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The great acceleration of plant phenological shifts

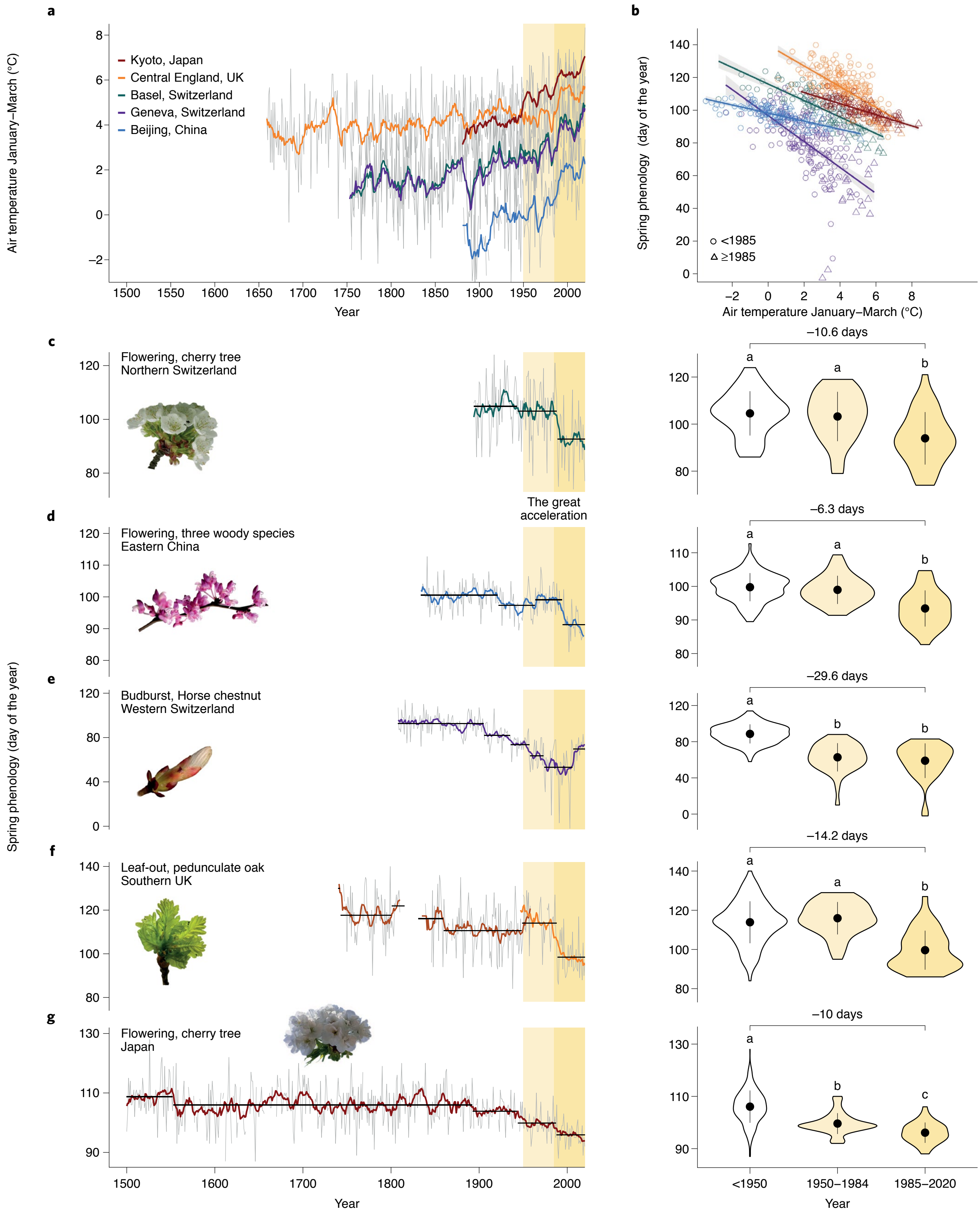
To the Editor — The world's longest time series of plant blooming and leaf-out in spring reveal unprecedented shifts since the middle of the 1980s in line with the acceleration of global warming. These long-term time series provide powerful evidence of the impact of global warming on life on Earth and can help raise awareness of the urgent need to mitigate greenhouse-gas emissions among citizens, decision makers and future generations.

