Open Access Article

Characteristics of Marine Heatwaves off West Sumatra Derived from High-Resolution Satellite Data

Mochamad Furqon Azis Ismail*

Research Center for Oceanography, Indonesian Institute of Sciences, Jakarta 13340, Indonesia

Abstract: Marine heatwaves (MHWs) are high sea surface temperature (SST) periods that last for several days or weeks. They have been observed worldwide in recent decades, and they are predicted to become more frequent and intense as the global ocean's SST rises. In this paper, high-resolution satellite SST is used to investigate the characteristics of MHWs off the coast of West Sumatra. This shelf region is bordered in the west by the equatorial eastern Indian Ocean. The aim is to identify the occurrence of MHWs and quantify its metrics over the period 1982-2018. The results demonstrate that MHWs occur at least 3 to 4 times per year for the offshore and nearshore sites of West Sumatra, respectively. Moreover, the nearshore MHWs having higher proportions in terms of duration, intensity, and the number of days than the offshore MHWs. The variations in duration, frequency, intensity, and the number of days were likely caused by an imbalance in local near-surface warming and physical oceanic processes offshore. The years with the severe MHW days were those following the strong El Niño events in 1998 and 2016. This study is a significant first step in the research of MHWs in Indonesian shelf water.

Keywords: marine heatwaves, sea surface temperature, satellite, West Sumatra, Eastern Indian Ocean.

基于高分辨率卫星数据的西苏门答腊海洋热浪特征

摘要： 海洋热浪是持续数天或数周的高海面温度时期。近几十年来，它们在世界范围内被观察到，随着全球海洋海面温度的升高，预计它们会变得更加频繁和强烈。本文利用高分辨率卫星海面温度研究了西苏门答腊近海海洋热浪的特征。该陆架区西部与赤道东印度洋接壤。目的是确定海洋热浪的发生并量化1982-2018年期间的指标。结果表明，在西苏门答腊的近海和近海地点，海洋热浪每年至少发生 3 到4次。此外，近岸海洋热浪在持续时间、强度和天数方面比近海海洋热浪具有更高的比例。持续时间、频率、强度和天数的变化可能是由局部近地表变暖和近海物理海洋过程的不平衡引起的。发生严重海洋热浪的年份是1998年和2016年强厄尔尼诺事件之后的年份。这项研究是印度尼西亚大陆架水域海洋热浪研究的重要第一步。

关键词： 海洋热浪、海面温度、卫星、西苏门答腊、东印度洋.

---

1. Introduction

Over the last half-century, the global sea surface temperature (SST) has risen significantly [1]. The major cause is likely to be rising anthropogenic aerosols and glasshouse gases [2]. These rapid ocean warming events have become a global concern due to their devastating impact on marine biodiversity and ecosystem worldwide and the fisheries of the region [3], [4]. The tropical Indian Ocean has the most severe warming signal around the global oceans [5], [6]. One of the recent documented extremely warm SST anomalies (SSTa) in the tropical eastern Indian Ocean was observed during the austral summer of 2015-2016

[7], which is the warmest on record for global SST in NOAA's 137-year sequence [8].

The unprecedented extreme marine warming genesis in the eastern Indian Ocean is linked to the 2015-2016 El Niño events in the tropical Pacific Ocean [7], [9]. Following the El Niño depletion, a positive Indian Ocean Dipole Mode (IOD) formed during austral autumn and winter of 2016 [7], [9], [10]. The interaction of physical oceanic processes offshore and asymmetry in locally near-surface warming are important factors in extending extreme warming events [11], [7]. Previous research by [12] found that asymmetry in ocean warming between the two hemispheres between 2005 and 2015 likely contributed to extreme marine warming in the Southern Indian Ocean.

The large patch of warm SST rose to 3°C above the climatological averages (Fig. 1) in most parts of the eastern Indian Ocean. This event caused coral bleaching and mortality off the coasts of West Sumatra [13] and Western Australia [14]. These bleaching reports occurred during one of the extensive global-scale bleaching events in history, which started in 2014 [1].
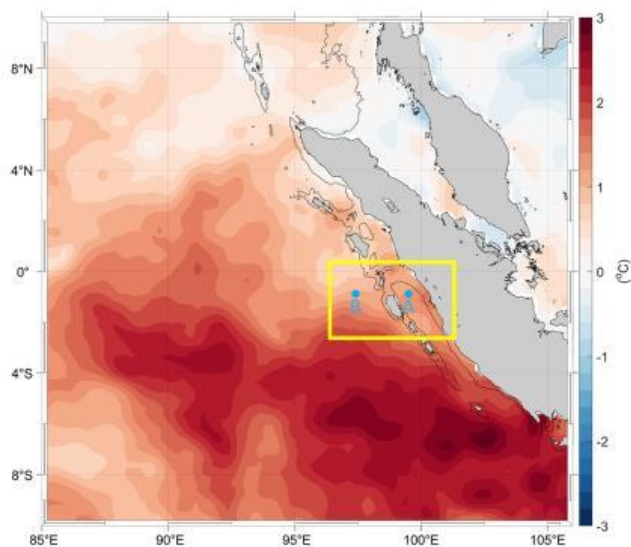

