The Verdet constant is obtained from the measurement at 52 G. The simulation reproduces all the observed features of the impedance as a function of temperature, including the maximum in the modulation at $T/T_C = 0.415$, $H = 101$ G, and the minimum at $T/T_C = 0.415$, $H = 152$ G, which confirms that the Faraday period is proportional to $1/H$. The simulation also produces the fine-structure oscillations in the impedance near the points labelled 90° and 270°. The fine structure is observed when the polarization rotates by an odd multiple of 90° upon a single round trip in the cell. Then waves that traverse the cell twice are 180° out of phase relative to the source wave, and consequently the period of the impedance oscillations is halved. The amplitude of the oscillations is substantially reduced because of attenuation over the longer path-length. This structure provides proof that impedance oscillations are modulated by the Faraday effect for propagating transverse waves. The impedance data from our experiments were analysed to obtain the spatial period for rotation of the polarization, and were found to be in agreement with the theoretical prediction[8] for the Faraday rotation period. The theoretical results for the period can be expressed in the form

$$\Lambda = K\frac{\sqrt{T/T_+ - 1}}{gH} \quad (2)$$

for fields $H \ll 1$ kG and temperatures above and near the extinction point B. The temperature T_+ corresponds to the extinction of transverse sound by resonant excitation of Cooper pairs with $J = 2$, $m_J = +1$, at a slightly higher temperature than the B extinction point in zero field as shown in Fig. 2 (for example, at $H = 100$ G, $T_+ - T_B \approx 1\,\mu$K). The magnitude of the Faraday rotation period depends on accurately known superfluid properties, contained in the parameter K; it also depends on one parameter that is not well-established, the Landé g-factor, g, for the Zeeman splitting of the Cooper-pair excited state with $J = 2$.

Movshovich *et al.*[21] analysed the splitting of the $J = 2$ multiplet in the absorption spectrum of longitudinal sound, finding a value of $g = 0.042$. In that experiment it was not possible to resolve the splitting except for fields above 2 kG. At these high fields, the nonlinear field dependence due to the Paschen–Back effect[22,23] becomes comparable to the linear Zeeman splitting[24,25], which makes it difficult to determine the Landé g-factor accurately. We have analysed our measurements of the acoustic Faraday effect to determine the g-factor with high accuracy at low fields, which eliminates the complication of the high-field Paschen–Back effect. We find $g = 0.020 \pm 0.002$. We interpret our significantly smaller value of the Landé g-factor as meaning that there are important $L = 3$ ('*f*-wave') pairing correlations in the superfluid condensate, about 7% of the dominant *p*-wave interactions[26]. □

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Similarities between the growth dynamics of university research and of competitive economic activities

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Quantifying the dynamics of research activities is of considerable current interest, not least because of recent changes in research and development (R&D) funding[1–9]. Here we quantify and analyse university research activities, and compare their growth dynamics with those of business firms[10–14]. Our study involves the analysis of five distinct databases, the largest of which is a National Science Foundation database of the R&D expenditures in science and engineering for a 17-year period (1979–95) in 719 United States universities. We find that the distribution of growth rates displays a 'universal' form that does not depend on the size of the university or on the measure of size used; and the width of this distribution decays with size as a power law. These findings are quantitatively similar to those of business firms[10–14], and so are consistent with the hypothesis that the growth dynamics of complex organizations are governed by universal mechanisms. One possible explanation for these similarities is that the combination of peer review and government direction leads to an outcome similar to that induced by market forces (where the analogues of peer review and government direction are, respectively, consumer evaluation and product regulation).

In the study of physical systems, the scaling properties of fluctuations in the output of a system often yield information regarding the underlying processes responsible for the observed macroscopic behaviour[15,16]. Here we analyse the fluctuations in the growth rates of university research activities, using five different measures of research activity. The first measure of the size of a university's research activities that we consider is R&D expenditure.

The rationale for using this as a measure of research activity is that research is an expensive activity that the university finances with external support.

