Pleistocene sea surface temperature, monsoonal hydrological variability and OMZ extension in the Northern Indian Ocean (Maldives Sea)

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GEOGRAPHICAL SETTING

The Maldives Inner Sea is a natural sediment trap within **the Indian Ocean** (Fig. 1). The new sedimentary record acquired **during IODP Expedition 359** in **The Maldives Sea** allows us to reconstruct variations in the Indian Ocean circulation patterns and in the regional climate from the Miocene to present time (Betzler et al, 2016a & b). The features observed in this record are intimately linked to the development South Asian Monsoon.

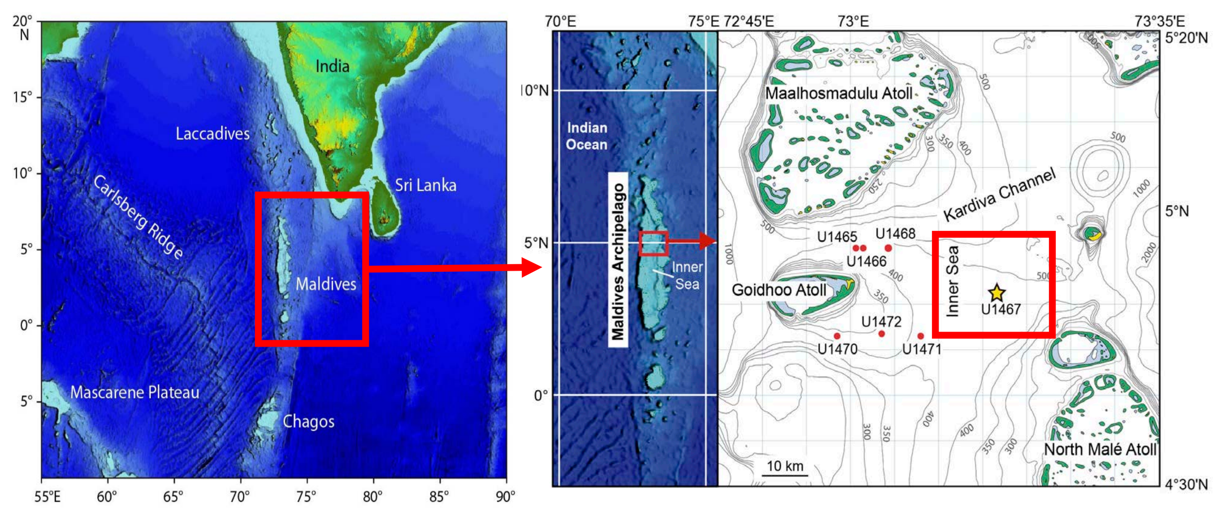

Figure 1. Location of The Maldives in the Indian Ocean and the sites drilled during IODP Expedition 359. IODP Site U1467 (4°51.03 °N, 73°17.02 °E, 487 m depth) is highlighted in the right panel within a red square.

SOUTH ASIAN MONSOON (SAM)

SAM generates **seasonally reversing winds and changes in precipitation** over the Northern Indian Ocean and South Asia as the Intertropical convergence zone (ITCZ) migrates due to the seasonal variation of the latitude of maximum insolation and the differential heating between land and sea (Fig. 2).

Summer monsoon (June-September): SW winds, high precipitation, SW monsoon current

Winter monsoon (November-April): NE winds, western flow of the North Equatorial current

Inter-monsoon seasons: strong Indian Ocean Equatorial westerlies (IEW)

