Paleoceanography and Paleoclimatology

ADVANCING EARTH AND SPACE SCIENCES

COMMENTARY
10.1029/2023PA004649

Key Points:

- Novel micro-analytical techniques allow seasonally resolved climate proxy data from varved marine sediments
- Potential to generate seasonal and inter annual resolution sea surface temperature proxy time series spanning >1,000 years
- Thorough assessment of processes that influence the climate signal recovered from proxies, validated with careful replication, is required

Correspondence to:
E. Hathorne,
ehathorne@geomar.de

Citation:
Hathorne, E., Dolman, A. M., & Laepple, T. (2023). Assessing seasonal and inter-annual marine sediment climate proxy data. *Paleoceanography and Paleoclimatology*, *38*, e2023PA004649. https://doi.org/10.1029/2023PA004649

Received 30 MAR 2023
Accepted 18 SEP 2023

Assessing Seasonal and Inter-Annual Marine Sediment Climate Proxy Data

Ed Hathorne[1], Andrew M. Dolman[2], and Thomas Laepple[2,3]

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany, [2]Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Research Unit Potsdam, Potsdam, Germany, [3]MARUM—Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Bremen, Germany

Abstract Three recently published papers including Napier et al. (2022, https://doi.org/10.1029/2021PA004355) utilize novel microanalytical approaches with varved marine sediments to demonstrate the potential to reconstruct seasonal and inter-annual climate variability. Obtaining paleoclimate data at a resolution akin to the observational record is vitally important for improving our understanding of climate phenomena such as monsoons and modes of variability such as the El Niño Southern Oscillation, for which appraisals of past inter-annual variability is critical. The ability to generate seasonal and inter annual resolution sea surface temperature proxy time series spanning a thousand years or more is revolutionary and has the potential to fill gaps in our knowledge of climate variability. Although generally limited to sediments from regions with oxygen depleted bottom waters, there is great potential to integrate shorter seasonal resolution climate "snap shots" from other archives such as annually banded corals into composite time series. But as paleoceanographic data are used more by the observational and modeling fields, we make the case for conducting a thorough case-by-case assessment of the processes that influence the climate signal recovered from proxies, using careful replication to validate new approaches. Understanding or exploring the potential influence of processes which effectively filter the climate signal will lead to more quantitative paleoceanographic data that will better serve the broader climate science community.

Plain Language Summary Year to year differences in the strength of climate phenomena like monsoons and El Niño drive droughts and floods with dramatic consequences for human society. The longest records of measurements of climate generally only extend back to the 1800s, meaning we have a very short period of data to assess the changing climate and test climate model predictions. To obtain longer records of climate we use proxies which relate a variable we can measure in an archive such as the width of growth bands of coral skeletons to a climate observation such as the temperature of the sea surface. Usually, proxy climate records from marine sediments would provide sea surface temperature (SST) values that are the average of some 100 or 1,000 years. However, a new technique to measure climate proxies at sub mm resolution now allows for marine sediments, especially those that accumulate distinctive dark and light layers with changing seasons, to be used in principle to produce SST proxy data for individual seasons and years. This enables records of year-to-year differences that extend for thousands of years to be created. These records will undoubtedly revolutionize our understanding of the climate system and how climate proxies work.

1. Main Text

Studies in the fields of paleoceanography and paleoclimatology often justify the expense of generating climate proxy time series with the hope that the data will improve climate models and therefore future predictions to help mitigate the effects of climate change. Tropical hydroclimate extremes cause disastrous droughts and floods, yet future predictions of tropical precipitation are still wide-ranging despite recent improvements (Katzenberger et al., 2021). Changes in the upwelling of nutrient-rich waters drive strong interannual variations in productivity and fishery yields in many regions (Rykaczewski & Checkley, 2008). The influence of tropical ocean-atmosphere coupling such as the El Niño Southern Oscillation mode, on sea surface temperature (SST) variability is well known (e.g., Fedorov & Philander, 2000; Roy & Reason, 2001) yet reanalysis SST data only covers the last 150 years (Huang et al., 2017). This short observational period limits the understanding of the character and origin of decadal and slower climate variability (Ault et al., 2013; Laepple & Huybers, 2014). Therefore, extending the marine observational record with high resolution paleoclimate data is vitally important for improving our understanding of climate phenomena and modes for which the inter-annual to multidecadal variability is of high

10.1029/2023PA004649

societal relevance. To date, such data are usually obtained from archives such as banded coral skeletons, with a few individual records being some 300 years long (DeLong et al., 2013; Linsley et al., 2006; Zinke et al., 2004), and longer composite records extending to >400 years (e.g., Cobb et al., 2003; Hendy et al., 2002). Cross dating methods employed in dendrochronology are now increasingly being employed with marine archives, generating annually resolved records spanning a few centuries (Black et al., 2019) or longer (Reynolds et al., 2016). Varved sediments offer annual resolution, but are mostly from lakes, with a few studies from marine settings investigating changes in sediment composition as a qualitative measure of runoff or dust deposition (e.g., Deplazes et al., 2013) with a centimeter sampling resolution producing a decadal temporal resolution (e.g., Giesche et al., 2019; Staubwasser et al., 2003).

