To the editor:

Below is a list of the major revisions to our manuscript. These changes should fully address the reviewers' comments. See our detailed replies at the end of this list for more detail, and our marked-up manuscript at the end of this document. Note that page and line below refer to the final version of the revision (not the marked-up document).

Thanks,

Rachel Spratt and Lorraine Lisiecki

1.)We added a discussion of Milankovitch theory and additional motivation for the sea level stack in background:

p. 1 line 26 – p. 2, line 3

2.)We expanded the background section, including many additional citations

    a) 1-2 paragraphs more about corals

    pp. 3-4, Section 2.1

    b)We cited more downcore sea level studies

    p. 4, lines 14-17

    p. 6, lines 14-16

3.) We updated the methods to clarify criteria for inclusion

p. 8, line 4-13

4.) We added more detail about age model methods and uncertainties

p. 8, line 15 – p. 9, line 8

5.) We added an explanation of why we use PCA to create the stack

p. 9, line 26, p. 10, lines 9.

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6.) We revised the sapropel interpolation text after including a floor function to minimize bias during missed glacial maxima

p. 10, lines 21-27

7) We changed the organization of the section headers to make it easier to find the existing and new uncertainty analysis

Section 4

8.) We added text comparing PC1 and an unweighted stack (and methods for unweighted stack)

p. 12, lines 22-31

9.)We added a section in which stack uncertainty is estimated with bootstrapping and Monte Carlo-style random sampling, and summarize these findings in the conclusion

p. 13, lines 1-20

p.18, lines 8-13

10.) We updated the tables, figures, and text to reflect very slightly different PCA results (resulting from changing the interpolation scheme used for Mediterranean sapropoels)

11.) We reorganized Tables 2 and 3 to make them easier to read.

12.) We added two new panels to Figure 2 to show the unweighted stack (2b) and bootstrap results (2c)

Referee #1 comments:

"A comparison and a meta-analysis of the continuous sea-level records analyzed here are highly valuable. However, the current meta-analysis suffers from two significant flaws, one critical. The critical flaw is that there appears to be no treatment of the uncertainty in the underlying records. These uncertainties are not negligible (indeed,

the authors state that one of their goals is to reduce the signal-to-noise ratios seen in the individual records). For example, as the authors note, the sea water oxygen isotope-derived records uncertainties have 1-sigma errors up to about 20 m and the

inverse ice volume model derived records has a 1-sigma error of 12 m. (These errors are, more over, not fully uncorrelated and should not be treated as such, when they aretreated.) But the authors appear to be working with simply the mean estimates of each

of the underlying records. It is therefore impossible to assess the robustness of their composite curve. If they retain their current meta-analysis methodology, a bootstrap assessment of errors would seem like a minimal necessary statement."

Authors' reply:

"Thank you for your considered response to our study. One form of uncertainty analysis included in the manuscript is a comparison of the individual records by calculation of standard deviation for each highstand and lowstand estimate (Tables 2 and 3). Additionally, as the reviewer requests, we have added a bootstrap assessment of errors **(pg. 13, Section 4.2 and Figure 2c)"**

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Referee #1 comment:

"The second significant flaw, which I view as serious but not critical, is that PCA is a bit of a slightly odd methodological choice for this analysis, as it ignores a key piece of prior information. All of the records are (supposedly) independent measures of a common signal. There are reasons to think that, say, the relative sea-level records will

be less correlated with total ice volume change (which I think may be what the authors actually mean by 'eustatic sea level') than measures of ice-volume derived from open-ocean d18O, but that relationship is more complex than the simple scaling provided

by a weighted average. So why do the authors think that the scalings associated withPC1 provide a better estimate of their target than an unweighted mean of the records?

If they don't, why are they throwing out the prior information that tells them they are all noisy measures of a common underlying signal?"

Authors' reply:

"Actually, we do not assume that all records are "independent measures of a common signal," and this is why we choose to use PCA instead of an unweighted mean. While all records should contain a strong ice volume signal, some of the "errors" (ie, non-ice volume signal) would most definitely be expected to be correlated with one another.

For example, as the d18O of ice in the ice sheet changes, the conversion from d18Osw to ice volume will be systematically biased. Additionally, changes in the hydrological cycle may induce changes in the spatial variability of d18Osw as measured at different locations in the ocean. In fact, we argue that PC2 and PC3 are indicative of these kinds of correlated biases in the records.

Other paleoclimate papers (e.g., Huybers and Wunsch, 2004; Clark et al, 2012; Gibbons et al, 2014) also use PCA (or equivalently EOF) for the creation of stacks or quantifying the common signal contained in core data. We will additionally address the reviewer's concern in our revised manuscript by comparing PC1 to an unweighted mean of all the records as another metric for evaluating uncertainty."

The paper now includes an explanation of why we use PCA (p. 9 line 26 – p. 10, line 7) and a comparison between PC1 and a conventional, unweighted stack (p. 12, lines 22-31; Figure 2b)

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Referee #1 comment:

"A minor note (p. 3711): the MIS5e sea-level estimate is usually (and appropriately) quoted as 6-9 m. The analysis in Kopp et al. (2013) of the well-resolved post-129 ka highstand stated, "within the LIG period, it is extremely likely (95 percent probability)/likely (67 per cent)/unlikely (33 per cent)/extremely unlikely(5 per cent)that the highest peak GSL well resolved by observations exceeded 6.4/7.7/8.8/10.9m", and is in agreement with a coral-record from the Seychelles, corrected for GIA and fingerprint effects, indicating a peak of 7.6

1.7 m (Dutton et al., 2015,doi:10.1016/j.quascirev.2014.10.025)."

Authors' reply:

"We quoted 8-9.3 m as the +/- one standard deviation estimate from Kopp et al (2009), which is most comparable to the 1-std error estimates provided by the authors of the 7 records included in the stack.

We now also cite the review paper of Dutton et al (2015), which arrives at an estimate of 6 to 9 m by comparing a large number of MIS 5e studies (p. 4, line 1)."

Referee #2 comments:

Referee comment:

"I thought this was going to be a great study to consider, but in the end felt disappointed.This study to me seems to be just another example of taking good records that have taken many years to perfect, smear them together in a fairly arbitrary manner, and then running some basic statistics over the top, to try and produce a 'synthesis' with an

'improved signal to noise ratio'. Earlier, work by Kopp et al. 2009 (which by the way was not, at all, an only-coral-based assessment, as suggested in the final paragraph of section 4) did something similar, albeit in a more sophisticated manner and for a shorter time interval, but even that study is blighted by the problem of arbitrary choices

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of chronological alignment between records, pulling some around to the limits of, or beyond, their stated uncertainties."

Authors' reply:

"Thank you for your in-depth critique. We corrected our assertion that Kopp et al. (2009) is an only coral-based assessment. That compilation also included sedimentological facies, non-coral biofacies, erosional features (e.g., raised beaches), and oxygen isotopes. **(pg. 3, lines 39-30)"**

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Referee comment:

"There have been several other 'syntheses' of late that all use versions of this approach; perhaps it is because of the lure of avoiding the hard graft of working up something original, in favor of writing yet another easy compilation with some statistics to get a

potentially well-cited paper."

Authors' reply:

"We appreciate the hard work that has gone into each individual sea level record. However, synthesis of these records is also valuable because each record has its own assumptions and errors. If these records are all well-constrained measures of sea level, then synthesis will reveal their respective levels of agreement or discrepancy.

As the referee notes, publication of syntheses of paleoclimate data is common and these syntheses often provide value to the paleoclimate community as evidenced by their citations. Some specific examples of other

recent synthesis studies are: Huybers and Wunsch (2004); Clark et al. (2012); Gibbons et al. (2014); Shakun et al. (2014)"

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Referee comment:

"The original LR04 stack was a game-changer in synthesizing benthic delta-O18records, but was later found to be blighted by assumptions of synchronicity between records that are made implicitly by use of the Match software (e.g., Skinner and Shackleton 2005 QSR). One of the authors of the current manuscript even had their own

paper in 2009 (Lisiecki and Raymo, Paleoceanography 2009) in which this implicitlyassumed synchronicity was demonstrated to be flawed. Yet here we see it again, and again without any attempt at proper propagation through all methods and conclusions

of the uncertainties and limitations."

Authors' reply:

"It is true that benthic d18O records are not synchronous by as much as 4 ka during terminations, so there is potentially some smoothing by neglecting these potential differences. We have added more discussion of this source of uncertainty **(page 8, line 15 – p. 9, line 8)** and included a simulation of age model uncertainty in our bootstrap analysis **(p. 13)**

However, our conclusions are not overly sensitive to this uncertainty because the manuscript focuses on highstands and lowstands, rather than the timing

or rate of glacial terminations. For example, note that the highstand and lowstand estimates in Table 2 were identified individually in each record (**pg. 11, line 28-30**) and, therefore, are not based on the assumption of synchronousd18O change. Nonetheless, these tables reveal large discrepancies in estimates from different records. For example, the standard deviation of MIS 11 sea level estimates

as compiled in Table 3 is 25 m. This level of disagreement is an example of the kind of valuable information a synthesis study can provide."

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Referee comment:

"The signal matching approach needs to be relegated to history, if it is not backed up by a strong physical rationale, and/or rigorous independent testing, and/or proper uncertainty propagation. Certainly in the way applied in the current study, it is an antiquated approach that is known to be flawed. I suggest that it would be time better spent for the researchers to instead start working on developing independent and testable chronologies for each of the records."

Authors' reply:

"Testable chronologies for each of the records would be a valuable contribution to science. However, basic comparisons can be done in advance of such work. In some cases, such as Bintanja et al, (2005) a locally developed chronology would not be possible because this record is based entirely on the LR04 benthic stack (Lisiecki and

Raymo, 2005). Although not perfect, the Lisiecki and Raymo (2005) benthic d18O age model is currently widely used in the paleoclimate community: For example, it has been used in a variety of ways for basic comparison to local climate records (e.g., Melles et al, 2012) and as a general measure by which to compare models of 100-kyr glacial cyclicity (e.g., Abe-Ouchi et al, 2013)."

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Referee comment:

"In this context, I was surprised that the Red Sea record used is not the most recent version that I have seen (Grant et al. Nature Comms 2014), which has an independent chronological assessment and full probabilistic assessment using the age uncertainties as well as the method uncertainties. That should be used, and then any chronological

adjustments needed would need to remain within the limits of that assessment."

Authors' reply:

"All records in the stack need to have comparable age models. Comparing records on independent age models would create larger errors by systematically smoothing (and hence, underestimating) highstands, lowstands, and orbital power. If we could

have correlated benthic d18O to Grant et al. (2014), we would have. Although we consider this age model better than LR04, the Red Sea sea level curve does not have an accompanying open-ocean benthic d18O time series to which other records could be correlated. Also, Grant et al (2014) does not span the full 800 kyr. **(p. 8, lines 18-20)**"

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Referee comment:

"Similar independent age assessments need to be developed for the other methods;this is where the real challenge lies, and where advancement of sea-level understanding will come from. It is only once that is done, that we come into a position to consider putting the records together (each on their own proper timescales) to evaluate common

signals and differences."

Authors' reply:

"We disagree that basic comparison has to wait for this. It may not be possible to produce independent age estimates for each marine core due to a lack of ways to date each record individually back to 800 ka."

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Referee comment:

"Even if we accept the chronological matching as done (though I don't see why we should; see above), then I still remain very worried about the lack of propagation of the legion uncertainties that arise from assumptions and adjustments in the chronologies, through the method and into the final conclusions. I am convinced that the uncertainties

around the end product, and any further manipulations based on it, will increase greatly when this is done."

Authors' reply:

"At the moment we don't provide uncertainties because there are too many poorly quantified sources of uncertainties (e.g., amount of lead/lag between benthic d18O at individual sites, amount of difference between sea level and d18O of seawater at specific locations). An estimate that does not include them all would be misleading. Therefore, we must rely on metrics of the amount of agreement between different records,

such as the standard deviations of (age-independent) highstand and lowstand estimates in Tables 2 and 3, and a bootstrap assessment of errors which includes +/- 2 kyr of age uncertainty. Allowing for age uncertainty smooths the resulting stack but does not greatly increase its uncertainty. The average standard deviation for our bootstrap results (which include age uncertainty and Holocene-LGM scaling uncertainty) is 9-12 m, which is better than the standard deviations of comparing individual highstand and lowstand estimates (12-25 m for MIS 5e to MIS 19). **See Section 4 (pg. 11-13), pg. 18 lines 7-13, Figure 2, and Tables 2 and 3.**

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Referee comment:

"I am particularly worried that the difference between linear and non-linear regressions in section 6 may not be robust when considered relative to fully and properly propagated uncertainties."

