How did the hydrologic cycle respond to the two-phase mystery interval?

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ABSTRACT

Lake Estancia's transition from a Big Dry episode during the first half of the Mystery Interval to a Big Wet episode during the second half has equivalents in records from across the planet. At the time of this transition, Chinese monsoons experienced pronounced weakening, closed-basin lakes in both the Great Basin of the western United States and in the southern Altiplano of South America underwent a major expansion, mountain glaciers in Southern Hemisphere middle latitudes had retreated, and the rates of increase of CO_2 and of $\delta^{18}O$ in Antarctic ice underwent a decrease. Finally, the precipitous drop in dust rain over Antarctica and the Southern Ocean terminated as did a similar drop in the ^{13}C to ^{12}C ratio in atmospheric CO_2. These changes are consistent with a southward shift of the thermal equator. The cause of such a shift is thought to be an expansion of sea ice caused by a shutdown in deep water production in the northern Atlantic. This creates a dilemma because a similar southward shift is an expected consequence of the Heinrich event #1 which initiated the Mystery Interval.

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1. Introduction

Allen and Anderson (2000) document the existence of a desiccation event (the Big Dry) in New Mexico's Lake Estancia. It began at the close of the LGM (about 18 ka) and lasted for about 2 ka. This time interval corresponds to the first half of the so-called Mystery Interval (H-1 stadial). It was preceded and followed by high stands of this now dry lake. The sediment deposited during the Big Dry interval is rich in gypsum and contain ostracods characteristic of salty water. By contrast, the sediments above and below are gypsum-free and contain ostracods characteristic of fresh water. The age of the Big Dry interval is constrained by numerous ^{14}C dates on ostracods (see Fig. 1).

As the changes in the Earth's hydrologic cycle appear to be globally orchestrated (Severinghaus et al., 2009; Asmerom et al., 2010; Broecker, in press), the question arises as to whether this is the case for the Big Dry to Big Wet transition. One problem is that a twofold division of the Mystery Interval doesn't seem to fit with the continuous drop in the atmosphere's ^{14}C content. As this drop is thought to represent the mixing of a ^{14}C-enriched upper ocean with a ^{14}C-depleted abyssal ocean, taken in isolation, the absence of a difference in the rate of ^{14}C decline between the first and second

half of the Mystery Interval suggests that no change in ocean circulation accompanied the Big Dry to Big Wet transition. Similarly, there is no significant early Mystery Interval to late Mystery Interval difference between the ^{231}Pa to ^{230}Th ratio in Atlantic sediments (McManus et al., 2004) suggesting that the shutdown of deep water production in the northern Atlantic prevailed during this entire interval. This is also consistent with the constancy of the high dust rain onto Greenland during the course of the Mystery Interval. But, as outlined below, the hydrologic record appears to require a southward shift in the thermal equator at the midpoint of the Mystery Interval (see Fig. 2 for location of the records to be discussed).

This paper is an update on a previous one (Broecker et al., 2009) that focused on the extent of the Big Dry in the Great Basin and its possible cause. Much of the discussion had to do with the uncertainty in the offset between radiocarbon-based ages and those based on ^{230}Th. With the publication of the highly precise calibration based on 40 ^{14}C–^{230}Th age comparisons in a Hulu Cave stalagmite spanning the Mystery Interval (Southon et al., 2011), these uncertainties have been resolved. Further, the similarity of the ^{18}O record for O_2 trapped in polar ice (Severinghaus et al., 2009) with that for ^{18}O in Chinese stalagmites (Wang et al., 2001) strengthens the case for a global extent for the twofold Mystery Interval. As the Mystery Interval is thought to have been triggered by a Heinrich event, then it should have begun with a southward shift. Hence the second southward shift required by the results summarized below appears to create a dilemma.

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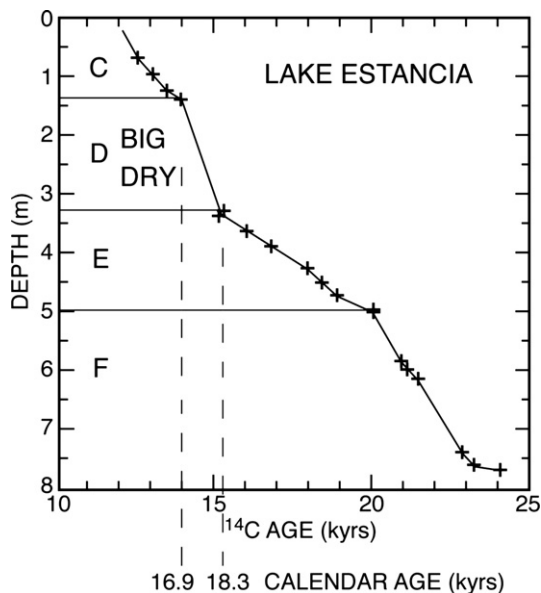 E-mail address: broecker@ldeo.columbia.edu (W. Broecker).

Fig. 1. Radiocarbon ages on ostracods as a function of depth in Lake Estancia's sediment (Allen and Anderson, 2000). Units F and E which were deposited during the LGM contain abundant ostracods which thrive in low salinity environments. Unit D which was deposited during the Big Dry contains rare ostracods capable of survival in salty water. Unit C which was deposited during the time of Lake Lahontan's Big Wet contains abundant fresh water ostracods. The pluses are the levels at which ^{14}C ages were obtained on ostracods.

2. Chronologies

Critical to this evaluation is a precise and accurate chronology. As many of the ages used here are based on ^{14}C measurements, it is important to correctly convert them to calendar ages. Although measurements on coral show that the [230]Th–[14]C age offset decreased from about 3 ka at the onset of the Mystery Interval to about 2 ka at its end, there are few coral measurements which document the course of this decline. Fortunately, a new record

obtained through cooperation between the Irvine group (^{14}C measurements) and the Minnesota group ([230]Th measurements) has remedied this situation (Southon et al., 2011). This remedy is based on a very detailed [14]C–[230]Th age comparisons on samples from China's Hulu Cave. Forty such comparisons show that the [230]Th–[14]C age difference underwent a linear decline from 3.25 ka to 2.25 ka during the course of the Mystery Interval (see Fig. 3).