Now, the full potential of varved marine sediments is being unlocked with novel microanalytical techniques to produce SST records across varves at a seasonal resolution (Alfken et al., 2020; Napier et al., 2022; Wörmer et al., 2022). Although micro-analytical techniques have already been employed to map the elemental composition of varve layers (e.g., Blanchet et al., 2021), it is the ability to measure temperature proxies at seasonal resolution that completely changes the scope of what can be achieved with varved sediments. Not only is an essential climate variable (Bojinski et al., 2014) driving tropical hydroclimate being reconstructed, but by utilizing the seasonal metronome which produces a regular annual maximum and minimum in SST in most locations, years can potentially be more reliably counted and a robust year-by-year age obtained. For example, sub annual resolution geochemical time series are used to support the annual density banding of corals, which can sometimes produce spurious or double-density bands (e.g., DeLong et al., 2013; Felis et al., 2000) and to help identify annual layers in ice cores using elements like calcium (e.g., Rasmussen et al., 2006). In the Napier et al. study an age model is produced by counting years in the SST proxy which appears consistent with varve counting and ^{210}Pb dates.

The annual progression of SST in the tropics is not simply driven by changes in solar insolation but is influenced by ocean-atmosphere interactions which are different in each ocean basin (Li & Philander, 1996, 1997). Wind-induced upwelling and mixing can act to cool SST, and such processes lead to interannual variability in SSTs that can be used as a marker to test proxy reconstructions during the observational period. When and where interannual variability is large, proxy records should be compared with instrumental data for coherence at the interannual level. Under ideal circumstances, interannual signals in long records from varved sediments could enable shorter records from archives like corals to be more accurately placed in time than is possible using radiometric dating techniques alone, potentially producing regional stacked records (Figure 1).

The great potential of this technique is to generate long continuous sub-annual resolution SST records on the order of 1,000 years. With 5,000 years of varved sediments at this location in the Arabian Sea (von Rad et al., 1999a, 1999b) and even longer varved sections at other locations (Schimmelmann et al., 2016), records of annual resolution >1,000 years long will fill an important data gap at this frequency range to better understand, for example, if climate models are reliably capturing climate variability at centennial and longer timescales (Laepple & Huybers, 2014). The currently poor annual resolution data coverage from most marine settings (Tierney et al., 2015) can now be greatly improved and soon there could be comparable marine records to terrestrial ones like the 6,700 years record of tree ring oxygen isotopes from East Asia (Yang et al., 2021). Marine sediments with varves occur at many places on continental shelves and in marginal seas where bottom water oxygen has been depleted by enhanced productivity related to upwelling (e.g., Peru margin), or where circulation is restricted in enclosed basins (e.g., Cariaco Basin, see map in Schimmelmann et al. (2016)). Not all unmixed marine sediments are varved, as varves are produced by a strong seasonality in sediment delivery (Hughen, 2013), meaning other locations with high sedimentation rates not disturbed by bioturbation could potentially produce annual resolution records.

Another important advance is in the detail obtained with the new resolution of these microanalytical techniques about the recording of the proxy signal itself. Proxies are by definition imperfect records of climatic variability; they go through different filter stages (Dee et al., 2015; Dolman & Laepple, 2018; Evans et al., 2013): (a) the sensor (e.g., the geochemical paleothermometer which is also sensitive to some degree to secondary factors), (b) the heterogenous production of the sensor carrier in time and space (e.g., seasonal bias or depth habitats), (c) archiving by sedimentation and mixing by bioturbation, where important diagenetic processes can also occur which can alter, for example, via dissolution, or even form the proxy signal in the case of authigenic phases, and (d) the observation by measuring properties of a discrete interval and volume of a sediment core. By applying