We first analyse a database containing the annual R&D expenditure for science and engineering of 719 US universities[17] for the 17-year period 1979–95 (~12,000 data points). The expenditures are broken down by school and department. The annual growth rate of R&D expenditures is, by definition, $g(t) \equiv \log[S(t+1)/S(t)]$, where $S(t)$ and $S(t+1)$ are the R&D expenditures of a given university in the years t and $t+1$, respectively. We expect that the statistical properties of the growth rate g depend on S, as it is natural that the fluctuations in g will decrease with S. Therefore, we partition the universities into groups according to the size of their R&D expenditure (Fig. 1a). Figure 1b suggests that the conditional probability density, $p(g|S)$, has the same functional form, with different widths, for all S.

We next calculate the width $\sigma(S)$ of the distribution of growth rates as a function of S. Figure 1c shows that $\sigma(S)$ scales as a power law

$$\sigma(S) \propto S^{-\beta} \tag{1}$$

with $\beta = 0.25 \pm 0.05$. In Fig. 1d, we collapse the scaled conditional probability distributions onto a single curve.

To test if these results for the dynamics of R&D expenditures are valid for other measures of research activity, we next analyse another measure of a university's research activities, the number of papers published each year[18–20]. We analyse data for the 17-year period 1981–97 from ref. 21, which records the number of papers published by the top 112 US universities (~1,900 data points). We find that the analogue of Fig. 1 holds. We note that the same exponent value, $\beta = 1/4$, is found (Fig. 2a) and that the same functional form of $p(g|S)$ is displayed (Fig. 2b).

Next, we consider as a measure of size the number of patents issued to a university[22]. We retrieve from ref. 23 the number of patents issued to each of 106 universities each year of the 22-year period 1976–97 (~2,300 data points). We confirm that the analogue of Fig. 1 holds, with the same exponent value, $\beta = 1/4$ (Fig. 2a), and the same functional form of $p(g|S)$, Fig. 2b.

To test if our findings hold for different academic systems, we analyse two databases on research funding of English[24] and Canadian[25] universities. The same quantitative behaviour is found for the distribution of growth rates and for the scaling of σ, with the same exponent value (Fig. 2a) and the same functional form of $p(g|S)$, Fig. 2b. Thus, the analysis of all five databases confirms that the same quantitative results hold across different measures of research activity and academic systems.

