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Exploring Multi-decadal Time Series of Temperature Extremes in Australian Coastal Waters

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Abstract.

The intensity and frequency of extreme ocean temperature events, such as Marine Heatwaves (MHWs) and Marine cold-spells (MCSs), are expected to change as our oceans warm. Little is known about marine extremes in Australian coastal waters, particularly below the surface. Here we introduce a multi-decadal observational record of extreme ocean temperature events starting in the 1940s/50s between the surface and the bottom (50-100m) at 4 coastal sites around Australia; the Australian Multi-decadal Ocean Time Series EXTreme (AMDOT-EXT) data product. The data products include indices indicating the timing of extreme warm and cold temperature events, their intensity, and the corresponding temperature time series and climatology thresholds. We include MHWs, MCSs and shorter duration heat spikes and cold spikes. For MHWs and MCSs, which are defined as anomalies above the seasonally-varying 90th percentile lasting more than 5 days, we also provide further event information, such as their category, and onset and decline rates. Using these multi-decadal data products we show the most intense and longest extreme temperature events at these sites, which have occurred below the surface. These data records highlight the value of long-term full water column ocean data for the identification of extreme temperature events below the surface.

1 Introduction

Long-term ocean temperature records have become extremely valuable as the oceans warm due to anthropogenic climate change (Masson-Delmotte et al., 2021). This warming is expected to affect the characteristics of extreme temperature events such as Marine Heatwaves (MHWs) and Marine cold-spells (MCSs) (Oliver et al., 2018; Frölicher et al., 2018) (which are defined to last 5 days or more) and their shorter variants lasting less than 5 days referred to as heat spikes (HSs) and cold spikes (CSs) (Hobday et al., 2016; Schlegel et al., 2021). Extreme warm and cold water events are having an impact on marine ecosystems, including coral bleaching (Zapata et al., 2011; Hughes et al., 2017), mass mortality of organisms, and shifts in the distribution of marine species (Woodhead, 1964; Vergés et al., 2014; Firth et al., 2015; Wernberg et al., 2016; Smale et al., 2019). The health of a marine ecosystem influences the amount of life that it can sustain, and thus MHWs and MCSs can affect fisheries and the blue economy (Smith et al., 2021). Globally, MHWs are expected to become more intense, more frequent,

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and longer-lasting as a result of climate change (Oliver et al., 2018; Frölicher et al., 2018), while the opposite is expected for MCSs (Schlegel et al., 2021).

Due to data availability in space and time, many MHW and MCS studies are focused at the surface (e.g. Oliver et al. (2018); Frölicher et al. (2018); Schlegel et al. (2021); Kajtar et al. (2021); Marin et al. (2021)). Schaeffer and Roughan (2017) were amongst the first to analyse MHWs below the surface at a coastal location and showed that the sub-surface structure of MHWs is highly variable and different to the surface. Using in situ data from sites off Sydney, Australia, they showed that MHWs are often at a maximum intensity below the surface, illustrating the importance of understanding the complex structure of MHWs below the surface.

Some of the longest subsurface temperature measurements in the southern hemisphere are located at four Australian coastal sites (Roughan et al., 2022b). One site is located on the west coast, influenced by the Leeuwin Current system and three sites are located on the east coast influenced by the East Australian Current system (Roughan et al., 2022b). These temperature records began as early as the 1940s and continue to the present day. The long temperature records at these sites are valuable for investigating ocean temperature variability at many timescales (Hemming et al., 2020; Roughan et al., 2022b, a) over periods of more than 65 years. Additionally they are valuable for the investigation of marine extremes, such as the characteristics of HSs, CSs, MHWs and MCSs in more recent decades when daily observations became available (Schaeffer and Roughan, 2017).

Here we describe four unique data products; one for each of Australia's long term national reference stations described in Section 2, that can be used for analysing individual or multiple extreme temperature events, such as HSs, CSs, MHWs and MCSs, at depth levels throughout the water column. We provide event metrics, such as intensity and duration for example, useful for characterising MHWs and MCSs, and the temperatures and daily climatologies that were used for event detection. Further, we demonstrate the use of these data products by briefly exploring some of the extreme temperature events.

