rejections. All extrema are visited. (The maximum is only visited a few times, but this is no surprise, as our trial function takes on larger values for a continuum of arguments on the boundary.) Table 1 collects computer data for the first 11 non-equal minima; the desired precision is indeed achieved.

The power of the random-walk constraint is best seen by comparison with naive sampling. With our accuracy \( e < 10^{-8} \) the range \(-1 < x_i < 1\) is divided into a lattice of more than 4 \( \times 10^{11} \) sites. The probability of hitting the global minimum at random is therefore \( 0.25 \times 10^{-10} \). On average, one encounters the global minimum about every 7,500 updates. Each update requires the recalculations of a table of 54 entries. Putting both together implies an improvement factor \( >10^4 \). Of course, random choices of coordinates followed by conventional determinations of the local extrema would do better for our trivial trial function. The real strength of the random-cost method is that it still works well for frustrated systems.

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Climate-induced fluctuations in sea level during non-glacial times

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DURING periods of time when the Earth supports ice caps, sea level fluctuates periodically at intervals of \( 10^{4}-10^{5} \) yr, with amplitudes of tens to more than 100 metres. These fluctuations result from expansions and contractions of continental ice sheets that occur in phase with the Milankovitch periodicities of the Earth's orbit. Smaller-amplitude sea-level fluctuations associated with Milankovitch periodicities are also evident during warm periods, such as the Late Triassic, which lacks strong evidence for continental glaciation. We argue here that, in times of limited ice volume, periodic climate-induced changes in lake and groundwater storage have the potential to produce small fluctuations in sea level. This mechanism could contribute a small component of the sea-level change observed in the Quaternary period, and may dominate the Milankovitch eustatic sea-level signal during earlier periods with limited ice volume. We present evidence of contemporaneous Milankovitch periodicities in Late Triassic lake sediments and sea-level fluctuation which support the causal link between lake water storage and eustasy.

The mechanism for periodic storage of lake and groundwater is based on the Quaternary record of climate change. The strength and region of influence of the monsoon fluctuates with a periodicity of \( 20 \) kyr as a consequence of precession of the equinoxes. When the Earth is closer to the Sun (perigee) during the Northern Hemisphere summer, as it was \( \sim 9000 \) years ago, global climate models indicate greater summertime heating and lower atmospheric pressure over the Asiatic land mass. These conditions result in greater monsoonal flow and increased summertime precipitation over North Africa and South Asia, an area encompassing more than 1/4 of the Earth's continental surface (Fig. 1).

To quantify the potential change in lake and groundwater storage, we determined the volumes of the 10 largest internally drained basins within the expanded region of influence of the early Holocene monsoon, and used these volumes to calculate a potential change in sea level (see Table 1 and Fig. 1). The Tarim basin alone, if filled with water, would lower sea level by 1 m. The volume of the 10 basins taken together is equivalent to 2.1 m of sea level.

Lakes represent the intersection of the water table with the ground surface, so lake level provides a proxy measure for groundwater storage. North and Central African lake basins were at highstand \( \sim 9000 \) years ago, as were lakes in South Asia. Before 10,000 years ago and after 5,000 years ago less than 20% of these lakes were at highstand. Although most of these basins are smaller than those in Table 1, many are associated with extensive aquifers such as the oasis complexes and the sand seas of the Sahara (Wadi Howar, Selima Oasis, Western Ergs, Oyo, and Grang Erg of Bilma). There are also many internally drained basins within the area of expanded monsoonal influence which have not been investigated in detail. These basins and their aquifers have large storage potential and the potential for rapid draw-down. Estimates of total groundwater on Earth vary, but they are of the same order of magnitude as continental ice volume. Consequently, even small percentage changes in groundwater storage could produce considerable changes in sea level. Given the large fraction of the Earth's surface affected by orbitally forced changes in the monsoon, the smaller basins combined with their groundwater storage potential could have considerably more effect than the 10 basins considered (Table 1). A water volume of 2-6 m could be accommodated in smaller basins and aquifers in the region of monsoonal influence. Lake basins and groundwater combined could store monsoonal rains equivalent to \( 4-8 \) m of sea level.

