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Diachronous benthic δ^{18}O responses during late Pleistocene terminations

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[1] Benthic δ^{18}O is often used as a stratigraphic tool to place marine records on a common age model and as a proxy for the timing of ice volume/sea level change. However, Skinner and Shackleton (2005) found that the timing of benthic δ^{18}O change at the last termination differed by 3900 years between one Atlantic site and one Pacific site. These results suggest that benthic δ^{18}O change may not always accurately record the timing of deglaciation. We compare benthic δ^{18}O records from 20 Atlantic sites and 14 Pacific sites to evaluate systematic differences in the timing of terminations in benthic δ^{18}O. Analysis of sedimentation rates derived from the alignment of benthic δ^{18}O suggests a statistically significant Atlantic lead over Pacific benthic δ^{18}O change during the last six terminations. We estimate an average Pacific benthic δ^{18}O lag of 1600 years for Terminations 1–5, slightly larger than the delay expected from ocean mixing rates given that most glacial meltwater probably enters the North Atlantic. We additionally find evidence of ~4000-year Pacific δ^{18}O lags at approximately 128 ka and 330 ka, suggesting that stratigraphic correlation of δ^{18}O has the potential to generate age model errors of several thousand years during terminations. A simple model demonstrates that these lags can be generated by diachronous temperature changes and do not require slower circulation rates. Most importantly, diachronous benthic δ^{18}O responses must be taken into account when comparing Atlantic and Pacific benthic δ^{18}O records or when using benthic δ^{18}O records as a proxy for the timing of ice volume change.

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1. Introduction

[2] Historically, δ^{18}O change is assumed globally synchronous to within the mixing time of the ocean (~1000 years) because the δ^{18}O composition of foraminiferal tests is primarily controlled by the storage of ^{18}O-depleted water in ice sheets [*Shackleton*, 1967]. The validity of this assumption is supported by the observation that radiocarbon ages of the Last Glacial Maxima (LGM) as identified in δ^{18}O agree to within 1000 years [*Duplessy et al.*, 1991]. If δ^{18}O change is not synchronous, paleoclimate age models based on the alignment of δ^{18}O stratigraphy would have significant errors. An ocean GCM simulation of modern circulation suggests that signals from passive tracers may take 4000 years or more to reach the deep North Pacific [*Wunsch and Heimbach*, 2008]. Diachronous changes in deep water temperature also have the potential to produce significant lags in benthic δ^{18}O. This effect could be especially important at some Atlantic sites where temperature and salinity change accounts for more than half of the glacial-interglacial change in benthic δ^{18}O [*Schrag et al.*, 1996; *Adkins et al.*, 2002].

[3] Evidence for diachronous responses in benthic δ^{18}O comes from high-resolution records of the last termination from the Iberian Margin (3146 m) and the eastern equatorial Pacific (3210 m). Radiocarbon-derived age models for these cores suggest that benthic δ^{18}O at the Pacific site lagged the Atlantic site by 3.9 kyr [*Skinner and Shackleton*, 2005]. On the basis of Mg/Ca paleothermometry, *Skinner and Shackleton* [2005] argue that these age discrepancies result from a late temperature increase in the Pacific and millennial-scale hydrographic changes in the Atlantic. Such a large discrepancy in the timing of δ^{18}O change could produce significant age model errors during the alignment of δ^{18}O stratigraphy or when benthic δ^{18}O is used as proxy for ice volume. Benthic δ^{18}O records from different depths in the same ocean basin may also experience diachronous responses. A comparison of radiocarbon-dated δ^{18}O records in the Atlantic, Indian, and Pacific Oceans suggests that some deglacial δ^{18}O changes are rapidly transmitted at intermediate depths and then take an additional ~1500 years to reach Atlantic and Pacific deep water [*Labeyrie et al.*, 2005; *Waelbroeck et al.*, 2006].

[4] The assumption of globally synchronous δ^{18}O change is the foundation for many paleoclimate studies. For example, benthic δ^{18}O is used to identify the timing of the LGM for mapping climate responses such as sea surface temperature [e.g., *Climate: Long-Range Investigation, Mapping, and Prediction Project Members*, 1981] and deep water mass boundaries [e.g., *Raymo et al.*, 1990; *Curry and Oppo*, 2005; *Marchitto and Broecker*, 2006]. Globally synchronous δ^{18}O response is also assumed in the creation of δ^{18}O

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Table 1. Summary of Uncertainty Analyses and the Alignment Methods to Which They Were Applied

Uncertainty Analysis	Alignment Method
Test significance of P:A SRR anomaly relative to 13-kyr running mean and for window sizes of 5–31 kyr	Automated
Assess sensitivity to identification of P:A SRR anomaly boundaries	Automated
Alignment of simulated δ^{18}O records; comparison of real and simulated P:A SRR anomalies	Automated
Calculate termination durations while excluding different regions	Automated and manual
Calculate termination durations for all subsets of 29 sites	Automated and manual
Monte Carlo simulation of error in termination start and end identification	Manual
Assess sensitivity to different outer window sizes (50–70 kyr)	Manual
Test for correlation between termination duration and sedimentation rate or water depth in Pacific	Manual

stacks, which average δ^{18}O records from different locations to improve the signal-to-noise ratio of global ice volume and temperature changes [e.g., *Imbrie et al.*, 1984; *Lisiecki and Raymo*, 2005]. A third important application is determining the relative timing of climate responses at different sites by calculating their phases relative to δ^{18}O [e.g., *Imbrie et al.*, 1992; *Lisiecki et al.*, 2008], with implications for how different parts of the climate system interact with one another. Even studies analyzing the relative timing of proxies recorded at a single site often assume that benthic δ^{18}O accurately records the timing of ice volume change [e.g., *Visser et al.*, 2003; *Cortese et al.*, 2007]. Therefore, diachronous δ^{18}O change has important implications for a wide range of paleoceanographic studies.

[5] In this study we investigate how widespread diachronous δ^{18}O responses may be during Late Pleistocene terminations. Differences in the timing of δ^{18}O change are estimated by comparing the sedimentation rates produced by the alignment of 20 Atlantic and 14 Pacific benthic δ^{18}O records, as described in section 2. Section 3 presents our results, tests of their statistical significance, and separate stacks of Atlantic and Pacific benthic δ^{18}O. In section 4 we review our assumptions, present the results of several sensitivity tests, demonstrate one possible cause of benthic δ^{18}O lags using simple mixing simulations, and discuss the practical applications of our results. Table 1 summarizes all of the uncertainty analysis we performed. Section 5 summarizes our conclusions.

2. Methods

[6] The age and duration of benthic δ^{18}O change during terminations has only been directly measured for the most recent termination [e.g., *Duplessy et al.*, 1991; *Skinner and Shackleton*, 2005; *Labeyrie et al.*, 2005; *Waelbroeck et al.*, 2006]. In this study, we estimate termination durations indirectly by comparing the sedimentation rates implied by the alignment of benthic δ^{18}O records. Previous studies have estimated the age of terminations (and other δ^{18}O stratigraphic features) by assuming a constant sedimentation rate at each site and then averaging age estimates across many sites [*Raymo*, 1997; *Huybers and Wunsch*, 2004]. Here, we alter this technique slightly by using sedimentation rates to estimate the duration of terminations rather than their absolute ages and by comparing the results between the Atlantic and Pacific rather than averaging the two together.

[7] The assumption of constant sedimentation rate implies that if benthic δ^{18}O change during a termination occurs over a longer period of time in the Pacific than the Atlantic, the stratigraphic length of sediment containing the termination will be a larger percentage of the glacial cycle length in the Pacific. Equivalently, if we estimate sedimentation rates during terminations using the alignment of δ^{18}O records, longer Pacific terminations would produce estimates of higher sedimentation rates in the Pacific than the Atlantic during terminations. This technique also has the potential to detect delays in the onset of Pacific terminations because such a delay would increase estimated Pacific sedimentation rates immediately before terminations.

[8] One complicating factor is that sedimentation rates at most sites are not constant throughout the glacial cycle. However, if we assume that sedimentation rate changes during terminations are not strongly correlated globally, then the average across many sites from different oceanographic settings will produce a good estimate of the mean difference in termination duration between ocean basins. The potential effects of regionally correlated sedimentation rate changes are evaluated in section 4.1.