The oceanographic sites are detailed in Section 2, and the steps used to construct the data products are described in Section 3. Example usages of the data products are described in Section 4. MHW and MCS events are explored in Section 5, and a summary is provided in Section 6. User guides on how to load, slice, and cite the data products are provided in the Appendix.

2 Oceanographic Sites

We use ocean temperature data at four long term national reference stations located around Australia (Fig. 1). These sites have been occupied weekly to monthly since the 1940s/50s (Roughan et al., 2022b; Lynch et al., 2014). The west coast site is close to Rottnest Island (ROT, 32 °S) offshore from Perth, Western Australia in approximately 55 m of water. The southern site is close to Maria Island (MAI, 42.6 °S), Tasmania in approximately 90 m of water. An additional two east coast sites are located close to Sydney (PHA and PHB/PH100, 34.1 °S), New South Wales in approximately 50 and 100 m of water, respectively.

Ocean temperatures have been collected at multiple depths between the surface and the bottom at PHA, PHB/PH100, MAI and ROT since the 1940/50s. The binned depths (or optimal depths) chosen for the data products described here are shown in Fig. 2 and Tab. 1. Originally, sampling was boat-based and weekly to monthly. In 2009, the ROT, MAI, and PHB/PH100 sites were incorporated into the Integrated Marine Observing System (IMOS) National Reference Station network (Lynch

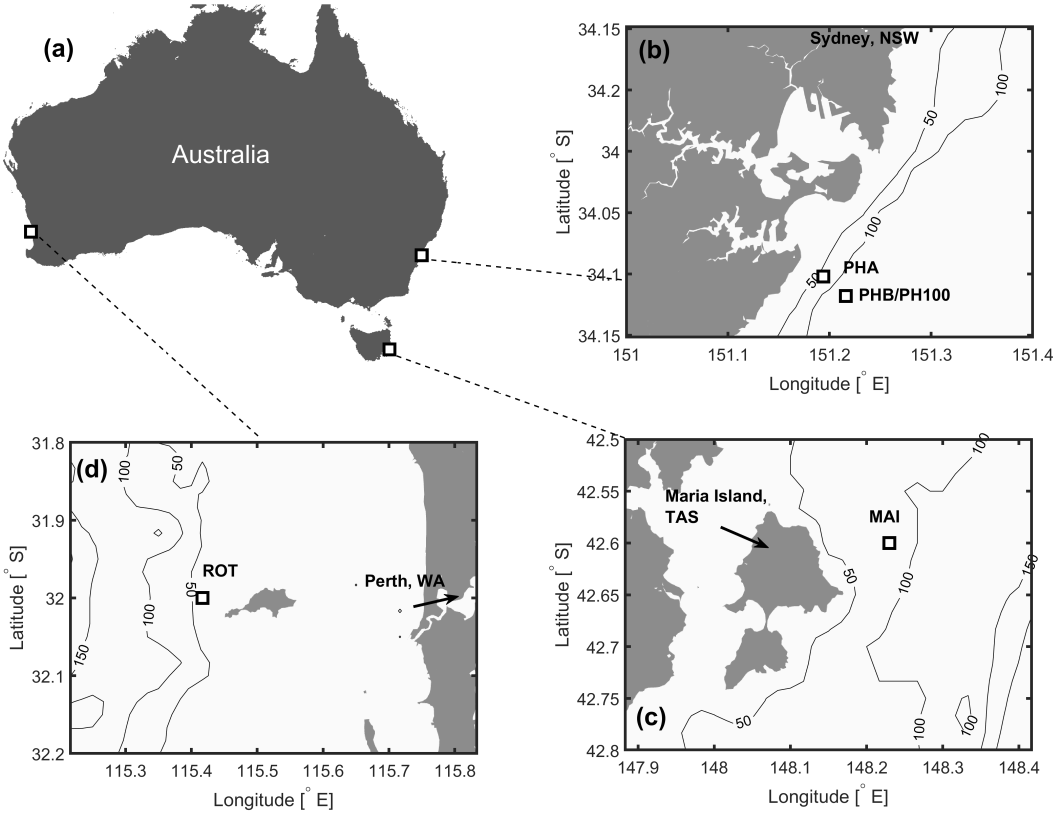

Figure 1. a) The 4 long-term oceanographic sampling sites at coastal locations around Australia. b) The Port Hacking stations (close to Sydney) at approximately 50 and 100 m depth (PHA and PHB/PH100). c) The Maria Island (Tasmania) station at approximately 90 m depth (MAI), and d) Rottnest Island (close to Perth, Western Australia) at approximately 55 m depth (ROT).