Authors' reply:

"The difference between the linear and nonlinear regression is 10-20 m during highstands and lowstands (**pg 15, line 28-29**). For MIS 5e and 7e, the scaled short stack and the mean of highstands from individual records agree to within 5 m (**Table 3**), and the standard error of the highstand means is 4.6

m (calculated from Table 3: sigma/sqrt(n) = 12/sqrt(7) = 4.6 m). Additionally, Kopp et al (2009, 2013) estimated that the MIS 5e sea level maximum was very unlikely greater than 10m, whereas the mean sea level for 5e must be lower. Thus, the linear regression is not consistent with uncertainty estimates for 5e and is also significantly too high for the Holocene. Ice core evidence also suggests a change in interglacial characteristics between MIS 11 and MIS 9 (**pg 16, lines 13-16**). Uncertainty is a larger concern for glacial lowstand estimates, as explained in the manuscript (pg 16, lines 17-26). This creates uncertainty about the exact functional form of the change after MIS 11, but the interglacial data are sufficient to demonstrate that some kind of shift occurred in the relationship between benthic d18O and sea level."

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"A further concern is that the various methods underlying the different sea-level records that are used, are not independent of each other. As such one could wonder if straight PCA is an appropriate analytical tool. After all, we're not just looking at covariances between independent estimates with a common signal, but at covariances between methodologically (partially) related estimates with a common signal. This is not discussed, and there is also no assessment of how the methodological dependence might affect the answers (and their uncertainties). I think this would need some se-

rious thought and discussion too."

Authors' reply:

"The revised manuscript now better explains our decision to use PCA (**pg. 9, line 26 – pg. 10, line 7**). See also our response to reviewer 1. For valid reasons our reviewer mentioned that the records are not 'unrelated'. This is exactly the reason why we use PCA, which can identify similarities and differences between the seven records used. PCA allows us to discern the common signal (PC1) as well as detect where the biases in the individual records are being replicated: our PC2 and PC3 scores elucidate differences between Atlantic vs. Pacific, and surface vs. deep, respectively. To address concerns about sensitivity of the result to the PCA method, the revised manuscript also includes a comparison of PC1 and the unweighted mean of the sea level records (**pg. 12, lines 22-31, Figure 2b**) See reply to referee #1."

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Referee comment:

"Finally, there are some unsupported manipulations, such as the 2 ka lag to the smoothed LR04, as applied in section 6."

Authors' reply:

"The 2 kyr lag was computed as the lag which maximized correlation between the two records. Therefore, we use this as the characteristic

lag between benthic d18O and sea level. We added text to the manuscript to clarify this step. (**pg. 15, lines 17-22**)"

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Referee comment:

"I don't think that this study as is does anything to advance understanding and to improve the state of the art. It's the sort of exercise that one might expect from an MSc student, perhaps, but it is not going to help us understand sea-level variability any better than the individual input records. The study would only introduce a false

sense of 'understanding' that is flawed because of the (often unspecified) underlying assumptions, uncertainties, and questionable manipulations. It is evident that the real challenge is to get the different records onto their own independent chronologies, and to then compare them statistically (using appropriate statistics and proper uncertainty

propagation). That may not be so easy to do, but true understanding doesn't need to come easy. Certainly not when 'easy' is using a known flawed approach. I recommend

rejection of the study as is."

Authors' reply:

"It is apparent that the reviewer has a different viewpoint about the best way to advance sea level studies; however, a variety of study approaches is healthy for the advancement of science. Although there are still many uncertainties (particularly with respect to age models), there is potential benefit to the community to performing initial comparison and synthesis as long as the manuscript is transparent about the study's limitations and sources of uncertainty."

Referee #3 comments:

Referee comment:

"Firstly, Spratt & Lisiecki use a handful of records from a range of different proxy/model approaches. In doing so, they use the published error associated with initial publication. I believe this is inadequate and need to apply a more rigorous, possibly a probabilistic assessment, to fully evaluate the uncertainties in each record. For example, the Mg/Ca-BWT derived records both quote a 1 to 1.1 C on BWT estimates, however, both records are based on core-top calibrations that are either regional or bootstrapped. Consideration of the uncertainty around this needs to be revisited along with the other records. "

Authors' reply:

"Thank you for your careful consideration. We quote the uncertainty estimated by the original authors as they are most familiar with their data and these error estimates have gone through a review process associated with their original publication. Reassessing the errors of each individual record (e.g., with regard to core top calibration) is beyond the scope of the current manuscript, although it would certainly be a valuable scientific contribution. The goals of the current manuscript are to identify (1) the common signal in Late Pleistocene sea level records, (2) correlated biases affecting multiple records (ie, PC2 and PC3), and (3) the overall level of agreement among the records (ie, the

standard deviation of highstand and lowstand estimates in Tables 2 and 3), which is an indirect measure of noise/uncertainty in the individual records. For clarification, we do not actually apply the authors' estimates of individual record uncertainty in any of our analyses."

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Referee comment:

"Also both Mg/Ca-derived BWT records lead the d18Osw record by 10-20 kyr. How does this phasing affect the alignment or interpretation of peak interglacial sea level estimates?"

Authors' reply:

"We do not interpret the phase of the sea level response because of significant age model uncertainties associated with the alignment techniques. Additionally, we identify the peak interglacial levels estimated by each record independent of their precise age in **Table 2**. Both benthic d18Osw records have above average interglacial sea level estimates, potentially indicating a bias in the approach. However, the bias may be counterbalanced in our stack by our signal pre-processing (ie, normalizing) and by the below average estimates from planktonic d18Osw. In fact, PC3 (which largely reflects differences between the benthic and planktonic signal) may be helpful for identifying/quantifying the bias associated with these signals. "

Referee comment:

"The authors do not clearly provide a criteria for their choice of sea level records. And although they provide a general review of the chosen records it does not seem to be exhaustive. Available for the late Pleistocene are the records of Dwyer et al. 1995 (ostracod Mg/Ca-BWT) and the record of Martin et al. 1999 (benthic foram Mg/Ca- BWT record). Additionally, they omit they record of Siddall et al. 2010 who expands up the technique of Waelbroeck et al 2002 applying a benthic d18Oc-coral regression. Does the stack have a sensitivity to records included or excluded?"

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Authors' reply:

"Thank you for these suggestions. Many of these records did not fit our inclusion criteria, which are described explicitly in the revised manuscript (**pg. 8, lines 5-13**). The criteria for inclusion in the stack were (a)availability, (b) at least 430 ka long, and (c) a minimum temporal resolution of 5 ka. The Dwyer et al. (1995) record was not long enough, spanning only 0-120 ka. We could not find Martin et al (1999); we wonder if instead the reviewer meant Martin et al (2002). This record was not included because it is only 350 kyr long. Additionally, Martin et al (2002) did not actually publish their d18Osw estimates (only d18Oc and temperature).

The sea level transform function of Siddall et al (2010) is significantly lower in resolution than the one from Waelbroeck (2002). Therefore, we consider the Waelbroeck estimate more reliable. We also looked at results from the follow-up study of Bates et al (2014) which applied a similar transformation to 10 different benthic d18O records (**pg. 6, line 14-16**). The mean highstand and lowstand values from these cores are now included for comparison in Table 2. However, because each record in that study is on a different age model and the authors did not produce their own summary of the results, there wasn't enough time during revision for us to incorporate all of these records into a revised stack. Doing so also seems to go against the wishes of those authors who advocate against benthic d18O alignment (**pg. 8, lines 10-13**). Because the mean hightsand and lowstand estimates from Bates are similar to the 7 records used in our study, including these records probably would not dramatically alter our results.

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As a sensitivity test, we compared PC scores 1, 2, and 3 of the shorter seven-record stack to the longer five-record stack. For PC1, we find almost no difference (**page 11, lines 18-20**). We have also bootstrapping (**pg. 13, lines 1-20**) which estimates a mean standard deviation of 9-12 m for the stack's uncertainty (including the effects of random sampling of records, uncertainty in scaling to sea level, and age model uncertainty).

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Referee comment:

"More clarification around the age model alignment for each record is needed. In the paper they authors state " the LRO4 age model has an uncertainty of 4ka" and state that their "age model alignment involved either aligning to the LRO4 d18Oc stack or aligning ..to other sea levels

on the LRO4 age model". Details about the alignment and records used need to be fully explained."

Authors' reply:

"We have added more detail and clarification of the method aligning the 5 records not already on the LR04 age model (**p. 8, line 23 – p. 9 line 20**)."

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Referee comment:

"Secondly, the authors seem to only briefly explore the features of the record. They make the point that roughly 40% of the benthic d18Oc record is derived

from ice volume change and 60% BWT change. How does this %ice:%BWT contribution change over the course of the record? "

Authors' reply:

"We include orbital band percentages in our paper (**pg. 14, lines 9-15**). However, we don't do more analysis because the conversion between sea level and md18O of seawater likely changes through time. For example, smaller ice sheets are likely less depleted in d18O. This would introduce bias to a time series of %sea level. Additionally, this calculation would be relatively sensitive to age model errors and the BWT:d18Osw phase shift described above by the reviewer. Lastly, similar calculations have been presented in several previous publications (eg, Bintanja et al, 2005, Elderfield, 2012, Sosdian and Rosenthal, 2009) and a re-calculation of it here would not be a significant contribution because it would be affected by similar (if not greater) uncertainties."

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Referee comment:

"The establishment of the stack allows for it to be compared to available CO2 records and other paleoclimate indicators to elucidate some basic appreciate for the Pleistocene climate. The authors are lacking a critical discussion beyond the stack features and contribution to the d18Oc variability. I would suggest they attempt to provide some

added observations."

Authors' reply:

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"Section 6 **(pg. 16, lines 7-26)** provides some comparison of ice volume versus ice core paleoclimate proxies (e.g., CO2 and d18Oice). A more detailed analysis is not possible due to relative age uncertainty between LR04 and the ice sheet age models (Lisiecki, 2010)."

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Referee comment:

"Thirdly, the authors choose to use PCA analysis for this task but don't specify the criteria they used to choose the most appropriate method."

Authors' reply:

"We added more discussion of our choice to use PCA in the revision **(p. 9 line 26 – p. 10, line 7)**. As in our answer to reviewer one, we choose PCA because it allows us to identify similarities and differences between the seven records used. PCA (equivalent to EOF) is also a very commonly used technique to create a stack (e.g., Huybers and Wunsch, 2004; Clark et al, 2012; Gibbons et al, 2014). The first principal component is representative of the common sea level signal and is not largely different from an unweighted mean.

Additionally, the subsequent components allow us to examine the other influences on the proxies: e.g., Atlantic vs. Pacific (PC2) and surface vs. deep (PC3). "

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Referee comment:

"Specific comments: Section 1 The introduction would be more suitable if the authors provided additional background info around Pleistocene sea level variations, mechanisms, and gaps. Currently it is missing some critical references and doesn't fully introduce the topic."

Authors' reply:

"We added more detail in our introduction about the current knowledge and gaps surrounding Pleistocene sea level variations (**pg. 1 line 27 – pg 2, line 7**)"

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Referee comment:

"Section 6 -the authors state that 40-65% of the benthic change is related to ice volume-does this derive from their H-LGM estimate and Pleistocene stack approximation?"

Authors' reply:

"The 65% estimate is derived for benthic change from the Holocene-Last Glacial Maximum estimate while the 45% is derived from our spectral analysis (**page 14, lines 9-15**) We clarify this in revision (**pg 14, line 30-31**)"

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Referee comment:

"The 607 mg/ca-bwt record shows a lead of temperature over ice volume as well. –the authors apply a 2ka lag to the smoothed LRO4 stack to improve the correlation-specify

reason for lag"

Authors' reply:

"The lag was empirically found as the phase shift which maximized correlation between benthic d18O and sea level, which we clarify this in the revised text. We now cite both Sosdian and Rosenthal (2009) and Elderfield et al (2012), to explain that the lag is likely a result of temperature changes (pg. 15, lines 20-21)."

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Referee comment:

"Figure 4C-it is hard to decipher between the two regression lines"

Authors' reply:

"We adjusted the line styles to enhance the difference between the regression lines."

