Are sea surface temperature satellite measurements reliable proxies of lagoon temperature in the south pacific?

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Abstract :

In remote coral reef environments, lagoon and reef *in situ* measurements of temperature are scarce. Sea Surface Temperature (SST) measured by satellite has been frequently used as a proxy of the lagoon temperature experienced by coral reef organisms (TL) especially during coral bleaching events. However, the link between SST and TL is poorly characterized. First, we compared the correlation between various SST series and TL from 2012 to 2016 in three atolls and one island in the Central South Pacific Ocean. Simple linear correlation between SST and TL ranged between 0.44 and 0.97 depending on lagoons, localities of sensors, and type of SST data. High-resolution-satellite-measurements of SST inside the lagoons did not outperform oceanic SST series, suggesting that SST products are not adapted for small lagoons. Second, we modelled the difference between oceanic SST and TL as a function of the drivers of lagoon water renewal and mixing, namely waves, tide, wind, and season. The multivariate models reduced significantly the bias between oceanic SST and TL. In atoll lagoons, and probably in other hydrodynamically semi-open systems, a correction taking into account these factors is necessary when SST are used to characterize organisms' thermal stress thresholds.

Highlights

► Oceanic satellite SST are not good proxies of lagoon temperature. ► Using SST can provide inaccurate maximal temperatures and thermal stress thresholds. ► Modelling ΔT as a function of tide, waves, and wind speed helps to reduce the bias.

Keywords : Atoll lagoon, Pacific islands, Reef aperture, Climate change, Sea surface temperature

1. Introduction

Understanding the vulnerability and resilience to climate change of coral reef organisms requires an accurate and long term characterization of the temperature they experience (T_L) on reefs and in lagoons (Doney et al., 2012). In remote coral reefs, unfortunately, temperature series from *in situ* sensors and data loggers are usually lacking, or they are often short and interrupted due to logger failure, maintenance and access constraints (but see Berkelmans et al., 2002; Hendee et al., 2006). To get the long term and continuous series necessary to answer climate-change questions in particular, satellite-derived Sea Surface Temperature (hereafter SST) products have been used instead of T_L . Satellite products are available since the 70s without interruptions, even for the most remote coral reefs where long term *in situ* data are unavailable. These measurements are therefore useful to coral reef biologists to relate biological processes (e.g., bleaching event, mass mortalities) with unusually high (or low) seawater temperature that may have exceeded some thermal resistance threshold for the organisms at stake (Logan et al., 2012, Van Hooidonk and Huber, 2009). Yet, the link between the two variables T_L and SST is far from being trivial.

The two variables T_L and SST are fundamentally distinct because they are not affected by the same processes. Satellite-derived SST is the temperature of a thin boundary layer at the air-sea interface (≈ 0.01 mm, the “skin layer”), and may not be appropriate to study nearshore subtidal habitats in case of vertical stratification of temperature (Small and Wernberg, 2009). The spatial resolution of SST data also matter, because spatially restricted fluctuations in temperatures induced by local processes (e.g., tides, upwellings) cannot be always adequately captured by coarse-resolution SST (Small and Wernberg, 2009). Finally, the value of SST for small size lagoons (few km^2 or less) is unclear compared to the resolution of SST datasets. High resolution SST products (1 km) may provide some measurements inside the lagoons, but thus far the accuracy of time-series remains unclear for most areas, especially if the signal can be polluted by environmental effect due to presence of land, large tidal range exposing variable surface areas of intertidal domain, and spatial pixel-per-pixel

misregistration. As a result, offshore open-ocean SST are commonly used as a proxy for shallow reefs and lagoon temperature in a variety of reef studies, including those related to climate change (Logan et al., 2012).

The renewal of lagoon water is primarily driven by tide and waves. Water inflow is prominent when ocean water level is above the lagoon water level, and *vice versa*. The higher the offshore tidal range, the stronger the water inflow and outflow to equilibrate the water levels between ocean and lagoon. Offshore waves (generated by distant storms or locally by wind) can also enhance lagoon water renewal because high waves bring water above the reef edges (Lowe and Falter, 2015). The intensity by which tide and waves determine the mixing between ocean and lagoon waters also strongly depends on the reef configuration itself. First, the nature of reef edges (reef passes, submerged reef flats, shallow channels) and their abundances determine the amount of water that can cross the reef. Second, the volume of exchange compared to the volume of the lagoon determines the extent by which oceanic waters influence lagoon waters. From these considerations, the linkages between T_L and SST may not be the same for all lagoons, due to variable water renewal time that can range from few hours to several weeks or months (Andréfouët et al., 2001a).

Finally, it is important to point out that wind also drives lagoon circulation and mixing by setting into motion the upper water layer, promoting exchanges at the water-atmosphere interface (Dumas et al., 2012). This role is critical for closed water bodies. Strong wind also promotes stronger vertical mixing of lagoon waters. In enclosed lagoons under limited influence from the ocean, a thermocline (usually < 5 m depth) can form during low wind periods, but this thermocline quickly disappears when the wind increases (Dumas et al., 2012).

Tide, waves, wind regimes, and reef geomorphology may therefore modulate the correlation between T_L and oceanic SST, especially when T_L is measured at a given point and a given depth inside the lagoon, where benthic communities of interest are located. In this study, we first compared the correlation between various SST series and T_L from 2012 to 2016 in three atoll lagoons and one island lagoon in the Pacific Ocean. This was performed for oceanic SST series and for lagoon SST series.

Because SST poorly matched T_L for some lagoons, we further modelled T_L from oceanic SST, offshore tide, waves and wind. To our knowledge, this exercise has never been undertaken. This model should clarify in our context the validity of using SST and, in a broader context, should help understanding SST limits when little knowledge of the exact physical processes operating in the focal area is available. Here, we looked for an empirical relationship to characterize lagoon temperature, targeting especially the needs of ecologists, but that should not preclude that analytical characterization and numerical modelling can also be investigated when possible. Finally, we discuss the consequences of the observed differences between T_L and SST when defining temperature-related variables of interest for ecologists.