[9] We compare 20 Atlantic and 14 Pacific benthic δ^{18}O records (Figure 1) using two different alignment techniques, one automated and one manual. The steps for both techniques are detailed below. Most of the δ^{18}O records used (see Figure 1 caption) were included in the LR04 benthic δ^{18}O stack [*Lisiecki and Raymo*, 2005]; sites not included in the original stack are ODP 926 and 928 [*Lisiecki et al.*, 2008] and PC18 [*Murray et al.*, 2000]. Sites were selected on the basis of the availability of benthic δ^{18}O data extending to at least 500 ka with an average sample spacing of $\leq$4 kyr. Note also that benthic δ^{18}O records are not evenly distributed spatially. Half of all Pacific sites are from the Eastern Equatorial Pacific (EEP) because it is one of the few places in the deep Pacific where calcium carbonate is well preserved. Additionally, not enough cores are available from depths of $\leq$2500 m to test for different δ^{18}O lags between intermediate and deep waters [*Labeyrie et al.*, 2005; *Waelbroeck et al.*, 2006]. Possible bias due to sites' spatial distribution is discussed in section 4.1.

2.1. Automated Alignment

[10] Briefly, the steps of the automated alignment technique are (1) automatically align each benthic δ^{18}O record to the LR04 stack, (2) evaluate alignments and revise if necessary, (3) stack Atlantic and Pacific sedimentation rates, (4) calculate the Pacific to Atlantic sedimentation rate ratio (P:A SRR), (5) integrate over the P:A SRR anomaly to estimate termination duration difference, and (6) create stacks of Atlantic and Pacific δ^{18}O and adjust their age models using estimates of termination duration differences.

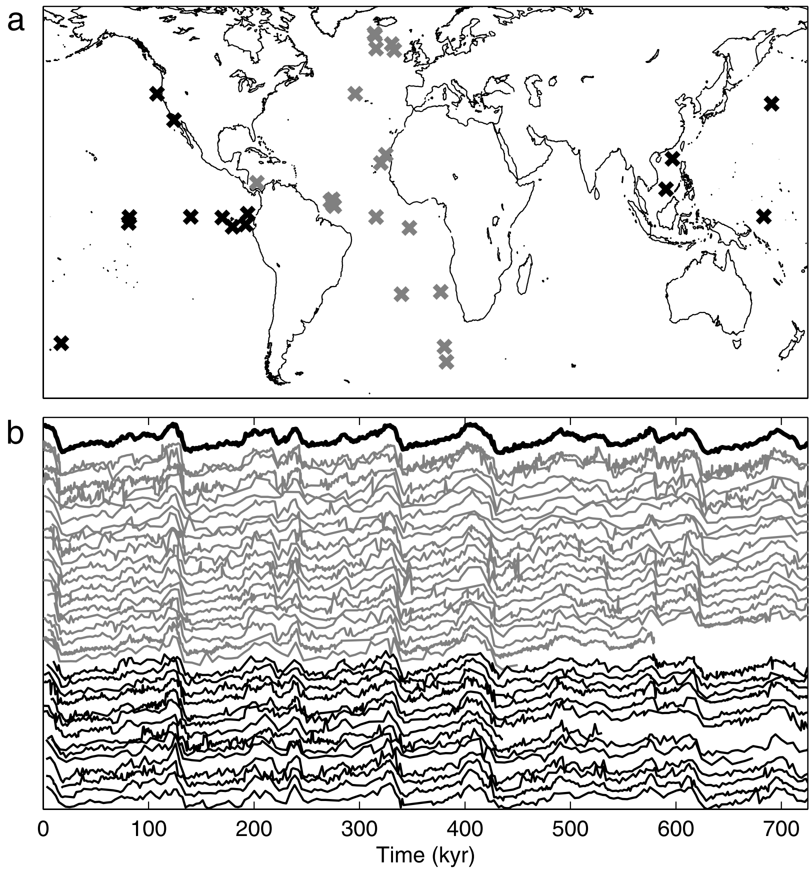

Figure 1. Benthic δ^{18}O records. (a) Map of sites. (b) Benthic δ^{18}O records from the Atlantic (gray) and Pacific (black) after automated alignment to the LR04 stack (thick black [*Lisiecki and Raymo*, 2005]). Atlantic records are from ODP sites 980, 982, 983, 984, 552, 607, 664, 502, 658, 659, 925, 926 [*Lisiecki et al.*, 2008], 927, 928 [*Lisiecki et al.*, 2008], 929, 1090, and 1089 and sites RC13-229, GeoB1041, and GeoB1214. Pacific records are from ODP sites 677, 846, 849, 1012, 1020, 806, 1123, 1143, and 1146 and sites V19-28, V21-146, PC72, and PC18 [*Murray et al.*, 2000]. Except where noted original references can be found in the work by *Lisiecki and Raymo* [2005].

[11] Sedimentation rates are estimated by aligning each benthic δ^{18}O record (Figure 1) to the LR04 benthic δ^{18}O stack [*Lisiecki and Raymo*, 2005] using an automated graphic correlation algorithm [*Lisiecki and Lisiecki*, 2002]. The algorithm uses two parameterized penalty functions to constrain sedimentation rates. The first, a sedimentation rate penalty, applies a penalty proportional to each deviation from the site's average sedimentation rate. The second, a rate change penalty, applies a penalty each time the site's sedimentation rate changes. (Rapid changes in sedimentation rate, such as those associated with Heinrich events [*Schmittner*, 2005], could interfere with the alignment of millennial-scale δ^{18}O responses. However, these events are not well resolved in many of our records because of temporal resolutions of 2–4 kyr.)

[12] For the initial alignment of each δ^{18}O record, we use a relatively large weighting of 0.25 for each penalty function to generate conservative estimates of sedimentation rate changes across terminations. If the initial alignment produces a poor fit to the stack, the algorithm is run with different penalty weightings or the addition of manually defined tie points until a satisfactory alignment is achieved. Penalty weightings were decreased for 13 of the 34 alignments, and one alignment required the addition of tie points. Figure 2 shows the sedimentation rate estimates for each site as well as the geometric mean for Atlantic and Pacific sites. The geometric mean is used to ensure that changes in the mean sedimentation rate are not dominated by a few high–sedimentation rate sites.

[13] These sedimentation rate estimates are based on the LR04 age model, which has an uncertainty of several thousand years [*Lisiecki and Raymo*, 2005]. Therefore, we focus our interpretation on the ratio of Pacific to Atlantic mean sedimentation rates (Figure 2c), which is not dependent on the age model used. The Pacific to Atlantic sedimentation rate ratio is potentially affected both by the alignment of diachronous δ^{18}O responses and by basin-wide changes in sedimentation rates. Most localized changes in sedimentation rate are averaged out by analyzing many globally distributed sites (section 4.1), but glacial cyclicity