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Referee comment:

"Overall, the authors need to be more precise in their referencing as some are missing."

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Authors' reply:

"Thank you. We have added many more references throughout the revised manuscript."

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References:

Clark, P. U., et al. (2012). Global climate evolution during the last deglaciation. Proceedings of the National Academy of Sciences, 109(19), E1134–E1142.

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1(12). http://doi.org/10.1029/2000gc000046

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Oceans. Earth and Planetary Science Letters, 387(0), 240–251.

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A Late Pleistocene Sea Level Stack

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Abstract

Late Pleistocene sea level has been reconstructed from ocean sediment core data using a wide variety of proxies and models. However, the accuracy of individual reconstructions is limited by measurement error, local variations in salinity and temperature, and assumptions particular to each technique. Here we present a sea level stack (average) which increases the signal-to-noise ratio of individual reconstructions. Specifically, we perform principal component analysis (PCA) on seven records from 0-430 ka and five records from 0-798 ka. The first principal component, which we use as the stack, describes ~80% of the variance in the data and is similar using either five or seven records. After scaling the stack based on Holocene and Last Glacial Maximum (LGM) sea level estimates, the stack agrees to within 5 m with isostatically adjusted coral sea level estimates for Marine Isotope Stages 5e and 11 (125 and 400 ka, respectively). Bootstrapping and random sampling yield a mean uncertainty estimates of 9-12 m (1σ) for the scaled stack. When we cComparinge the sea level stack with the $\delta^{18}O$ of benthic foraminifera, we find suggests that sSea level change accounts for about ~4045% of the total orbital-band variance in benthic $\delta^{18}O$, compared to a 65% contribution during the LGM-to-Holocene transition. Additionally, the second and third principal components of our analyses reflect differences between proxy records associated with spatial variations in the $\delta^{18}O$ of seawater.

1   Introduction

Glacial-interglacial cycles of the Late Pleistocene (0-800 ka) produced sea level changes of as much asapproximately 130 meters, primarily associated with the growth and retreat of continental ice sheets in 100-ka cycles. Recent ice sheet modeling studies support the assertion of Milankovitch theory that Late Pleistocene glacial cycles are primarily driven by insolation changes associated with Earth's orbital cycles (Ganopolski and Calov, 2011; Abe-Ouchi et al.

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2013). However, modeling ice sheet responses over orbital timescales remains quite challenging, and the output of such models should be evaluated using precise and accurate reconstructions of sea level change. Thus, Late Pleistocene sea level reconstructions. Precise and accurate reconstructions of sea level change during these cycles are important both for understanding the mechanisms responsible for 100-ka glacial cycles and for quantifying the amplitude and rate of ice sheet responses to climate change. Sea level estimates for warm interglacials at 125 and 400 ka are also of particular interest as potential analogs for future sea level rise (Kopp et al., 2009; Raymo and Mitrovica, 2012; Dutton et al., 2015).

Nearly continuous coral elevation data have generated well-constrained sea level reconstructions since the Last Glacial Maximum (LGM) at 21 ka (Clark et al., 2009; Lambeck et al., 2014). However, beyond the LGM sea level estimates from corals are discontinuous and have relatively large age uncertainties (e.g., Thompson and Goldstein, 2005; Medina-Elizalde, 2013). Several techniques have been developed to generate longer continuous sea level reconstructions from marine sediment core data. Each of these techniques is subject to different assumptions and regional influences. Here, we identify the common signal present in seven Late Pleistocene sea level records as well as some of their differences.

These sediment core records convert $\delta^{18}O_c$, the oxygen isotope content of the calcite tests of foraminifera, to sea level using one of several techniques. In three records, temperature proxies were used to remove the temperature-dependent fractionation effect from $\delta^{18}O_c$ in order to solve for the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$). Other techniques for transforming $\delta^{18}O_c$ to sea level include the polynomial regression of $\delta^{18}O_c$ to coral-based sea level estimates, hydraulic control models of semi-isolated basins, and inverse models of ice volume and temperature. Each of these techniques produce slightly different results for a variety of reasons. For example, $\delta^{18}O_{sw}$ varies spatially due to differences in water mass salinity and deep water formation processes (Adkins et al., 2002). Reconstructions also vary based on sensitivity to eustatic versus relative sea level (RSL) and temporal resolution.

Principal component analysis (PCA) is used to identify the common sea level signal in these seven records (i.e., to produce a sea level "stack") and to evaluate differences between reconstruction techniques. By combining multiple sea level records with different underlying assumptions and sources of noise, the sea level stack has a higher signal-to-noise ratio than the individual sea level records used to construct it.

2 Sea level reconstruction techniques

2.1 Corals and other coastal sea level proxies

Corals provide the most prominent Late of thePleistocene sea level proxiesy. Corals have the advantageThey can be of radiometrically datinged and provide especially accurate sea level estimates between 0-21 ka because of nearly continuous pristine coral specimens from several locations (Fairbanks, 1989; Bard et al., 1990; Edwards et al., 1993; Bard et al., 1996; Clark et al, 2009; Fairbanks, 1989; Hanebuth et al., 2000; Lambeck et al., 2002; Stein et al., 1993; Stirling et al., 1995). Dated coral sea level estimates extend as far back as ~600 ka (Stein et al., 1993; Stirling et al., 1995; Medina-Elizalde, 2013; Muhs et al., 2014; StirlingAndersen et al., 20098). However. However, coral, coral data isare increasingly discontinuous and inaccurate prior to 21 ka due to difficulty finding pristine and in situ older corals (particularly during sea level lowstands) and due to U-Th age uncertainties in older corals caused by isotope free exchange with the surrounding environment (e.g., Thompson and Goldstein, 2005; Blanchon et al., 2009; Medina-Elizalde, 2013). Interpretation of sea level from corals often requires a correction for rates of continental uplift, which may not be known precisely. Glacial isostatic adjustment (GIA) and species habitat depth (up to 6 m below sea level) may also affect sea level estimates (Raymo and Mitrovica, 2012; Medina-Elizalde, 2013). Wave destruction and climate variations also alter coral growth patterns and may affect the height of colonies relative to sea level (Blanchon et al., 2009; Medina-Elizalde, 2013).

Organic proxies such as peat bogs and shell beds can also be used as sea level proxies and can be radiometrically dated (e.g., Horton, 2006). Geological formations indicating sea level such as abandoned beaches and sea cliffs can also be used as sea level proxies and these can be stratigraphically indexed (Hanebuth et al., 2000; Boak and Turner, 2005; Bowen, 2010).

Corals and other coastal proxies are indicators of relative (local) sea level and, thus, are affected by in situ glacio isostatic effects, ocean siphoning processes, and other local effects of sea level rise and fall. However, their wide spatial distribution, particularly corals in tropical regions, allows for modeling of glacioisostatic adjustments (GIA) to create a global estimate of mean sea level change (e.g., Kopp et al., 2009; Lambeck et al., 2014; Dutton and Lambeck, 2012; Hay et al., 2014). GIA models constrained by these coastal indicators provide robust sea level change estimates of -130 to -134 m for the LGM (Clark et al, 2009; Lambeck et al., 2014). A compilation of dozens of corals and other sea level indicators also provide relatively well-

constrained estimate of 7~~8.7~~2 ± ~~1~~0.7~~3~~ m for global mean sea level at the last interglacial (Kopp et al., 2009). ~~Additionally, e~~Estimates from multiple studies using different data are all in relatively good agreement yielding a consensus estimate of 6~~.7 ± 3.4 m~~ to 9 m above modern (Dutton et al., 2015). ~~Additionally, these compilations are giving researchers the tools to investigate~~Additionally, sea level during last interglacial likely experienced several meters of millenial-scale ~~sea level occurrences within given~~variability ~~highstands such as~~during the last ~~interglacial~~LIG, ~~with insight into meltwater changes which raise sea level~~ (Kopp et al., 2013; Govin et al., 2012). ~~However, u~~Uncertainties increase for older interglacials. GIA-corrected coastal sea level proxies for Marine Isotope Stage (MIS) 11 at ~400 ka suggest a global mean sea level of~~of~~ 6-13 m above modern ~~for Marine Isotope Stage (MIS) 11 at ~400 ka~~ (Raymo and Mitrovica, 2012)~~, but other GIA estimates suggest sea level more similar to present day (Bowen, 2010)~~.

2.1 Seawater $\delta^{18}O$

Global ice volume is a main control on the global mean of $\delta^{18}O$ in seawater ($\delta^{18}O_{sw}$)~~.~~, with g~~.~~ ~~G~~lobal mean $\delta^{18}O_{sw}$ ~~is~~ estimated to decrease by 0.008‰ to 0.01‰ per meter of sea level rise (Adkins et al., 2002; Elderfield 2012; Shakun et al., 2015). However, $\delta^{18}O_{sw}$ also varies spatially based on patterns of evaporation and precipitation and deep water formation processes. The $\delta^{18}O$ of calcite ($\delta^{18}O_c$) is affected both by the $\delta^{18}O_{sw}$ and temperature. In the absence of any post-depositional alteration, subtracting the temperature-dependent fractionation effect from $\delta^{18}O_c$ (Shackleton, 1974) should yield a good estimate of the $\delta^{18}O_{sw}$ in which the calcite formed. ~~The method of determining~~Pioneering studies for estimating time series of ~~sea level from the~~ $\delta^{18}O_{sw}$ ~~was~~using independent measures of temperature include ~~developed from the efforts of~~ ~~(~~Dwyer et al. (1995)~~,~~; Martin et al~~.~~ (2002)~~, and~~; Lea et al. (2002). Dwyer et al. (1995) used ostracod Mg/Ca ratios to determine temperature whereas Martin et al (2002) and~~;~~ Lea et al (2002) ~~pioneered the method using foraminiferal data from Cocos ridge with~~used benthic and plankt~~o~~ic foraminifera, respectively. The $\delta^{18}O_c$ of benthic foraminifera reflects the temperature and $\delta^{18}O_{sw}$ of deep water, while the $\delta^{18}O_c$ of planktonic foraminifera is affected by sea surface temperature (SST) and the $\delta^{18}O_{sw}$ of near-surface water.

2.2 Benthic $\delta^{18}O_{sw}$

Our analysis includes two benthic $\delta^{18}O_{sw}$ records from the North Atlantic and South Pacific, which use the Mg/Ca ratio of benthic foraminifera as a temperature proxy. ~~The method of~~

The South Pacific benthic $\delta^{18}O_{sw}$ record (Elderfield et al., 2012) comes from Ocean Drilling Program (ODP) site 1123 (171 W, 41 S, 3290 m). This site reflects the properties of Lower Circumpolar Deep Water, which is a mix of Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW). Mg/Ca ratios and $\delta^{18}O_c$ were determined from separate samples of the same species of *Uvigerina,* which is considered fairly insensitive to the deep water carbonate saturation state (Elderfield et al., 2012). Elderfield et al. (2012) interpolate their data to 1 ka spacing, perform a 5-ka Gaussian smoothing, and convert from $\delta^{18}O_{sw}$ to sea level using a factor of 0.01‰m^{-1}. Measurement uncertainties for temperature and $\delta^{18}O_c$ generate a $\delta^{18}O_{sw}$ uncertainty of ±0.2‰, corresponding to bottom water temperature range of ±1°C or about 22 m of sea level.

The North Atlantic $\delta^{18}O_{sw}$ reconstruction is from Deep Sea Drilling Program (DSDP) site 607 (32 W, 41 N, 3427 m) and nearby piston core Chain 82-24-23PC (Sosdian and Rosenthal, 2009). These sites are bathed by NADW today but were likely influenced by AABW during glacial maxima (Raymo et al., 1990). Mg/Ca was measured using two benthic foraminiferal species, *Cibicidoides wuellerstorfi* and *Oridorsalis umbonatus,* which may be affected by changes in carbonate ion saturation state, particularly when deep water temperature drops below 3°C (Sosdian and Rosenthal, 2009). The $\delta^{18}O_c$ data come from a combination of *Cibicidoides* and *Uvigerina* species. Sea level was estimated from benthic $\delta^{18}O_{sw}$ using a conversion of 0.01‰m^{-1} and then taking a 3-point running mean. Combining the reported uncertainties for temperature (±1.1°C) and $\delta^{18}O_c$ (±0.2‰) yields a sea level uncertainty of approximately ±20 m (one standard error) for the 3-point running mean.

