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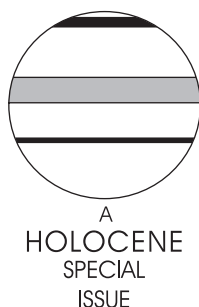
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Is spring starting earlier?

R. Thompson^{1*} and R.M. Clark²

(¹School of GeoSciences, The University of Edinburgh, Edinburgh UK EH9 3JN, UK; ²School of Mathematical Sciences, Monash University, 3800 Victoria, Australia)



Abstract: Time series of leafing phenology, air temperature and precipitation along with regional changes in carbon dioxide concentration, are analysed in addressing three questions: ‘what magnitude of changes in flushing day are likely with climate change?’, ‘which taxa have a chilling requirement?’ and ‘is spring starting earlier?’. Phenological observations of leafing, starting in 1739, are used to calibrate a new model that describes the time of flushing. Statistical methods are used to provide full standard errors on the model coefficients. All 13 tree types studied are found to show an association between flushing date and air temperature. Nine out of the 13 tree types show non-linear temperature behaviour. Model output indicates that climate change has a particularly strong effect on flushing date in oceanic climates, such as that of Britain. The modelled responses can be used to estimate the impact that recent changes in temperature have had on the timing of the start of spring. We find that in any future climate-warming, flushing dates of tree types sensitive to ‘chilling’, for example beech and horse chestnut, are likely to move 30 days, or more, out of synchronicity with those sensitive only to springtime warmth. The new phenological model is also applied to fluctuations in the carbon dioxide mixing-ratio. Changes in the phase of the annual CO₂ cycle are isolated and used as evidence for an earlier spring. We make use of a complex demodulation analysis of carbon dioxide, as monitored at 27 stations around the world, to reveal that the timing of the annual CO₂ cycle has become steadily earlier in recent decades. Finally we show that the estimates of the effect of rising temperatures on the earliness of spring, made using our new phenological model, are in good agreement with global observations of changes in the timing of the annual carbon dioxide cycle if about 50% of the biomass of the world’s terrestrial biosphere is fully temperature sensitive and about 50% sensitive to chilling (or to an equivalent inhibitory effect).

Key words: Accumulated temperature, carbon dioxide, climate change, spring, complex demodulation, phenology, Mauna Loa.

Preamble

This paper is a tribute to Frank Oldfield. It owes its genesis to three of his enduring interests, namely: human impact on the environment, pollen, and archives (Oldfield, 1983). In the article we continue our earlier collaborations on statistical and time-series methods. Our association with Frank stems from his perceptive observation in 1972 that magnetic susceptibility logs of Holocene sediment cores from Lough Neagh, that one of us (R.T.) had made in the palaeomagnetic laboratory in Newcastle, matched pollen profiles produced in Frank’s lab in Coleraine. Frank’s realization that Man’s impact on the Lough Neagh catchment, on its vegetation, soil development and soil erosion was recorded by *both* pollen and mineralogical (mineral magnetic) erosion indicators (figure 13 in Thompson *et al.*, 1975) was the starting point for an extremely wide range of later studies. This work came to be known as environmental magnetism. It grew to encompass subjects as diverse as pedogenesis, Chinese loess, deep-sea sediments, diagenesis, biomagnetism, magnetic pollution, dust and atmospheric transport and palaeolimnology (Thompson and Oldfield, 1986). In particular

Frank’s desire in the 1970s and 1980s to use magnetic susceptibility for lake-sediment correlation and palaeomagnetic secular-variation for lake-sediment dating helped inspire us to collaborate on improved statistical methods for the alignment of time series (Clark and Thompson, 1979; Thompson and Clark, 1989) and the smoothing of palaeomagnetic paths (Clark and Thompson, 1978, 1984; Thompson and Clark, 1981).

The present study involves the analysis of historical observations (=archives), of flowering and budding (=pollen), and of CO₂ concentrations (=human impact) on decadal and centennial timescales. In our study we follow the Ed Deevey adage of ‘Coaxing history to conduct experiments’ (Deevey, 1969) that Frank was so fond of promoting. The basic idea of the adage is that in ecology (*sensu stricto*) the experimental method is necessarily restricted to those experimental situations that history already happens to have provided for you. In particular we investigate relationships of long series of leaf flushing dates with temperature (using the well known Central England data set generated by Gordon Manley, a colleague, and mentor, of Frank during his sojourn at Lancaster). The two main data sets we study reflect Frank’s capacity for working at the local scale (we study the temperature responses of individual taxa in SE England) but with a

*Author for correspondence (e-mail: roy@ed.ac.uk)

broad vision (we study global CO₂). The paper is structured as follows. First, we analyse long series of leaf flushing dates, and relate them to climatic variables. Second, we develop an enhanced phenological model to quantify the responses of leafing dates for 13 temperate trees to wintertime chilling and to springtime warmth. Third, we 'force' our phenological models with climate change scenarios to determine the impacts on flushing date. Fourth, we address the question 'at the global scale, are plants developing earlier in spring?'. Finally we use our enhanced phenological model to help explain recent changes in the phase (ie, earliness) of the global carbon dioxide cycle.

Introduction

The aim for many models of flowering, or bud-burst, dates in temperate plants has been an ability to predict the responses of plants to seasonal variations (Cannell, 1989; Chuine, 2000). The increasing likelihood that global warming will strongly impact on plant behaviour, and that recent climate changes, particularly temperature increases, have already affected many physical and biological systems (eg, Hughes, 2000; Walther *et al.*, 2002) serve to emphasize the environmental and economic value of phenological models. For many trees of temperate origin, additional springtime warmth serves to advance the date of budding and flowering. However, in other temperate tree-species insufficient winter chilling is found to delay budburst (eg, Murray *et al.*, 1989; Hänninen, 1990; Falusi and Calamassi, 1990; Heide, 1993a, b). In most situations the advancement effects associated with spring warmth are stronger than the opposing, delaying effects of lack of winter chilling, so that flushing takes place earlier in warmer climates. Murray *et al.* (1989) suggest that in certain localities in Britain climatic warming may increase winter temperatures so much that the lack of chilling will cause species such as *Picea sitchensis*, and in particular late-budding trees such as *Fagus sylvatica*, to delay their budburst, and perhaps even to become unviable. Seasonal changes of phenology and biomass production significantly affect the rates and properties of carbon exchanges to the atmosphere because terrestrial plants fix carbon from the atmosphere in the growth season when photosynthesis dominates over respiration. As terrestrial plant photosynthesis greatly exceeds photosynthesis in the oceans, the annual variations in carbon dioxide are widely thought to be associated with the seasonal changes of terrestrial biota (eg, Denning *et al.*, 1995; Quay, 2002). Thus long-term measurements of CO₂ can provide alternative records of changes in the earliness of spring to those of leaf flushing, or of flowering date. A particularly well-known example of a long time-series of CO₂ that we analyse is Keeling's Mauna Loa data set (Keeling, 1998).

