Observed strong subsurface marine heatwaves in the tropical western Pacific Ocean

Shijian Hu 1,2,3,4,*, Shihan Li 1,2, Ying Zhang, Cong Guan 1,2,3,4, Yan Du, Ming Feng, Kentaro Ando, Fan Wang 1,2,3,4, Andreas Schiller 1,2,3 and Dunxin Hu 1,2,3,4

1 CAS Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, People’s Republic of China
2 Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao 266071, People’s Republic of China
3 Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao 266237, People’s Republic of China
4 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
5 State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, People’s Republic of China
6 CSIRO Oceans and Atmosphere, Crawley, Western Australia and Centre for Southern Hemisphere Oceans Research, CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia
7 Research and Development Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokosuka 237-0061, Japan
8 CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia
* Author to whom any correspondence should be addressed.

E-mail: sjhu@qdio.ac.cn

Keywords: marine heatwaves, tropical western Pacific, subsurface ocean, fishery production, Ekman pumping

Abstract
Marine heatwaves (MHWs), which are discrete extreme oceanic warming events, have important impacts on the marine ecosystem, fishery resources, and social economy. Previous studies based on sea surface temperature suggest that MHWs in the tropical western Pacific Ocean are very weak. However, here we show that the MHWs observed by the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network buoys in the tropical western Pacific Ocean are unexpectedly strong in the subsurface layer (50–300 m depth). The ensemble mean intensity of subsurface MHWs shows a peak of about 5.2 °C at 150 m, and the maximal mean intensity reaches 8.9 °C at 5° N, 137° E. Subsurface MHWs occur almost every year with an ensemble mean duration ranging from 13 to 22 days, and show no statistically significant correlation with the El Niño–Southern Oscillation index although the subsurface MHWs during La Niña events are slightly stronger and more frequent than during El Niño events. It seems that the subsurface MHWs are strong and frequent in April–June but relatively weaker and less frequent in September and October than in other months. Anomalous sea surface convergence and Ekman down-welling play an important role in the development of subsurface MHWs. Strong subsurface MHWs are likely to affect the fishery production of tropical western Pacific.

1. Introduction
Marine heatwaves (MHWs), defined to be discrete prolonged anomalously warm water events, can cause disastrous effects on the marine ecosystem structures, biological productions, and economic industries including fish mortality, coral bleaching, and so on (e.g. Pearce and Feng 2013, Hobday et al 2016, 2018, Oliver et al 2017, Frölicher et al 2018, Arafeh-Dalmau et al 2020). MHWs have been observed in many and widespread parts of the world’s oceans (e.g. Scannell et al 2016, Holbrook et al 2019, Viglione 2021). In the context of global climate warming, simulations from the Coupled Model Intercomparison Project Phase 5 indicate that the MHW intensity may be significantly increased, and annual MHW days are projected to accelerate to the end of the 21st century (Oliver et al 2019). Hence, a better understanding of MHWs’ spatiotemporal features and underlying dynamics is very important to predict well (Gillanders and Kingsford 2002, Firth et al 2011, De’ath et al 2012, Hobday et al 2018).

The drivers of MHWs are complex and vary from region to region (e.g. Holbrook et al 2019,
A MHW observed in the northern Mediterranean Sea in the boreal summer of 2003 was attributed to weak winds (Garrabou et al. 2009). Anomalous heat advection associated with the strong La Niña event and strengthened Leeuwin Current is suggested to cause anomalous warm sea surface temperature (SST) and 2010/2011 MHW off Western Australia (Feng et al. 2013). Both air-sea heat exchange and heat advection associated with a La Niña event are important in forming a MHW event in 2012/2013 in the Western Australia region (Xu et al. 2018). On the other hand, El Niño drives MHWs in the tropical Australia, e.g. the 1997/98 and 2015/16 events (Zhang et al. 2017, Benthuysen et al. 2018).