2. Methods

2.1. Study sites

Our study focused on four lagoons in the Central Pacific (Fig. 1). The lagoon of Tubuai (90 km²) located in Austral Archipelago, French Polynesia, is open because it is permanently connected to oceanic waters through a large subtidal reef flat, or shallow pass, in the northern part of the lagoon, and two narrow shallow passes at the southwest end of the lagoon (Fig. 1D). All other reef edges consist in intertidal crests, therefore exposing the lagoon to waves especially at high tide and during periods of strong swell.

The atolls of Tatakoto and Takaroa in Tuamotu Archipelago, French Polynesia, are semi-closed atolls (Andréfouët et al., 2001b). The atoll rim of Tatakoto is closed in its northern part, but the lagoon (11.46 km²) is connected to the ocean by several shallow channels that bisect the southern part of the rim (Fig. 1B). The lagoon of Takaroa (90 km²) is closed, except by a narrow reef pass in the north and by several shallow channels in the south of the rim (Fig. 1C).

The atoll rim of Manihiki in the Cook Islands has no pass but the lagoon (40 km²) is connected to oceanic waters through large submerged reef flats in both the northwestern and southern part of the

lagoon (Fig. 1E). Manihiki is therefore an open atoll (Andréfouët et al., 2001a; 2001b; Callaghan et al., 2006).

2.2. Temperature loggers

The temperature experienced by benthic coral reef organisms (T_L) was recorded by using temperature loggers deployed at the four sites. Several of the sensors also recorded pressure, which provided supporting information on the water levels inside lagoons. The exact positions, measurement types, mean depths, and deployment period of sensors are provided in supplementary material SM1.

At Tatakoto, one sensor (TAT3) recorded temperature and pressure in the south part of the lagoon (mean depth: 3.4 m) from November 2012 to October 2014 and two additional temperature sensors (TAT1 and TAT2) were placed at the opposite ends of the lagoon (Fig. 1B) until June 2016 at 1.0 and 2.8 m depth.

At Takaroa, one sensor (TAK2) in proximity to the reef pass (Fig. 1C) recorded temperature and pressure from November 2012 to June 2015, and two additional sensors (TAK1 and TAK3) recorded temperature respectively in the south part of the lagoon until March 2016, and in an enclosed shallow basin located in the southwestern part of the atoll until January 2016.

At Manihiki, three sensors were deployed along the same pinnacle located in the middle of the lagoon, but at various depths (Fig. 1E). One sensor (MAN3) recorded temperature and pressure from October 2012 to December 2013 at 15-m (mean-depth), while two other sensors (MAN1 and MAN2) recorded temperature at 5 and 20 m depth from October 2012 to February and March 2015.

At Tubuai, one sensor (TWR2050 TUB3) recorded temperature and pressure from April 2013 to June 2015, on the top of a submerged coral patch located in the south-eastern part of the lagoon (Fig. 1D).

2.3. Sea surface temperature time series

We used three independent data sources for open-ocean SST time series at high spatial resolution.

First, we used the daily SST data from the UK Met Office's Global, daily, Operational SST and Sea Ice (OSTIA) SST analyses at 0.05 degrees (i.e. around 5 km) resolution (Donlon et al., 2012; http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html).

Second, we used the Global, daily Multi-scale Ultra-high Resolution (MUR) SST analyses at 0.01 degree (around 1 km) resolution (Chin et al., 2017; <https://mur.jpl.nasa.gov/>).

Third, we used the Global, daily Level 4 G1SST Global Foundation Sea Surface Temperature Analysis (Chao et al., 2009; https://podaac.jpl.nasa.gov/dataset/JPL_OUROCEAN-L4UHfnd-GLOB-G1SST/) at 1 km resolution.

For the three datasets, SST were extracted from October 2012 to June 2016 to match our period of *in situ* measurements, and a mean was computed with two different spatial domains around the island/atoll. First, we averaged the daily data over a 1° by 1° grid around the four sites. Second, the daily mean was computed over a smaller grid of 0.15° by 0.15°, located 0.15° westward of each study site to avoid any effect of land on SST measurements (Fig. 2A-2C). The three datasets (OSTIA, G1SST and MUR) and the two spatial domains considered for computing the mean (1° by 1° and 0.15° by 0.15°) provided 6 SST time series for each study site, respectively designated as OSTIA-1°, OSTIA-0.15°, G1SST-1°, G1SST-0.15°, MUR-1° and MUR-0.15° throughout this manuscript (Fig. 2A-2C).

Since the high spatial resolution of the MUR datasets (1 km) also provided several SST measurements inside the lagoons (see supplementary material SM2), we also considered one lagoon SST series, designated as MURLAG throughout this manuscript. The MURLAG dataset was a subset of the MUR dataset, but averaging SST values inside lagoons only (Fig. 2D) instead of averaging SST values over the 1° by 1° and 0.15° by 0.15° grids described above (Fig. 2C).

To evaluate the extent by which the various SST series can be used as a proxy of T_L , the Pearson's correlation between SST and the daily mean of T_L ($\bar{T}_L$) was computed using the `cor` function in `stats` package in R.3.1.0.

2.4. Offshore tide, offshore waves, and wind

An offshore tide signal, composed from 32 harmonic constituents, was generated for each study site using a MARS hydrodynamic configuration (Lazure and Dumas, 2008) used in its barotropic (2D) mode. The spatial domain of the model (130°W-170°W ; 4°S-30°S) covers the four study sites at a resolution 0.09° in latitude and longitude. Bathymetry was derived from Etopo 5-minute gridded data and open boundaries were forced by the global tidal solution FES2012 (Carrère et al., 2012). For each site, the sea surface height above sea level was averaged over a 1° x 1° window, subtracted by its mean over the study period (October 2012 – June 2016). We defined TR_d as the difference of sea surface height between the highest tide and the lowest tide of the day. The mean tidal range (MTR) was also calculated, as the mean of TR_d over the study period.

