Indian Ocean Climate and an Absolute Chronology over Dansgaard/Oeschger Events 9 to 13

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Oxygen-isotope ratios of a stalagmite from Socotra Island in the Indian Ocean provide a record of changes in monsoon precipitation and climate for the time period from 42 to 55 thousand years before the present. The pattern of precipitation bears a striking resemblance to the oxygen-isotope record from Greenland ice cores, with increased tropical precipitation associated with warm periods in the high northern latitudes. The largest change, at the onset of interstadial 12, occurred very rapidly, in about 25 years. The chronology of the events found in our record requires a reevaluation of previously published time scales for climate events during this period.

The climate of the last glacial period is marked by large, rapid variations in climate termed Dansgaard/Oeschger (D/O) events. First identified in the oxygen-isotope values of ice cores from Greenland (*1*, *2*, *3*) and interpreted as indicating large temperature variations, correlative climate changes have been identified in a number of highresolution climate records from areas as distant as central Asia (*4*), southern Europe (*5*), and South America (*6*). In the Indian Ocean, marine records of upwelling intensity also show a strong similarity to D/O cycles (*7*, *8*). Little is known, however, about possible changes in the tropical hydrological cycle in the Indian Ocean or on the adjacent continents. The relationships between tropical convection and the intensity and location of the Indian/East African monsoon precipitation to D/O oscillations is of particular importance because Earth's heat exchange between the oceans and atmosphere is dominated by the tropics. In addition, the absolute timing of D/O events during this time interval is not well constrained. The latter is important for comparison with possible forcing mechanisms, such as solar variation, and for time series analysis of cyclical climate components during this period. Here, we reconstruct changes in monsoon precipitation for a part of the last glacial period, using oxygen stable isotope ratios of calcite from a stalagmite recovered from Socotra Island, Yemen, in the Indian Ocean. Our results indicate that time scales derived from the ice cores from Greenland may be in error by thousands of years between 42 and 53 thousand years before the present (ky B.P.)

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Socotra Island is in the northern tropics (12° 30' N 54°E) in the Indian Ocean, a region whose climate is dominated by the East African–Indian Monsoon (*9*, *10*). During the boreal summer, the intertropical convergence zone (ITCZ) migrates northward across the Indian Ocean and the Indian subcontinent, bringing with it summer monsoon rainfall. In late fall, the ITCZ retreats southward. On Socotra Island, this weather pattern results in a bimodal distribution of rainfall (*11*), with rainy seasons in early summer and fall associated with the convective activity of the ITCZ. The intervening periods are dominated by the southwest (summer) and northeast (winter) trade winds, which are associated with dry subsiding air (*9*). Variations in rainfall on interannual and longer time scales are controlled by variation in moisture derived from convective activity of the ITCZ with no other source of water vapor. In many low-latitude areas, particularly those dominated by convection, the stable isotopic ratios of rainfall are inversely proportional to the amount of rain (*12*, *13*). Previous work on speleothems from northern and southern Oman demonstrates that the oxygen-isotope ratio of speleothem calcite faithfully records changes in the isotopic composition of rainfall and, further, that those changes may be interpreted in terms of changes in precipitation (*14*, *15*, *16*). This relationship appears valid on time scales ranging from annual to hundreds of thousands of years (*14*, *16*).

Stalagmite M1-2 was collected from Moomi Cave on the eastern side of Socotra Island. The cave is overlain by ~20 m of limestone bedrock, and the sample was found 100 m from the cave entrance. We made a total of 22 $^{234}U/^{230}Th$ age determinations and 895 stable isotope measurements (*17*) (table S1) on the 1.73-m stalagmite. An age model was developed using a 3rd-order polynomial fit to the age-depth curve of the $^{234}U/^{230}Th$ data (Fig. 1). The base of the stalagmite dates to 54,670 years B.P. and the top to 42,200 years B.P. On average, the time interval between stable isotope measurements is 14.5 years, which is slightly higher resolution than the Greenland Ice Core Project (GRIP) ice core (~20 years) over this time period (*2*). The results of the oxygen stable isotope measurements are shown plotted versus age in Fig. 2. Calcite $\delta^{18}O$ values vary between –1.5 and 0.5‰ [Vienna Pee Dee belemnite (VPDB)], except for a very brief excursion to +1.3‰ at 50 ky B.P. In general, the absolute change in $\delta^{18}O$ for the running average is on the order of 1 to 1.5‰, which reflects changes in cave temperature and in the isotopic composition of precipitation (*18*).