An important challenge in the science of phenology is the development of a quantitative understanding of interannual variations. Many phenologies, like the tree leafing records analysed here, can be classified as population phenologies (Harper *et al.*, 2004) as opposed to single organism phenologies. Harper *et al.* (2004) describe the pros and cons of these two types of phenology and point out that in climate-change studies population phenologies require particularly careful data analysis and modelling. In this paper we begin the data analysis by enhancing a general phenological model (Thompson and Clark, 2006). We go on to use the enhanced model to study long time-series of leafing dates for 13 temperate trees, and to quantify their responses to chilling. We obtain confidence limits on all the model parameters. Next we show how the models can be used to determine the changes to flushing date and flushing temperature that (a) have occurred in recent centuries and (b) can be anticipated with future climate change. We continue with an analysis of the carbon dioxide concentration record from Mauna Loa, and of 26 shorter time-series

from a wide range of latitudes. Complex demodulation is used to isolate and quantify the annual variations in carbon dioxide. Lastly, we couple the changes in tree phenology, prescribed by our model, with trends in the Mauna Loa carbon dioxide cycle in order to make an estimate of the proportion of the world's vegetation that is influenced by phenological inhibitory effects, such as chilling.

Data

Long time-series of phenological observations at the same locality are very rare. However, records of leafing (or flushing) for 13 types of temperate trees come from the information recorded by Robert Marsham and his descendents in England (Fenn, 1790). Robert Marsham first began recording phenological events in 1736 on his family estate around Stratton near Norwich, 20 km from the Norfolk coast (52°43'N, 1°16'E). Records continued down the generations (with occasional gaps) until 1958 (Sparks and Carey, 1995). The leafing observations began in 1739 (Margary, 1926) with hawthorn and sycamore. Leafing is defined as the date when leaves were of recognizable shape for the first tree on the estate. All dates down to 1752 have been corrected from the old style calendar.

Old climate data are relatively scarce. Fortunately, however, nearby (~110 km) temperature data are available from the central England series. This continuous series, which begins in 1659, is the longest available instrumental record of temperature in the world (Manley, 1953, 1974). Temperature fluctuations in the central England region are representative of those for much of the UK (Parker *et al.*, 1992), and so provide us with an excellent data set for comparison with the Marsham phenology.

Similarly we are fortunate that nearby (~90 km) precipitation data are available from long series based at Pöde Hole (Lincolnshire), Kew and Oxford. The monthly precipitation means are relatively well correlated between these three sites and so they provide a regional precipitation series that can be compared with the first leafing records from Norfolk. Correlations between the monthly means of precipitation during winter and spring are found to range between 0.81 (April and May) and 0.90 (February).

The rise of carbon dioxide gas in the atmosphere has been measured on a continuous basis since March 1958 when Keeling began measurements as part of the IGY (International Geophysical Year). Daily atmospheric carbon dioxide (CO₂) concentrations have been measured at the Mauna Loa Observatory (19.5°N, 155.6°W, and elevation of 3400 m) on Hawaii, with few interruptions, ever since. Details about the sampling methods and calibration procedures at Mauna Loa are given in Keeling *et al.* (1982). The Global Atmosphere Watch programme of the World Meteorological Organization now promotes systematic observations of the global atmospheric environment. Measurements of CO₂ at tens of stations from around the world are archived by the World Data Centre for Greenhouse Gases (<http://gaw.kishou.go.jp/wdcdgg.html>, last accessed 16 October 2007). As of December 2005, 317 stations in 66 countries were contributing data. We selected 27 stations with particularly long (>20 yr) records for our time-series work.

Methods and techniques

Accumulated temperature, or heat sum, model

The main type of phenological model we investigate is the heat-unit approach first introduced by the French physicist Rene de Reaumur (1735). In this approach temperatures above a given threshold are accumulated (as degree-days) until a heat-sum requirement is achieved, with the idea that the thermal limit can be used to tell when certain plants will germinate, flower or release

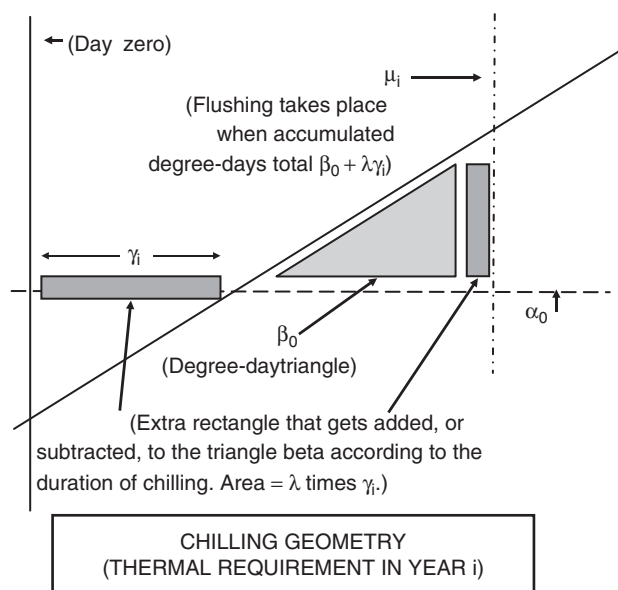


Figure 1 Geometry of the accumulated temperature model of Equation (2). The horizontal axis represents day of the year, the vertical axis temperature. The diagonal line plots the linear increase of spring time temperature in year i where the temperature on day x in year i is given by the linear equation: $T_i(x) = m_i x + c_i$, c_i is the air temperature when $x = 0$ and m_i is the rate of increase of temperature in degrees per day. The dashed horizontal line is the thermal threshold (α). The intersection of the diagonal and horizontal lines marks the change-over date in year i (γ_i) between chilling and heat accumulation. Beta is the area of the triangle. Flushing occurs when the accumulated heat-sum reaches $\beta + \lambda\gamma_i$.

their pollen. For example, two days with 25°C mean temperature would contribute 30 degree-days to the heat sum when using a temperature threshold of 10°C [(25–10) × 2 = 30].