Key to our arguments are radiocarbon ages on calcites precipitated in closed basin lakes. Such ages are subject to reservoir corrections. As discussed below, it is tempting to call on corrections ranging up to 700 years in order to align events in these lakes with those recorded in ice cores and stalagmites. However, unless the lakes had extremely high alkalinities such corrections are unreasonably large. The argument is as follows. As shown by Wanninkhof et al. (1985), the preindustrial invasion rate of CO_2 into these lakes is on the order of 8 mol/m^2 yr. Taking into account the somewhat lower atmospheric CO_2 content during the deglacial time interval, the rate would have been closer to 6 mol/m^2 yr. In order to achieve a reservoir correction on the order of 500 years would require a water column $\sum CO_2$ inventory of 3000 moles per m^2. This is about one half that for the ocean. The only lake we know of with this high a water column inventory is Mono Lake in California. Pyramid Lake, one of the remnants of Lahontan, has a current inventory on the order of 1000 moles/m^2 (i.e., a turnover time of 170 years). Indeed, this is the magnitude of the correction obtained by Broecker and Walton (1959) based on ^{14}C measurements on lake and river water. For lakes like Mono and Pyramid, the input of ^{14}C-free CO_2 from hot springs increases the reservoir correction but, as such contributions are difficult to quantify, it is not possible to say what it was during the Mystery Interval. In any case, the reservoir corrections are unlikely to explain the range in radiocarbon ages to be discussed in the following sections.

Another consideration is contamination with secondary [14]C. The limited number of acid leaching experiments conducted on $CaCO_3$ from limnic sediments show that the ^{14}C ages often increase with progressive mass loss. In order to evaluate the importance of secondary ^{14}C will require a new round of measurements.
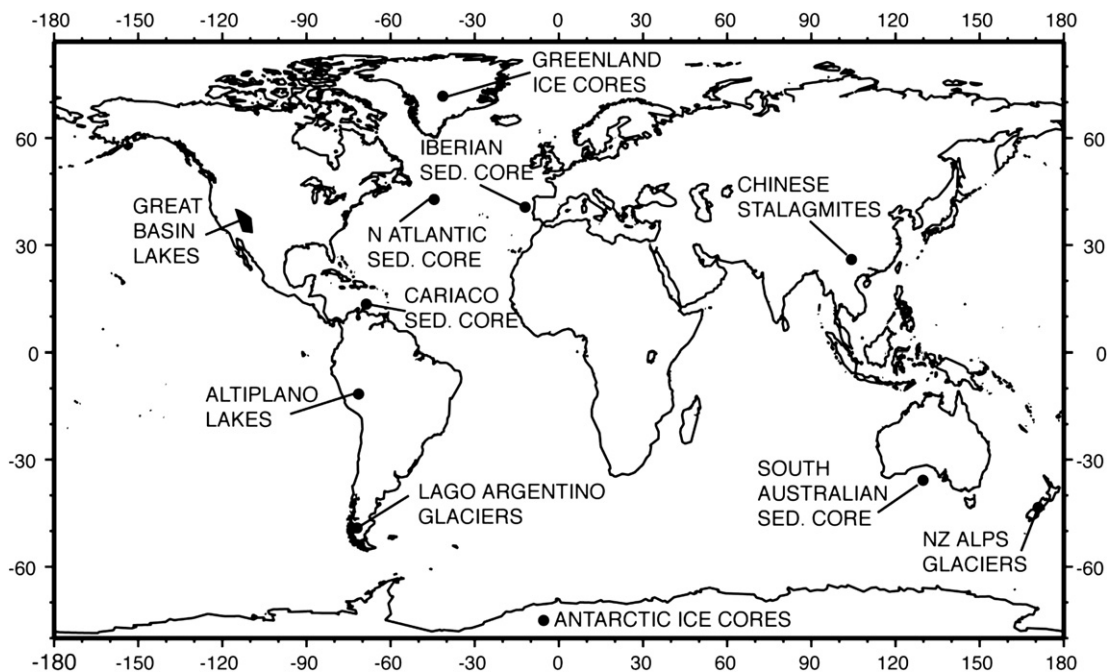

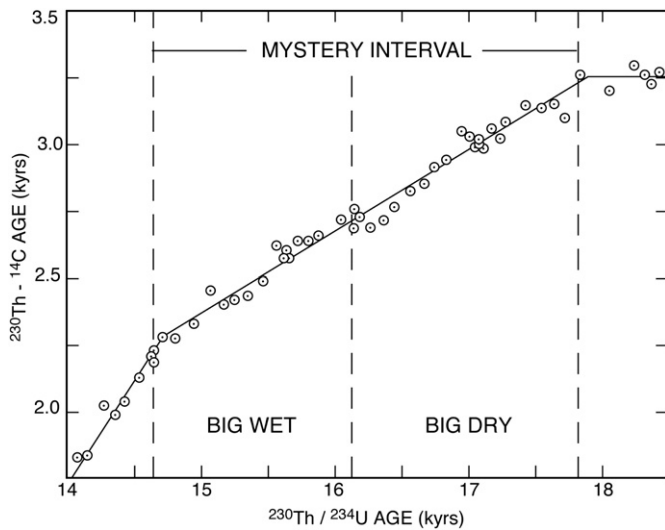**Fig. 2.** Map showing the locations of the records on which this paper is based.

