North Pole; (ii) $1.4 \times 10^{16}$ kg uniformly distributed from one hemisphere to the other; or (iii) $1.1 \times 10^{16}$ kg from the oceans to land at high latitudes. We suggest that any reasonable model should therefore have a total seasonal transported mass within 40% of $1.0 \times 10^{16}$ kg. Secondly, models should predict that the load peaks near the poles in their respective late-winter seasons. Thirdly, models should predict that the load’s trajectory follows an approximate great circle over the continents (Fig. 3).

From remote sensing, it is known that the mass of snow in the Northern Hemisphere peaks during February to March at $0.3 \times 10^{16}$ kg (5, 16). Recent analysis in atmospheric research (6) confirms earlier interpretations (7) on the existence of interhemispheric oscillations in atmospheric mass at the level of $0.4 \times 10^{16}$ kg, which appears to be driven in part by anomalous cooling over snow-covered areas, particularly over Siberia and Canada (17). Our results therefore suggest that the observed pattern of deformation is dominated by winter groundwater storage enhanced by atmospheric pressure. Assuming an upper bound on the net redistributed mass at $1.4 \times 10^{16}$ kg, we infer the non-snow component of winter groundwater to be $<0.7 \times 10^{16}$ kg.

The load’s trajectory over the continents (in approximately the $y$-$z$ plane) is consistent with the land’s ability to sustain loads (unlike the ocean’s tendency to rapidly approach equilibrium). An interesting feature of the load moment time series is the asymmetric pattern of $z$ oscillations (Fig. 1) and the rapid southward equatorial crossing of mass (Fig. 3) in May. This is consistent with rapid water runoff, which is known to peak during late spring in the Northern Hemisphere (18). A small $y$ component of load moment also appears during the transition seasons traversing regions of known intense hydrological loading (9) in southeast Asia and South America (Fig. 2). An anomaly in the $\pm y$ direction is apparent during 1996/1997, immediately preceding the 1997/1998 El Niño event. Possible mechanisms that might enhance the $y$ component include an equatorial oscillation in (nonsteric) sea level across the Pacific (driven by wind stress) and anomalous monsoon precipitation over land.

To conclude, we detected a global-scale mode of Earth deformation that we have identified as the response of an elastic Earth to redistribution of surface load, specifically the degree-one spherical harmonic mode that theoretically corresponds to change in the load moment. This mode compresses one hemisphere and expands the opposite hemisphere in such a manner that it does not change Earth’s overall shape, but nevertheless stretches its surface and so affects site coordinates. In Earth’s center-of-figure frame, the poles appear to be displaced downward by 3.0 mm during their respective winter.

The Asian and Australasian Monsoons are important because they transport heat and moisture from the warmest part of the tropical ocean (the West Pacific Warm Pool) across the equator and to higher latitudes. The East Asian Monsoon, a sub-system of the Asian Monsoon, affects an area east of the Bay of Bengal and the Tibetan Plateau (1). Spring heating of Asia initiates the summer monsoon, which transports northward moisture and heat from north of Australia across the Warm Pool, as far as northern China. The winter monsoon is characterized by cold, dry Siberian air flowing southward across eastern China, ultimately contributing to the Australian summer monsoon (1).

**References and Notes**

11. For deformations up to degree $n$, a network can be considered “well distributed” if neighboring stations everywhere are spaced much less than $180^\circ / n$, for which $n = 1$ implies multiple stations in arbitrary hemispheres.
13. Information on relevant GPS station data is provided at www.sciencemag.org/cgi/content/full/294/5550/2342/DC1.
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**A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu Cave, China**


Oxygen isotope records of five stalagmites from Hulu Cave near Nanjing bear a remarkable resemblance to oxygen isotope records from Greenland ice cores, suggesting that East Asian Monsoon intensity changed in concert with Greenland temperature between 11,000 and 75,000 years before the present (yr. B.P.). Between 11,000 and 30,000 yr. B.P., the timing of changes in the monsoon, as established with $^{230}$Th dates, generally agrees with the timing of temperature changes from the Greenland Ice Sheet Project Two (GISP2) core, which supports GISP2’s chronology in this interval. Our record links North Atlantic climate with the meridional transport of heat and moisture from the warmest part of the ocean where the summer East Asian Monsoon originates.

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Plausible factors affecting the monsoon are orbitally controlled changes in insolation (2, 3), shifts in sea level causing changes in Warm Pool surface area (4), and circulation changes internal to the climate system (5). Loess records (6, 7) show clear evidence for monsoon changes (4) that are possibly linked to global climate (7) and Heinrich Events (5). However, resolution and dating problems limit the loess work. We reconstruct mon-
soon history with the oxygen isotopic composition of speleothem calcite, which has key advantages over many archives of past conditions. Well-chosen inorganic calcite can be dated precisely \(^{230} \text{Th}\) with mass spectrometric methods \(^{10}\) and \(^{230} \text{Th}\) ages and errors are color-coded by stalagmite. Numbers indicate GISs and correlated events at Hulu Cave. The YD and Heinrich events are depicted with vertical bars \(^{24}\). The brown and blue bars indicate two possible correlations to H5. The average number of years per \(^{18} \text{O}\) analysis is 130 for MSD and 140 for MSL. The \(^{18} \text{O}\) scales are reversed for Hulu (increasing down) as compared with Greenland (increasing up).

