Botanical Records Reveal Changing Seasons in a Warming World

Malcolm Clark and Roy Thompson examine how global warming is shifting the times that flowering plants bloom.

Without being told by TV weather girls, most people think they know whether this past winter was colder than usual. Yet few of us notice if plants have flowered earlier or later than usual, or whether such differences in first flowering day are related to inter-annual variation in weather patterns.

The only way to understand scientifically the pattern of changes in the flowering of plants is to keep records. Fortunately a few far-sighted organisations and enthusiasts have been doing this for some time. In Norfolk, England, there are long-term records of "indications of Spring", such as leafing, birds and other animals (e.g. butterflies), from the Marsham family estate since 1736. There are also early records of the leafing, flowering and fruiting of plants in the Royal Society of Tasmania Gardens in Hobart, dating from 1858 to December 1885.

Particularly extensive old records have recently been found in the archives of the Royal Botanical Garden, Edinburgh. Once a week, for more than 30 years, the gardeners would meticulously make a note of which flowering species were in bloom.

From these records it has been easy to work out when any given species first came into flower in any given year. This gave us the first flowering days (FFDs) of 97 species from 1908 to 1939 (record-keeping ceased during World War 1 and at the outbreak of World War 2). Monitoring was only resumed in 2002, and several hundred individual plants are now being checked on a daily basis.

Daily weather records for Edinburgh for the 1908–39 period are also available, giving minimum and maximum temperature as well as hours of sunshine, barometric pressure and rainfall. Armed with this extensive data on daily weather and FFD, we have examined whether there is any relationship between the two and, if so, what that relationship was.

It was clear that there was consistent variation in FFD in many species, but not in others. Figure 1 shows the deviation in FFD from its long-term average for eight typical species. Points above the horizontal line correspond to later flowering than usual, while points below the line indicate earlier flowering.

The upper panel in Figure 1 shows the behaviour of four species with a consistent pattern in FFDs. These species generally flowered much earlier in 1920, 1923 and 1926, and much later in 1922 and 1924. For example, *Saxifraga sancta ssp. pseudosancta* flowered 30 days earlier than usual in 1923 and 35 days later than usual in 1924.

In contrast, the four species in the lower panel are typical of those with little or no consistent pattern.

What was it that was causing such behaviour? An investigation of Edinburgh's meteorological data showed that while the monthly barometric pressure, pattern of hours of sunshine and especially the rainfall varied considerably from year to year, they were not related to the flowering date. This left daily temperature as the most likely explanation for varying flowering times from year to year.

Agriculturalists and botanists are well-aware of two key features regarding the spring flowering and growth of plants. In temperate regions, plants essentially remain dormant or in a state of hibernation over the winter, and "wake up" when the mean daily temperature reaches a threshold value. Once that happens, the plant then requires a certain amount of "thermal energy" until it comes into bloom. The latter is usually measured as growth degree-days (GDD) above the threshold temperature.

This works as follows. Suppose the threshold temperature is 6°C, and the average temperature on a particular day is 10°C. This difference of 4°C is equivalent to 4 GDD. If the average temperature on the next day is 7°C above the threshold, then this equates to another 7 GDD, making a total of 11 GDD so far. This cumulative procedure continues, with days colder than the threshold temperature being ignored.

A crucial assumption in our analysis is that the threshold temperature and thermal energy requirement for any species remain fixed from year to year.

If we look more closely at the meteorological data in Edinburgh, we can see that in any given year the daily temperature in early spring (mid-March) to early summer (mid-June) increased approximately linearly. In some years the mean temperature in mid-March was relatively low, while in other years it was relatively high. Furthermore, in some years the temperature increased slowly, while in other years it increased more quickly. Thus, for each year the spring temperature variations in Edinburgh could be summarised by just two numbers: the