We use the relationship

$$\mu_i = \sqrt{\frac{2\beta}{m_i}} + \frac{\alpha - c_i}{m_i} \quad (1)$$

in order to generate a linear model of the association between flushing, and flowering, date (μ) and temperature (see equation (6) in Thompson and Clark (2006) for details). In this parameterization the temperature threshold (α) and the degree-day requirement (β) form a regression with flushing date (μ_i) where m_i is the rate of increase of spring temperatures in year i and c_i is the air-temperature on day 0 in year i . The square root in Equation (1) is not arbitrary but arises directly from our linear parameterization of spring temperature rise (Thompson and Clark, 2006).

Equation (1) can be readily extended to include additional effects. Here we extend it to model inhibitory effects, in particular the well-known chilling effect. We expand α and β so that Equation (1) becomes:

$$\mu_i = \sqrt{\frac{2(\beta_0 + \lambda\gamma_i)}{m_i}} + \frac{(\alpha_0 + \kappa\gamma_i) - c_i}{m_i} \quad (2)$$

where κ is the change in the temperature threshold associated with differences in the duration of winter chilling, and γ is the day on which the spring temperature rise reaches the temperature threshold (ie, $\gamma_i = (\alpha_0 - c_i)/m_i$), λ is the change in thermal requirement associated with differences in the duration of winter chilling, α_0 is the temperature threshold, and β_0 the thermal requirement. In practice we use daily temperature measurements spanning the range of ± 60 days about the mean flushing date to estimate m_i and

c_i each year. Equation (2) thus allows the thermal requirement (and/or the temperature threshold) to depend on temperatures experienced during the previous weeks and months, as well as temperature close to the flushing date. In our model degree-day accumulation starts immediately after the cessation of winter chilling. Figure 1 illustrates the main terms used in Equation (2).

For each taxon we use residual plots to check the adequacy of our model (Equation (2)) and to check that our assumption of normally distributed errors is reasonable. Analysis of variance is used to compare models and to identify the most parsimonious model (using an F -value of 4).

In practical terms it is necessary to transform the term ($\beta_0 + \lambda\gamma_i$) in Equation (2) into $\exp(\beta_0 + \lambda\gamma_i)$ in order to help prevent it taking on negative values. As a consequence, in our chilling model the effect of duration of winter chilling on thermal requirement involves a multiplicative factor.

In summary, we model flushing in terms of just four parameters. These are temperature threshold, α ; thermal requirement, β ; and their dependences, κ and λ , on duration of winter chilling. A major advantage of this approach is that all four phenological parameters can be obtained directly by least-squares regression. Although Equation (2) is non-linear, all the parameters can be estimated by standard non-linear methods (Bates and Watts, 1988) since there are no constraints. Furthermore confidence limits for each parameter are automatically provided.

Effect of climate change on the date of flushing

In order to answer the question of how flushing phenology, for each of our species, will change from the ‘present’ climate to some ‘future’ climate we represent the present climate by the average linear spring-temperature rise in recent years. We call M and C the slope and intercept of this average temperature rise. It is then very straightforward to apply our models to any future climatic scenarios, with new values of M and C .

Confidence limits for flushing date and flushing temperature

As we have a reasonable sample size one way to get the confidence limits associated with any global warming prognoses is by the bootstrap technique. Here one recreates (bootstraps) the population by duplicating the sample by re-sampling. We draw 1000 samples from the original population, each of the same size as the original sample. In any given sample, some years will appear twice or more, while others are not present at all. Next we calculate the values of our outcome statistics (the flushing date and flushing temperature) for each of the 1000 samples for climate changes of between –4.5 and +4.5°C. Finally, we find the middle 95% of the values (ie, the 2.5th percentile and the 97.5th percentile) to give the 95% confidence interval for our outcome.

Complex demodulation

An elegant and convenient way to study annual cycles, and their change with time, is through complex demodulation. Complex demodulation is a type of band-pass filter that gives the time variation of the amplitude and phase of a time series in a specified frequency band. Briefly, in complex demodulation the time series is first frequency-shifted by multiplication with $e^{-i\Omega t}$, where Ω is the central frequency of interest. Then the shifted time series is low-pass filtered, which removes frequencies not near the central frequency. This low-pass acts as a band-pass filter when the time series is reconstructed. The resulting complex time series can then be expressed as a time-varying amplitude and phase of the variability of any given harmonic component. Bloomfield (1976) provides a detailed account of the method. We use the complex demodulation method to assess changes in seasonality of regional CO₂ records.

Table 1 Flushing date, number of observations, RMSE, model coefficients and standard errors for 13 deciduous trees

Taxa ^a	μ^b (day)	N^c	RMSE (day)	$\ln(\beta_0)^d$ ln(deg day)	Std error	$\ln(\lambda)^e$ ln(deg day)/day	Std error	α_0^f °C	Std error	κ^g deg/ day	Std error
Hawthorn <i>Crataegus monogyna</i>	68	144	15.7	3.7	0.3	0	–	3.0	0.3	–0.04	0.005
Sycamore <i>Acer pseudoplatanus</i>	91	134	10.6	3.8	0.7	–0.01	0.004	3.4	1.3	0	–
Horse chestnut <i>Aesculus hippocastanum</i>	94	144	8.2	2.2	1.0	–0.04	0.02	5.9	0.5	–0.01	0.003
Birch <i>Betula</i> spp.	96	140	10.7	4.9	0.1	0	–	1.6	0.6	–0.03	0.004
Elm (common) <i>Ulmus procera</i>	96	117	11.6	4.2	0.8	–0.01	0.004	2.9	1.9	0	–
Mountain ash <i>Sorbus aucuparia</i>	96	139	7.6	4.1	0.6	–0.01	0.003	3.1	1.4	0	–
Hornbeam <i>Carpinus betulus</i>	98	136	11.8	5.8	0.6	–0.005	0.001	3.9	3.5	0	–
Lime <i>Tilia</i> spp.	103	139	7.6	4.4	0.7	–0.01	0.002	2.8	1.8	0	–
Chestnut <i>Castanea sativa</i>	109	135	8.0	4.9	0.3	0	–	2.8	1.1	–0.03	0.006
Maple <i>Acer campestre</i>	109	97	11.6	4.4	1.5	–0.01	0.006	3.0	4.6	0	–
Beech <i>Fagus sylvatica</i>	110	142	5.8	4.0	0.4	–0.02	0.01	4.5	1.4	–0.02	0.009
Oak <i>Quercus</i> spp.	113	142	6.7	4.6	0.5	–0.007	0.001	3.5	1.7	0	–
Ash <i>Fraxinus excelsior</i>	119	130	9.6	5.2	0.5	0	–	2.3	1.6	–0.04	0.009

^a Latin species names are included where appropriate. Margary (1926) notes that there is no means to discover exactly what species were observed in the earliest years. Nevertheless he points out that as the records relate to first leafing, the most likely taxa are the most forward, common English species.