We collected five stalagmites from 35 m depth in Hulu Cave, 28 km east of Nanjing (32°30′N,119°10′E). We halved samples along growth axes and sub-sampled on cut surfaces for \(^{230} \text{Th}\) dating by thermal ionization \(^{10}\) and inductively coupled plasma mass spectroscopy \(^{11, 12}\) and \(^{18} \text{O}\) analysis \(^{13}\). Fifty-nine \(^{230} \text{Th}\) dates (Fig. 1) \(^{14}\), all in stratigraphic order, have analytical errors equivalent to about ±150 years at 10,000 years and ±400 years at 60,000 years. The oldest age is 74,875 ± 1,010 yr. B.P. (relative to 1950 A.D.) and the youngest is 10,933 ± 160 yr. B.P., with at least one stalagmite active during all intervening times. Sample YT has visible banding throughout, and three \(^{230} \text{Th}\) ages with errors of ±60 to ±90 years. Numbers of bands are equal to differences in age between dated sub-samples, indicating that the banding is annual. We established the time scale for sample H82 with two \(^{230} \text{Th}\) ages (Fig. 2) \(^{14}\), by matching its oxygen isotope record to YT’s at 14.6 thousand years ago (ka), and by band counting between 11.0 and 11.8 ka and between 13.0 and 14.6 ka.

A key issue is whether calcite \(^{18} \text{O}\) can be interpreted solely in terms of the \(^{18} \text{O}\) of meteoric precipitation and equilibrium fractionation during calcite precipitation. Hendy \(^{15}\) described additional processes (e.g., kinetic fractionation) that could also affect \(^{18} \text{O}\). A robust test is the comparison of \(^{18} \text{O}\) for contemporaneous stalagmites from the same cave \(^{16}\). If the records replicate, the net effect of additional processes on \(^{18} \text{O}\) must have been the same. Consistent offsets are unlikely because each stalagmite-precipitating drip has a unique combination of flow path, \(\text{CO}_2\) partial pressure, residence time, concentration of solutes, and degassing history. Thus, replicated records strongly suggest that such additional processes are not important. With modern dating and \(^{18} \text{O}\)
measurement techniques, the replication test can be made with high resolution and little temporal ambiguity.

Stalagmites MSD and MSL (Fig. 1) (14) grew contemporaneously between 53 and 36 ka. Considering dating errors and resolution differences, the records are virtually identical over this interval. At least two stalagmites (out of PD, YT, and H82) grew contemporaneously for all times between 17 and 10.5 ka (Figs. 1 and 2) (14). Samples YT and H82, both sampled at high resolution, have an overlapping section with $\delta^{18}O$ values that replicate. Sample PD was sampled at lower resolution and has $\delta^{18}O$ values offset from the others by a small amount (about 0.5‰) compared with the 5% amplitude of the record. Nevertheless, the pattern of $\delta^{18}O$ variation is similar among overlapping sections of all five stalagmites, suggesting we can treat them as replicated records. We also tested for positive correlation between $\delta^{13}C$ and $\delta^{18}O$ values, plausibly indicative of kinetic fractionation (15). R² values are either low or the correlation is negative for each of six data groupings [data for each of five speleothems grouped individually and as one group; see (14)], thus showing no evidence for kinetic fractionation.

Given records that replicate and the lack of a clear positive correlation between $\delta^{13}C$ and $\delta^{18}O$ values, the issue becomes how to interpret the record in terms of the $\delta^{18}O$ of summer precipitation and temperature. Mean annual rainfall and temperature at Hulu Cave are 1015 mm and 15.4°C. The summer monsoon (June to September) contributes 80% of annual precipitation with $\delta^{18}O_{VSMOW}$ of −9‰ to −13‰. The rest comes during the winter monsoon with $\delta^{18}O$ about 10‰ higher (−3 to +2‰) (17). Because of the large seasonal difference, a mechanism that may explain large changes in mean annual $\delta^{18}O$ of precipitation is a change in the ratio of the amount of summer to winter precipitation. Temperature effects are likely to be small because changes in the temperature-dependent fractionation between calcite and water are small (on the order of $-0.25%\text{/}°C$ (18)).

On the basis of modern data (19), the effects of summer temperature and rainfall amount on mean $\delta^{18}O$ of summer precipitation are also small, with similar relations holding for winter (19).

Hulu Cave $\delta^{18}O$ values range from −4 to −9‰ between 75 and 10 ka (14). The large range suggests that a primary control is variation in the summer/winter precipitation ratio. If so, a change in the ratio by a factor of 3 (from today’s value of 4 to 1.3) is required to explain the 5% amplitude. This factor is likely an upper limit because temperature and amount effects may also contribute.