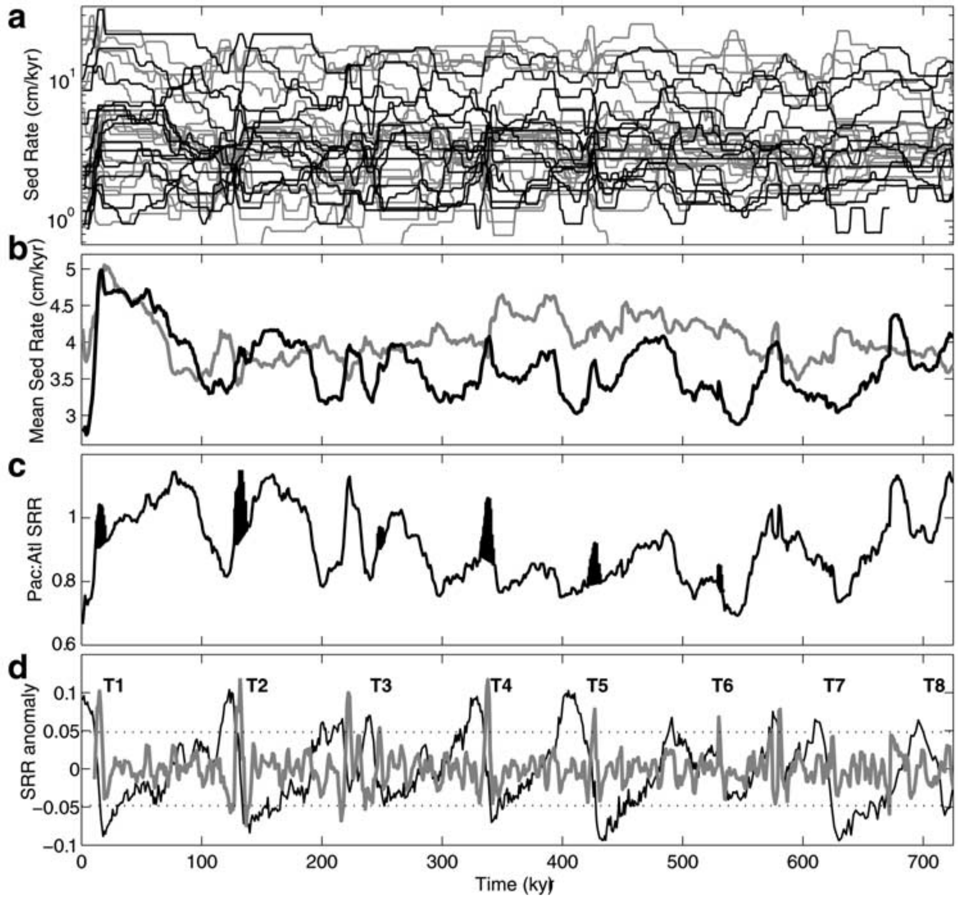

Figure 2. Sedimentation rates and ratios based on automated alignments. (a) Sedimentation rates for Atlantic (gray) and Pacific (black) sites. (b) Average Atlantic (gray) and Pacific (black) sedimentation rates (geometric mean). (c) Pacific to Atlantic sedimentation rate ratio. Filled areas denote the area of integration for estimating differences in the mean duration of terminations. (d) Short-term P:A SRR anomaly (gray) defined as the P:A SRR (from Figure 2c) minus its 13-kyr running mean. Horizontal dotted lines mark two standard deviations from the mean. Comparison with the LR04 benthic stack (black [*Lisiecki and Raymo*, 2005]) shows that statistically significant P:A SRR anomalies are uniquely associated with terminations and other times of rapid δ^{18}O change.

remains in the P:A SRR because of basin-wide oceanographic changes. In addition to 100-kyr cyclicity, the P:A SRR clearly shows abrupt, short-term changes at some terminations (T1, T2, T4, and T5), potentially suggestive of diachronous δ^{18}O changes in the Atlantic and Pacific. The magnitude and statistical significance of these differences are presented in sections 3 and 4.

2.2. Manual Alignment

[14] Because the automated alignment technique is conservative in its estimates of sedimentation rate change, we additionally estimate differences in mean termination duration between the Atlantic and Pacific by manually identifying the start and end of each termination in the 34 benthic δ^{18}O records. Although this technique is more subjective than the automated technique, it provides an informative, alternate method of measuring the differences between Atlantic and Pacific benthic δ^{18}O records. For example, sensitivity tests (section 4.2) suggest that the automated alignment technique cannot distinguish between delays in the onset of terminations and differences in the duration of δ^{18}O change. However, the manual alignment technique only detects differences in termination durations and does not include effects from potential delays in termination onsets.

[15] Briefly, the steps of the manual alignment technique are (1) manually identify the depths at which terminations start and end in each record, (2) identify the boundaries of 60-kyr outer windows using the automated alignments, (3) exclude sites with low resolution or abnormal termination durations, (4) estimate termination durations by assuming a constant sedimentation rate within each outer window, and (5) calculate the average termination duration difference between Atlantic and Pacific sites.

[16] We measure the stratigraphic length of each termination by identifying the start and end depths of rapid δ^{18}O

change at each site. Then the termination duration is estimated by assuming the site's sedimentation rate is constant over a 60-kyr window centered on each termination. (For Termination 1 we use a window length of 50 kyr because of end of the time series, and for Termination 5 we use 70 kyr because of the greater duration of the termination.) The boundaries of the 60-kyr outer windows are identified using the LR04 age model (i.e., the automated alignment of each site to the LR04 stack). The automated results should be more consistent than manual identification of these outer boundaries because they often lack easily identifiable stratigraphic features and because abrupt changes in sedimentation rate are less likely to occur at these outer boundaries where climate change is more gradual. Termination duration estimates are not highly sensitive to uncertainties in the identification of the outer window boundaries because they have a relatively small effect (<10%) on estimates of the 60-kyr mean sedimentation rate. Tests performed with 50-kyr or 70-kyr outer windows or with window centers shifted by 5 kyr produced similar results.

[17] Sites with low temporal resolution will result in a greater uncertainty in the estimated termination duration. Therefore, we exclude from our calculations sites for which the outer window contains fewer than 15 δ^{18}O measurements. Additionally, we exclude sites for which the termination represents <10% or >50% of the outer window because these abnormal durations may be indicative of stratigraphic disturbance or errors in identification of the outer window boundaries. After these exclusions, the duration difference for each termination is based on 13–18 Atlantic records and 10–13 Pacific records.

3. Results

3.1. Automated Alignment

[18] To test the statistical significance of short-term changes in the P:A SRR at terminations, we calculate the difference between the P:A SRR and its 13-kyr running mean (Figure 2d). Over the last 725 kyr, we find that differences greater than two standard deviations from the running mean ($2\sigma = 0.05$) are uniquely associated with the rapid δ^{18}O changes of Terminations 1–6 and pseudoterminations at 220 and 580 ka. We do not detect statistically significant changes in the P:A SRR during Terminations 7 and 8. It is unclear whether Terminations 7 and 8 were different than more recent terminations or whether we are simply unable to detect diachronous responses during these terminations, perhaps because of fewer benthic δ^{18}O records (Figure 1b).

[19] Using a smaller window size for the running mean would place more emphasis on the abruptness of sedimentation rate change in our statistical evaluation, and a larger window size would place more emphasis on the magnitude of the total deviation. Our evaluation of statistical significance is unchanged if P:A SRR deviations are measured relative to 11-kyr or 15-kyr running means. Running means calculated with 5–9 kyr windows result in a significant P:A SRR deviation for Termination 7. Running means from 17–23 kyr windows result in a lack of significance for the P:A SRR deviation at Termination 3, and window sizes of 25–31 kyr additionally eliminate the significance of the deviation at Termination 6. For all window sizes of 9–31 kyr, statistically significant deviations in P:A SRR are predominantly associated with terminations; the number of statistically significant deviations that are not associated with terminations is three or fewer.

[20] We estimate the magnitude of the sedimentation rate anomaly associated with each termination by comparing the observed P:A SRR with a linearly interpolated P:A SRR based on its values immediately before and after the termination (Figure 2c). This comparison allows us to calculate the additional stratigraphic length associated with terminations in the Pacific relative to the expected length if δ^{18}O change were synchronous between ocean basins. The linearly interpolated P:A SRR is then used to convert from length to time. For example, consider an observed P:A SRR from 14–15 ka of 1.2, with an interpolated value of 0.8, and a mean Atlantic sedimentation rate of 4 cm/kyr. The actual mean stratigraphic length in the Pacific from 14–15 ka would be 4.8 cm compared to an expected length of 3.2 cm. According to the interpolated Pacific sedimentation rate, this additional 1.6 cm of sediment corresponds to an excess duration of 0.5 kyr in the Pacific for the δ^{18}O change that occurs from 14–15 ka in the Atlantic. We can then add together the excess durations calculated in 1-kyr increments over the entire length of the anomaly to find the total duration difference between the two ocean basins. This yields estimates that terminations are 0.7, 1.3, 0.2, 1.2, 0.8, and 0.2 kyr longer in the Pacific than the Atlantic for Terminations 1–6, respectively (Table 2).

[21] The P:A SRR termination anomalies are identified on the basis of deviation from the gradual ~100-kyr variability in the P:A SRR (Figure 2c). Because this is a somewhat subjective criterion, we attempt to be conservative in our identification of anomaly boundaries. Adjusting the anomaly boundaries by ±1 kyr changes the estimated duration differences by <50%. The manual alignment technique provides another estimate of termination duration differences based on different evaluation criteria.

3.2. Manual Alignment

[22] As described in section 2.2, the manual alignment technique estimates the termination duration at each site by assuming a constant sedimentation rate at that site over a 60-kyr interval centered on the termination. These estimates suggest that the mean duration of δ^{18}O change was 1.9, 1.6, −2.1, 1.9, and 1.0 kyr longer in the Pacific than the Atlantic for Terminations 1–5 (shorter in the case of Termination 3).