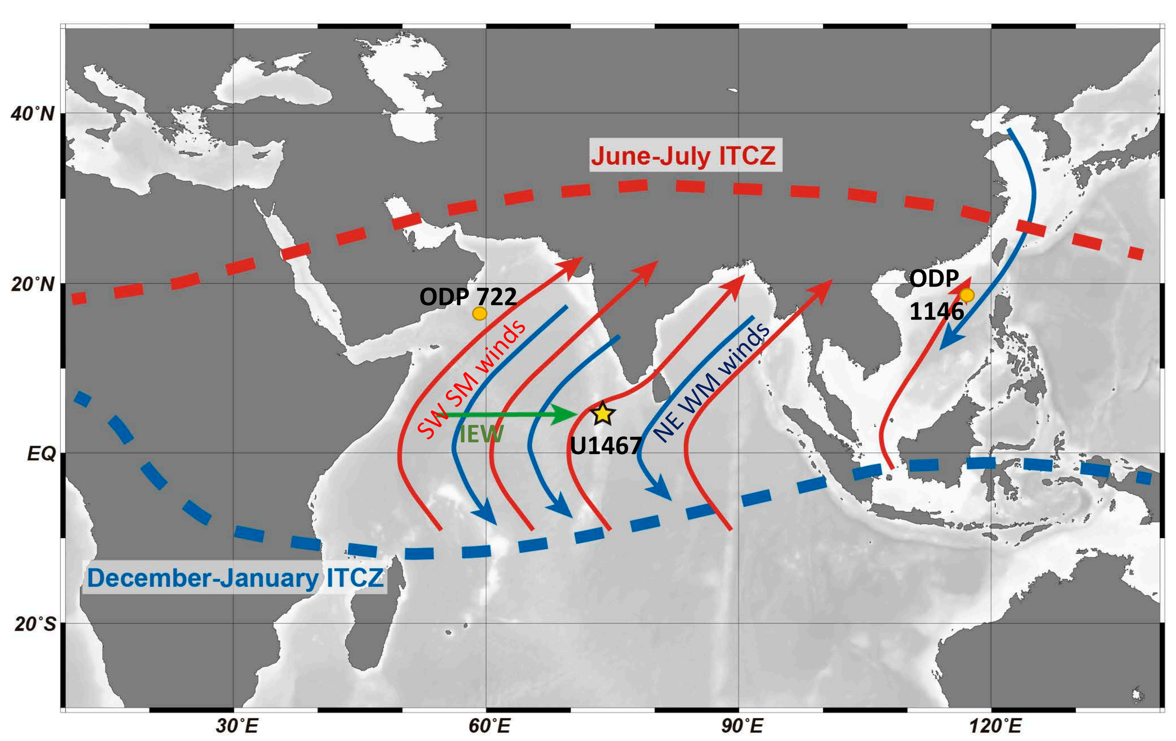

Figure 2. Position of the ITCZ in the Indian Ocean at present during the boreal summer (red dashed line) and winter (blue dashed line) seasons. The arrows indicate the predominant winds during boreal summer (red arrows), boreal winter (blue arrows), and the development of the inter-monsoon Indian Ocean Equatorial Westerlies (IEW) (green arrow) during April-May and October-November (Wyrtki, 1973a).

OXYGEN MINIMUM ZONE

One of the most characteristic features of the northern Indian Ocean water masses is the oxygen minimum zone (OMZ, Fig. 3) related to oceanic productivity in the water column, and intimately linked to the SAM. The Maldives Sea is a perfect location to study past changes in the monsoon dynamics and its associated impact on the Indian Ocean OMZ.