The tropical western Pacific Ocean is the place of the western Pacific warm pool, thousands of islands, rich biodiversity, and many fishing grounds such as tuna (e.g. Kim et al. 2020). But previous studies based on SST indicate that the intensity of MHWs in the tropical western Pacific Ocean is much weaker than in other regions (e.g. Oliver et al. 2018, Holbrook et al. 2019). Holbrook et al. (2019) suggested that MHW events are few in the western boundary current regions as shown in daily satellite SSTs from 1982 to 2016. On the other hand, surface MHWs are found to influence the subsurface ocean. For example, Scannell et al. (2020) found that warming temperature anomalies due to surface MHWs in the northeast Pacific Ocean penetrate the subsurface ocean in wintertime when mixing is strong. Schaeffer and Roughan (2017) found that subsurface intensification of MHWs in the regions off southeastern Australia. However, in the tropical western Pacific Ocean, it is not clear whether there are subsurface MHWs.

This study uses high-temporal-resolution subsurface measurements collected by the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) buoys to explore the subsurface MHWs and examine their spatiotemporal features and mechanisms in the tropical western Pacific Ocean. Unexpected strong subsurface MHWs are found in the subsurface layer of the tropical western Pacific Ocean, and these subsurface MHWs appear to be independent of surface warming. The existence of strong subsurface MHWs implies that heatwaves may have much more serious influence on the tropical western Pacific Ocean than expected.

2. Data and methods

The TAO/TRITON buoys collected upper ocean temperatures between the sea surface and 500 m depth in the tropical Pacific Ocean since 1977 and continue to the present (McPhaden et al. 1998, 2010, Ando et al. 2017) as Tropical Pacific Observing System (https://tropicalpacific.org). About 19 TAO/TRITON buoys have been deployed in the tropical western Pacific Ocean. Most of the TAO/TRITON buoys have collected high-frequency measurements of upper-layer temperature since the early 1990s. The TAO/TRITON provides a valuable opportunity to study the synoptic scale variability of the ocean.

We use daily mean temperature data from 19 TAO/TRITON buoys deployed in between 130 and 170° E. The positions of these buoys are: 8° S/165° E, 8° N/165° E, 8° N/156° E, 8° N/137° E, 5° S/165° E, 5° S/156° E, 5° N/165° E, 5° N/156° E, 5° N/147° E, 5° N/137° E, 2° S/165° E, 2° S/156° E, 2° N/147° E, 2° N/137° E, 0° N/165° E, 0° N/156° E, and 0° N/147° E (figure 1). Temperature observations at 165° E are available from 1 m to 500 m depth with 11–23 vertical levels, while temperature observations at other longitudes are available from 1 m to 750 m depth with 12–20 vertical layers. The observation duration ranges from 7023 (8° N, 137° E) days to 12 986 days (2° S, 165° E) with a mean of 10 001 days, which is generally appropriate to obtain a daily climatology of temperature. Quality of the temperature is flagged in the TAO/TRITON data product, and data that are flagged with ‘Lower Quality’ are discarded.

To investigate the underlying dynamics of the observed subsurface MHWs, we also examined temperature products based on Argo floats produced by Roemmich and Gilson (2009, hereafter RG Argo). Daily products of sea surface wind stress and its derivative upwelling velocity NOAA Coast Watch (hereafter ERDAPP wind stress curl product), which is based on wind velocity measurements from the Advanced Scatterometer (ASCAT) instrument onboard EUMETSAT’s METOP satellite, are employed to examine the role of wind forcing in the generating of subsurface MHWs. Monthly AVISO sea level anomaly product and three-day Ocean Surface Current Analyses Real-time (OSCAR) surface currents are used to investigate ocean dynamic processes during MHWs. In addition, we use the Oceanic Niño Index (ONI, Huang et al. 2017), which is calculated using the Extended Reconstructed Sea Surface Temperature (ERSST) v5 SST anomalies in the Niño 3.4 region (5° N–5° S, 120°–170° W), to discuss the relationship between subsurface MHWs and El Niño-Southern Oscillation (ENSO).