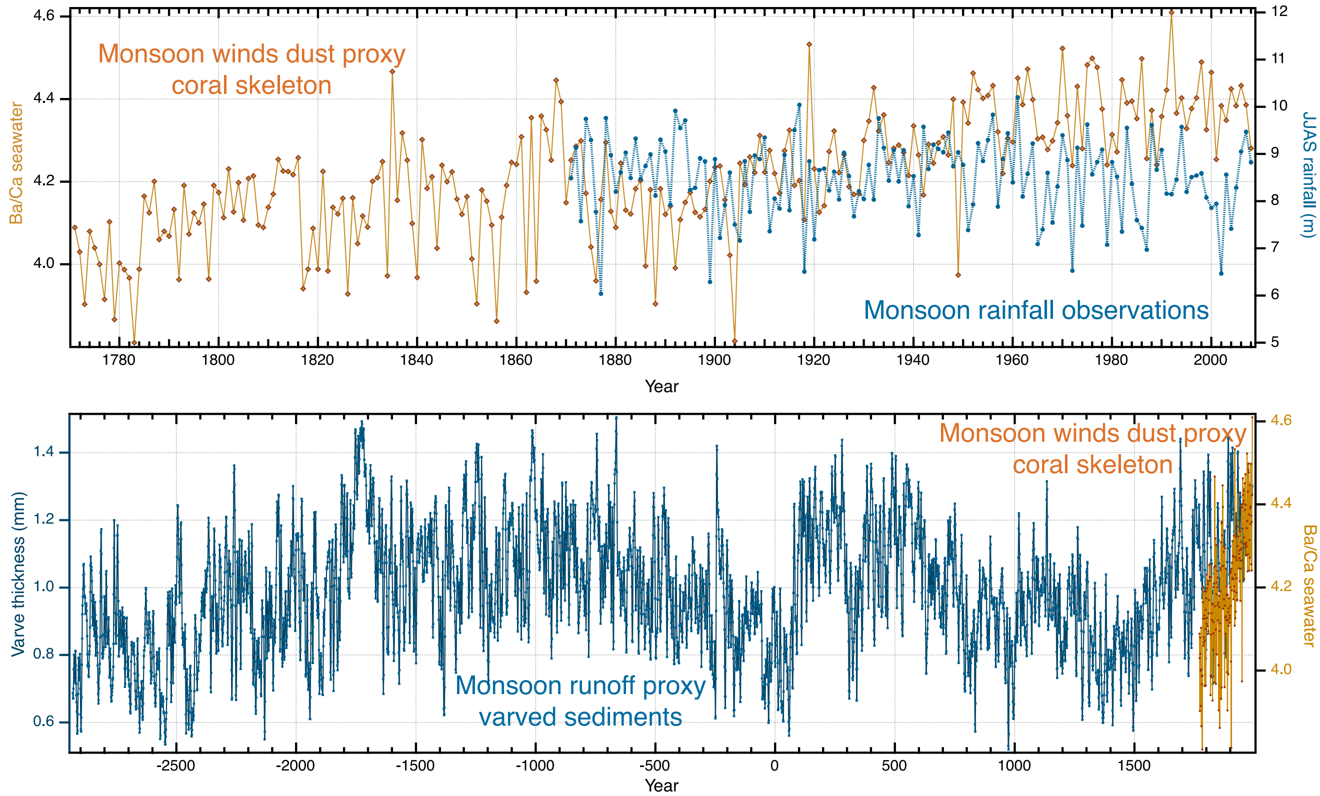

Figure 1. Example of the hierarchy of observational and proxy data time series possible with varved marine sediments; comparison of observations of summer monsoon season (JJAS) homogenous All India Rainfall (Kothawale & Rajeevan, 2017), dust deposition in the Red Sea recorded by annual banded coral skeletons (Bryan et al., 2019a, 2019b) and the varve thickness runoff proxy data from the N. Arabian Sea (von Rad et al., 1999a, 1999b). The annual Ba/Ca seawater and rainfall data have a weak correlation $R = 0.21$, $p < 0.05$ after linear detrending. There is no statistically significant correlation between annual Ba/Ca seawater and the varve thickness data after detrending calling for a better process understand of the proxy signals.

micro analytical techniques to varved sediments (with no bioturbation) the filtering by stages 3 and 4 has been removed or greatly reduced and hence more can be learned about filters 1 and 2, or the parts of 3 and 4 remaining. Napier et al. (2022) report that the UK37 SST measured across the varved sediments does not have the full annual amplitude, being muted in range compared to the observations (Figure 2). The authors suggest this is likely because of the seasonal deposition of the molecules carrying the UK37 signal, which are too small to sink alone and thus require packaging into larger particles to be deposited. This raises an often overlooked and complex topic involving the transition between filters 2 and 3, which influences any proxy carried by small particles including clays and organics which would remain suspended unless they aggregate, flocculate (Schieber et al., 2007), or are consumed and defecated to form larger sinking particles (e.g., Le Moigne, 2019). This involves the interaction of physical transport processes and the dynamics of biological productivity with the excess density provided by $CaCO_3$ and lithogenic particle inclusions adding ballast that enhances sinking while the overall abundance of particles is a strong factor in determining export fluxes (Xiang et al., 2022). As the export of organic carbon from the photic zone controls the efficiency of the biological carbon pump, this is an area of intense research activity with some recent studies highlighting the role viruses play in releasing sticky substances (Yamada et al., 2018) which can enhance aggregation and export (Laber et al., 2018) and mucospheres produced by dinoflagellates for foraging that package and export smaller organisms (Larsson et al., 2022). The varves at this location are formed of carbonate poor dark regions (background sedimentation) and carbonate rich light layers produced by strong winter sedimentation events (Lückge et al., 2001) that have been observed by sediment traps (Schulz & von Rad, 2014).

With so many physical, chemical and ecological factors involved, developing a fully mechanistic understanding will be a lengthy process. In the meantime, we can use forward models to investigate what combination of seasonal production and temporal smoothing before deposition, perhaps through lateral advection across the shelf (e.g., Mollenhauer et al., 2007), could produce the filtered SST records observed. To demonstrate this, we

