# Surface sediment samples from early age of seafloor exploration can provide a late 19th century baseline of the marine environment

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## ABSTRACT

Historical seafloor samples collected up to 150 years ago represent an important archive to benchmark the extent of current ocean acidification and pollution trends. Such benchmarking requires that the historical sediment samples represent the state of the environment at- or shortly before the time of collection. However, early oceanographic expeditions sampled the ocean floor using devices like the sounding tube or a dredge, which potentially disturb the sediment surface and recover a mix of Holocene (surface) and Pleistocene sediments. Here we use climate-sensitive microfossils as a fast and efficient biometric method to assess to what degree historical seafloor samples contain a mixture of modern and glacial sediments. Our assessment is based on comparing the composition of planktonic foraminifera (PF) assemblages in historical samples with Holocene and Last Glacial Maximum (LGM) global reference datasets. We show that eight out of the nine historical samples contain PF assemblages more similar to the Holocene than to the LGM PF assemblages. This result suggests that the majority of sediment samples from historical collections should be suitable to provide baseline of the state of marine ecosystems in the late 19th century.

**Keywords: natural history collections (NHCs), historical collections, pre-Anthropocene, pre-industrial, beta-diversity, global change**

## 1 INTRODUCTION

Late nineteenth and early twentieth century oceanographic expeditions set out to explore the vast and then widely unknown deep ocean. The voyage of HMS *Challenger* is a legendary example, as she sailed around the globe between 1872−76, mapping for the first time the shape of the ocean basins and describing

over 4,500 new species of marine life (Manten, 1972). These early expeditions have important historical significance, as they mark the beginning of modern oceanography and stimulated further ocean exploration (Wüst, 1964).

From a scientific perspective, the observations and material acquired by these historical expeditions have great potential for global change research, as they extend beyond the last century, potentially providing a pre-industrial baseline of the marine environment (Lister and Group, 2011; Johnson et al., 2011). For example, global seawater temperature measurements taken by the *Challenger* expedition were compared to the Argo Programme data (2004−10) and revealed that the modern upper ocean is substantially warmer than 135 years ago (Roemmich et al. 2012, see also Gleckler et al. 2016). Similarly, marine biological specimens sampled by these historical expeditions (with corresponding geographic coordinates) serve as species' occurrence records (Johnson et al., 2011) and have been used to investigate whether species' biogeographical ranges have changed in the past century (Hoeksema et al., 2011).

Historical seafloor sediment samples bear the same potential, but have been used to a lesser extent. This is because early seafloor sampling techniques involved collecting surficial sediments with instruments like the sounding tube, dredge or even the anchor (Thomson and Murray, 1891), which may penetrate below the surface and disturb the top layer of the sediment. As a result, such historical samples might contain surface (Holocene) sediments mixed in with deeper, glacial material (Hayward and Kawagata, 2005). If such mixing occurred, the resulting sediment samples could not serve as a baseline for modern marine environment. This would be unfortunate, because historical sediments provide an important time-point sample of the deep oceans that can be as much as 50 years earlier than the earliest samples collected by modern coring techniques (Wüst, 1964). HMS *Challenger*'s seafloor metalliferous sediment samples, for example, were investigated for their chemical content assuming they represent pre-anthropogenic lead (Pb) pollution state of the deep sea (Dekov et al., 2010). Similarly, surface sediment samples have been used to assess the impact of ocean acidification on calcareous microplankton shells (Moy et al., 2009). Moy et al. (2009) used core-top sediments collected in the past decades and assumed that the majority of the microfossil shells in these surface sediments were deposited in pre-industrial times. However, this approach cannot be used for analyses based on individual organisms or for investigations of species range shifts and invasions as these analyses would require material without any object deposited during the last decades (*i.e.* collected before the last century). Therefore, it is important to assess to what degree historical sediment samples represent Holocene or mixed-Pleistocene sediments.

