Impact of the Late Miocene Cooling on the loss of coral reefs in the Central Indo-Pacific

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Abstract. The Late Miocene Cooling (~~LCM~~LMC) has been recognized as a global event in the climate record and posited as the start of modern ecosystems. Whereas shifts in modern tropical terrestrial ecosystems around 7.0 - 5.~~5~~ 4 Ma ~~occur globally~~are known, little is known about ~~changes in aquatic ecosystems. This is especially true of shallow water carbonate ecosystems, such~~the impact of the cooling on ~~as~~ coral reefs, where few good proxy records exist. ~~-~~During the Pliocene, ~~there was~~ a~~A~~ stratigraphic interval ~~“reef gap”~~ is present ~~existed during the Pliocene~~ in ~~the area of~~ the c~~C~~entral Indo-Pacific, where reefs that were~~had been~~ present at the start of the Messinian~~ (7 – 5 Ma)~~ ~~drowned by thehave~~ disappeared by the Early Pliocene ~~(5 – 3 Ma)~~. ~~THowever, the~~This “Pliocene reef gap” has often been ascribed to non-climatic factors. However, ~~there is still due to~~ a lack of proxy data ~~that allows~~prevents an understanding of climatic~~e~~ changes during this time. Here, we present a TEX_{86}^{H}-based sea surface temperature ~~(SST)~~ record for the Coral Sea, suggesting that the LMC ~~was more pronounced than previously thoughta major cooling in the~~is present across the C~~cC~~entral Indo-Pacific. During the LMC, ~~the~~ SST~~s~~ at ODP Site 811 declined by about 2ºC, and cooling lasted from 7.0 Ma to ~~possibly as late as~~ 5.4~~0~~ Ma. This ~~level of~~ cooling has also been seen in other parts of the c~~C~~entral Indo-Pacific. ~~-Previous research showed that coral reefs across the Central Indo-Pacific experienced a major ecosystem change, leading to the collapse of the coral reefs by 5 Ma. This event led to a lack of coral reefs during the Pliocene, an event that has often been described as the “Pliocene reef gap.~~The LMC ~~leads~~caused~~s to~~ many changes in~~ the~~ the c~~C~~entral Indo-Pacific, including~~inducing cooling SSTs ,~~ a southwest shift of~~in~~ the monsoon belt, ~~and and~~ changes in~~ the intensity of~~ terrestrial inputs, and the strength of ocean ~~-changing~~ current~~s-strengths” The timing of the onset of this event matches the cooling in the records~~. ~~-~~All these factors ~~changes are~~can be stressors ~~for~~affecting coral reef growth~~s.-~~ This suggests ~~that the~~the overall impact of the LMC ~~was a final~~was to increase the stress on reef systems, ~~and this~~which could have ~~-stressor that~~ provided a ~~regional~~ driver for the collapse of individual reefs and, therefore, a potential cause for the “Pliocene Coral Gap.” The ~~relatively rapid and intense~~ change in SST and other stressors associated with the cooling caused coral reef systems to collapse across the Central Indo-Pacific.

1. Introduction

1.1 LMC background~~1.1 LMC background~~

~~The Late Miocene Cooling (LMC) is one of the most puzzling climatic shifts in climate record.~~ Global ~~climate~~ Sea Surface Temperature (SST) records have identified the Late Miocene Cooling (LMC) as a worldwide event occurring ~~during the Messinian~~ between 7.~~2~~0- 5.~~5~~4 Ma when SST globally decreased by about 6 °C ~~Ma~~ (Herbert et al., 2016~~a~~; Holbourn et al., 2018; Martinot et al., 2022~~a~~; Tanner et al., 2020; Wen et al., 2023)~~ when SSTs globally decreased by about 6 °C~~. However, ~~as~~ the LMC does not occur in ~~global~~ benthic $\delta^{18}O$ stacks or splices ~~, it has only recently been identified as a global event~~ (Westerhold et al., 2020; Zachos et al., 1994). ~~Therefore, i~~It is a major climatic ~~shift that~~cooling that does not seem to be associated with any changes in ice volume or deep water temperatures (Herbert et al., 2016~~b~~; Martinot et al., 2022~~a~~; Tanner et al., 2020). Therefore, it has often been overlooked as a low-latitude climatic ~~climatic~~ factor impacting tropical marine ecosystems~~e driver.~~. ~~This has led to questions about the causes and impact of the event. It also means that the LMC is often overlooked as a driver of changes during the Late Miocene. The Yet the research shows that the LMC has been suggested to be a~~is a ~~critical step in developing modern ecosystems (CITE) and has been seen as a potential precursor to the changes associated with the later onset of the northern hemisphere cooling~~ .

The LMC has been linked to aridification in Asia and Africa due to changes in the monsoonal system (Dupont et al., 2013; Feakins, 2013; Wen et al., 2023). This resulted in significant shifts from C_3 to C_4 plants in tropical zones, indicating the expansion of tropical grasslands (Huang et al., 2007; Steinthorsdottir et al., 2021; Strömberg and Strömberg, 2011). Due to ~~to the~~ grassland expansion in East Africa, it is thought that some of the earliest hominids ~~first~~began to evolve~~d~~ around 7 Ma to ~~take~~adapt to ~~advantage of~~ the changed climatic conditions (Brunet, 2020). In the ocean, a ~~it is known that the~~ "biogenic bloom" ~~is~~ marked by an increase in the $\delta^{13}C$ of benthic foraminifera occurred just before the onset of the LMC at around 8 Ma (Diester-Haass et al., 2004~~a~~; Drury et al., 2018; Lübbers et al., 2019).

1.2 Causes of the LMC

The causes of the LMC are not well understood. The paradox of a major cooling without a concurrent increase in glaciation~~ers~~ has still not been fully explained. There are a series of short-lived glacials, but these only occur after 6 Ma, almost 1 Mya after the onset of the cooling~~, and~~ and at the start of the warming following the LMC (Jöhnck et al., 2020). Therefore, whatever triggered the LMC must have either had little impact on the size of glaciers or deep-water temperatures. There are two primary explanations for the cooling associated with the LMC. These are gateway changes causing shifts in ocean circulation and changes in atmospheric CO_2.

~~It is known that there were o~~Ongoing re-organization~~ns~~~~shifts~~ in the Indonesian Throughflow (Hall, 2002, 2009) and the Isthmus ~~closure~~ of Panama (Collins et al., 1996; Haug et al., 2001)~~,~~ may offer a tectonic mechanism for the LCM due to the re-organization of the global thermohaline circulation~~. Both are ongoing and~~. ~~could have caused changes in ocean circulation~~~~be responsible for the changes.~~ However, almost all known major ~~changes~~thresholds in these systems date to the Pliocene ~~era~~ or later (Auer et al., 2019; Haug et al., 2001; De Vleeschouwer et al., 2018, 2019), making these tectonic restrictions of oceanic gateways an unlikely cause. Furthermore, available SST data shows that ~~the climatic~~ changes observed during the LMC eventually reversed after 5.4 Ma.~~,~~ ~~suggesting~~This temporary and reversible pattern further emphasizes that ~~that~~long-term and permanent ~~if a change at an~~tectonic, oceanic gateway closure could not have been the primary driver of the LMC~~was responsible, it must have~~ ~~been a temporary change~~. ~~Also, the changes seen during the LMC are r~~eversed, ~~with no evidence of permanent changes, suggesting that if a change in an oceanic gateway is responsible, it must be a temporary change.~~

An alternative~~The other major~~ hypothesis is that there was a reduction of atmospheric *p*CO_2 during the LMC.- L~~The~~ ~~l~~ower ~~wer~~ *p*CO_2 ~~CO^2~~ would explain~~s~~ the difference between the increased tropical presence of C4 grasses, which were ~~and the~~ better~~er~~ ~~adaptata~~adapted~~ion~~ to lower atmospheric ~~a low~~ CO_2~~CO^2~~ ~~environment~~concentrations (Herbert et al., 2016~~b~~; Wen et al., 2023). -Model estimates, including atmospheric ~~a~~ CO_2 reductions, also fit well with temperature reconstructions, showing a cooling of about 2-3°C in the central Indo-Pacific ~~Also, model estimates of a lowering of CO^2 fit the temperature reconstructions well, showing about 2-3 C of cooling in the Central Indo-Pacific~~ (Martinot et al., 2022~~a~~).- The cause~~s~~ of the Late Miocene ~~lowering of~~ CO_2~~CO^2~~ reduction is~~are~~ not well understood~~defined~~. One suggestion is that it~~they~~ was related to higher oceanographic productivity, which would draw~~ing~~ down atmospheric CO_2 ~~CO^2~~ (Holbourn et al., 2018). –This could be a consequence of~~related to~~ the "biogenic bloom" between 8-7 Ma (Diester-Haass et al., 2004~~b~~; Grant and Dickens, 2002). Another theory is that changes in plate motion during the LMC led to a reduction~~decrease~~ of~~in~~ CO_2~~CO^2~~ input to the atmosphere ~~during the LMC~~ (Herbert et al., 2022).- Finally, it has been suggested that the tectonic uplift of Papua New Guinea led to a long-term decrease in atmospheric CO_2 ~~CO^2~~ (Martin et al., 2023; Clift et al., 2024).

1.3 Miocene reef history

~~**1.3 Miocene Reef history**It has been hypothesized that tThe LMC marks the start of "modern ecosystems," and it has been tied to aridification in Asia and Africa due to changes in the monsoonal system . Additionally, the LMC has been linked to major shifts from C_3 to C_4 plants in tropical zones, indicating the establishment of expansion of grasslands worldwide . Finally, dDue to the grassland expansion in East Africa, it is thought that some of the earliest hominids first evolved around 7 Ma to take advantage of the changed conditions . In the ocean, it is known that the "biogenic bloom" is marked by an increase in the $\delta^{13}C$ of benthic foraminifera just before the onset of the LMC at around 8 Ma. This has been thought to be due to ocean circulation changes around the same time as the LMC, although the connections are still unclear~~ .

There was an extensive coral reef system on the Queensland Plateau during the Early-Middle Miocene (Feary et al. 1991; ~~C.~~ Betzler and Chaproniere 1993). After 11 Ma, however, the coral reefs appear to have retreated (Isern et al., 1993, 1996). Large benthic foraminiferal reconstructions of sea level show a gradual increase in relative water depth between 13-8 Ma (Katz and Miller 1993). ~~(Betzler et al., 1995)However, after 11 Ma, the coral reefs appear to retreat (Isern et al., 1993a, 1996b). Large benthic foraminifera-based reconstructions of sea level show a gradual increase in relative water depth between 13-8 Ma (Katz and Miller 1993b).~~ Other reefs in the Coral Sea and surrounding areas show~~have~~ evidence of a much later collapse,~~.~~ m~~M~~any occurring ~~of themse ocure~~ between 7.0-5.4 Ma ~~-5.4~~ during the LMC.~~d~~ For instance, in the ~~S~~southern Coral Sea, coral reefs on Marion Plateau disappeared between 7.5-5.7 Ma (Bashah et al., 2024~~a~~; Eberli et al., 2010; Ehrenberg et al., 2006). On the other side of Australia, the NW ~~S~~shelf ~~great~~ barrier reef experienced~~has~~ a major drowning event ~~until~~ between 7.2-5.9 Ma (Belde et al., 2017~~b~~; Rosleff-Soerensen et al., 2012, 2016~~; Thronberens et al., 2022~~). Finally, studies of~~n the~~ Early Pliocene sediments~~, even~~ on the Queensland Plateau ~~,~~show ~~pelagic sedimentation even~~hardgrounds on the shallow carbonate platforms, suggesting a complete absence of ~~C~~coral reefs during the 'Pliocene reef gap' (Droxler et al. 1993).