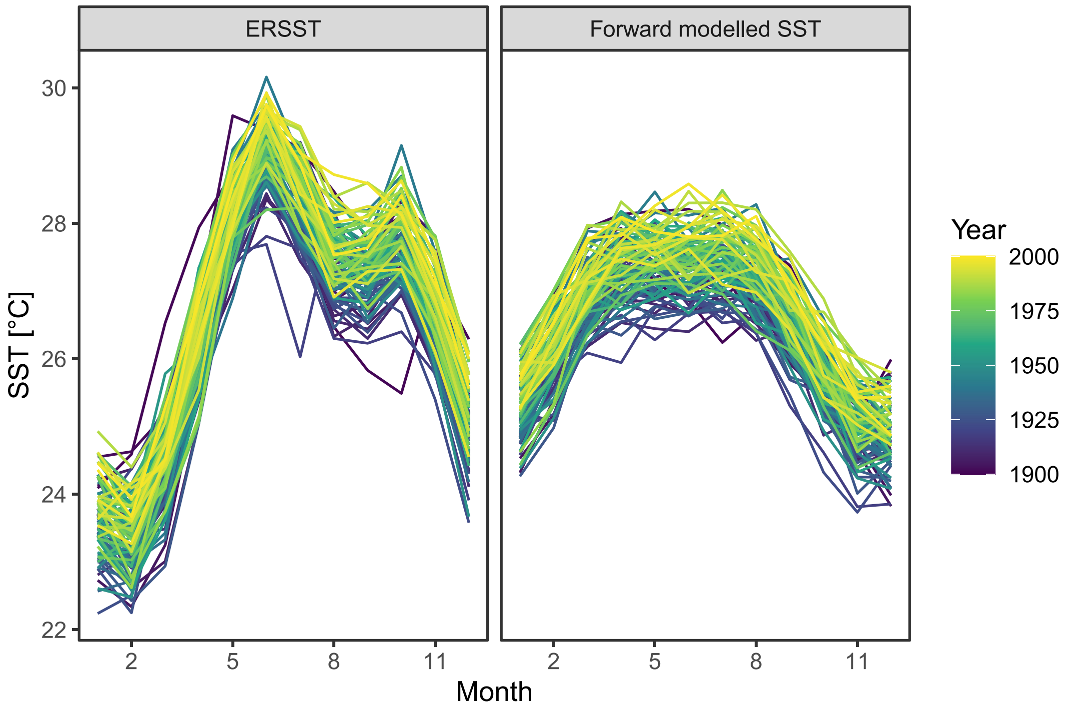

Figure 2. The potential effect on high resolution proxy records of mixing in the water column prior to archival in laminated sediments. (a) Monthly ERSST for 1900–2000 as used in Napier et al. (2022). (b) A pseudo Uk37 record generated from the ERSST data using the proxy forward model "sedproxy," simulating a mean period of 3-month mixing of the alkenone-bearing coccolithophores and particles in the water column before they are archived in the non-mixed, varved, sediment. Random Gaussian measurement error of 0.23°C (1sd) was added to each modeled sea surface temperature value.

have used "sedproxy" (Dolman & Laepple, 2018) to forward model the UK37 SST using the observational SST data as the starting point (Figures 2a–2d). This exercise reveals that the muted SST signal could result from the mixing of the signal before deposition (in the water column and/or sediment reworking) and is difficult to reconcile with a seasonal production bias alone which should shift values to warmer or cooler temperatures. Future work should explore the effects of winter deposition events on the formation of varves and the archiving of the elemental climate signal. Forward modeling, in which proxy filtering processes are sequentially added, might be used to identify which combination of processes best produce the observed proxy time series and which filtering processes need better observational constraints to potentially distinguish between them.

While these new methods have huge potential, the complexity of the system means that many analytical and statistical steps are necessary, which introduces the possibility of inadvertently introducing artifacts. The analytical possibilities to measure a time-series at ultra-high resolution do not imply that the climate signal can be recovered at the same resolution and noisy data can also lead to apparent cycles that might be mis-interpreted as seasonal climate changes (Laepple et al., 2018; Rice, 1945). For example, in Napier et al. (2022) the Uk37 timeseries was bandpass filtered in order to count seasonal peaks. By then assigning consecutive peaks to the central month of the seasonal cycle an apparent annual cycle could be created even if the original signal is pure noise (Figure 3). This seems to be less of a problem in the Santa Barbara basin sediments where the SST is much cooler (Alfken et al., 2020) than in the Arabian Sea (Napier et al., 2022). Careful consideration and modeling of these analytical steps will be one way to check whether we are misinterpreting artifacts as climate, but in some cases, it may still be hard to distinguish climate from noise. However, we still have the fundamental tool of the scientific method to fall back on: replication. Careful replication of other high-resolution proxies has been used to assess their reliability as a proxy for climate (e.g., corals; Sayani et al., 2019, tree rings; Büntgen et al., 2012, and ice-cores; Münch & Laepple, 2018) and we recommend such replication be applied to records from varved marine sediments in the future. Even further, we should aim to quantitatively test our understanding of the proxy signal at different steps of the proxy formation. Replication inside one core allows to determine the variability due to measurement uncertainty and (sediment) archive heterogeneity (Zuhr et al., 2022). Comparison of different