[23] The uncertainty associated with these estimates is evaluated using Monte Carlo simulations. We assume that the manual identification of the start and end depth of terminations is unlikely to be off by more than one data point. Therefore, we define a Gaussian probability distribution such that each start (end) depth has a 95% probability of falling between the data points on either side of the δ^{18}O measurement identified as the start (end) of the termination. We also define a Gaussian distribution for the start and end of each 60-kyr outer window with a standard deviation of 1 kyr to account for uncertainty in the automated alignment.

Table 2. Pacific Minus Atlantic Termination Durations With 2-σ Error Bars From Monte Carlo Simulation and All Subsets of 29 Sites[a]

	T1	T2	T3	T4	T5
Automated alignment					
All sites	0.7	1.3	0.2	1.2	0.8
29-site subsets	0.7 ± 0.2	1.3 ± 0.5	0.2 ± 0.1	1.2 ± 0.4	0.8 ± 0.3
Excluding North Atlantic	0.4	1.0	0.2	1.3	0.9
Excluding deep Atlantic	0.8	1.5	0.2	1.1	0.8
Excluding shallow Pacific	0.6	0.7	0.3	1.2	0.9
Excluding deep Pacific	0.6	1.2	0.2	1.1	0.7
Excluding EEP	0.8	1.1	0.2	1.0	0.3
Manual alignment					
All sites	1.87	1.64	−2.09	1.85	1.03
Monte Carlo	1.7 ± 1.5	1.64 ± 1.61	−1.9 ± 1.6	1.9 ± 1.8	0.5 ± 1.9
29-site subsets	1.9 ± 1.2	1.6 ± 0.9	−2.1 ± 1.1	1.9 ± 1.0	1.0 ± 1.5
Excluding North Atlantic	0.8	1.7	−1.8	1.3	1.7
Excluding deep Atlantic	3.0	2.3	−2.4	2.0	0.4
Excluding shallow Pacific	1.7	1.4	−2.3	2.0	0.2
Excluding deep Pacific	1.9	1.9	−2.0	1.0	1.2
Excluding EEP	1.2	−0.1	−3.0	−0.1	−1.5
Mean Pacific stack lag	1.3	2.0	1.4	2.0	1.5

[a]Termination durations are in kyr. See sections 3.2 and 4.1 for error calculation from Monte Carlo simulation and all subsets of 29 sites, respectively.

Table 2 gives the mean excess Pacific duration for each termination and its 2-σ uncertainty range on the basis of 10,000 iterations.

[24] Both the automated and manual techniques produce statistically significant estimates that Terminations 1, 2, and 4 were longer in the Pacific than the Atlantic. There is good agreement between techniques on the magnitude of the duration difference for Terminations 2, 4, and 5. Both techniques are subject to additional uncertainty during Termination 1 because of possible coring disturbances near the top of each sediment core, particularly in cores with low sedimentation rates. The biggest discrepancy between the two techniques occurs at Termination 3, where the automated estimate of duration difference is +0.2 kyr and the manual estimate is −2.1 kyr. The reason for this discrepancy becomes clear when we compare (below) the Atlantic and Pacific stacks of benthic $\delta^{18}O$ during Termination 3.

3.3. Atlantic and Pacific Stacks

[25] Atlantic and Pacific benthic $\delta^{18}O$ stacks for the last 800 kyr (Figure 3; stacks available for download at www.ncdc.noaa.gov) are created by averaging all $\delta^{18}O$ measurements within ±1 kyr based on automated alignments to the LR04 stack. (Because fewer data points are available from 500 to 800 ka, the Atlantic and Pacific stacks are smoothed using data from ±2 kyr for 500–800 ka.) The age models for the Atlantic and Pacific stacks are based on the LR04 age model with adjustments to include the differences between Atlantic and Pacific termination durations estimated above. Because we analyzed sedimentation rates based on alignments to the LR04 stack, we have specifically calculated how these alignments should be adjusted to remove anomalies in the P:A SRR. After making a few assumptions, we can use these calculations to introduce estimated lags between the Atlantic and Pacific stacks. The tentative age models we develop below are intended to aid in visualizing the implications of our termination duration estimates. They are not meant to be definitive, and an alternate interpretation of our results is discussed at the end of this section.

[26] Regardless of the age models used, the Atlantic and Pacific reveal some consistent differences in the amplitude of $\delta^{18}O$ change between the two ocean basins. The amplitudes of isotopic stages and substages tend to be slightly larger in the Atlantic than the Pacific [*Zahn and Mix*, 1991; *Waelbroeck et al.*, 2002], presumably because of larger temperature and/or salinity changes in the Atlantic [*Schrag et al.*, 1996; *Adkins et al.*, 2002] associated with hydrographic changes. The amplitudes of isotopic features in the LR04 "global" stack [*Lisiecki and Raymo*, 2005] are not exactly the average of the Atlantic and Pacific stacks because it contains more data from the Atlantic than the Pacific and two sites from the Indian Ocean. (For the last glacial cycle, the LR04 stack contains data from 31 Atlantic sites and 15 Pacific sites. At 800 ka, the LR04 stack contains 14 Atlantic sites and 10 Pacific sites.) Additionally, the LR04 stack resolves some suborbital variability better because it allows more variability in sedimentation rate and has less smoothing than the Atlantic and Pacific stacks. (More smoothing is necessary in the Atlantic and Pacific stacks because they contain fewer sites and, therefore, a lower signal-to-noise ratio.)

[27] To develop tentative age models for the Atlantic and Pacific stacks, we first extend the duration of terminations in the Pacific stack by the duration difference estimates in section 3.1 (thus removing anomalies in the P:A SRR). The assumption that our sedimentation rate analysis reflects differences in the duration of terminations rather than delayed onsets is supported by the fact that our manual alignment calculations agree with our automated estimates despite the fact that the manual estimates would not detect the effects of delayed onsets. (The one exception is Termination 3. Below we will demonstrate that this discrepancy is probably due to the delayed onset of $\delta^{18}O$ change in the Pacific during Termination 3.)

[28] Extended Pacific termination durations are achieved by making the ends of Pacific terminations younger. The other alternative would be to make terminations begin earlier in the Pacific. However, Pacific $\delta^{18}O$ should never

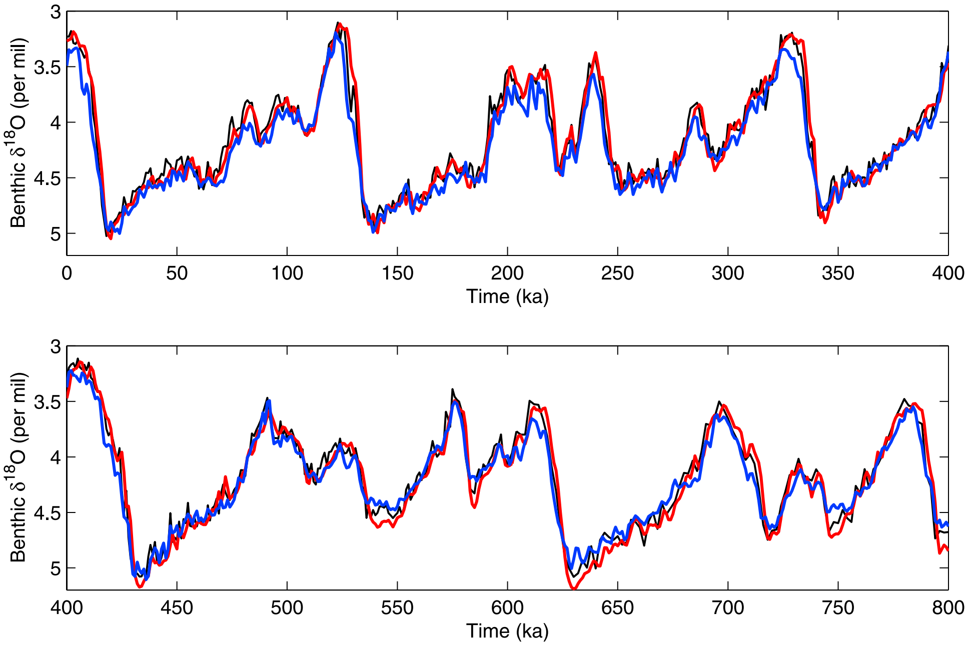

Figure 3. Atlantic (red) and Pacific (blue) benthic δ^{18}O stacks and the "global" LR04 stack (black [*Lisiecki and Raymo*, 2005]). Atlantic and Pacific age models have been adjusted as described in text.

lead Atlantic δ^{18}O because (1) most isotopically light glacial meltwater enters the North Atlantic, (2) the deep Pacific is far from any deep water formation sites, and (3) the deep Pacific (below 2000 m) lacks water mass boundaries whose movement could cause rapid δ^{18}O change [*Matsumoto et al.*, 2002; *Skinner and Shackleton*, 2005].