Globally,~~ a~~ similar reef trends are~~rend is~~ seen. The highest ~~density~~abundance of coral reefs occurs in the Mid-Miocene, followed by a slight decline towards the Late Miocene ~~The highest reef density exists during the mid-Miocene, followed by a slight decrease towards the Late Miocene~~ (Harrison et al., 2023a; Perrin and Kiessling, 2012). However, ~~there appearsseems to have been a major loss ofin coral reefs by the Early Pliocene~~by the Early Pliocene there appears to have been a major loss of coral reefs. This suggests that the major reef loss ~~of corals~~ occurred between the end of the Messinian and the beginning of the Early Pliocene (7.25 – 5.334 Ma). Harrison et al. (2023) attribute~~scribe the~~ reef loss in the c~~C~~entral Indo-Pacific to several ~~multiple individual~~ factors impacting~~changes for~~ individual reefs differently (Fig. 2). These include ~~changes in~~ tectonic processes~~s~~, sea level changes, and increases in terrestrial input. ~~(Perrin and Kiessling, 2012)~~The authors reject climate change as a causal factor, ~~because they~~ argu~~e~~ing that SSTs during the ~~l~~Late Miocene are similar to modern ones, and there is no evidence of major warming across this time (Harrison et al. 2023). However, there is evidence that the ~~warm~~ tropical water belt ~~both~~ cooled and contracted during the LMC (Martinot et al. 2022; Liu et al. 2022). Moreover, there were ~~There is also evidence of~~ changes~~global shifts~~ in the global distribution of reef~~s abundance~~ during this time, including a decrease in their latitudinal range~~abundance~~ (Perrin and Kiessling, 2012). ~~(Brachert et al. 2020)rResearch has shown that across the Central Indo-Pacific, including the Coral Sea, more extensive coral reefs prevailed during the Mid-Miocene . However, during the~~

~~Late Miocene, most of these systems seemed to have collapsed (Isern et al., 1996), leading to what has been described as the "Pliocene Reef Gap" (Fig. 2). The timing of this event is poorly constrained but in Australia there is evidence of reef collapse at 7 Ma on the NW shelf (CITE) and the Marion Plateau (CITE). Furthermore, it seems like in Indonesia many of the reefs had disappeared by the start of the Early Pliocene (CITE). The timing of this event is poorly constrained but in Australia there is evidence of reef collapse at 7 Ma on the NW shelf and the Marion Plateau . Furthermore, it seems like many of the reefs in Indonesia disappeared by the start of the Early Pliocene . On a broader scale these changes are linked to global shifts in reef areas during the Late Miocene. So, there is evidence of a loss of reef coverage around the same time as the LMC.~~

1.4 Tropical SST change during the LMC

As discussed above, the climatic impact of the LMC has not been investigated as a driver of the Pliocene Reef Gap, because many previous studies of benthic δ^{18}O isotopes ~~or BWT~~ records did not show an increase of ~~cooling~~glaciation during the LMC ~~However, as shown above, the climatic impact of LMC has not been investigated as a driver for the "Pliocene Reef Gap" because many initial studies of benthic δ^{18}O isotopes or BWT showed no cooling over the LMC~~ (Harrison et al., 2023~~a~~; Perrin and Kiessling, 2012).~~-~~ Furthermore, even after ~~identifying~~ the LMC was identified, many early~~initial~~ tropical records showed less than ~~>~~1 °C cooling during the LMC (Herbert et al., 2016~~b~~). ~~-~~As a result, it was concluded that the ~~there seemed to be very little~~ temperature impact of the LMC in~~on~~ the tropics was small.~~-~~ However, this conclusion~~initial assumption about the cooling~~ has been challenged~~questioned~~, as ~~because~~ ~~many of the~~most LMC records are ~~of the LMC are~~ based on U$^{K}_{37}$' SST proxy~~s~~ (Herbert et al. 2016).~~-~~ These alkenone-based SST records have a saturation limit of 28 to 29 °C (Müller et al. 1998) when the proportion of the $C_{37:3}$ isomer used for the temperature calculation approaches zero (Grimalt et al. 2001). Especially ~~in a lithology such as~~ carbonate rocks~~s~~ with low~~out high~~ organic ~~preservation~~ ~~(~~content and poor organic matter preservation~~?)~~, U$^{K}_{37}$' SSTs are considered unreliable above temperatures of 26-27 °C (Pelejero and Calvo 2003; Grimalt~~, Calvo, and Pelejero~~ et al. 2001). ~~-~~M~~Therefore, m~~odels show that many parts of the tropical and sub-tropical Miocene Ocean were too warm for applying the~~to reconstruct SST with~~ U$^{K}_{37}$' proxy (Burls et al. 2021). ~~-~~In fact, ~~with the exception of~~except ODP ~~s~~Site 722~~except for ODP Site 722~~, all the sites where~~used for~~ the U$^{K}_{37}$' proxy was used to reconstruct SST~~sion~~ are located~~are~~ in the cold tongue originating from the ~~the relatively cool~~ East Pacific Equatorial Upwelling Zone ~~-~~(Herbert et al. 2016). ~~-~~ODP Site 722 is located in the Arabian Sea upwelling cell and is cooled ~~thus actually defined by localized monsoonal wind patterns~~ by~~forcing~~ coastal upwelling driven by monsoonal winds~~in the western Arabian Sea~~ (Bialik et al. 2020).

Mg/Ca and TEX_{86} records show a stronger cooling during the LMC. For instance, the West Pacific Warm Pool (WPWP) stack of TEX_{86} SSTs shows a cooling of 2 °C~~2-degree cooling~~ during the ~~(~~LMC (Liu et al. 2022).~~-~~ Furthermore, between 7-5 Ma, all the sites included in the WPWP stack ~~(?)~~ show a cooling of 2-3 °C~~degrees between 7-5 Ma~~, suggesting a ~~wide-scale~~ cooling of the entire ~~(?)~~ WPWP (Liu et al. 2022; Zhang, Pagani, and Liu 2014).~~-~~ This cooling is also confirmed by~~using~~ a Mg/Ca SST record from ODP Site 1146, one of the sites included in the WPWP TEX_{86} SST stack. In agreement with the TEX_{86} SSTs, the Mg/Ca SST shows a~~, with~~ cooling of 2 ºC ~~in the Mg/Ca~~ (Holbourn et al., 2018).~~-~~ In the Indian Ocean, ~~the~~ ~~IODP 1443~~ a Mg/Ca record from IODP ~~site~~Site 1443~~record~~ shows a cooling of about 2 ºC (Martinot et al., 2022a).

However, these records mainly derive from~~cover~~ the northern margins~~edges~~ of the c~~C~~entral Indo-Pacific warm water area. Therefore, while the magnitude of cooling and timing of the LMC in these ~~central Indo-Pacific~~ records is ~~seem~~ similar, it is unclear whether~~if~~ this was~~is~~ a ~~warm pool-wide (~~large-scale, tropical-wide~~?)regional-wide~~ event that could have affected coral reefs across the Central Indo-Pacific. ~~Red: check order of Figure references?~~

~~1.4 Tropical SST change during the LMC~~

~~However as shown above the climatic impact of LMC has not been investigated as a driver for the "Pliocene Reef Gap" because of many initial studies of benthic d18O isotopes or BWT showed no cooling over the LMC . Furthermore, even after the identification of the LMC many of the tropical records shown showed less than>1 C cooling during the LMC . As a result, there seemed to be very little temperature impact on the tropics. However, this initial assumption about the cooling has been questioned because many of the records of LMC are based on U^{K}_{37}' SSTs . These have a saturation limit of 28 to 29 °C when the proportion of the $C_{37:3}$ isomer used for calculation approaches zero. Especially in a lithology such as carbonates without high organic preservation, U^{K}_{37}' SSTs are considered unreliable above 26-27 °C . Therefore, models show that many parts of the tropical and sub-tropical Miocene Ocean were too warm to reconstruct SST with U^{K}_{37}' . In fact, except for ODP Site 722, all the sites used for the U^{K}_{37}' reconstruction were located in the East Pacific Equatorial Upwelling Zone . ODP Site 722 is in the Arabian Sea upwelling cell and thus actually defined by localized monsoonal wind patterns forcing upwelling in the western Arabian Sea .~~

~~Mg/Ca and TEX86 records show a stronger cooling during the LMC. For instance, the West Pacific Warm Pool stack of TEX86 SSTs shows a 2-degree cooling during the LMC . Furthermore, all the sites show a cooling of 2-3 degrees between 7-5 Ma, suggesting a wide-scale cooling of the WPWP . This cooling is also confirmed using a Mg/Ca SST record from ODP site 1146, one of the sites also in the WPWP TEX86 SST stack. This shows ait cooling of 2 C in the Mg/Ca . In the Indian Ocean, the IODP 1443 Mg/Ca record shows a cooling of about 2 degrees . However, these records mainly cover the northern tropics. Therefore, while the cooling and timing of the LMC in these central Indo-Pacific records seems to be similar, it is not clear if this is a regional wide event. . Therefore, more work needs to be done to understand the impact of cooling on coral reefs.~~

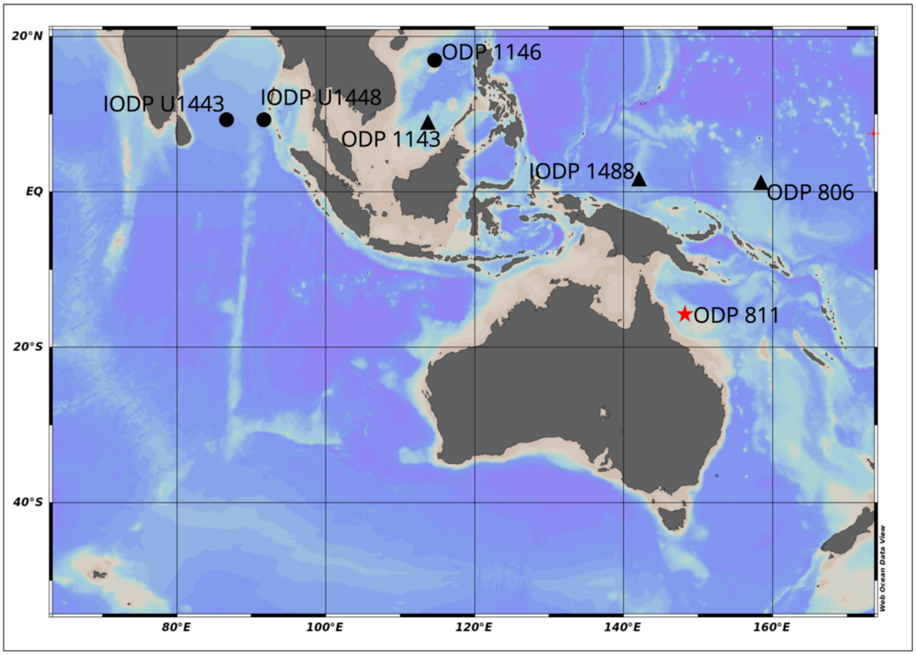
1.5 ~~Project Introduction This study~~Objective?