Fig. 3. Plot of the differences between the ^{230}Th/^{234}U age and the ^{14}C age as a function of calendar age for Mystery Interval samples from Hulu Cave (Southon et al., 2011).
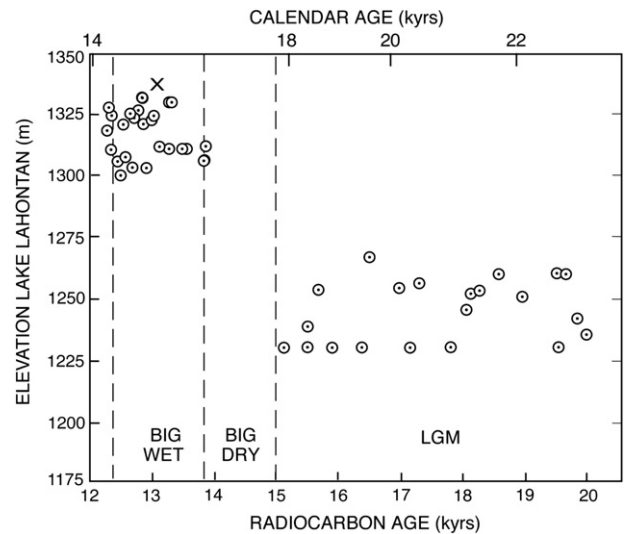

Fig. 4. Summary by Benson et al. (1990) of radiocarbon ages for tufas from Lake Lahontan's raised shorelines (open circles). The x is for collagen isolated from a camel bone (Adams and Wesnousky, 1998). Note that none of these ages fall within the 16–18 ka calendar age range.

Still another consideration involves dating of small entities such as ostracods. As they are easily reworked, it is possible that the radiocarbon ages for Estancia are too old.

Finally, the time intervals for the high stands of Nevada's Lake Lahontan and the Altiplano's Lake Tauca are constrained by the range in tufa ages rather than stratigraphically. Scatter related to the measurement error and variations in the extent of secondary ^{14}C uptake tend to widen the apparent duration of these high stands.

3. The Great Basin record

It is clear that in the western U.S.'s Great Basin the second part of the Mystery Interval was the wettest in the last 30 ka. Not only did Lake Lahontan achieve its largest size but the Great Basin's interior lakes located between Lakes Lahontan and Bonneville did as well. Although no low-elevation shorelines with Big Dry ages have been documented in any of these basins, their absence of any shoreline dates in this time interval suggests that, like Estancia, the lakes were much smaller.

3.1. Lahontan

As summarized in Fig. 4, 25 radiocarbon ages on tufa from the highest Lahontan shoreline (1300–1325 m) fall into that age range 12.3–13.8 ^{14}C ka (14.4–16.5 calendar ka). Its LGM size is documented by 20 radiocarbon ages from an intermediate stand (1225–1250 m). They fall in the age range 15–20 ^{14}C ka (18–23 calendar ka). None of the radiocarbon measurements fall within the Big Dry 16.5–18.0 calendar ka range. Although this is consistent with the existence of a low lake stand during the first half of the Mystery Interval, in absence of any direct documentation, the size of the lake at that time remains unconstrained. Unfortunately, no datable sedimentary sections comparable to those exposed in the Estancia basin have been found in Lahontan's basin.

3.2. Interior playas

Several of the playas in the interior of the Great Basin have high shorelines yielding radiocarbon ages falling within the bounds of the second half of the Mystery Interval (see Table 1).

Unlike Lahontan, which received most of its water from the high mountains which form the western boundary of the Great Basin, these lakes were fed by precipitation falling within the basin. Again, as is the case for Lahontan, there are no radiocarbon-dated deposits corresponding to the first half of the Mystery Interval.

3.3. Bonneville

The situation for Lake Bonneville is complicated by its overflow and the subsequent down-cutting of its outlet. Both occurred during the course of the Mystery Interval. As shown in Fig. 5, taken at face value, the radiocarbon dates on shore-zone CaCO$_3$ materials suggest that the down cutting took place just prior to 17 calendar ka ago. In a recent paper, McGee et al. (2012) present highly precise ^{230}Th ages on dense CaCO$_3$ coatings deposited well beneath Bonneville's surface in small shore-zone caves. In Cathedral Cave, deposition of this CaCO$_3$, while continuous during the LGM, ceased at close to 18 ka. One interpretation would be that the lake dropped below the level of Cathedral Cave at this time. If so, ten or so radiocarbon ages from the Provo level would have to be disregarded. Instead, as McGee et al. (2012) suggest, the cessation of CaCO$_3$ deposition was instead the result of a change in the lake's chemistry. Perhaps, as a result of its overflow, it became undersaturated with respect to CaCO$_3$. Hence there is no evidence for a Big Dry episode at Lake Bonneville. At best, one might postulate that a decrease in the intensity of overflow took place during this time interval.

Table 1
Radiocarbon ages on high shorelines of now dry lakes located near the Utah–Nevada border in the central Great Basin.

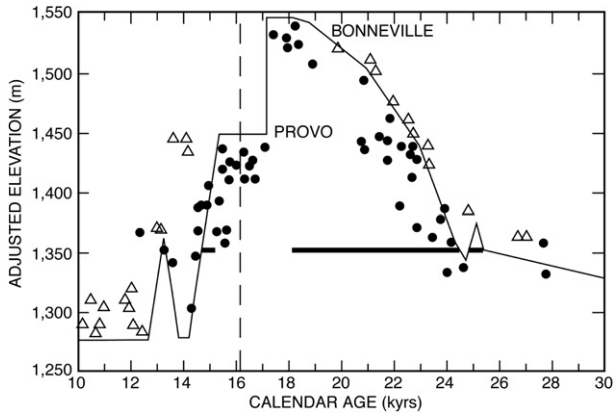| Location	Radiocarbon age (ka)	Calendar age (ka)	Reference
Jakes Valley	13.87	16.7	Garcia and Stokes (2006)
Newark Valley	13.78	16.6	Redwine (2003)
Diamond Valley	13.50	16.3	Tackman (1993)
Franklin Valley	13.33	16.0	Lillquist (1994)

Fig. 5. Elevation versus time (in calendar years) for Lake Bonneville. The circles are for radiocarbon measurements on tufa or shells formed within the lake. The triangles are for radiocarbon measurements for terrestrial plants grown above the lake surface (Oviatt et al., 1992). The light line is a reconstruction of the lake-level history based on these radiocarbon measurements. The sharp drop, close to 17 ka, represents the down cutting from the Bonneville to the Provo level. The three segments of the heavy horizontal line represent times when $CaCO_3$ was deposited in wave cut Cathedral Cave (McGee et al., 2012). Note that there seems to be no evidence for a lake-level change at 16.1 ka.