[29] After delaying the end of Pacific terminations to extend their duration, there are still several occasions during the terminations when Pacific δ^{18}O briefly leads Atlantic δ^{18}O by as much as 1 kyr. This physically implausible Pacific lead could be an artifact of the inability of our alignment and sedimentation rate analysis techniques to detect a constant age offset between Atlantic and Pacific δ^{18}O records. Therefore, we assign a constant offset which makes all Atlantic δ^{18}O records 1 kyr older and prevents Pacific δ^{18}O from ever leading Atlantic δ^{18}O during terminations. Physically, this constant 1-kyr offset could result from the average mixing time for deep water formed in the Atlantic to reach the deep Pacific.

[30] We choose to make the Atlantic record older instead of making the Pacific δ^{18}O younger because Atlantic benthic δ^{18}O leads ice volume during Terminations 1 and 2 [*Skinner and Shackleton*, 2006; *Waelbroeck et al.*, 2008]. Shifting Atlantic δ^{18}O to be older than the LR04 global stack is reasonable because the LR04 stack age model is based on estimated ice sheet response times and does not account for temperature changes that might lead ice volume change. After shifting the Atlantic ages older by 1 kyr, termination onsets are approximately synchronous between the Atlantic and Pacific during Terminations 2 and 4, and termination onsets are delayed by 1–2 kyr in the Pacific during Terminations 1, 3 and 5 (Figure 4). The adjusted age models of the Atlantic and Pacific stacks are <2 kyr different from the original LR04 stack age model (Figure 3).

[31] On the basis of our tentative analysis of the relative timing of δ^{18}O change in the Atlantic and Pacific stacks (Figure 4), we find that the average Pacific δ^{18}O lag is 1.3, 2.0, 1.4, 2.0, and 1.5 kyr for Terminations 1–5, respectively. Collectively, the average Pacific lag for Terminations 1–5 is 1.6 kyr. The largest Pacific lags are approximately 4 kyr at 128 ka (T2) and 330 ka (T3). The manual alignment estimate that Termination 3 is ~2 kyr shorter in the Pacific than the Atlantic appears to result from a small, step-like change in Atlantic δ^{18}O 2 kyr before the onset of rapid δ^{18}O change. This feature is present in nearly all Atlantic δ^{18}O records of Termination 3 but absent in Pacific records. The automated technique aligns the start of Pacific Termination 3 with the later, rapid Atlantic δ^{18}O change rather than the early small change and, therefore, finds that T3 has approximately the same duration in both the Atlantic and Pacific.

[32] We strongly emphasize that the new Atlantic and Pacific age models do not provide any additional information about the absolute ages of change in δ^{18}O or ice volume and, therefore, have the same uncertainty of several kiloyears as the LR04 stack (derived from tuning ice responses to orbital forcing). However, the relative ages between Atlantic and Pacific δ^{18}O are likely to be better estimated here than in the LR04 stack, which assumes that all δ^{18}O change is globally synchronous. More sophisticated stratigraphic analysis [e.g., *Channell et al.*, 2009] and radiometric age estimates [e.g., *Labeyrie et al.*, 2005; *Thompson and Goldstein*, 2006] are needed to improve estimates of absolute ages and constrain potential delays in the onset of Pacific δ^{18}O change.

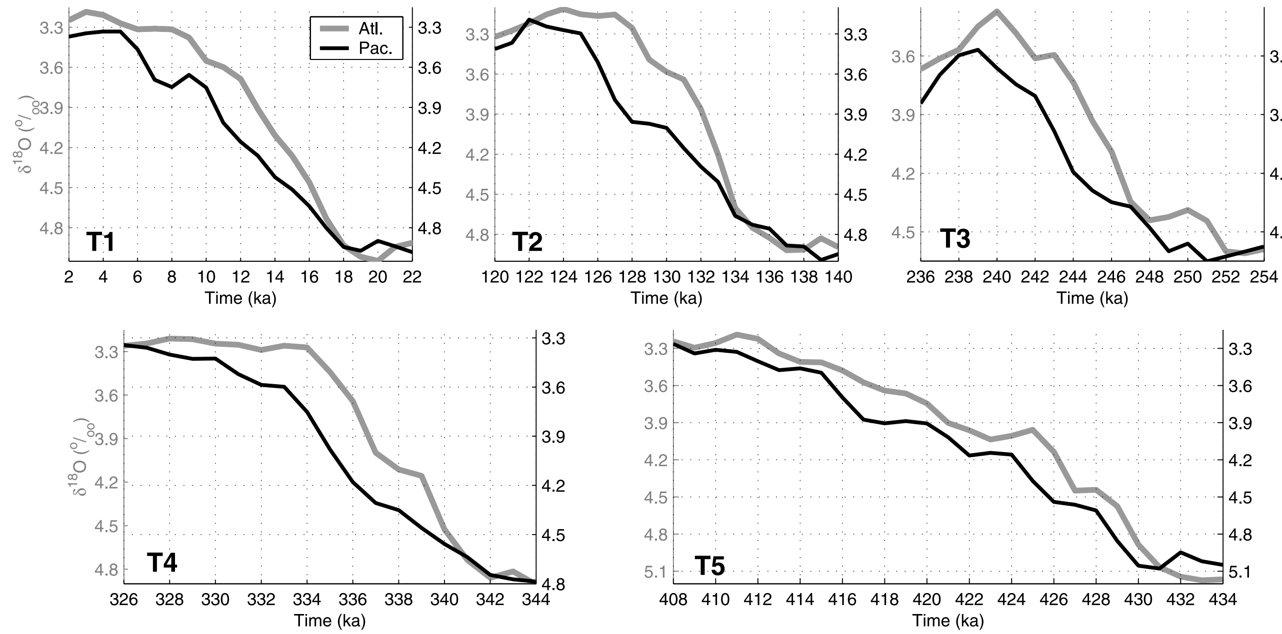

Figure 4. Atlantic (gray) and Pacific (black) benthic δ^{18}O stacks for Terminations 1–5. Pacific termination durations are extended on the basis of the estimates derived from Figure 2c. The Atlantic stack is shifted 1 kyr older than the LR04 age model so that the Pacific stack never leads the Atlantic.

[33] If the results of the automated technique were interpreted as delays in the onset of Pacific terminations rather than differences in termination duration, Pacific lags at the beginning of terminations would be larger. Lags at the ends of terminations would be ~1 kyr smaller because we would not need to shift Atlantic ages 1 kyr older. However, we prefer the interpretation presented in Figures 3 and 4 because a 1-kyr delay between the Atlantic and Pacific should be expected from the average ocean mixing time and because termination duration differences are also observed using the manual alignment technique, which is not affected by delays in the onset of terminations. Age models based on delayed onsets in the Pacific would still have ~3-kyr Pacific lags during Terminations 2 and 4. In order to eliminate these large lags, either our sedimentation rate analysis would have to be flawed or benthic δ^{18}O change would have to begin first in the Pacific and later in the Atlantic (which is physically implausible).

4. Discussion

4.1. Assumptions and Uncertainty

[34] Sources of uncertainty in the alignment of Atlantic and Pacific δ^{18}O include the choice of alignment penalties, the temporal resolution of the δ^{18}O data, measurement uncertainty, local variability, and coring disturbances. The uncertainty associated with the automated alignment technique is ~2 kyr (for synchronous δ^{18}O change), compared to an absolute age uncertainty of ~4 kyr for the LR04 age model because of orbital tuning. Because analysis of the P:A SRR can only detect abrupt changes in the lag between ocean basins, constant or slow variations in the lag between ocean basins also have an uncertainty of ~2 kyr. The timing of benthic δ^{18}O change may also vary within each ocean basin [*Labeyrie et al.*, 2005; *Waelbroeck et al.*, 2006].

[35] Additionally, we assume that sedimentation rate changes during terminations are small or randomly distributed. This assumption clearly fails at some study sites. Widespread, termination-specific changes in sedimentation rates (e.g., due to IRD deposition, abyssal currents, carbonate dissolution, or productivity changes) have the potential to bias our results. For example, IRD could lengthen termination stratigraphy in the North Atlantic and cause us to underestimate Pacific termination durations.