One way to assess the degree of mixing in the historical material would be the determination of its absolute age using *e.g.* the radiocarbon dating technique. However, in cases where the extent of mixing is small, the result of such a comparison could be ambiguous. For example, an average sediment age of 5,000 years could either mean that the sediment is Holocene deposited under low sedimentation rate and vertical mixing, or it could indicate a contamination during sampling by a small amount of glacial material. Here we propose an alternative method using planktonic foraminifera assemblage composition as a climate-sensitive fingerprint of the sediment age. Planktonic foraminifera (PF) are single-celled zooplankton that produce calcium carbonate shells and, upon death, accumulate in great numbers on the ocean floor (Hemleben et al., 1989). PF assemblage composition is sensitive to sea-surface temperature (Morey et al., 2005; Fenton et al., 2016) and its change between glacial and interglacial times has been used to determine the magnitude of glacial ocean cooling (MARGO Project Members, 2009).

In this brief report, we make use of the temperature sensitivity of PF and compare the composition of their assemblages in nine historical (> 100 years old) samples against reference PF assemblages from the Holocene (Siccha and Kucera, 2017) and the Last Glacial Maximum (Kucera et al., 2005a).

## 2 MATERIAL AND METHODS

### 2.1 Historical samples

Historical samples were retrieved from the Ocean-Bottom Deposits (OBD) Collection held by The Natural History Museum in London. The OBD Collection contains most of the sediment samples from the HMS *Challenger* expedition as well as samples collected by the British Royal Navy survey ships (*e.g.* HMS *Egeria*, HMS *Penguin*, HMS *Sealark* and HMS *Waterwitch*) (Kempe and Buckley, 1987). The OBD samples are kept sealed in their original glass jars and tubes and are usually dry as the result of the long (over 100 years) storage. We selected nine samples collected between 1874 and 1905, chosen to cover different oceans, latitudes and historical marine expeditions (Table 1). Half of the amount available in the OBD containers was further split into two equal parts, leaving an archive sample and a sample to be processed. The sample processing consisted of weighing, wet washing over a 63$\mu$m sieve and drying in a 60°C oven. The residues were further dry sieved over a 150$\mu$m sieve and the coarser fraction was split with a microsplitter as many times as needed to produce a representative aliquot containing around 300 PF shells (see Al-Sabouni et al. 2007). All PF specimens in each of the nine final splits were identified under a stereomicroscope to species level, resulting in a total of 2,611 individuals belonging to 31 species (Table 1).

### 2.2 Holocene and Last Glacial Maximum data

To test whether the composition of PF assemblages in the historical samples is more similar to assemblages of the Holocene (last 11,700 years, Walker et al. 2008) or the Last Glacial Maximum (LGM, 21,000 years ago, MARGO Project Members 2009). The Holocene census data (*i.e.*, marine surface sediment samples taken by coring methods after 1945) were recently curated and published as the ForCenS dataset, comprising 4,205 assemblage counts from unique sites (Siccha and Kucera, 2017). Three LGM datasets from the MARGO project (Kucera et al., 2005a,b,c; Barrows and Juggins, 2004) were merged into one, following the taxonomic standardisation of Siccha and Kucera (2017). This merged LGM final dataset included 1165 counts from 389 unique sites, the assemblages were then averaged per site. The assemblage compositions of the historical samples were then compared to the samples from the geographically nearest site in the Holocene and LGM datasets. The distances between sites were calculated using the World Geodetic System of 1984 (Hijmans, 2015). The median distance between our nine sites and their nearest neighbours in in the Holocene dataset was 261 km and in the LGM dataset was 384 km. Assemblage compositions were also compared between the LGM and Holocene sites worldwide. The median distance between the LGM and Holocene sites was 1.5 km.

### 2.3 Compositional similarity

Assemblage similarity was expressed using the Morisita-Horn index (Morisita, 1959; Horn, 1966), which is an abundance-based overlap measure that preserves essential properties of similarity measurements (Jost et al., 2011). The Morisita-Horn calculates the compositional similarity by pairwise comparison of the relative abundance of each species, and is robust to under-sampling (*i.e.*, rare species occurrence) (Jost et al., 2011). The index was calculated using the under-sampling bias correction (Chao et al., 2006) and bootstrap confidence intervals based on 100 replicates (Chao et al., 2016).