Fig. 1 Map of the equatorial eastern Indian Ocean showing the SSTa on 2 January 2016 The yellow rectangle represents the study area. Points A and B denote the nearshore and offshore locations, respectively, used to quantify the MHWs metric in Fig. 2. The thin black lines depict 500 m isobaths

The sustained positive anomalies in SST that last for days to months are referred to as marine heatwaves (MHWs) [15], [16]. MHWs are characterized by their length, frequency, strength, and spatial extent following atmospheric accords [15], [16], [17]. [17] coined the term "marine heatwave" to describe a series of widespread, persistent, and extremely warm SST events along Western Australia's coast in 2011 [18]. The MHWs off Western Australia in 2011 sparked a global initiative to characterize marine heatwaves and comprehend their statistical properties [19]. There is mounting evidence that MHWs can occur anywhere

and at any time in the ocean as a result of global warming [20], [21], [22]. In addition, MHWs are expected to increase their intensity, frequency, length, and spatial extent throughout the twenty-first century [21], [22], [23]. Strong El Niño years (i.e., 1982-1983, 1997-1998, and 2015-2016) appear to enhance the physical characteristics of MHWs in the global ocean [7], [10], [23].

MHWs have been identified and studied in various parts of the world ocean. However, no study focuses on the area off the coast of West Sumatra, where Mentawai indigenous people and an ecosystem with remarkable conservation value are located [24]. In the early 1980s, the Mentawai Islands were designated as a Man and Biosphere Reserve to preserve the region's unique wildlife and human culture [24]. Therefore, this study aims to assess the characteristics of MHWs and quantify their metrics off the coast of West Sumatra. This region is one of the important biosphere reserve regions in Indonesia. SST data from January 1983 to December 2018 were analyzed to assess the climatology required to detect MHWs. We document that the severe MHW days took place following strong El Niño events in 1998 and 2016. This paper is the first study that has identified and quantified MHWs in Indonesian shelf waters.

2. Data and Methods

2.1. Satellite Data

The SST provides information on processes occurring at the ocean-atmosphere boundary layer. The high-resolution SST for January to December 2018 within the rectangular region from 96°E to 102°E and 0.5°N to 3.25°S (Fig. 1) were utilized to identify MHWs events. The SST data were obtained from the Met Office as part of the Operational Sea Surface Temperature and sea-ice Analysis (OSTIA) system [25], [26]. The OSTIA products are based on a multi-scale optimal interpolation developed for implementations in numerical weather prediction and ocean forecasting systems [25]. The OSTIA utilizes multiple satellite data, including the Group for High-resolution SST (GHRSST), the in-situ SST data available over the Global Telecommunication System, and EUMETSAT Ocean and Sea Ice Satellite Application Facility [25]. The remotely-sensed OSTIA SST data are distributed by the European Union Copernicus Marine Environment Monitoring Service (CMEMS) and can be accessed at [27]. The data are cloud-free with a horizontal spatial grid resolution of about 5 km x 5 km every day until 31 December 2018.

2.2. Detection of Marine Heatwaves

The SST is analyzed using the hierarchy metrics approach from [15], [16] to detect and quantify the MHW metrics in the study region. MHWs are described as a discrete period during which daily SST

exceeds a specified threshold for at least five days in a row [15]. The 90th percentile of seasonally changing mean climatology based on a 30-year historical reference period is used as the threshold [15], [16]. The nearshore location along the Mentawai Basin has been chosen at 1.32°S and 99.62°E, while the deeper offshore waters have been chosen at 1.32°S and 97.52°E. These two stations were used to assess the physical characteristics of MHW in the study region and measure statistical occurrences (see Table 1). Following the approach by [16], the MHWs are categorized into moderate, strong, severe, and extreme events based on which temperatures surpass the local climatology.

3. Result and Discussion

3.1. Characteristics of MHWs

The daily SST and the corresponding MHW events from January 1982 to December 2018 for each nearshore and offshore site of the West Sumatra's shelf waters are shown in Fig. 2, respectively. At similar times in 1995 and 1998, the temporal SST patterns show the occurrence of extremely low temperatures below 26°C at both nearshore (Fig. 2a) and offshore (Fig. 2b) sites. These events correspond with the co-occurrence of medium to strong El Niño and the positive IOD [7]. The analysis reveals that severe MHWs events were discovered in 1995, 1998, and 2016. In 1995, severe MHWs events were identified in May and July at the offshore site. The duration of these two events was approximately 2 and 1 days (Fig. 2d), respectively. In contrast, the severe MHWs events in 1998 and 2016 were only occurred at the nearshore site.