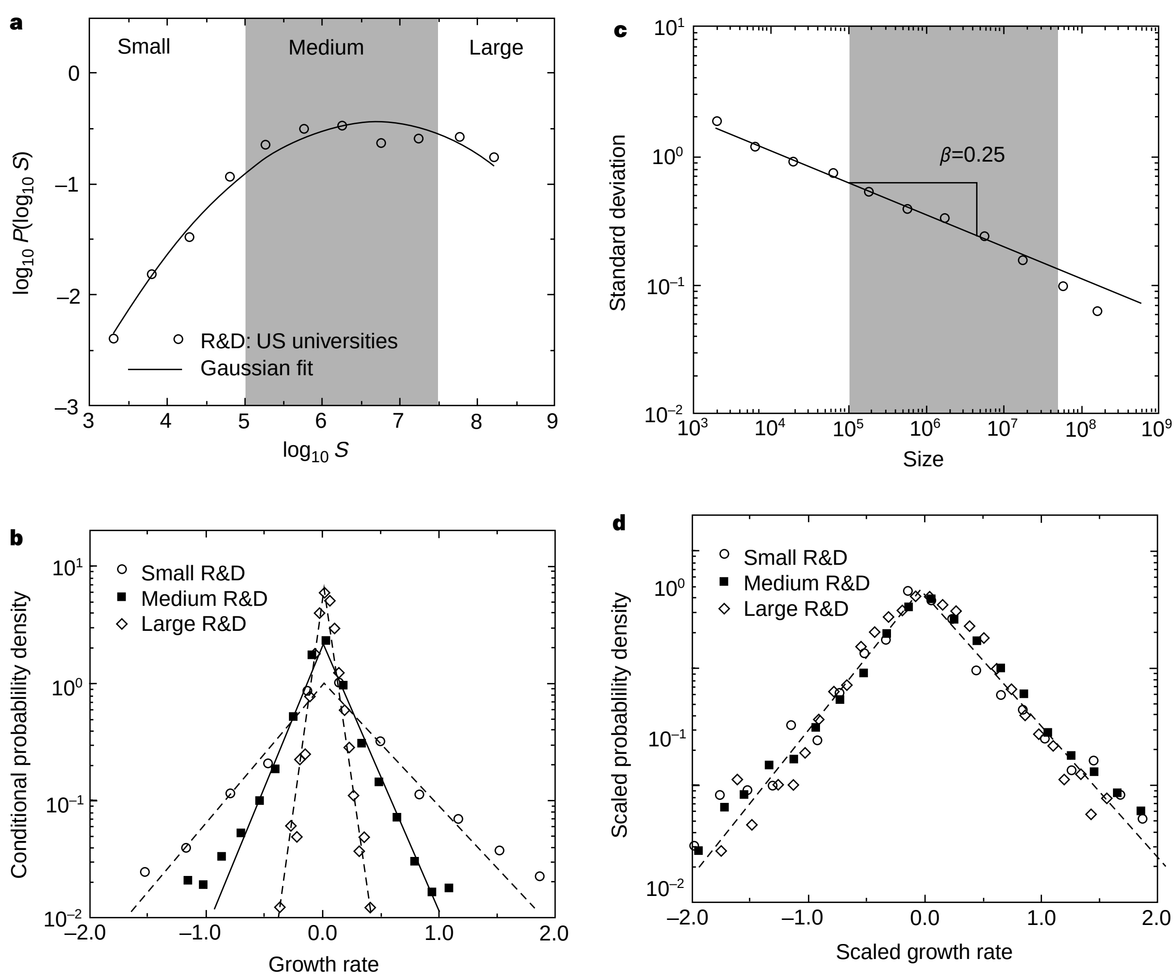

Figure 1 Growth dynamics of research activities at universities. **a**, Histogram of the logarithm of the annual R&D expenditure of 719 US universities for the 17-year period 1979–95, expressed in 1992 US dollars. Here S denotes the R&D expenditures detrended by inflation so that values for different years are comparable. The bins were chosen equally spaced on a logarithmic scale with bin size 0.5. The line is a gaussian fit to the data, which is a prediction of Gibrat's theory[10,12]. **b**, Conditional probability density function $p(g|S)$ of the annual growth rates g. For this plot the entire database is divided into three groups (depicted in **a** by different shades). **c**, Standard deviation $\sigma(S)$ of the distribution of annual growth rates as a function of S. The straight line is a power-law fit to the data, and its slope gives the exponent $\beta = 0.25 \pm 0.05$. **d**, Scaled probability density function $p(g|S)/\sigma^{-1}(S)$ plotted against the scaled annual growth rate $(g-\bar{g})/\sigma(S)$ for the three groups defined in **b**. Note that the scaled data collapse onto a single curve.

We next address the question of how to interpret our empirical results. We start with the observation that research is an expensive activity, and that the university must 'offer' its research to external sources such as governmental agencies and business firms. Thus, an increase in R&D expenditures at university A and a decrease at university B implies that the funders of research increasingly choose their research from university A as opposed to university B[1]. This qualitative picture parallels the competition among different business firms, so it is natural to enquire if there is quantitative support for this analogy between university research and business activities. To quantitatively test this analogy, we note that the results of Fig. 1 are remarkably similar to the results found for firms[13,14] and countries[26–28]. We plot in Fig. 2c the scaled conditional probabilities $p(g|S)$ for countries, firms and universities, and find that the distributions for the different organizations fall onto a single curve.

There is, however, one difference: for firms and countries, we find $\beta \approx 1/6$, while for universities, $\beta \approx 1/4$. We can understand this difference using a model for organization growth[29]. In the model, each organization—university, firm or country—is made up of units. The model assumes these units grow through an independent, gaussian-distributed, random multiplicative process with variance W^2. Units are absorbed when they become smaller than a 'minimum size', which is a function of the activity they perform. Units can also give rise to new units if they grow by more than the minimum size for a new unit to form. The model predicts $\beta = W/[2(W + D)]$, where D is the width of the distribution of minimum sizes for the units[29]. For firms, the range of typical sizes is very broad—from small software and accounting firms to large oil and car firms—suggesting a large value of D. On the other hand, for universities, the range of typical sizes is much narrower, suggesting a small value of D and implying a larger value of β than for business firms. This is indeed what we observe empirically.