For each of the nine historical assemblages, we calculated the Morisita-Horn index three times: between (1) historical and neighbouring Holocene assemblages, (2) historical and neighbouring LGM assemblages and (3) neighbouring Holocene and LGM assemblages. This last comparison gives us a baseline Morisita-Horn index value between Holocene and LGM assemblages for each historical sample site. This baseline comparison informs us how much the PF assemblage composition changed locally across the last glacial

cycle. If historical samples are representative of surface sediments, the similarity index calculated for the Holocene data should be higher than for the LGM data, with non-overlapping confidence intervals. However, if historical samples are a mixture of Holocene and LGM material, the similarity index between historical and LGM should be significantly higher than the local baseline similarity between Holocene and LGM.

Lastly, we calculated the Morisita-Horn index value between the nearest Holocene neighbours of all LGM sites worldwide. Geographical regions where there are large differences between Holocene and LGM assemblages (*i.e.*, low Morisita-Horn index) have a greater statistical potential to detect whether a historical sediment is a surface or deeper sample.

## 3 RESULTS AND DISCUSSION

In eight out of the nine samples, the compositional similarity was higher between the historical and Holocene assemblages than between historical and LGM assemblages (Fig. 1A, binomial test with equal probability: p-value = 0.04). Compositional similarity between historical and Holocene was always above 0.75, and in five samples historical and Holocene assemblages reached the similarity index maximum value of one, indicating that the same species were present in both samples at proportions that are statistically indistinguishable.

In six samples, the confidence intervals of the three comparisons overlapped, and all the compositional similarity indexes were above 0.75. Since LGM and Holocene PF assemblages showed higher compositional similarity at these six sites (Fig. 1A), the test we use is less diagnostic. In contrast, the samples at latitudes of 24.3°N and 26.9°S showed the greatest differences in assemblage composition between LGM and Holocene assemblages (Fig. 1A and B), suggesting a greater change in PF assemblage composition during the last glacial cycle. These were also the two locations where the confidence intervals between historical-Holocene and historical-LGM comparisons did not overlap, confirming a Holocene age for the historical sediments. Contrastingly, the historical sample at 40.4°S showed no overlap between historical-Holocene and the baseline Holocene-LGM, but the historical-LGM comparison overlapped with both comparisons, suggesting that this sample has possibly a mix of Holocene and glacial material.

The historical sample at 7.6°S was the only one that showed higher similarity with LGM than Holocene assemblages, and the species *Trilobatus sacculifer* was the source of most difference, with relative abundance of 15.9% in the Holocene sample, 4.3% in the historical sample and 0% in the LGM sample.

The global comparison between the Holocene and the LGM datasets shows the magnitude of PF assemblages turnover since the last ice age (Fig. 1B). In general, upwelling (eastern boundary currents and equatorial regions) and temperate sites showed greatest change, showing where our methodology would be most diagnostic.

## 4 CONCLUSION

Our results indicate that historical ocean-floor sediment samples (collected more than 100 years ago by deep-sea dredging and sounding tubes) usually represent surface (Holocene) sediments. Despite the use of pioneering technology not designed to recover undisturbed sediment surface, much of the historical sediments collections should not be contaminated by glacial material and can thus act as a baseline for the state of the marine environment in the late 19th century. The method we used is simple and fast and allows a non-destructive assessment of glacial contamination. Moreover, the spatial distribution of PF assemblage

turnover since the LGM (Fig. 1B) can be used to identify regions that are particularly suitable for our method.

The result of our analysis highlights the potential of historical ocean floor sediment collections in global change research. Such collections are surprisingly rich and have global coverage. The Ocean-Bottom Deposits (OBD) Collection at The Natural History Museum in London holds about 40,000 historical samples from all the world's oceans (https://doi.org/10.5519/0096416), including most of the deposits collected by the *Challenger* expedition. The *Challenger* sediment samples are the most widely distributed collection of the 19th century (Roemmich et al., 2012), and can be searched using the database https://www.hmschallenger.net/. Similarly, the Muséum National d'histoire Naturelle in Paris holds material from the *Travailleur* and *Talisman* expeditions (1880−83) and the Museum für Naturkunde in Berlin holds the historical collection of the German Deep Sea Expedition (1898−99) (Keltie 1898; Sandeman 1900, see also http://www.mfn-wissensdinge.de/wertvoller-dreck-in-schoenem-glas/. As human activities increasingly modify the marine environment (Boyd and Hutchins, 2012; Jones et al., 2018), these historical samples potentially remain the only direct source of information on the 19th century state of marine ecosystems.

## CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## AUTHOR CONTRIBUTIONS

All authors designed the research question. MR processed the historical sediments, with input from GM. MR and MK identified all specimens. MR designed and performed the analysis, with input from MK and TE. MR wrote the initial draft, and all authors reviewed and edited the final manuscript.

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## DATA AVAILABILITY STATEMENT

Upon acceptance of the manuscript, the datasets used and generated for this study will be available online at the NHM Data Portal (with DOI number). The R Code used for the analysis and figures will be available at MCR GitHub page.

## TABLE

**Table 1.** Information about the historical sediment samples from the Ocean Bottom Deposits (OBD) Collection at The Natural History Museum, London (NHMUK). Columns: NHMUK sample number; vessel that collected the sample (HMS stands for Her/His Majesty's Ship); date that sample was collected; method used for sampling; ocean where sample was collected; latitude and longitude in decimal degrees; water depth in meters (tranformed from fathoms); sampled mass before processing, in grams; number of splits to reach around 300 planktonic foraminifera (PF) individuals; number of PF individuals identified; number of PF species identified.

| Sample | Vessel HMS | Date | Method | Ocean | Lat | Long | Depth | m(g) | N(spl) | N(ind) | N(sp) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M.25 | *Challenger* | 21/02/1873 | Sounding | Atlantic | 24.33 | -24.47 | 5011 | 2.73 | 5 | 260 | 18 |
| M.192 | *Challenger* | 07/03/1874 | Sounding | Indian | -50.02 | 123.07 | 3976 | 0.19 | 5 | 318 | 7 |
| M.284 | *Challenger* | 11/03/1875 | Sounding | Pacific | -0.70 | 147.00 | 2012 | 1.98 | 7 | 331 | 16 |
| M.408 | *Challenger* | 21/03/1876 | Dredge | Atlantic | -21.25 | -14.03 | 3639 | 9.35 | 7 | 265 | 21 |
| M.3787 | *Egeria* | 31/10/1887 | Sounding | Indian | -19.57 | 64.63 | 2869 | 1.23 | 5 | 376 | 24 |
| M.4080 | *Egeria* | 26/08/1889 | Sounding | Pacific | -15.65 | -179.06 | 2579 | 2.42 | 8 | 300 | 13 |
| M.5246 | *Penguin* | 16/04/1891 | Sounding | Indian | -26.94 | 111.18 | 3676 | 1.49 | 5 | 279 | 18 |
| M.8780 | *Waterwitch* | 22/01/1895 | Sounding | Indian | -40.45 | 49.82 | 3780 | 1.51 | 6 | 177 | 11 |
| M.7487 | *Sealark* | 09/11/1905 | Sounding | Indian | -7.59 | 61.48 | 3758 | 2.86 | 8 | 305 | 18 |
| **Total** | | | | | | | | | | 2,611 | 31 |