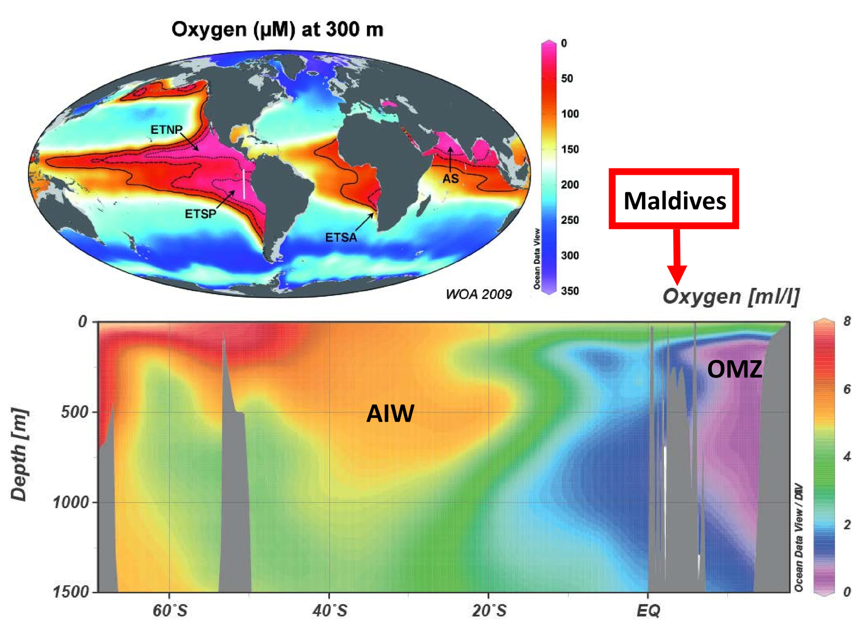

Figure 3. A) Oxygen distribution in the surface of the indian Ocean and B) oxygen distribution in a N-S profile. Data from World Ocean Atlas 2013 (Garcia et al., 2014). AIW= Antarctic Intermediate water.

INDIAN OCEAN DIPOLE (IOD)

The IOD index (Saji et al., 1999) is the SST anomaly between the western Indian Ocean and the southeastern Indian Ocean (off Sumatra). During the positive phase, weak IEW during October-November brings high precipitation in Eastern Africa and India, whereas the correlation with the April-May rainfall season is weaker.

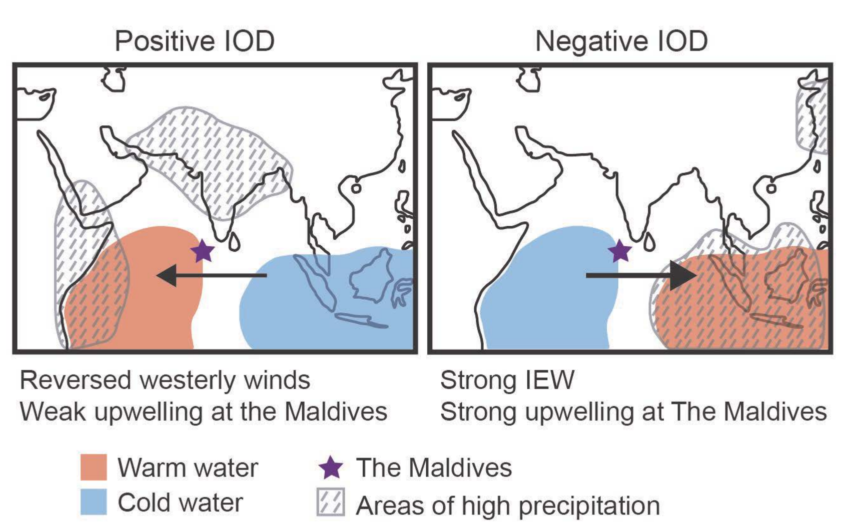

Fig. 7. Sketch depicting the effects of the Indian Ocean Dipole modes and how they may have affected precipitation in the Northern Indian Ocean as well as the Maldives water column mixing and productivity (Alonso-Garcia et al., 2019). Distribution of water masses and precipitation compiled from Marchant et al. (2007), Hastenrath et al. (1993) and Saji et al. (1999).

TAKE HOME MESSAGES

The SAM system underwent a big change throughout the last 1.5 Ma that resulted in the strengthening of the winter monsoon during glacial periods but also a wetter climate is observed during interglacial periods, indicating the intensification of summer monsoon during interglacials.

This created a strong contrast between glacial and interglacial conditions, particularly after the Mid-Brunhes event (MBE).

BOTTOM WATER OXYGENATION (BWO)

Before MIS 28 the HPA index shows that BWO was low and quite stable across glacial-interglacial cycles.

After MIS 28 BWO started to increase with higher oxygenation during glacial periods

At MIS 12 (MBE) a further BWO increase occurred during glacial periods, probably linked to the enhancement of winter monsoon and retraction of the OMZ. **Antarctic Bottom water (AIW)** gained a higher influence in the region during those times.

Ostracod assemblages corroborate the higher BWO during glacial periods.