10.1029/2023PA004649

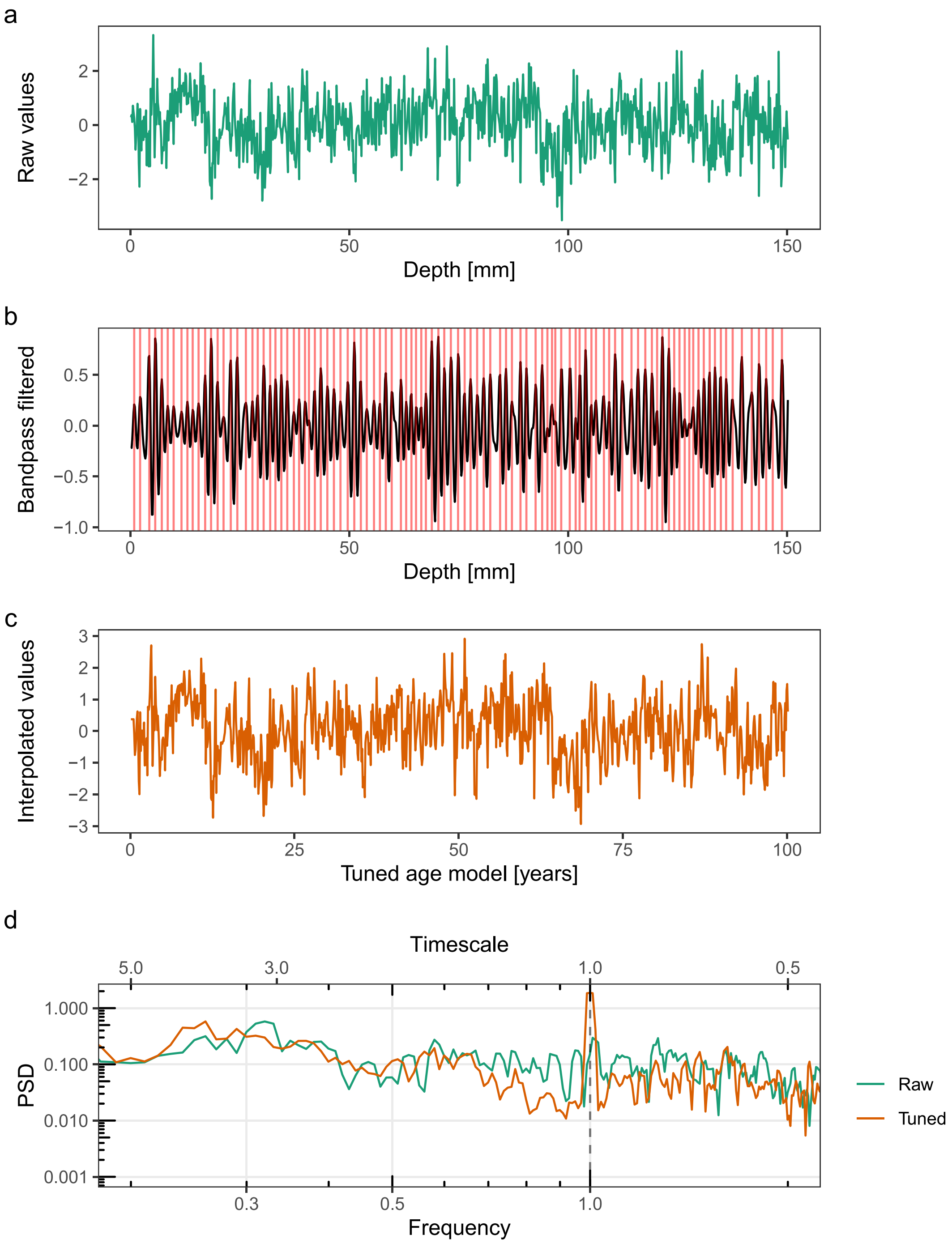

Figure 3. Illustration of the potential issues with bandpass filtering before counting peaks, employing the age-model tuning procedure performed by Napier et al. (2022) on random data not containing any cyclicity. (a) We first simulate a 100-years long timeseries with 10 points per year from temporally autocorrelated noise and place it on a nominal depth scale, assuming a mean of 1.5 mm per year. (b) We then apply a bandpass filter centered at the frequency of 1 year and automatically identify local maxima in this filtered timeseries. Similar to Napier et al. (2022), a tuned age-model is then established by assuming that each peak represents the center of 1 year. (c) The raw timeseries is then interpolated onto this tuned age model. (d) The power spectral density of the tuned timeseries shows a clear peak at the annual frequency, whereas the original noise timeseries does not. This shows that such a statistical processing step can create an artificial seasonal cycle as even on random timeseries peaks will on average be identified at the center frequency of the bandpass filter.

proxies for the same physical variable such as temperature measured in the same sample or core (Groeneveld et al., 2019; Ho & Laepple, 2015) allows to test the interpretation and attribution of the climate signal in the proxies. Comparison of replicates of nearby cores with similar sedimentary conditions additionally shows the effects of age-model and sampling uncertainty and comparing nearby replicates from different sedimentation settings (e.g., in different water depths) reveals the effect of site-specific sedimentary conditions such as signal preservation. Finally, a comparison of the proxy signal with instrumental data includes the effect of all signal formation steps (Alfken et al., 2020; Münch et al., 2017) but is limited to very short time-periods. While such studies require considerable efforts and are not possible on all occasions, they are crucial to test our understanding often implemented in proxy forward models and identify the right model complexity for the interpretation of the proxy signal and the reconstruction of the climate signal.

The work of Napier et al. (2022) and others (Alfken et al., 2020; Wörmer et al., 2022) is a great example of advances in analytical and computational technology revolutionizing our research capabilities. Currently some 10 m of sediment core can be subjected to micro-analysis in 1 year of laboratory work and as technology advances and becomes more widely available this will likely increase. As proxy climate data at a resolution akin to the observational data becomes increasingly available, the paleoceanography and paleoclimatology community has the opportunity, and responsibility, to assess the proxy data as fully as possible, using numerical frameworks such as "sedproxy" and theoretical frameworks such as the spectral error model "PSEM" (Dolman et al., 2021; Kunz et al., 2020) to understand the signal of proxy climate data. To facilitate this will require more information on seasonal and interannual particle fluxes and proxy carriers from sediment traps, tows and pumps from the water column in specific regions. Such research is resource intensive and would require a strong community effort to achieve this. However, this should be a priority as it will ensure the paleo-proxy data are widely used by the broader climate science community, contributing to the improvement of climate models to help focus the mitigation of climate change.

Data Availability Statement

The data used to produce Figure 1 are available at Bryan et al. (2019a, 2019b), Kothawale and Rajeevan (2017) and von Rad et al. (1999a, 1999b). The R code and data used to produce Figures 2 and 3 are available at Dolman and Laepple (2023).

Acknowledgments
This work was supported by the German Federal Ministry of Education and Research (BMBF) as a Research for Sustainability initiative (FONA); through the PALMOD project (FKZ: 01LP1509C) and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement no. 716092). Open Access funding enabled and organized by Projekt DEAL.