In January 1998, the severe MHWs event took place for about 5 days, while the severe MHWs event in April 1998 lasted just about 3 days (Fig. 2e). The severe MHWs event in January and February 2016 lasted around 6 and 3 days, respectively. Apart from the nearshore severe MHWs, the offshore MHWs events in 1998 and 2016 were only categorized as moderate and strong events (Fig. 2f and 2h). Compared to previous MHW events in Australia's shelf waters, our 2016 MHW results were consistent with the previous MHW studies by [7] and [10]. Furthermore, [7] indicates that the widespread intense and extensive MHWs in 1998 and 2016 were likely driven by changes in the atmospheric conditions linked to the strong El Niño.
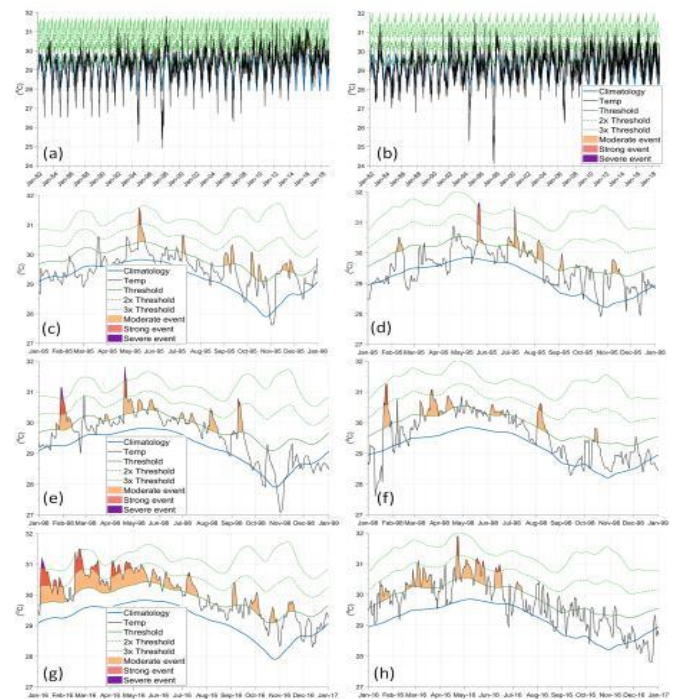

Fig. 2 The daily SST and the corresponding MHW events for each nearshore (left column) and offshore (right column) site off the coast of West Sumatra. The bottom three rows denote the snapshot of severe MHW events in 1995 (c, d), 1998 (e, f), and 2016 (g, h), respectively

The annual mean of MHW metrics for the nearshore and offshore sites off the coast of West Sumatra are summarized in Table 1. From January 1982 to December 2018, about 139 and 126 MHW events occurred in the nearshore and offshore sites, respectively. On average, there are about 4 (3) MHW events in the nearshore (offshore) each year from 1982 to 2018. The annual mean of nearshore MHW duration is 12.65 days, higher than the offshore duration of 9.37 days. The MHWs take place at least about 3.76 events per year in the nearshore and about 3.41 events per year offshore (Table 1).

The annual mean of maximum intensity somewhat similar between nearshore and offshore, though its cumulative intensity varies. The maximum nearshore intensity is 1.39°C compare to 1.38°C offshore. The annual mean cumulative intensity of MHW is 13.46°C on the nearshore and 10.02°C on the offshore. The annual mean count of days per year is 47.54 and 31.89 for the nearshore and offshore. Generally, the metrics of MHW off West Sumatra are somewhat comparable to those found in the eastern Indian ocean of the Indo-Australian basin by [7] and off eastern Tasmania by [10].

Table 1 Annual mean and decadal trends of MHW metrics for the nearshore and offshore sites off the coast of West Sumatra

Location	Duration (days)	Frequency	Maximum intensity (°C)	Cumulative intensity (°C)	Count
Annual Mean					
Nearshore	12.65	3.76	1.39	13.46	47.54
Offshore	9.37	3.41	1.38	10.02	31.89
Trend (per decade)					