Quaternary and Holocene climates are complicated by the influence of glacial artesian flow and retardation on glacial circulation. Consequently, the more northerly basins in Asia may not have filled completely or synchronously. The Caspian basin may have received glacial meltwater from the Volga and Turgai during Pleistocene/Holocene glacial retreat as well as receiving water from the Amu Darya and other drainages that should respond to expanded monsoonal precipitation. Drainages leading to Qinghai Lake and those leading to Tarim and Qaidam are intimately associated. Qinghai Lake does show the influence of the expanded monsoon. Lake levels rose rapidly beginning 10,000 years ago and then declined after 6,000 years ago. Tarim and Qaidam must have had a similar influx during this period, but it is not clear whether the Tarim basin filled completely. Our estimate of water storage is intended only as an indication of potential sea-level change in the past, not an exact model of events in the Quaternary. This estimate also does not account for greater monsoonal intensity or larger storage potential associated with different continental configurations in the past.

Triassic palaeogeography seems to have been particularly amenable to monsoonally driven fluctuations in water storage. Triassic land masses were associated into one large continent (Pangea), much of which lay in subtropical to temperate latitudes. Sea level was generally low, resulting in large continental area, and a large seaway (Tethys) extended into the Pangean continent at tropical latitudes. These factors are thought to have enhanced monsoonal circulation, and widespread sedimentological evidence indicates a strongly seasonal climate. Global climate models based on Triassic continental configurations also

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indicate strong monsoonal flow, leading to the term 'mega-
monsoon' for this circulation pattern.

During the Triassic, incipient continental breakup produced a broad belt of graben and pull-apart basins extending from what is now the Gulf of Mexico along the east coast of North America to northern Europe and the Arctic. Lacustrine sediments fill nearly the entire Newark graben, and lacustrine deposits, which often contain evidence of flooding and desiccation, are exposed from South Carolina to Nova Scotia as well as in Morocco and the Southwestern United States. Triassic evaporite deposits are the most extensive of any period, testifying to the frequent flooding and desiccation of many Triassic basins. Rift graben, lacustrine deposits, and evaporite deposits and dune fields associated with lakes all had a greater areal extent in the Triassic than today, and these features were concentrated in the Northern Hemisphere sub-tropics, the region of precessionally forced fluctuations of monsoonal precipitation. Thus the Late Triassic may have shown more response to monsoonal fluctuation than could occur today.

Lake sediments of the Newark Supergroup form cyclic packages. Spectral analyses of these cycles, in the Carnian-age Locatton formation and the overlying Norian-age Passaic formation, indicate a dominant periodicity of ~20 kyr, the periodicity of equinox precession and changing monsoon intensity. Lower-frequency Milankovitch parameters were also observed, suggesting that orbital forcing of the monsoon resulted in fluctuating water flow into these basins.

The Lofer sequences of the Dachstein in the northern Alps and the Latemar cycles from the Dolomite mountains of northern Italy are composed of nearshore marine carbonate rocks that exhibit metre-scale eustatic cycles. The Norian Lofer cycles correlate with lacustrine beds of the Passaic formation. The Ladinian Latemar cycles immediately precede the Carnian Locatton cycles. The Lofer and Latemar sections consist of progradational packages with subaerially exposed caps indicating repeated eustatic flooding of a continuously subsiding platform. Spectral analyses suggest a dominant 20-kyr periodicity and bundling of these cycles into groups of five similar to the Milankovitch structure observed in the correlative lacustrine sediments. These results are consistent with a causal relationship in which periodic storage of water in lakes and aquifers led to sea-level fluctuation.

Models of eustatically produced nearshore carbonates assume rates of carbonate deposition and inferred subsidence rates. Such models suggest that 10 m relative changes in sea level would optimize the production of the Lofer and Latemar cycles and isostatic loading contributes to relative sea-level change and reduces the required eustatic change to ~7 m, within the range of water storage suggested by Holocene monsoonal fluctuation (Table 1), and well within the lacustrine and groundwater storage potential associated with the stronger Triassic monsoon.

An ice-sheet explanation for the sea-level changes implied by the modelling of Triassic carbonates would require the expansion and melting of an ice cap larger than that of Greenland every 20 kyr (ref. 33). There is no evidence for a Triassic ice sheet even a fraction of the size of the Greenland ice cap. In addition, fossil floras containing ferns and cycads are known from high palaeo-latitudes in the Triassic, indicating that climates were equable near the poles. There is thus considerable evidence that cyclic lacustrine and groundwater storage rather than changes in ice volume made the main contribution to Late Triassic sea-level fluctuation.