With the rise of *Homo sapiens*, the Earth has experienced drastic landscape changes and biodiversity losses. For example, during the prehistoric and preindustrial periods, forest cover and biodiversity declined massively in the world's most populated regions due to the rise of agriculture and the increasing need for firewood and building materials[1,2]. These abrupt changes have been highlighted by the scientific community through paleoecological and archaeological records and modelling, without being directly visible or understandable to the general public because the sources do not constitute tangible continuous records. More recently, since the Industrial Revolution, human activities have led to massive changes in climatic, biotic and socio-economic indicators, a period now called the Anthropocene[3]. These changes accelerated considerably after the 1950s, a period often referred to as 'the great acceleration'[4], with particularly strong ecological and biogeochemical changes since the 1980s (ref. [5]). Unlike the pre-Anthropocene changes, climatic changes and seasonal plant activity have been recorded continuously for several centuries in a few locations and can be used to demonstrate the impact of human activities on global warming and its consequences for living organisms. In fact, the phenological cycle of plants and animals is strongly temperature dependent, and spring phenological events (for example, flowering or egg hatching in birds) in boreal, temperate and subtropical regions have progressively advanced over recent warmer decades[6,7]. However, phenological observations are very limited before 1950, and we thus lack important information on whether current trends during the great acceleration of the Anthropocene are unique over longer timescales. Here we present the five world's longest phenological time series known to date to provide evidence for an abrupt change linked to the current acceleration of global warming.

The longest phenological time series ever recorded is the blooming of cherry trees (*Prunus jamasakura*) in Kyoto, Japan, with observations extracted from old diaries and chronicles stretching back to the year AD 812 (ref. [8]). The longest European time series was recorded by the Marsham family in the southeast of the United Kingdom and includes leaf-out dates of several common tree species from 1736–1958 (ref. [9]). Fortunately, also in lowland southeast United Kingdom, a unique series of oaks budburst (*Quercus robur*) has been recorded since 1950 by a single observer, J. Combes, allowing the Marsham's series to be extended to the present day. (See also related Feature on J. Combes in this issue.) The three other series presented here are reconstructed flowering dates of three Chinese woody species (*Amygdalus davidiana*, *Cercis chinensis* and *Paeonia suffruticosa*) based on phenological records from old diaries since 1834 (ref. [10]); budburst dates of a horse chestnut (*Aesculus hippocastanum*) observed since 1808 in Geneva, Switzerland, by the Grand Conseil de la République et canton de Genève; and flowering dates of a cherry tree (*Prunus avium*) recorded in the north of Switzerland since 1894 by the Landwirtschaftliches Zentrum Ebenrain, Sissach and the Federal Office of Meteorology and Climatology MeteoSwiss.

The five world's longest plant phenological time series showed fairly stable flowering and leaf-out dates throughout the nineteenth century (Fig. 1). Spring phenological events started to advance in the first half of the twentieth century in Switzerland and Japan, in parallel with the temperature increase. No major shift was observed during the period 1950–1985, except for the blooming of cherry trees in Kyoto continuing to advance, matching the increase in spring temperature observed in this location (Fig. 1). In contrast, the strongest advance of spring phenology was detected in the middle of the 1980s for most of the series, again consistent with the

Fig. 1 | The world's longest phenological time series with the associated spring temperatures. **a**, Mean air temperature from January to March in the different sites or areas where the phenological series have been conducted. **b**, Correlation between spring temperature from January to March and phenology for each series. Pearson correlation coefficients are indicated and phenological observations before and after 1985 are distinguished by the circle and triangle symbols. **c**, Flowering dates of the wild cherry tree (*P. avium* L.) in Liestal, Switzerland (1894–2020). **d**, Spring flowering index derived from three woody species (flowering of *A. davidiana* (Carrière) Franch., *C. chinensis* Bunge and *P. suffruticosa* Andrews) in China (1834–2020). **e**, Budburst dates of horse chestnut (*A. hippocastanum*) in Geneva, Switzerland (1808–2020). **f**, Budburst dates of pedunculate oak (*Q. robur* L.) in southeast United Kingdom from the Marsham series (dark orange; 1736–1958) and J. Combes series (light orange; 1950–2020). The mean difference between the two series of observations (~3 days) indicates that the latter represent a reliable continuation of the Marsham's series. **g**, Blooming of the yamazakura cherry tree (*P. jamasakura* L.) in Kyoto, Japan (1500–2020). Note that the series goes as far back as the year AD 812 but is shown here since the year 1500 only. In all graphs, grey thin lines represent the annual phenology or temperatures and grey thick lines represent ten-year moving averages. In the phenological series, horizontal lines represent the periods detected by the breakpoint analysis, allowing a break minimum that significantly decreases the penalty value using the R package 'changepoint' with the cpt.mean function, BinSeg method and Bayesian information criterion (BIC) penalty. On the right side of each phenological series, graphs show the data distribution (violin plots and mean ± 1 s.d.) for three periods, that is, before the great acceleration (<1950), during 1950–1984 and during 1985–2020. Different letters among the different time periods indicate significant differences in spring phenology (Tukey's honestly significant difference test). Source of temperature data: Beijing (1881–2020), cleaned and homogenized data by the National Aeronautics and Space Administration (NASA) to account for urban effects, downloaded from https://data.giss.nasa.gov; Basel (1755–2020) and Geneva (1753–2020), homogenized data available from the Federal Office of Meteorology and Climatology MeteoSwiss; Central England (1659–2020), longest available instrumental record of temperature in the world[16], representative of a roughly triangular area of the United Kingdom enclosed by Lancashire, London and Bristol, made available by the Hadley Centre Central England Temperature; Kyoto (1881–2020), data available from the Japan Meteorological agency. Flower graphics courtesy of: Imaginechina Limited / Alamy Stock Photo (**d**); Pat Bennett / Alamy Stock Photo (**e**); Mim Friday / Alamy Stock Photo (**g**).