WIND PROXIES

Dust input (Fe) and *n*-alkanes indicate **winter monsoon enhancement** throughout the last 1.5 Ma

After MIS 24 increase in winter monsoon wind strength.

At MIS 12 (MBE) further increase in winter monsoon.

PRECIPITATION PROXIES

The ratio of Fe vs K (chemical weathering proxy) and the ACL index indicate a long-term **increase in summer monsoon precipitation** maybe linked to conditions more similar to the **positive phase of IOD.**

After MIS 31 precipitation starts to increase moderately.

After MIS 12 increase in the summer monsoon rainfall during interglacials as well as in the contrast between glacial and interglacial precipitation.

SEA SURFACE TEMPERATURE (SST)

Equatorial SST from the Indian Ocean, South China Sea and Western Equatorial Pacific shows:

Before MIS 24 only moderate SST decreases during **MIS 38 and 30.**

MIS 24-22 first remarkable SST drop.

From MIS 22 to 12 glacial-interglacial cycles show small variability with moderate drops during glacial periods.

At MIS 12 (MBE) prominent shift in SST, with the emergence of large amplitude glacial-interglacial cycles. Other mid to high latitude records (such as the Southern Ocean) show lukewarm interglacials from MIS 22 to 12 and enhanced interglacial warmth at the MBE.