The significant height of wind and swell waves (SWH) and mean wave direction (θ_m) came from the wave model Wavewatch III (WW3) (Rascle and Ardhuin, 2013), every 3-hours and at 0.5° lon x 0.5° lat resolution. For both SWH and θ_m , the mean over a 1° x 1° grid around the four sites was computed, and used to calculate the significant wave height of effective waves (SWH_e), as the Significant Wave Height, but excluding waves whose direction is perpendicular to the shoreline of closed (emerged) sections of the atoll rims. These rim sections do not authorize exchanges between ocean and lagoon, hence the contribution of the waves impacting these sections to the ocean-lagoon fluxes can be neglected (Andréfouët et al., 2001a). SWH_e was thus the significant wave height of waves from south-southeast for Tatakoto ($90 < \theta_m < 270$), waves from south, southeast and northwest for Manihiki and Takaroa ($90 < \theta_m < 360$), and waves from all directions for Tubuai ($0 < \theta_m < 360$).

The zonal (U) and meridional (V) wind components were extracted from the ERA-Interim atmospheric reanalysis (<http://www.ecmwf.int/en/research/climate-reanalysis/era-interim>) available for the studied period (October 2012 - June 2016) every 6 hours. The mean was computed over a 1° x 1° grid around each site, and wind speed (WS) was calculated as the square root of the sum of squares of U and V. We did not consider wind direction as a relevant variable to include in the models, since

wind direction is not expected to drive lagoon temperature in the same order of magnitude than wind speed (Dumas et al., 2012).

2.5. Modelling the difference between T_L and oceanic SST

The difference between $\bar{T}_L$ and oceanic SST (ΔT) was computed and modelled as a function of various parameters, following eq. 1.

$$\bar{T}_L - SST = T_v \sin\left(\frac{2\pi}{365} \times (DOY + c)\right) + s(TR_d) + s(SWH_e) + s(WS) \quad (\text{eq. 1})$$

Since ΔT was affected by a strong seasonal trend (see results), a first model (model 1) expressed ΔT as a seasonal function of the day of year (DOY) added to a constant (c), and the seasonal amplitude (T_v). The parameters T_v and c were fitted using the nls function of stat package, and the relevance of accounting for seasonality in the model was assessed by comparison of the Aikaike Information Criteria (AIC) with *versus* without the seasonal term.

Once the seasonal term was parameterized, we tested the effect of offshore wave, offshore tide, and wind on the intra-seasonal variability of ΔT by modelling residuals of model 1 as smooth functions (notified “s()” in eq. 1) of TR_d , WS and SWH_e (model 2). The smooth functions were first considered one by one then all together, and were parameterized by using a generalized additive model fitted by the gam function of mgcv package. Colinearity of factors was not addressed because no relationship between TR_d , WS and SWH_e was apparent (Supplementary material SM3). The relevance of these parameters in model 2 was assessed by comparison of the Aikaike Information Criteria (AIC) with them *versus* without them. The relative importance of each term was further evaluated by comparison of p.values provided by the summary.gam function. Fitted values of ΔT were then used to infer lagoon temperature ($\hat{T}_L$), and a R-square term was calculated to assess the proportion of $\bar{T}_L$'s variance explained by $\hat{T}_L$.

2.6. Temperature-related variables in ecological studies

Satellite derived SST time series and lagoon temperature (both $\bar{T}_L$ from *in situ* sensors TAT1, TAK1, TUB3 and MAN1, and $\hat{T}_L$ from modelling) were used to calculate three variables of interest in ecological studies. First, we identified the maximal daily temperature recorded during the study period (T_m), because short-term acute extreme temperature may affect survival of coral reef organisms. Then, we computed NOAA Coral Reef Watch Program bleaching prediction indices by calculating the mean monthly maximum (MMM) and the HotSpot metric over the study period. These metrics are used to empirically predict bleaching of coral organism, and often to critically examine a posteriori if they were good predictors of bleaching (McClanahan et al., 2007; Eakin et al., 2010). For SST data and $\hat{T}_L$, T_m , MMM, and HotSpot were calculated across the same time period as those recorded by *in situ* sensors.

3. Results and discussion

3.1. Correlation between $\bar{T}_L$ and SST

The best correlations between $\bar{T}_L$ and SST were usually obtained when using the oceanic SST from OSTIA or MUR datasets (Table 1). The OSTIA-1° and OSTIA-0.15° series were very similar because the OSTIA dataset displayed little variability at small spatial scale (Fig. 2A; SM4; SM5). By contrast, MUR-1° could differ from MUR-0.15° (Fig. 2C; SM5), and surprisingly the latter showed poorer correlation with $\bar{T}_L$, especially for Manihiki. Lower correlations were obtained for the G1SST dataset than for the OSTIA and MUR datasets (Table 1). Indeed, the G1SST products displayed short term variations that poorly matched $\bar{T}_L$ from *in situ* sensors (SM5). The surprisingly lower ability of the 1-km-resolution G1SST dataset to match with *in situ* sensors compared to the 5-km-resolution OSTIA dataset suggests that increasing the spatial resolution of SST measurements outside the lagoons do not necessarily inform better on temperature inside the lagoon. The MUR, G1SST, and OSTIA analyses also involve slightly different data streams, data quality control, and statistical interpolation

procedures (multi-resolution variational Analysis for MUR, multi-scale two-dimensional variational analysis for G1SST, and optimal interpolation for OSTIA; see Chao et al. 2009; Donlon et al. 2012; Chin et al., 2017), that may have provided contrasted outputs.

Using the MURLAG lagoon SST dataset did not outperform the oceanic MUR-1° dataset for Tatakoto and Tubuai and Manihiki, and only provided negligible improvements for Takaroa (Table 1; SM5). Several features may explain the poor congruence between lagoon SST and $\bar{T}_L$. First, satellite measurements inside the lagoon might be biased by emerged reefs and land (Miller et al., 2005). Second, when the Infra-Red measurements are contaminated by clouds, only the 25-km resolution Micro-Wave measurements are used to calculate SST in the MUR analysis, which do not provide a spatial resolution fine enough to picture lagoons. Finally, the data quality control and statistical interpolation procedures performed in MUR analyses are adapted for offshore waters, but not for small lagoons dotted by small emerged structures. These results suggest that lagoon SST is not a reliable proxy of $\bar{T}_L$ for small lagoons in the Central Pacific, and that oceanic SST remain in these cases the only reliable basis to infer $\bar{T}_L$.