^b μ , Mean date of leafing. Table ordered by μ .

^c N , Number of years with observations.

^d β_0 , Thermal requirement. (On account of our choice of origin β_0 is the thermal requirement based on a timescale centred at the time of flushing.) Here the growing degree-days are specified on a log-scale, so the units of beta and lambda involve ln(days*deg) and ln(deg*day)/day, respectively.

^e λ , Rate of change of thermal requirement.

^f α_0 , Temperature threshold. (On account of our choice of origin α_0 is the temperature threshold based on a timescale centred at the time of flushing.)

^g κ , Rate of change of temperature threshold.

Results

The Marsham series

As a first step in assessing any association between the flushing and climate data we began by calculating simple correlation coefficients between flushing date and monthly mean temperatures (cf. Fitter *et al.*, 1995; Sparks *et al.*, 2000). We found, as expected from previous studies (Sparks and Carey, 1995), that air temperatures in the February and March of the year of flushing (ie, in the months immediately prior to flushing) showed the strongest associations with flushing date, with correlation coefficients of –0.68 and –0.57, respectively. The negative sign indicates that warmer temperatures are associated with earlier flushing. Less clear are the April correlations for the year of flushing. They have an average correlation of only –0.27. However, when individual taxa are considered, later flushing taxa such as oak, beech and chestnut yield their strongest correlations with April temperatures. So April temperatures in the year of flushing would also appear to have a

significant association with first flushing dates. Similarly, although the average coefficient for January temperatures (in the year of flushing) is rather weak at –0.18, we find that January temperatures are most closely matched with the early flushing taxa, and so are also deemed to be significant. Although autumnal chilling effects, in which warm autumn temperatures cause delayed leafing or flowering in the subsequent spring, are quite frequently reported (eg, Fitter *et al.*, 1995; Sparks *et al.*, 2000; Heide, 2003), in the Marsham series they are weak (Sparks and Carey, 1995).

In contrast with air temperature, precipitation shows no obvious relationship with flushing date. We found that precipitation coefficients for months near to the flushing dates showed no difference from coefficients for months well separated in time.

We regard correlation coefficients as providing a rough, but very valuable, first guide to the underlying relationships between the variables temperature, precipitation and day-of-the-year. Encouraged by the strong correlations between flushing dates and air temperatures of late winter and early spring we move on to

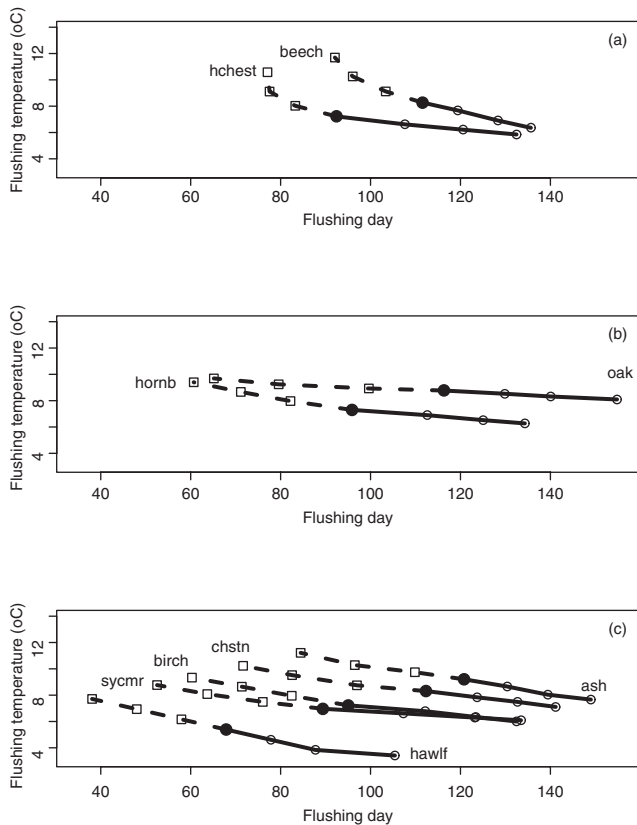


Figure 2 Plot of the day of the year on which flushing takes place against the mean air-temperature on the day of flushing. The curves show the response of flushing date and of flushing temperature to a change in air temperature. Average conditions for the present-day climate are plotted as a solid symbol. Open squares and dashed lines show the conditions for climate warmings of 1.5, 3 and 4.5°C calculated using Equation (2). Small open circles and continuous lines show the conditions for climate coolings of 1.5, 3 and 4.5°C. (a) The two species showing the strongest 'chilling effect'. Their flushing temperatures increase the most in warmer conditions, while their flushing dates advance the least. (b) The two species showing the weakest 'chilling effect'. These taxa are strongly sensitive to springtime temperatures, so their flushing dates respond the most to a warming of the climate. (c) Examples of five species showing an intermediate 'chilling effect'

examine the relationships in more detail by adopting a modelling approach.

We began our modelling work by using the basic heat-sum formulation set out in Equation (1). It quickly became clear that while for some taxa, such as oak and lime, a reasonable fit was being achieved, for several others, such as hawthorn, birch, beech and horse chestnut, an alternative model was needed. As the budding of beech seedlings has been demonstrated in greenhouse-controlled experiments (Murray *et al.*, 1989; Falusi and Calamassi, 1997a, b) to be strongly influenced by chilling, we proceeded without more ado to the inhibitor model of Equation (2). This model produced much more acceptable fits. Table 1 tabulates, for each taxon, the phenological coefficients along with their standard errors. For each taxon an ANOVA was used to determine the simplest model giving an adequate fit to the data. Any unnecessary coefficients were set to zero. For each of the 13 taxa studied we found the fits of Equation (2) to be significantly better than those of Equation (1) and requiring at least one inhibitory parameter to describe their phenological behaviour. All these coefficients were found to be negative, so demonstrating how in each case growing-degree-day requirements decrease in cold years and increase in warm years (such that reduced winter chilling duration causes an increase in the thermal requirement and a delay in flushing). This situation is fully consistent with an explanation that involves chilling duration.