[36] To test the sensitivity of our automated alignment results to regional variability in sedimentation rates, we repeat our calculations while excluding sites from a particular oceanographic setting: the North Atlantic, the deep Atlantic (>4010 m), the deep Pacific (>3400 m), the shallow Pacific (<3000 m), or the Eastern Equatorial Pacific (EEP) (Table 2). Each of the first four settings contain four or five of the 34 sites. Terminations 1, 2, 4 and 5 produced statistically significant deviations in the P:A SRR in all tests which exclude one of these four regions. One particular concern is that half of our Pacific records come from the EEP, which has enhanced productivity and calcium carbonate deposition during terminations [*Lyle et al.*, 2002, 2005; *Siddall et al.*, 2008]. If we exclude all EEP sites (i.e., 677, 846, 849, RC13-110, V19-28, PC18 and PC72), we are left with only seven Pacific sites which may not represent enough sites from which to draw statistically robust conclusions. Nevertheless, when we exclude EEP sites from the automated alignment calculations, we still find statistically significant Pacific lags for Terminations 1, 2, and 4. However, the manual alignment results from these seven non-EEP sites suggest a greater termination duration

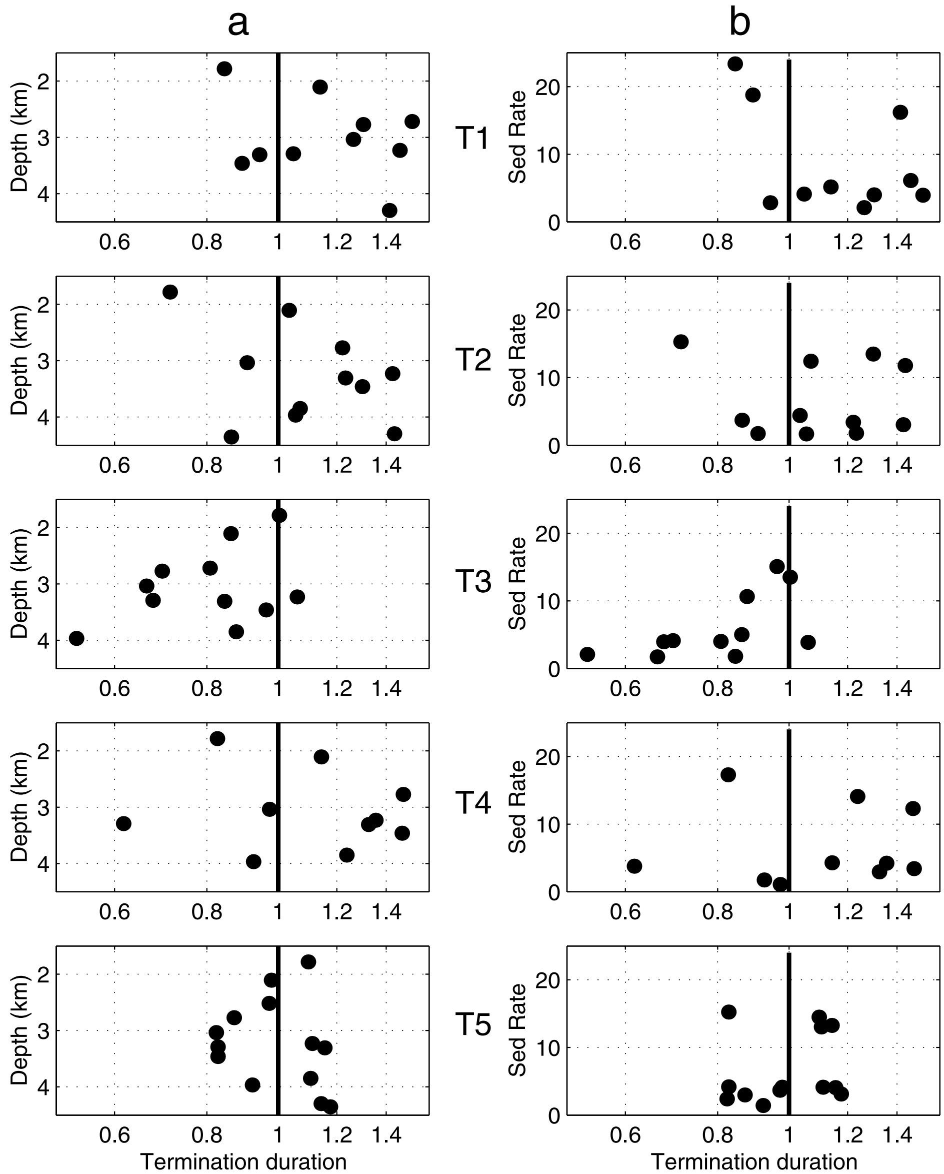

Figure 5. The manually estimated termination duration at each Pacific site as a fraction of the mean Atlantic duration for Terminations 1–5, compared to (a) seafloor depth and (b) the mean sedimentation rate (cm/kyr) of the 60-kyr outer window for each termination. Duration estimates greater than one indicate that the estimated Pacific duration is greater than the mean Atlantic duration. Note that Pacific termination duration does not correlate with depth or sedimentation rate.

in the Pacific only during Termination 1. One possible reason why a significant lag may appear using the automated technique but not the manual one is that the automated technique is sensitive to delays in the onset of Pacific terminations and the manual technique is not. More non-EEP benthic δ^{18}O records are needed to address this uncertainty.

[37] We also calculate termination duration estimates for every possible subset of 29 sites. On the basis of this ensemble of calculations (Table 2), the automated technique yields estimates that terminations were longer in the Pacific by 0.7 ± 0.2, 1.3 ± 0.5, 0.2 ± 0.1, 1.2 ± 0.4, and 0.8 ± 0.3 kyr (2-σ uncertainty) for Terminations 1–5, respectively. Manual duration estimates for Terminations 1, 2 and 4 are greater in the Pacific than the Atlantic in 99.99% of subsets with 29 sites (Table 2).

[38] Could Pacific sedimentation rate anomalies be an artifact of basin-wide changes in carbonate preservation during terminations? Because changes in carbonate preservation associated with movement of the lysocline should be depth-dependent, we compare the manual estimates of Pacific termination duration with water depth. Figure 5a illustrates that estimated Pacific termination durations do not appear to be a function of water depth; the correlation between the two is only 0.13. Therefore, termination duration differences are unlikely to be an artifact of increased

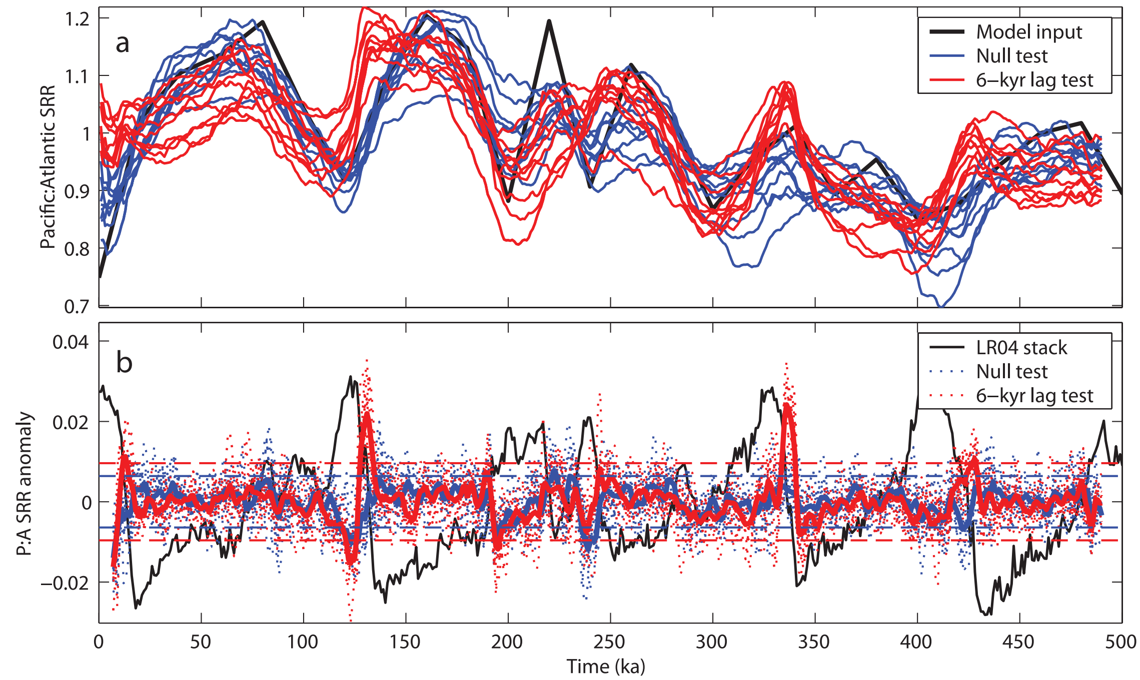

Figure 6. Sensitivity tests of the automated alignment technique. (a) The P:A SRR from simulated δ^{18}O data (see text) with no termination duration difference (blue) and with a 6-kyr lag between ocean basins (red). Sedimentation rates in the simulated Pacific records vary every 20 kyr, on the basis of the P:A SRR (black) plus white noise. (b) The P:A SRR minus its 13-kyr running mean for each test (dotted lines) and the average for 10 null tests (blue) and 10 lag tests (red). Horizontal dashed lines denote two standard deviations from the mean P:A SRR anomaly for the null test average (blue) and lag test average (red). The benthic δ^{18}O stack (black [*Lisiecki and Raymo*, 2005]) is plotted for comparison.