Business firms are comprised of divisions and universities are made up of schools or colleges, so it is natural to consider the internal structure of these complex organizations[30]. We next quantify how the internal structure of a university depends on its size by calculating the conditional probability density $\rho(\xi|S)$ to find a school of size ξ in a university of size S (Fig. 3a). The model predicts that $\rho(\xi|S)$ obeys the scaling form[29]

$$\rho(\xi|S) \propto S^{-\alpha} f(\xi/S^{\alpha}) \quad (2)$$

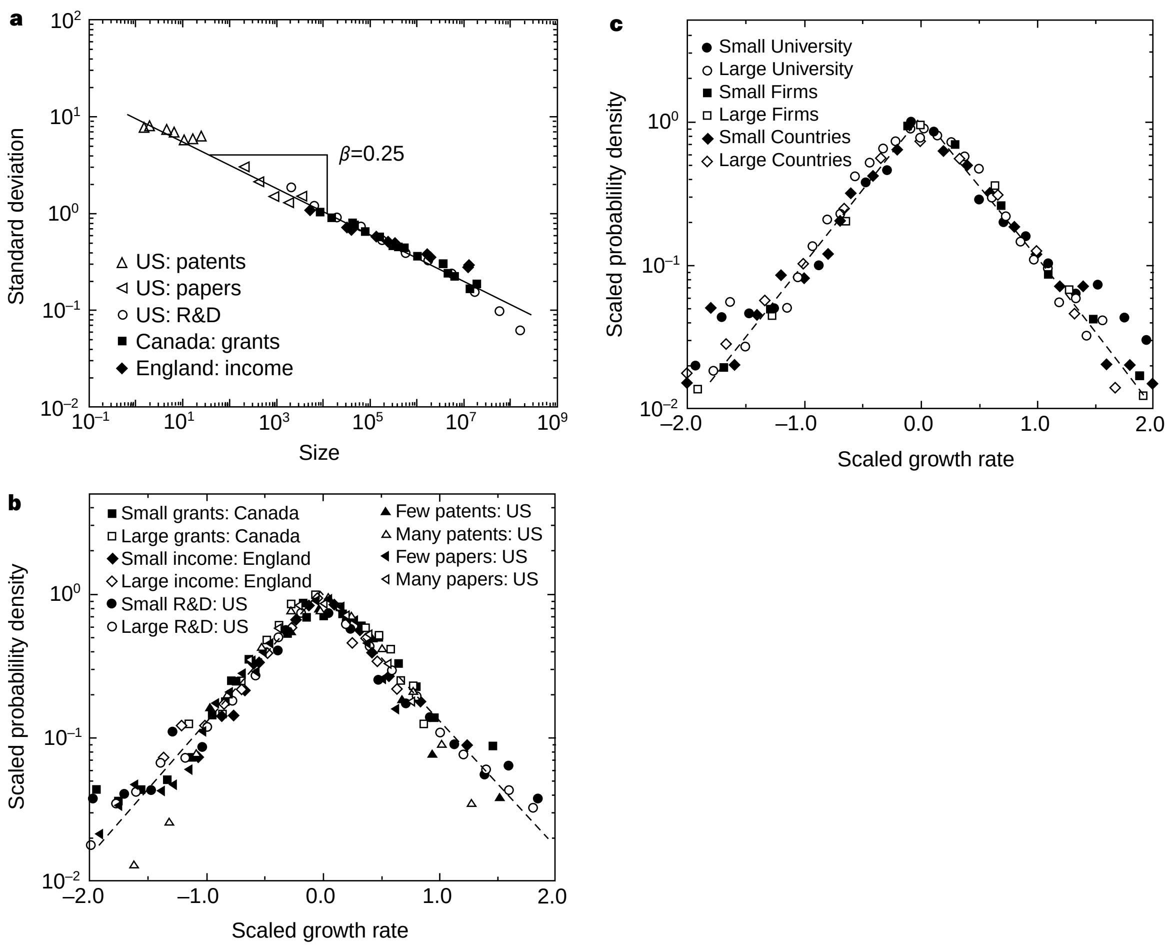

Figure 2 Robustness of empirical findings for the distribution of growth rates. **a**, Standard deviation $\sigma(S)$ of the distribution of annual growth rates for different measures of research activities and different academic systems from the data in the five distinct databases analysed: (1) the number of papers published each year at 112 US universities, (2) the number of patents issued each year to 106 universities, (3) the R&D expenditures in US dollars of 719 US universities, (4) the total amount in Canadian dollars of the grants to 60 Canadian universities, and (5) the external incomes in British pounds of 90 English universities. It is apparent that for all measures and all academic systems analysed, we find a power-law dependence–with the same exponent, $\beta \approx 1/4$. The values of σ for the different measures were shifted vertically for better comparison of the estimates of the exponents. **b**, The distribution of annual growth rates, scaled as in Fig. 1d, for the five databases. We show the distribution of growth rates for two different groups, obtained in a way similar to that described in Fig. 1b, for each of the five measures. The data appear to collapse onto a single curve, suggesting that the different measures have similar statistical properties. **c**, The distribution of scaled annual growth rates for different organizations: R&D expenditures of US universities, sales of firms, and GDP of countries. The data collapse onto a single curve, suggesting that the scaled distributions have the same functional form.