et al., 2014), and continuously-recording thermistor moorings have been deployed alongside monthly boat-based sampling. All moored data have continued to be collected through IMOS since 2009 at a sampling interval of 5-60 minutes at multiple depths through the water column. A full description of sites PHA, PHB/PH100, MAI, and ROT, their available data, and corresponding metadata is provided by Roughan et al. (2022b).

3 The Data Products

3.1 Multi-decadal Time Series Data Products

We build on recently-released aggregated multi-decadal ocean temperature time series products at the four oceanographic sites (Roughan et al., 2022b, a), which we refer to as the Australian Multi-Decadal Ocean Time series (AMDOT) data products. The AMDOT data products at PHA, PHB/PH100, MAI, and ROT include multiple-depth ship-based temperatures from bottle

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Site	Depth	# MHWs	# MCSs	# HSs	# CSs	Relative % Record Available	# Days Sampled
PHA		Time Period		Time Period			
		1942 - 2022		1942 - 2022			
	2	N/A	1	259	206	100	2100
	10	N/A	1	234	225	99.33	2086
	20	N/A	1	262	240	100.1	2102
	31	N/A	1	281	240	99	2079
	40	N/A	1	255	259	97.76	2053
	48	N/A	N/A	224	294	95.43	2004
PHB/PH100		Time Period		Time Period			
		1953 - 2022		2009 - 2022			
	2	29	8	284	231	100	3680
	22	43	10	373	268	129.73	4774
	40	43	13	372	295	146.52	5392
	50	49	8	366	298	157.88	5810
	59	41	6	294	218	126.71	4663
	75	40	7	302	200	133.75	4922
	98	47	12	271	251	140.54	5172
MAI		Time Period		Time Period			
		1944 - 2022		2008 - 2022			
	2	37	N/A	225	116	100	3138
	21	31	N/A	196	138	158.32	4968
ROT		Time Period		Time Period			
		1951 - 2022		2008 - 2022			
	2	41	3	287	131	100	3008
	29	55	6	309	213	172.71	5195
	38	38	4	276	207	120.81	3634
	47	28	17	190	305	122.17	3675

Table 1. The number of Marine Heatwaves (MHWs), Marine Cold-Spells (MCSs), Heat Spikes (HSs) and Cold Spikes (CSs) identified at sites Port Hacking A and B (PHA and PHB/PH100, respectively), Maria Island (MAI), and Rottnest Island (ROT) at multiple depths. The time periods used for event detection are shown, as well as the percentage of the record available over time relative to data available at 2 m depth, and the unique number of days sampled.