On the basis of estimates of changes in sea surface temperature (SST) in the region, we can estimate the fraction of total variance attributable to temperature change. Changes in SST for the tropical Pacific and Indian Oceans from the last glacial maximum to the present are on the order of 2° to 3°C (*19*, *20*, *21*). Changes in SST during D/O events were likely to have been somewhat less, with 2°C a reasonable upper limit for the larger D/O events. Given the oceanic setting of Socotra Island, this is also an appropriate estimate of changes in cave temperatures. With calcite-water oxygen-isotope fractionation (*22*), a temperature decrease of 2°C results in 0.45‰ increase in calcite $\delta^{18}O$. Thus, we estimate that about one-third of the variance in the record is due to temperature and two-thirds is caused by changes in $\delta^{18}O$ of precipitation. In tropical settings, the isotopic ratio of precipitation is strongly anticorrelated to the amount of rainfall (*12*, *13*). Thus, the M1-2 oxygen-isotope record reflects changes in the amount of rainfall reaching Socotra Island and, to a lesser extent, temperature, with more neg-

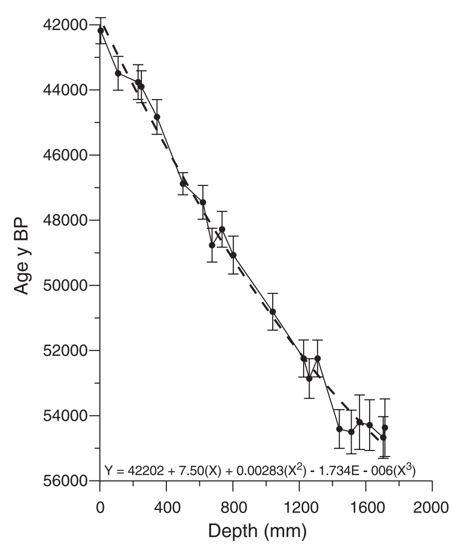

Fig. 1. Age versus depth for stalagmite M1-2. Individual U/Th age determinations are shown with errors. The dashed line and polynomial equation are the age model used to calculate ages for stable isotopic measurements.

ative speleothem values indicative of higher rainfall and increased temperature. Because rainfall on the island is related to the intensity of tropical convective activity, it is likely representative of the tropical hydrological cycle in the Indian Ocean and perhaps to variations in monsoon rainfall over a much larger area.

Although there is considerable short-time scale variation, millennial-scale variation in the M1-2 isotopic record, as represented by the 13-point running mean, strongly resembles the pattern of isotopic variation in the Greenland ice cores (Fig. 2) when the isotopic scale on one record is reversed and the ice-core data are shifted 3000 years back in time compared with the most recent ice-core time scale (*2*). We discuss the difference in chronologies below. All of the major features of the ice-core isotopic record are mirrored in the M1-2 record: the saw-toothed nature of D/O events; the evenly spaced triplet of smaller D/O events 9, 10, and 11; and the presence of D/O event 13 on top of a background trend of slowly changing values. The $\delta^{18}O$ records of Greenland ice cores have been interpreted to be mainly a function of air temperatures above Greenland (*1*–*3*), and this interpretation is supported by studies of N isotopes in air trapped in the ice (*23*, *24*). The data show a pattern of gradual cooling and sudden warming. The correlation to M1-2 indicates that the hydrological cycle in the Indian Ocean was changing synchronously with high-latitude temperature. High-latitude cooling was associated with gradual decreases in precipitation, and sudden high-latitude warming was associated with rapid increases in precipitation. To estimate how rapidly tropical climate was changing, we took more closely spaced isotopic measurements, with an average time resolution of 8 years, over the transition from dry to wet climate at the start of D/O event 12 (Fig. 3). The data indicate an initial further drying, to the driest conditions in the entire record. The following transition to a much wetter climate took place in approximately 25 years, providing independent confirmation of the rapid nature of these transitions, as previously observed in Greenland ice cores.

What causes the strong climate teleconnection between the tropics in the Indian Ocean and the North Atlantic region is an intriguing question. The monsoon is primarily driven by the land-sea temperature gradient between the Indian Ocean and central Asia (*9*, *10*). Over the past several decades, warm Eurasian winters with anomalously low snow cover are correlated with anomalously strong monsoon precipitation the following summer (*25*, *26*). The same relationship does not hold true for snow cover on the Tibetan plateau itself (*26*), as has often been suggested. Warm Eurasian winters with little snow appear to propagate warmth eastward from winter to spring, leading to warming of the central Asian landmass (*26*) and an increase in the land-sea thermal contrast. That such a teleconnection is detectable for the relatively small variations in climate over the past few decades suggests that the much larger temperatures changes experienced by northern Eurasia over the large D/O climate oscillations would have strongly influenced the Indian monsoon, and perhaps also the East Asian monsoon.