~~1.5 Project Introduction~~

~~Here, we present an SST record based on the TEX_{86}^{H} molecular paleothermometer for the Late Miocene and Pliocene from the Coral Sea to investigate these changes and their effects on coral reefs during the LMC.~~

~~However, T~~to better understand the link between tropical~~changes in~~ SSTs and the LMC, new records need to be produced from across the ~~tropiscal~~ central Indo-Pacific~~ in areas where coral reefs grow today~~. ~~The~~ In this study, we present a TEX_{86}^{H} ~~record was established using sediments taken~~ SST record covering the LMC from ODP Site 811, located on the Queensland Plateau in the Coral Sea ~~that covers the LMC~~ (Fig. 1). This is an extension of a record ~~between 7-12 Ma that was~~ previously published in Petrick et al. (2023~~a~~) that spanned the period ~~—~~from ~~7~~6.6-1~~2~~1.1 Ma. In this study~~ we have added~~

~~additional samples between 2.5 -~~, we added new TEX_{86}^{H} SST data~~samples~~ between 2.5 and ~~7.0~~6.6 Ma to investigate the LMC and the Pliocene.~~-~~ ~~The~~ We ~~developedchose this record (~~chose this site~~ ?)~~ because the Coral Sea has one of the highest coral reef densities in the world (Bridge et al., 2019)~~,~~ and is bordered ~~as highlighted~~ by the Great Barrier Reef off ~~bordering~~ the East Australian coast ~~in the modern Coral Sea~~. ~~Our~~ This ~~study is near the modern Coral Triangle, an area with a unique density of coral reefs centered on the Indonesian archipelago in the Indo-Pacific (Vernon et al., 2009) (Fig. 1). Today, the Coral Sea is outside of the biologically defined Coral Triangle (Vernon et al., 2009). Instead, the Coral Sea and the Coral Triangle are part of the larger biologically defined Central Indo-Pacific (Crandall et al., 2019; Spalding et al., 2007). This area is~~The c~~C~~entral Indo-Pacific is ~~actually thought to be~~ a~~the focus of~~ hotspot of ~~Coral~~ coral ~~Reef~~ reef diversity during the Miocene and, therefore, a key reef area ~~to target~~ (Renema et al., 2008).~~-~~ ~~Finally,~~There is ~~there is~~ abundant evidence of reef loss during the Late Miocene period in the ~~c~~Coral ~~s~~Sea ~~(~~(Bashah et al., 2024~~a~~; Betzler et al., 2024). ~~Therefore, we will refer to the area as the Central Indo-Pacific in this article. . There is, however, a dearth of data to understand the factors that led to the Pliocene reef gap because many SST records for the Central Indo-Pacific have not covered the LMC and early Pliocene. Furthermore, because of the variations seen within the LMC, even in near proximity sites, more records are necessary to understand the spatial heterogeneity of the event. Finally, even in the records produced, the relationship to shallow water ecosystem change was not discussed. Therefore, this paperIn this paper, we~~This paper ~~will~~ investigates whether climate changes~~ during the~~the ~~LMC~~ during the LMC could have ~~acted as a final stressor leading~~led to the collapse of ~~other~~ reef systems across the c~~C~~entral Indo-Pacific ~~also~~and globally.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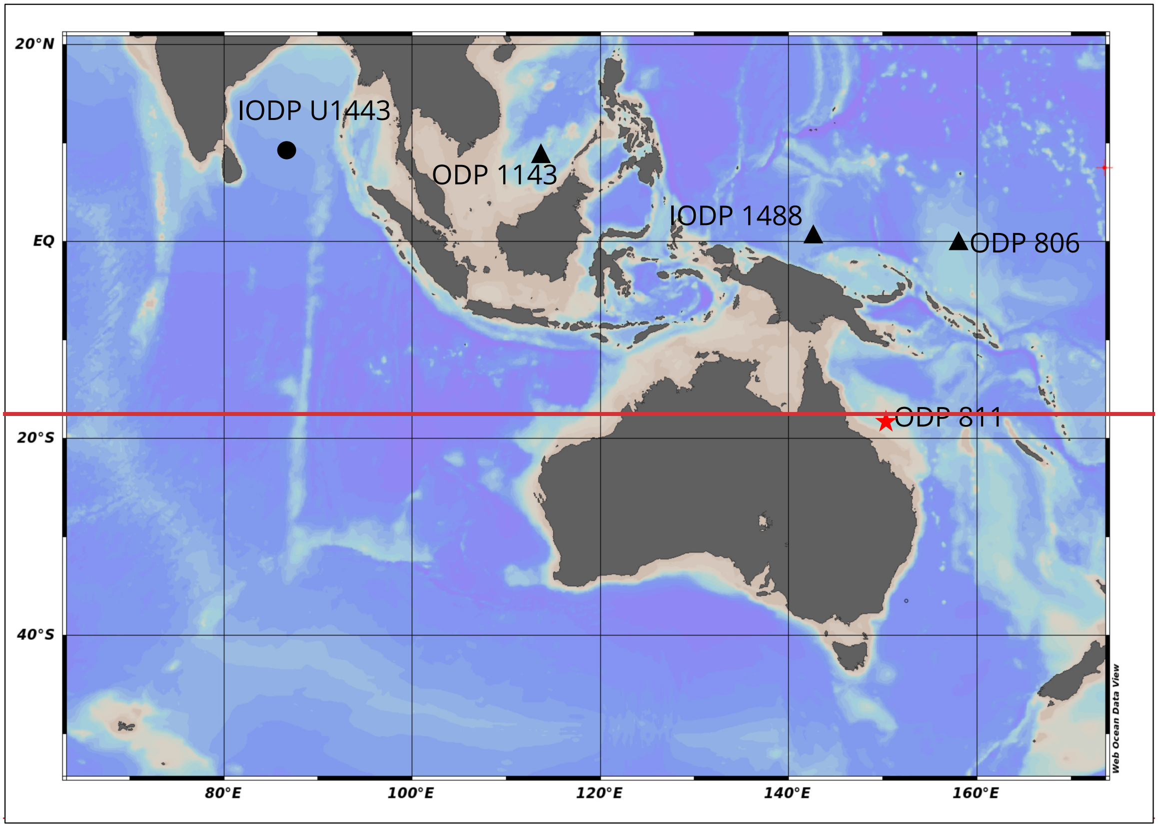
ODP 806
ODP 811
Web Ocean Data View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ODP 811
Web Ocean Data View

Figure 1: Map showing the c~~C~~entral Indo-Pacific and the location of ODP ~~site~~Site 811 studied here (red star). All the ~~Other sites, including those~~sites included ~~of the~~ in the TEX_{86}–derived West Pacific Warm Pool stack (Liu et al., 2022), are indicated with black triangles (Fig 6).~~,~~ ~~and IODP site U1443 is shown by a filled circle~~All Mg/Ca records are shown with black dots (Fig 5).~~-~~ The base map is from Ocean Data View (Schlitzer 2021).

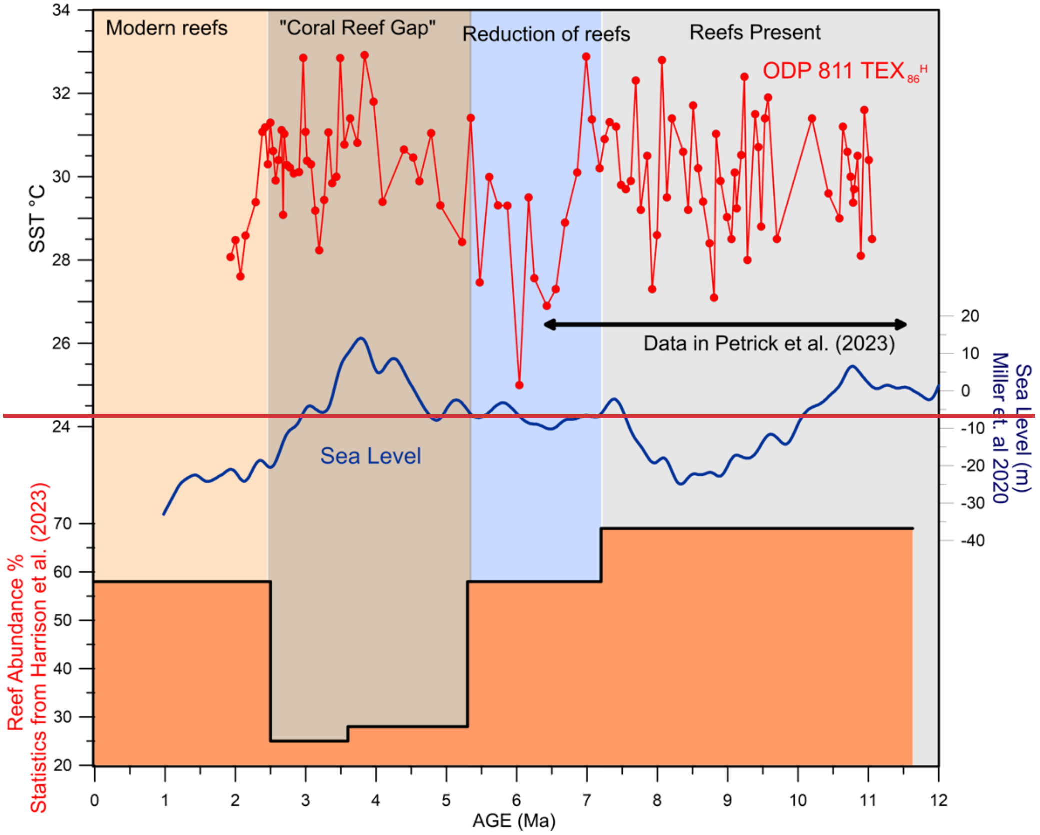
2 Methods

2.1 Biogeochemistry

We extracted 50 cc of sediment for this project, which resulted in between 50 and 60 g of sediment, suitable for extracting sufficient organic material for TEX_{86} determination. Dried and homogenized samples were Soxhlet extracted for 48 h using a solvent mixture of DCM: MeOH (9:1, v/v). The addition of activated copper turnings removed elemental sulfur. A Büchi solvent evaporator reduced excess solvent to a final volume of 2 ml. Samples were then transferred into a 4 ml vial, where the total extract (TE) was taken to dryness under a gentle stream of nitrogen. TEs were fractionated into aliphatic, aromatic, and polar fractions by silica gel-column chromatography (6 ml SPE column, 2.8 g Silica 60 mesh, 25–40 µm) using solvents with increasing polarity in an LC-TECH automated SPE system. NSO (polar) compounds were eluted with 14 ml DCM/ MeOH (1:1, v/v). The polar fraction was reconstituted in hexane/isopropanol (9:1, v/v) and re-chromatographed over aminopropyl-substituted silica gel (3 ml SPE column, 1.0 g aminopropyl-silica, 25–40 µm). The alcohol fraction containing the GDGTs was eluted with 5 ml of hexane/isopropanol (9:1, v/v) and, after drying, was re-dissolved in hexane/isopropanol (99:1, v/v) to a final concentration of 6 mg/ml for injection into the HPLC/MS system.

GDGTs were measured on an AGILENT liquid chromatograph coupled to an AGILENT single quadrupole mass spectrometer following the analytical protocol of Hopmans et al. (Hopmans et al., 2016). The HPLC instrument was equipped with an AGILENT HILIC silica column (2.1 x 150 mm; 1.5 µm particle size) and a guard column maintained at 30°C. Detection of archaeal core lipids was achieved by single ion recording of their protonated molecular ions $[M + H^+]$, and compounds were quantified by integration of peak areas using AGILENT Masshunter© software. Calculation of TEX_{86}^H followed (Kim et al. 2010). Reproducibility upon duplicate measurements showed a relative standard error of <2%.

3 Results



~~Figure 2: The TEX$_{86}^{H}$-derived SST record for site ODP 811 is shown in red, including data from 6 to 12 Ma taken from Petrick et al. (2023).Kim et al. (2010b) The evolution of sea level is shown in blue after Miller et al. (2020). The relative abundance (%) of areas covered by reefs in the Central Indo-Pacific is shown in orange shading at the bottom, with data taken from Harrison et al. (2023). Shaded boxes at the top indicate phases of reef evolution in the Central Indo-Pacific.~~

~~3.1 Site details~~

~~ODP site 811 is located in the central coral sea at xxxxxxx and has a modern water depth of XXXX. Large benthic foraminifera data shows that the site was probably much shallower during the start of the Late Miocene (<500 m) and that the site only reached its current depth around the Early Pliocene. For this study, we focused on the record from Hole A between X and X m. Therefore, we have decided to focus on this part of the core because this is where the SST data originated. The age model from this site was done using a new nannofossil stratigraphic study. This, including the data and error, was published by . In that article, information on how this was produced and a full nannofossil abundance record are shown. For this study, this age model was not updated. The core is almost entirely nannofossil ooze, with a couple of sections described as nannofossil ooze with foraminifera. In the original shipboard description, the core was broken up into units based primarily~~

~~on the macrofossil components of the core. The interpretation of these has been disputed so for this study, we have based the lithologic interpretation on the original description from the published iniall reports. None of these unit boundary match major changes in the TEX86 data. The site today has a SST of X degrees based on the time between X and X. The average summer temperature is X and winter temperature is X.~~

3.1 Site details

ODP ~~site~~ Site 811 is located in the ~~central~~ ~~c~~Coral ~~s~~Sea ~~at~~ (16.516° S, 148.~~2~~157 E)~~xxxxxxx~~ and has a modern water depth of 9~~48~~37.0 m (Fig. 1)~~XXXX.~~- Large benthic foraminifera data shows that the site was probably ~~much~~ shallower during the start of the Late Miocene (<500 m) and that the site only reached its current depth around the Early Pliocene (Katz and Miller 1993~~a~~). For this study, we focused on the record from Hole A between ~~X~~113 and ~~X~~27 m. ~~Therefore, we have decided to focus on this part of the core because this is where the SST data originated.~~ The age model from this site was ~~was done~~ created using a new nannofossil stratigraphic study. -This, including the data and error, was published by Petrick et al. (2023~~a~~). ~~In that article, information on how this was produced and a full nannofossil abundance record are shown. For this study, this age model was not updated.~~ The ~~core~~studied interval ~~is~~consists almost entirely of nannofossil to foraminifer ooze~~, with a couple offew sections described as nannofossil ooze with foraminifera~~. In the upper 70 mbsf, the pelagic components are mixed with fine, shallow water bank--derived particles~~, and t~~. The sediment was interpreted as periplatform ooze (Fig. 2). One debris flow occurs close to the top of the studied interval (811A-4H-6), which was avoided during sampling (Fig. 2). The interval between 70 and 113 mbsf is characterized by purely pelagic sediments (Fig. 2). The carbonate content in the studied section always exceeds 90 wt. %. ~~In the original shipboard description, the core was dividedbroken up into sedimentary units based primarily on the macrofossil components of the core. The interpretation of these has been disputed (Betzler et al., 2024; Droxler et al., 1993b), so for this study, we have based the lithologic interpretation on the original description from the published inialtial reports.~~ None of th~~ese~~ese ~~unit~~lithologic boundar~~y~~ries match ~~major~~ changes in the TEX_{86} data or the timing of the LMC (Fig 2).- The modern annual average SST at Site 811 is~~The site todayoday's site has a meann SST of X~~ 26.1 °C ~~degrees~~(World Ocean Atlas 2018, 2022~~a~~)~~based on the time between X and X~~. -The average summer temperature is ~~X~~28.32 °C,~~;~~ and the average winter temperature is ~~X~~25.09 °C (World Ocean Atlas 2018, 2022~~a~~).