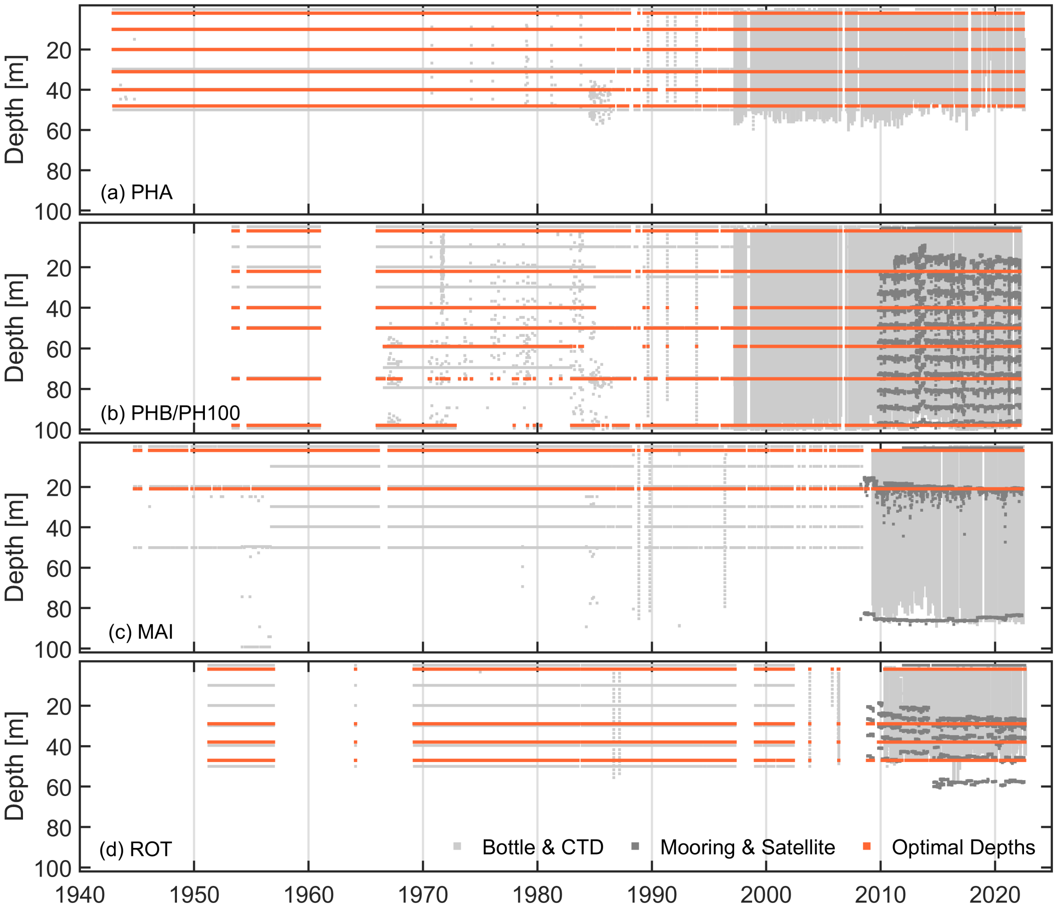

Figure 2. Depiction of available temperature data from bottle and CTD profiles (light grey), mooring and satellite (dark grey), and data binned at optimal depths (orange) for a) Port Hacking 50 m (PHA), b) Port Hacking 100 m (PHB/PH100), c) Maria Island (MAI), and d) Rottnest Island (ROT).

samples and electronic CTD sensor profiles. In addition, the aggregated AMDOT data products at sites PHB/PH100, MAI, and ROT contain multiple-depth moored temperature measurements. At sites PHB/PH100, MAI, and ROT at the surface (0.2 m) we include remote sensed sea surface temperature (SST) data from the IMOS Multi-sensor night-time L3S SST data composites (Griffin et al., 2017; Beggs et al., 2019). A full description of the data QC, and how these aggregated data products were created is provided by Roughan et al. (2022b).

To produce statistics through the water column, we use aggregated temperature data at optimal depth levels for identifying temperature extremes. These depth levels (listed in Table 1 for each site) were selected based on the vertical distribution of the data, similar to the method by Roughan et al. (2022b) to produce daily climatologies.

3.2 Deriving Extreme Temperature Event Statistics

The method of deriving extreme temperature event statistics is summarised in the flow chart in Fig. 3. We use the free Python MHW software package (Oliver, 2020) that uses the widely-adopted definitions (Hobday et al., 2016; Schlegel et al., 2021) for deriving MHWs and MCSs relative to a baseline climatology. However, instead of producing new daily climatologies using this MHW software package, we adapted the code to use the daily temperature climatologies produced by Roughan et al. (2022b) who use the method described by Hemming et al. (2020) as input for detecting extreme temperature events. These daily temperature climatologies (Roughan et al., 2022a) at the four coastal sites are derived from the aggregated temperatures used here, described in Sect. 3.1. The climatologies were created for each day of the year (01 Jan until 31 Dec, excluding 29 Feb during leap years) using temperature data within a time-centred moving window of 11 days. They have been further smoothed using a moving average window of 31 days, following the recommendation of Hobday et al. (2016). As the climatologies are provided at regular 10 m intervals between the shallowest and deepest depth, for the purpose of extreme temperature identification we interpolated the climatology statistics back to optimal depth levels. The reader is referred to Roughan et al. (2022b) for further details on how these daily climatologies were produced.