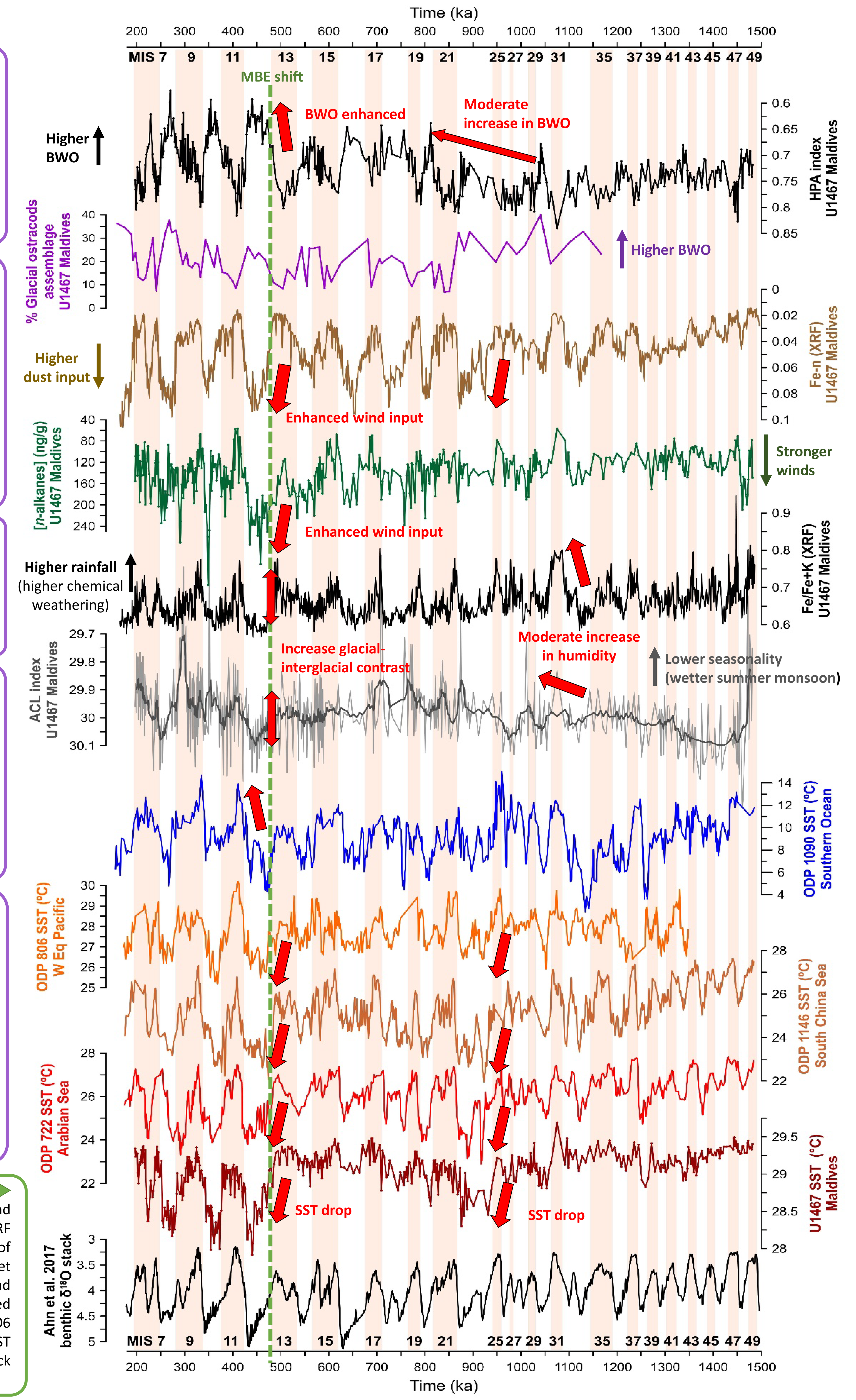

Figure 5. Data from Site U1467 compared to other sites. a) Site U1467 Higher Plant n-alcohols/(n-alcohols +n-alkanes) (HPA) index (Poynter and Eglinton,1991), ▶ indicates degradation of the organic matter and therefore oxygenation of the bottom waters; b) Site U1467 ostracod assemblage (*Bradleya*, *Agrenocythere* and *Polycope*) typical of glacial periods and highly oxygenated water (Alvarez-Zarikian et al. submitted); c) Site U1467 Fe normalized record obtained through XRF scanning (Kunkelova et al., 2018), indicates dust input and therefore winter monsoon wind intensity; d) Site U1467 *n*-alkanes concentration, indicates input of plant remains and therefore winter monsoon wind intensity (Alonso-Garcia et al., 2019); e) Site U1467 ratio between Fe and K from XRF scanning (Kunkelova et al., 2018), indicates chemical weathering intensity and therefore summer monsoon intensity; f) Site U1467 *n*-alkane average chain length (ACL) index (Poynter and Eglinton, 1990), high values of this index indicate enhanced dryness, seasonality and reduced summer monsoon (Alonso-Garcia et al., 2019); g) alkenone-based sea surface temperature (SST) for ODP Site 1090 (Southern Ocean) (Martinez-Garcia et al., 2010); h) planktic foraminifer Mg/Ca-based SST for ODP Site 806 (Western Equatorial Pacific) (Medina-Elizalde et al., 2005); i) alkenone-based SST for ODP Site 1146 (South China Sea) (Herbert et al., 2010); j) alkenone-based SST for ODP Site 722 (Arabian Sea) (Herbert et al., 2010); k) alkenone-based SST for IODP Site U1467 (Maldives Sea) (Herbert et al., 2005); l) global benthic $\delta^{18}O$ stack (Ahn et al., 2017). Interglacial Marine Isotope stages (MIS) are highlighted with light red bars and numbered.

ACKNOWLEDGEMENTS: We are grateful to the International Ocean Discovery Program and Expedition 359 Scientific party for taking the sediment cores. Thanks to FCT for funding MAG to participate in Expedition 359, for the CCMAR UID/Multi/04326/2019 funding, WarmWorld project (PTDC/CTA-GEO/29897/2017) and MAG and TR postdoc fellowships (SFRH/BPD/96960/2013 and SFRH/BPD/108600/2015). Thanks to the funding of Spanish Ministerio de Ciencia, Innovación y Universidades (grant RTI2018-099489-B-I00). C.A.Z. acknowledges support from NSF award no. OCE-1326927.

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Sea-surface temperature, productivity and hydrological changes in the Northern Indian Ocean (Maldives) during the interval ~575-175 ka (MIS 14 to 7)

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Kunkelova *et al. Progress in Earth and Planetary Science*
https://doi.org/10.1186/s40645-018-0238-x

Progress in Earth and Planetary Science

RESEARCH ARTICLE Open Access

A two million year record of low-latitude aridity linked to continental weathering from the Maldives

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