References

Alfken, S., Wörmer, L., Lipp, J. S., Wendt, J., Schimmelmann, A., & Hinrichs, K. (2020). Mechanistic insights into molecular proxies through comparison of subannually resolved sedimentary records with instrumental water column data in the Santa Barbara Basin, Southern California. *Paleoceanography and Paleoclimatology*, *35*(10), e2020PA004076. https://doi.org/10.1029/2020PA004076

Ault, T. R., Deser, C., Newman, M., & Emile-Geay, J. (2013). Characterizing decadal to centennial variability in the equatorial Pacific during the last millennium. *Geophysical Research Letters*, *40*(13), 3450–3456. https://doi.org/10.1002/grl.50647

Black, B. A., Andersson, C., Butler, P. G., Carroll, M. L., DeLong, K. L., Reynolds, D. J., et al. (2019). The revolution of crossdating in marine palaeoecology and palaeoclimatology. *Biology Letters*, *15*(1), 20180665. https://doi.org/10.1098/rsbl.2018.0665

Blanchet, C. L., Tjallingii, R., Schleicher, A. M., Schouten, S., Frank, M., & Brauer, A. (2021). Deoxygenation dynamics on the western Nile deep-sea fan during sapropel S1 from seasonal to millennial timescales. *Climate of the Past*, *17*(3), 1025–1050. https://doi.org/10.5194/cp-17-1025-2021

Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., & Zemp, M. (2014). The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society*, *95*(9), 1431–1443. https://doi.org/10.1175/BAMS-D-13-00047.1

Bryan, S. P., Hughen, K. A., Karnauskas, K. B., & Farrar, J. T. (2019a). Two hundred fifty years of reconstructed South Asian summer monsoon intensity and decadal-scale variability. *Geophysical Research Letters*, *46*(7), 3927–3935. https://doi.org/10.1029/2018GL081593

Bryan, S. P., Hughen, K. A., Karnauskas, K. B., & Farrar, J. T. (2019b). NOAA/WDS paleoclimatology—Red Sea Coral Ba/Ca and Sr/Ca covering 1760-2009 CE [Dataset]. NOAA National Centers for Environmental Information. https://doi.org/10.25921/qg9j-2818

Büntgen, U., Tegel, W., Heussner, K., Hofmann, J., Kontic, R., Kyncl, T., & Cook, E. (2012). Effects of sample size in dendroclimatology. *Climate Research*, *53*(3), 263–269. https://doi.org/10.3354/cr01107

Cobb, K. M., Charles, C. D., Cheng, H., & Edwards, R. L. (2003). El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, *424*(6946), 271–276. https://doi.org/10.1038/nature01779

Dee, S., Emile-Geay, J., Evans, M. N., Allam, A., Steig, E. J., & Thompson, D. M. (2015). PRYSM: An open-source framework for PRoxY System Modeling, with applications to oxygen-isotope systems. *Journal of Advances in Modeling Earth Systems*, *7*(3), 1220–1247. https://doi.org/10.1002/2015MS000447

DeLong, K. L., Quinn, T. M., Taylor, F. W., Shen, C.-C., & Lin, K. (2013). Improving coral-base paleoclimate reconstructions by replicating 350 years of coral Sr/Ca variations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *373*, 6–24. https://doi.org/10.1016/j.palaeo.2012.08.019

Deplazes, G., Lückge, A., Peterson, L. C., Timmermann, A., Hamann, Y., Hughen, K. A., et al. (2013). Links between tropical rainfall and North Atlantic climate during the last glacial period. *Nature Geoscience*, *6*(3), 213–217. https://doi.org/10.1038/ngeo1712

Dolman, A. M., Kunz, T., Groeneveld, J., & Laepple, T. (2021). A spectral approach to estimating the timescale-dependent uncertainty of paleoclimate records—Part 2: Application and interpretation. *Climate of the Past*, *17*(2), 825–841. https://doi.org/10.5194/cp-17-825-2021

Dolman, A. M., & Laepple, T. (2018). Sedproxy: A forward model for sediment-archived climate proxies. *Climate of the Past*, *14*(12), 1851–1868. https://doi.org/10.5194/cp-14-1851-2018

Dolman, A., & Laepple, T. (2023). EarthSystemDiagnostics/Hathorne-Dolman-Laepple-2023: Hathorne et al. 2023—Figures 2 and 3 (v.1.0.0) [Software]. Zenodo. https://doi.org/10.5281/zenodo.8273307

Evans, M. N., Tolwinski-Ward, S. E., Thompson, D. M., & Anchukaitis, K. J. (2013). Applications of proxy system modeling in high resolution paleoclimatology. *Quaternary Science Reviews*, *76*, 16–28. https://doi.org/10.1016/j.quascirev.2013.05.024

Fedorov, A. V., & Philander, S. G. (2000). Is El Niño changing? *Science*, *288*(5473), 1997–2002. https://doi.org/10.1126/science.288.5473.1997

Felis, T., Pätzold, J., Loya, Y., Fine, M., Nawar, A. H., & Wefer, G. (2000). A coral oxygen isotope record from the northern Red Sea documenting NAO, ENSO, and North Pacific teleconnections on Middle East climate variability since the year 1750. *Paleoceanography*, *15*(6), 679–694. https://doi.org/10.1029/1999PA000477

Giesche, A., Staubwasser, M., Petrie, C. A., & Hodell, D. A. (2019). Indian winter and summer monsoon strength over the 4.2 ka BP event in foraminifer isotope records from the Indus River delta in the Arabian Sea. *Climate of the Past*, *15*(1), 73–90. https://doi.org/10.5194/cp-15-73-2019

Groeneveld, J., Ho, S. L., Mackensen, A., Mohtadi, M., & Laepple, T. (2019). Deciphering the variability in Mg/Ca and stable oxygen isotopes of individual foraminifera. *Paleoceanography and Paleoclimatology*, *34*(5), 755–773. https://doi.org/10.1029/2018PA003533