Regardless of the SST dataset considered, the correlations between $\bar{T}_L$ and SST were lower for Tatakoto, Manihiki, and Takaroa, than for Tubuai (Table 1; SM5). The high correlation found at Tubuai between temperature recorded *in situ* and oceanic SST is in agreement with previous studies on well-flushed and open coastal areas (Van Hooidek et al., 2012). However, our results also confirm that oceanic SST time series poorly inform on lagoon temperature when lagoon and ocean water masses are little connected.

3.2. Characterizing the differences between $\bar{T}_L$ and oceanic SST

The differences between $\bar{T}_L$ and oceanic SST presented a seasonal trend, with $\bar{T}_L$ usually higher than SST in summer, and $\bar{T}_L$ usually lower than SST in winter (Fig. 3). In summer, the shallow waters are heated more easily than the deeper open ocean waters. In winter, heat is released from the ocean to the

atmosphere and the shallow waters cool more easily than open ocean waters. The seasonal amplitudes (T_v) were a function of the *in situ* sensors and SST datasets used (Supplementary material SM6), but were higher for Tatakoto (from 1.01°C to 1.19°C, SM6), than for Takaroa (from 0.21°C to 0.70°C), Manihiki (from 0.16°C to 0.39°C) and Tubuai (from 0.16°C to 0.27°C). The higher seasonal trend recorded at Tatakoto compared to other sites probably resulted from lower connection between ocean and lagoon waters, and lower thermal capacity due to the small volume of Tatakoto's lagoon. Considering a seasonal term for modelling ΔT improved significantly the model for Tatakoto (ΔAIC up to 908, SM6), Takaroa (ΔAIC up to 283), and Tubuai ($\Delta AIC = 99$), but this was not the case for Manihiki ($\Delta AIC < 0$ for most sensors and SST datasets used). Interestingly, spatial variability was noticeable at Takaroa, with a stronger seasonal trend recorded for sensor TAK3 located in the shallow enclosed basin (T_v from 0.57 to 0.70) than for the two other sensors in the main lagoon (T_v from 0.21 to 0.54).

Detailed descriptions of tide, lagoon water level, waves and wind patterns that characterize the four sites are provided in Supplementary materials SM5 and SM7. Accounting for SWH_e to model the intra-seasonal variability of ΔT further improved models significantly for all sites when considering the OSTIA and MUR SST datasets (all p.values < 0.001 , SM6), with stronger influence at Tatakoto, than at Takaroa, Manihiki and Tubuai. The influence of WS on ΔT was also significant for all sites and most sensors and SST datasets used (SM6), but was stronger for Tatakoto (ΔAIC from 86 to 242), than for Takaroa (ΔAIC from 14 to 119), Tubuai (ΔAIC from 17 to 118), and Manihiki (ΔAIC from -0.24 to 66). By contrast, the influence of TR_d on ΔT was of lower magnitude (ΔAIC from -1.89 to 31) compared to SWH_e and WS (SM6).

Statistical models selected to infer $\hat{T}_L$ explained up to 92% of $\bar{T}_L$'s variance for Tatakoto, 94% for Takaroa, 95% for Tubuai, and 77% for Manihiki. These results highlight that considering a seasonal trend as well as tide, waves and wind forcing can help reduce the offset between SST and $\bar{T}_L$, but statistical models cannot entirely represent all processes that influence short-term variations of ΔT (Supplementary material SM8). As a result, statistical models can be poorly skilled to infer $\bar{T}_L$ from

SST for lagoons that display low seasonality in ΔT (i.e., Manihiki), but they are very helpful to identify which forcing factors would be the most critical when studying a variety of lagoons.

In parallel to the same exercise we did here, to advance further and analytically characterize the intra-seasonal variation of ΔT , we advocate when possible the use of numerical modelling which account for the thermodynamic processes at the ocean-lagoon and the atmosphere-lagoon interfaces (McCabe et al., 2010). However, such approach requires significant work to obtain a realistic configuration (Andréfouët et al., 2006) and is beyond the scope of the present paper.

3.3. Consequences for ecological studies

Differences between $\bar{T}_L$ and SST highlighted in the previous sections have clear implications for ecological studies requiring knowledge on temperature regimes such as coral bleaching or mass mortalities (Andréfouët et al., 2015). The values of T_m calculated from SST were usually similar to the values of T_m calculated from $\bar{T}_L$ for Tubuai, with less than 0.3°C difference (Supplementary material SM9). By contrast, the difference in T_m was higher for Takaroa (from 0.3 to 0.8°C depending on SST datasets used), Manihiki (up to 0.9°C), and reached 1.6°C for Tatakoto. Similarly, the differences between the MMM calculated from SST and MMM calculated from $\bar{T}_L$ reached 0.2°C , 0.5°C , 0.2°C and 0.6°C for Tubuai, Takaroa, Manihiki and Tatakoto respectively. This resulted in different values for the HotSpot metrics. The accumulation of HotSpot values of 1°C or more is used by NOAA as a predictor for bleaching event (Van Hooidonk et al., 2012; Liu et al., 2013). In our study, the number of days for which HotSpot is > 1 was strongly underestimated when using SST as proxy of $\bar{T}_L$ (from 49 to 59 days of difference for Tatakoto depending on the SST dataset used, up to 10-days for Takaroa, and up to 18 days for Manihiki, SM9). In most cases, the various SST datasets used lead to different thermal stress thresholds estimations (SM9). These results highlight that using SST alone as a proxy of $\bar{T}_L$ can lead to erroneous conclusions concerning the level of thermal stress experienced by coral reef organisms located in lagoons of poor water renewal. Many populations of coral reef species (either mobile or sessile) found within a region of connected atoll and islands, can be composed of

individuals that inhabit open well flushed waters and individuals that inhabit closer lagoon waters (e.g., species inhabiting both reef slopes and lagoons). Thermal stress thresholds established on the basis of SST alone are unlikely to provide accurate estimates for a population that is spread in different lagoons.