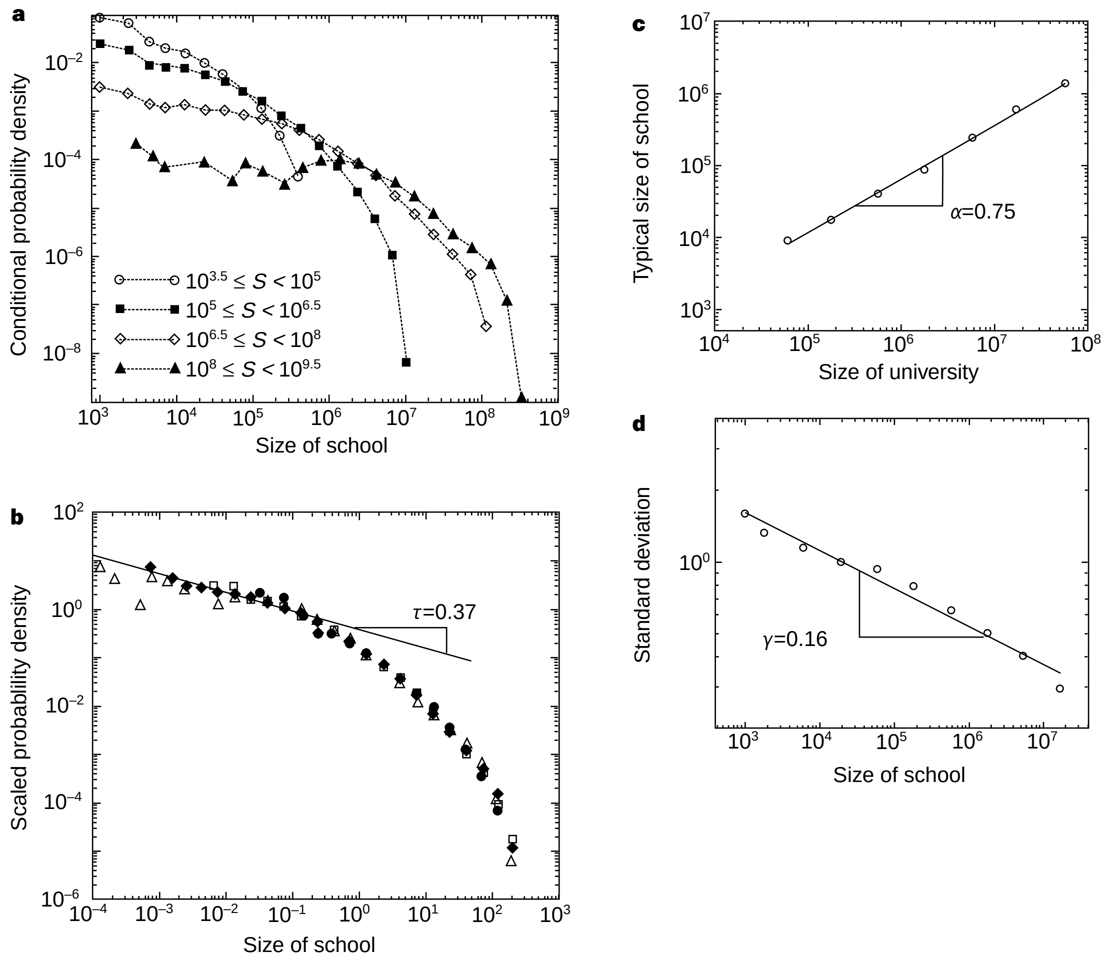

Figure 3 Statistical analysis of the units forming the internal structure of a university, the schools. **a**, Conditional probability function $\rho(\xi|S)$ of finding a school of size ξ in a university of size S. To improve the statistics, we partition the universities by size into four groups. **b**, To illustrate the scaling relation (equation (2)), we plot the scaled probability density $\rho(\xi|S)/S^{-\alpha}$ versus the scaled size of the school ξ/S^{α}. In agreement with equation (2), we find that the scaled data fall onto a single curve. **c**, Scaling of the typical size of a school in a university of a given size for different university sizes. The data obey a power law with exponent $\alpha = 0.75 \pm 0.05$. **d**, Standard deviation W of the distribution of growth rates of schools versus school size ξ. The data obey a power law with exponent $\gamma = 0.16 \pm 0.05$. Using equation (4) and this value of γ, we obtain an independent estimate $\beta = 0.25 \pm 0.05$.

where $f(u) \approx u^{-\tau}$ for $u \ll 1$, and $f(u)$ decays as a stretched exponential for $u \gg 1$. We find $\tau = 0.37 \pm 0.10$ (Fig. 3b), and $\alpha = 0.75 \pm 0.05$ (Fig. 3c). We test the scaling hypothesis (equation (2)) by plotting the scaled variables $\rho(\xi|S)/S^{-\alpha}$ versus ξ/S^{α}. Figure 3b shows that all curves collapse onto a single curve, which is the scaling function $f(u)$.

Equation (2) implies that the typical number of schools with research activities in a university of size S scales as $S^{1-\alpha}$, while the typical size of these schools scales as S^{α}. Hence, we can calculate how σ depends on S:

$$\sigma(S) \propto (S^{1-\alpha})^{-1/2} W(\xi) \tag{3}$$