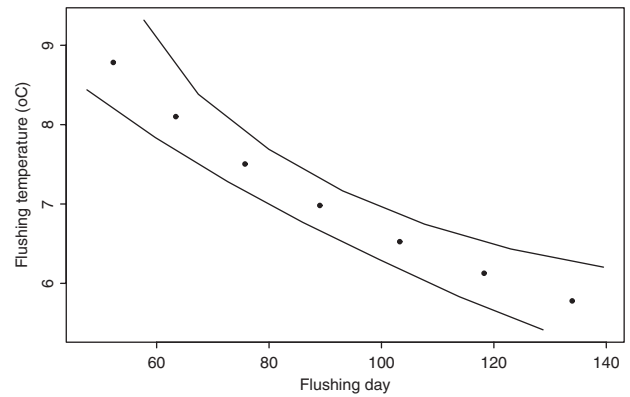


Figure 3 Bootstrap 95% confidence limits on the change in flushing conditions resulting from climate change for sycamore. Circles at 1.5°C intervals. The middle symbol is for present-day conditions in Central England (as in Figure 2). The limits are joint confidence intervals for flushing date and flushing temperature. The formulae on which the calculations are based can be found in Chapter 5 of Davison and Hinkley (1997)

We next turn to estimating the effect of climate change on the date of flushing. Figure 2 summarizes the climate-change responses that we have found. First consider the behaviour of horse chestnut, as plotted in Figure 2a. The large solid circle shows the present-day situation where the average first budding date is day 94, and the average temperature on this day is 7.2°C. The associated dashed line shows the modelled changes with climate warming. The first open square, on the dashed line, shows, for a 1.5°C warming, that the average date of flushing will advance to day 84 when the average temperature on that day will have risen to 7.9°C. A further 1.5°C temperature rise (second open square) produces a smaller advancement to day of the year 78. Finally with a 4.5°C warming, no further advancement in flushing date is found (because the effects of increased springtime warmth and reduced wintertime chilling-duration happen to cancel exactly). In contrast, cooling (solid line and small open circles in Figure 2a) causes horse chestnut to flush at slightly lower temperatures but much later in the year. We find the greatest changes in flushing temperatures occur for beech and horse chestnut (Figure 2a), ie, for those taxa that are sensitive to chilling. Turning to flushing date we note that in a warmer climate the taxa in Figure 2a will advance their average flushing date by only 4 days for every degree rise in mean temperature. By way of contrast, we find only modest changes in flushing temperatures for oak and hornbeam (Figure 2b). However, while their flushing temperature will not change much in a warmer climate they will greatly advance their flushing dates, by about 37 days for a 4.5°C warming. In short, global warming is likely to change the flushing behaviour of different trees in many ways, such that the normal progression of flushing will be altered. In contrast, climate cooling mainly retards flushing date, for all 13 tree types, and has only a modest effect on flushing temperature and causes little desynchronization. This is because the 13 tree types are well chilled in normal climatic conditions and so any extra chilling duration has little further effect.

Figure 3 plots one example of bootstrap confidence limits. It shows the results for sycamore, a typical taxon. The bootstrap analyses show how the behaviour is well constrained by the phenological observations, even for quite pronounced warming scenarios of 3 or 4.5°C.

Retrodiction of flushing dates

Retrodiction of past changes in phenological behaviour can be easily made using Equation (2). As an example Figure 4 plots a 235-yr hindcast of the flushing date for oak in Norfolk, between

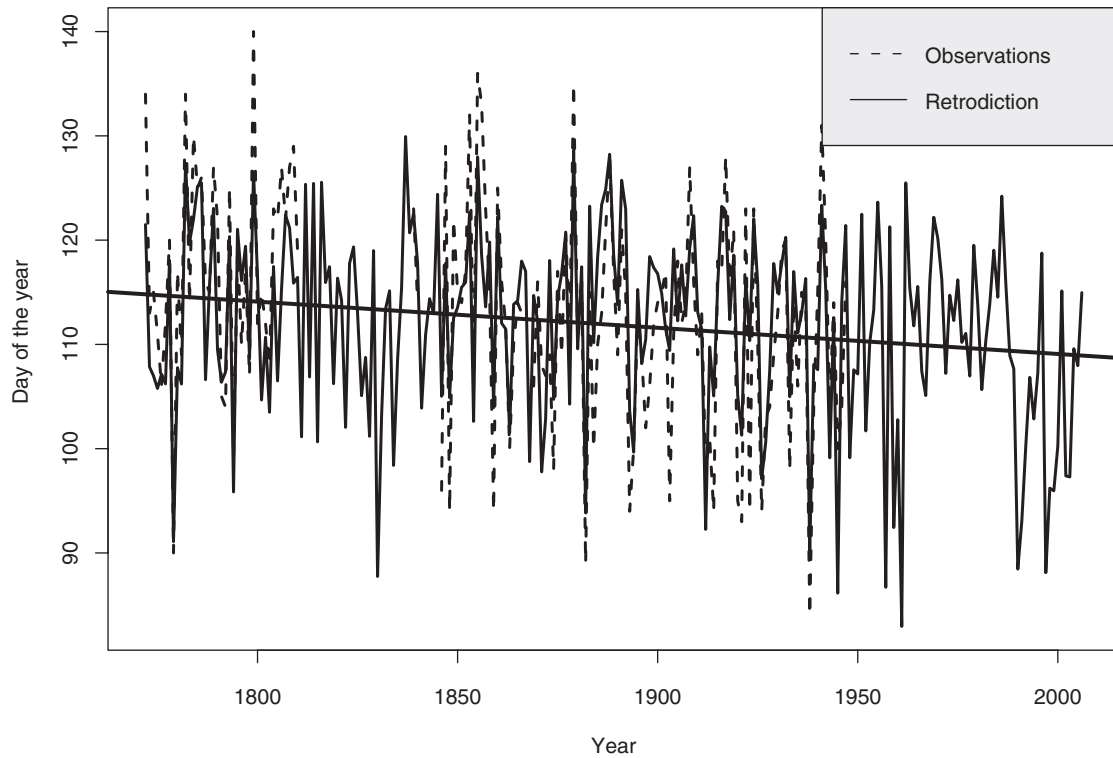


Figure 4 Retrodiction of flushing dates for oak. Retrodictions obtained using the coefficients (from Table 1) and daily Central England temperatures to force Equation (2) to obtain a hindcast for every year between 1772 and 2006. The rate of change has been -2.5 ± 1.7 days per century (95% confidence intervals)