Modelling lagoon temperature as a function of SST OSTIA-1° dataset, SWH_e, TR_d, and WS reduced the offset between T_m calculated from SST and T_m calculated from $\hat{T}_L$ down to 0.1°C for Tubuai and Manihiki, 0.2°C for Takaroa, and 0.5°C for Tatakoto. Similarly, the offset between MMM calculated from SST and MMM calculated from $\hat{T}_L$ was reduced down to 0.1°C for Tubuai, Tatakoto, and Takaroa, and 0.0°C for Manihiki, but a significant bias remained in the number of days for which HotSpot is > 1 (SM9). Similar results were obtained when using the MUR-1° dataset, except that in this case the bias in T_m could not be reduced for Manihiki. These results highlight that knowledge of the main parameters that drive the variability of ΔT are needed to characterize the thermal stresses of coral reef populations more accurately than currently in the literature when only SST are used.

4. Conclusion

Our study highlights that neither lagoon SST nor oceanic SST are accurate proxies of $\bar{T}_L$ for atoll lagoons. Using SST alone as a proxy of $\bar{T}_L$ can lead to erroneous conclusions concerning the level of thermal stress experienced by coral reef organisms. Modelling ΔT from the drivers of lagoon water renewal and mixing, namely waves, tide, wind, and season, can help reducing the bias. A correction taking into account these factors is therefore necessary when using SST to define organisms' thermal stress thresholds.

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Figure captions

Fig. 1: (A) Location of Manihiki (Cook Islands), and Takarua, Tatakoto and Tubuai (French Polynesia) in the South Pacific Ocean. (B-E): maps of Tatakoto (B), Takarua (C), Tubuai (D), and Manihiki (E) based on the Millennium mapping project.

Fig. 2: Spatial coverage and resolution of SST series considered in this study, with the example of Manihiki atoll in February 2013. (A) OSTIA-1° (mean of values over the entire window) and OSTIA-0.15° (mean over the dashed box). (B) G1SST-1° (mean of values over the entire window) and G1SST-0.15° (mean over the dashed box). (C) MUR-1° (mean of values over the entire window) and MUR-0.15° (mean over the dashed box). (D) MURLAG (i.e., MUR values that fell in the lagoon).

Fig. 3: Time series of ΔT on the basis of the “OSTIA-1°” dataset. Positive values of ΔT indicate warmer lagoon waters than SST, and *vice versa*. Red: TAT2, TAK2, MAN3, black: TAT3, TAK3, MAN2, TUB3, green: TAT1, TAK1, MAN1.

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439 **Tables**

440 **Table 1:** Pearson's correlation between $\bar{T}_L$ (Logger) and the various SST series. For each logger, the
 441 highest correlations are bolded.

<div>SST</div> <div>Logger</div>	OSTIA-1°	OSTIA-0.15°	G1SST-1°	G1SST-0.15°	MUR-1°	MUR-0.15°	MURLAG
TAT1	0.83	0.83	0.79	0.76	0.83	0.82	0.82
TAT2	0.84	0.84	0.79	0.77	0.84	0.83	0.83
TAT3	0.87	0.87	0.83	0.81	0.87	0.87	0.86
TAK1	0.92	0.92	0.87	0.81	0.91	0.90	0.92
TAK2	0.95	0.95	0.88	0.81	0.94	0.93	0.95
TAK3	0.84	0.84	0.79	0.73	0.83	0.82	0.85
MAN1	0.82	0.81	0.53	0.44	0.72	0.67	0.73
MAN2	0.82	0.82	0.57	0.48	0.70	0.66	0.70
MAN3	0.91	0.89	0.62	0.48	0.81	0.75	0.80
TUB3	0.97	0.97	0.94	0.91	0.97	0.96	0.97

442

Figures

Fig. 1

448 **Fig. 2**

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450 **Fig. 3**

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454 **Glossary**455 T_L : Temperature experienced by coral reef organisms. Unit: Degree Celsius ($^{\circ}\text{C}$).456 $\bar{T}_L$: Daily mean of T_L . Unit: Degree Celsius ($^{\circ}\text{C}$).457 SST: Sea surface temperature. Unit: Degree Celsius ($^{\circ}\text{C}$).

- 458 ΔT : Difference between $\bar{T}_L$ and SST. Unit: Degree Celsius ($^{\circ}\text{C}$).
- 459 SWH: Significant wave height. Unit: Metre (m).
- 460 θ_m : Mean wave direction. Unit: Degree ($^{\circ}$).
- 461 SWH_e : Significant height of waves, excluding waves whose direction is perpendicular to the
 462 shoreline of close (emerged) ring only and therefore not supposed to drive lagoon water renewal. Unit:
 463 Metre (m).
- 464 TR_d : Daily range between highest tide and lowest tide. Unit: Metre (m).
- 465 MTR: Mean tidal range over the study period. Unit: Metre (m).
- 466 WS: Wind speed. Unit: Metre per second ($\text{m}\cdot\text{s}^{-1}$)
- 467 T_v : Seasonal amplitude of ΔT . Unit: Degree Celsius ($^{\circ}\text{C}$).
- 468 $\hat{T}_L$: Temperature experienced by coral reef organisms as modelled from SST, T_v , SWH_e , TR_d , and WS.
 469 Unit: Degree Celsius ($^{\circ}\text{C}$).
- 470 T_m : The maximal temperature recorded during the study period. Unit: Degree Celsius ($^{\circ}\text{C}$).
- 471 MMM: Mean monthly maximum over the study period. Unit: Degree Celsius ($^{\circ}\text{C}$).

472 **Supplementary material**473 **SM1:** Main characteristics of sensors used in this study. T: Temperature, P: Pressure.