To determine σ, we first find the dependence of W on ξ. Figure 3d shows that $W \propto \xi^{-\gamma}$ with $\gamma = 0.16 \pm 0.05$. Substituting into equation (3) and remembering that the typical size of the schools is S^{α}, we obtain $\sigma(S) \propto (S^{1-\alpha})^{-1/2}(S^{\alpha})^{-\gamma}$, which leads to the testable exponent relation:

$$\beta = \frac{1-\alpha}{2} + \alpha\gamma \tag{4}$$

For $\alpha \approx 3/4$ and $\gamma \approx 1/6$, equation (4) predicts $\beta \approx 1/4$, in agreement with our empirical estimate of β from the five distinct databases analysed (Fig. 2a).

Our results are consistent with the possibility that the statistical properties of university research activities are surprisingly similar for different measures of research activity and for distinct academic systems. Moreover, our findings for university research resemble those independently found for business firms[10–14] and countries[26–28]. One possible explanation is that peer review, together with government direction, may lead to an outcome similar to that induced by market forces, where the analogue of peer-review quality control may be consumer evaluation, and the analogue of government direction may be product regulation.

Practical implications of our finding of similar growth dynamics for academic research and business are not obvious, but one possibility is that there seems to be no need to make academic research at universities still more like business—it already is. Some may claim that the business sector could be regarded as a yardstick for organizing academic research. If so, the research departments already behave like business units and hence are sufficiently 'effective'. On the other hand, others may maintain that the 'economization' of academic research has been pushed too far, and that the research system will become 'ineffective' if this continues. □

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Abrupt changes in North American climate during early Holocene times