2.3 Planktonic $\delta^{18}O_{sw}$

A 49-core global stack uses the $\delta^{18}O_c$ from planktonic foraminifera paired with SST proxies from the same core. The planktonic species in this reconstruction were: *G ruber*, *G bulloides*, *G inflata*, *G sacculifer*, *N dutretriei*, and *N pachyderma*. Forty-four records span the most recent glacial cycle, and seven records extend back to 798 ka. Thirty-four records use Mg/Ca temperature estimates, and fifteen use the alkenone $U^{k'}_{37}$ temperature proxy. Because $U^{k'}_{37}$ measurements derive from coccolithophore rather than foraminifera, there is some chance the

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temperature measured may differ slightly from that affecting $\delta^{18}O_c$ (Schiebel et al. 2004). However, Shakun et al. (2015) observed no significant differences in $\delta^{18}O_{sw}$ estimated from the two SST proxies. An additional concern is that the surface ocean is affected by greater hydrologic variability and characterizes a smaller ocean volume than the deep ocean. Thus, planktonic $\delta^{18}O_{sw}$ may differ more from ice volume changes than benthic data. However, these potential disadvantages of using planktonic records may be largely compensated by the use of a global planktonic stack.

The first principal component (stack) of the planktonic records spanning the last glacial cycle represents 71% of the variance in the records (n=44), suggesting a strong common signal in planktonic $\delta^{18}O_{sw}$. However, the 800-ka planktonic $\delta^{18}O_{sw}$ stack appears to contain linear trends that differ from other sea level estimates. Therefore, Shakun et al. (2015) corrected their sea level estimate by detrending planktonic $\delta^{18}O_{sw}$ based on differences between planktonic and benthic $\delta^{18}O_c$. Standard errors in the $\delta^{18}O_{sw}$ stack increase from 0.05‰ for the last glacial cycle to 0.12‰ at 800 ka due to the reduction in the number of records. The equivalent sea level uncertainties are ±6 m and ±18 m (1σ), respectively. All data were interpolated to even 3 ka time intervals.

2.4 Benthic $\delta^{18}O_c$ - coral regression

The sea level reconstruction of Waelbroeck et al. (2002) was developed by fitting polynomial regressions between benthic $\delta^{18}O_c$ from North Atlantic cores NA 87-22/25 (55 N, 15 W, 2161 and 2320 m) and equatorial Pacific core V19-30 (3 S, 83 W, 3091 m) to sea level estimates for the last glacial cycle, primarily from corals. Quadratic polynomials were fit during times of ice sheet growth and during the glacial termination in the North Atlantic whereas a linear regression was fit to the Pacific glacial termination. A composite sea level curve was created from the most reliable sections of several cores, primarily from the Pacific. The composite time series was interpolated to an even 1.5 ka time window, and the uncertainty associated with this technique is was estimated to be ±13 m of sea level. Transfer functions between benthic $\delta^{18}O_c$ and coral sea level estimates have also been estimated at lower resolution and applied to 10 different benthic $\delta^{18}O$d18O records spanning 0-5 Ma (Siddall et al., 2010; Bates et al., 2014).

2.5 Inverse ice volume model

The inverse model of Bintanja et al. (2005) is based on the concept that Northern Hemisphere (NH) subpolar surface air temperature plays a key role in determining both ice sheet size and deepwater temperature, which are the two dominant factors affecting benthic $\delta^{18}O_c$. A three-dimensional thermomechanical ice sheet model simulates ice sheet $\delta^{18}O$ content, height, and volume for NH ice sheets (excluding Greenland) as forced by subpolar air temperature, orbital insolation, and the modern spatial distributions of temperature and precipitation. Antarctic and Greenland ice sheets are assumed to account for 5% of ocean isotopic change and 15% of sea level change. Deep water temperature is assumed to scale linearly with the 3-ka mean air temperature. At each time step air temperature is adjusted to maximize agreement between predicted $\delta^{18}O_c$ and the observed value 0.1 ka later in a benthic $\delta^{18}O_c$ stack (Lisiecki and Raymo, 2005). The model solves for ice volume, temperature, and sea level changes since 1070 ka in 0.1 ka time steps; however, the $\delta^{18}O_c$ stack used to constrain the model has a resolution of 1-1.5 ka. Uncertainty in modeled sea level is approximately ±12 m (1σ).

2.6 Hydraulic control models of semi-isolated basins

Two sea level reconstructions use hydraulic control models to relate planktonic $\delta^{18}O_c$ from the Red Sea and Mediterranean Sea to relative sea level. In these semi-isolated basins, $\delta^{18}O_{sw}$ is strongly affected by evaporation and exchange with the open ocean as affected by relative sea level at the basin's sill.

Red Sea RSL (Rohling et al., 2009) from 0-520 ka is estimated using the $\delta^{18}O_c$ of planktonic foraminifera from the central Red Sea (GeoTü-KL09). Because extremely saline conditions killed foraminifera during MIS 2 and MIS 12, $\delta^{18}O_c$ data for these time intervals were estimated by transforming bulk sediment values. Sea level is estimated using a physical circulation model for the Red Sea combined with an oxygen isotope model (Siddall et al., 2004). The physical circulation model simulates exchange flow through the Bab-el-Mondab strait which depends strongly on sea level. The current sill depth is 137 m, and its estimated uplift rate is 0.2 m ka^{-1}. The isotope model assumes steady state with exchange through the sill and evaporation/precipitation. Assumptions of the isotope model include: (1) modern evaporation rates and humidity, (2) open ocean $\delta^{18}O_{sw}$ scales as 0.01‰m^{-1}, and (3) SST scales linearly with sea level. A 5° C change in SST between Holocene and LGM is used to optimize the model's LGM sea level estimate. Steady state model solutions for different sea level estimates are used

to develop a conversion between $\delta^{18}O_c$ and sea level, which is approximated as a fifth-order polynomial. Sensitivity tests using plausible ranges of climatic values yield a 2-σ uncertainty estimate of $\pm$ 12 m.

A Mediterranean RSL record (Rohling et al, 2014) is derived from a hydraulic model of flow through the Strait of Gibraltar (Bryden and Kinder, 1991) combined with evaporation and oxygen isotope fractionation equations for the Mediterranean (~~Rohling~~ Siddall et al., 2004). Runoff and precipitation are parameterized based on present-day observations, humidity is assumed constant, and temperature is assumed to covary with sea level. The $\delta^{18}O_{sw}$ of Atlantic inflow is scaled using 0.009‰m^{-1}, and net heat flow through the sill is assumed to be zero. The combined models yield a converter between $\delta^{18}O_c$ and sea level, which is approximated as a polynomial. This polynomial conversion is applied to an eastern Mediterranean planktonic $\delta^{18}O_c$ stack (Wang et al., 2010) after identification and removal of sapropel layers. Model uncertainty is evaluated using random parameter variations, which yield 95% confidence intervals of $\pm$20 m for individual $\delta^{18}O_c$ values. In a probabilistic assessment of the final sea level reconstruction with 1-ka time steps these uncertainties are reduced to $\pm$6.3 m. Additionally, the authors propose that RSL at this location is linearly proportional to eustatic sea level.

3   Methods

3.1   Record inclusion criteria

The criteria ~~of~~for record inclusion in our stack ~~in order of priority~~ were ~~1.)~~availability, ~~2.)~~a ~~minimum~~ temporal resolution of at least 5 ka, and a length of ~~3.)~~at least 4~~0~~30 ka ~~long; additionally,.~~ ~~those records in the short stack~~T~~t~~he five records which extended to 798 ka were also included in ~~the~~a longer stack. Some available records were too short for inclusion ~~in the principal component analysis~~ (e.g., Dwyer et al., 1995; Martin et al, 2002; Lea et al., 2002). The record of Siddall et al (2010) was not included because it was based on the same technique as Waelbroeck et al (2002) but with lower resolution. Bates et al (2014) extended this technique to many benthic $\delta^{18}O$~~d18O~~ records but advocated against placing them all on a common age model; therefore, we include a summary of that study's lowstand and highstand estimates in Table~~s~~ 2 ~~and 3~~ rather than aligning them for inclusion in the stack.

Several important records were considered for inclusion in the stack which we did not include for the reasons stated above. For example the benthic Mg/Ca temperature record (Martin, et al 2002) was considered, but it was not long enough at 350 ka. Additionally, this temperature record had not been converted to sea level. The (Lea et al., 2002) planktonic record of sea level was based on the (Martin et al, 2002) method; data from a nearby core (Lea et al., 2006) was included in the planktonic stack record (Shakun et al., 2014) so we did not include it additionally in our analysis. Likewise, although (Dwyer et al., 1995) published a late Quaternary record of sea level from ostracod data; it was only 220 ka in length.

Finally, (Bates et al, 2010) published sea level of several individual records. This study was an attempt to discern the relative contributions of obliquity and eccentricity to glacial cyclicity through the examination of the spectra of several individual records of sea level; because of the intent of the author to examine the overarching Milankovitch forcing among individual records of sea level, we did not include these records in our study. Furthermore, 3 core records in (Bates et al., 2010) are already included in three separate sea level records in our study (Sosdian and Rosenthal, 2009; Elderfield, 2012; Waelbroeck, 2002). All core records in the (Bates et al., 2010) study are also included in the (Lisiecki and Raymo, 2005) stack, whose record was used as the basis for the (Bintanja, 2005) sea level record. However, we included the (Bates et al., 2010) data in our tables Tables 2 and 3).

2.83.2 Age models

To create an average (or stack) of sea level records, all of the time series must be placed on a common age model (Fig. 1). Here we use the age model of the orbitally tuned "LR04" benthic $\delta^{18}O_c$ stack (Lisiecki and Raymo, 2005). Because the LR04 age model, which has an uncertainty of 4 ka in the Late Pleistocene., our interpretation focuses on the amplitude of sea level variability rather than its precise timing. An age model for the Red Sea reconstruction based on correlation to speleothems is generally similar to LR04 with smaller age uncertainty but only extends to 500 ka (Grant et al., 2014) and, thus, does not provide an age framework for the entire 800798 ka stack. Therefore,Due to age model uncertainty, our interpretation focuses on the amplitude of sea level variability rather than its precise timing.

We do not assume that sea level varies synchronously with benthic $\delta^{18}O_c$. Rather, our aAge models development involved eitherfor three of the reconstructions are based on aligning individual $\delta^{18}O_c$ records to the LR04 $\delta^{18}O_c$ stack, and one reconstruction (Bintanja et al., 2005)

was derived directly from the LR04 stack. The other three ~~or aligning individual~~ sea level ~~records~~ reconstructions were dated by aligning their sea level estimates to a preliminary stack of the ~~other~~ four sea level records that ~~had been~~were ~~placed on the LR04 age model~~ dated ~~based on~~using $\delta^{18}O_c$ alignments. ~~A~~All ~~a~~lignments were performed using the Match graphic correlation software package (Lisiecki and Lisiecki, 2002).

The three records which use $\delta^{18}O_c$ alignments to the LR04 stack are Sites 607, 1123, and the planktonic $\delta^{18}O_{sw}$ stack. For Site 607 we perform our own alignment of benthic $\delta^{18}O_c$ to the LR04 stack, whereas for the other two we use the same age models published by Elderfield et al. (2012) and Shakun et al (2015). One potential concern about aligning benthic $\delta^{18}O_c$ records is that the timing of benthic $\delta^{18}O_c$ change at different sites may differ by as much as 4 kyr during glacial terminations (Skinner and Shackleton, 2005; Lisiecki and Raymo, 2009; Stern and Lisiecki, 2014). The potential effects of lags in benthic $\delta^{18}O_c$ are ~~included in our~~evaluated using bootstrap uncertainty analysis (Section 4.2). ~~The benthic $\delta^{18}O_c$ records from sites 1123 and 607 were aligned to the LR04 stack. Similarly, the published age model for the planktonic $\delta^{18}O_{sw}$ stack was developed by aligning each core's benthic $\delta^{18}O_c$ record (or planktonic $\delta^{18}O_c$ where benthic data were unavailable) to the LR04 stack. The original age model of Bintanja et al. (2005) is also consistent with the LR04 age model because the LR04 stack was used as a constraint for the inverse model.~~

~~However, f~~For three reconstructions (Waelbroeck et al., 2002; Rohling et al., 2009, 2014) we aligned the individual sea level records with a preliminary sea level stack based on the other four sea level records on the LR04 age model. This was necessary because the local $\delta^{18}O_c$ signals in semi-isolated basins (Rohling et al., 2009; 2014) differ substantially from global mean benthic $\delta^{18}O_c$. In the coral-regression reconstruction, Waelbroeck et al. (2002) pasted together portions of individual cores to form a preferred global composite. Although each core has benthic $\delta^{18}O_c$ data, generating new age estimates for these cores could alter their $\delta^{18}O_c$ regression functions or create gaps or inconsistencies in the composite. The procedure of aligning these three sea level records (Waelbroeck et al, 2002; Rohling et al., 2009, 2014) to a preliminary sea level stack should be approximately as accurate as the $\delta^{18}O_c$ alignments. However, the direct sea level alignments do have a slightly greater potential to align noise or local sea level variability.