Although the evidence for a Milankovitch-forced monsoonal influence on sea level is most compelling in the Triassic, there is evidence for sea-level fluctuation contemporaneous with extensive lacustrine water storage in the Jurassic, Cretaceous and
The temperatures and oxygen-isotope composition of early Devonian oceans

Guoqiu Gao

The oxygen isotope composition of pre-Carboniferous (>360 Myr old) marine carbonates, cherts and phosphates has been reported to be lower than that of later (post-Devonian) samples. According to one explanation, this is a reflection of warmer (generally >40 °C) pre-Carboniferous oceans relative to modern oceans. Alternatively, it has been proposed that the pre-Carboniferous oceans were depleted in 18O (by 2% SMOW) relative to modern oceans. Here I report high δ18O values (~1.9 to ~2.9‰ PDB) in normal, shallow-marine limestones and three brachiopod shells from the Lower Devonian Haraqan and Bois d’Arc formations in south-central Oklahoma. I interpret these values as near-primitive, and therefore constraining the temperature and oxygen isotope composition of early Devonian sea water to 25 ± 7 °C and 0 ± 1% SMOW respectively. In conjunction with similarly high δ18O values obtained from older (Ordovician and Silurian) samples, these results imply that the temperature and oxygen isotope composition of pre-Carboniferous oceans may, at least during some time intervals, have been similar to that of modern oceans.

Limestones were sampled from the Haraqan and Bois d’Arc formations of the upper Hunton Group of Oklahoma. These formations have been dated to be Lochkovian (early Devonian) in age by brachiopod and conodont biostratigraphy. These two formations, less than 100 m thick, crop out locally in the Arbuckle mountains of south-central Oklahoma, and consist mainly of skeletal wackestones and lime mudstones. Samples were collected in the Arbuckle mountains at a quarry located in section 31, TIS and R2E of Oklahoma. In previous studies, brachiopod shells and marine cements were selected for oxygen isotope analysis to reconstruct the temperatures and oxygen isotopic composition of ancient oceans. Here I chose lime mud matrix without visible fossils and cements for isotopic and elemental analysis. Sampling sites were located on thin, polished slabs under both binocular and cathodoluminescence microscopes. Except for three dolomite-containing samples, sample powders were obtained from homogeneous, nonluminescent lime mud matrix by using a bench-top drill with dental drill bits. Three brachiopod shells were later analysed to compare the carbon and oxygen isotopic data of the lime mud matrix. The δ13C and δ18O values of the Haraqan and Bois d’Arc limestones range from ~1.1 to ~2.6% (PDB) and ~1.9 to ~4.0‰ (PDB), respectively (Table 1). The δ13C values (~1.5 to ~2.5‰) of three brachiopod shells fall within the δ13C range of the limestones, and the δ18O values (~2.1 to ~2.5‰) of the shells are similar to those (~1.9 to ~2.9‰) of most limestones (25 analysed samples). The similarity suggests that the isotope data for the lime mud matrix are reliable, because brachiopod shells, composed of relatively stable low-Mg calcite, are considered by many to be the ideal carbonate component for reconstruction of the temperatures and oxygen isotopic composition of ancient oceans. Although the δ13C values of the Haraqan and Bois d’Arc limestones are similar to Lower Devonian carbonates elsewhere, the δ18O values (~1.9 to ~2.9‰) of most limestones (including three brachiopod shells, hereafter) are the highest δ18O values yet documented for lower Devonian limestones (Fig. 1). In fact, such high δ18O values are not common in pre-Mississippian carbonates.

There could be several reasons for the high δ18O values of the Haraqan and Bois d’Arc limestones, including: (a) early Devonian (pre-Carboniferous), unusual depositional settings, and post-depositional (diagenetic) alteration. Dolomite should be enriched in 18O by 2.4‰ (PDB) relative to calcite if both minerals are formed under similar conditions. Thus, a marine limestone with minor amounts of syndepositional dolomite should have a higher δ18O value than a pure limestone. For the analysed Haraqan and Bois d’Arc limestones, minor amounts (~0.5 mol %) of dolomite were observed petrographically and detected by X-ray diffraction in three samples (H2-2, H2-5, and H2-8, Table 1). These three samples have lower δ18O values (~3.4 to ~4.0‰, Fig. 1), as well as higher Fe and Mn concentrations (Table 1), than dolomite-free