4. Other terrestrial records

Bolivia's Altiplano is a closed basin. Today it has two lakes, large Titicaca in the north and small Poopo in the south. Tufa-coated abandoned shorelines surrounding the dry solars to the south of Lake Poopo were formed in Lake Tauca which was several times larger than today's Titicaca. As documented by both ^{14}C and ^{230}Th ages, this lake was present from about 16.3 ka to about 14.4 ka (see Fig. 6). Prior to 16.3 ka only small and shallow lakes were present. Based on stratigraphic evidence, Placzek et al. (2006) conclude that a shallow LGM-age lake (Sajsi) largely dried up before the creation of large and deep Lake Tauca. If correct, then this desiccation may correspond to Estancia's Big Dry. But again, no convincing documentation has been reported.

Complementing the record for Bolivia's Altiplano is that from a sediment core in the Cariaco Basin. As shown in Fig. 7, abrupt

changes in reflectance occur at about 16.3 ka and at about 14.6 ka. As interpreted by Peterson et al. (2000), the lower the reflectance, the greater the input of river-born debris. If so, then the high reflectance interval between 16.3 and 14.6 ka represents a time of reduced debris input from Venezuelan rivers. This is consistent with a southward shift in the location of the Amazonian rain belt. It can also be seen that during the time interval prior to 16.3 ka the reflectance was lower, suggesting a greater input of debris from rivers and hence wetter conditions in the northern part of Venezuela during the first half of the Mystery Interval.

Edwards' group in Minnesota has obtained a highly precisely ^{230}Th-dated ^{18}O record for stalagmites from China's Hulu cave (Wang et al., 2001). It has a pronounced 20-ka cycle which tracks Northern Hemisphere summer insolation. Times of stronger summer insolation are characterized by isotopically light calcite and times of weaker summer insolation by isotopically heavy calcite. This cycle is attributed to a greater contribution of isotopically light monsoon rainfall during warmer than average summers. These records also show millennial shifts corresponding to Heinrich and Dansgaard−Oeschger events. As shown in Fig. 8, there is a pronounced shift toward heavy oxygen at 16.1 ka suggesting that China's monsoons were stronger during the first half of the Mystery Interval than during the second half.

The designation 'Mystery Interval' was created because of the uncertainties in the cause for the 15 percent decline in the ^{14}C to C ratio in atmospheric CO_2 and upper ocean $\sum CO_2$ between 17.8 and 14.7 ka (Broecker, 2009). As mentioned above, this decline has been beautifully verified by ^{14}C and ^{230}Th measurements on calcite from Hulu Cave. As can be seen in Fig. 3, the decline is linear. Almost all the points lie within the 2 sigma error of the ^{14}C ages (i.e., 0.08 ka) of this line. Clearly, no significant change in slope occurred at the time of the mid-Mystery Interval transition (i.e., 16.1 ka).

Finally, mountain glaciers in southern middle latitudes underwent recession beginning in the first half of the Mystery Interval. This glacier retreat has been well dated at Lago Argentino on the eastern flank of the Andes of southern South America. There, Strelin et al. (2011) showed that the large ice tongue that occupied Lago Argentino during the LGM had receded to a position well inside its Lateglacial moraines by as early as ∼16.4 yrs ago. Glacier recession during the Mystery Interval also occurred on the other side of the South Pacific in the Southern Alps of New Zealand,
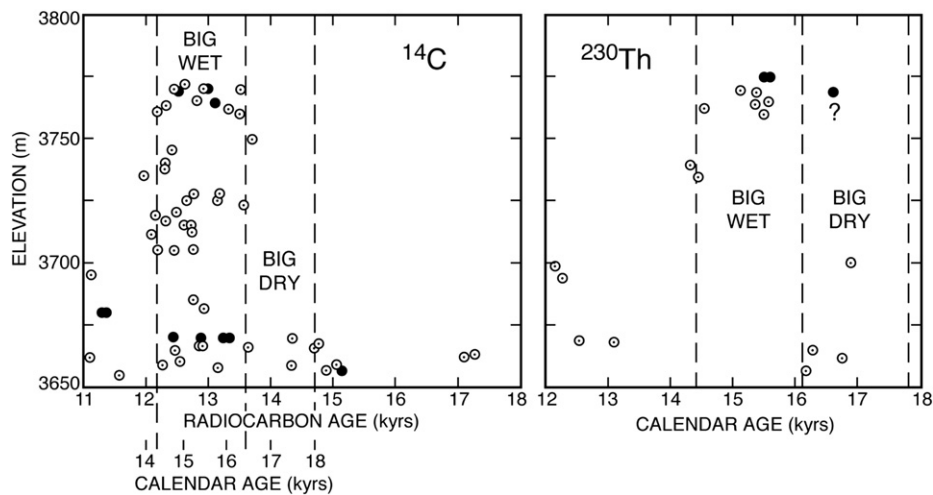

Fig. 6. Summary of ^{14}C and ^{230}Th results for closed basin lakes in the southern portion of Bolivia's Altiplano. The open circles are from Placzek et al. (2006) and the closed circles are from Blard et al. (2011). As can be seen, the highest water levels achieved in this region occurred between 16.3 and 14.4 calendar years. It should be noted that only those ^{230}Th results with ^{230}Th to ^{238}Th activity ratios exceeding 9 are plotted. As the floor of playa Uyuni has an elevation of 3653 m, the samples with ages in the Big Dry interval represent lakes with water depths no more than 15 m.
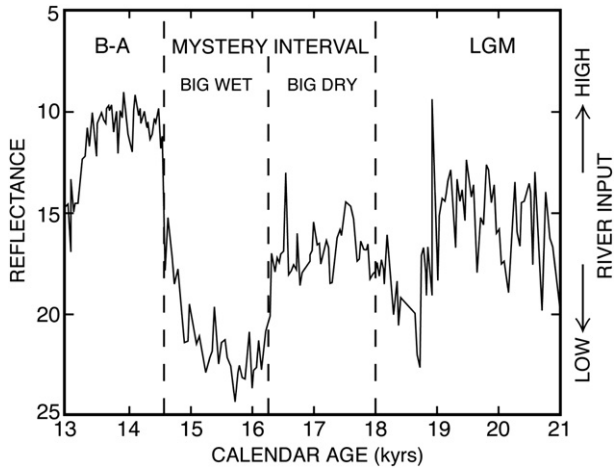
Fig. 7. Reflectance record for a core from the Cariaco Basin (in the Caribbean, north of Venezuela). It should be noted that the conversion of the ^{14}C-based chronology to calendar years is not based on the Hulu calibration (Peterson et al., 2000). This record indicates that during the Big Wet, the delivery of river-born material was unusually low. The southward shift in the Amazonian rain belt dried out northern Venezuela.