Figure 1(b) presents time-mean temperature profiles at each buoy site, while figure 1(c) shows profiles of standard deviation (STD) of daily temperature at each buoy site. Temperature profiles at these buoy sites possess quite similar vertical structures: well-mixed in the upper 50 m layer, and the thermocline layer occupies from about 50 m to 300 m depth (figure 1(b)). STDs of temperature are less than 0.5°C in the mixed layer and the layer below 300 m but reach a maximum of 2°C–4°C at about 150 m depth, indicating significant variability of subsurface temperature in the thermocline layer that independent of surface temperature.

Following the method proposed by Hobday et al. (2016), we define a MHW as a discrete anomalously
warming event, which lasts for five or more days and with anomalous temperatures warmer than the 90th percentile based on the observational duration period corresponding to each buoy site. A detailed description of the MHW definition can be found in the paper by Hobday et al (2016).

3. Results

3.1. Characteristics of subsurface MHWs

Subsurface-intensified warming is one of the key features of MHWs occurred in the tropical western Pacific Ocean. As shown in figure 2, discrete warming events are detected at every buoy site and from surface to deeper than 700 m depth. The maximum intensity of almost every MHW event is found in the subsurface layer, and many of MHWs occurred even when no significant warming anomalies in the surface layer. The vertical structure of these MHWs suggests that they are very different from surface intensified MHWs and is why we call them subsurface MHWs.

The intensity and duration of subsurface MHWs differ from buoy sites, but the occurrence of these MHWs seems to be coherent changes within the tropical western Pacific Ocean. For example, the MHWs in 2005, 2007, 2008, 2010, 2011, and 2012 are detected at basically all stations simultaneously (figure 2). A comparison between MHWs and isotherms indicates that a subsurface MHW event corresponds to a deepening of thermoclines.

Figures 3(a)–(c) present statistical features, including mean intensity, the yearly number of events and duration of the subsurface MHWs at each buoy site. As suggested in previous studies, the intensity of MHWs in the surface layer is quite small. However, the intensity of subsurface MHWs in the tropical western Pacific Ocean is clearly intensified in the 50–300 m layer, which is also identified by figure 2, with a significant peak at 150–200 m depth (figure 3(a)). A comparison between figures 3(a) and (b) indicates that the subsurface MHWs occur in the thermocline layer. The vertical structure of MHWs’ intensity at each buoy site is very similar (figure 3(a)).
The maximum of the ensemble mean intensity (average of all the 19 sites) is about 5.2 °C, which is much greater than surface MHWs (∼1.3 °C) and is twice as big as the STD of temperature at the same depth. The subsurface MHWs occur about 1.3 ± 0.3 times a year on average for the whole period (vertical mean over 50–300 m), and the mean duration of the MHWs in this region is about 13–22 days at depths with a mean of about 17 days (figures 3(b) and 3(c)).

Given that the 150–200 m layer is a typical layer of subsurface MHWs, we present the intensity of subsurface MHWs averaged over 150–200 m in figure 3(d).
Vertical bands shown in figure 3(d) suggest that the MHWs’ intensity at different positions have coherent features in terms of dates and duration, implying that the MHWs occurred at these buoy sites might be a result of a common large-scale process. It is shown that subsurface MHWs have occurred almost every year during 1985–2020 in the tropical western Pacific Ocean, but in some particular years they were distributed on a broader area than in other years and showed stronger intensity.