After age models were adjusted, five of the records ended within the Holocene. Therefore, we appended a value of 0 m (i.e., present day sea level) at 0 ka. In the two records which did end

at 0 ka, modern sea level estimates were slightly below zero: -1.5 m (Bintanja, 2005) and -1.3 m (Rohling et al., 2014).

2.93.3 Principal component analysis

Principal Component Analysis (PCA) PCA is commonly used to create stacks of paleoclimate data (e.g., Huybers and Wunsch, 2004; Clark et al, 2012; Gibbons et al, 2014) and to quantify the common signal contained in core data. Synthesis is valuable because each record has its own assumptions and errors. If these records are all well-constrained measures of sea level, then PCA will reveal their respective levels of agreement or discrepancy. Additionally, PCA does not require the assumption that each sea level record represents an independent measure of common signal. In contrast, a sea level estimate based on the unweighted mean of records would imply that uncertainties are uncorrelated across individual reconstructions. While all records contain a strong ice volume signal, some of the non-ice volume signal would beare expected to correlate with one another. For example, as the $\delta^{18}O$ of ice sheet changes as it melts or freezes, the conversion from the $\delta^{18}O_{sw}$ to ice volume will be systematically biased, andwhereas changes in the hydrological cycle may induce changes in the spatial variability of $\delta^{18}O_{sw}$ as measured at different locations in the ocean.

We use include both relative and eustatic sea level estimates in the Principal Component Analysis (PCA)the analysis because PCA should identify the common variance that dominates both relative and eustatic sea level records.

PCA is commonly used to create stacks of paleoclimate data (e.g., Huybers and Wunsch, 2004; Clark et al, 2012; Gibbons et al, 2014) for the creation of stacks or quantifying the common signal contained in core data. Synthesis is valuable because each record has its own assumptions and errors. If these records are all well-constrained measures of sea level, then synthesis will reveal their respective levels of agreement or discrepancy. Specific examples of other recent synthesis studies include (Milker et al., 2013; Shakun et al., 2014).

.Additionally, PCA does not require the assumption that each sea level record represents an independent measure of common signal. In contrast, a sea level estimate based on the unweighted mean of records would imply that uncertainties are uncorrelated across individual reconstructions. While all records contain a strong ice volume signal, some of the non-ice volume signal would be expected to correlate with one another. For example, as the $\delta^{18}O$ of ice sheet changes as it melts or freezes, the conversion from the $\delta^{18}O_{sw}$ to ice volume will be

Three records are proxies for relative sea level at their respective locations: the strait of Gibraltar (Rohling et al., 2014), the Bab el Mondab strait (Rohling et al., 2009), and tropical coral terraces (Waelbroeck et al., 2002). The inverse model generates eustatic sea level from a modeled ice volume estimate (Bintanja et al., 2005), and the three $\delta^{18}O_{sw}$ records (Elderfield et al., 2012; Sosdian and Rosenthal, 2009; Shakun et al., 2015) were scaled to eustatic sea level. However, for the planktonic stack we use the $\delta^{18}O_{sw}$ record rather than the eustatic sea level conversion because the sea level conversion involved detrending to make planktonic $\delta^{18}O_c$ values agree with benthic $\delta^{18}O_c$. Because PCA is designed to identify the common variance between the sea level proxies, it is preferable to keep the planktonic and benthic $\delta^{18}O_{sw}$ records independent of one another.

In the Mediterranean RSL record we removed putative sapropel layers at 434-452 ka, 543-558 ka, and 630-663 ka as visually identified by Rohling et al. (2014). and linearly interpolatedInstead ofBecause interpolating linearly across these gaps (Fig. 1) , which would bias thesea level analysisestimates towards higher lowstands atfor the deglaciationsglacial maxima occurring during these sapropel layers, we created a floor function for the duration of each sapropel which then skipsassumed that sea level remained constant at its pre-sapropel (glacial) level and then immediately jumped to the higher sea level values atobserved the conclusionends of the sapropel layers (midway through the glacial terminations). Although interpolation across large gapsthis solution is not ideal, we must assume some sea level value at these times in order to include this record in the PCA. Additionally, since our analysis is focused on estimating eustatic highstands and lowstands at the various Marine Isotope Stages rather than the timing of each individual records' highstands and lowstands, we view the floor function rather than linear interpolation an appropriate choice for this record.

Before PCA, all seven records were interpolated to an even 1-ka time step. Then, to ensure equal weighting for each record in the PCA, each time series was normalized to a mean of zero and a standard deviation of one within each of the two time windows (0-430 ka and 0-798 ka). PCA was performed on seven records from 0-430 ka and five records from 0-798 ka (Fig. 2). Because PC1 produces similar loadings for each record (Table 1), the PC1 scores

approximate the average of all records for each point in time, which we refer to as a sea level stack.

We scaled the short and long stacks to eustatic sea level using an LGM value of -130 m at 24 ka based on a GIA-corrected coral compilation (Clark et al., 2009) and a Holocene value of 0 m at 5 ka. We scale the Holocene at 5 ka because eustatic sea level has been essentially constant for the past 5 ka (Clark et al., 2009), whereas the sea level stacks display a trend throughout the Holocene perhaps due to bioturbation in the sediment cores. Scaling the sea level stack based on the mid-Holocene (rather than 0 ka) should more accurately correct for the effects of bioturbation on previous interglacials because those highstand values have been subjected to mixing from both above and below. Finally, a composite sea level stack was created by joining the 0-430 ka stack with the 431-798 ka portion of the long stack after each was scaled to sea level. Because the two scaled sea level stacks produce similar values for 0-430 ka (Fig. 2), no correction was needed to combine the records.

4   Uncertainty analysis

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3   Mean sea level estimates

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Because each of the records in the PCA is a sea level proxy and PC1 describes the majority of variance in the records, PC1 should represent the underlying common eustatic sea level signal in all proxies. PC1 describes 82% of the variance in the seven records from 0-430 ka and 76% of proxy variance from 0-798 ka. Where the two time windows overlap (Figure 2), the scaled sea level stacks have a root mean square error of only 3.4 m, thereby suggesting that the long stack is nearly as accurate as the short stack although it contains two fewer records. The scaled PC1 also closely resembles the unweighted mean of the seven individual records, except that the unweighted mean underestimates LGM sea level (Figure 2b). We assess the uncertainty of the scaled PC1 using threemultipletwo techniques: comparison with highstand and lowstand estimates from individual records (Section 4.1)., comparison with the comparison with the unweighted mean s of all records in the stack (sSection 4.1), and and a combination ofusing bootstrapping and Monte Carlo-style random sampling (Section 4.2).

4.1 Mean sea level estimates

To test the effectiveness of using the scaled PC1 as a record of mean sea level, we compared our stack with highstand and lowstand values identified from individual records and with coral-based estimates where available (Tables 2 and 3). We picked the relevant highstand or lowstand for each individual record by choosing the peak that lies within the age range of each Marine Isotope Stage (MIS) as identified in the sea level stack. Highstand or lowstand peaks which occurred outside of the age range of each particular glacial or interglacial stage were not used (e.g., extreme values at ~250 ka from ODP Sites 1123 and 607).

Highstand sea level estimates vary widely between individual records with standard deviations of 11-26 m for each isotopic stage (Table 3). For example, individual estimates for ~~Marine Isotope Stage (~~MIS) 11 at ~400 ka vary between ~~-1~~ 5 to 57 m above modern, with a mean of ~~20~~ 18 m and a standard deviation of ~~26~~ 25 m. MIS 5e (119-126 ka) estimates range from ~~-6~~ 4 to 28 m above modern with a mean of ~~9~~ 7 m and a standard deviation of 12 m. Generally, the highstand means have slightly greater amplitudes than our scaled stack; for example, the scaled stack estimates are ~~16~~ 18 m and ~~3~~ 7 m for MIS 11 and MIS 5e, respectively. On the other hand, the mean of individual lowstands for the LGM (~~-121~~ 123 m) underestimates eustatic sea level change, which is estimated to be ~~-125~~ 130 to -134 m (Clark et al, 2009; Lambeck et al., 2014~~; Rohling et al., 2014~~).

The means of the individually picked highstands may be biased by the additive effects of noise. Conversely, the stack may underestimate sea level highstands if the individual age models are not properly aligned. The most definitive sea level estimates come from GIA-corrected coral compilations, which yield highstand estimates of 6-13 m above modern for MIS 11 (Raymo and Mitrovica, 2012) and 8-9.4 m for MIS 5e (Kopp et al., 2009). These values suggest that the stack may be more accurate for MIS 11 than MIS 5e, potentially because age model uncertainty would have less effect on the longer MIS 11 highstand. In contrast, MIS 5e may have consisted of two highstands each lasting only ~2 ka separated by several thousand years with sea level at or below modern (Kopp et al., 2013). Thus, the stack's highstand estimates likely fail to capture short-term sea level fluctuations but rather reflect mean sea level during each interglacial.

To further ~~illustrate how the scaled PC1 compares to the mean record of sea level~~test the sensitivity of our method, we ~~graphed~~ compared the scaled PC1 with the unweighted mean of the seven~~our~~ interpolated sea level records (Figure 2b). The unweighted-mean stack incorporates the same data as scaled PC1 except that it excludes Mediterranean estimates from

sapropel intervals and uses the detrended sea level estimates from Shakun et al. (2015) instead of the raw $\delta^{18}O_{sw}$ data. The unweighted stack closely resembles PC1 because the loadings of PC1 are very similar for all seven records (Table 1). However, the unweighted stack underestimates LGM sea level, possibly because some records (e.g., Rohling et al, 2009) may contain brief gaps at the glacial maximum. Thus, we prefer to scale PC1 to agree with well-constrained LGM sea level estimates. ~~Additionally,~~The scaled PC1 is in ~~glacial sea level estimates are in good~~better agreement with the glacial sea level estimates ~~between the scaled PC1 and~~of the unweighted five-record stack from 430-798 ka. ~~To create Figure 2b, we pasted the unweighted mean of the short stack of seven records to the unweighted mean of the long stack with five records. The planktonic stack in the unweighted mean is the undetrended record of $\delta^{18}O_{sw}$ scaled to sea level (-130 m at the LGM and 0 m at 3 ka). As with the individual means, the lowstands in the unweighted mean graph underestimate sea level change with respect to scaled PC1 at the glacial maxima, particularly for MIS 2-10, by an average of 11 m. However, for the majority of the scaled PC1, mean sea level highstands match scaled PC1, with the exception of MIS 11, with an approximate 3 m underestimate by the unweighted mean as compared to PC1. Smoothing occurs with respect to the mean highstands and lowstands in Figure 2b as compared to the means of the individual records in Tables 2 and 3; thereforefore the glacial/interglacial sea level maxima may not be as great as in PC1 or the individual means. Table 1 shows loads for the short and long PC1 records of ~ .4 indicating that all the records receive similar weightings in our scaled PC1 and therefore will strongly resemble the unweighted mean.~~

4.2   Bootstrapping and random sampling

We estimate uncertainty in the stack using a bootstrap technique instead of using the published uncertainty estimates for each sea level reconstruction, which are based on different assumptions and techniques and do not necessarily include all sources of uncertainty (e.g., uncertainty in benthic $\delta^{18}O_c$ alignments). We ran 1000 bootstrap iterations while also performing random sampling to account for several of the uncertainties associated with our method. Before each iteration of the bootstrapped PCA, we simulate the effects of uncertainty associated with our age model alignments by applying an independent age shift of -2, -1, 0, +1, or +2 ka to each component record, with each potential value selected with equal probability.