Location	Sensor ID	Sensor Type	Measurement	Depth (m)	Deployment time	Frequency
Tatakoto	TAT1	Seabird SBE56	T	1.0	Nov2012-Jun2016	30 min
Tatakoto	TAT2	Seabird SBE56	T	2.8	Nov2012-Jun2016	30 min
Tatakoto	TAT3	RBR RBRduo	T, P	3.4	Nov2012-Oct2014	30 min
Tubuai	TUB3	RBR TWR2050	T, P	1.2	Apr2013-Jun2015	15 min
Takaroa	TAK1	Seabird SBE56	T	4	Nov2012- Mar2016	30 min
Takaroa	TAK2	RBR RBRduo	T, P	4	Nov2012-Jun2015	30 min
Takaroa	TAK3	Seabird SBE56	T	2	Nov2012-Jan2016	30 min
Manihiki	MAN1	Seabird SBE56	T	5	Oct2012-Fev2015	30 min
Manihiki	MAN2	Seabird SBE56	T	20	Oct2012-Mar2015	30 min
Manihiki	MAN3	RBR RBRduo	T, P	15	Oct2012-Dec2013	30 min

474

475 **SM2:** Maps of MUR SST. Plotted values are the monthly means for February (A, C, E, G) and July
 476 (B, D, F, H) around Tatakoto (A and B), Takaroa (C and D), Manihiki (E and F), and Tubuai (G and
 477 H). Note the different scale bars.

479 **SM3:** Plot of values which highlight no apparent collinearity between the daily range between highest
 480 tide and lowest tide (TR_d), wind speed (WS), and the significant wave height of effective waves
 481 (SWH_e), which excludes waves whose direction is perpendicular to the shoreline of close (emerged)
 482 ring only and therefore not supposed to drive lagoon water renewal.

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484 **SM4:** Maps of OSTIA (left), MUR (middle), and G1SST (right) SST series. Plotted values are the monthly means for February 2013 (upper panels) and July
 485 2013 (lower panels) around Manihiki, Cook Islands.

487 **SM5:** Time series (December 2012 – June 2016) of offshore tide and lagoon water level (upper panel),
488 wind intensity (second panel), offshore wave height and direction (third panel), SST from OSTIA-1°,
489 OSTIA-0.15°, G1SST-1°, G1SST-0.15°, MUR-1°, MUR-0.15°, and MURLAG datasets and lagoon
490 temperature recorded by *in situ* sensors (lower panel) at the four studied sites. (TAT) Tatakoto (TAK)
491 Takaroa (MAN) Manihiki (TUB) Tubuai. Available at: 10.5281/zenodo.997599

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495 **SM6:** Results from modelling ΔT as a function of seasonality (T_v), significant height of effective waves (SWH_e), daily tidal range (TR_d), and Wind speed
 496 (WS). ΔAIC refers to the difference of AIC between models that do consider *versus* do not consider predictors. Significance of the GAM parameters when
 497 considered individually are indicated by * ($\alpha = 0.05$), ** ($\alpha = 0.01$) and *** ($\alpha = 0.001$). Significance ($\alpha = 0.05$) of the GAM parameters when considered all
 498 together are indicated by (1) for SWH_e , (2) for TR_d and (3) for WS, ordered from the most significant to the less significant. R^2 is the proportion of variance of
 499 ΔT explained by the selected models.

logger	SST data	Seasonal trend			Intra-seasonal trend				R^2
		T_v	C	ΔAIC (season)	ΔAIC (SWH_e)	ΔAIC (TR_d)	ΔAIC (WS)	ΔAIC (SWH_e , TR_d , WS)	
TAT1	OSTIA-1°	1.14	77.7	898	130***	5.57*	204***	239 ^(3,1)	0.89
TAT1	OSTIA-0.15°	1.14	77.8	908	122***	5.28*	195***	229 ^(3,1)	0.88
TAT1	G1SST-1°	1.18	76.2	815	89.7***	6.19*	141***	167 ^(3,1,2)	0.85
TAT1	G1SST-0.15°	1.19	75.4	815	83.0***	5.35*	124***	147 ^(3,1,2)	0.82
TAT1	MUR-1°	1.06	80.1	779	102***	4.67*	170***	197 ^(3,1,2)	0.87
TAT1	MUR-0.15°	1.05	79.8	759	86.5***	3.40 ^{ns}	147***	174 ^(3,1)	0.86
TAT2	OSTIA-1°	1.13	76.7	751	145***	10.3**	242***	301 ^(3,1,2)	0.90
TAT2	OSTIA-0.15°	1.13	76.9	757	135***	9.60**	230***	287 ^(3,1,2)	0.90
TAT2	G1SST-1°	1.17	75.4	657	95.3***	10.4**	160***	201 ^(3,1,2)	0.86
TAT2	G1SST-0.15°	1.19	74.5	680	87.3***	9.03**	141***	176 ^(3,1,2)	0.84
TAT2	MUR-1°	1.06	79.1	632	114***	9.41**	201***	247 ^(3,1,2)	0.89
TAT2	MUR-0.15°	1.05	78.8	634	98.2***	7.36**	173***	218 ^(3,1,2)	0.88
TAT3	OSTIA-1°	1.13	78.1	561	102***	7.82**	126***	142 ^(3,1,2)	0.92
TAT3	OSTIA-0.15°	1.12	77.9	553	98.7***	7.01*	126***	141 ^(3,1)	0.92
TAT3	G1SST-1°	1.18	76.4	552	62.8***	8.65**	89.8***	97.0 ^(3,2)	0.88
TAT3	G1SST-0.15°	1.18	74.9	533	62.8***	8.50**	86.1***	93.7 ^(3,2,1)	0.87
TAT3	MUR-1°	1.03	81.8	520	80.3***	6.70*	105***	118 ^(3,1,2)	0.91
TAT3	MUR-0.15°	1.01	80.4	466	71.9***	4.87*	98.9***	111 ^(3,1)	0.90
TAK1	OSTIA-1°	0.54	71.9	-0.46	60.9***	-1.76 ^{ns}	65.3***	86.6 ^(3,1)	0.90
TAK1	OSTIA-0.15°	0.54	70.4	71.9	61.0***	-1.31 ^{ns}	67.0***	87.8 ^(3,1)	0.90
TAK1	G1SST-1°	0.51	66.9	-54.0	24.9***	0.96 ^{ns}	38.8***	45.5 ^(3,1)	0.81