Nearshore	0.29	0.16	0.01	0.38	3.48
Offshore	0.001	0.14	-0.004	-0.03	1.49

Fig. 3 shows the spatial metrics of MHWs from January 1982 to December 2018. It is observed that pixels with high annual mean values of duration, frequency, and counts of days occur within the shallower shelf region of the Mentawai Basin waters. The Mentawai Basin's shallower mixed layer depth seems to have intensified these MHW metrics. [7] revealed that the shallowed mixed layer depth would increase the near-surface warming temperature. In general, the annual mean of intensity higher than 1ºC occurred almost all over the nearshore and offshore of the study region off West Sumatra, though the most robust intensity observed well away from the coast in the open ocean (Fig. 3c). The spatial discrepancy in MHWs duration, intensity, and count of days is likely attributed to offshore physical oceanic processes [12] and the asymmetry in the local- and regional scales of near-surface warming [7].
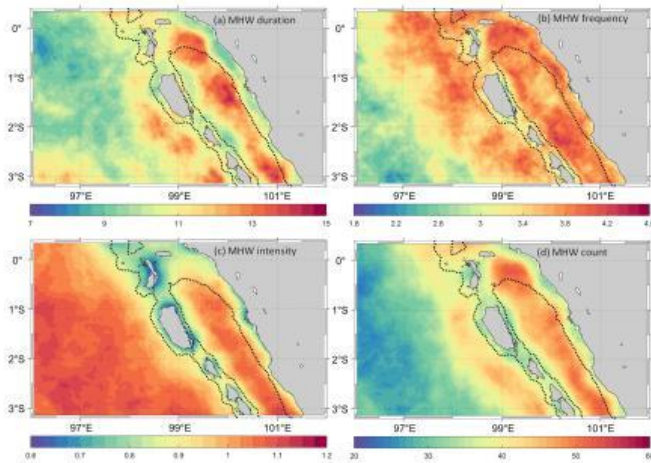

Fig. 3 The spatial distribution of MHW events showing the annual mean of duration (a), frequency (b), intensity (c), and number of days (d) along the shelf waters of West Sumatra

3.2. Trend of MHWs

The decadal trends of MHW metrics from two representative sites of the nearshore and offshore off the coast of West Sumatra are given in Table 1. The decadal trends of MHWs duration, frequency, maximum intensity, cumulative intensity, and count of days display a positive trend per decade at the nearshore location. In contrast to the nearshore, the decadal trends at offshore locations show a positive trend for the duration, frequency, and count. At the same time, they display a negative trend for maximum and cumulative intensity (Table 1). The trend of MHWs duration experienced an increase of 0.29 days per decade at the nearshore and 0.001 days per decade offshore. The decadal trend of frequency exhibits a slightly similar rate of change per decade, around 0.16 and 0.14 at the nearshore and offshore, respectively.

The decadal trend of MHWs maximum and cumulative intensity for the nearshore (offshore) site is 0.01ºC (-0.004ºC) and 0.38ºC (-0.03ºC), respectively. The count of days at the nearshore increased faster than offshore by around 50%. The decadal trends of the number of MHW days for the nearshore are about 3.48 days compare to about 1.49 days for the offshore (Table 1). The decadal trend of MHW metrics in this study is comparable with the long-term MHW study by [10] across the shelf waters off Tasmania. The decadal trend of MHWs spatial metrics distribution across the shelf waters of West Sumatra is shown in Fig. 4. The spatial patterns of MHWs' decadal trends shown in Fig. 4 were consistent with the spatial pattern of the annual mean of MHWs displayed in Fig. 3. The Mentawai Basin waters had the highest trends per decade of the MHWs metrics (i.e., duration, frequency, intensity, number of days). However, a negative trend in MHW duration and intensity was observed primarily in the offshore waters west of 98º East.
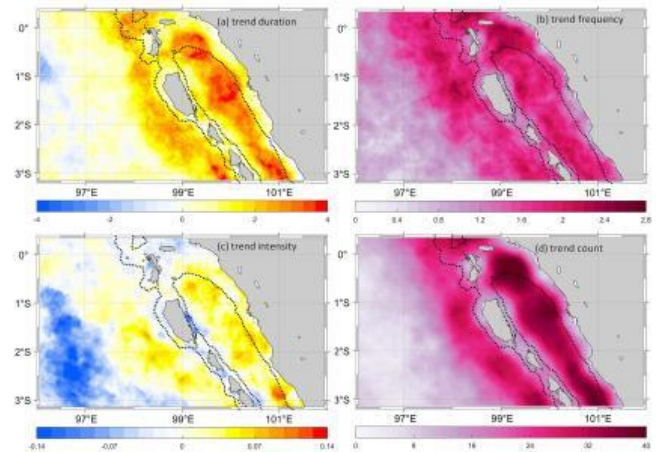

Fig. 4 The spatial distribution of MHW events showing the decadal trends of duration (a), frequency (b), intensity (c), and number of days (d) along the shelf waters of West Sumatra

4. Conclusion

The study for assessing MHW characteristics in the equatorial eastern Indian Ocean off the coast of West Sumatra is presented in this paper. The results of MHW detection using satellite SST data over a 37-year duration show a range of MHW events across the study area. Between January 1982 and December 2018, there were 139 and 126 MHW events in nearshore and offshore sites. There are approximately 4 (3) MHW events in the nearshore (offshore) per year. The annual mean state of MHWs indicates a longer duration, more robust cumulative intensity, and a greater number of days in the nearshore than in the offshore, despite a nearly identical frequency and maximum intensity between the two.

