larix decidua* LU *Sorbus aucuparia* LU *Betula pubescens*	LU *Betula pendula*
4	Late spring II	F *Prunus cerasus* F *Pyrus communis* F *Malus domestica*	F / FF *Prunus avium* (2 clones)	F *Prunus avium* F *Malus domestica*
5	Late spring III	F *Syringa vulgaris* F *Aesculus hippocastanum*	LU *Populus tremula* M *Picea abies* (2 clones) LU *Robinia pseudoacacia*	F *Syringa vulgaris*
6	Early summer	F *Sambucus nigra* F *Robinia pseudoacacia* F *Rubus idaeus*	F / FF *Robinia pseudoacacia* F *Sambucus nigra*	F *Robinia pseudoacacia*
7	Mid summer	F *Tilia cordata* F *Tilia platyphyllos* FR *Ribes rubrum*	F / FF *Tilia cordata*	F *Tilia cordata* F *Tilia platyphyllos*
8	Early / mid autumn	F *Colchicum autumnale* FR *Sambucus nigra* FR *Aesculus hippocastanum*		FR *Aesculus hippocastanum*
9	Late autumn	LC *Fagus sylvatica* LC *Quercus robur* LC *Aesculus hippocastanum* LC *Betula pendula*	LC *Betula pubescens* LC *Tilia cordata* LC *Prunus avium* LC *Fagus sylvatica*	LC *Betula pendula*

Table 2

Multiple regression coefficients [days deg^{-1} latitude / longitude] of overall mean seasonal onset dates in Europe for three different phenological datasets (see text) against latitude (LAT) and longitude (LON) (S season see Table 1, P significance of the regression coefficients, DF degree of freedom, R^2 explained variation). All significant coefficients in bold

	IHNE						IPG						POSITIVE					
S	LAT	P	LON	P	R^2	DF	LAT	P	LON	P	R^2	DF	LAT	P	LON	P	R^2	DF
1	0.39	0.46	**1.53**	**0.00**	0.45	67	**2.42**	**0.00**	**0.77**	**0.00**	0.55	50	**1.11**	**0.00**	**0.86**	**0.00**	0.52	379
2	**1.08**	**0.01**	**0.79**	**0.00**	0.40	71	**1.68**	**0.00**	**0.59**	**0.01**	0.41	49						
3	**2.14**	**0.00**	**0.83**	**0.00**	0.53	116	**1.31**	**0.00**	**0.47**	**0.03**	0.29	47	**1.07**	**0.00**	**0.22**	**0.00**	0.36	314
4	**2.18**	**0.00**	**0.52**	**0.00**	0.50	126	**2.26**	**0.00**	**0.65**	**0.00**	0.60	42	**1.53**	**0.00**	**0.42**	**0.00**	0.46	348
5	**2.18**	**0.00**	**0.30**	**0.01**	0.47	89	**1.11**	**0.00**	0.35	0.10	0.20	56	**1.08**	**0.00**	**0.14**	**0.00**	0.22	397
6	**2.57**	**0.00**	0.15	0.37	0.42	79	**1.77**	**0.05**	-0.56	0.33	0.48	21	**1.36**	**0.00**	-0.11	0.20	0.12	99
7	**1.01**	**0.03**	0.02	0.90	0.08	63	1.80	0.16	-0.81	0.23	0.48	12	**1.50**	**0.00**	-0.02	0.70	0.23	221
8	0.81	0.07	0.20	0.45	0.14	44							**-1.16**	**0.00**	0.04	0.75	0.14	240
9	-0.15	0.68	**-0.46**	**0.02**	0.12	63	-0.26	0.33	-0.05	0.74	0.02	45	**-1.75**	**0.00**	**-0.59**	**0.00**	0.71	216

Table 3

Pearson's correlation coefficients of latitudinal (LAT) and longitudinal (LON) gradients (IHNE dataset) of the onset of phenological seasons (see Table 1) on mean monthly or combined mean monthly temperatures in Europe (T, number denotes the month, underscore a month of the previous year). The respective highest correlation coefficients are given, all significant at the 5 % level

S	1	2	3	4	5	6	7	8	9
LAT	-0.38	-0.52	-0.31	-0.32	-0.38	-0.33	-0.28	-0.39	-0.36
T	$\underline{11}$ - 3	$\underline{11}$ - 3	3 - 5	5	5	5	6	6	$\underline{12}$ - 2
LON	-0.29	-0.29	0.37	-0.34	-0.32	-0.35	-0.45	-0.31	0.38
T	$\underline{10}$ -$\underline{12}$	1	3	5	1	1	1	5	$\underline{10}$