After performing each iteration of the PCA, we use random sampling to evaluate the effects of uncertainty associated with scaling PC1 to Holocene and LGM sea level. The particular Holocene point scaled to 0 m is randomly sampled from 0 – 6 ka with uniform distribution. The LGM age is identified as the minimum sea level estimate between 19-34 ka, and the sea level to which it is scaled is sampled with a normal distribution centered at 132 m with a standard deviation of 2 m. ~~Using this technique, we find that the~~The bootstrap results for the scaled PC1 yield a mean standard deviation ~~for scaled PC1 is~~of 9.4 m with seven records (0-430 ka) and 12 m with five records (0-798 ka). ~~Simulating~~Additionally, the inclusion of age uncertainty in the bootstrap analysis has the effect of systematically smoothing the record. Because many of the individual reconstructions are of low resolution relative to brief interglacial highstands such as MIS 5e and 7e, the ~~smoothing associated with our simulation of age uncertainty is~~bootstrap results are biased towards underestimating these ~~sea level~~highstands (Figure 2c).

45 The sea level contribution to benthic $\delta^{18}O_c$

The sea level stack and the LR04 benthic $\delta^{18}O_c$ stack are strongly correlated (r = -0.90). However, because $\delta^{18}O_c$ contains both an ice volume and temperature component, the $\delta^{18}O_c$ record has a greater amplitude than the ice volume-driven $\delta^{18}O_{sw}$ record. The spectral variance of $\delta^{18}O_{sw}$ and $\delta^{18}O_c$ in each orbital band can be used to determine the relative contributions of sea level and temperature variability in $\delta^{18}O_c$. For this comparison, we convert the sea level stack to $\delta^{18}O_{sw}$ using 0.009‰ m^{-1}.

Although some studies have used 0.01‰m^{-1} (e.g., Sosdian et al., 2009; Elderfield et al., 2012; Rohling et al., 2009), this conversion factor is likely too high for global mean $\delta^{18}O_{sw}$ change at the LGM. Several lines of evidence suggest an LGM $\delta^{18}O_{sw}$ change of 1–1.1‰ (Duplessy et al., 2002; Adkins et al., 2002; Elderfield et al., 2012; Shakun et al., 2015), while LGM sea level was likely 125-134 m below modern (Clark et al., 2009; Lambeck et al., 2014; Rohling et al, 2014). These estimates suggest a conversion factor between 0.008-0.009‰m^{-1}. A conversion of 0.008‰m^{-1} would be consistent with a $\delta^{18}O_{ice}$ of -32‰ (Elderfield et al., 2012), similar to estimates for the Laurentide and Eurasian ice sheets (Duplessy et al., 2002; Bintanja et al., 2005; Elderfield et al., 2012). Therefore, 0.009‰m^{-1} may be more appropriate when also considering changes in Greenland and Antarctic ice. However, the conversion factor between sea level and

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mean $\delta^{18}O_{sw}$ also likely varies through time as a result of changes in the mean isotopic content of each ice sheet (Bintanja et al, 2005) and their relative sizes.

Spectral analysis shows strong 100-ka and 41-ka peaks in both the LR04 benthic $\delta^{18}O_c$ stack and the sea level stack (Figure 3). When converted to $\delta^{18}O_{sw}$, the sea level stack contains 4~~7~~% as much 100-ka power (using a frequency band of 0.009-0.013 ka^{-1}) as benthic $\delta^{18}O_c$ and 3~~7~~% as much 41-ka power (0.024-0.026 ka^{-1}). Considering all frequencies less than 0.1 ka^{-1}, $\delta^{18}O_{sw}$ explains 4~~4~~% of the variance in $\delta^{18}O_c$. Therefore, we conclude that on average about 40~~45~~% of the glacial cycle variance in benthic $\delta^{18}O_c$ derives from ice volume change and 55~~60~~% from deep sea temperature change.

This ~4~~5~~0% ice volume contribution to benthic $\delta^{18}O_c$ is smaller than the contribution estimated across the LGM to Holocene transition. An LGM sea level change of 130 m (Clark et al., 2009) should shift mean $\delta^{18}O_{sw}$ by 1.17‰, whereas benthic $\delta^{18}O_c$ changed by 1.79‰ (Lisiecki and Raymo, 2005), suggesting that 65% of the LGM $\delta^{18}O_c$ change was driven by ice volume. Many other studies have similarly found that the ice volume ($\delta^{18}O_{sw}$) contribution to $\delta^{18}O_c$ is greatest during glacial maxima (Bintanja et al, 2005; Elderfield et al, 2012; Rohling et al., 2014; Shakun et al, 2015). Additionally, the $\delta^{18}O_{sw}$ contribution varies by location, ranging from 0.7‰ to 1.37‰ based on glacial pore water reconstructions (Adkins et al., 2002). The wide variability in $\delta^{18}O_{sw}$ between sites suggests that changes in deep water formation processes (e.g., evaporation versus brine rejection) greatly affect the $\delta^{18}O_{sw}$ signal regionally or locally. Therefore, the $\delta^{18}O_{sw}$ at a single site may differ considerably from eustatic sea level.

~~5~~6 Converting from benthic $\delta^{18}O_c$ and sea level

Many studies have used benthic $\delta^{18}O_c$ as a proxy for ice volume based on the argument that temperature and ice volume should be highly correlated through time (e.g., Imbrie and Imbrie, 1980; Abe-Ouchi et al., 2013). However, calculations based on the sea level stack spectral power and LGM-to-Holocene change, suggest that~~Although~~ ice volume change accounts for only 4~~5~~0-65% of ~~the~~ benthic $\delta^{18}O_c$ glacial cyclicity. Additionally, ~~change, many studies have used benthic $\delta^{18}O_c$ as a proxy for ice volume based on the argument that temperature and ice volume should be highly correlated through time (e.g., Imbrie and Imbrie, 1980; Abe-Ouchi et al., 2013). However,~~ over the course of a glacial cycle the relative contributions of ice volume and temperature change dramatically, ~~and~~ with temperature change preced~~es~~ing ice volume change (Bintanja et al., 2005; Elderfield et al., 2012; Shakun et al., 2015). Despite these

complications the LR04 benthic $\delta^{18}O_c$ stack is strongly correlated with the sea level stack (r = -0.9). Here we explore more closely the functional relationship between benthic $\delta^{18}O_c$ and sea level as inspired by Waelbroeck et al (2002).

Waelbroeck et al. (2002) solved for regression functions between several benthic $\delta^{18}O_c$ records and coral elevation data over the last glacial cycle and found different functional forms for glaciation versus deglaciation and for the North Atlantic versus equatorial Pacific $\delta^{18}O_c$. ~~Transfer functions between benthic $\delta^{18}O_c$ and sea level have also been estimated at lower resolution for 0-5 Ma (Siddall et al., 2010; Bates et al., 2014)~~ Here we compare the LR04 global benthic stack with the sea level stack from 0-798 ka. One advantage of this comparison is that both records use the same age model. We evaluate whether a single regression can be used for the Late Pleistocene and identify a potential change in the relationship between benthic $\delta^{18}O_c$ and sea level at ~400 ka.

One difference between the two stacks is that the sea level stack is smoother (Fig. 2), likely because some of the sea level records are low resolution and all records were interpolated to 1 ka spacing for PCA. Smoothing the LR04 stack using a 7-ka running mean improves the correlation between benthic $\delta^{18}O_c$ and sea level from -0.90 to -0.92. Additionally, we estimate the phase lag between the two records by measuring their correlation with different time shifts. ~~We find~~This analysis suggests a 2 ka phase lag between LR04 and the sea level stack, likely resulting from the fact that deep water temperature change ~~leads~~leads ice volume change (e.g., Sosdian and Rosenthal, 2009; Elderfield et al., 2012; Shakun et al., 2015). When~~Next~~ we apply ~~a~~this 2 ka lag to the smoothed LR04 stack, ~~which improves the~~its correlation with sea level improves to -0.94.

OLS linear regression between the ~~smoothed~~smoothed and ~~and~~lagged LR04 benthic $\delta^{18}O_c$ stack (x) and sea level in meters (h) yields the equation

$$h = -7\underline{3}~\text{\sout{2.5}}x + 2\underline{51}\text{\sout{49.1}} \tag{1}$$

(Fig. 4, black line). The root mean square error (rmse) for this model is 10.~~5~~7 m, but the fit is better for the older portion of the record (398-798 ka, rmse=~~9.7~~10.2 m) than the more recent portion (0-397 ka, rmse=11.~~3~~2 m). In particular, the linear model estimates sea levels that are 10-20 m too high during most highstands and lowstands back to MIS 10 at ~345 ka. A plot of sea level versus the smoothed and lagged benthic $\delta^{18}O_c$ (Figure 4b) suggests that the relationship between the two is approximately quadratic

$$h = -26 \ x^2 + 135 \ x \ -\underline{-} \ 16\underline{3}\sout{2} \tag{2}$$

from 0 – 397 ka (rmse = 9.$\underline{4}\sout{5}$ m) and linear from 398-798 ka. This transition appears to take place between 360-400 ka because MIS 11 clearly falls on the linear trend ~~(Figure 4c)~~ whereas MIS 10 is much better fit by the quadratic (Figure 4$\underline{a}\sout{b}$). Because this transition occurs after MIS 11, the extreme duration or warmth of this interglacial might have played an important role in the transition.

A change in the relationship between benthic $\delta^{18}O_c$ and sea level could be caused by a change in the mean isotopic content of ice sheets or the relationship between ice volume and deep water temperature (possibly also global surface temperature). To explain this transition, interglacials after MIS 11 were likely warmer or had more depleted $\delta^{18}O_{sw}$ relative to ice volume. Similarly, glacial maxima were probably warmer and/or had less $\delta^{18}O_{sw}$ change. Combined changes in temperature and isotopic fractionation may be the most likely explanation since warmer ice sheets also probably have less depleted $\delta^{18}O_{ice}$. In fact Antarctic ice cores are isotopically less depleted during MIS 5e and MIS 9 than MIS 11 (Jouzel et al., 2010). Additionally, Antarctic surface temperatures and CO_2 levels were similar for all three interglacials (Masson-Delmotte et al., 2010; Petit et al., 1999) despite the smaller ice volume during MIS 11.

There is little direct evidence to explain the changing relationship between $\delta^{18}O_c$ and sea level during in glacial maxima because glacial values for both deep water temperature and the isotopic composition of Antarctic ice are similar throughout the last 800 ka. The change in glacial maxima after 400 ka could be caused by less depleted $\delta^{18}O_{ice}$ in Northern Hemisphere (NH) ice sheets. Although no long records of NH $\delta^{18}O_{ice}$ exist, global mean SST was 0.5-1°C warmer during MIS 2, 6, and 8 than during MIS 12 (Shakun et al., 2015). Alternatively, the apparent linear trend between sea level and $\delta^{18}O_c$ during glacial maxima before 400 ka (Figure 4c) could be an artifact of poor sea level estimates for MIS 12 and 16, which may be biased 10-20 m too high (Table $\underline{2}\sout{3}$) by ~~interpolation across~~$\underline{\text{missing data during}}$ sapropel intervals in the Mediterranean RSL record (Rohling et al., 2014).

In conclusion, a systematic relationship can be defined between Late Pleistocene benthic $\delta^{18}O_c$ and sea level, and the functional form of this relationship likely changed after MIS 11. Change in the $\delta^{18}O_c$-sea level relationship during interglacials likely results from warmer high latitudes with less depleted $\delta^{18}O_{ice}$ after 400 ka. Glacial maxima after 400 ka may also have been warmer with less depleted NH $\delta^{18}O_{ice}$, but this apparent change during glacial maxima could be an

artifact of bias in the sea level stack during MIS 12 and 16. Changes in the relationship between benthic $\delta^{18}O_c$ and sea level are also likely to have occurred during the early or mid-Pleistocene. For example, the same regression probably would not apply to the 41-ka glacial cycles of the early Pleistocene (Tian et al., 2003).