The analysis shows that MHWs detected nearshore and offshore exhibited an increasing trend in durations, frequencies, and the count of days. In contrast, the maximum intensity and cumulative intensity in the offshore region showed a slight decline. Spatially, the shallower shelf region of the Mentawai Basin waters had the highest annual mean and long-term trend of MHWs. This finding was most likely caused by a difference in the local near-surface warming and physical oceanic processes offshore. Following the discovery of MHWs off the coast of West Sumatra, a follow-up study should investigate the ocean-atmosphere interaction at local and regional scales and the coupling of the processes, which was a major driver of MHW worldwide. This study was a first step in the investigation of MHWs in Indonesian shelf waters.

Acknowledgment

References

[1] HERON S. F., MAYNARD J. A., VAN HOOIDONK R., & EAKIN C. M. Warming Trends and Bleaching Stress of the World's Coral Reefs 1985–2012. *Scientific Reports*, 2016, 6(1): 1-14. https://doi.org/10.1038/srep38402

[2] DONG L., ZHOU T., and WU B. Indian Ocean Warming during 1958-2004 Simulated by a Climate System Model and its Mechanism. *Climate Dynamics*, 2014. 42: 203–217. https://doi.org/10.1007/s00382-013-1722-z

[3] CAVOLE L. M., DEMKO A. M., DINER R. E., GIDDINGS A., KOESTER I., PAGNIELLO C. M. L. S., PAULSEN M.-L., RAMIREZ-VALDEZ A., SCHWENCK S. M., YEN N. K., ZILL M. E., and FRANKS P. J. S. Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future. *Oceanography*, 2016, 29(2): 273–285. https://doi.org/10.5670/oceanog.2016.32

[4] MILLS K. E., PERSHING A. J., BROWN C. J., CHEN Y., CHIANG F.-S., HOLLAND D. S., LEHUTA S., NYE J. A., SUN J. C., THOMAS A. C., and WAHLE R. A. Fisheries Management in a Changing Climate: Lessons from the 2012 Ocean Heat Wave in the Northwest Atlantic. *Oceanography*, 2013, 26(2): 191–195. https://doi.org/10.5670/oceanog.2013.27

[5] KIM S. T., YU J. Y., and LU M. M. The Distinct Behaviors of Pacific and Indian Ocean Warm Pool Properties on Seasonal and Interannual Time Scales. *Journal of Geophysical Research Atmospheres*, 2012, 117(5): 1–12. https://doi.org/10.1029/2011JD016557

[6] ROXY M. K., RITIKA K., TERRAY. P., and MASSON S. The Curious Case of Indian Ocean Warming. *Journal of Climate*, 2014, 27(22): 8501–8509. https://doi.org/10.1175/JCLI-D-14-00471.1

[7] BENTHUYSEN J. A., OLIVER E. C. J., FENG M., and MARSHALL A. G. Extreme Marine Warming Across Tropical Australia During Austral Summer 2015–2016. *Journal of Geophysical Research: Oceans*, 2018, 123(2): 1301–1326. https://doi.org/10.1002/2017JC013326

[8] HARTFIELD G., BLUNDEN J., and ARNDT D. S. State of the Climate in 2017. *Bulletin of the American Meteorological Society*, 2018, 99(8): 1-310. https://doi.org/10.1175/2018BAMSStateoftheClimate.1

[9] OLIVER E. C. J., DONAT M. G., BURROWS M. T., MOORE P. J., SMALE D. A., ALEXANDER L. V., BENTHUYSEN J. A., FENG M., SEN GUPTA A., HOBDAY A. J., HOLBROOK N. J., PERKINS-KIRKPATRICK S. E., SCANNELL H. A., STRAUB S. C., and WERNBERG T. Longer and More Frequent Marine Heatwaves over the Past Century. *Nature Communications*, 2018, 9(1): 1–12. https://doi.org/10.1038/s41467-018-03732-9

[10] OLIVER E. C. J., BENTHUYSEN J. A., BINDOFF N. L, HOBDAY A. J., HOLBROOK N. J., MUNDY C. N., and PERKINS-KIRKPATRICK S. E. The Unprecedented 2015/16 Tasman Sea Marine Heatwave. *Nature Communications*, 2017, 8(1): 1-12. https://doi.org/10.1038/ncomms16101

[11] SCHLEGEL R. W., OLIVER E. C. J., PERKINS-KIRKPATRICK S., KRUGER A., and SMIT A. J. Predominant Atmospheric and Oceanic Patterns during Coastal Marine Heatwaves. *Frontiers in Marine Science*, 2017, 4(323): 1–15. https://doi.org/10.3389/fmars.2017.00323

[12] RATHORE S., BINDOFF N. L., PHILLIPS H. E., and FENG M. Recent Hemispheric Asymmetry in Global Ocean Warming Induced by Climate Change and Internal Variability. *Nature Communications*, 2020, 11(1): 1–8. https://doi.org/10.1038/s41467-020-15754-3

[13] ELVAN AMPOU E., JOHAN O., MENKES C. E., NIÑO F., BIROL F., OUILLON S., and ANDRÉFOUËT S. Coral Mortality Induced by the 2015-2016 El-Niño in Indonesia: The Effect of Rapid Sea Level Fall. *Biogeosciences*, 2017, 14(4): 817–826. https://doi.org/10.5194/bg-14-817-2017