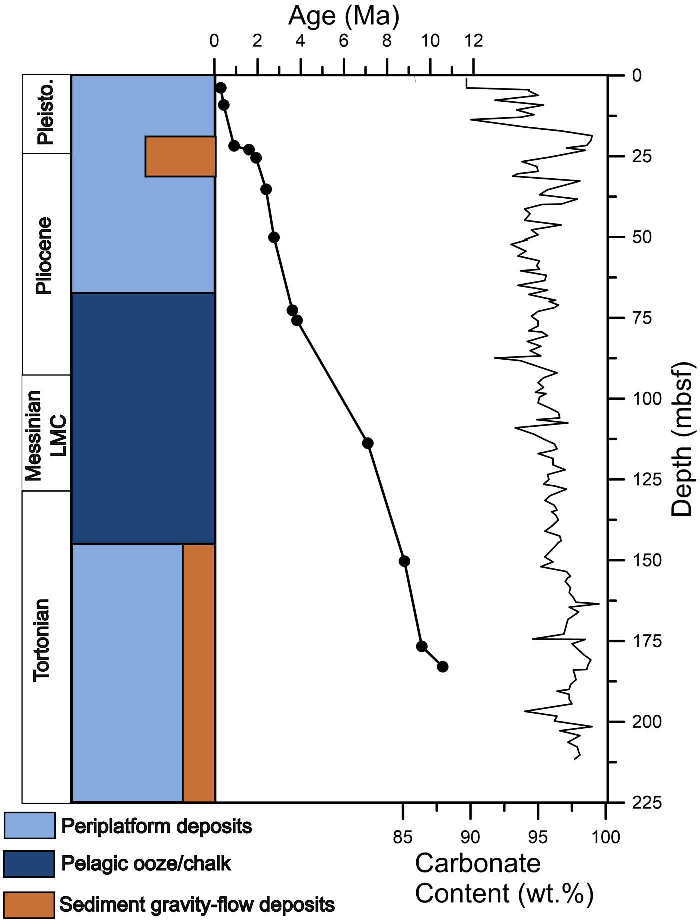


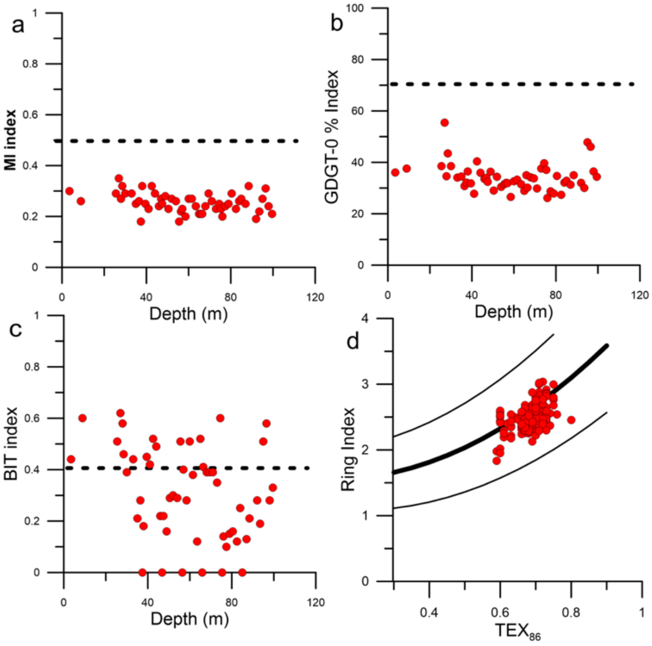
Figure 2: Lithologic column for ODP ~~Site~~Hole 811A. The descriptions are from (cite). Age model data from ~~[NO_PRINTED_FORM]~~Petrick et al. (2023a). Carbonate content data is from Davies et al. (1991a). The LMC is marked on the figure.

3.~~1~~ 2 TEX_{86} tests

The new TEX_{86}^H ~~data generated here for the period of~~ for ~~2~~1.9-~~6~~ 6.6 Ma complements previous data covering ~~the period 6~~ 6.6 to ~~12~~ 11.1 Ma~~-~~ (Petrick et al., 2023). –The data ~~both~~ for this study and ~~the previous~~data from Petrick et al. (2023) ~~is~~are presented ~~study is found as~~in supplemental data 1. Several tests were performed to evaluate the new data and ensure that it ~~is reflecting~~reflects SST changes and is not ~~produced~~the result of ~~by~~ nonthermal GDGTs~~performed~~. With only a few exceptions, the TEX_{86}^H data passed all ~~the~~applied tests.- We will discuss the various tests, what they show, and why we decided to remove (or retain) data points.

The Methane Index (MI) excludes any data affected by gas-hydrate-related anaerobic oxidation of methane (Zhang et al. 2011). ~~Our~~ The MI values are below the 0.5 value for rejection (Fig. ~~3a~~3a). We also used the GDGT0% index to eliminate samples with GDGTs substantially originating from sedimentary archaeal methanogenesis (Weijers et al. 2006; Sinninghe Damsté et al. 2012). The values were well below the 67% cut-off for excessive methanogenesis (Fig. ~~3b~~3b). We used the ring index (RI) to evaluate whether the GDGTs deviate from modern values (Zhang, ~~Pagani, and Wang~~et al. 2016). ~~All of~~All our data fell within the acceptable error envelope of 0.3 (Fig. ~~3d~~3d). Finally, we used the 2/3 index to ensure that the GDGTS were being formed near the surface (Taylor et al. 2013; Hernández-Sánchez et al. 2014). This measures the relationship between the compounds GDGT 2 and GDGT 3. While the appropriate cut-off for this test is still being debated, ~~our~~ the data values are low < 5 and indicate surface production. This ~~data is~~data is shown in ~~supplement~~ Supplement 1.

One GDGT index that did not fit ~~comply in full with~~ recommendations for quality assurance was the BIT index (Fig. ~~3e~~3c). This index was developed to track the amount of terrigenous material that could interfere with the TEX$_{86}$ values via soil-sourced GDGTs (~~Stefan~~ Schouten et al. 2013). The original cut-off point is 0.4, although there is a debate about whether that cut-off ~~is a~~is too strict ~~strict cutoff~~ (~~Stefan~~ Schouten et al. 2013) and how to evaluate variations in crenarcheol shown to affect the BIT index (Fietz et al. 2011). Although within the GDGT suite ~~analyzed~~analyzed here, 11 samples exceed a BIT value of ~~of~~ 0.5 (Fig ~~3e~~3c). The data shows no covariance with either time, depth, or SST (Supplementary Figure 1). The highest BIT values neither match the highest nor lowest SST data. Finally, removing the high BIT samples ~~doesn't~~ does not affect the major trends or conclusions of the paper. Therefore, we have decided to ~~keep~~ retain all data ~~the points~~ in ~~our~~ the results ~~because of the uncertainty~~based on the current debate regarding the reliability ~~of the meaning~~ of the BIT index.


a
MI index
1
0.8
0.6
0.4
0.2
0
0
40
80
120
Depth (m)
b
GDGT-0 % Index
100
80
60
40
20
0
0
40
80
120
Depth (m)
c
BIT index
1
0.8
0.6
0.4
0.2
0
0
40
80
120
Depth (m)
d
Ring Index
4
3
2
1
0
0.4
0.6
0.8
1
TEX_{86}

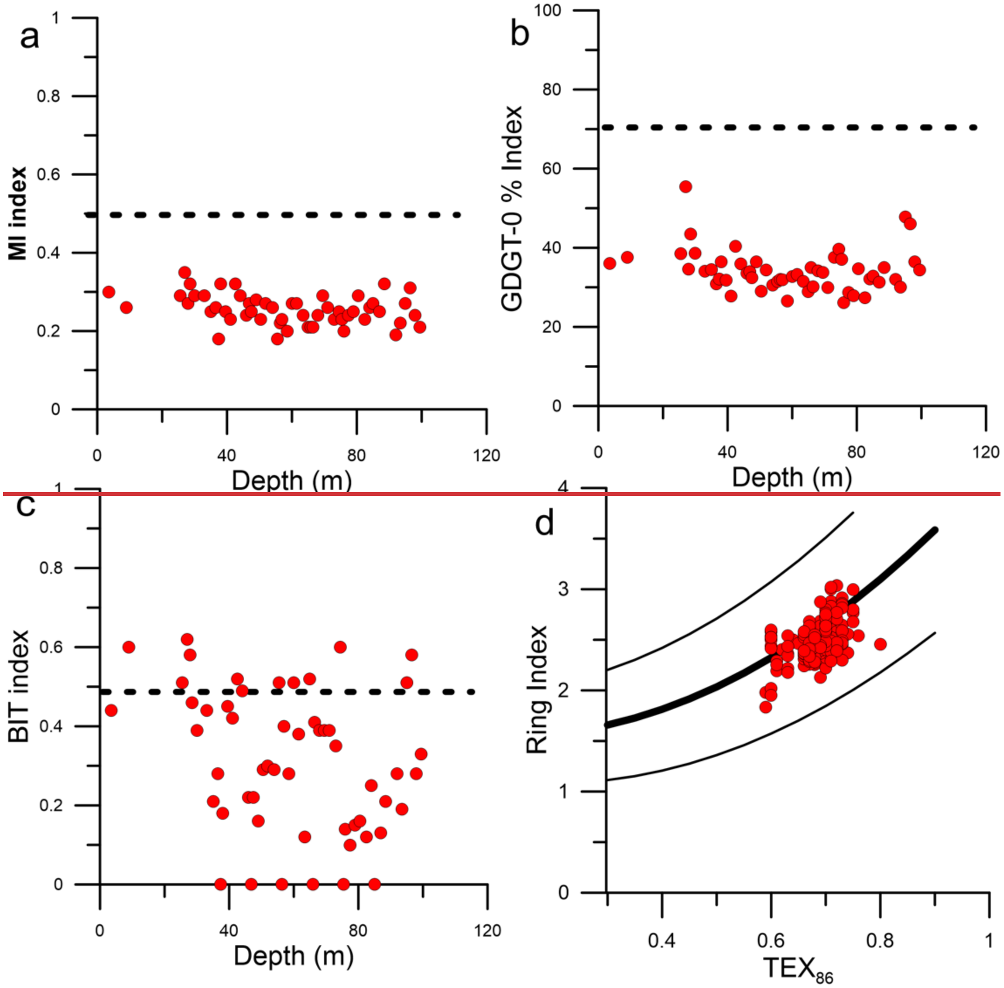


Figure ~~3~~3: Graphic illustration of the new ODP Site 811 data for various GDGT indices used for quality assurance~~,~~ for previously published data ~~see~~ (Petrick et al., 2023). Quality criteria shown are a. Methane Index (MI, after (Zhang et al., 2011)), b. %GDGT-0-index (after (Sinninghe Damsté et al., 2012)), c. Branched *vs.* isoprenoid Index (BIT, proposed by (Schouten et al., 2002)), d. Ring Index (RI, proposed by ~~(~~Zhang et al., ~~,~~ 2016~~)~~). Quality assurance tests indicate that GDGT data are suitable for SST reconstruction and are not compromised by other environmental drivers.