where a [10]Be surface-exposure chronology of moraines nearby Lake Pukaki places the onset of deglaciation at ~18.0 yrs ago, i.e., at the beginning of the Mystery Interval (Schaefer et al., 2006; Putnam et al., 2010a,b). By the time of the Antarctic Cold Reversal, the glacier tongue in the Pukaki valley had retreated by more than one half of its full-glacial length (Putnam et al., 2010b). However, it remains unclear from available data whether glaciers in southern mid-latitudes registered a prominent switch at the transition from the first to the second half of the Mystery Interval, or if recession occurred at a constant rate throughout the entire interval. This remains an important question of Southern Hemisphere paleoclimatology.

5. Ice core records

In Fig. 9, the oxygen isotope record for atmospheric O_2 trapped in polar ice (Severinghaus et al., 2009) is compared with that in Chinese stalagmites (Wang et al., 2001). As can be seen, the fluctuations in the two records match beautifully. This suggests that monsoons across the Northern Hemisphere weaken and strengthen in synchrony and, in so doing, imprint the isotopic composition of atmospheric O_2. This is perhaps the strongest evidence in support of the global scope of the twofold Mystery Interval.
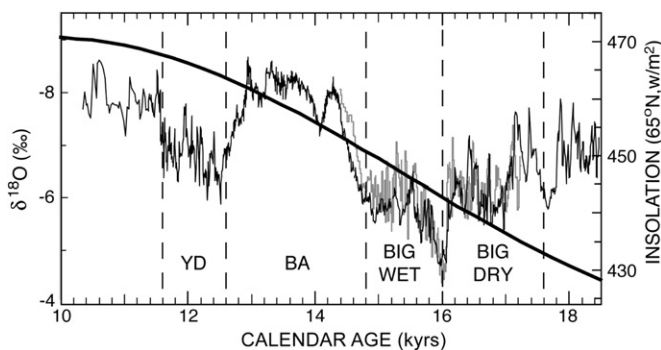

Fig. 8. The portion of the [18]O record in stalagmites from China's Hulu Cave which covers the deglacial time interval. Shown by the solid curve is the summer insolation at 65°N. Note that during the time of the Big Wet, the monsoons are weaker and during the time of the Big Dry are stronger than expected from the magnitude of the summer insolation (Wang et al., 2001).
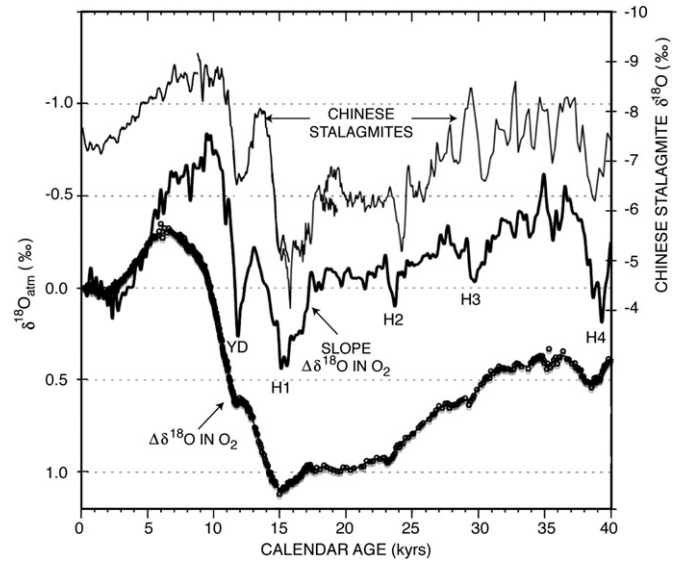

Fig. 9. Comparison of the [18]O record for atmospheric O_2 (Severinghaus et al., 2009) with that of [18]O in Chinese stalagmites (Wang et al., 2001). The lower curve is that for the actual atmospheric O_2 measurements and the middle curve, the deconvolved instantaneous composition of the O_2 being produced. This deconvolution is necessary because the residence time of O_2 in the atmosphere is about 1 ka. The similarity of the two isotopic records suggests that the Chinese monsoons are representative of the global monsoons. Note that the amplitude of the global signal is about one quarter of that for the Chinese stalagmites suggesting that monsoon vegetation accounts for about one quarter of the Earth's O_2 production. The small offset of the time scales is not real but rather a deficiency in the ice-core chronology.

The [18]O to [16]O record in Antarctic ice has a two-stage Mystery Interval. As shown in Fig. 10, a steep post-LGM rise in $\delta^{18}O$ begins at 17.8 ka and continues until 16.1 ka, at which time the rise flattens. This rise continues until 14.5 ka, at which time it dips into the Antarctic Cold Reversal.

Measurements on air trapped in Antarctic ice show that the atmosphere's CO_2 content underwent a continuous rise during the course of the Mystery Interval. However, at 16.1 ka a small upward jump occurs. It is followed by a decrease in slope (see Fig. 11).

