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Phenology Under Global Warming

Christian Körner, *et al.*

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ular beam techniques have been steadily refined. Dong *et al.*'s experiment was fully "state-to-state": The reactants were cooled to prepare the HD in its ground rovibrational state, and the cross sections were measured for the HF products in specific rovibrational quantum states as a simultaneous function of collision energy and scattering angle (of the HF products with respect to the F + HD approach vector).

The theoretical calculations used a potential surface obtained at a very high level of theory, which correctly describes electron correlation and spin-orbit coupling (*12*, *13*). Earlier studies on this system used a potential surface (*14*) that was able to reproduce the transition-state spectrum of FHD (*15*) and to predict qualitatively the features in the cross section produced by the rotationally averaged resonances (*4*). The surface used by Dong *et al.* describes much better the interactions that hold together the nuclei within the resonances. This is why the individual resonance peaks obtained from it agree so closely with the experimental data.

The study by Dong *et al.* is a major benchmark in the understanding of chemical reactions from the point of view of first-principles quantum mechanics. The ability to detect and perhaps target individual reactive resonances may also allow chemists to better control chemical reactions, especially at very low temperatures.

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PLANT SCIENCE

Phenology Under Global Warming

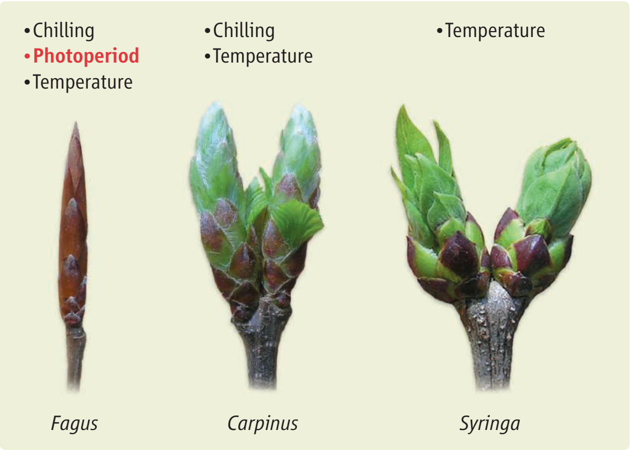
In most temperate tree species, phenological events such as flowering and autumnal cessation of growth are not primarily controlled by temperature.

Christian Körner and David Basler

Phenological events such as bud burst, flowering, and senescence have received increased interest in the light of global warming (*1*–*3*). Spring events at temperate latitudes have advanced by 2.5 days per decade since 1971 (*4*). As global warming progresses, how will it affect the arrival of spring and the length of the growing season?

In humid extratropical areas, the three most important factors controlling phenology in dominant forest tree species are the degree of winter chilling, photoperiod (day length relative to night length), and temperature (*5*–*7*) (see the figure). Because the seasonal course of temperature varies strongly from year to year, sensitivity to photoperiod protects plants from the potentially fatal consequences of simply tracking temperatures at the "wrong" time of the year. Photoperiod controls the induction (formation of winter buds, leaf abscission meristems, and freezing resistance) (*8*–*10*) and release from dormancy, the onset of growth, and reproductive events, including synchronous flowering (*11*, *12*). Temperature plays a modulating role and triggers the visible progress of phenology, such as leaf coloration, in many species.

Because the photoperiod is equally long in autumn and spring, dormancy release in spring requires the information that winter has passed, obtained from the dose of low temperatures experienced by the plant. When this chilling requirement is fulfilled, plants become receptive to photoperiod signals. Once a critical photoperiod has passed, actual bud break is a matter of concurrent temperature. A lack of sufficient chilling in mild winters delays bud break (*13*) but may be partially replaced by long photoperiods and/or very high temperatures (*14*).



Not just temperature. Spring development in many ornamental plants from warm regions, such as lilac (*Syringa*), is primarily controlled by temperature, whereas early successional species native to temperate latitudes, such as hornbeam (*Carpinus*), only become temperature-sensitive once their chilling demand has been fulfilled. Late successional taxa, such as beech (*Fagus*), are photoperiod controlled, with temperature only exerting a limited modulating effect once the critical day length has passed. This mechanism prevents such taxa from sprouting at the "wrong" time.

Not all tree species are sensitive to photoperiod, but the long-lived, late successional species that become dominant in mature forests commonly are. The genetic controls of plant development by photoperiod even remain in action when these temperate tree species are transplanted to subtropical parks, where bud break in hackberry (*Celtis*), beech (*Fagus*), and oak (*Quercus*) species was never found to occur before early March, despite exceptionally high temperatures in this exotic environment (*15*). It is thus a misconception to linearly extrapolate a few days advance of leafing during warm years into a proportional lengthening of the growing season in climate warming scenarios (*16*, *17*).