3.~~2~~ 3 SST trends

For this study, we follow the age model of Petrick et al. (2023), which updated the original shipboard (Davies et al., 1991) and a previously published age model (Isern et al., 1993~~b~~, 1996~~b~~) (Fig. 2) ~~for the entire ODP Site 811 record~~. A part of the record presented in this study -(~~6~~~~7~~6.6-~~12~~ 11.1 Ma) was previously published in Petrick et al. (2023) and discussed in more detail in section 4.1 (Fig. ~~2~~4). It is also important to note that the ODP Site 811 SST record has a lower resolution than other nearby records. This may mean that internal variability within the record could exaggerate the LMC cooling trend~~ seen in the record~~. Therefore, we ~~wanted to ~~used both a running average and a fixed time window for the LCM ~~definition ~~to ~~constrain (quantify?)understand~~ the amount of cooling in the record. However, ~~Please see the original publication for a more detailed description of that data. ~~the boundaries of ~~one issue with ~~the LMC are~~is that there is~~ uncertain~~ty about the boundaries of the event~~. ~~Despite some variability~~W~~To resolve this, we~~, therefore, estimated LMC cooling using~~ used~~ two different definitions of the LMC (Table 1). First, we compared SSTs before the LMC (11.1-7.0 Ma) to the LMC, following~~as~~ Herbert et al. (2016), where the LMC is defined as 7.0-5.4 Ma. We then used the windows used ~~,~~in ~~the ~~Martiont et al. (2022) ~~paper ~~for the pre-LMC (8.5-7.5 Ma) and height of the LMC (6.5-5.5 Ma~~0.~~). ~~Finally, we defined the height of the LMC using our record (7.0-5.9 Ma) and compared it to a pre-LMC window (7.0-11.1 Ma).~~ The~~ All this~~ data is summarized in Table 1. T~~It shows that t~~he average cooling at ODP Site 811 during the LMC ~~using all windows ~~is~~ about~~ 2 +/- 0.2 ºC across all windows. We will be using~~ this~~ 2 ºC as our best estimate of LMC cooling at Site 811.~~ to compare to other SST records produced for the Central Indo-Pacific~~

Citation	**Pre-LMC window**	**Average Pre-LMC SST ~~°C~~ a~~A~~t ODP Site 811**	**LMC window**	**LMC average SST C at ODP Site 811**	**Difference Pre-LMC minus ~~-~~ LMC**
Herbert et al. (2016)	11.1-7.0 Ma	30.0 °C	7.0-5.4 Ma	28.2 °C	1.8 °C
Martinot et al. (~~(~~2022)	8.5-7.5 Ma	29.9 °C	6.5-5.5 Ma	27.9 °C	2.0°C
~~This Study~~	~~11.1-7.0 Ma~~	~~30.0 °C~~	~~7.0-5.9 Ma~~	~~27.8 °C~~	~~2.2 °C~~

Table 1: different definitions of the LMC compared in this study, ~~and ~~average SSTs, and LMC cooling at Site 811~~used in this text~~.

~~SSTs were stable overall between 11.0 and 6.9 Ma (Fig. 2), averaging an SST of 30.0 °C, which is 3-4 °C warmer than the modern SST. The LMC has a complex signal at ODP Site 811 with a rapid cooling between 6.9-6.6 Ma, followed by relatively cool SSTs until ~5.0 Ma. However, it is hard to define the exact boundaries of the end of the LMC at theour site because there is an initial cooling and then a recovery that seems to last as late as 3.5 Ma. The Messinian (originally defined as the boundaries of the LMC) has an average SST of 28.2 °C, about 2 degrees cooler than the previous Late Miocene SSTs. Using the definitions used by Martinot et al. (2022) for the pre-LMC and the coldest part of the LMC in the nearby tropical Indian Ocean, the pre-LMC SSTs (8 Ma +/- 0.5) are 29.9 °C, and the coldest part of LMC SSTs (6 Ma +/-5) is 27.9 °C. This, again, is about 2 degrees. Finally, if we just look at the coldest period at ODP 811 (6.7-5.9 Ma), it is 27.8 °C during the LMC. This average cooling is about 2 °C, with SSTs possibly getting as low as 25 °C. After the LMC, SSTs reach an average of 30 °C in the Mid-Pliocene, followed by a cooling starting at around 2.5 Ma. There then appears to be a cooling starting around~~

~~2.5 Ma. However, because of a condensed sediment interval and coarse-grained material in the core around 2 Ma, the full details of the cooling are unknown.~~

4 Discussion

4.1 Previous work at ODP 811

~~ODP Site 811 was drilled by the Jordies Resolution~~The Joides Resolution drilled ODP Site 811 as part of Expedition 133 ~~on the~~in the Coral Sea (Davies et al., 1991a) (Fig. 1).~~-~~ ODP Site 811 was located further south during the Late Miocene (~~20°S at most~~likely ~ 19.4 to 17.5°S) (Van Hinsbergen et al. 2015).~~-~~ As part of the post-cruise work, a $\delta^{18}O$ ~~$\delta^{18}O$~~ record was produced using ~~$\delta d^{18}O$~~ planktonic foraminifera, which ~~that showed that~~showed~~ing~~ SSTs were between 18-24 ~~degrees~~°C ~~-~~during the Late Miocene ~~-~~(Isern et al., 1993~~b~~, 1996~~b~~). ~~–~~These cold temperatures were~~is cooling was~~ proposed to be the reason for the collapse of the coral reefs in the C~~c~~oral S~~s~~ea between 11-8 Ma. H~~–H~~owever, many ~~of these~~ similar foraminiferal $\delta^{18}O$ records showing cool tropical SSTs ~~based on foraminiferal $\delta^{d18}O$~~ have ~~come under scrutiny~~been re-evaluated subsequently~~scrutinized.~~ ~~A re-analysis of themany records~~ using biomarkers and ~~new records based on~~ well-preserved foraminifera. These studies show~~s~~ that post-depositional alteration of~~ the~~ calcite ~~was a~~is a larger source of error than~~ was~~ originally thought (Nairn et al., 2021; Wilson et al., 2002). ~~2). In~~ Petrick et al. (2023~~a~~) ~~we~~ used TEX_{86}^{H} to reconstruct SSTs over the 8-12 Ma period when the reefs in the Coral Sea ~~were supposed to have~~ drowned (Isern et al., 1993~~a~~) (Fig. 4).~~-~~ ~~Our~~This record showed an average SST of 30 °C ~~degrees~~ between 8-12 Ma. ~~–W~~Petrick et al., (2023) ~~The authors~~concluded that a combination of low~~ess~~ aragonite saturation and~~,~~ heat stress impaired~~causing slower-growing~~ coral growth~~s grow slower to cope with warmer SSTs,~~ and that regional ~~a local uplift ized~~ sea level rise combined with these~~as~~ stressors led to~~ to cause~~ the drowning of the ~~to allow the~~ coral reefs~~s to drown~~ (Petrick et al., 2023~~a~~). Therefore,~~Also, while the collapse in carbonate shelves in the coral sea has previously been directly tied to the loss of reefs (CITES) this does not seem to be the case here . However it is clear that~~ at ODP Site 811, the period of ~~there were major changes~~major reef losses occurred ~~in the Holms reef next tothe Coral Sea at ODP Site 811~~ before the LMC (Isern et al., 1993~~a~~, 1996~~a~~).~~-~~ However, other major reef systems~~sites~~ in the Coral Sea d~~o~~id~~ show~~ drown~~ings~~ between 7-5.4 Ma, including~~ the X reef next to ODP site XXX and~~ the Marion Plateau (Bashah et al., 2024~~a~~).~~-~~ Therefore, while~~ the~~ ODP Site 811~~ record~~ is not located~~directly~~ in an area that experienced coral reef loss during the LMC, it can still be used to understand the climatic impact of the LMC on the C~~c~~oral S~~s~~ea and the wider c~~C~~entral Indo-Pacific.~~is This coolimg~~~~Explaining the apparent difference between the different tropical records is important to understanding the dynamics of the LMC. The original study of the LMC was based on U^{K}_{37}' SSTs . These have a saturation limit of 28 to 29 °C when the proportion of the $C_{37:3}$ isomer used for calculation approaches zero. Especially in a lithology such as carbonates without high organic preservation, U^{K}_{37}' SSTs are considered unreliable above 26-27 °C . Therefore, models show that many parts of the tropical and sub-tropical Miocene ocean were too warm to reconstruct SST with U^{K}_{37}' . In fact, except for ODP Site 722, all the sites used for the U^{K}_{37}' reconstruction were located in the East Pacific Equatorial Upwelling Zone . ODP Site 722 is in the Arabian~~

~~Sea upwelling cell and thus actually defined by localized monsoonal wind patterns forcing upwelling in the western Arabian Sea . Therefore, it is possible that the U^{K}_{37}' data reflects more reduced cooling in upwelling cells than global tropical cooling. Furthermore, the individual records that make up the TEX_{86} stack show that there was cooling at the individual sites during the LCM . All the sites show a cooling of 2-3 degrees between 7-5 Ma . The major difference seems to be that the cooling is not as rapid, and not all sites show the post-cooling recovery seen at ODP site 811 and IODP site U1443 (Fig. 4). This seems to suggest that while the timing and rapidity of the cooling differed across the Central Indo-Pacific, there was about a 2 degree cooling at all the sites during the LMC.~~

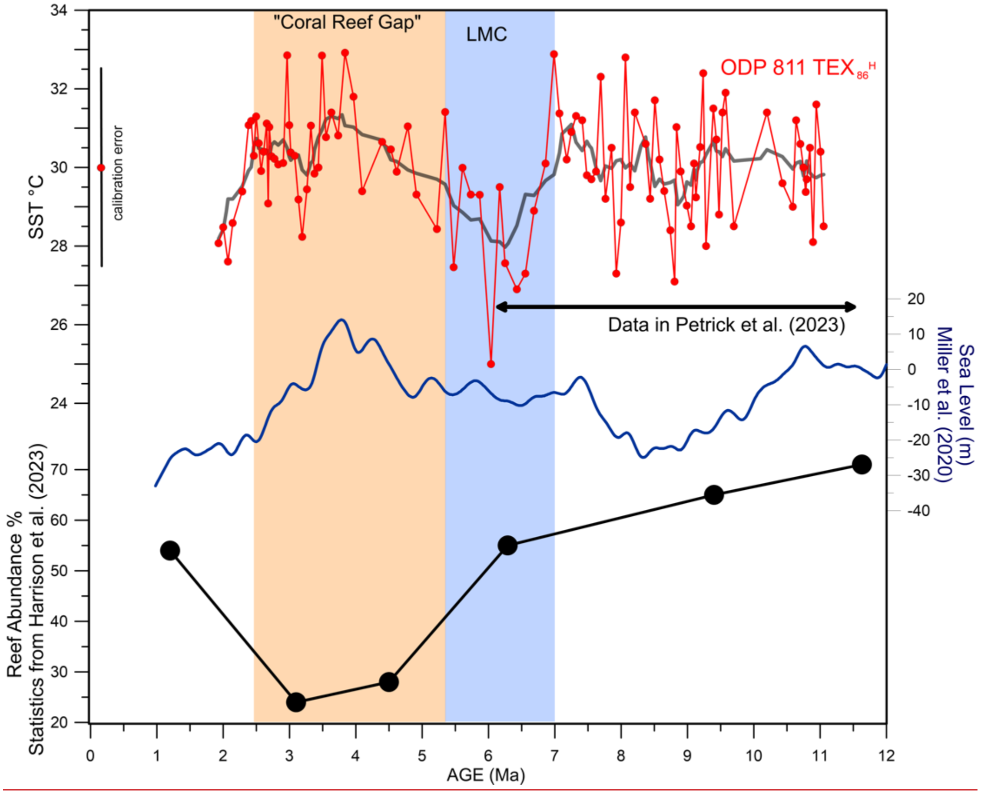


Figure 4: The TEX_{86}^{H}-derived SST record for ODP Site 811 is shown in red, including data from 6.6 to 11.1 Ma taken from Petrick et al. (2023). The grey line represents an 8-point running average. The calibration error from Kim et al. (2010) is shown at the top. The sea level evolution is shown in blue after Miller et al. (2020). The relative abundance (%) of areas covered by reefs in the Central Indo-Pacific is shown by black line and dots at the bottom, with data taken from Harrison et al. (2023). Note we have followed Harrison et al. (2023) figures by putting the Reef Abundance % for each faunal stage at the midpoint of the stage. The exception is the value of the Serravallian, which is shown at the end of the period (11.63 Ma) to fit it into the figure.