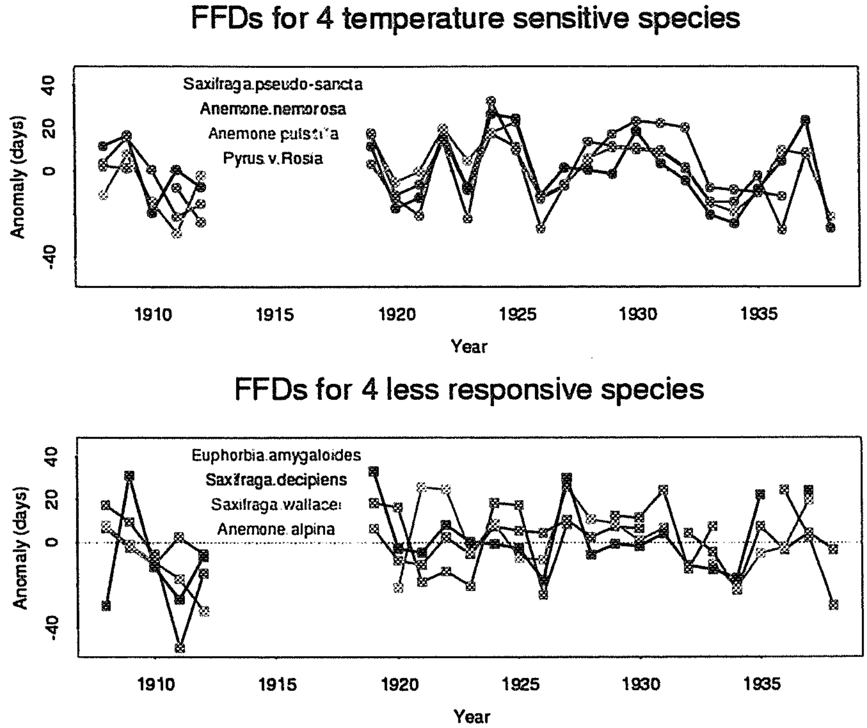


Figure 1. The deviation in FFD from its long-term average for eight typical species. Points above the horizontal line correspond to later flowering than usual, while points below the line indicate earlier flowering.

slope and intercept of a line.

We then set about testing two hypotheses regarding each species. The first was that there was no temperature effect at all – the species came into flower on essentially the same day each year, regardless of the temperature.

The second hypothesis was that flowering was determined by the GDD model. In this case, FFD would vary from year to year because of temperature variations. For example, if it was relatively warmer at the start of spring then the threshold temperature would arrive sooner. Similarly the quota of thermal energy would be reached sooner if the temperature rose quickly. In either case, the plant would come into flower sooner. Conversely, the plant would come into flower later if the spring temperature was lower or the temperature increased relatively slowly from mid-March to mid-June.

All of these features could be combined into a single equation relating the change in FFDs to the changing temperature regimes as specified by the slope and intercept of the straight line fit to spring temperatures.

We next assumed that each species had its own fixed threshold temperature and total energy (GDD) requirement. Both of these were initially unknown but, using our simple equation, we estimated them by combining the observed FFDs and temperature regimes over the 31 years for which data were available.

We then tested our two hypotheses by the usual procedure of comparing how well the data fitted either statistical model. This showed that, of the 97 species examined, 56 strongly supported our GDD model. We judged these 56 species as "temperature-sensitive".

Although we were only looking at late-spring/early-summer flowering plants, we found that the temperature thresholds varied widely so that each species had its own characteristic behavioural response. The temperature thresholds for the four species in the upper panel of Figure 1, for example, were found to range from 4.9°C to 6.3°C, while the thermal requirements were as high as 112 GDD.

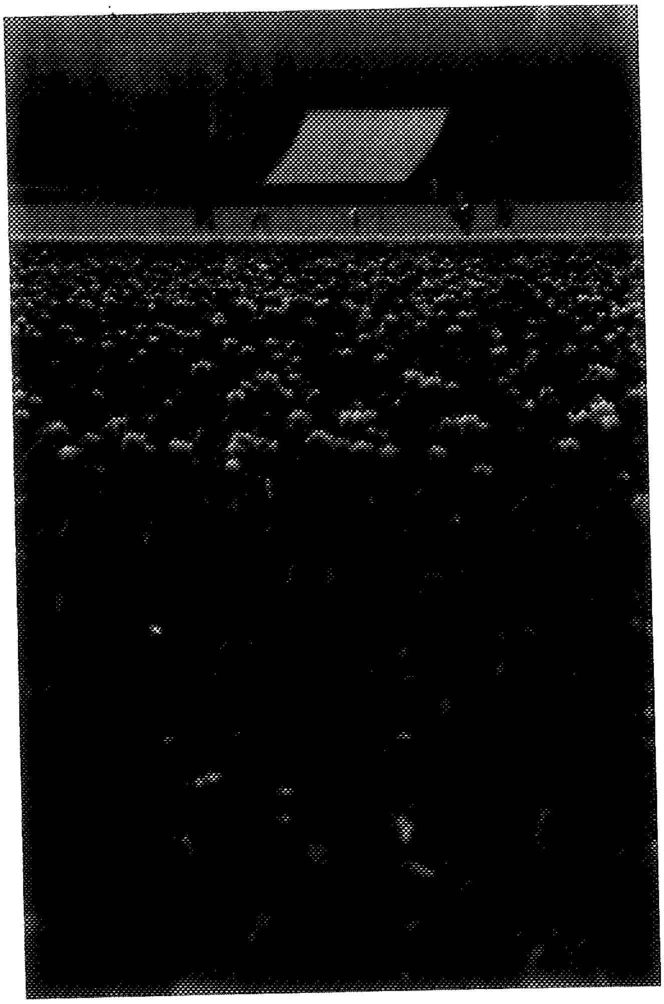
As we had a simple equation relating threshold temperature and thermal energy requirement to a linear equation specifying the temperature regime during spring, it was then possible to predict the likely or expected FFD for any temperature-sensitive species under any future climate regime. In particular, we could predict the likely change in average FFD under global warming scenarios.