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Recent studies of the Greenland ice cores have offered many insights into Holocene climatic dynamics at decadal to century timescales[1–3]. Despite the abundance of continental records of Holocene climate, few have sufficient chronological control and sampling resolution to compare with the Greenland findings[4]. But annually laminated sediments (varves) from lakes can provide high-resolution continental palaeoclimate data with secure chronologies. Here we present analyses of varved sediments from Deep Lake in Minnesota, USA. Trends in the stable oxygen-isotope composition of the sedimentary carbonate indicate a pronounced climate cooling from 8.9 to 8.3 kyr before present, probably characterized by increased outbreaks of polar air, decreased precipitation temperatures, and a higher fraction of the annual precipitation falling as snow. The abrupt onset of this climate reversal, over several decades, was probably caused by a reorganization of atmospheric circulation and cooling of the Arctic airmass in summer that resulted from the final collapse of the Laurentide ice near Hudson Bay and the discharge of icebergs from the Quebec and Keewatin centres into the Tyrell Sea. The timing and duration of this climate reversal suggest that it is distinct from the prominent widespread cold snap that occurred 8,200 years ago in Greenland and other regions[1,5,6]. No shifts in the oxygen-isotope composition of sediment carbonate occurred at 8.2 kyr before present at Deep Lake, but varve thickness increased dramatically, probably as a result of increased deposition of aeolian dust. Taken together, our data suggest that two separate regional-scale climate reversals occurred between 9,000 and 8,000 years ago, and that they were driven by different mechanisms.

We retrieved three temporally overlapping sediment cores from Deep Lake (47° 41′ N, 95° 23′ W; Fig. 1), a topographically closed basin located ~45 km east of the prairie–forest border in northwestern Minnesota. The early Holocene sediments of these cores are varve couplets consisting of calcite precipitated through photosynthesis in summer paired with darker, clastic and organic debris deposited in other seasons. Annual laminae are easily identifiable under a low-power microscope, providing a high-quality chronometer. To minimize the accumulative error of varve counting from the surface, we anchored our varve counts on a reliable AMS (accelerator mass spectrometry) ^{14}C date of 8,090 ± 85 years (calibrated to 8.986 kyr calendar age[7]) on a large wood sample[8]. A second AMS ^{14}C date of 8, 740 ± 60 years, also on a piece of wood, is supportive of the annually laminated nature of early Holocene sediments from Deep Lake, but this date is less useful because it is on a ^{14}C plateau and yields ambiguous calibrated ages[7]. Varve thickness was measured, and subsamples from the cores were analysed for stable isotopes at multi-decadal resolution to reconstruct early Holocene climate. Our results provide an opportunity to test whether decadal to century scale climate changes observed in Greenland ice also occurred near the centre of the North American continent.

Bulk-carbonate $\delta^{18}O$ of the Deep Lake core shows distinct stratigraphic changes between 10.0 and 8.0 calendar kyr before present (cal. kyr BP; Fig. 2a). $\delta^{18}O$ increases by ~2‰ about 9.5 cal. kyr BP, reflecting the effects of regional climate warming related to increased summer insolation and the retreat of the Laurentide ice sheet[4], as well as the associated increase in evaporation from Deep Lake itself and the reduced influence on climate of glacial Lake Agassiz as it retreated into Canada[8,9]. Around 8.9 cal. kyr BP, $\delta^{18}O$

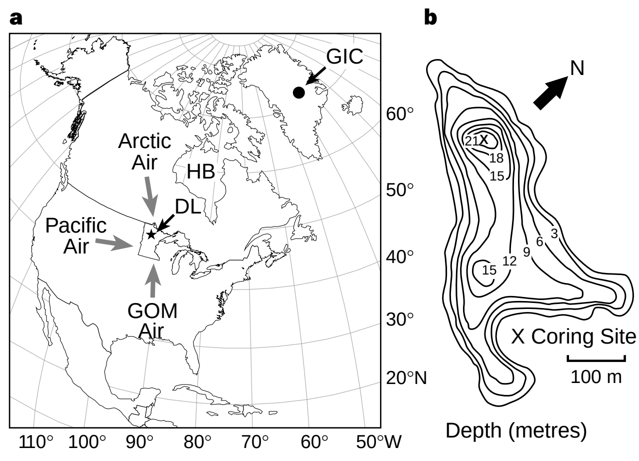

Figure 1 Air masses, site locations and lake bathymetry. **a**, General directions of the three main airmasses controlling the climate of Minnesota (GOM, Gulf of Mexico); also shown are the locations of Deep Lake (DL), Greenland ice cores (GIC), and Hudson Bay (HB). **b**, Bathymetry of Deep Lake.