4.~~2~~2 ODP Site 811 and the LMC~~ Causes of the LMC~~

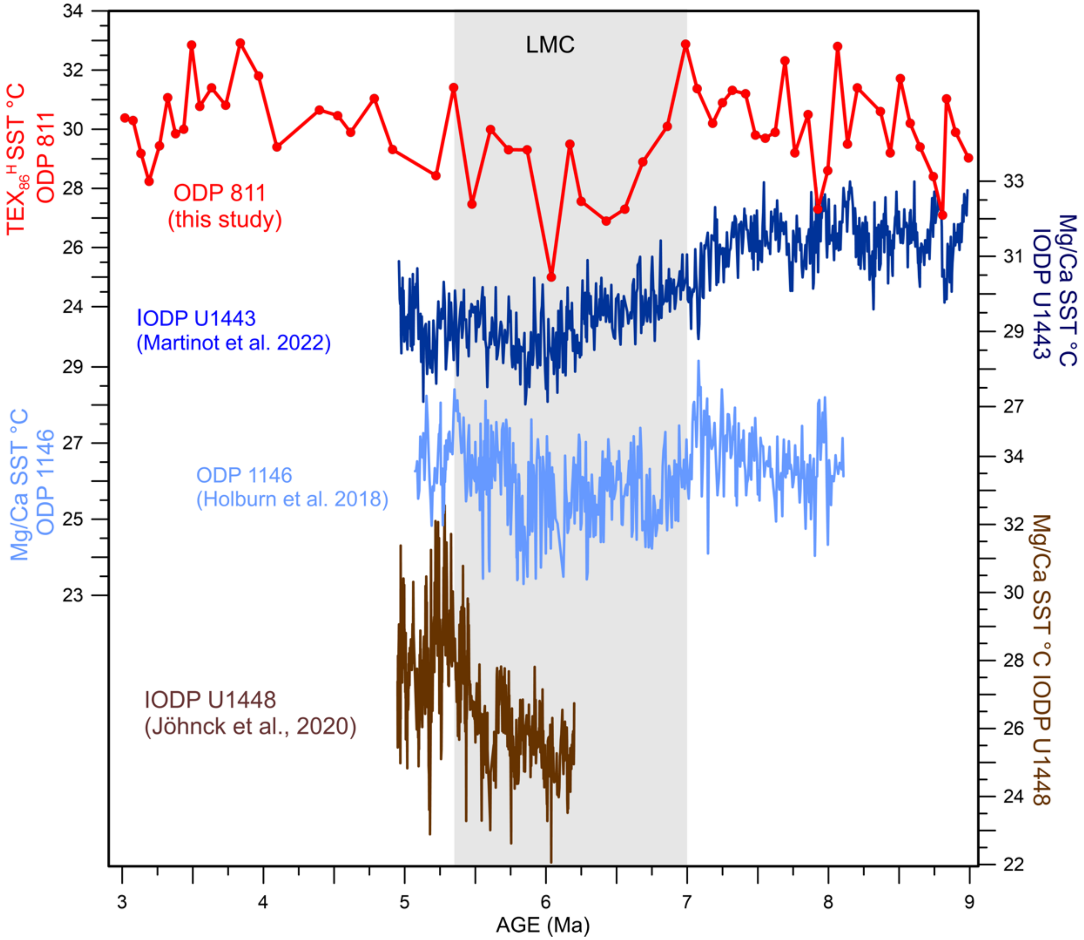
~~The causes of the LMC are not well understood. The paradox of a major cooling without a subsequent increase in glaciers has still not fully explained. There are two major explanations for the cooling associated with the LMC. These are gateway changes causing shifts in ocean circulation and changes in CO2. It is known that there were ongoing shifts in the Indianition throughflow and the closure of the ismith of Panama. Both of these are ongoing at this time and could be responcbel for the changes. However, right now major changes in this system are both dated to the early and mid Pliocene or later . Also the changes seen are reverced with no evedince of permiante changes. Trestrral changes shuch as the uplift of the Hymolas have also been sug(Herbert et al., 2016a)(Martinot et al. 2022)(Burls et al., 2021)Tdifference between the increased tropical presence of C4 grasses and the better adaptationT FinalTthan~~As shown above, the cooling at ODP Site 811 during the LMC is about 2 °C (Fig 4). -This is consistent with~~matches~~ other records from the Central Indo-Pacific, including ODP Site 1146 and IODP Site U1448 (Holbourn et al., 2018; Martinot et al., 2022~~a~~) (Fig 5).- This~~It~~ also matches~~fits~~ the magnitude of cooling seen in TEX$_{86}$ records from the WPWP (Liu et al., 2022b; Zhang et al., 2014b) (Fig 6).- Therefore, the new ODP Site 811 data confirms previous findings~~ed~~ (Holbourn et al., 2018; Liu et al., 2022; Martinot et al., 2022) ~~(Fig 6)~~, showing that the ~~what had been found before the~~ cooling of the tropics was greater than the 0.5 °C during the LMC originally suggested by ~~cooling suggested before~~ (Fig 6) (Herbert et al.~~,~~ (2016)~~b; Holbourn et al., 2018; Liu et al., 2022b; Martinot et al., 2022a)~~. -Furthermore, t~~T~~he data suggests that the~~his suggests~~ cooling in the c~~C~~entral Indo-Pacific was uniform during the LMC~~experienced a uniform SST change during the LMC~~.

Unfortunately, our record~~ can only provide~~~~shed limited information regarding~~~~about the causes of thes~~ can only provide limited information regarding the causes of LMC.- The ~~The cooling at~~ ODP Site 811 temperature trends are~~is~~ consistent with~~fits~~ the expected cooling inferred using climate model~~l~~ing~~ presented in~~ (Martinot et al. ~~2021~~2022), which estimates~~suggests~~ SSTs of around 28 °C and a cooling of about 2 °C at ODP Site 811 when atmospheric CO_2 is lowered to 280-ppm. -Given that ODP Site 811 and IODP Site 1448 are both located in the ~~c~~Central Indo-Pacific warm pool~~,~~ but in different ocean basins and hemispheres~~parts of the Central Indo-Pacific~~, the fact that mean ~~the~~ SSTs and LMC cooling~~temperature change~~ are consistent with climate~~fit the~~ models could~~, might~~ strengthen the argument that a change in atmospheric CO_2 caused~~s~~ the LMC.- Therefore, our ODP Site 811 record suggests that changes in pCO_2 may be responsible for the cooling seen in the record~~the ofsApart from establishing that the cooling is consistent with model predictions, nothing further can be done to explore the cause of the LMC~~.

~~(Herbert et al. 2016)(Müller et al. 1998)(Pelejero and Calvo 2003; Grimalt, Calvo, and Pelejero 2001)(Burls et al. 2021)(Herbert et al. 2016)(Bialik et al. 2020)(Liu et al. 2022)(Liu et al. 2022; Zhang, Pagani, and Liu 2014)~~The major difference between the ODP Site 811 record and other records from ~~the rest of~~ the c~~C~~entral Indo-Pacific seems to be ~~that not all sites show the temperature change during~~ the~~he~~ post-cooling recovery of temperatures ~~seen at ODP Site 811~~ (Fig. 5,6). Not all sites return to pre-LMC temperatures. -The timing of post LMC recovery is also~~also~~ different between~~ different~~ sites. ODP Site 811 remained ~~seems to have stayed~~ cooler after the LMC but fully recovered by the Early to L~~l~~ate Pliocene boundary (Fig.

4).- O~~While o~~ther records show a dramatic post-LMC recovery, such as IODP Site 1448 (Jöhnck et al., 2020) ~~it is more rapid than seen at ODP Site 811, occurring~~ between 5.5-5 Ma (Fig 5).

In contrast, t~~Other records, such as t~~he TEX_{86} WPWP stack~~,~~ shows a long-term cooling trend and no clear~~do not show the~~ recovery after the LMC, although there is warming around 4 Ma (Liu et al., 2022~~b~~) (Fig. 6).- Therefore, while the c~~C~~entral Indo-Pacific experienced the same 2-3 °C cooling during the LMC~~;~~ the recovery was heterogeneous (Figs 5,6). -We therefore conclude that~~Therefore,~~ if the “Pliocene Reef Gap” was triggered by~~a~~ climatic change, it~~ triggered~~ ~~the “Pliocene Reef Gap,” it~~ was most likely the LMC cooling, not the post-LMC recovery.


LMC
ODP 811
(this study)
IODP U1443
(Martinot et al. 2022)
ODP 1146
(Holburn et al. 2018)
IODP U1448
(Jöhnck et al., 2020)
TEX$_{86}$^{H} SST °C ODP 811
Mg/Ca SST °C ODP 1146
Mg/Ca SST °C IODP U1443
Mg/Ca SST °C IODP U1448
AGE (Ma)
34
32
30
28
26
24
29
27
25
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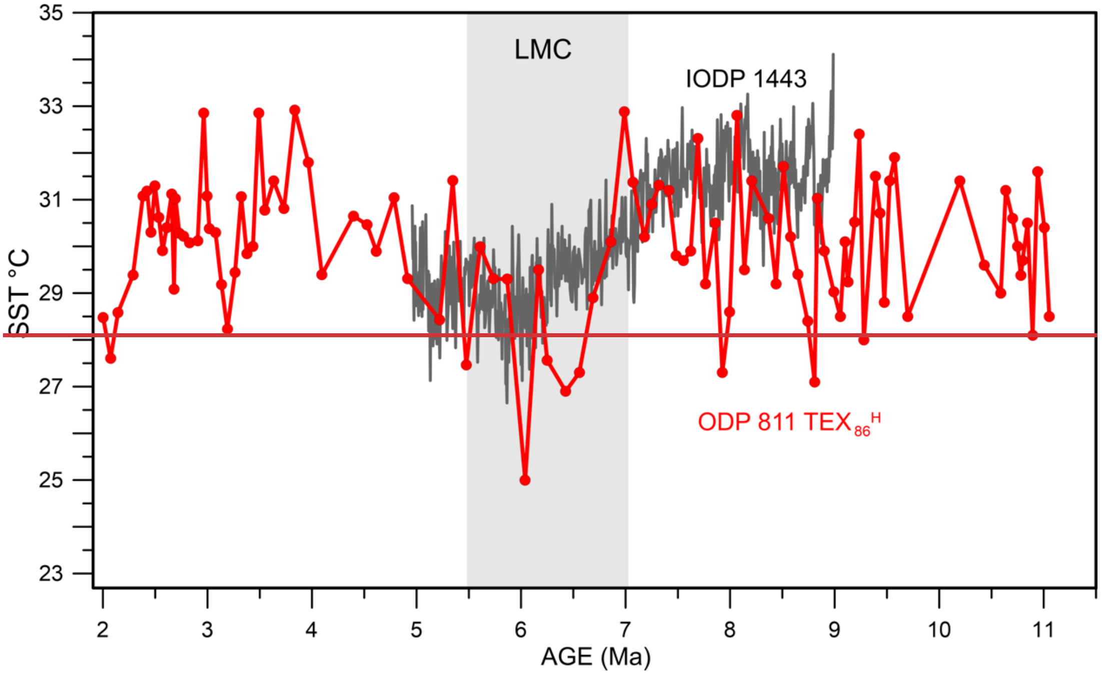
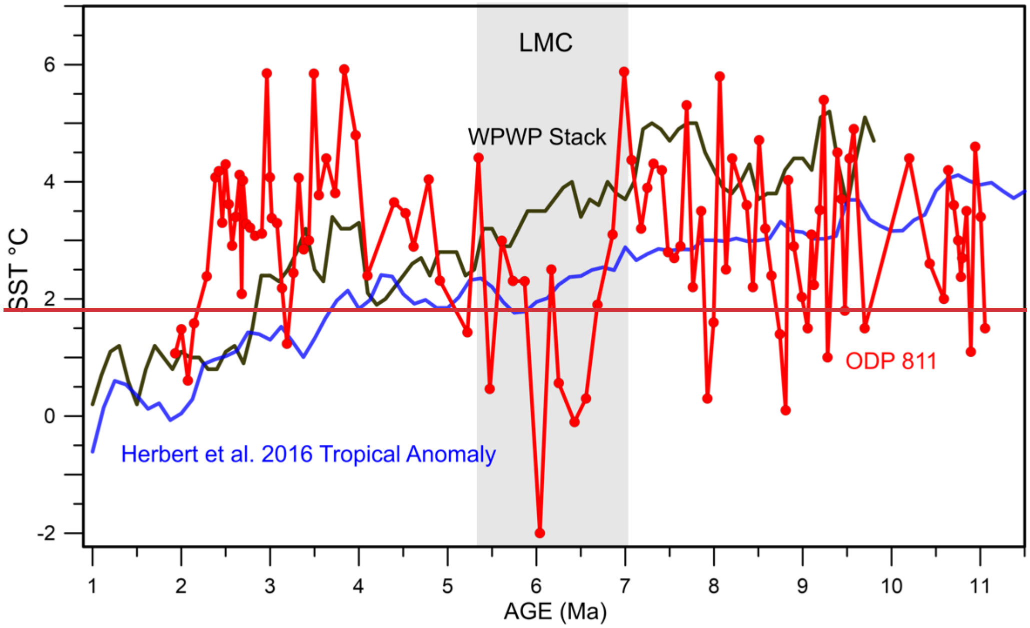