We identify HSs and CSs when temperatures exceed the 90^{th} and 10^{th} percentiles, respectively. When continuous daily fixed time series are available (after 2008 / 2009, see Table 1), we further consider MHWs and MCSs when the spikes last for 5 or more consecutive days (as per the widely adopted definition, where a MHW/MCS event needs to last more than 5 days). As suggested by Hobday et al. (2016), we ignore intermittent periods of 2 days or less when temperature extremes ease if followed by another MHW or MCS event. These intermittent periods are identified using daily-binned temperatures centred at 12:00 UTC, hence periods of 2 days or less are represented by one less anomalous daily-binned temperature. To increase data coverage, gaps of 2 days or less are filled using linear interpolation prior to detecting MHWs and MCSs using the MHW software package (Oliver, 2020).

The number of extreme temperature events that we detect depends on the site, depth, and data availability (Table 1). Between 190 and 373 HSs, and between 116 and 305 CSs were detected when considering all sites and depths. PHB/PH100 had the most MHWs (49) at a depth of 50 m, while ROT had the least number of MHWs (28) and most MCSs (17) at a similar depth of 47 m. No MCSs were detected at MAI, but 31 and 37 MHWs were detected at 21 m and 2 m, respectively. It was not possible to detect MHWs and MCSs at PHA (by definition) because we only have data that were collected weekly to monthly. However, one MCS was detected at multiple depths in late May 1944 when bottle samples were collected less than 5 days apart.

Because data availability over time is often non-uniform throughout the water column, we detect a different number of events with varying duration at multiple depths between the surface and the bottom. However, the variability over depth can also derive from the characteristics of the MHW dynamics. For example, during atmospherically-forced shallow MHWs we might expect there to be fewer days when temperatures exceed the 90^{th} percentile at depths below the mixed layer depth when compared with temperatures at the surface as identified by **?**.

https://doi.org/10.5194/essd-2023-252
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3.3 Data Products and Variables

We provide one data product at each of the four sites that contains: extreme temperature event information, the temperature data used, and climatology statistics. We refer to these data products as the Australian Multi-Decadal Ocean Time series EXTreme (AMDOT-EXT) data products. Two temperature variables are included in the AMDOT-EXT files; each temperature variable includes the daily-binned temperatures at each depth level (± 3 m bins), however one temperature variable has gaps of ≤ 2 days filled. This latter gap-filled temperature variable was used for detecting extreme temperature events. The AMDOT-EXT data products also include the corresponding time and depth (constant over time), and the climatological mean, 10^{th} and 90^{th} percentiles. Table 2 summarises the names of the variables contained in the AMDOT-EXT files. Event information (e.g. event number, duration, intensity etc.) is accessible using matrix variables with dimensions 'TIME' and 'DEPTH'. These matrices have the same dimensions as the temperature data and climatology parameters.

The individual MHW and MCS event numbers and the categories defined by Hobday et al. (2018) and Schlegel et al. (2021) are included in the AMDOT-EXT files, with their variable names listed in Table 2. The MHW/MCS category is presented as flags from one to four representing in order a 'Moderate','Strong','Severe' or 'Extreme' event as per the definition described by Hobday et al. (2018). Due to the inconsistencies in data sampling over depth and / or regional dynamics, an extreme temperature event may be detected at one depth, but not at another, or the length of an event may vary. Hence, the user should keep in mind that there may be inconsistent event numbers and timings of such events when analysing a particular event over depth.

The AMDOT-EXT data products contain an extreme temperature index variable ('TEMP_EXTREME_INDEX') that is useful for identifying the type of extreme temperature event: CS (flag 1), MCS (flag 2), HS (flag 11), and MHW (flag 12). For MHWs and MCSs we also provide the mean, maximum, and cumulative intensities, variance of intensity, and event onset and decline rates. These metrics are calculated using the MHW software package (Oliver, 2020) according to the methodology described by Hobday et al. (2016), detailed in their Table 2.