To investigate the relationship between ENSO and the interannual changes of subsurface MHWs, we present the monthly ONI during 1984–2020 in figure 3(e). The subsurface MHWs in 1988, 1995,
1996, 1999, 2000, 2003, 2004, 2007, 2008, 2009, 2010, 2011, 2013, 2016, and 2017 have greater intensities than in other years (figure 3(d)), but it seems that the subsurface MHWs are not unequivocally related to ENSO. The four strongest subsurface MHWs occurred during: (a) a phase transition from an El Niño in 1987 to a La Niña in 1988; (b) a La Niña event in 2007; (c) a phase transition from an El Niño in 2009 to a La Niña in 2010; and (d) a neutral phase in the first half of 2017 (figure 3(e)). As shown in figure 3(e), during the observation period, about 22% of subsurface MHWs have occurred during warming phases (ONI ⩾ 0.5), 36% during cold phases (ONI ⩽ −0.5), and 42% under normal conditions (−0.5 < ONI < 0.5), suggesting that the vast majority (~78%) of subsurface MHWs have occurred in durations without La Niña events. The intensity of subsurface MHWs is 5.0 ± 1.1 °C during warm phases (ONI ⩾ 0.5), 5.2 ± 0.9 °C during cold phases (ONI ⩽ −0.5), and 5.2 ± 1.0 °C during normal conditions (−0.5 < ONI < 0.5). Hence, the difference in MHWs’ intensity between El Niño and La Niña phases is much smaller than the uncertainty, indicating that the intensifying of subsurface MHWs during La Niña phases is very weak and not significant. Therefore, we suggest that, although the ENSO cycle is probably able to affect subsurface MHWs, the occurrence of subsurface MHWs have no statistically significant correlation with the ENSO index.

The subsurface MHWs in the tropical western Pacific Ocean show interesting seasonality. We present the climatological monthly intensity and percentage number of the subsurface (150–200 m) MHWs in figures 3(f) and (g). The intensity ranges from about 3.7 °C in September to 5.4 °C in April–June with a mean of 4.9 °C and an STD of about 0.5 °C, indicating that the seasonal change of the subsurface MHWs’ intensity is weak (figure 3(f)). In contrast, the percentage number of subsurface MHWs shows a well-defined seasonal cycle: about 55% of subsurface MHWs occur in March–June, but only about 13% of subsurface MHWs occur in August–November and merely 4% in September and October (figure 3(g)). Hence, it seems that the subsurface MHWs in September and October are relatively weaker and less frequent than in other months.

### 3.2. Possible mechanism of subsurface MHWs

Temperature anomalies associated with subsurface MHWs occurred mainly in the layer between 50 and 300 m centered at 150–200 m, in the depths of the surface Ekman layer and upper thermocline layer. For example, the surface Ekman layer depth at 5° N, assuming a steady, homogeneous and horizontal flow with friction on a rotating earth, is 102 m when the sea surface wind speed is 3 m s⁻¹ and 257 m when the sea surface wind speed is 10 m s⁻¹ (e.g. Stewart 2008). The tropical western Pacific Ocean is a complex place of strong equatorial currents and western boundary currents: the North Equatorial Current and South Equatorial Current flows westward and feed the Mindanao Current and New Guinea Coastal Current and New Guinea Coastal Undercurrent, which converge in the equatorial western Pacific Ocean and provide sources of outflowing North Equatorial Counter Current, Equatorial Undercurrent and Indonesian Throughflow (Hu et al 2015, 2016, 2018).

Hence, temperature variability in the subsurface tropical western Pacific Ocean could be caused by vertical heat transport (isotherm heaving) related to upwelling/downwelling and horizontal heat advection. Hu et al (2017) found that enhanced upwelling leads to significant cooling in the upper layer and the western Pacific warm pool split. If that is the case, a downwelling anomaly may give rise to significant warming in the tropical western Pacific Ocean. To examine the role of related ocean dynamics in generating subsurface MHWs, we investigate changes in sea surface wind forcing, Ekman pumping velocity, sea level, and ocean currents during subsurface MHWs. The Ekman pumping velocity \(w_E\) can be estimated with sea surface wind stress when its curl is non-zero (Cushman-Roisin and Beckers 2011):

\[
w_E = \frac{1}{\rho} \left[ \frac{\partial}{\partial x} \left( \frac{\tau_y}{f} \right) - \frac{\partial}{\partial y} \left( \frac{\tau_x}{f} \right) \right]
\]

where \(\rho\) is sea water density, \(f\) is Coriolis coefficient, and \(\tau_x\) and \(\tau_y\) are zonal and meridional components of sea surface wind stress.