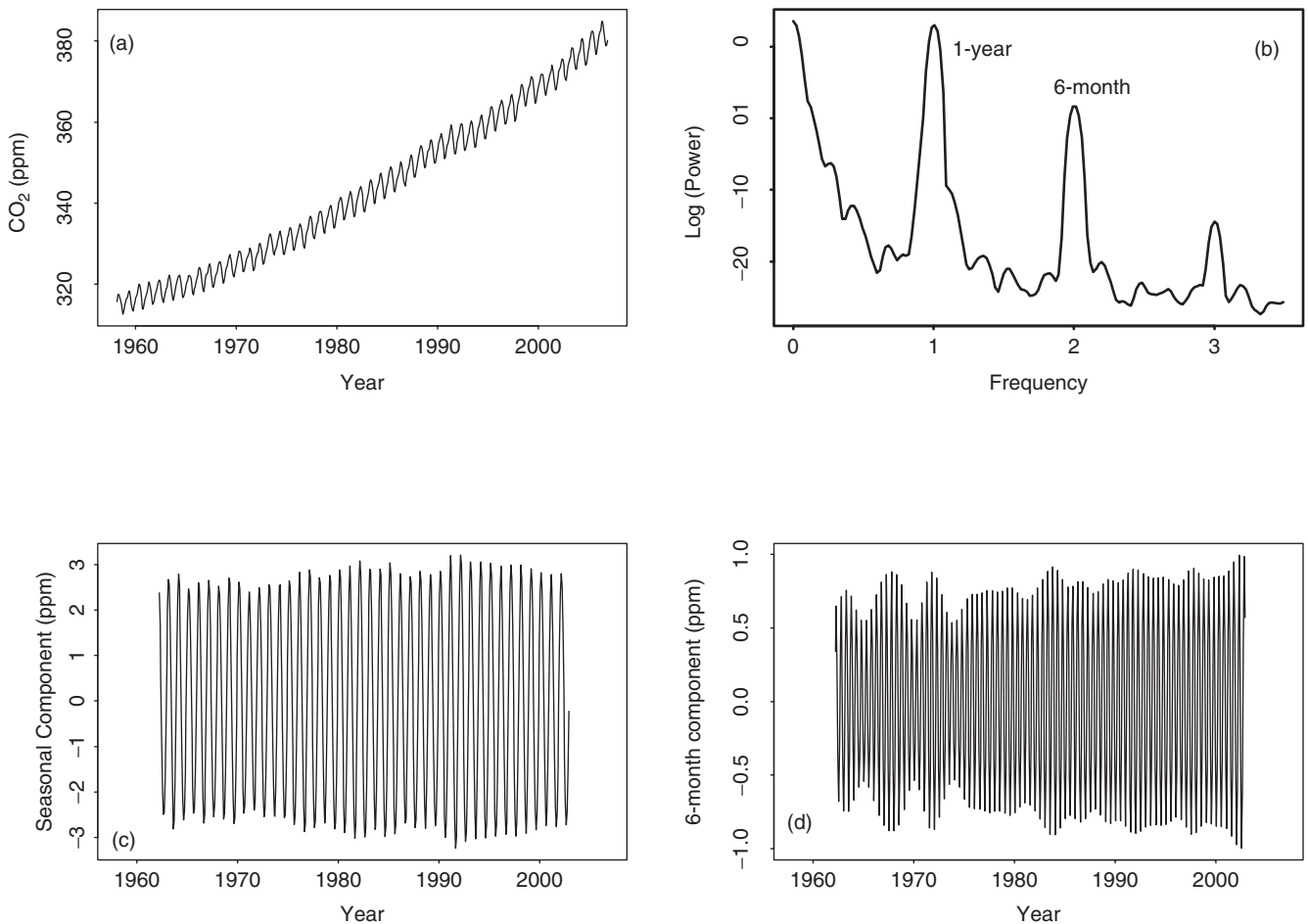


Figure 5 Mauna Loa carbon dioxide from 1958 to 2006. (a) Monthly averages, (b) spectrum, (c) annual cycle, (d) six-month cycle

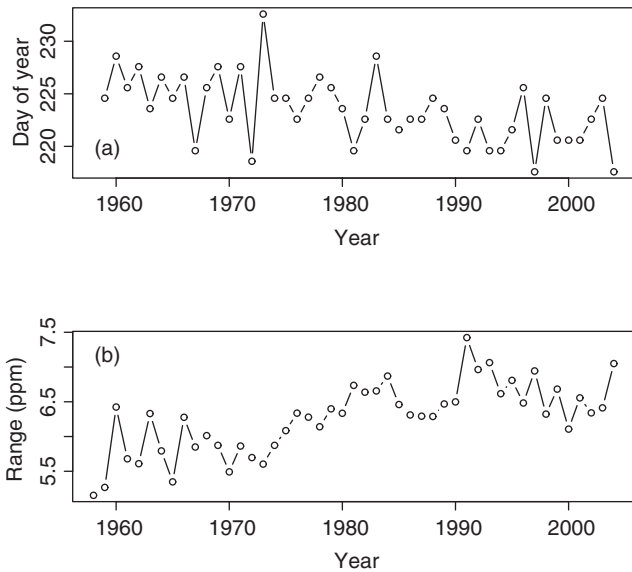


Figure 6 Mauna Loa time series. (a) Date of the annual maximum of CO₂, (b) annual range of CO₂