6 7   Differences between sea level proxies

Whereas PC1 tells us about the common variance between the sea level proxies, PC2 and PC3 tell us about their differences. PC2 represents 6% and 8% of the variance for the short and long time windows, respectively. The scores and loads are similar for both analyses (Fig. 5 and Table 1) except for a sign change; therefore, we multiply by -1 the scores and loads of PC2 and PC3 of the short t/long(???) time window. Because the loadings of short PC2 are opposite in sign to long PC2, we multiply the scores of the short window PC2 by -1 for equivalent comparison. Additionally, the loadings of long PC3 are opposite in sign to short PC3, so we also multiply long PC3 by minus one. Large PC2 loadings with opposite sign contributions for the 1123 and 607 benthic $\delta^{18}O_{sw}$ records suggest that PC2 represents differences in the $\delta^{18}O_{sw}$ of deep water in the Atlantic and Pacific basins. Most notably, PC2 has a strong peak at approximately 250 ka (Fig. 5), associated with very low values in the 607 benthic $\delta^{18}O_{sw}$ record and very high values in the 1123 benthic $\delta^{18}O_{sw}$ record (Fig. 1).

PC3 captures 5% of the variance in the 430-ka stack and 6% of the variance in the 798-ka stack. Unlike PC1 and PC2, the loads vary between the short and long PC3 (Table 1); here we focus on the short version because it contains more proxy records. In the 430-ka stack, PC3 is most highly represented by the planktonic $\delta^{18}O_{sw}$ stack with a load of -0.7 and the 1123 and 607 benthic $\delta^{18}O_{sw}$ records with loads of about -0.75 4. These loads suggest that PC3 dominantly reflects planktonic versus benthic differences in $\delta^{18}O_{sw}$. PC3 scores exhibit a linear trend from 0-430 ka, which supports the findings of previous studies that suggest planktonic $\delta^{18}O_{sw}$ should be detrended for conversion to sea level (Lea et al., 2002; Shakun et al., 2015). Furthermore, PC3 suggests that benthic $\delta^{18}O_{sw}$ may also need to be detrended in the opposite direction. This effect could be caused by long-term changes in the hydrologic cycle or deep water formation processes, which lead to a change in the partitioning of oxygen isotopes between the surface and deep ocean.

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7̶8 Conclusions

PCA indicates a strong common sea level signal in the seven records analyzed for 0-430 ka and five records for 0-798 ka. Furthermore, the similarity between the short and long stacks indicate that the longer stack with five records is nearly as good an approximation of sea level as the seven-record stack. Sea level estimates for each interglacial vary greatly between records, producing standard deviations of 11-26 m. Generally, the mean for each individual highstand is greater in magnitude than our stack estimate. Based on comparison with GIA-corrected coral sea level estimates for MIS 5e and 11, the stack likely reflects mean sea level for each interglacial and fails to capture brief sea level highstands, such as those lasting only ~2 ka during MIS 5e (Kopp et al., 2̶0̶0̶9̶13).

A comparison of individual records shows that high and lowstand estimates have a mean standard deviation of 17 m (for MIS 5e - 19). Uncertainty in the stack is estimated using bootstrapping and random sampling, which yields a mean standard deviation for scaled PC1 of 9.4 m with seven records (0-430 ka) and 12 m with five records (0-798 ka). The bootstrap uncertainty estimates also include age uncertainty; however, this systematically smooths the bootstrap results and, thus, underestimates individual highstands relative to both individual records and scaled PC1 (Figure 2c).

Using the bootstrapping technique to estimate uncertainty in the stack, we find that the mean standard deviation for scaled PC1 is 9.4 m with seven records (0-430 ka) and 12 m with five records (0-798 ka). Comparison to the mean standard deviation of all high and lowstand records in this analysis shows a standard deviation of 16-17 m, for the short and long records, respectively. Simulating age uncertainty in our bootstrap analysis has the effect of systematically smoothing the record and underestimating individual highstands.

We estimate that sea level change accounts for only about 4̶0̶45% of the orbital-band variance in benthic $\delta^{18}O_c$, compared to 65% of the LGM-to-Holocene benthic $\delta^{18}O_c$ change. Nonetheless, benthic $\delta^{18}O_c$ is strongly correlated with sea level (r = -0.9). If LR04 benthic $\delta^{18}O_c$ stack is smoothed and lagged by 2 ka, the relationship between benthic $\delta^{18}O_c$ and sea level is well-described by a linear function from 398-798 ka and a quadratic function from 0-398 ka. In particular, interglacials MIS 9 and 5e which had larger ice sheets than MIS 11 appear to have been as warm (or warmer) than MIS 11 with isotopically less depleted ice sheets.

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The second and third principal components of the sea level records describe differences between the proxies. PC2 represents the difference between the $\delta^{18}O_{sw}$ of deep water in the Atlantic and Pacific basins; a peak in PC2 scores at 250 ka indicates large differences between the basins at this time. PC3 represents the differences between planktonic and benthic $\delta^{18}O_{sw}$ records and suggests a linear trend between the two from 0-430 ka. Thus, $\delta^{18}O_{sw}$ records vary across ocean basins and between the surface and the deep. In conclusion, the stack of sea level proxies presented here should be a more accurate eustatic sea level record than any of the individual records it contains.

Data availability

The sea level stack is archived in the Supporting Information and (upon publication) at the World Data Center for Paleoclimatology operated by the National Climatic Data Center of the National Oceanographic and Atmospheric Association.

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Table 1. Principal Component Analysis (PCA) loading for each proxy record. "Short" refers to the 0-430 ka time window, and "Long" refers to 0-798 ka. Numbers in parentheses give the percent variance explained by each principal component.

	PC1 Short (83%)	PC1 Long (77%)	PC2 Short (6%)	PC2 Long (8%)	PC3 Short (5%)	PC3 Long (6%)
Inverse model (Bintanja et al., 2005)	0.4	0.48	-0.05	-0.11	-0.16	0.02
Pac. benthic $\delta^{18}O_{sw}$ (Elderfield et al., 2012)	0.34	0.44	-0.7	-0.5	0.52	0.67
Planktonic $\delta^{18}O_{sw}$ (Shakun et al., 2015)	0.37	0.45	-0.01	-0.19	-0.65	-0.65
RSL$_{Med}$ (Rohling et al, 2014)	0.38	0.45	0	0.01	0.04	-0.27
Atl. benthic $\delta^{18}O_{sw}$ (Sosdian and Rosenthal, 2009)	0.35	0.42	0.7	0.84	0.51	0.26
$\delta^{18}O_c$ regression (Waelbroeck et al., 2002)	0.4	-	0.08	-	-0.11	--
RSL$_{Red}$ (Rohling et al., 2009)	0.4	-	-0.01	-	-0.07	--

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RSL_{Med} (Rohling et al, 2014)	
. benthic $\delta^{18}O_{sw}$ (Sosdian and Rosenthal, 2009)	
$\delta^{18}O_e$ regression (Waelbroeck et al., 2002)	—
RSL_{Red} (Rohling et al., 2009)	—

Table 2. Sea level highstand and lowstand estimates from individual records (in meters above modern). See Table 1 for references. The last column gives the mean values from nine cores in Bates et al (2014); these estimates were not included in our PCA.

Marine Isotope Stage	Age Range (ka)	Invers nodel	Pac. $\delta^{18}O_{sw}$	RSL Red	RSL Med	Plank. $\delta^{18}O_{sw}$	Atl$\delta^{18}O_{sw}$	$\delta^{18}O_c$ regression	Mean from Bates et al. (2014)
2	18-25	-123	-113	-114	-120	-130	-124	-123	-133
5e	119-126	0	3	18	-4	-10	28	4.9	12
6	135-141	-123	-130	-99	-94	-138	-97	-129	-130
7a-c	197-214	-20	12	14	12	-16	34	-3.6	-3
7e	236-255	-18	16	-3	1	-20	-6.2	-9.4	-10
10	342-353	-111	-96	-114	-77	-96	-112	-126	-122
11	399-408	0	58	4	12	-5	57	5.7	9
12	427-458	-126	-146	-118		-143	-100		-147
13	486-502	-29	18		-8	-11	32		-5
16	625-636	-126	-113			-145	-125		-141
17	682-697	-23	31		0.5	-12	8.1		-4
19	761-782	-21	21		7.2	-1	-6.8		-2

Marine Isotope Stage	Age (ka)	Inverse model	Pac. benthic $\delta^{18}O_{sw}$	RSL Red	RSL Med	Plank. $\delta^{18}O_{sw}$	Atl. benthic $\delta^{18}O_{sw}$	$\delta^{18}O_c$ regression	Bates et al. (2014) mean
2	18-25	-123	-113	-114	-120	-130	-124	-123	-133
5e	119-126	0	3	18	-4	-10	28	4.9	12
6	135-141	-123	-130	-99	-94	-138	-97	-129	-130

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7a-c	197-214	-20	12	14	12	-16	34	-3.6	-3
7e	236-255	-18	16	-3	1	-20	-6.2	-9.4	-10
9	315-331	-0.5	40	11	-5	-27	43	5	8
10	342-353	-111	-96	-114	-77	-98	-112	-126	-122
11	399-408	0	58	4	12	-5	57	5.7	9
12	427-458	-126	-146	-118		-142	-100		-147
13	486-502	-29	18		-8	-11	32		-5
16	625-636	-126	-113			-144	-125		-141
17	682-697	-23	31		0.5	-12	8.1		-4
19	761-782	-21	21		7.2	-1	-6.8		-2

Table 3. Mean and standard deviation of sea level highstand and lowstand estimates (in meters above modern) from Table 2 compared to scaled PC1 and GIA-corrected from corals and other coastal proxies. GIA-corrected estimates for MIS 2 are from Clark et al. (2009) and Lambeck et al. (2014), for MIS 5e from Kopp et al. (2009) and Dutton et al. (2015), and for MIS 11 from Raymo and Mitrovica (2013).

Marine Isotope Stage	Age Range (ka)	Standard deviation	Mean	Scaled PC1 (0-430 ka)	Scaled PC1 (0-798 ka)	GIA-corrected estimates
2	18-25	7	-123	-130	-130	-130 to -134
5e	119-126	12	7	3	-1	6 to 9
6	135-141	18	-118	-123	-125	
7a-c	197-214	18	4	-7	-5	
7e	236-255	11	-6	-9	-13	
9	315-331	23	9	-1	-2	
10	342-353	16	-107	-108	-103	
11	399-408	25	18	16	19	6 to 13
12	427-458	19	-130		-124	
13	486-502	22	-1		-11	
16	625-636	13	-130		-15	
17	682-697	19	0		-9	
19	761-782	14	0		-6	