TAK1	G1SST-0.15°	0.50	64.9	83.3	15.7***	3.25*	25.4***	30.8 ^(3,1,2)	0.73
TAK1	MUR-1°	0.38	82.9	-31.1	41.5***	4.8*	37.9***	61.8 ^(1,3,2)	0.86
TAK1	MUR-0.15°	0.37	78.4	40.1	30.6***	5.57*	25.3***	45.9 ^(1,3,2)	0.85
TAK2	OSTIA-1°	0.41	47.5	31.98	70.1***	7.31**	53.3***	81.3 ^(1,3,2)	0.94
TAK2	OSTIA-0.15°	0.41	47.1	80.8	72.6***	7.06**	56.4***	83.8 ^(1,3,2)	0.94
TAK2	G1SST-1°	0.50	41.0	140	26.6***	3.62*	23.2***	38.1 ^(1,3,2)	0.87
TAK2	G1SST-0.15°	0.52	42.8	209	18.5***	3.76*	14.4***	25.3 ^(1,2,3)	0.78
TAK2	MUR-1°	0.21	43.3	34.0	57.8***	31.0***	27.5***	90.6 ^(1,2)	0.91
TAK2	MUR-0.15°	0.24	40.4	86.3	45.4***	22.2***	16.8***	65.3 ^(1,2)	0.90
TAK3	OSTIA-1°	0.70	93.1	233	101***	1.82 ^{ns}	118***	162 ^(3,1)	0.87
TAK3	OSTIA-0.15°	0.69	91.8	283	101***	2.72*	119***	163 ^(3,1,2)	0.87
TAK3	G1SST-1°	0.66	91.5	127	49.4***	4.26*	83.0***	98.9 ^(3,1,2)	0.78
TAK3	G1SST-0.15°	0.66	89.4	221	36.0***	6.34*	60.7***	74.1 ^(3,1,2)	0.71
TAK3	MUR-1°	0.58	105.2	175	64.4***	13.2***	80.5***	122 ^(3,1,2)	0.82
TAK3	MUR-0.15°	0.57	102	224	51.9***	13.6***	63.9***	101 ^(3,1,2)	0.81
TUB3	OSTIA-1°	0.19	98.0	98.8	25.3***	0.36 ^{ns}	44.5***	50.5 ^(3,1)	0.95
TUB3	OSTIA-0.15°	0.18	83.2	86.8	33.3***	3.97*	60.3***	76.4 ^(3,1)	0.95
TUB3	G1SST-1°	0.24	58.4	4.21	0.97 ^{ns}	0.96 ^{ns}	17.4***	17.1 ⁽³⁾	0.89
TUB3	G1SST-0.15°	0.27	47.4	47.9	1.26 ^{ns}	2.12*	23.6***	29.1 ^(3,2,1)	0.86
TUB3	MUR-1°	0.17	79.3	37.7	43.4***	0.968 ^{ns}	118***	122 ^(3,1,2)	0.95
TUB3	MUR-0.15°	0.16	62.6	53.6	27.8***	3.62*	111***	116 ⁽³⁾	0.93
MAN1	OSTIA-1°	0.26	82.8	-177	62.3***	5.92*	64.7***	85.6 ^(3,1,2)	0.69
MAN1	OSTIA-0.15°	0.25	83.4	-143	63.7***	6.54*	66.0***	86.7 ^(3,1,2)	0.69
MAN1	G1SST-1°	0.21	82.3	-143	16.0***	-1.79 ^{ns}	13.3***	20.2 ^(1,3)	0.17
MAN1	G1SST-0.15°	0.19	86.6	-274	8.69**	-1.72 ^{ns}	10.3**	11.7 ^(1,3)	0.00
MAN1	MUR-1°	0.19	2300	-106	30.0***	15.1**	32.8***	53.7 ^(2,1,3)	0.55
MAN1	MUR-0.15°	0.16	-2077	-118	28.6***	9.60**	33.7***	50.5 ^(3,1,2)	0.45
MAN2	OSTIA-1°	0.29	81.5	-107	42.2***	1.62 ^{ns}	23.1***	46.8 ^(1,3)	0.69
MAN2	OSTIA-0.15°	0.28	82.2	-74.1	42.9***	2.06 ^{ns}	25.0***	47.2 ^(1,3)	0.68
MAN2	G1SST-1°	0.24	80.7	-155	14.5***	0.35 ^{ns}	-0.24 ^{ns}	12.9 ⁽¹⁾	0.17
MAN2	G1SST-0.15°	0.20	84.5	-301	7.62***	1.92*	-0.23 ^{ns}	7.85 ⁽¹⁾	0.00
MAN2	MUR-1°	0.23	469	-61.8	14.8***	11.6***	10.9***	28.1 ^(2,1)	0.49
MAN2	MUR-0.15°	0.19	106	-111	12.8***	7.7*	13.3***	26.2 ^(2,1,3)	0.39
MAN3	OSTIA-1°	0.29	37.0	-99.9	60.5***	4.63*	54.7***	72.7 ^(3,1,2)	0.77

MAN3	OSTIA-0.15°	0.30	38.3	-57.6	65.8 ^{***}	4.80 [*]	58.3 ^{***}	78.3 ^(3,1,2)	0.77
MAN3	G1SST-1°	0.39	27.5	43.9	23.8 ^{***}	-1.53 ^{ns}	20.0 ^{***}	27.2 ^(1,3)	0.43
MAN3	G1SST-0.15°	0.39	29.1	-9.70	17.8 ^{***}	-1.89 ^{ns}	17.3 ^{***}	20.7 ^(1,3)	0.19
MAN3	MUR-1°	0.21	57.1	33.1	48.5 ^{***}	5.76 [*]	42.0 ^{***}	58.4 ^(1,3,2)	0.70
MAN3	MUR-0.15°	0.21	55.1	44.2	51.0 ^{***}	3.42 ^{ns}	42.3 ^{***}	57.8 ^(1,3)	0.62

ACCEPTED MANUSCRIPT

SM7: Detailed description of offshore wave, tide and wind patterns.

