extend back only to about 1982, are limited by cloud cover, and may not distinguish between overstorey (the dominant trees in the forest) and understorey (shrubs and herbaceous plants on or near the forest floor) phenology in forests[2,5].

Other biospheric phenomena have been assessed globally through strategic combinations of satellite and surface measurements[3]. The above limitations of remote-sensing 'phenology' highlight the complexity of the green wave, and suggest the need for a similar strategy here. What the satellite senses and what is observed on the ground are both integral parts of the green wave. Conventional phenological data — carefully selected according to species, and globally distributed — should play a crucial role in global green-wave research. As global-scale phenological networks do not yet exist, empirical green-wave models can partly fill the void.

Models that simulate phenology using meteorological data offer several advantages, if based on appropriate plants[10,11]. They allow reconstruction of green waves back through the period for which instrumental records of weather are available, providing a context for short-interval satellite data. Also, models serve as 'anchor points', binding together commonalities among records for native species in adjacent biomes and remote-sensing observations. Empirical models (spring indices) can closely mimic actual plant first-leaf and first-bloom events, correlate with native-species data, and reveal changes in lower-atmospheric processes at the ecosystem scale[5,6,10,12,13], illustrating their potential use in longer-term studies (Fig. 1).

As an example, I studied green-wave changes in eastern North America[5] from 1900 to 1995 (Fig. 2). Meteorological data were from the Historical Climatology Network Daily Temperature and Precipitation Data (CDIAC, Oak Ridge National Laboratory). I calculated several indices for each year for all stations over their respective periods of record. All indices showed considerable year-to-year variation, without striking long-term trends, but with significant shorter-period changes. For example, from 1978 to 1990, first-leaf spring index dates became earlier at a rate of about 1 day per year (trend adjusted $r^2 = 0.43$, α-level $= 0.009$; Fig. 2).

The tendency of global phenology research to concentrate on satellite-based measurements makes this approach fundamentally incomplete. Satellite measurements provide broad areal coverage but reveal only one aspect of green-up. All measures — empirical models, native-species phenology, and appropriately calibrated satellite indices — need to be understood and interconnected for maximum effectiveness[5,6].

Global-scale plant phenology networks should be established to strengthen this research strategy. However, empirical models offer a way to reconstruct past green waves, and allow regional comparisons. Although imperfect and of limited geographical application, these models provide one of the few independent comparisons available for satellite measurements of plant activity[9]. Connections between conventional phenology and remotely sensed greenness measures at the ecosystem level are being confirmed, and further studies are underway[4]. It is encouraging that a satellite-derived change in green-up[9] (earlier by 8 ± 3 days over the 1981–91 period) is consistent with the trend, over roughly the same period, that I describe here (ten days earlier during the 1980–90 period, inferred from the 1978–90 regression line). But this short period appears unremarkable when compared with the overall first-leaf spring index variability in eastern North America (Fig. 2).

My results endorse empirical models as useful partners for satellite-derived green-wave measures. Studies of other regions, especially those with long-term warming trends, can provide a context for evaluating satellite measurements that indicate earlier greenness onset over large areas. Energy budget analyses coupled with surface and satellite phenology (for example, examination of phenological effects on the exchange of latent and sensible heat between the surface and the atmosphere) should also prove rewarding in further understanding and monitoring spring plant–climate interactions.

Mark D. Schwartz
Department of Geography,
University of Wisconsin–Milwaukee,
Milwaukee, Wisconsin 53201-0413, USA
e-mail: mds@uwm.edu

1. Moulin, S., Kergoat, L., Viovy, N. & Dedieu, G. *J. Clim.* **10,** 1154–1170 (1997).
2. Reed, B. C. *et al. J. Veg. Sci.* **5,** 703–714 (1994).
3. Sellers, P. J. *et al. J. Clim.* **9,** 706–737 (1996).
4. White, M. A., Thornton, P. E. & Running, S. W. *Glob. Biogeochem. Cycles* **11,** 217–234 (1997).
5. Schwartz, M. D. in *Phenology of Seasonal Climates* (eds Lieth, H. & Schwartz, M. D.) 23–38 (Backhuys, Netherlands, 1997).
6. Schwartz, M. D. *Int. J. Biometeorol.* **38,** 18–22 (1994).
7. Running, S. W. & Hunt. E. R. in *Scaling Physiological Processes, Leaf to Globe* (eds Field, C. & Ehleringer, J.) 144–157 (Academic, New York, 1993).
8. Leopold, A. & Jones, E. *Ecol. Monogr.* **17,** 81–122 (1947).
9. Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G. & Nemani, R. R. *Nature* **386,** 698–702 (1997).
10. Schwartz, M. D. *Phys. Geogr.* **14,** 536–550 (1993).
11. Hopp, R. J. & Vittum, M. T. *Organic Gard. Farm.* **24,** 127–129 (1977).
12. Schwartz, M. D. *J. Clim.* **9,** 803–808 (1996).
13. Schwartz, M. D. *Month. Weather Rev.* **120,** 2570–2578 (1992).