Pacific carbonate preservation due to deepening of the lysocline during terminations.

[39] Finally, we consider whether greater Pacific termination durations could be an artifact of bioturbation in low–sedimentation rate Pacific cores. This does not appear to be the case for two reasons. First, the mean sedimentation rate for our study sites in the Atlantic (5.6 cm/kyr) is only slightly higher than in the Pacific (4.8 cm/kyr). Second, the correlation coefficient between the manual estimates of Pacific termination duration and mean sedimentation rate is only 0.05 over a sedimentation rate range of 1–23 cm/kyr (Figure 5b).

4.2. Sensitivity Test

[40] To gauge the automated alignment algorithm's ability to detect differences in termination duration accurately, we perform null tests by aligning δ^{18}O data with simulated sedimentation rate changes but no mean duration differences. We create individual records for alignment by interpolating the LR04 stack to 2-kyr resolution and adding white noise ($\sigma = 0.05$‰). Sedimentation rates are assigned stochastically every 20 kyr and interpolated between these points. Atlantic sedimentation rates are drawn from an independent Gaussian distribution with a mean of 5.6 cm/kyr and a standard deviation σ of 1.7 cm/kyr. Pacific sedimentation rates are assigned using the observed P:A SRR interpolated to a 20-kyr resolution (Figure 6a, black curve) plus white noise with a mean of zero and a standard deviation of 1.7 cm/kyr.

[41] In each of 10 null tests, a simulated P:A SRR (blue curves in Figure 6a) is generated by using the automated algorithm to align 15 simulated Atlantic records and 15 simulated Pacific records to the LR04 stack. These null tests do not show any consistent short-term anomalies in the P:A SRR associated with terminations, as demonstrated by the difference between the P:A SRR records and their 13-kyr running means (dotted blue lines in Figure 6b). The short-term anomalies in the average of the 10 null tests (blue line in Figure 6b) are not statistically significant at the 2-σ level during any of the last 5 terminations. Therefore, the detection of termination anomalies in the real data is unlikely to be the result of bias in our alignment algorithm.

[42] Additionally, we performed tests in which we simulated termination duration differences between the Atlantic and Pacific. Sedimentation rates are assigned stochastically as before, and then Atlantic terminations are shortened by 2 kyr relative to the LR04 age model, and Pacific terminations are lengthened by 4 kyr relative to LR04. Ten tests were performed by generating ten simulated P:A SRR records (red lines in Figure 6a), each based on 15 simulated Atlantic records and 15 simulated Pacific records aligned to the LR04 stack. The simulated P:A SRR records display short-term deviations from the 13-kyr running mean during terminations, but the deviations at terminations are not always statistically significant (dotted red lines in Figure 6b). However, the average of the 10 tests shows statistically significant short-term increases relative to the

13-kyr running mean only at terminations (solid red line in Figure 6b). The simulated anomalies are approximately five times smaller than those from the real data, but the pattern of variation closely resembles the results generated by the real data (compare Figures 6b and 2d). The difference in anomaly magnitude does not necessarily suggest that the actual difference in termination duration between the Atlantic and Pacific is more than 6 kyr. The alignment algorithm may have greater sensitivity to termination durations in the real data because the temporal resolution of some of the real δ^{18}O records is higher than the 2-kyr resolution used for the simulated records.

[43] Finally, we performed simulations (not shown) to determine whether the automated technique could distinguish between termination duration differences and delayed termination onsets. The P:A SRR anomalies produced by the two scenarios were indistinguishable.

4.3. Interpretation

[44] Figure 7 shows the results of two simple simulations that illustrate how termination lags can be generated. We simulate the propagation of surface signals (ice volume and deep water formation temperature) to the deep ocean using simple transit time distributions (TTD) inspired by the TTDs calculated for Atlantic and Pacific sites in an ocean general circulation model [*Rutberg and Peacock*, 2006]. Transit time is defined as the time since a given parcel of water last had contact with the surface. We assume that each ocean basin is uniform and that the TTDs have a constant Gaussian distribution with a mean of 300 years and a standard deviation of 200 years in the Atlantic and a mean of 1200 years and a standard deviation of 750 years in the Pacific (Figure 7a). Both TTDs are truncated at 0 years (i.e., no water reaches the deep ocean before it leaves the surface).

[45] In the first simulation (Figure 7b), we assume temperature change is synchronous at all deep water formation sites. The timing of ice volume and temperature changes are modeled to be approximately consistent with radiocarbon dates for the last interglacial (neglecting the Younger Dryas reversal) [*Skinner and Shackleton*, 2005; *Waelbroeck et al.*, 2008; *Lambeck and Chappell*, 2001]. Temperature and ice volume change at a constant rate from 100 to 24 ka, and both are constant during the glacial maximum from 24 to 19 ka. Next, temperature increases linearly from 19 to 11 ka, and ice volume decreases linearly from 19 to 10 ka. The simulated records of Atlantic and Pacific benthic δ^{18}O are both at their glacial maxima at 20 ka, and both terminations begin at approximately 19 ka. The longer mixing time in the Pacific results in a smaller initial δ^{18}O change and a lag of 1000 years throughout most of the termination. Interglacial benthic δ^{18}O values are reached at approximately 9.5 ka in the Atlantic and 8 ka in the Pacific.

[46] Larger termination lags in the Pacific, such as the 4 kyr lags observed by *Skinner and Shackleton* [2005] and in our results at 128 and 330 ka, could be generated by temporary decreases in deep water circulation rates or by diachronous hydrographic changes. The scenario in Figure 7c demonstrates how these Pacific termination lags could be produced without any change in circulation rates if North Atlantic Deep Water (NADW) warms faster than Pacific Deep Water. In this example, the Atlantic temperature component, which simulates warming at the NADW formation site and expansion of NADW boundaries, reaches full interglacial levels during the first half of the termination. The Pacific temperature component represents the mean formation temperature of Circumpolar Deep Water and Pacific Deep Water and reaches interglacial levels 4 kyr later. For this simulation we assume that temperature change is responsible for approximately half of benthic δ^{18}O change in the Atlantic and 35% of benthic δ^{18}O change in the Pacific. (Estimates from pore water measurements [*Schrag et al.*, 1996; *Adkins et al.*, 2002] suggest that the proportion of change related to temperature is even larger at some sites.) With no change in circulation rate, this model produces Pacific benthic δ^{18}O lag of 2–4 kyr throughout most of the termination.

4.4. Practical Applications

[47] Our results have important implications for estimating the age model uncertainty associated with the alignment of δ^{18}O records from different locations and suggest that particular alignment techniques may exaggerate these errors. For example, some previous studies have used times of rapid δ^{18}O change, particularly terminations, for more than half of their stratigraphic tie points [e.g., *Raymo*, 1997; *Huybers and Wunsch*, 2004; *Lea*, 2004; *Shackleton*, 2000]. Our results and those of *Skinner and Shackleton* [2005] suggest that the age of termination midpoints can differ by as much as 4 kyr between the deep Atlantic and deep Pacific.