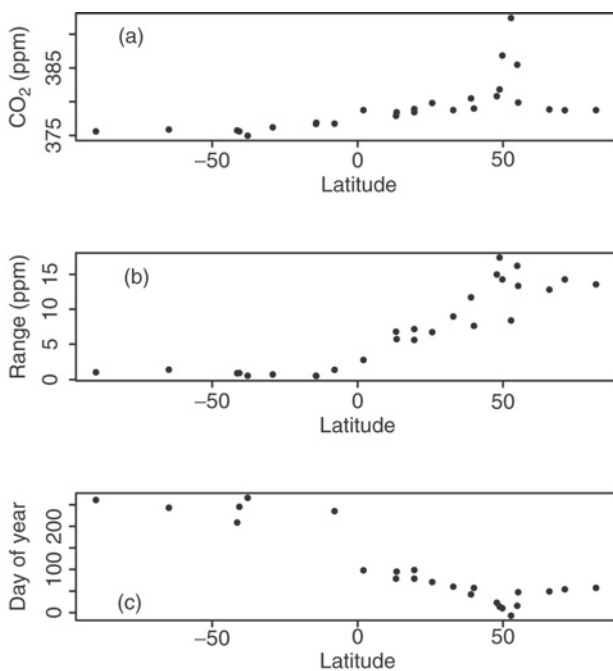


Figure 7 Latitude versus (a) mean CO₂ level in 2000, (b) annual range and (c) date of CO₂ maximum. The stations ordered by latitude are South Pole, Palmer, Baring Head, Cape Grim, Amsterdam Is, Kermadec Is, Cape Matatula, Samoa, Tutuila, Ascension, Christmas Is, Kiribati, Ragged Point, Guam, Mauna Loa, Cape Kumukahi, Key Biscayne, La Jolla Pier, Ryori, Niwot, Schaanisland, Brotjacklriegel, Deuselbach, Waldhof, Westerland, Cold Bay, OceanM, Point Barrow and Alert

1772 and 2006. The hindcast is based on the model coefficients (of Table 1) and daily measurements of Central England temperatures. We find that the rate of change, for oak, based on the observations and our modelling has been -2.5 ± 1.7 days (95% confidence intervals) per century. All 13 taxa studied show similar trends towards an earlier start to spring over the 235-yr time period. These range between -3.3 ± 2.3 and -1.8 ± 0.6 days per century, for beech and hornbeam, respectively. The average rate, across all 13 taxa, is -2.4 days per century. Such past rates of

change of around 2.5 days per century are much smaller than our forecasts of changes of almost 40 days this century. The contrast serves to highlight the magnitude of the impacts on the world's vegetation that can be anticipated with the steep increases in temperature within the next few decades as predicted by various Global Climate Models.

Carbon dioxide

We now turn to the global scale. If deciduous trees worldwide follow the type of phenological behaviour we find for Norfolk, then marked changes in the amplitude and phase of global CO₂ fluctuations should result from any changes in global temperature. Figure 5a plots the CO₂ fluctuations observed at Mauna Loa. The main feature of note is the rising quadratic trend. But our focus remains on the changes in timing of the annual cycle. Close inspection of Figure 5a also reveals the presence of small, short-lived, changes in the rate of increase. Complex demodulation allows all these features to be isolated. In particular the rising trend (mainly resulting from anthropogenic CO₂ emissions) and the minor fluctuations, which Bacastow (1976) attributes to El Niño events, can be quantified and removed.

The spectrum (Figure 5b) reveals significant low-frequency power and pronounced annual and six-month cycles. Once prepared with this spectral information we can move on to using complex demodulation to decompose the carbon dioxide time series into a long-term trend (Figure 5a), an annual signal (Figure 5c) and a six-month signal (Figure 5d). Changes in amplitude of the cycles are readily apparent. For example, the annual component reaches a peak around 1991 (Figure 5c).

Figure 6 plots the results of the demodulation of the annual CO₂ fluctuations at Mauna Loa in terms of time series of changes to the phase (Figure 6a) and amplitude (Figure 6b). The annual changes have been constructed by recombining the 1-year and six-month cycles obtained during the complex demodulation. The key result is that the date of the CO₂ maximum has become gradually earlier. It has changed by $-4.8 (\pm 1.6)$ days in the 48 years since the IGY of 1958 (Figure 6a).

We have checked for similar behaviour at other CO₂ monitoring sites. The same decomposition has been applied to the 27 stations of Figure 7, which span latitudes from the South Pole, 90°S, to Alert, at 82°N. Figure 7 presents the change, with latitude, in mean CO₂ level (Figure 7a), annual range (Figure 7b), and the day of the year of the maximum CO₂ level (Figure 7c). We use Figure 7 to detect anomalous stations. The main points to note are: (i) the unusually high average CO₂ concentrations found in the European stations. (Despite the rural nature of these central European stations, regional pollution effects must still be heavily influencing the CO₂ mixing ratio.) (ii) the general declines in CO₂ levels found as one moves either south, or north, away from 60°N, and (iii) the phase is indeterminate around 25°S, where the annual range is extremely low. When the anomalous stations are set aside, namely the five (high CO₂) European stations, four north of 55°N, and three (minimal annual signal) between 30 and 10°S, we found that the remaining stations of Figure 7 yielded an average rate of change to the earliness of spring of -0.09 days per year, a result in excellent support of our Mauna Loa trend (of -0.10 days per year).

Discussion

Model performance

Because we are using a new phenological method it is useful to compare the performance of our model against the performance of other models, and to check its applicability in other geographical, or climatic, regions. Suitable test data are the combined time series of bud-burst of *Betula* spp. in central Finland during 1896–1955

published by Häkkinen (1999a). This excellent data set, built up from 19 time series centred on Jyväskylä (Linkosalo *et al.*, 1996) has been widely discussed, eg, by Linkosalo *et al.* (1996, 2000), Häkkinen *et al.* (1998), Häkkinen (1999b) and Linkosalo (1999, 2000). A range of models have been applied to the *Betula* data (Häkkinen, 1999a). The four models most similar to ours are the period-unit sum and temperature sums, both being based on ontogenetic development starting (i) at the end of dormancy and (ii) during dormancy. The models follow the approaches of Sarvas (1972) and Hänninen 1990. Häkkinen *et al.* (1998) and Häkkinen (1999a) found root mean square errors (RMSE) ranging between 3.1 and 4.4 days for these four models. For the *Betula* data from central Finland we have a RMSE of 3.2 days that, considering the daily Jyväskylä temperature data used in the earlier studies are unpublished and only monthly temperatures from Helsinki (250 km distant) were available to us, seems highly satisfactory.

For completeness we also tested the difference between models based on a sine-wave fit (Thompson and Clark, 2006) rather than a linear fit to the rise in spring temperature. Almost identical results (not presented) were found using the sine-wave fit to the temperature cycle. A simple linear-fit to the rise in spring temperature generally performs well because plants accumulate degree-days over a period of several months and the critical period is late-winter/early-spring, when the temperature-trend is close to being linear.