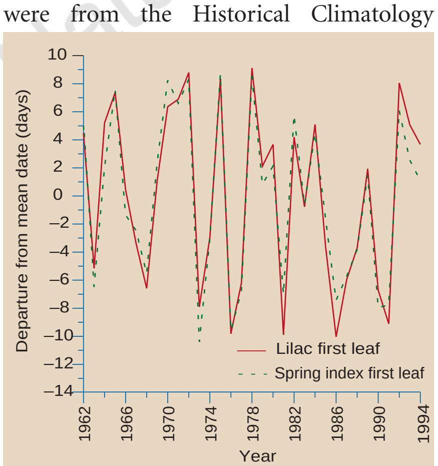

Figure 1 Comparison of annual departures from the mean of spring index first-leaf dates (derived from an empirical model) and of *Syringa chinensis* 'red rothomagensis' (lilac) first-leaf dates (derived from actual data), 1962–94 (details of the network of the 183 stations with relevant data, and methods, are available from the author).

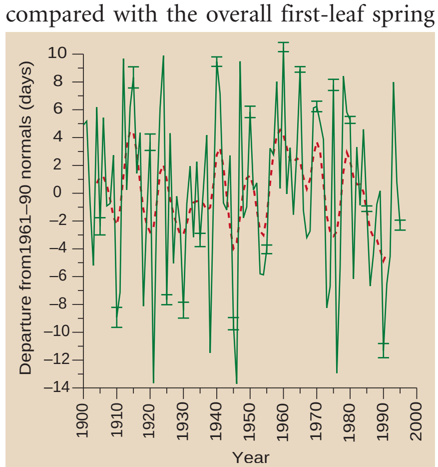

Figure 2 Eastern North American[5] departures from the mean of spring index first-leaf dates, 1900–95, with ± 1 standard error bars, and smoothed trend produced by a nine-year, moving average, normal curve filter (dotted line) (details of the network of the 465 relevant stations, and methods, are available from the author).

A posteriori teleportation

The article by Bouwmeester *et al.*[1] on experimental quantum teleportation constitutes an important advance in the burgeoning field of quantum information. The experiment was motivated by the proposal of Bennett *et al.*[2] in which an unknown quantum state is 'teleported' by Alice to Bob. As illustrated in Fig. 1, in the implementation of this procedure by Bouwmeester *et al.*[1], an input quantum state is 'disembodied' into quantum and classical components, as in the original protocol[2]. However, in contrast to the original scheme, Bouwmeester *et al.*'s procedure necessarily destroys the state at Bob's receiving terminal, so a 'teleported' state can never emerge as a freely propagating state for subsequent examination or exploitation. In fact, teleportation is achieved only as a postdiction.

Bouwmeester *et al.* used parametric down-conversion from two sources (SI, SII in Fig. 1) in an attempt to teleport the

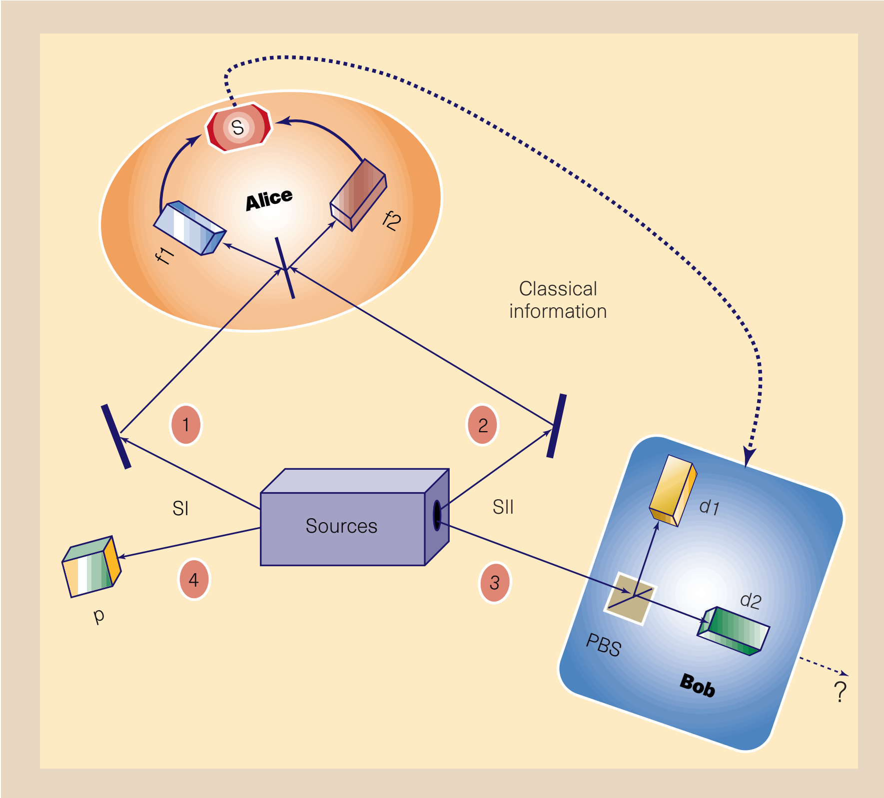

Figure 1 The teleportation set-up of ref. 1. PBS, polarizing beam splitter.

polarization state of a single-photon wavepacket (in beam 1) from Alice's sending station to Bob's receiving station (in beam 3). Statistics consistent with teleportation are obtained for events with a fourfold coincidence (from detectors f1 and f2, d1 or d2, and p). We ask whether the detection of all four quanta is essential for teleportation in this scheme. To answer this question, we calculated the teleportation fidelity, F, when the coincidence condition is relaxed to exclude detection at Bob's station (d1, d2).