Tidal forcing was low for the four sites, with offshore MTR of 0.71 m for Tatakoto, 0.59 m for Takaroa, 0.41 m for Manihiki, and 0.35 m for Tubuai. TR_d ranged from 0.58 m (Tubuai) to 1.06 m (Tatakoto) during spring tides. The results of the tidal model for Takaroa were congruent with those obtained at a nearby atoll (Ahe) by Dumas et al. (2012) who validated their tidal model using extensive field data. For all sites, the lagoon water level followed a semi-diurnal trend induced by tide (see time-series of measurements in Supplementary material SM5), but delays from several minutes to hours were recorded between lagoon's high tide and offshore ocean's high tide depending on lagoon closure.

Offshore wave regimes were contrasted between sites, with waves from South-Southeast prevalent from April to November at Tatakoto, Takaroa and Manihiki. From December to March, waves were usually from North-Northeast at Tatakoto, Takaroa and Manihiki. By contrast, high waves from the south were prevalent most of the year at Tubuai. Episodic events of high SWH_e increased lagoon water level at all sites (see time-series of measurements in Supplementary material SM5). This pattern was however more pronounced for Tatakoto, whose lagoon's water level as well as the semi-diurnal oscillation due to tides decreased markedly during prolonged periods of low waves from the south, indicating very weak connection between the open ocean and lagoon during these periods. By contrast, this pattern was less evident at Takaroa where the highest waves, from South-Southeast, were of lower height than in Tatakoto. This is likely because Takaroa is protected by other nearby atolls located further south in the Tuamotu Archipelago as it has been shown for Ahe atoll, westward from Takaroa (Andréfouët et al., 2012).

For all sites, wind regimes were mostly composed of alternate southeasterlies and northeasterlies, with short windless periods (usually < 3-5 days, see time-series of measurements in Supplementary material SM5). Southeasterlies were prominent during the Austral winter and northeasterlies during the summer, in agreement with the main wind regimes defined for Ahe atoll (Thomas et al., 2014). These wind regimes are typical for the Central Pacific. However, Tubuai, the southeast site, was usually

subject to higher wind speed ($6.55 \pm 2.55 \text{ m.s}^{-1}$, mean $\pm$ sd) than other sites. Tatakoto and Takaroa displayed similar wind regimes, with mean ($\pm$ sd) wind speed of $6.22 \pm 2.13 \text{ m.s}^{-1}$ and $6.15 \pm 2.14 \text{ m.s}^{-1}$ respectively. Manihiki was subject to lower wind than other sites ($5.51 \pm 2.14 \text{ m.s}^{-1}$).

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541 **SM8:** Tatakoto's time series of lagoon temperature recorded by *in situ* sensors (solid black line), SST (OSTIA-1°, dashed blue line), and fitted values of
 542 selected model (red). The upper panel display the entire series available for TAT1, and the lower panel is a zoom on the 2016 El Niño event.

545 **SM9**: maximal daily mean temperature (T_m) and mean monthly maximum (MMM), calculated from
 546 $\bar{T}_L$ and from SST. In brackets are the values of T_m and MMM calculated from modelled $\hat{T}_L$.

Site	Data source	T_m	MMM	Number of days hotspot > 1
Tubuai	TUB3	27.9	27.1	0
Tubuai	SST OSTIA-1°	27.8 (27.8)	26.9 (27.0)	0 (0)
Tubuai	SST OSTIA-0.15°	27.8 (27.9)	26.9 (27.0)	0 (0)
Tubuai	SST G1SST-1°	27.9 (28.0)	27.0 (27.0)	0 (0)
Tubuai	SST G1SST-0.15°	27.9 (28.1)	27.0 (27.1)	0 (0)
Tubuai	SST MUR-1°	27.6 (27.8)	27.0 (27.0)	0 (0)
Tubuai	SST MUR-0.15°	27.8 (27.9)	27.0 (27.1)	0 (0)
Tubuai	SST MURLAG-500m	27.8	27.0	0
Tatakoto	TAT1	31.4	29.2	61
Tatakoto	SST OSTIA-1°	29.9 (30.9)	28.7 (29.3)	6 (18)
Tatakoto	SST OSTIA-0.15°	29.9 (30.9)	28.7 (29.3)	6 (17)
Tatakoto	SST G1SST-1°	30.0 (30.9)	28.6 (29.3)	7 (21)
Tatakoto	SST G1SST -0.15°	29.9 (31.0)	28.6 (29.2)	12 (27)
Tatakoto	SST MUR-1°	29.8 (30.9)	28.7 (29.3)	2 (17)
Tatakoto	SST MUR-0.15°	29.9 (30.8)	28.8 (29.3)	3 (19)

Tatakoto	SST MURLAG-500m	29.9	28.7	5
Takaroa	TAK1	30.8	29.4	11
Takaroa	SST OSTIA-1°	30.0 (30.6)	29.0 (29.5)	1 (3)
Takaroa	SST OSTIA-0.15°	30.1 (30.6)	29.0 (29.5)	1 (4)
Takaroa	SST G1SST-1°	30.4 (30.9)	28.9 (29.5)	6 (7)
Takaroa	SST G1SST-0.15°	30.5 (31.0)	29.0 (29.5)	12 (19)
Takaroa	SST MUR-1°	30.2 (30.6)	29.1 (29.4)	2 (2)
Takaroa	SST MUR-0.15°	30.5 (30.8)	29.1 (29.4)	7 (8)
Takaroa	SST MURLAG-500m	30.2	29.2	4
Manihiki	MAN1	30.6	29.4	19
Manihiki	SST OSTIA-1°	30.3 (30.5)	29.2 (29.4)	1 (3)
Manihiki	SST OSTIA-0.15°	30.4 (30.6)	29.2 (29.4)	1 (2)
Manihiki	SST G1SST-1°	30.8 (31.1)	29.2 (29.3)	20 (26)
Manihiki	SST G1SST-0.15°	31.3 (31.5)	29.2 (29.3)	29 (39)
Manihiki	SST MUR-1°	30.7 (30.9)	29.3 (29.4)	3 (1)
Manihiki	SST MUR-0.15°	31.5 (31.6)	29.3 (29.4)	4 (5)
Manihiki	SST MURLAG-500m	30.7	29.2	11