[14] HUGHES T. P., KERRY J. T., ÁLVAREZ-NORIEGA M., ÁLVAREZ-ROMERO J. G., ANDERSON K. D., BAIRD A. H., BABCOCK R. C., BEGER M., BELLWOOD D. R., BERKELMANS R., BRIDGE T. C., BUTLER I. R., BYRNE M., CANTIN N. E., COMEAU S., CONNOLLY S. R., CUMMING G. S., DALTON S. J., DIAZ-PULIDO G., EAKIN C. M., FIGUEIRA W. F., GILMOUR J. P., HARRISON H. B., HERON S. F., HOEY A. S., HOBBS J.-P. A., HOOGENBOOM M. O., KENNEDY E. V., KUO C.-Y., LOUGH J. M., LOWE R. J., LIU G., MCCULLOCH M. T., MALCOLM H. A., MCWILLIAM M. J., PANDOLFI J. M., PEARS R. J., PRATCHETT M. S., SCHOEPF V., SIMPSON T., SKIRVING W. J., SOMMER B., TORDA G., WACHENFELD D. R., WILLIS B. L., and WILSON S. K. Global Warming and Recurrent Mass Bleaching of Corals. *Nature*, 2017, 543(7645): 373–377. https://doi.org/10.1038/nature21707

[15] HOBDAY A. J., ALEXANDER L. V, PERKINS S. E., SMALE D. A., STRAUB S. C., OLIVER E. C. J., BENTHUYSEN J. A., BURROWS M. T., DONAT M. G., FENG M., HOLBROOK N. J., MOORE P. J., SCANNELL H. A., SEN GUPTA A., and WERNBERG. T. A Hierarchical Approach to Defining Marine Heatwaves. *Progress in Oceanography*, 2016, 141: 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

[16] HOBDAY A. J., OLIVER E. C. J., SEN GUPTA A. BENTHUYSEN J. A., BURROWS M. T., DONAT M. G., HOLBROOK N. J., MOORE P. J., THOMSEN M. S.,

WERNBERG T., and SMALE D. A. Categorizing and Naming Marine Heatwaves. *Oceanography*, 2018, 31(2): 162–173. http://dx.doi.org/10.5670/oceanog.2018.205

[17] PEARCE A. F., & FENG M. The Rise and Fall of the "Marine Heat Wave" off Western Australia during the Summer of 2010/2011. *Journal of Marine Systems*, 2013, 111: 139–156. https://doi.org/10.1016/j.jmarsys.2012.10.009

[18] HOLBROOK N. J., SEN GUPTA A., OLIVER E. C. J., HOBDAY A. J., BENTHUYSEN J. A., SCANNELL H. A., SMALE D. A., and WERNBERG T. Keeping Pace with Marine Heatwaves. *Nature Reviews Earth and Environment*, 2020 1(9): 482-493. https://doi.org/10.1038/s43017-020-0068-4

[19] PERSHING, A. J., MILLS, K. E., DAYTON, A. M., FRANKLIN B. S., KENNEDY B. T. Evidence for Adaptation from the 2016 Marine Heatwave in the Northwest Atlantic Ocean. *Oceanography*, 2018, 31(2): 152–161. https://doi.org/10.5670/oceanog.2018.213

[20] OLIVER E. C. J. Mean Warming not Variability Drives Marine Heatwave Trends. *Climate Dynamics*, 2019, 53(4): 1653–1659. https://doi.org/10.1007/s00382-019-04707-2

[21] FRÖLICHER T. L., FISCHER E. M., and GRUBER N. Marine Heatwaves under Global Warming. *Nature*, 2018, 560(7718): 360–364. https://doi.org/10.1038/s41586-018-0383-9

[22] OLIVER E, C. J., BURROWS M. T., and DONAT M. G. Projected Marine Heatwaves in the 21st Century and the Potential Ecological Impact. *Frontiers in Marine Science*, 2019, 6(734):1-12. https://doi.org/10.3389/fmars.2019.00734

[23] OLIVER E, C. J., BENTHUYSEN J. A., and DARMARAKI S. Marine Heatwaves. *The Annual Review of Marine Science*, 2021, 13: 20.1-20.30. https://doi.org/10.1146/annurev-marine-032720-095144

[24] CHOU L., TUAN V., and PHILREEFS Y. Status of Coral Reefs of the World. *GCRMN Report*. Australian Institute of Marine Science, Townsville, Australia, 2002: 123-152.