Under relaxed conditions, requiring only threefold coincidence of detectors p and (f1, f2), teleportation is achieved when the fields of beams 1 and 3 match with sufficiently high fidelity. In the simplest approximation, type II parametric down-conversion of modes (i, j) generates wavepacket states as follows:

$$A_0|0\rangle_{ij} + A_1|\psi^-\rangle_{i,j} + A_2|\chi\rangle_{i,j} + \ldots, \quad (1)$$

where A_0, A_1 and A_2 are the coefficients for obtaining no (vacuum), one and two down-converted pairs, respectively, and $(i, j) = (1, 4)$ $(2, 3)$. Of these terms, only states corresponding to the second term are selected by fourfold coincidence, as specified by equations (2) and (3) of ref. 1. However, anything less than complete destruction of the output 3 necessarily leaves undesirable terms that reduce F.

The initial input state to Alice's station, $|\Phi\rangle$, is prepared by detecting the state in field 4 at detector p, which projects the field in beam 1 accordingly. Joint detection at (f1, f2) then provides threefold coincidence with p, yielding a statistical mixture for the field 3 arriving at Bob's station. The fraction of the state $|\Phi\rangle$ in this mixture gives F. To the lowest order in the down-converter coupling strength, the Bouwmeester *et al.* scheme yields a 50:50 mixture of the vacuum state $|0\rangle$ and the desired state $|\Phi\rangle$, with $F = 1/2$, so that there is never a physical state with high teleportation fidelity. Indeed, Bob could achieve this same fidelity, $F = 1/2$, by abandoning teleportation altogether and transmitting randomly selected polarization states. Faced with this state of affairs, the experiment of ref. 1 obtains a surrogate for high fidelity by destructively recording the field 3 at (d1, d2).

We emphasize that the nature of the mixture containing the vacuum state has definite physical implications, which can be verified by more general measurements than photon counting (for example, by quantum-state tomography). Moreover, the freedom of a potential consumer of the output from Bob's receiving station to select alternative detection strategies means that classical analogies fail.

To achieve conventional *a priori* teleportation, the set-up in ref. 1 would have to be modified to eliminate the vacuum from the mixture. Because the vacuum appears when two pairs of (1, 4) photons are created, we might seek to resolve one- and two-photon detection events at p. Upgraded detection (for example, by cascading conventional detectors) could provide an effective remedy. Appropriate selection could be implemented with a polarization-independent quantum non-demolition measurement of the total photon number at Bob's end. Alternatively, pre-selection could be implemented by enhancing the coupling between modes (2, 3) relative to modes (1, 4).

Despite our comments, we believe that the experiment of Bouwmeester *et al.* is a significant achievement in demonstrating the non-local structure of teleportation.

Samuel L. Braunstein
SEECS, University of Wales,
Bangor LL57 1UT, UK
H. J. Kimble
Norman Bridge Laboratory of Physics 12–33,
California Institute of Technology,
Pasadena, California 91125, USA

1. Bouwmeester, D. *et al. Nature* **390,** 575–579 (1997).
2. Bennett, C. H. *et al. Phys. Rev. Lett.* **70,** 1895–1899 (1993).

Bouwmeester et al. *reply* — Braunstein and Kimble observe correctly that, in the Innsbruck experiment, one does not always observe a teleported photon conditioned on a coincidence recording at the Bell-state analyser. In their opinion, this affects the fidelity of the experiment, but we believe, in contrast, that it has no significance, and that when a teleported photon appears, it has all the properties required by the teleportation protocol. These properties can never be achieved by "abandoning teleportation altogether and transmitting randomly selected polarization states" as Braunstein and Kimble suggest. The fact that there will be events where no teleported photons are created merely affects the efficiency of the experiment. This suggests that the measure of fidelity used by Braunstein and Kimble is unsuitable for our experiment.

During the detection of the teleported photons, no selection was performed based on the properties of these photons. Therefore, no *a posteriori* measurement in the usual sense as a selective measurement was performed. The detection of the teleported photon could have been avoided altogether if we had used a more expensive detector, p, that could distinguish between one- and two-photon absorption. The inability of our teleportation experiment to perform such refined detections does not, however, imply that "a teleported state can never emerge as a freely propagating state…". Braunstein and Kimble do not, therefore, reveal a principal flaw in our teleportation procedure, but merely address a non-trivial practical question.

D. Bouwmeester, J.-W. Pan, M. Daniell,
H. Weinfurter, M. Zukowski, A. Zeilinger
Institut für Experimentalphysik,
Universität, Innsbruck, Technikerstrasse 25,
A-6020 Innsbruck, Austria