Table 4

Pearson correlation coefficients of latitudinal (LAT) and longitudinal (LON) gradients in Europe and mean monthly or combined mean monthly North Atlantic Oscillation indices (NAO, number indicates the month, underscore a month of the previous year). The respective highest correlation coefficients are given where significant at the 5 % level

S		1	2	3	4	5	6	7	8	9
IHNE	LAT	-0.56	-0.53	-0.52	-0.43	-0.38	-0.32	-0.30	-0.25	-0.30
	NAO	$\underline{11}$ - 3	$\underline{11}$ - 3	$\underline{11}$ - 3	$\underline{11}$ - 3	5	2 - 5	3 - 5	3 -5	$\underline{11}$ - 3
	LON	0.26	0.23	0.36		0.29	-0.21	-0.27		-0.26
	NAO	$\underline{11}$ -3	3	$\underline{11}$ - 3		3 - 4	1	1		3
IPG	LAT			-0.52	-0.36		0.43			-0.55
	NAO			$\underline{11}$ - 3	1		4			1
	LON		0.46	0.45	0.60					- 0.49
	NAO		2	2	2					5
POSITIVE	LAT	-0.54		-0.42	-0.20	-0.27	0.29	-0.51	-0.40	
	NAO	$\underline{12}$ - 2		2	2	$\underline{11}$ - 3	4	2	9	
	LON	0.38		0.30	0.25	0.26	0.33	0.30	-0.31	
	NAO	2		2	2	2	2	2 - 5	9	

Figure 1
Long-term record stations (black dots) in the three datasets (IHNE, IPG, POS5POSITIVE), displayed for the onset of late spring (season 3, day of the year, see Table 1). The vertical and horizontal axes represent degrees of latitude and longitude, respectively.

Figure 2
Boxplots comparing seasonal onsets in the three datasets (IHNE, IPG, POSITIVE): the boxes identify the 10%, 25%, Mean, 75%, and 90 % of the frequency distribution of mean onset dates at IPG (up to 5), IHNE (up to 40) and POSITIVE (up to 55) sites in western Germany (51°N>LAT>48.7°N, 6.5°E<LON<9.3°E). Note that underlying time periods, plants, phases, and sites are different (see data chapter, Table 1)

Figure 3
Upper two plates: The mean onset of season 2 (mid spring, day of the year) in Europe for the 10 years with the highest (1990, 1882, 1928, 1903, 1993, 1910, 1880, 1997, 1989, 1992, NAO high) and the 10 years with the lowest (1969, 1936, 1900, 1996, 1960, 1932, 1886, 1924, 1941, 1895, NAO low) NAO winter and spring index (November–March) in 1879–1998; Lower plate left: differences between the mean onset of season 2 (days) in Europe in NAO high and low years (upper two plates); Lower plate right: correlation coefficient between the yearly onset of season 2 and NAO index (1879–1998). The vertical and horizontal axes represent degrees of latitude and longitude, respectively. Upper two plates: The mean onset of season 2 (mid spring, day of the year) in Europe for the 10 years with the highest (1990, 1882, 1928, 1903, 1993, 1910, 1880, 1997, 1989, 1992, NAO high) and the ten years with the lowest (1969, 1936, 1900, 1996, 1960, 1932, 1886, 1924, 1941, 1895, NAO low) NAO winter and spring index (Nov – Mar) in 1879-1998;