The long-term Hulu trend (Fig. 1) appears to follow summer (integrated over June, July, and August) insolation (20, 21) at Hulu Cave (33°N), at least for a good portion of the record, suggesting that high summer insolation increases the continent-ocean temperature difference, enhancing the summer monsoon (2, 3). However, the record is punctuated by numerous millennial-scale events and by shifts in $\delta^{18}O$ over centuries or less, much shorter than orbital timescales.

These features resemble the Greenland ice-core $\delta^{18}O$ records (22, 23). If analogous features do represent coincident events, Greenland temperature correlates positively with the summer/winter precipitation ratio in eastern China. To the extent that changes in the ratio result from changes in summer precipitation, warmer Greenland temperatures correlate with a more intense summer East Asian Monsoon. Between 10 and 15 ka, an interval for which ice core chronologies are robust, we can test for synchronicity. In this interval, samples PD and H82 (Fig. 2) exhibit features similar to the Younger Dryas (YD) and the Bolling-Allerod (BA). On the basis of independent time scales, these features are synchronous within errors (Fig. 2), demonstrating a link between the East Asian Monsoon and Greenland temperatures.

In detail, there are both similarities and differences in the Hulu and Greenland glacial sequences (22, 23). The Hulu record has a sharp increase (about 2‰) in $\delta^{18}O$ at 16,073 ± 60 yr. B.P., which takes place in <20 years, at about the time of Heinrich Event 1 (H1) (24). A similar feature is not apparent in the ice records. The slopes of the records during the BA differ, which could result, in part, from the decrease in marine $\delta^{18}O$ associated with glacial melting, because this would affect the records in opposite senses. The most rapid portion of the transition into the BA appears to be more gradual at Hulu (180 years by band counting centered at 14,645 ± 60 yr. B.P.) as compared with Greenland (about 100 years centered at about 14,680 ± 290 yr. B.P. in GISP2). In contrast, the transition at the beginning of the YD (12,823 ± 60 yr. B.P. at Hulu and 12,880 ± 260 yr. B.P. in GISP2) is of similar short duration (<20 years). The transition ending the YD (11,473 ± 100 yr. B.P. at Hulu, 11,550 ± 70 yr. B.P. in the Greenland Ice Core Project (GRIP) (23), and 11,640 ± 250 yr. B.P. in GISP2 (22)) is also extremely rapid at both localities (<10 years). The duration of the YD as recorded at Hulu (1350 ± 120 years) is the same within error as its duration in Greenland.

Given the apparent synchronicity between Hulu and Greenland for times when the ice core chronologies are robust, we may correlate older events, for which ice core chronologies are less certain (Fig. 1). This correlation appears straightforward as far back as 38 ka. The highest Hulu $\delta^{18}O$ values (at 16,032 ± 60 yr. B.P.) correspond to low Greenland temperatures associated with H1. Low Hulu $\delta^{18}O$ values (at 23,310 ± 100 yr. B.P.) correspond to Greenland Interstadial (GIS) 2, which is immediately preceded by high $\delta^{18}O$ values (24,180 ± 100 yr. B.P.) corresponding to low Greenland temperatures associated with H2. Low $\delta^{18}O$ excursions correspond to GIS 3 through 8 (Fig. 1). With these correlations, we assign times to Greenland events with Hulu ages. For times between GIS 1 and 8, age offsets between GISP2 and Hulu are less than several hundred years, whereas offsets between GRIP and Hulu are much larger (25). For GIS 9 through 13, we present two possible correlations. Those represented by
blue numbers (Fig. 1) appear to follow logi-
cally as we correlate peaks back from GIS 8.
However, this correlation places the begin-
ing of GIS 12 (the end of H5) at 48 ka. Both
GISP2 (25) and GRIP (23) as well two other
high-precision stalagmite records place the
end of H5 at ~45 ka (26, 27). The differenc-
es among stalagmite records [Hulu, Sorel
Cave, Israel (26), and Crevice Cave, Missou-
ri (27)] highlight important regional differ-
ences in past climate at this time. If we take
the end of H5 at 45 ka as a tie point, we
obtain the correlation depicted by the brown
numbers. At present, we cannot distinguish
between the two. Beyond GIS 13, the corre-
lation appears straightforward and is consis-
tent with the only other high-resolution spe-
climatic changes are more zonal
spheric/oceanic circulation patterns and are
important for evolutionary biology, genomics,
and biomedical sciences (7, 8). Studies based
on different, multikilobase molecular data
sets (5, 6) independently resolved placental
mammals into four superordinal groups:
 Afrotheria, Xenarthra, Laurasiatheria, and
Euarchontoglires. However, hierarchical rela-
tionships within these groups and at deeper
levels in the placental tree remain unclear. A
precise resolution of the relationships among
the major groups and elucidation of the root
of the placental tree are critical for interpret-
ing biogeographic patterns and evolutionary
processes involved in the early diversification
of placental mammals. We combined and ex-
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