Figure 1. Eustatic and relative sea level estimates for the seven records on the LR04 age model (Lisiecki and Raymo, 2004). Yellow bars mark the sapropel layers removed from the Mediterranean RSL record (Rohling et al, 2014).
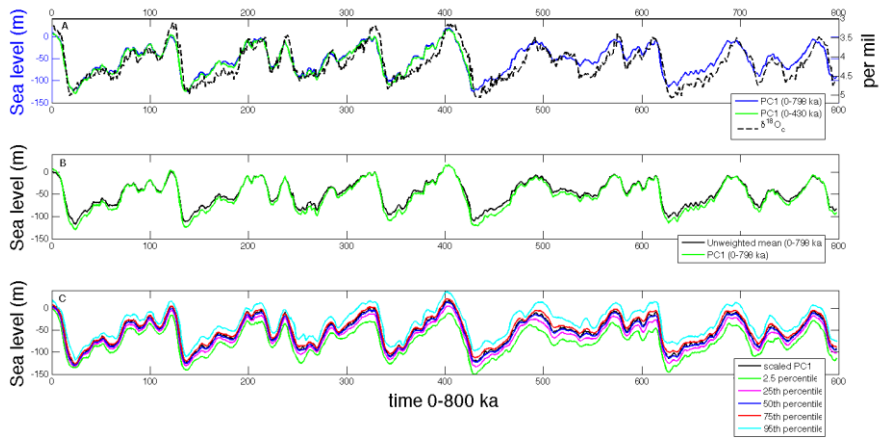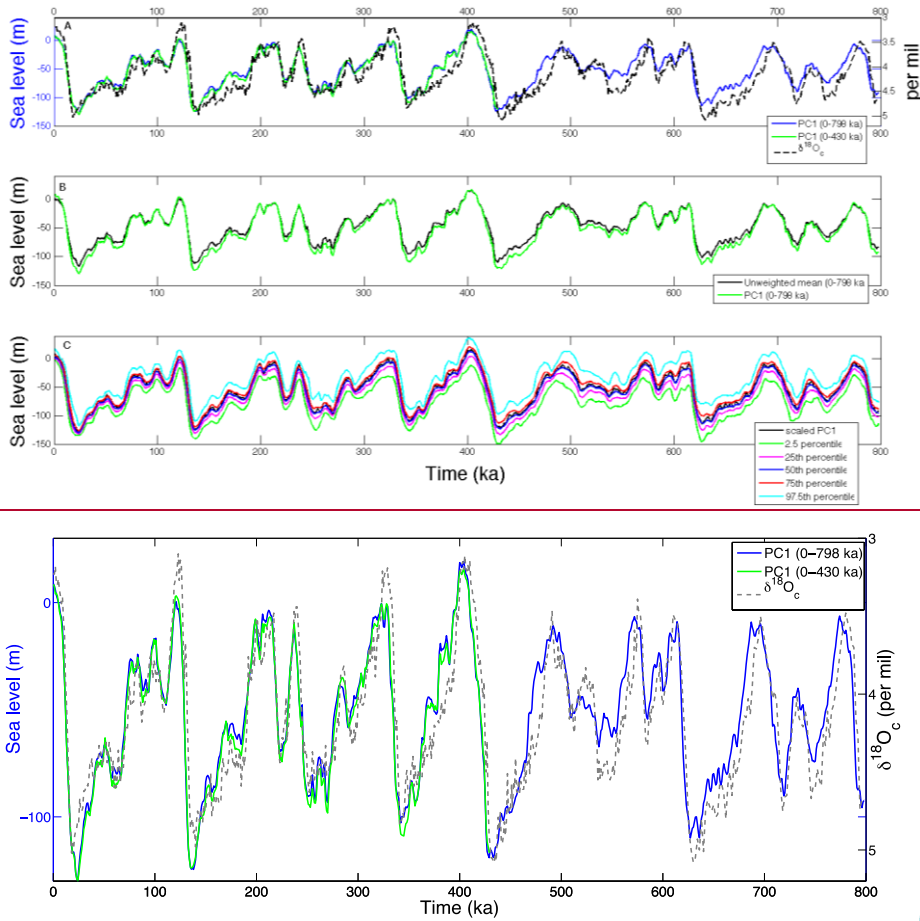
Figure 2. A. Long and short sea level stacks compared to the LR04 benthic $\delta^{18}O_c$ stack (Lisiecki and Raymo, 2005). B. Scaled PC1 compared to unweighted mean of individual records. Scaled PC1 is comprised of short PC1 (0-431 ka) pasted to long PC1 (431-798 ka). C. Scaled PC1 compared with percentile levels from the bootstrap results, which are also plotted as a composite of the short (0-431 ka) and long (431-798 ka) time windows of 2.5[th], 25th, 50th, 75th, and 95th percentiles.
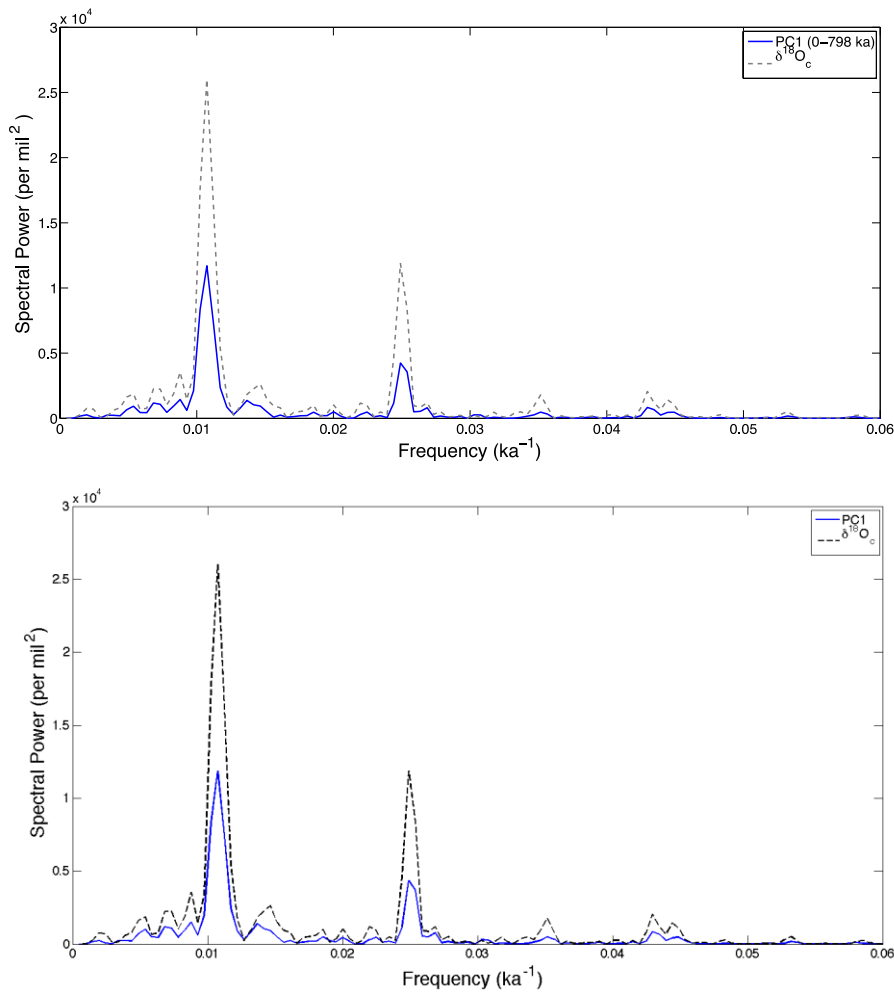
Figure 3. Spectral analysis for composite sea level stack (scaled PC1) converted to its $\delta^{18}O_{sw}$ contribution using 0.009‰m^{-1} and benthic $\delta^{18}O_c$ stack (Lisiecki and Raymo, 2005) from 0-798 ka.
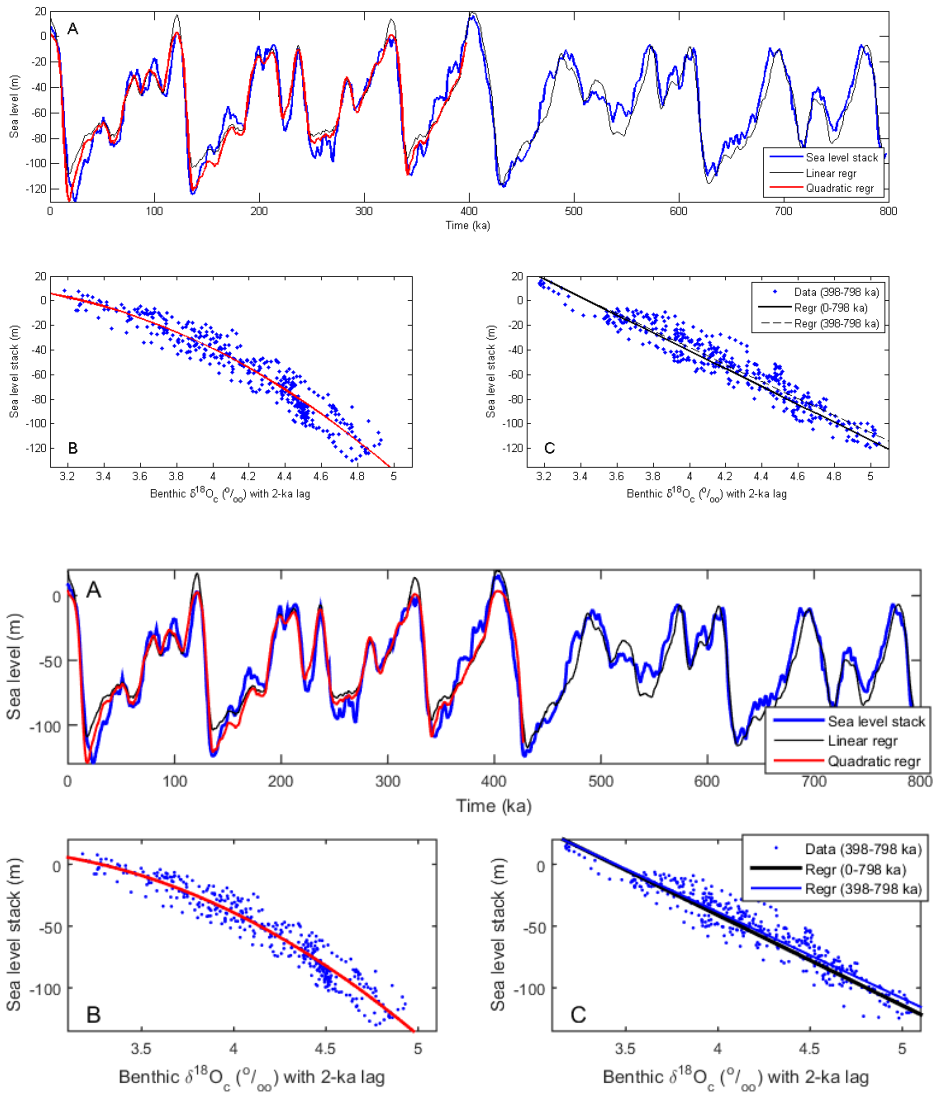
Figure 4. Comparison of benthic $\delta^{18}O_c$ and sea level. A. Linear and quadratic sea level models (Eq. 1 and 2, respectively) using smoothed benthic $\delta^{18}O_c$ (Lisiecki and Raymo, 2005) lagged by 2 ka (Lisiecki and Raymo, 2004). B. Time windowData from 0-397 ka withwith quadratic regression (red line). C. Time windowData from 398-798 ka with linear regression for 0-798 ka (black line) and 398-798 ka (blue line).
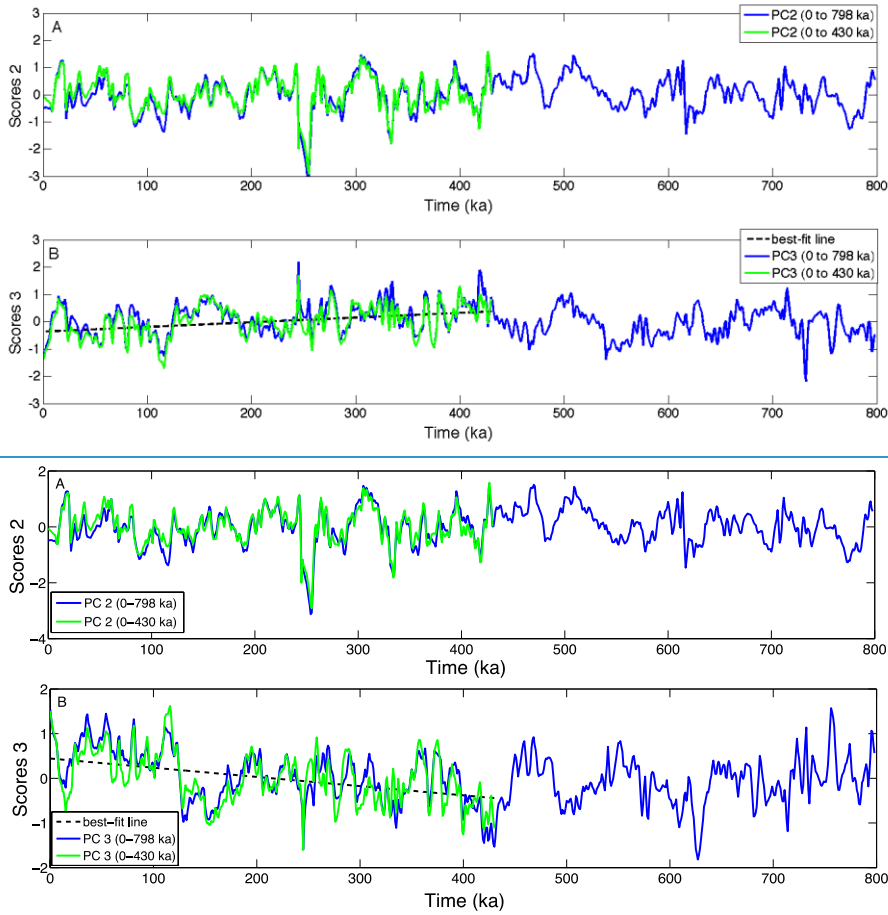
Figure 5. Second and third principal components for 0-430 ka and 0-798 ka. A. Scores for PC2 largely reflect difference between Atlantic and Pacific benthic $\delta^{18}O_{sw}$. B. Scores for PC3 largely reflect the difference benthic and planktonic $\delta^{18}O_{sw}$. Dashed black line marks linear trend from 0-430 ka.