Whether warming and cooling in the North Atlantic are initiated there or in the tropics remains an open question. The presence of D/O cycles in the M1-2 record and other tropical climate records (*4*, *6*–*8*) suggests that the tropics would at minimum act as an amplifier of climate change. The most important atmospheric greenhouse gas is water vapor, and most atmospheric water vapor comes from the tropical ocean. The intensity of tropical convection is to a large degree determined by the latent heat component of precipitating water vapor (*10*), which would provide a positive feedback mechanism by varying atmospheric water vapor.

As mentioned, the best visual fit between the M1-2 and GRIP isotopic curves is achieved by shifting the ice-core data 3000 years back in time. Similarly, the time scale for the Greenland

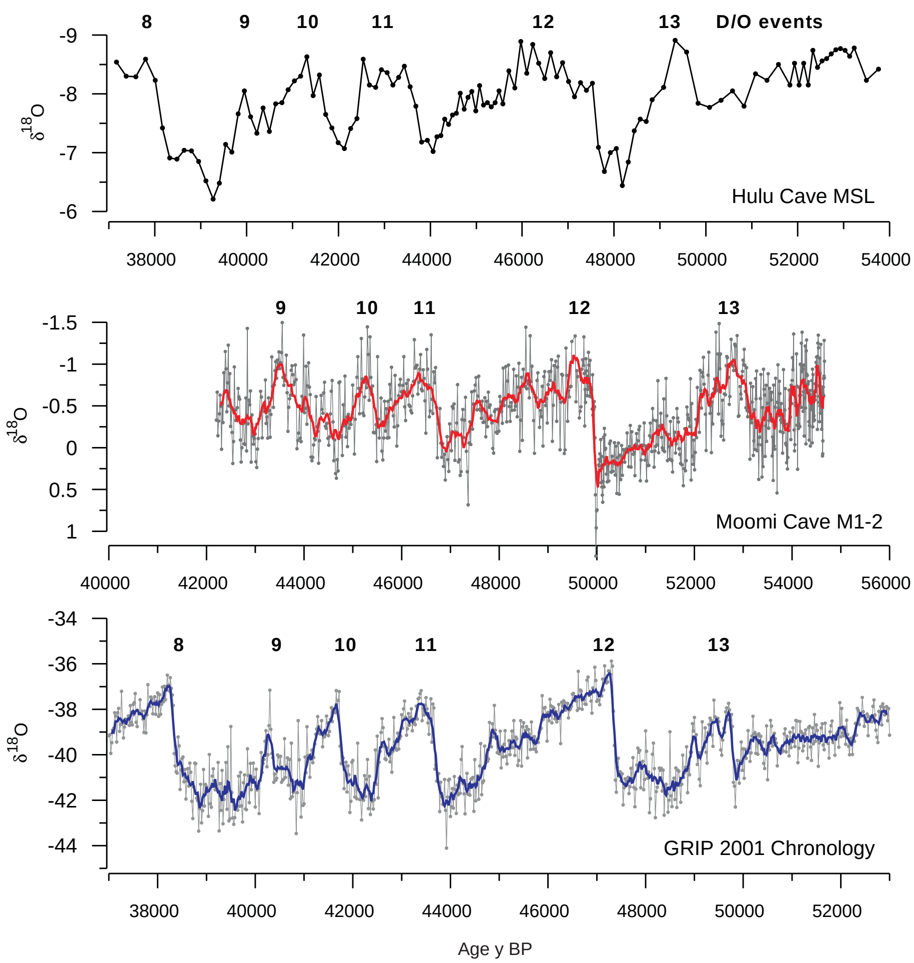

Fig. 2. Comparison of the oxygen-isotope ratios of stalagmite M1-2 with oxygen isotopes from the GRIP ice core (*2*) and the $\delta^{18}O$ record of a stalagmite from Hulu Cave in central China (*4*). The time scales are independent and shifted to give the best fit for D/O events. The oxygen isotopic scales for the stalagmite records are reversed. The locations of D/O events 9 through 13 as identified in each record are also shown.

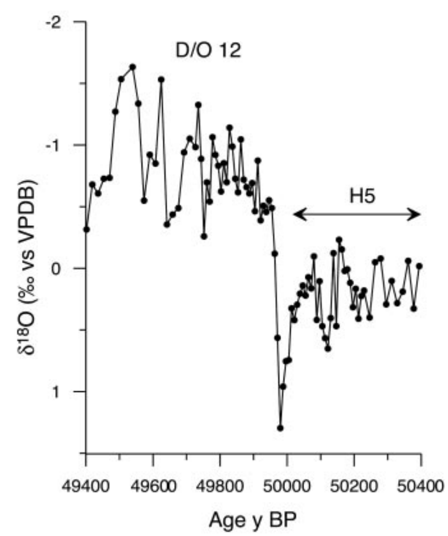

Fig. 3. Detailed view of the oxygen-isotope record during the end of Heinrich event 5 and the transition into D/O event 12. Isotopic measurements were taken every millimeter across the transition. The time interval between samples is about 8 years.