[48] Our methodology cannot test whether δ^{18}O change is synchronous during glacial maxima or termination onsets. More radiometric age estimates are needed [e.g., *Duplessy et al.*, 1991; *Skinner and Shackleton*, 2005; *Labeyrie et al.*, 2005]. The benthic δ^{18}O lag between the Atlantic and Pacific could also vary for different terminations because of differences in the amount of ice volume at the glacial maximum and/or the insolation forcing [e.g., *Parrenin and Paillard*, 2003]. Our comparison of Atlantic and Pacific stacks suggests that initial δ^{18}O change began $\sim$2 kyr earlier in the Atlantic than the Pacific during Termination 3 (perhaps because of millennial variability). Age differences may also occur between intermediate and deep sites within the same ocean [*Labeyrie et al.*, 2005; *Waelbroeck et al.*, 2006]. At this point, one should assume that any strategy for aligning benthic δ^{18}O records from different oceanographic settings could produce age model errors of several thousand years during terminations and other abrupt δ^{18}O changes.

[49] To avoid the age uncertainties associated with stratigraphic correlation, many studies compare the phases of different paleoceanographic proxies in a single sediment core [e.g., *Lea et al.*, 2002; *Visser et al.*, 2003; *Cortese et al.*, 2007]. However, *Skinner and Shackleton* [2005] explain that diachronous δ^{18}O responses also have important implications for the use of δ^{18}O stratigraphy as a proxy for the phase of ice volume change. The timing of benthic δ^{18}O change across terminations may differ significantly from ice

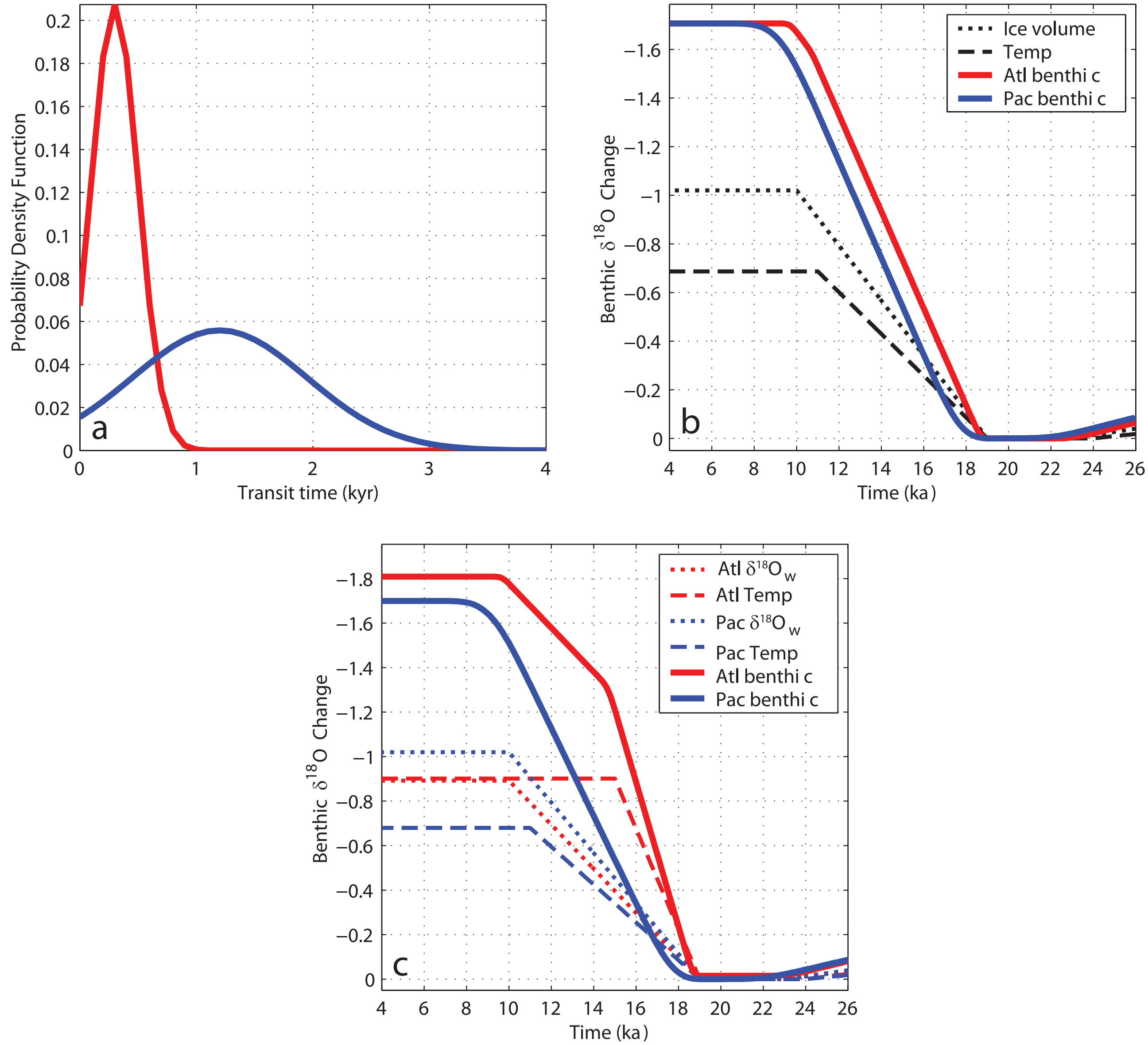

Figure 7. Simulated benthic δ^{18}O responses to simple surface forcing (see text). (a) Idealized mean transit time distributions (TTD) for Atlantic (red) and Pacific (blue) deepwater. (b and c) Simulated Atlantic (red solid) and Pacific (blue solid) mean benthic δ^{18}O response, assuming the constant TTDs in Figure 7a and prescribed changes in water δ^{18}O composition (dotted, ice volume effect) and temperature (dashed) at the time of deepwater formation. In Figure 7b, forcing (black) is assumed to be identical for all deep water. In Figure 7c, water δ^{18}O composition and temperature at the time of deepwater formation is different for Atlantic (red) and Pacific (blue) deepwater. Because of the early Atlantic temperature change in Figure 7c, Atlantic benthic δ^{18}O leads Pacific benthic δ^{18}O by 2–4 kyr.

volume/sea level change because of hydrographic changes and/or delays in meltwater reaching the deep Pacific. Therefore, site location should be taken into account when analyzing termination leads and lags, even if the data are all from a single core. Importantly, a surface proxy which leads benthic δ^{18}O in a Pacific core may not necessarily indicate that the climate response occurred before ice volume change. Additionally, at many Atlantic sites benthic δ^{18}O may significantly lead ice volume because of early hydrographic changes [*Skinner and Shackleton*, 2006; *Waelbroeck et al.*, 2008].

5. Conclusions

[50] Both automated and manual alignments of benthic δ^{18}O produce statistically significant short-term deviations in the ratio of mean sedimentation rate between the Pacific and the Atlantic during Late Pleistocene terminations.

Stacks of Atlantic and Pacific benthic $\delta^{18}O$ suggest that Pacific $\delta^{18}O$ lags the Atlantic by an average of 1.6 kyr during the last five terminations and that the lag between ocean basins is occasionally as large as 4 kyr. These results support the findings of *Skinner and Shackleton* [2005] for Termination 1 and additionally suggest that diachronous $\delta^{18}O$ responses are widespread and occur during the last six terminations. In addition, the timing of benthic $\delta^{18}O$ change may also vary within each ocean [*Labeyrie et al.*, 2005].

[51] Benthic $\delta^{18}O$ lags could be even larger than estimated here because our automated alignment technique seeks to minimize changes in sedimentation rates and we assume that Pacific lags during the onset of terminations are $\leq$2 kyr. Sensitivity tests with simulated data confirm that our automated technique tends to underestimate sedimentation rate anomalies. The automated and manual alignment results and the uncertainty analysis performed for each are summarized in Tables 1 and 2. The largest source of uncertainty in our results is likely to be associated with the small number of Pacific $\delta^{18}O$ records available outside of the EEP.

[52] We conclude that age models based on the alignment of benthic $\delta^{18}O$ stratigraphy have an uncertainty of ~4 kyr during terminations and, therefore, termination midpoints make particularly poor stratigraphic tie points. Similar uncertainties apply to the use of benthic $\delta^{18}O$ as a proxy for the timing of ice volume change during terminations. More data such as radiometric age estimates [e.g., *Labeyrie et al.*, 2005] or relative paleointensity magnetic stratigraphy [e.g., *Channell et al.*, 2009] are needed to constrain more precisely the timing of deglacial benthic $\delta^{18}O$ change in different oceanographic settings.

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