Figure ~~6~~5: ODP ~~site~~Site 811 TEX$_{86}^{H}$-derived SSTs compared to the Mg/Ca-derived SST records~~ from IODP site U1443 in the Bay of Bengal (Fig 1) (Martinot et al. 2022)~~. The gray bar marks the LMC as defined in Herbert et al. 2016. Sites are shown in Figure 1.

~~However, as mentioned, this degree of cooling has been seen elsewhere in the tropics, with an Mg/Ca SST record from IODP Site U1443 in the northern Indian Ocean showing a very similar degree of cooling (Fig. 4). In the study at IODP Site U1443, the authors used existing models to show that the amount of cooling in the tropical Indian Ocean was not an anomaly. They showed that the amount of cooling they saw in the tropical Indian Ocean would be explainable by a decrease in CO_2 (. The cooling at ODP site 811 roughly fits the model data presented in this article, which suggests SSTs of around 28 °C and a cooling of about 2 °C at ODP site 811 . Therefore, the cooling at ODP Site 811 fits the model for the LMC.~~

~~Explaining the apparent difference between the different tropical records is important to understanding the dynamics of the LMC. The original study of the LMC was based on U$^{K}_{37}$' SSTs . These have a saturation limit of 28 to 29 °C when the proportion of the C$_{37:3}$ isomer used for calculation approaches zero. Especially in a lithology such as carbonates without high organic preservation, U$^{K}_{37}$' SSTs are considered unreliable above 26-27 °C . Therefore, models show that many parts of the tropical and sub-tropical Miocene ocean were too warm to reconstruct SST with U$^{K}_{37}$' . In fact, except for ODP Site 722, all the sites used for the U$^{K}_{37}$' reconstruction were located in the East Pacific Equatorial Upwelling Zone . ODP Site 722 is in the Arabian Sea upwelling cell and thus actually defined by localized monsoonal wind patterns forcing upwelling in the western Arabian Sea . Therefore, it is possible that the U$^{K}_{37}$' data reflects more reduced cooling in upwelling cells than global tropical cooling. Furthermore, the individual records that make up the TEX$_{86}$ stack show that there was cooling at the individual sites~~

~~during the LCM . All the sites show a cooling of 2-3 degrees between 7-5 Ma . The major difference seems to be that the cooling is not as rapid, and not all sites show the post-cooling recovery seen at ODP site 811 and IODP site U1443 (Fig. 4). This seems to suggest that while the timing and rapidity of the cooling differed across the Central Indo-Pacific, there was about a 2 degree cooling at all the sites during the LMC.~~



~~Figure 5: SST data for this plot has been normalized to modern temperatures to better compare with the anomaly data presented by Herbert et al. (2016). This was done for ODP site 811 and the WPWP stack by subtracting modern SSTs from the data. ODP Site 811 (red) change compared to the Tropical Anomaly data (blue) and the WPWP stack (black) . The gray bar delineates the LMC as defined by Herbert et al. (2016)~~

~~4.2 Loss of Carbonate Platforms in the Central Indo-Pacific~~

~~There was an extensive coral reef system on the Queensland Plateau during the Early-Mid Miocene . This is confirmed by microfacies analysis, which showed the presence of reef corals and other tropical species . However, after 11 Ma, the coral reefs appear to retreat . Some authors put the collapse of this system to 13 Ma and relate it to changes in the bottom water current strength .~~

~~Large benthic foraminifera-based reconstructions of sea level show a gradual increase in relative water depth between 13-8 Ma . This matches both an increase in sea level and a subsidence event that has been seen in the coral sea . A major transition between 14-11 Ma reduced the coral coverage in the coral sea . However, it is unclear whether this led to the collapse of reef~~

~~systems on the Queensland Plateau or whether there were active atolls after the initial collapse, as there is still shallow water bank material in ODP Site 811 until around 8 Ma . However, it is clear that the loss of corals in the northern coral sea predates the cooling of LMC and is probably a result of the rise in sea level, changing currents, and high SSTs, as we suggested previously .~~

~~However, while local processes might have caused the early collapse of the Queensland Plateau, other reefs in the Coral Sea and surrounding areas have evidence of a much later collapse. Interestingly, a similar timing of coral reef loss is seen in the Southern Coral Sea on the Marion Plateau. Areas in the northern part of the platform with no evidence of reefs drowned around 13 Ma, while the southern part, where coral reefs have been found, survived until around 7 Ma . On the other side of Australia, the NW shelf great barrier reef did not fully drown until around 7 Ma . Finally, the studies on the Early Pliocene sediments, even on the Queensland Plateau, show pelagic sedimentation even on the shallow carbonate platforms . Therefore, there is abundant evidence of coral reef collapse in Australia during the LMC.~~

~~Throughout the Central Indo-Pacific, a similar trend is seen (Fig. 2). The highest reef density exists during the mid-Miocene, followed by a slight decrease towards the Late Miocene . However, there seems to have been a major loss in coral reefs by the Early Pliocene. This suggests that the major loss of corals occurred between the Messinian and the beginning of the Early Pliocene (7 – 4 Ma). Harrison et al. (2023) ascribes the loss to multiple individual changes for individual reefs. These include changes in tectonics, sea level, and increases in terrestrial input. Furthermore, they suggested different drivers for coral reef loss in different parts of the Central Indo-Pacific. However, given the amount of coral reef loss within such a narrow window of time, there is likely some regional change that might have combined with changes in local conditions to drive the loss of coral reefs. The authors reject climate change because they argue that SSTs during the late Miocene are similar to modern ones, and there is no evidence of major warming across this time . However, as mentioned above, there is some evidence that the warm water belt both cooled and contracted during the LMC . Furthermore, in the WPWP, this cooling is part of a long-term cooling trend . Finally, as pointed out above, there is evidence that the corals here had adapted to the warmer but stable Late Miocene SSTs, with lower growth and calcification rates than modern corals . The ODP 811 record shows a major SST shift prior to the Pliocene reef gap. Therefore, it is necessary to understand if cooling during the LMC could be a key factor in the loss of coral reefs in the Central Indo-Pacific.~~

4.~~3~~ 5 Potential stressors in the c~~C~~entral Indo-Pacific

~~In the last paper on ODP Site 811, we proposed that high temperatures together with additional stressors might have contributed to the loss of the reef systems in the Coral Sea between 8-11 Ma . These additional stressors include changes in the aragonite saturation of seawater , an increase in the sea level , and changes in the location and strength of ocean currents . So, the question is how the LMC might have impacted these already stressed reefs in the Coral Sea and the wider central Indo-Pacific reef province.~~

As shown above, ODP ~~site~~ Site 811 experienced a rapid and strong cooling associated with the LMC (Fig 2). Furthermore, SSTs did not recover until at least 5 Ma, well into the “Pliocene Reef Gap.” ~~Therefore, it seems likely that t~~The cooling was widespread, as it was recorded at many sites in the central Indo-Pacific. Therefore, it could have had negative~~an~~ impacts on ~~and led to the loss of the~~ coral reefs and carbonate platform ecosystems. Studies show that globally, there is a reduction in the latitudinal extent of c~~C~~oral reefs during the Late Miocene, including~~during~~ the late LMC (Perrin and Kiessling, 2012). ~~Further south of ODP Site 811~~O~~o~~n the Marion Plateau, south of ODP Site 811, reefs disappeared around 7 Ma (Bashah et al., 2024~~a~~; Ehrenberg et al., 2006; Isern et al., 2004~~b~~). Today, an SST gradient of about 4 degrees exists between ODP Site 811 and the southern Marion Plateau (Locarnini et al., 2019). ODP Site 811 had~~s an~~ average SSTs of about 28 °C and possibly as cold as 24 °C during the LMC. Therefore, SSTs could have been as cold as 20 °C on the southern Marion Plateau. ~~There is abundant evidence that~~ C~~c~~oral reefs have ~~experience l~~slower carbonate ~~productiongrowth rates,~~accumulation due to lower coral growth rates~~,~~ at these temperatures (Laugié et al., 2019; Lough, 2008; Lough, and Barnes, 2000)~~References!~~). ~~,~~This~~which~~ can impair~~act~~ their ability to adapt to ~~handle~~ changing oceanographic conditions (Higuchi et al., 2015). So, ~~the~~ the colde ~~r~~ SSTs during the LMC could have negatively impacted many~~ost~~ of these higher-latitude~~southern~~ ~~(subtropical?)~~ coral reefs and contributed~~aused~~ to the latitudinal contraction~~reduction seen in the~~of coral reefs ~~record for the LMC~~ (Perrin and Kiessling, 2012).

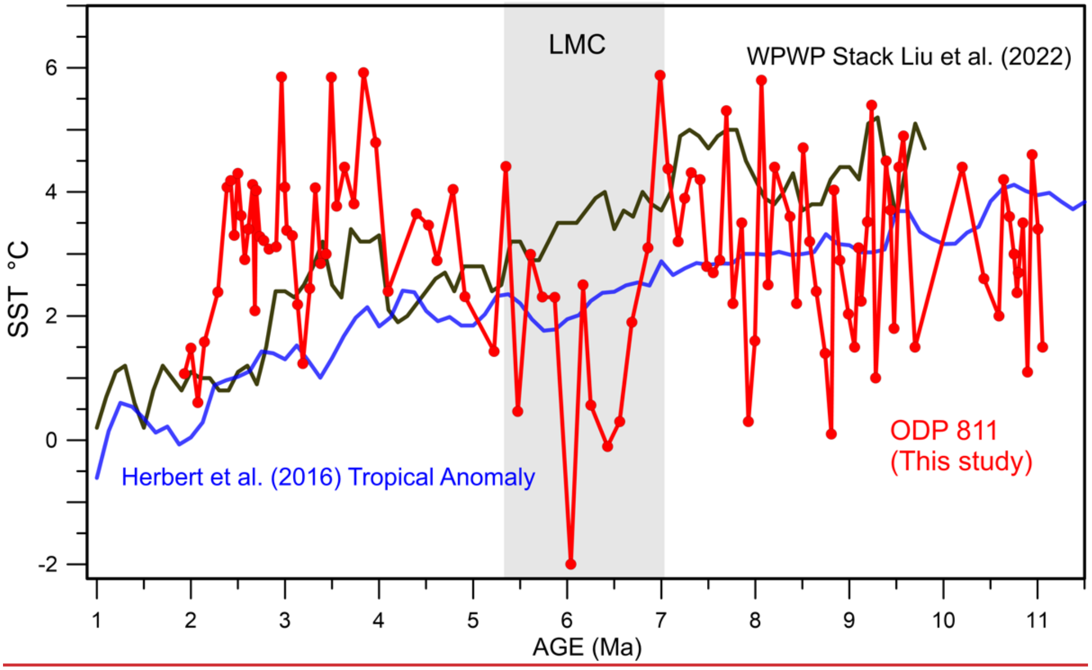


Figure 6: ODP Site 811 (red) temperature anomalies compared to the Tropical Anomaly (blue) from Herbert et al. (2016) and the WPWP stack (black) (Liu et al., 2022). SST data for this plot has been normalized to modern temperatures to better compare with

the anomaly data presented by Herbert et al. (2016). This was done for ODP Site 811 and the WPWP stack by subtracting modern SSTs from the data. The gray bar delineates the LMC as defined by Herbert et al. (2016). Sites included in the WPWP stack are shown in Figure 1.