Ice Sheet Project 2 (GISP2) (*3*, *27*) isotopic curve (which is nearly identical to the GRIP isotope curve) over this time period is ~5 ky younger than the M1-2 chronology. Both ice-core time scales are based on layer counting and deposition rate/ice flow models and have been revised several times (*1–3*, *27*). Our chronology is based on 22 radiogenic isotope measurements (*28*) (table S1). It is not realistic to infer that the differences in age scales indicate any lead-lag relationship in climate events. Thus, we suggest that the ice-core chronologies need to be revised to fit the absolute chronology of stalagmite M1-2 for D/O events 9 through 13.

Two similar comparisons of isotopic records from stalagmites and Greenland ice cores have been made. Using primarily a carbon isotopic record for comparison with the ice cores, Genty *et al.* (*29*) suggested an absolute age for D/O event 12 of ~45 ky B.P., approximately matching the GISP2 (*3*) and earlier GRIP (*1*) ice-core chronologies. The match between Genty's isotope curve and the ice cores, however, is somewhat ambiguous, and we suggest that what they identified as D/O events 12 and 14 in their record are actually D/O events 10 and 12, respectively. A better fit between ice core and stalagmite $\delta^{18}O$ curves comes from Hulu Cave in China (*4*), although two possible correlations were presented for the period from 40 to 50 ky B.P. Even the older of these (Fig. 2), however, yields an absolute age estimate for D/O 12 of ~47.5 ky B.P., an age ~2 ky younger than the M1-2 record. The age difference between the two records is larger, ~3 ky, for D/O events 10 and 11. We are not certain of the reason for this discrepancy. Recent work by Beck *et al*. (*30*) on Bahamian stalagmites supports an age for D/O event 10 that is close to our chronology. They identified an extremely large anomaly in atmospheric ^{14}C concentration that occurs at 43.4 to 44.4 thousand years ago. This event is very likely to be coincident with a large anomaly in Be-10, another cosmogenic isotope, found in the GRIP ice core at D/O event 10 (*31*). Thus, D/O event 10 would be dated to ~44 ky B.P. in the Bahamas record, whereas it occurs at ~45 ky B.P. in our record. D/O event 10 is dated at ~41 ky B.P. in the Hulu Cave record.

The M1-2 stable isotope record demonstrates that the climate of the tropical Indian ocean is strongly linked to temperature variations in the North Atlantic region. The most likely mechanism for this connection indicates that the Indian monsoon is changing in response to high northern latitude temperature, although the initial cause of highlatitude climate change could still lie in the tropics. The chronologies derived from U/Th dating of stalagmites provide important constraints on the absolute ages of observed climate events. In this particular case, previously proposed ice-core chronologies appear to be several thousand years too young during the period from 42 ky B.P. to 55 ky B.P.

References and Notes

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28. Stalagmite M1-2 has high U content and high $^{230}Th/^{232}Th$ activity ratios (*17*). The age determinations are therefore robust with respect to corrections for incorporated detrital Th or nonzero initial ^{230}Th.
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Supporting Online Material

www.sciencemag.org/cgi/content/full/301/5638/1365/DC1

Methods

Table S1

References

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Constitutive Display of Cryptic Translation Products by MHC Class I Molecules

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Major histocompatibility complex (MHC) class I molecules display tens of thousands of peptides on the cell surface, derived from virtually all endogenous proteins, for inspection by cytotoxic T cells (CTLs). We show that, in normal mouse cells, MHC I molecules present a peptide encoded in the 3′ "untranslated" region. Despite its rarity, the peptide elicits CTL responses and induces self-tolerance, establishing that immune surveillance extends well beyond conventional polypeptides. Furthermore, translation of this cryptic peptide occurs by a previously unknown mechanism that decodes the CUG initiation codon as leucine rather than the canonical methionine.

The set of peptides displayed by MHC class I molecules comprises the information available to CTLs, which detect the presence of viral, bacterial, or otherwise foreign peptides in this complex mix. Recent evidence has questioned the conventional wisdom that most of these peptides are derived from cellular protein turnover (*1–4*). Instead, it appears that a major source of these peptides is newly synthesized polypeptides (*5*, *6*). Independently, examples of antigenic peptides derived from "noncoding" regions of mRNA 5′ and 3′ of the open reading frame, and in alternate reading frames, have accumulated (*3*). These reports suggest that an additional source of information is available to CTLs surveying for a foreign presence inside the cell (*7*). We developed a transgenic mouse model to determine whether such "cryptic" peptides derived from noncoding regions were anomalies found in rare tumor or virally infected cells or whether cryptic translation contributes to the pool of available antigenic peptides within normal cells.

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