Figure 1

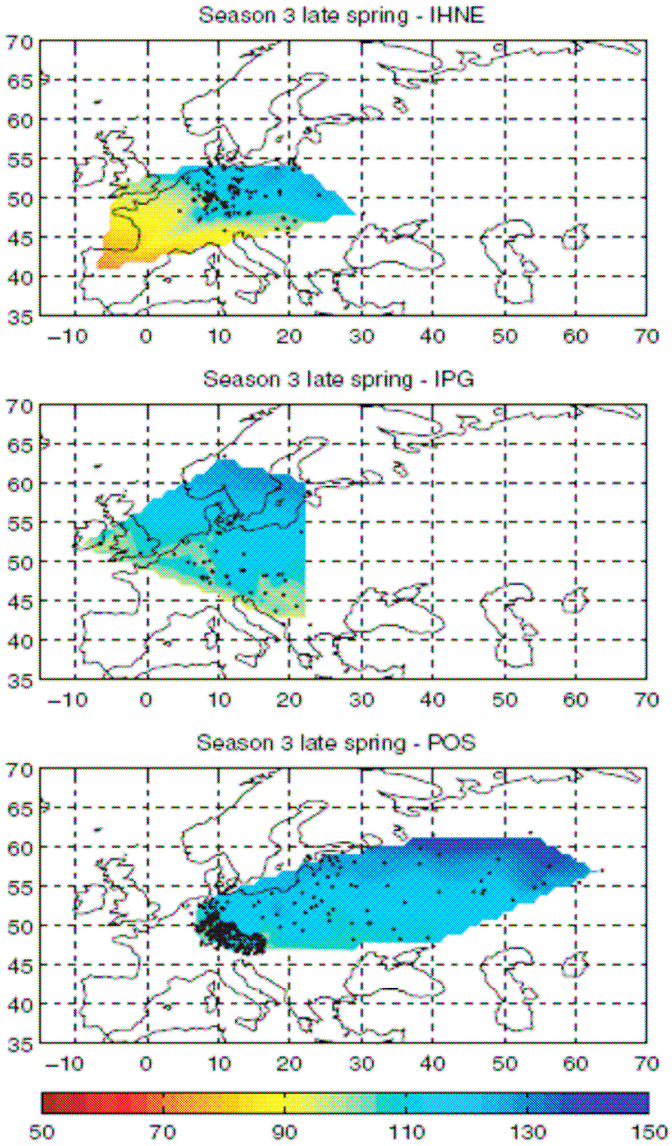

Season 3 late spring - IHNE
Season 3 late spring - IPG
Season 3 late spring - POS
70
65
60
55
50
45
40
35
−10
0
10
20
30
40
50
60
70
50
70
90
110
130
150