[25] DONLON C. J., MARTIN M., STARK J., ROBERT-JONES J., FIEDLER E., and WIMMER W. The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) System. *Remote Sensing of Environment*, 2012, 116: 140–158. https://doi.org/10.1016/j.rse.2010.10.017

[26] STARK J. D., DONLON C. J., MARTIN M. J., and MCCULLOCH M. E. OSTIA: An Operational, High Resolution, Real Time, Global Sea Surface Temperature Analysis System. *Institute of Electrical and Electronics Engineers Oceans Europe*, 2007: 1–4. https://doi.org/10.1109/OCEANSE.2007.4302251

[27] COPERNICUS. *Copernicus Marine Service.* http://marine.copernicus.eu/

参考文:

[1] HERON S. F., MAYNARD J. A., VAN HOOIDONK R., & EAKIN C. M. 1985-2012年世界珊瑚礁的变暖趋势和漂白压力。科学报告, 2016, 6(1): 1-14. https://doi.org/10.1038/srep38402

[2] DONG L., ZHOU T., 和 WU B. 1958-2004年印度洋变暖的气候系统模型及其机制模拟。气候动力学, 2014. 42: 203–217. https://doi.org/10.1007/s00382-013-1722-z

[3] CAVOLE L. M., DEMKO A. M., DINER R. E., GIDDINGS A., KOESTER I., PAGNIELLO C. M. L. S., PAULSEN M.-L., RAMIREZ-VALDEZ A., SCHWENCK S. M., YEN N. K., ZILL M. E., 和 FRANKS P. J. S. 2013-2015年东北太平洋暖水异常的生物影响：赢家、输家和未来。海洋学, 2016, 29(2): 273–285. https://doi.org/10.5670/oceanog.2016.32

[4] MILLS K. E., PERSHING A. J., BROWN C. J., CHEN Y., CHIANG F.-S., HOLLAND D. S., LEHUTA S., NYE J. A., SUN J. C., THOMAS A. C., 和 WAHLE R. A. 气候变化中的渔业管理：2012年西北大西洋海洋热浪的教训。海洋学, 2013, 26(2): 191–195. https://doi.org/10.5670/oceanog.2013.27

[5] KIM S. T., YU J. Y., 和 LU M. M. 太平洋和印度洋暖池特性在季节和年际时间尺度上的不同行为。地球物理研究大气杂志, 2012, 117(5): 1–12. https://doi.org/10.1029/2011JD016557

[6] ROXY M. K., RITIKA K., TERRAY. P., 和 MASSON S. 印度洋变暖的奇特案例。气候杂志, 2014, 27(22): 8501–8509. https://doi.org/10.1175/JCLI-D-14-00471.1

[7] BENTHUYSEN J. A., OLIVER E. C. J., FENG M., 和 MARSHALL A. G. 2015-2016年澳大利亚夏季期间热带澳大利亚的极端海洋变暖。地球物理研究杂志：海洋, 2018, 123(2): 1301–1326. https://doi.org/10.1002/2017JC013326

[8] HARTFIELD G., BLUNDEN J., 和 ARNDT D. S. 2017年气候状况。美国气象学会公报, 2018, 99(8): 1-310. https://doi.org/10.1175/2018BAMSStateoftheClimate.1

[9] OLIVER E. C. J., DONAT M. G., BURROWS M. T., MOORE P. J., SMALE D. A., ALEXANDER L. V., BENTHUYSEN J. A., FENG M., SEN GUPTA A., HOBDAY A. J., HOLBROOK N. J., PERKINS-KIRKPATRICK S. E., SCANNELL H. A., STRAUB S. C., 和 WERNBERG T. 过去一个世纪更长、更频繁的海洋热浪。自然通讯, 2018, 9(1): 1–12. https://doi.org/10.1038/s41467-018-03732-9

[10] OLIVER E. C. J., BENTHUYSEN J. A., BINDOFF N. L, HOBDAY A. J., HOLBROOK N. J., MUNDY C. N., 和 PERKINS-KIRKPATRICK S. E. 前所未有的 2015/16 塔斯曼海海洋热浪。自然通讯, 2017, 8(1): 1-12. https://doi.org/10.1038/ncomms16101

[11] SCHLEGEL R. W., OLIVER E. C. J., PERKINS-KIRKPATRICK S., KRUGER A., 和 SMIT A. J. 沿海海洋热浪期间的主要大气和海洋模式。海洋科学前沿, 2017, 4(323): 1–15. https://doi.org/10.3389/fmars.2017.00323

[12] RATHORE S., BINDOFF N. L., PHILLIPS H. E., 和 FENG M. 气候变化和内部变异引起的全球海洋变暖的近期半球不对称性。自然通讯, 2020, 11(1): 1–8. https://doi.org/10.1038/s41467-020-15754-3

[13] ELVAN AMPOU E., JOHAN O., MENKES C. E., NIÑO F., BIROL F., OUILLON S., 和 ANDRÉFOUËT S. 印度尼西亚 2015-2016年厄尔尼诺现象导致的珊瑚死亡：海平面快速下降的影响。生物地球科学, 2017, 14(4): 817–826. https://doi.org/10.5194/bg-14-817-2017