Hendy, E. J., Gagan, M. K., Alibert, C. A., McCulloch, M. T., Lough, J. M., & Isdale, P. J. (2002). Abrupt decrease in tropical Pacific sea surface salinity at end of little ice age. *Science*, *295*(5559), 1511–1514. https://doi.org/10.1126/science.1067693

Ho, S. L., & Laepple, T. (2015). Glacial cooling as inferred from marine temperature proxies TEX86 and UK′37. *Earth and Planetary Science Letters*, *409*, 15–22. https://doi.org/10.1016/j.epsl.2014.10.033

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2017). Extended reconstructed sea surface temperature, version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. *Journal of Climate*, *30*(20), 8179–8205. https://doi.org/10.1175/JCLI-D-16-0836.1

Hughen, K. A. (2013). Marine varves. In W. J. Rink, & J. Thompson (Eds.), *Encyclopedia of scientific dating methods* (pp. 1–8). Springer Netherlands. https://doi.org/10.1007/978-94-007-6326-5_162-1

Katzenberger, A., Schewe, J., Pongratz, J., & Levermann, A. (2021). Robust increase of Indian monsoon rainfall and its variability under future warming in CMIP6 models. *Earth System Dynamics*, *12*(2), 367–386. https://doi.org/10.5194/esd-12-367-2021

Kothawale, D. R., & Rajeevan, M. (2017). Monthly, seasonal and annual rainfall time series for all-India, homogeneous regions and meteorological subdivisions: 1871-2016 (Vol. *169*). Retrieved from https://www.tropmet.res.in/~lip/Publication/RR-pdf/RR-138.pdf

Kunz, T., Dolman, A. M., & Laepple, T. (2020). A spectral approach to estimating the timescale-dependent uncertainty of paleoclimate records—Part 1: Theoretical concept. *Climate of the Past*, *16*(4), 1469–1492. https://doi.org/10.5194/cp-16-1469-2020

Laber, C. P., Hunter, J. E., Carvalho, F., Collins, J. R., Hunter, E. J., Schieler, B. M., et al. (2018). Coccolithovirus facilitation of carbon export in the North Atlantic. *Nature Microbiology*, *3*(5), 537–547. https://doi.org/10.1038/s41564-018-0128-4

Laepple, T., & Huybers, P. (2014). Ocean surface temperature variability: Large model–data differences at decadal and longer periods. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(47), 16682–16687. https://doi.org/10.1073/pnas.1412077111

Laepple, T., Münch, T., Casado, M., Hoerhold, M., Landais, A., & Kipfstuhl, S. (2018). On the similarity and apparent cycles of isotopic variations in East Antarctic snow pits. *The Cryosphere*, *12*(1), 169–187. https://doi.org/10.5194/tc-12-169-2018

Larsson, M. E., Bramucci, A. R., Collins, S., Hallegraeff, G., Kahlke, T., Raina, J.-B., et al. (2022). Mucospheres produced by a mixotrophic protist impact ocean carbon cycling. *Nature Communications*, *13*(1), 1301. https://doi.org/10.1038/s41467-022-28867-8

Le Moigne, F. A. C. (2019). Pathways of organic carbon downward transport by the oceanic biological carbon pump. *Frontiers in Marine Science*, *6*, 634. https://doi.org/10.3389/fmars.2019.00634

Li, T., & Philander, S. G. H. (1996). On the annual cycle of the eastern equatorial Pacific. *Journal of Climate*, *9*(12), 2986–2998. https://doi.org/10.1175/1520-0442(1996)009<2986:OTACOT>2.0.CO;2

Li, T., & Philander, S. G. H. (1997). On the seasonal cycle of the equatorial Atlantic Ocean. *Journal of Climate*, *10*(4), 813–817. https://doi.org/10.1175/1520-0442(1997)010<0813:OTSCOT>2.0.CO;2

Linsley, B. K., Kaplan, A., Gouriou, Y., Salinger, J., de Menocal, P. B., Wellington, G. M., & Howe, S. S. (2006). Tracking the extent of the South Pacific Convergence Zone since the early 1600s. *Geochemistry, Geophysics, Geosystems*, *7*(5), Q05003. https://doi.org/10.1029/2005GC001115

Lückge, A., Doose-Rolinski, H., Khan, A. A., Schulz, H., & von Rad, U. (2001). Monsoonal variability in the northeastern Arabian Sea during the past 5000 years: Geochemical evidence from laminated sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *167*(3–4), 273–286. https://doi.org/10.1016/S0031-0182(00)00241-8

Mollenhauer, G., Inthorn, M., Vogt, T., Zabel, M., Sinninghe Damsté, J. S., & Eglinton, T. I. (2007). Aging of marine organic matter during cross-shelf lateral transport in the Benguela upwelling system revealed by compound-specific radiocarbon dating: Aging of marine organic matter. *Geochemistry, Geophysics, Geosystems*, *8*(9), Q09004. https://doi.org/10.1029/2007GC001603

Münch, T., Kipfstuhl, S., Freitag, J., Meyer, H., & Laepple, T. (2017). Constraints on post-depositional isotope modifications in East Antarctic firn from analyzing temporal changes of isotope profiles. *The Cryosphere*, *11*(5), 2175–2188. https://doi.org/10.5194/tc-11-2175-2017

Münch, T., & Laepple, T. (2018). What climate signal is contained in decadal- to centennial-scale isotope variations from Antarctic ice cores? *Climate of the Past*, *14*(12), 2053–2070. https://doi.org/10.5194/cp-14-2053-2018