Figure 4(a) presents composited upwelling velocity anomaly and surface wind stress curl anomaly during subsurface MHWs. Daily wind stress data from NOAA/ERDDA, available during 2000–2009, are used here. Negative upwelling velocity anomaly and wind stress curl anomaly can be found in the tropical western Pacific Ocean, indicating anomalous down-welling during the MHWs. The spatial distribution of the intensity of subsurface MHWs is in agreement with the Ekman down-welling velocity anomaly (figure 4(a)), except the one at 5° N, 137° E where the meandering of North Equatorial Counter Current (NECC) is also important (e.g. Messié and Radenac 2006).

The anomalous down-welling in the tropical western Pacific Ocean is accompanied by ocean convergence in the sea surface. We composite the sea level anomaly and surface meridional velocity anomaly during the subsurface MHWs, using monthly AVISO sea level anomaly and OSCAR surface current velocity products. As shown in figure 4(b), positive sea level anomalies relative to a multi-year mean are found in the western Pacific Ocean, indicating a strengthening of convergence in the surface layer. The composite surface meridional velocity anomalies relative to the multi-year mean suggest that southward current anomalies occurred in the northern hemisphere but
northward current anomalies occurred in the southern hemisphere, indicating a clear meridional convergence of surface water in the equatorial western Pacific Ocean. It should be noted that changes in the zonal currents, i.e. North Equatorial Current, South Equatorial Current, and NEC, are also important components of the processes of surface convergence (e.g. Hu et al 2015).

The spatial pattern of Ekman down-welling and surface convergence is in agreement with the spatial structure of isothermals during subsurface MHWs. Given that no daily subsurface temperature observations are available on synoptic scales and in such a big domain, we examined the temperature anomaly at 150–200 m in a specific MHW event using a monthly temperature product from RG Argo. We choose the month of February 2011 during a strong La Niña event, when a MHW event occurred at several buoy sites, as shown in figure 3(d). The spatial patterns of the MHW related temperature anomalies and MHW’s intensity (figure 4(c)) are very similar to that of down-welling velocity anomaly and surface wind stress curl anomaly during MHWs (figure 4(a)). Given that the temperature gradient in the mixed layer is much smaller than that in the thermocline layer, the temperature anomalies induced by down-welling are expected to be larger in the thermocline layer than in the surface, and this explains why the subsurface MHWs have a peak intensity in the thermocline layer and are independent from surface MHWs that usually related to heat flux.
In addition to the local wind forcing, equatorial Kelvin waves and intra-seasonal Rossby waves might also be important mechanisms of the subsurface. But as shown in figure 2, subsurface warming events were detected at 5 and 8° N/S, where is away from the equator and beyond the equatorial Kelvin waves’ sphere of influence. Given the existence of intra-seasonal Rossby waves in the tropical Pacific Ocean (e.g. Hu et al 2018), the westward propagation of intra-seasonal Rossby waves may also play an important role.

3.3. Possible influence on fishery production
The subsurface layer between 50 and 300 m depth is the biota of several fishes like tuna and thermal changes in these depths may affect the fishery catches (e.g. Cai et al 2020, Kim et al 2020). Kim et al (2020) suggested that the annual catch amount of skipjack tuna in the Federated States of Micronesia (FSM) was much less than normal during 1997–2001 and 2008–2012, but much greater than normal during 1991–1995 and 2003–2007.

The intensities of subsurface MHWs in the FSM region (here we use observations collected at 165° E, and 5° N and 8° N) were 4.1 °C during 1997–2001 and 4.9 °C during 2008–2012. In contrast, when the catch amount of skipjack tuna was greater than normal years, the average intensities of subsurface MHWs were 2.5 °C during 1991–1995 and 2.8 °C during 2003–2007. The differences of subsurface MHWs’ intensities are about 1.6 °C between 1991–1995 and 1997–2001, and 2.1 °C between 2003–2007 and 2008–2012, which are greater than the STD of subsurface MHWs’ intensities (about 1.6 °C), indicating the difference is significant.

Thus, strong subsurface MHWs are likely able to affect the fishery production of the tropical western Pacific. But it should be noted that, it is not clear whether the correlation between subsurface MHWs and catch amount of skipjack tuna is significant or not, and it is expected that their relationship would be complex. Further and more detailed studies are needed to uncover the influence of subsurface MHWs on fishery production in the tropical western Pacific Ocean.