## FIGURE

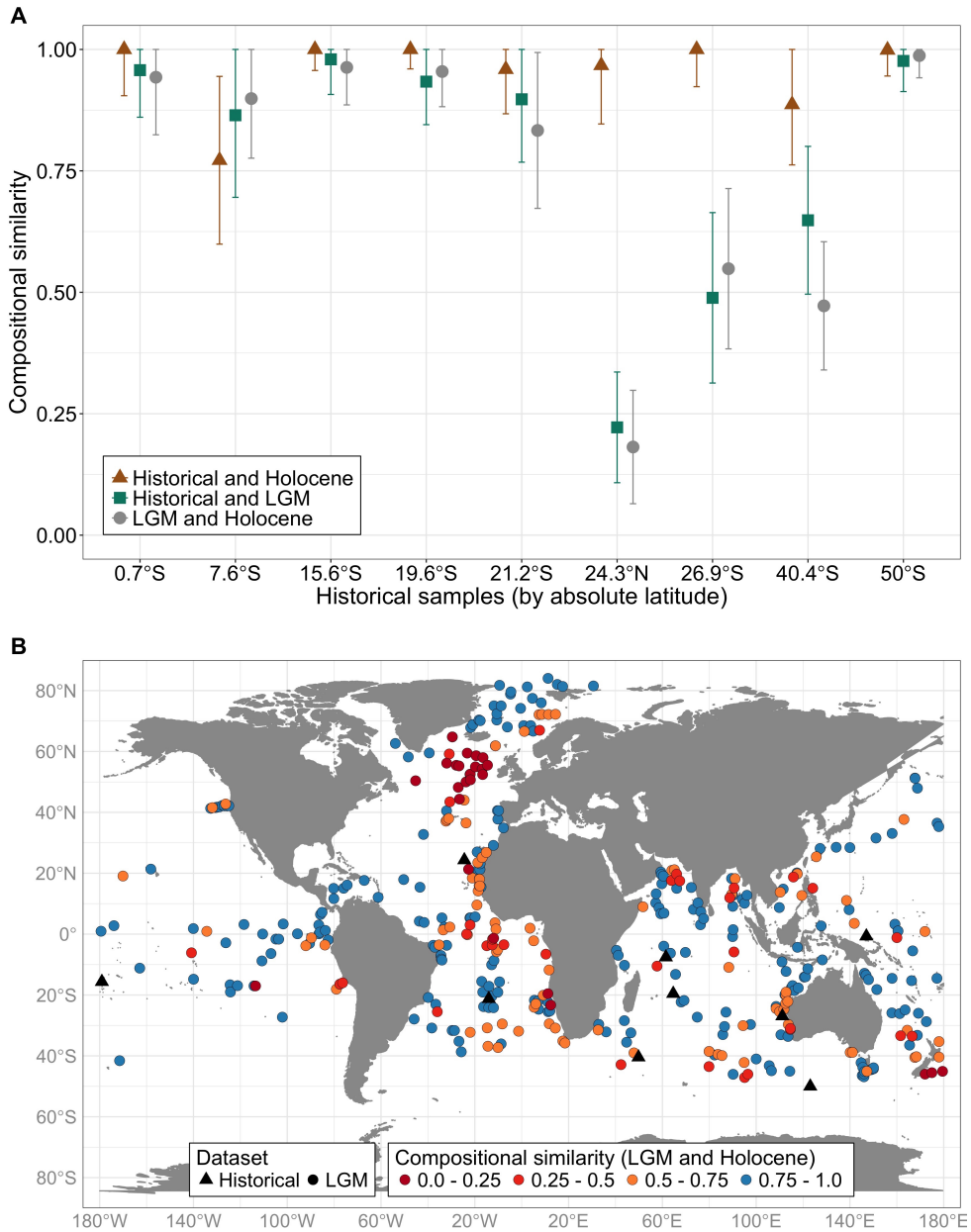


**Figure 1. (A)** Compositional similarity (Morisita-Horn index) between planktonic foraminiferal assemblages from historical sediment samples and assemblages from surface sediments (Holocene, brown triangle) and from the Last Glacial Maximum (LGM, green squares); and between Holocene and LGM assemblages (grey circle). The value of 0 means that the two assemblages share no species and 1 means that the relative abundances of all species in both assemblages are statistically identical. Lines represent confidence intervals based on 100 bootstrap replicates. Samples are ordered by absolute latitude of the historical sample site. **(B)** Black triangles: historical samples (nine in total). Dots: LGM samples for 389 sites worldwide. The colours of the dots represent the compositional similarity (Morisita-Horn index) between the assemblage of the LGM sample and its neighbouring Holocene sample. Red to orange dots indicate low similarity (*i.e.*, high species turnover since the LGM), whereas blue dots indicate similar Holocene and LGM planktonic foraminifera assemblages.

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