Napier, T. J., Wörmer, L., Wendt, J., Lückge, A., Rohlfs, N., & Hinrichs, K. (2022). Sub-annual to interannual Arabian Sea upwelling, sea surface temperature, and Indian monsoon rainfall reconstructed using congruent micrometer-scale climate proxies. *Paleoceanography and Paleoclimatology*, *37*(3), e2021PA004355. https://doi.org/10.1029/2021PA004355

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., et al. (2006). A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research*, *111*(D6), D06102. https://doi.org/10.1029/2005JD006079

Reynolds, D. J., Scourse, J. D., Halloran, P. R., Nederbragt, A. J., Wanamaker, A. D., Butler, P. G., et al. (2016). Annually resolved North Atlantic marine climate over the last millennium. *Nature Communications*, *7*(1), 13502. https://doi.org/10.1038/ncomms13502

Rice, S. O. (1945). Mathematical analysis of random noise. *The Bell System Technical Journal*, *24*(1), 46–156. https://doi.org/10.1002/j.1538-7305.1945.tb00453.x

Roy, C., & Reason, C. (2001). ENSO related modulation of coastal upwelling in the eastern Atlantic. *Pacific Climate Variability and Marine Ecosystem Impacts*, *49*(1), 245–255. https://doi.org/10.1016/S0079-6611(01)00025-8

Rykaczewski, R. R., & Checkley, D. M. (2008). Influence of ocean winds on the pelagic ecosystem in upwelling regions. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(6), 1965–1970. https://doi.org/10.1073/pnas.0711777105

Sayani, H. R., Cobb, K. M., DeLong, K., Hitt, N. T., & Druffel, E. R. M. (2019). Intercolony $\delta^{18}O$ and Sr/Ca variability among *Porites* spp. corals at Palmyra Atoll: Toward more robust coral-based estimates of climate. *Geochemistry, Geophysics, Geosystems*, *20*(11), 5270–5284. https://doi.org/10.1029/2019GC008420

Schieber, J., Southard, J., & Thaisen, K. (2007). Accretion of mudstone beds from migrating floccule ripples. *Science*, *318*(5857), 1760–1763. https://doi.org/10.1126/science.1147001

Schimmelmann, A., Lange, C. B., Schieber, J., Francus, P., Ojala, A. E. K., & Zolitschka, B. (2016). Varves in marine sediments: A review. *Earth-Science Reviews*, *159*, 215–246. https://doi.org/10.1016/j.earscirev.2016.04.009

Schulz, H., & von Rad, U. (2014). Vertical and lateral flux on the continental slope off Pakistan: Correlation of sediment core and trap results. *Biogeosciences*, *11*(12), 3107–3120. https://doi.org/10.5194/bg-11-3107-2014

Staubwasser, M., Sirocko, F., Grootes, P. M., & Segl, M. (2003). Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability: South Asian Holocene climate change. *Geophysical Research Letters*, *30*(8), 1425. https://doi.org/10.1029/2002GL016822

Tierney, J. E., Abram, N. J., Anchukaitis, K. J., Evans, M. N., Giry, C., Kilbourne, K. H., et al. (2015). Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. *Paleoceanography*, *30*(3), 226–252. https://doi.org/10.1002/2014PA002717

von Rad, U., Schaaf, M., Michels, K. H., Schulz, H., Berger, W. H., & Sirocko, F. (1999a). A 5000-yr record of climate change in varved sediments from the oxygen minimum zone off Pakistan, northeastern Arabian Sea. *Quaternary Research*, *51*(1), 39–53. https://doi.org/10.1006/qres.1998.2016

von Rad, U., Schaaf, M., Michels, K. H., Schulz, H., Berger, W. H., & Sirocko, F. (1999b). Varved sediments of the Arabian Sea [Dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.735718

Wörmer, L., Wendt, J., Boehman, B., Haug, G. H., & Hinrichs, K.-U. (2022). Deglacial increase of seasonal temperature variability in the tropical ocean. *Nature*, *612*(7938), 88–91. https://doi.org/10.1038/s41586-022-05350-4

Xiang, Y., Lam, P. J., Burd, A. B., & Hayes, C. T. (2022). Estimating mass flux from size-fractionated filtered particles: Insights into controls on sinking velocities and mass fluxes in recent U.S. GEOTRACES cruises. *Global Biogeochemical Cycles*, *24*(4). https://doi.org/10.1029/2021gb007292

Yamada, Y., Tomaru, Y., Fukuda, H., & Nagata, T. (2018). Aggregate formation during the viral lysis of a marine diatom. *Frontiers in Marine Science*, *5*, 167. https://doi.org/10.3389/fmars.2018.00167

Yang, B., Qin, C., Bräuning, A., Osborn, T. J., Trouet, V., Ljungqvist, F. C., et al. (2021). Long-term decrease in Asian monsoon rainfall and abrupt climate change events over the past 6,700 years. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(30), e2102007118. https://doi.org/10.1073/pnas.2102007118

Zinke, J., Dullo, W.-C., Heiss, G. A., & Eisenhauer, A. (2004). ENSO and Indian Ocean subtropical dipole variability is recorded in a coral record off southwest Madagascar for the period 1659 to 1995. *Earth and Planetary Science Letters*, *228*(1–2), 177–194. https://doi.org/10.1016/j.epsl.2004.09.028

Zuhr, A. M., Dolman, A. M., Ho, S. L., Groeneveld, J., Löwemark, L., Grotheer, H., et al. (2022). Age-heterogeneity in marine sediments revealed by three-dimensional high-resolution radiocarbon measurements. *Frontiers in Earth Science*, *10*, 871902. https://doi.org/10.3389/feart.2022.871902