[14] HUGHES T. P., KERRY J. T., ÁLVAREZ-NORIEGA M., ÁLVAREZ-ROMERO J. G., ANDERSON K. D., BAIRD A. H., BABCOCK R. C., BEGER M., BELLWOOD D. R., BERKELMANS R., BRIDGE T. C., BUTLER I. R.,

BYRNE M., CANTIN N. E., COMEAU S., CONNOLLY S. R., CUMMING G. S., DALTON S. J., DIAZ-PULIDO G., EAKIN C. M., FIGUEIRA W. F., GILMOUR J. P., HARRISON H. B., HERON S. F., HOEY A. S., HOBBS J.-P. A., HOOGENBOOM M. O., KENNEDY E. V., KUO C.-Y., LOUGH J. M., LOWE R. J., LIU G., MCCULLOCH M. T., MALCOLM H. A., MCWILLIAM M. J., PANDOLFI J. M., PEARS R. J., PRATCHETT M. S., SCHOEPF V., SIMPSON T., SKIRVING W. J., SOMMER B., TORDA G., WACHENFELD D. R., WILLIS B. L., 和 WILSON S. K. 全球变暖和珊瑚反复大量漂白. 自然, 2017, 543(7645): 373–377. https://doi.org/10.1038/nature21707

[15] HOBDAY A. J., ALEXANDER L. V, PERKINS S. E., SMALE D. A., STRAUB S. C., OLIVER E. C. J., BENTHUYSEN J. A., BURROWS M. T., DONAT M. G., FENG M., HOLBROOK N. J., MOORE P. J., SCANNELL H. A., SEN GUPTA A., 和 WERNBERG. T. A定义海洋热浪的分层方法. 海洋学进展, 2016, 141: 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

[16] HOBDAY A. J., OLIVER E. C. J., SEN GUPTA A. BENTHUYSEN J. A., BURROWS M. T., DONAT M. G., HOLBROOK N. J., MOORE P. J., THOMSEN M. S., WERNBERG T., 和 SMALE D. A. 海洋热浪的分类和命名。海洋学, 2018, 31(2): 162–173. http://dx.doi.org/10.5670/oceanog.2018.205

[17] PEARCE A. F., & FENG M. 2010/2011 年夏季西澳大利亚海域"海洋热浪"的兴衰。海洋系统杂志, 2013, 111: 139–156. https://doi.org/10.1016/j.jmarsys.2012.10.009

[18] HOLBROOK N. J., SEN GUPTA A., OLIVER E. C. J., HOBDAY A. J., BENTHUYSEN J. A., SCANNELL H. A., SMALE D. A., 和 WERNBERG T. 与海洋热浪保持同步。自然评论地球与环境, 2020 1(9): 482-493. https://doi.org/10.1038/s43017-020-0068-4

[19] PERSHING, A. J., MILLS, K. E., DAYTON, A. M., FRANKLIN B. S., KENNEDY B. T. 2016 年西北大西洋海洋热浪的适应证据。海洋学, 2018, 31(2): 152–161. https://doi.org/10.5670/oceanog.2018.213

[20] OLIVER E. C. J. 平均变暖而不是变异驱动海洋热浪趋势。气候动力学, 2019, 53(4): 1653–1659. https://doi.org/10.1007/s00382-019-04707-2

[21] FRÖLICHER T. L., FISCHER E. M., 和 GRUBER N. 全球变暖下的海洋热浪。自然, 2018, 560(7718): 360–364. https://doi.org/10.1038/s41586-018-0383-9

[22] OLIVER E, C. J., BURROWS M. T., 和 DONAT M. G. 21 世纪预计的海洋热浪和潜在的生态影响。海洋科学前沿, 2019, 6(734):1-12. https://doi.org/10.3389/fmars.2019.00734

[23] OLIVER E, C. J., BENTHUYSEN J. A., 和 DARMARAKI S. 海洋热浪。海洋科学年度回顾, 2021, 13: 20.1-20.30. https://doi.org/10.1146/annurev-marine-032720-095144

[24] CHOU L., TUAN V., 和 PHILREEFS Y. 世界珊瑚礁状况。全球珊瑚礁监测网络报告。澳大利亚海洋科学研究所，澳大利亚汤斯维尔, 2002: 123-152.

[25] DONLON C. J., MARTIN M., STARK J., ROBERT-JONES J., FIEDLER E., 和 WIMMER W. 操作海面温度和海冰分析系统。环境遥感, 2012, 116: 140–158. https://doi.org/10.1016/j.rse.2010.10.017

[26] STARK J. D., DONLON C. J., MARTIN M. J., 和 MCCULLOCH M. E. 一种可操作的高分辨率实时全球海面温度分析系统。欧洲海洋电气和电子工程师协会, 2007: 1–4. https://doi.org/10.1109/OCEANSE.2007.4302251

[27] 哥白尼. 哥白尼海事处. http://marine.copernicus.eu/