a
Air temperature January–March (°C)
Kyoto, Japan
Central England, UK
Basel, Switzerland
Geneva, Switzerland
Beijing, China
Year
b
Spring phenology (day of the year)
<1985
≥1985
Air temperature January–March (°C)
c
Flowering, cherry tree
Northern Switzerland
−10.6 days
The great acceleration
d
Flowering, three woody species
Eastern China
−6.3 days
e
Budburst, Horse chestnut
Western Switzerland
−29.6 days
f
Leaf-out, pedunculate oak
Southern UK
−14.2 days
g
Flowering, cherry tree
Japan
−10 days
Spring phenology (day of the year)
Year
<1950
1950–1984
1985–2020
Year

accelerated warming trend observed in the sites and across the Northern Hemisphere[11]. On average, spring phenology occurred 6 (China) to 30 days (Switzerland) earlier in the last 36 years (1985–2020) compared to the period before 1950 (Fig. 1). Notably, the blooming of cherry trees in Kyoto in spring 2021 was the earliest date ever recorded in more than 1,200 years, further underscoring the ongoing rapid phenological shifts.

The acceleration of global warming since 1985 (Fig. 1a) led to historically unprecedented advances in spring phenology in all series that spanned over two centuries (or, for the Japan series, even over a millennia). Because of the strong relationship between spring phenology and temperature (Fig. 1b), we argue that plant phenological shifts are an important bioindicator of the current acceleration of global warming. The series presented here are not situated in those parts of the world where warming trends have been the most pronounced, and we can therefore expect even stronger phenological shifts towards the circumarctic and central Asian regions where more than 2.5 °C warming has occurred over 150 years[12]. To the best of our knowledge, no continuous long-term phenology series exist for North and South America, Africa and Australia. However, recent and promising efforts have been made to combine historical information from herbarium specimens with contemporary records, especially in the northeastern United States[13].

Unlike the rise of carbon dioxide in the atmosphere, seasonal biological events such as leaf-out or blooming are easily identifiable by everyone — including children — and represent concrete and visible evidence of how climate change is affecting the ecosystems around us. We therefore believe that these long-term series are particularly useful in communication to raise citizen awareness about the urgency to mitigate climate change and to foster public engagement in citizen science, in education to further sensitize the coming generations, and in politics to promote sustainable environmental decisions. Such abrupt changes in the timing of key phenological events can have multiple implications for ecosystem functioning, species interactions via the foodweb[14] and global carbon balance[15], and should therefore attract greater attention from society. ❐

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Competing interests

The authors declare no competing interests.

Understanding urban plant phenology for sustainable cities and planet

To the Editor — Alongside the unparalleled changes in global climate, our home planet is experiencing an unprecedented period of urbanization, which is expected to continue across the next few decades. For plants, the impacts of urbanization, such as altered air quality, light regimes and water and nutrient availability, can induce large shifts in phenology (the timing of recurring life events[1]) with consequences for fitness, and for the ecological, climate, health and economic services that plants provide. Additionally, urbanization can elevate temperature and carbon dioxide (CO_2) concentration (Fig. 1a), which can mimic or magnify impacts of climate change. Understanding urban plant phenology is necessary to protect plants, cities and occupants under future change.

The broad impacts of urbanization on plant phenology can include advanced spring leaf-out and flowering, delayed autumn senescence and extended growing-season length[1,2] (Fig. 1b). These shifts can have benefits, such as increased cropping seasons for urban agriculture[3] or improved vegetation-based cooling in urban areas[4]. However, faster growth of urban trees due to extended growing-season length may lead to shortened lifetimes compared to trees in rural areas[5]. The advancement of spring leaf-out can also increase plant vulnerability to spring frost damage[6] and cause phenological mismatches, resulting in loss of pollination services and biological control of plant pests[7]. Moreover, phenology changes in cities have important cultural and economic implications by shifting significant events (for example, cherry blossom and maple foliage)[8] and can impact human health (for example, through changes in allergenic pollen release)[9]. Overall, phenological changes in urban areas already have a variety of ecological, climate, health and economic consequences (Fig. 1c), with