~~However, the absolute temperatures at the site during the LMC that s were around 28 °C during the late Miocene raise some issues with this interpretation. SSTs are around 27 °C during the late Miocene. These are similar to modern-day SSTs in the Coral Sea (Boyer et al. 2018). Research shows that SSTs around 27 °C areis ideal for coral reef development in the modern ocean (Lough and Cantin 2014). Although cooling may have reduced reef growth at higher latitudes, it therefore seems unlikely that this was also the case in the core region of the Central Indo-Pacific. is possible that the growth window of differeds. Modern corals adapted to colder temperatures followinglong-term (Brachert et al. 2020)As shown above, there is evidence that Miocene corals were predominantly hypo-calcifying, while modern corals are hyper-calcifiers . However there is no change is seen despite no major changes in species diversity . This might mean the Miocene corals had a growth window different from modern coral reefs, which first developed during the cooling associated with the onset of northern hemisphere glaciations .(Bellworthy and Fine, 2021; Rich et al., 2022)Is this paragraph necessary? I find it confusing. Site 811 does not have coral reefs in the LMC anymore.Therefore, colder SSTs during the LMC alone should not have caused a collapse of these coral reefs, despite their adaptation to warm temperatures, as pointed out before .~~

However, as discussed~~shown~~ in Petrick et al., (2023~~a~~), stressors other~~multiple stressors beyond~~ than SSTs can affect the~~ may~~ ~~have affected the~~ coral reefs~~s~~. ~~As shown above, many stressors impacted the carbonate ecosystems even before the LMC . While the high SSTs between 11-8 Ma, changes in sea level, changes in nutrients, tectonic changes, changes in turbidity, and changes in circulation might not cause the loss of shallow carbonate ecosystems individually, together, they might have led to a system under stress and on the verge of collapse . In a system like this, a major change, such as an SST drop, might be the final trigger that causes a collapse. (Note that both warm and cold temperatures may contribute to coral reef loss .~~

~~Also, there might be additional stressors besides SST associated with the LMC. Oceanic current changes might also be linked with~~ A~~the~~~~With a~~ larger latitudinal~~change in the~~ SST gradient during the LMC may ~~, there might~~ have been associated with changes in the ocean circulation,- ~~during the LMC,~~ as seen during ~~with~~ other major cooling events~~s~~ (Petrick et al. 2018; 2019).- It has already been proposed that changes in the strength of ocean ~~the~~ currents could have caused greater erosion of carbonate platforms, possibly impacting the expansion of coral reefs (Betzler et al., 2024; Betzler and Eberli, 2019~~b~~)~~This might have led to some of the erosional characteristics that mark the top of these platforms, making it harder for reefs to re-establish themselves after the cooling~~. T~~Furthermore, th~~here is some evidence of stronger~~changes in~~ ocean ~~This~~currents during the LMC in the c~~C~~entral Indo-Pacific. ~~has been shown recently o~~On the Marion Plateau, ~~around~~ between 7.5 and 5.7 Ma, the intensification of the East Australian current caused an increase ~~of~~in~~d~~ drift deposits. (Bashah et al., 2024~~b~~).- On the NW Shelf, there is~~was~~ evidence of an intensification of NNE-SSW--oriented ~~the Holloway Current system, causing more erosion of the inner shelf platforms~~ bottom currents starting in the Late Miocene after 7.2 Ma (Thronberens et al., 2022), contributing to the demise of the regional reef system (Belde et al., 2017). Therefore, a similar c~~C~~entral Indo-Pacific~~–~~-wide strengthening ~~intensification~~ of ocean currents ~~strength~~ could have occurred~~T~~ during the LMC.~~his~~

~~IncreasedChanges in~~ Changes in terrestrial input could also result from a~~changes larger latitudinal temperature gradient~~shifts in SSTs~~in temperature gradients.,~~ T~~as t~~here is evidence that SST cooling during the Late Miocene led to ~~northward~~southward ~~leads to~~ shif~~ts of~~ts ~~in~~ the rain belts ~~northward~~ (Jöhnck et al., 2020). ~~(Santodomingo, Renema, and Johnson 2016; Groeneveld et al. 2017).~~ ~~, and~~S~~(Groeneveld et al., 2017b; Jöhnck et al., 2020)This could have result in changes in the amount of terrestrial inputd~~This may have increased rainfall and terrestrial input~~-changes due to more rainfall~~in northern Australia and the Indonesian Archipelago (Jöhnck et al., 2020). Finally, in the Coral Sea, the weathering of Papua New Guinea intensified, and there is evidence of increased terrestrial input to the northern Coral Sea from DSDP Sites 210 and 287 (Clift et al., 2024). ~~– (Belde et al., 2017a)there w coincides with the basegot its name due to the absence (Liu et al., 2011; Tagliaro et al., 2018),fuGuineaintensified there is coral reefs (? What site)At the same time,~~During the late Miocene, many ~~-cAt the same time, there is evidence that some c~~oral reefs in the Indonesian Archipelago grew in ~~have adapted to~~ turbid environments (Santodomingo et al., 2016~~b~~). ~~-~~However, increases in sediment input could have upset the delicate balance on which these corals depended~~Changes in th~~S~~these cr.~~ ~~dominant (Santodomingo et al., 2015, 2016b)~~Therefore, changing rainfall patterns during the LMC could have been an additional stressor for the coral reefs. ~~As a result, the LMC can be associated with numerous stressors beyond the SST drop.~~

Therefore, the LMC was associated with ~~a number of~~ major environmental changes that could have acted as stressors ~~, which would have led to major~~ impact~~ings on~~ the coral reefs, causing widespread drowning. This is similar to modern coral systems, where current temperature ~~climatic~~ changes are accompanied by multiple other environmental stressors, such as sea-level rise~~,~~, and increased sediment loads ~~impacting coral reef systems~~ (Cornwall et al. 2021). While coral reefs might be able to adapt to single stressors, such as higher sea levels, multiple stressors may add up synergistically and ~~cause the~~trigger coral reef ~~to~~ collapse ~~much quicker than normal~~ (Darling and Côté 2013). ~~**ODP Site 811 (red) temperature anomalieschange compared to the Tropical Anomaly data (blue)** (Herbert et al. 2016) **and the WPWP stack (black)** (Liu et al. 2022).~~

~~4.6 Late Pliocene Coral Reefs~~

~~The next question is, could a major cooling of 2 °C cause that much damage to coral reefs in the late Miocene? Today, corals have been shown to grow in very warm SSTs >30 °C in the Red Sea . While our the understanding of SSTs in tropical environments during the Mid-Miocene is poor, given the SSTs found for the late Miocene means that SSTs were likely persistently warmer than modern SSTs in the Coral Sea for the Early-Mid Miocene when the coral reefs were developing . Therefore, it is likely that these corals were warm water-adapted corals. As shown above, there is evidence that Miocene corals were predominantly hypo-calcifying, while modern corals are hyper-calcifiers . Interestingly, this change is seen despite no major changes in species diversity . This might mean the Miocene corals had a growth window different from modern coral reefs, which first developed during the cooling associated with the onset of northern hemisphere glaciations . The sudden change to much cooler SSTs could be a final stressor for these warm, water-adapted, stressed corals. This has been seen in the~~

~~modern Great Barrier Reef, where it has been shown that anomalously cold SSTs can cause the bleaching of coral reefs . Studies also show this temperature threshold can be lower when combined with other stressors . Therefore, in summary, there is good evidence that coral reefs are susceptible to rapid SST changes, particularly when combined with other stressors. Given the global nature of the LMC, this could have led to a collapse of reef systems for at least some of the reefs in the central Indo-Pacific reef province, leading to the coral “Reef Gap” during the early Pliocene.~~

Finally, while the LMC cooling ~~temperature decrease of the LMC~~ was ~~not~~ unrelated to a sea level change, ~~. However,~~ the global sea level increased after 5 Ma (Miller et al. 2020) (Fig. ~~2~~4~~.),~~). ~~During this time, while temperatures at ODP Site 811 remained relatively low~~. As a result, the carbonate platform tops were no longer in the photic zone w~~This means that w~~hen SSTs eventually returned to the Mid-Miocene ~~SST~~ levels during the Mid-Pliocene. As a result, the corals could not grow back. ~~, the carbonate platform tops were no longer in the photic zone, allowing corals to regrow.~~ It was noted that the reestablishment of coral reefs in the Coral Sea was linked to a global sea level drop~~lowering~~ ~~around~~ ~2.9 Ma, which would have brought the platforms back into the photic zone, ~~and~~ allowing~~ed~~ coral reefs to develop again (Droxler et al. 1993) (Fig ~~2~~4). Therefore, it is likely that after the drowning during the LMC, the reestablishment of the reefs was more related to changes in sea level than SST.

5 Conclusions

The new TEX$_{86}^{H}$-derived SST data at ODP ~~site~~ Site 811 shows that the LMC led to a relatively rapid drop in SSTs by about 2 °C in the southern part of the central Indo-Pacific reef province ~~led to a relatively rapid drop in SSTs by about 2 °C~~. -This is consistent with~~matches~~ other records from the eC~~C~~entral Indo-Pacific, which show a 2-3 °C drop in SSTs between about 7-6 Ma. ~~This contradicts the idea that the tropics were not strongly affected by the LMC. It shows for the first time that a contraction of the equatorial belt happened not only in the Indian Ocean but also in the Pacific.~~ This decline in tropicale ~~sudden and relatively extreme~~ SST ~~drop in the tropics that~~ preceded the “Pliocene Reef Gap” and could have been a~~e~~ ~~proved to be an additional~~ stress factor~~or~~ contributing~~leading~~ to the loss of coral reefs ~~loss~~ in the central Indo-Pacific reef province. It~~and~~ is probably ~~likely~~ responsible for ~~.~~the loss of reefs on the Southern Marion Plateau. ~~The cooling could have impacted corals that had adapted to the warmer conditions of the Miocene more strongly than they would modern corals.~~ Additionally, there is evidence that the changes in global and regional~~local~~ SSTs caused~~triggered~~ by the LMC ~~have~~ led to shifts in ~~the~~ ocean currents, as well as rain belts. Together with the cooling of SST ~~changes~~, these multiple stressors may explain some of the changes seen previously in individual late Miocene reefs ~~of the late Miocene~~ and provide an overall explanation~~driver~~ for ~~explaining~~ the region-wide coral reef decline~~loss~~ over such a short ~~time relatively constrained period~~time interval ~~of time~~. ~~Our This study indicates that major climate changes may combine with and/or give rise to multiple stressors impacting coral reefs.~~ This likely explains the massive reduction in the extent of coral reefs in the ‘Pliocene Reef Gap.’ Therefore, this study~~it~~ emphasizes the~~how~~ detrimental impacts of climate change~~s~~ on coral~~are to the~~ reefs and the importance of limiting additional stressors, such as pollution, on reef ecosystems ~~in a time of~~during global temperature change.

Data availability

The data for this paper is available both in supplementary data one and at Zenodo with a doi of 10.5281/zenodo.10902264.

Author Contribution

All authors approved the manuscript and agreed to its submission. The corresponding author is B.P. All authors discussed the results and provided significant input to the final version of the manuscript. B.P. and L.R. designed the study. B.P. r~~R~~an the project and processed the samples. L.S. performed the biomarker analysis in his lab and interpreted data with B.P. G.A.~~, who~~ provided a new-age model for the site. B.P., L.S., L.R., M.P., and G.A. provided vital feedback on the article.

Competing Interests

The authors declare they have no competing interests in this paper.

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