4. Summary and discussion
Previous studies show that surface MHWs in the tropical western Pacific Ocean are weaker than in other parts of the global ocean (e.g. Oliver et al 2018, Holbrook et al 2019). However, in this study, we find that MHWs in the subsurface layer (about 50–300 m depth) of the tropical western Pacific Ocean are unexpectedly strong and occur almost every year as measured by the TAO/TRITON buoys. We call them subsurface MHWs, given that they are independent of the surface MHWs. The ensemble mean intensity of these subsurface MHWs reaches a maximum of about 5.2 °C at 150 m, and the ensemble mean duration of the subsurface MHWs is about 13–22 days with a mean of about 17 days. The subsurface MHWs during La Niña events are slightly stronger and more frequent than during El Niño events, but show no statistically significant correlation with the ENSO index. It seems that the subsurface MHWs are strong and frequent in April–June but relatively weaker and less frequent in September and October than in other months.

We suggest that anomalous oceanic convergence and Ekman down-welling play an important role in the occurrence of subsurface MHWs. It should be noted that the difference between subsurface MHWs and intra-seasonal subsurface warming is significant although they overlap in some ways. For example, the MHWs are synoptic events while the intra-seasonal variability is lower-frequency.

A better understanding of subsurface MHWs is essential to advancing marine science and solving socio-economic issues. In future studies, it is necessary to quantitatively investigate the dynamics underlying the subsurface MHWs, further assess the influence of subsurface MHWs on society, and develop forecasting techniques of subsurface MHWs.

Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments
The TAO/TRITON data are available at www.pmel.noaa.gov/tao/drupal/disdel/. The RG Argo data set is available at http://sio-argo.ucsd.edu/RG_Climatology.html. The NOAA ERDDAP wind stress curl and upwelling velocity products can be found at https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdrQAstressmday.html. AVISO sea level anomaly product is available at https://sso.altimetry.fr/ (Readers may need to register for an account with AVISO to access the data). OSCAR surface currents can be found at www.esr.org/research/oscar/oscar-surface-currents/. We thank the Global Tropical Moored Buoy Array Project Office NOAA/Pacific Marine Environmental Laboratory for providing the TAO/TRITON data. This work is supported by the Chinese Academy of Sciences (CAS) –Commonwealth Scientific and Industrial Research Organisation Project Fund (No. 133244KYSB20190031), the National Natural Science Foundation of China (Grant 42022040), the Strategic Priority Research Program of CAS (No. XDB42010403) and Shandong Provincial Natural Science Foundation (Grant ZR2020JQ18). SH is a
member of the Youth Innovation Promotion Association of CAS (No. 2018240) and the CAS Interdisciplinary Innovation Team (JCTD-2020-12). DH is supported by the Key Projects of Foreign Cooperation of the Bureau of International Cooperation Chinese Academy of Sciences (132B61KYSB20170005).

ORCID ID

Shijian Hu https://orcid.org/0000-0002-6142-7441

References

Ando K et al 2017 Fifteen years progress of the TRITON array in the Western Pacific and Eastern Indian Oceans J. Geophys. Res. 123 1301–26

Arafeh-Dalman N, Schoeman D S, Montaño-Moctezuma G, Micheli F, Rogers-Bennett L, Olguín-Jacobson C and Possingham H P 2020 Marine heat waves threaten kelp forests Science 367 635

Benthuysen J A, Oliver E C J, Feng M and Marshall A G 2018 Extreme marine warming across tropical Australia during austral summer 2015–2016 J. Geophys. Res. 123 1301–26

Cai L, Xu L, Tang D, Shao W, Liu Y, Zuo J and Ji Q 2020 The effects of ocean temperature gradients on brye tuna (Thunnus obesus) distribution in the equatorial eastern Pacific Ocean Adv. Space Res. 65 2749–60

Cashman-Noisín B and Beckers J M 2011 Introduction to geophysical fluid dynamics: Physical and Numerical Aspects Acad. Press 101–828