The recently published ^{13}C record for CO_2 trapped in polar ice (Schmitt et al., 2012) shows that during the first half of the Mystery Interval, the $\delta^{13}C$ dropped by about 0.3‰. Then at about 16 ka, the slope changed and during the second half of the Mystery Interval, it
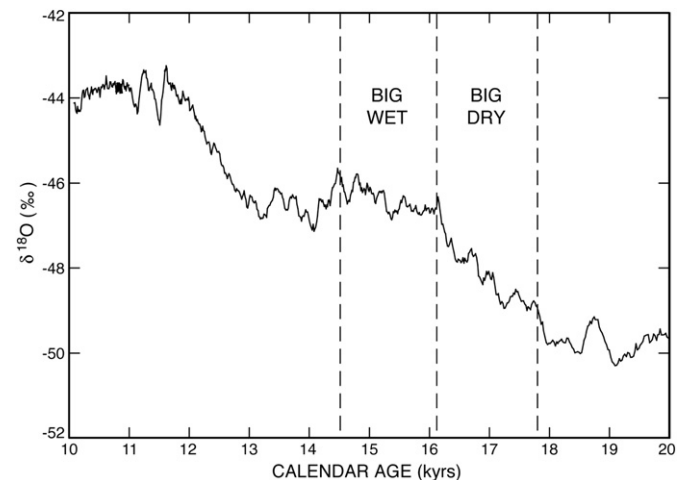

Fig. 10. Oxygen isotope record for Antarctic ice. As can be seen, the slope of the rise changes at about 16.1 ka.
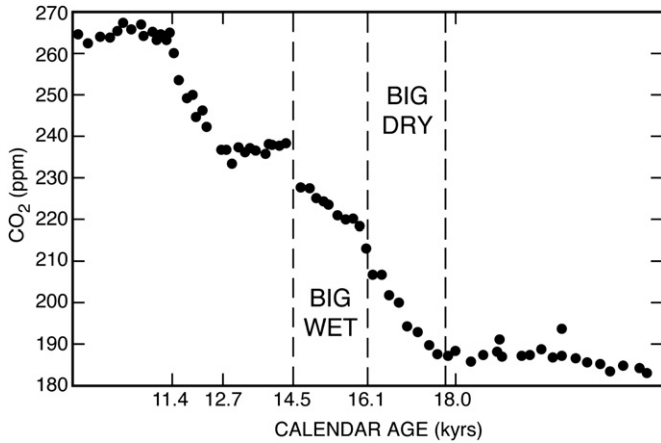
Fig. 11. CO_2 record for bubbles trapped in Antarctic ice. As can be seen, a jump to higher values occurs at close to 16.1 ka. Also, the slope of this rise after 16.1 ka is smaller than that before 16.1 ka.

Fig. 13. A record for Greenland dust rain based on calcium concentrations in the ice (Mayewski et al., 1994). Note that no significant change occurs at 16.1 ka.

underwent a small increase (see Fig. 12). Hence the slope of the ^{13}C record differs markedly from those for CO_2 and for the ^{14}C to C ratio in atmospheric CO_2. Both of the latter undergo unidirectional changes during the course of the Mystery Interval.

Schmitt et al. (2012) call on the release of ^{13}C-deficient CO_2 from the ocean to explain the 0.3‰ drop. But, as a pronounced change in slope occurs at 16 ka, it is difficult to come up with an oceanic explanation consistent with the CO_2 and ^{14}C records (see Fig. 12). As shown by Broecker and McGee (submitted for publication), the dramatic slope change at about 16 ka corresponds to the end of a precipitous drop in the rain of dust onto the Antarctic ice cap (Röthlisberger et al., 2008) and also into the ocean off the southern coast of Australia (De Deckker et al., 2012). They suggest that the 0.3‰ drop in ^{13}C was the result of demise of iron fertilization in the Southern Ocean.

As reproduced in Fig. 13, the dust record in Greenland ice shows no change at the midpoint of the Mystery Interval. If McGee et al. (2010) are correct that dustiness is driven by gustiness and gustiness by the latitudinal temperature gradient, then, the very high calcium rain onto the Greenland ice cap through the entire course of the Mystery Interval requires the continued presence of extensive sea ice in the northern Atlantic. However, as already mentioned, the dust rain in Antarctica and the Southern Ocean comes to an end close to 16 ka ago (see Fig. 14). Further, unlike
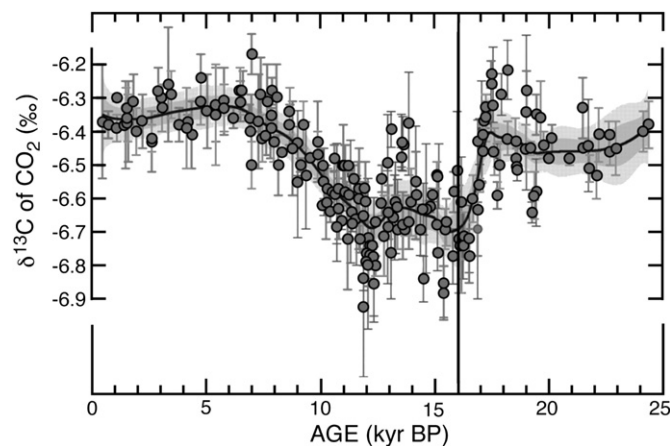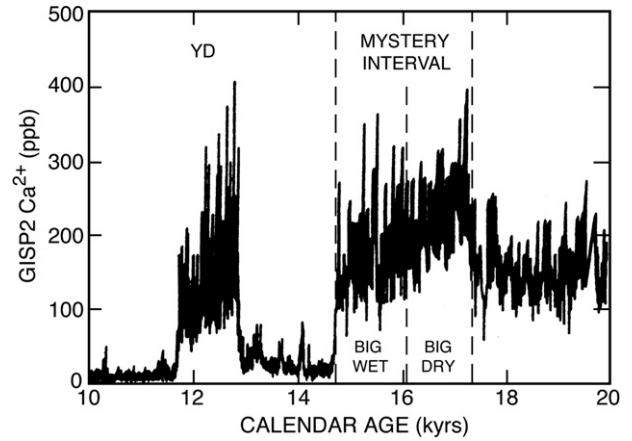
Greenland, there was no rejuvenation of the dust rain during the Younger Dryas.