Figure 2

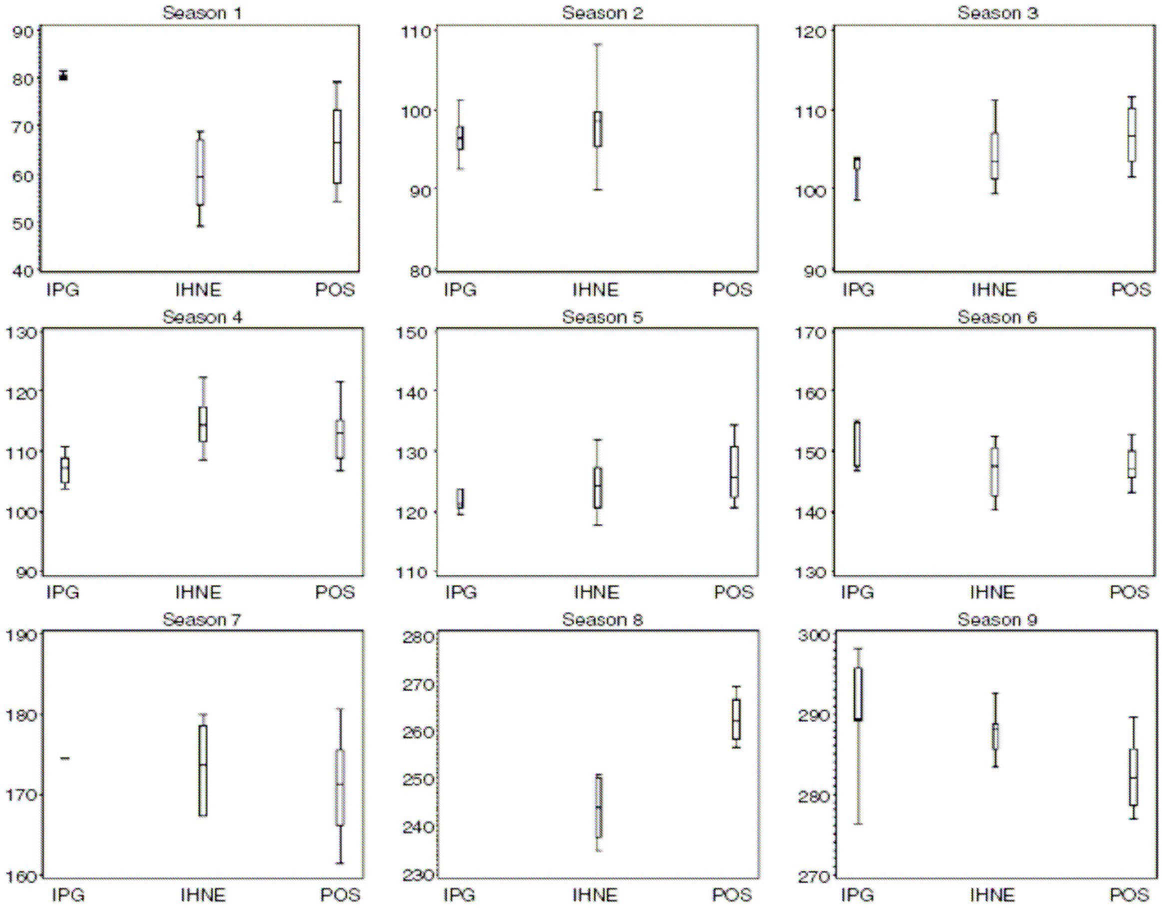
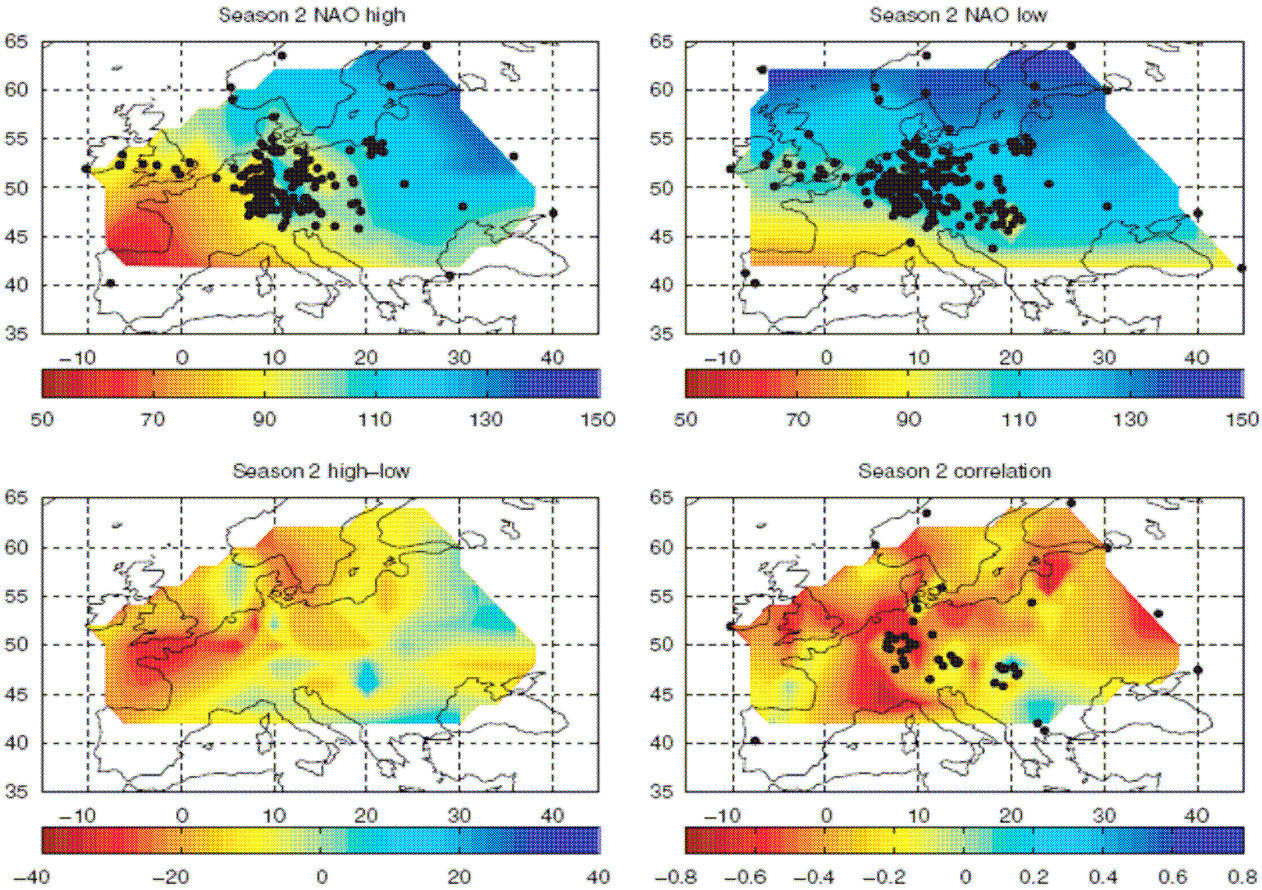

Season 1
90
80
70
60
50
40
IPG
IHNE
POS
Season 2
110
100
90
80
IPG
IHNE
POS
Season 3
120
110
100
90
IPG
IHNE
POS
Season 4
130
120
110
100
90
IPG
IHNE
POS
Season 5
150
140
130
120
110
IPG
IHNE
POS
Season 6
170
160
150
140
130
IPG
IHNE
POS
Season 7
190
180
170
160
IPG
IHNE
POS
Season 8
280
270
260
250
240
230
IPG
IHNE
POS
Season 9
300
290
280
270
IPG
IHNE
POS

Figure 3


Season 2 NAO high
Season 2 NAO low
Season 2 high–low
Season 2 correlation
65
60
55
50
45
40
35
–10
0
10
20
30
40
50
70
90
110
130
150
–40
–20
0
20
40
–0.8
–0.6
–0.4
–0.2
0
0.2
0.4
0.6
0.8