De’ath G, Fabricius K E, Sweatman H and Puotinen M 2012 The 27-year decline of coral cover on the Great Barrier Reef and its causes Proc. Natl Acad. Sci. 109 17995

Feng M, McPhaden M J, Xie S-P and Hafner J 2013 La Niña forces the Western Pacific warm pool structure associated with El Niño Clim. Dyn. 49 2431–49

Hu S, Hu D, Guan C, Xing N, Li J and Feng J 2017 Variability of the western Pacific warm pool structure associated with El Niño Clim. Dyn. 49 2431–49

Hu S, Sprintall J, Guan C, Sun B, Wang F, Yang G, Jia F, Wang J, Hu D and Chai F 2018 Spatiotemporal features of intraseasonal oceanic variability in the Philippine Sea from mooring observations and numerical simulations J. Geophys. Res. 123 4874–87

Huang B, Thorne P W, Banzon V F, Boyer T, Chepurin G, Lawrimore J H, Menne M J, Smith T M, Vose R S and Zhang H-M 2017 Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons J. Clim. 30 8179–205

Kim J, Na H, Park Y-G and Kim Y H 2020 Potential predictability of skipjack tuna (Katsuwonus pelamis) catches in the Western Central Pacific Sci. Rep. 10 3193

McPhaden M J, Busalacchi A J, Cheney R, Donguy J R, Gage K S, Halpern D, Ji M, Julian P, Meyers G and Mitchum G T 1998 The tropical oceanic global atmosphere observing system: a decade of progress J. Geophys. Res. (1978–2012) 103 14169–240

McPhaden M et al 2010 The global tropical moored buoy array Proceedings of OceanObs’09: Sustained Ocean Observations and Information for Society 9 668–82

Messé M and Radenac M-H 2006 Seasonal variability of the surface chlorophyll in the western tropical Pacific from SeaWiFS data Deep Sea Res. 53 1581–600

Misra R, Sérazin G, Meissner K J and Sen Gupta A 2021 Projected changes to Australian marine heatwaves Geophys. Res. Lett. 48 e2020GL091123

Oliver E C J et al 2018 Longer and more frequent marine heatwaves over the past century Nat. Commun. 9 1324

Oliver E C J et al 2019 Projected marine heatwaves in the 21st century and the potential for ecological impact Front. Mar. Sci. 6 734

Oliver E C J, Benthuysen J A, Bindoff N L, Hobday A J, Holbrook N J, Mundy C N and Perkins-Kirkpatrick S E 2017 The unprecedented 2015/16 Tasman Sea marine heatwave Nat. Commun. 8 16101

Pearce A F and Feng M 2013 The rise and fall of the "marine heat wave" off Western Australia during the summer of 2010/2011 J. Mar. Syst. 111–112 139–56

Roemhildt M and Gilson J 2009 The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program Prog. Oceanogr. 82 81–100

Scannell H A, Johnson G C, Thompson L, Lyman J M and Riser S C 2020 Subsurface evolution and persistence of marine heatwaves in the Northeast Pacific Geophys. Res. Lett. 47 e2020GL090548

Scannell H A, Pershing A J, Alexander M A, Thomas A C and Mills K E 2016 Frequency of marine heatwaves in the North Atlantic and North Pacific since 1950 Geophys. Res. Lett. 43 2069–76

Schaeffer A and Roughan M 2017 Subsurface intensification of marine heatwaves off southeastern Australia: the role of stratification and local winds Geophys. Res. Lett. 44 5025–33

Stewart R 2008 Introduction To Physical Oceanography (Texas: Department of Oceanography, Texas A & M University) p 345

Viglione G 2021 How heatwaves ravage the seas Nature 593 26–28

Vu X, Lowe R J, Ivey G N, Jones N L and Zhang Z 2018 Contrasting heat budget dynamics during two La Niña marine heat wave events along Northwestern Australia J. Geophys. Res. 123 1563–81

Zhang X, Feng M, Hendon H H, Hobday A J and Zinke J 2017 Opposite polarities of ENSO drive distinct patterns of coral bleaching potentials in the southeast Indian Ocean Sci. Rep. 7 2443