6. Ocean circulation record

Based on the down-core measurements of the ratio of ^{231}Pa to ^{230}Th in sediments northeast of Bermuda, McManus et al. (2004) make a case that during the entire Mystery Interval, the export of North Atlantic Deep Water largely shut down. They found no difference between the two parts of the Mystery Interval. So, this record can be added to that for the ^{14}C decline and for Greenland dust deposition as showing no break at 16.1 ka.
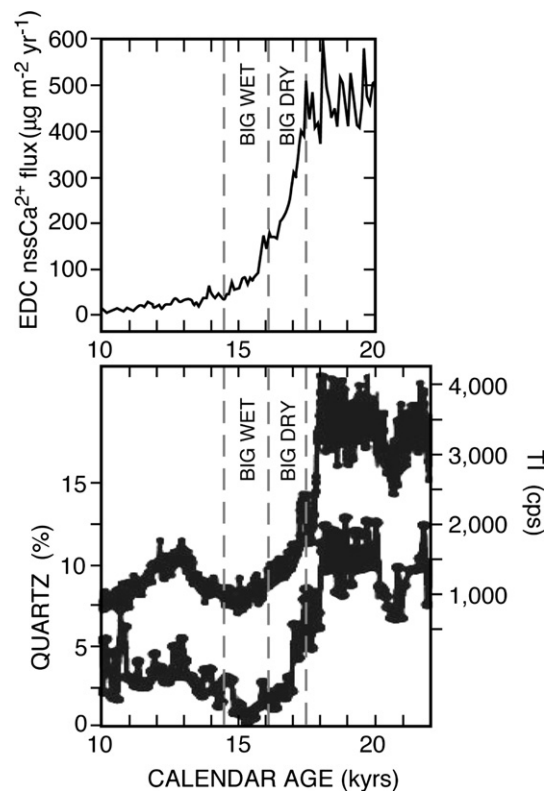

Fig. 14. Records of calcium rain onto the Antarctic ice cap (Röthlisberger et al., 2008) and of quartz and titanium onto the ocean just south of Australia (De Deckker et al., 2012). Both show sharp declines during the first half of the Mystery Interval.

Fig. 12. The record for the δ^{13}C in atmospheric CO_2 trapped in polar ice for the last 25 ka (Schmitt et al., 2012).

7. Summary

As summarized in Fig. 15, the most reliably dated of these records are those for ^{18}O in Chinese stalagmites and for CO_2 and ^{18}O in Antarctic ice. They yield an age of close to 16.1 ka for the mid Mystery Interval shift (see Figs. 8, 10 and 11). However, two of the other three records yield older ages (i.e., 16.9 ka for Estancia and 16.5 ka for Lahontan). So the question arises as to whether these differences are real or whether they are the artifacts of errors in the ^{14}C ages. Although for Lahontan, it is possible that the near zero reservoir age has been underestimated, it is extremely unlikely that Estancia had a reservoir age of 0.8 ka. But it is possible that the samples included reworked ostracods. In the case of the Altiplano, the ^{230}Th-based transition age could be as low as 16.1 if the outlying ^{230}Th age of 16.6 ka is rejected. Three radiocarbon measurements on this same sample average 13.2 ^{14}C ka (15.9 calendar ka). A 0.2 ka-reservoir correction would bring the age of this transition in line with those for the ^{18}O records in stalagmite, calcite and ice. Of course, the age differences may be real, in which case things are more complicated. In the following discussion, we opt for a single age of 16.1 ka for all the records.

8. What triggered the Big Dry to Big Wet change?

It is generally agreed that the onset of the Mystery Interval was triggered by the H-1 armada of icebergs which, upon melting, capped the Northern Atlantic with a low salinity lid leading to a shutdown deep water formation. During the time interval when

Fig. 15. Comparisons of nine Mystery Interval records. As can be seen, while there is good agreement regarding the timing of the end date, those for the Big Dry–Big Wet transition range over 0.9 ka. Of these, that of 16.1 ka for the weakening of the Chinese monsoons and change in slope of the ice ^{18}O and CO_2 records have by far the smallest uncertainty. Most anomalous is the 16.9-ka age for the dry to wet change in Estancia.

deep water production was suspended, a large expansion of sea ice cover in the northern Atlantic is thought to have occurred. The shutdown also appears to have had repercussions at the other end of the Atlantic which led to a reduction in sea ice extent around Antarctica (Anderson et al., 2009). As a result, the thermal equator underwent a southward shift carrying with it the tropical rain belt. Further, the steepening of the pole to equator temperature gradient in the Northern Hemisphere created by the expanded sea-ice increased gustiness and hence dustiness (McGee et al., 2010). The high dust rain persisted during the entire Mystery Interval.

The most reliable age for the H-1 armada is that of 14.5 ^{14}C ka obtained by Bard et al. (2000) for ice-rafted debris in a core from off the Iberian Peninsula. Based on the Southon et al. (2011) calibration, this translates to 17.6 calendar ka. This is broadly consistent with the radiocarbon-based age of H-1 in the Atlantic's IRD belt. But for a number of reasons, this age has a large uncertainty (Hemming, 2004). The end of the Mystery Interval has been dated in many places by both ^{14}C and ^{230}Th. The result is about 14.6 calendar years. These times bound prominent features of the marine record including: changes in the ratio of ^{231}Pa to ^{230}Th in abyssal Atlantic sediments (McManus et al., 2004), a sharp drop in the ^{14}C to C ratio in benthic foraminifera in an intermediate-depth sediment off Baja California (Marchitto et al., 2007), and an increase in rate of opal deposition in the Southern Ocean (Anderson et al., 2009). As already mentioned, these dates also bound the first phase of the rise in the atmosphere's CO_2 content (see Fig. 11) and the decline of the ^{14}C to C ratio in upper ocean $\sum CO_2$ and atmospheric CO_2 (see Fig. 3).

There is, however, evidence for second ice-rafting event. It comes from Bard et al.'s (2000) off-Iberia sediment core. It has a ^{14}C date of 13.7 ka (i.e., 16.5 calendar ka), which places it close to the right time. The problem with the two-Heinrich event explanation is that, as mentioned above, the consequence of ice armadas is thought to bring about a freeze-over of the northern Atlantic pushing the thermal equator and its associated rain belts to the south. This appears to be the explanation for the increased wetness on the Altiplano and the weakening of the Northern Hemisphere monsoons. To make sense, it would have to be the second of Bard's ice armadas that shut down the deep water formation and allowed sea ice to form in the northern Atlantic. But, to initiate the reduction of the sea ice around Antarctica, the onsets of the ^{14}C decline, Anderson's opal maximum and the release of CO_2 from the ocean and in the increased calcium rain onto Greenland, requires that the primary event was the onset of the Mystery Interval. If so, what happened at the midpoint of this interval?