Shorter-lived, early successional species adopt a more risky life strategy (*6*). Many phenological observations in the literature come from such pioneer species as hazel, poplars, or birch, which are opportunistic (photoperiod-insensitive in spring). Other opportunistic species include weeds, as well as ornamental plants from warmer climates.

Institute of Botany, University of Basel, 4056 Basel, Switzerland. E-mail: ch.koerner@unibas.ch, david.basler@unibas.ch

For instance, the famous phenological time series for horse chestnut in the streets of Geneva (*18*), showing clear advances in leafing, is for an exotic species from a sub-Mediterranean setting. Another prominent time series shows early flowering of domestic cherry trees (*18*), which exhibit adaptive traits from central Asia, from where the cultivars originate. In these continental regions, the advent of spring is rather invariable, presumably due to the great distance from the sea, and phenological tracking of temperature bears no risk. In fact, trees in these regions should be more likely to keep tracking climatic warming than those in climates with more unpredictable weather systems, an interesting question to be explored in future work. Many ornamental plants in temperate gardens are photoperiod-insensitive, and their spring phenology tracks temperature with only very minor chilling requirements, as exemplified by lilac (*Syringa*) (*19*).

Phenology in late successional species will thus not continue to track climatic warming (the lengthening of the potential growing season) but will increasingly become constrained by internal controls, as the photoperiod threshold (set by genes) is approached. For most extratropical trees, seasons will not become substantially longer until new genotypes emerge, which will take a few tree generations (a few hundred years) (*20*).

Opportunistic taxa may profit from a warmer climate and may thus gain a competitive advantage over photoperiod-sensitive taxa. Rapid climatic warming may also drive current tree genotypes into a disparity between their insurance against "misleading" (too early in the season) warm temperatures and concurrent temperature-sensitive soil processes such as mineralization. Ecosystem nutrient losses are a potential consequence of trees getting out of phase with the climate system. Climatic warming should thus not be seen as a self-evident cause for more tree growth.

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APPLIED PHYSICS

Controlling Turbulence

Beverley J. McKeon

Injecting a fluid jet into a pipe at an optimized location can control the development of turbulent flow.

Pipes feature strongly in the infrastructure of everyday life, from domestic water pipes to oil and natural gas conduits. A primary consequence of the onset of turbulence in the fluid flowing through the pipes is the dramatically increased power required to pump stuff at the same rate. Thus, the incentives to understand and control the transition process are strong. However, more than 100 years after Osborne Reynolds's seminal experiments on the transition of flow through a pipe from a laminar (smooth) to a turbulent state, the exact physical mechanism that drives this phenomenon still vexes the fluid mechanics community. On page 1491 of this issue, Hof *et al.* (*1*) describe a mechanism that feeds energy into a turbulent flow system, allowing the onset of the transition to be manipulated and even the suppression of the turbulence.

Reynolds's 1883 paper (see the figure, left panel) (*2*) initiated an enduring framework with which to understand the flow of fluid, and particularly the range of conditions under which the transition from an ordered laminar state to a three-dimensional turbulent one will occur. The ratio of inertial to viscous forces is typically expressed in terms of the Reynolds number, $Re_D = UD/\nu$ in pipeflow (where U is the average velocity in the pipe cross section, D is the pipe diameter, and ν is the kinematic viscosity of the fluid). If the Re_D is identical between two idealized, incompressible flows in similar geometries, then similar flow behavior will occur. Thus, an experiment in which air compressed to a pressure of 200 atmospheres flows through a 12-cm-diameter pipe, or liquid helium through a 0.47-cm pipe, can accurately mimic flow through a transcontinental natural gas pipeline of diameter larger than one meter (see the figure, right panel) (*3*).

For all Reynolds numbers, laminar pipe flow is linearly stable. Yet a transition to turbulence still occurs at Reynolds numbers on the order of a few thousands, with the flow displaying the characteristic, spatially intermittent structure of turbulent "puffs" followed by extents of laminar flow (*4*) (see also figure 4 in Hof *et al.*). Although considerable progress has been made in using unstable, traveling wave solutions of the Navier-Stokes equations, which govern fluid flow to define the state-space boundary between laminar and turbulent flow (*5*), these concepts still do not explain the origin of the observed puffs.

Hof *et al.* introduce controlled disturbances using small jets at an upstream location in a fully developed laminar pipe flow experiment, which permits the study of "designer puffs." The physics of their observations is elegant. In the reference frame of the disturbance, the transition is a local phenomenon—the streamwise velocity gradients associated with a change from a laminar to a turbulent velocity distribution lead to a local inflectional instability in the radial profile of streamwise velocity. This instability is capable of driving turbulent dynamics in the puff. When a second identical disturbance is introduced at an optimal point upstream, the leading edge of the second puff can reduce the local velocity gradient at the trailing edge of the first puff, suppressing the inflectional instability that feeds the turbulence.

The control of turbulence has long been a "holy grail" of fluid mechanics, and the field

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Graduate Aerospace Laboratories, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA. E-mail: mckeon@caltech.edu