Phenological observations versus glasshouse experiments

Murray *et al.* (1989) studied the effect of climatic warming on the date of budburst of 15 tree species by subjecting healthy seedlings to a variety of greenhouse conditions. This allows us to compare our estimates of the effect of climate warming on leafing, as modelled using old phenological records of mature trees in a natural setting, with Murray *et al.*'s (1989) estimates based on budding of young seedlings in 'artificial' glasshouse situations. The two approaches are in broad agreement. Both find an advancement of flushing of about a month, for a 3° warming. Three of the 13 taxa chosen for observation by the Marsham family, namely beech, birch and hawthorn, were also used in the glasshouse studies of Murray *et al.* (1989). Murray *et al.*'s (1989) results thus provide an independent check on our findings. By moving batches of seedlings into warm glasshouses (15–20°C, 17-h photoperiods) on various dates between 15 January and 23 April they were able to assess the effect of a 'lack of chilling' on budding date. Murray *et al.*'s (1989) assessment of the importance of chilling on the flushing date is in good agreement with ours. They find that beech has the largest chilling requirement of any of their 15 species. We similarly categorize beech as displaying a stronger chilling control than either birch or hawthorn.

Chilling

Many authors (eg, Cumming and Burton, 1996; Saxe *et al.*, 2001) have pointed out that a lack of winter chilling associated with global warming could have profound impacts on trees. For example, Whetton *et al.* (2000) point out that Western Australian vineyard and orchard enterprises that need chilling to produce a quality product may find adaptation to higher temperatures difficult as there are land constraints in moving operations further south or to higher areas. In Britain failure of plants to shut down metabolic activity in winter might increase frost damage (Cannell and Smith, 1984). In addition, a lack of winter chilling/vernalization may lead to developmental problems. This could be a particular problem with natural regeneration if seed fertility is reduced. Cumming and Burton (1996) suggest that in the coastal areas of British Columbia lowland temperate forests will be severely stressed because forest tree species will no longer have their winter chilling requirements met, and trees may even become unviable in their native habitats.

The large impacts forecast by our model, particularly for temperate regions with maritime (equitable) climates, add further weight to all the above concerns.

Seasonal changes to the global carbon dioxide cycle

We can compare past changes in the seasonality of the global carbon dioxide record with those expected to have taken place if our phenological model applies throughout the world's temperate bioclimatic zones. Atmospheric tracer transport models (eg, Rödenbeck *et al.*, 2003) demonstrate that the timing of carbon exchange in the world's extra-tropical terrestrial ecosystems is an especially important driver of short-term CO₂ variations. Our degree-day model can be applied to any desired climatic regime. The basic model has a sensitivity of budding date to temperature of $1/m$, where m is the rate of increase of spring temperature in a typical year (cf. Equation (1)). For the maritime climate of Britain it works out that our model has a sensitivity of 10 days per degree, whereas continental climatic regions have much lower sensitivities (Clark and Thompson, 2004; Thompson and Clark, 2006). By applying our ' $1/m$ ' sensitivities to the global situation we are able to model changes in the seasonality of CO₂ variations. First, we estimate, using the Leemans and Cramer (1991) global climatological data set, that the typical rate of increase of spring temperature in the world's mid-latitude biomes has been 0.2°/day. Second, we note that since 1958 (the period of interest to us) temperatures in the Northern-Hemisphere (NH) temperate regions have risen around 1.02°C (Lugina *et al.*, 2006). By plugging these two figures (0.2°/day, and 1.02°C) into our degree-day model along with an assumption that approximately 25% of taxa exhibit winter chilling, or equivalent inhibitor effects, we derive a phase change in the 'global' earliness of spring, since 1958, of 4 days. This modelled estimate of the change in the earliness of spring since 1958 is in good agreement with the 4.8 days observed at Mauna Loa (Figure 6a).

Amplitude of annual carbon dioxide cycle

It is important when studying cyclic behaviour to consider both phase and amplitude. A powerful aspect of complex demodulation is that it allows amplitude and phase changes to be deduced simultaneously. We find that the amplitude of the annual CO₂ fluctuations monitored at Mauna Loa increased between 1958 and 1991 (see Figure 6a). This finding is in good agreement with the work of Keeling (1998). However, we also find that the amplitudes have subsequently decreased. We find similar trends, in annual range, at 15 other low-latitude stations we have studied. Accounting for the changes in amplitude of the global annual carbon dioxide cycle is somewhat involved. A common explanation for the increases in amplitude, at least for the period prior to 1990, is that warmer NH temperatures have promoted increases in plant growth during summer and in plant respiration during winter (Keeling *et al.*, 1996; Keeling, 1998). Such enhanced photosynthetic activity of terrestrial vegetation has been observed by satellite observations of reflectance, or greenness, from 1981 to 1991 (eg, Myneni *et al.*, 1997). Why, then, has the amplitude of the carbon dioxide cycle decreased (Figure 6b) over the last decade and a half when surface air temperatures have continued to increase globally? Angert *et al.* (2005) and Goetz *et al.* (2005) provide a possible answer. They suggest that although the Arctic is continuing to green (owing to higher temperatures) the northern forests have slowed their growth. Indeed satellites are revealing a browning trend in reflectance data through much of the mid and northerly latitudes (eg, Bunn and Goetz, 2006). Summer drought, burning, increased insect outbreaks or early acclimatization to CO₂ fertilization are all potential causes of the slowdown in growth of northern forests.

Conclusions

(1) Phenological observations allow the main climatic controls on the flushing behaviour of temperate trees to be analysed and modelled statistically.

(2) All 13 tree types studied show an association between flushing date and air temperature, so that their springtime behaviour starts earlier in warm years.

(3) Nine out of the 13 tree types show non-linear temperature behaviour. After cold winters they are found to flush with a reduced thermal, degree-day requirement.

(4) Climate change will have a particularly strong effect on flushing date in maritime climates, such as that of Britain, especially on taxa such as oak and hornbeam, which exhibit low or modest chilling duration requirements. These taxa will desynchronize by 30 days, or more, with respect to taxa with high chilling duration requirements such as beech and horse chestnut.

(5) No associations were found between flushing date and precipitation.

(6) Complex demodulation of CO₂ monitoring data, observed at a wide range of latitudes, reveals good reproducibility of annual amplitude trends and of an increasing earliness to the onset of spring.

(7) Recent decreases in the amplitude of annual CO₂ cycles are suggestive of a major slowdown in the rate of increase of photosynthetic activity.

(8) Observed changes in phase of annual CO₂ cycles are consistent with the application of our enhanced phenological model throughout the world's temperate bioclimatic zones.

(9) Spring is starting earlier.

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