We consider three possible scenarios to explain these observations. First, one possibility is that, as registered by Asian monsoons, southward migration of Earth's thermal equator, caused by sea-ice expansion in the North Atlantic, occurred steadily throughout the first part of the Mystery Interval and achieved its maximum southward displacement at ~16.1 yrs ago. This is consistent with marine records from the Southern Hemisphere (Anderson et al., 2009; De Deckker et al., 2012), and the rise of palaeolake Tauca, which began at ~17.5 yrs ago and achieved its maximum level by ~16.0 yrs ago (Blard et al., 2011). If correct, this would imply that, taken alone, IRD concentrations in North Atlantic sediments might not be directly indicative of overall sea-surface conditions, and hence the behavior of Earth's thermal equator. Improved chronologies documenting whether the signature of lake-level rise during the first half of the Mystery Interval in the Great Basin was abrupt or gradual could help to elucidate the cause of the transition at 16.0 yrs ago.

A second, complementary possibility is that lake levels in the American southwest were driven by a combination of global temperature gradients and local modification due to the orographic influence of Laurentide Ice Sheet on the subtropical jet (Benson et al., 1990). In this case, local influences of the Laurentide Ice
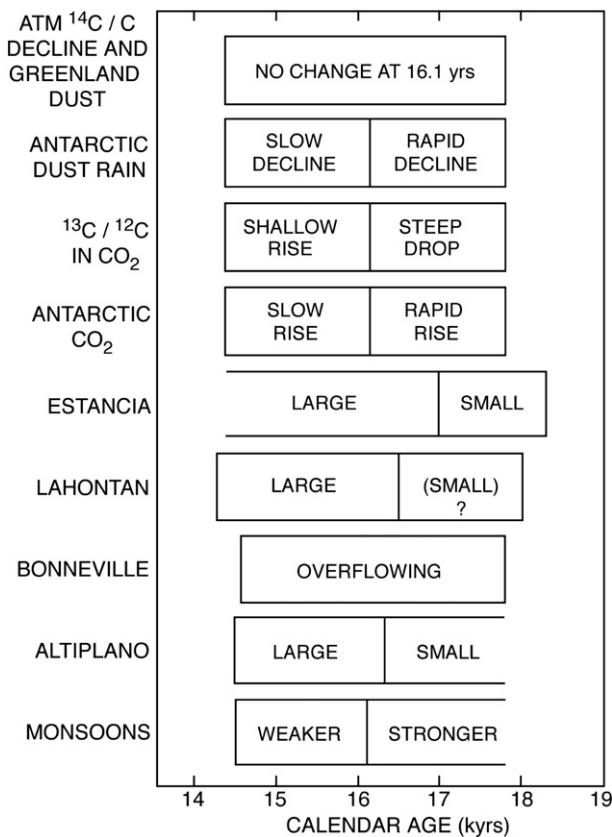
Sheet on the jet stream must have been transmitted globally in order to explain climate switches occurring at ~16,000 yrs ago elsewhere across the planet.

Finally, a third possibility is that something happened in the Southern Ocean which further reduced its sea ice cover. Such a change would not significantly impact the pole to equator temperature gradient in the Northern Hemisphere (and hence the magnitude of the dust rain in Greenland), but it would give the thermal equator an additional push to the south and also change the location of the westerly wind belts. This idea is supported by the results on the core from Australia (De Deckker et al., 2012). Not only does it record an abrupt drop in dust rain between 17.5 and 16.0 ka but also a concurrent large warming of the surface ocean. In any case, something very important must have occurred in the Southern Ocean.

9. Conclusions

Estancia's Big Dry—Big Wet alternation appears to be part of a global hydrologic reorganization. It shows up in the ice core records for CO_2, for the ^{13}C to ^{12}C ratio in the CO_2 and for the ^{18}O to ^{16}O ratio in both ice and trapped O_2. It is prominent in the ^{18}O record in Chinese stalagmites. In these records, the time for the transition is firmly fixed at 16.1 ka. Except for Estancia, there is no direct confirmation of the existence of a Big Dry in other Great Basin closed lakes. However, during the Big Wet, lakes in the Great Basin achieved their largest Late Quaternary size. The exception is Lake Bonneville, but its record is complicated by its overflow and the major down cutting of its outlet.

The absence of any change in rate of dust fall in Greenland and in ^{231}Pa to ^{230}Th in the North Atlantic suggests that the extent of sea ice cover in the northern Atlantic underwent no significant change at 16.1 ka. Further, the absence of any change in the rate of Mystery Interval ^{14}C to C drop at 16.1 ka is hard to explain if a change in ocean circulation is to be invoked. But the changes in lake size and in monsoon strength at 16.1 ka appear to require a major southward shift of the thermal equator. Such a shift is thought to result from an expansion of sea ice cover in the northern Atlantic and hence an ice armada or melt-water flood. However, another possibility is that at 16.1 ka some change occurred in the Southern Ocean which led to a reduction in sea ice causing a second push to the south of the thermal equator.

Although the answer is not yet clear, any explanation for the operation of Earth's climate during the Last Glacial termination must account for the observed global hydrological switch that occurred midway through the Mystery Interval. A step toward understanding what the 16.1 ka transition is trying to tell us requires precise chronologies. More accurate and precise chronologies of hydrological change in all of Earth's drylands are essential for tracking the response of Earth's thermal equator to conditions in the polar oceans. It is also important to nail down the precise age of the Heinrich #1 ice armada. As foraminifera in the debris layers are extremely rare, the dates come from sediment just below and just above the layer itself. Even with these in hand, questions regarding the appropriate reservoir correction remain. Does the 16.1 ka event correspond to the second debris layer in Shackleton's Iberian core? Or does this point to a more complicated relationship between Heinrich IRD layers, sea-surface conditions, and the position of Earth's thermal equator?

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