We considered three different scenarios, each corresponding to an increase of 90 GDDs from mid-March to mid-June. Under a uniform increase of 1°C , our equation predicted that all of the temperature-sensitive species would come into flower 11 days earlier.

Second, if the climate became both warmer and more oceanic, so that the temperature rose by 1.5°C at mid-March and 0.5°C at mid-June (but there was otherwise a steady linear increase), then our model predicted that early-flowering plants would bloom about 16 days earlier and late-flowering plants would flower about 11 days earlier. In other words, if the temperature increase is greater in mid-March than in mid-June, as climatologists predict, then the early flowering plants are affected more than the later flowering ones.

Conversely, if the climate warms but becomes more continental, so that the increase in temperature is 0.5°C in mid-March and 1.5°C in mid-June, then the early flowering plants would first bloom about 7 days sooner than now.

The predicted average change in FFD of 11 days may seem to be of little practical significance, but most greenhouse warming models predict an overall increase in temperature at latitudes similar to Edinburgh of 3°C by the middle of the century. Further, the increase is likely to be greater in winter than in summer. Provided our model is reasonably valid under such condi-



tions, then all of our temperature-sensitive plants would come into flower about 1 month earlier than now.

The widely varying temperature thresholds of plants, and the diverse range of weather–flowering relationships previously discovered, have led other investigators to suggest that future climate change will put plant and animal behaviour dangerously out-of-sync. It has been claimed that some plants will advance their flowering by several months, some will delay their flowering by many weeks, while the behaviour of others will be governed by a wide spectrum of intermediate responses.

However, our model forecasts quite a different situation. We predict that at any given locality the great majority of plants will modify their average flowering times in a closely orchestrated and harmoniously coordinated fashion. Consider a uniform 3°C increase (a typical "business-as-usual" global warming scenario) in a currently oceanic setting such as Norway, Oregon or New Zealand. Most plants (the temperature-sensitive species) will advance their flowering by 33 days, the warming having enabled the plants to get started on their annual growth cycles much earlier than usual, while the remaining plants will have shown no change.

Furthermore, our model forecasts that exactly the same plants subjected to exactly the same temperature change, but when growing in different climatic regions, will modify their behaviour in diverse but nevertheless locally conformable ways. For example, in a more continental area such as Eastern Europe, where the rate of spring temperature rise is twice as fast as in oceanic regions, our model predicts that the plants will only change their flowering dates by half as much. We forecast the greatest changes to average flowering date will be on islands and archipelagos with hyper-oceanic climates.

Our model, although very simple, is naturally an approximation to the very complex interaction between plants and the weather. We believe, though, that it is a reasonable first approximation. Unlike other empirical models derived by regression techniques, our model is based on fundamental knowledge about the flowering of plants, and we can easily predict the effect of any pattern of global warming using our single simple equation.

Our approach can be applied to any similar data from anywhere within the world's temperate climate zones. In particular, it could be applied to the flowering of certain Australian eucalypts, such as *Eucalyptus regnans* (the mountain ash), an extremely important timber species. This, in collaboration with Marie Keatley of the University of Melbourne and Victorian foresters, is one of our next projects.

Future work will involve extending our basic model in three ways. First, we will use the fact that, in general, temperature is related to hours of sunshine, which in turn depends on the number of hours of daylight. This varies throughout the year in a sinusoidal fashion, with maxima and minima governed by the solstices. By modelling the full annual cycle it will be possible to adapt our GDD model for plants flowering at any time of the year, not just in the mid-spring to mid-summer period. Further, it will be possible to apply the same basic method to other phenological events such as the ripening of grapes, the onset of winter (first leaf-fall) and the first shooting of buds on deciduous trees.

Second, some plants may respond to the length of day as well as temperature. An expanded version of our model here will be that spring-flowering plants remain dormant until the length of day reaches a certain value, and then start to accumulate "thermal energy".

Third, the response of certain species that grow over a wide range of habitats may vary according to latitude. In principle, our procedure can be used to examine and quantify such behaviour.

In short, for most spring flowering plants global warming will prove to be a boost rather than a blooming nuisance.

Malcolm Clark is a Senior Lecturer in Monash University's School of Mathematical Sciences. Roy Thompson is Professor of Environmental Geophysics in the University of Edinburgh's School of GeoSciences.