In addition to the AMDOT-EXT NetCDF data products, we provide CSV spreadsheets containing all of the MHW and MCS event information and characteristics at each of the four sites, with individual sheets for each depth level and event type. These CSV spreadsheets can be opened using Excel and are provided alongside the AMDOT-EXT data products (Hemming, 2023).

Please see Appendix Sect. A1 for details on how to cite the AMDOT-EXT data products and the CSV spreadsheets. Tutorials written in Python, MATLAB, and R demonstrating how to load and use these data products are available here:*OneDriveLink* and are described in Appendix sections A2 and A3.

3.4 Effects of Data Availability and Choice of Baseline

It is important to consider data availability and the daily climatologies that were used when detecting and discussing extreme temperature events. Subsurface measurements used at PHA, PHB/PH100, MAI, and ROT consist of water samples, electronic CTD sensor profiles, and at PHB/PH100, MAI, and ROT, mooring data. Data availability over time and in space can be seen in Fig. 2, with notable gaps at PHB/PH100 between the 1960s and 1990s, and at ROT during the 1950s, 1960s and 2000s.

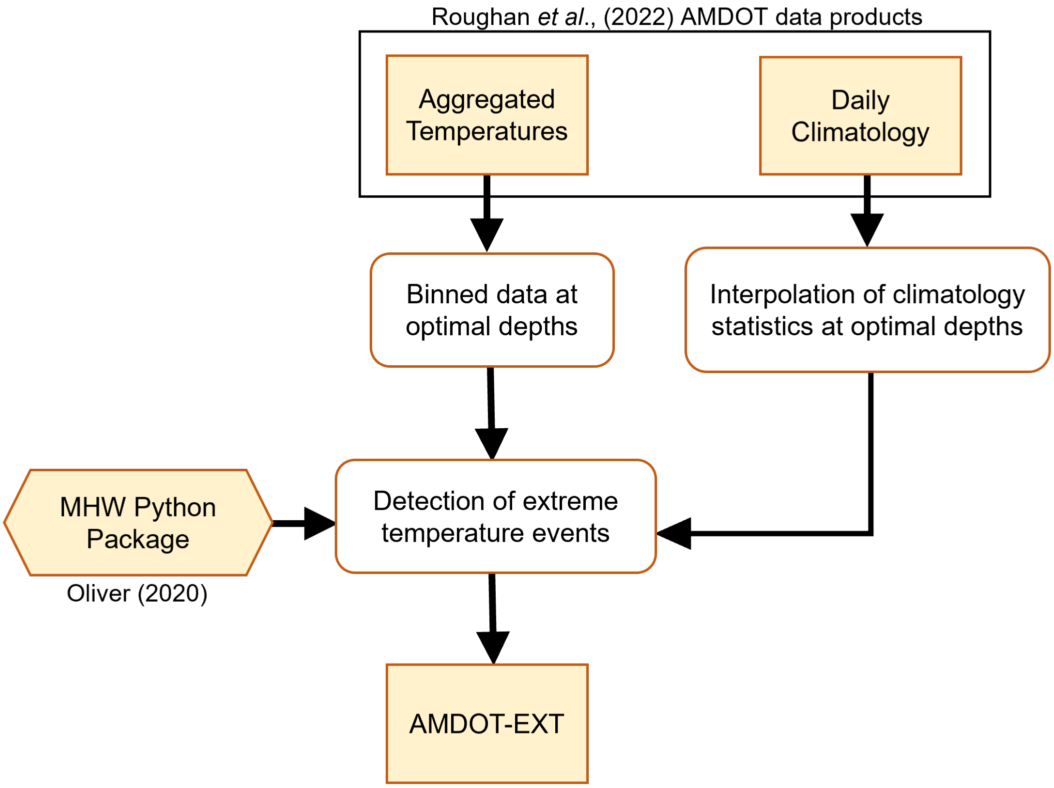

Figure 3. A flow chart showing the process of creating the Australian Multi Decadal Ocean Time series EXTreme (AMDOT-EXT) data products.

Temperature data availability over depth relative to the surface is also shown in Table 1. Additionally, the depths that samples were taken has changed with time, which presents a challenge when it comes to detecting extreme subsurface temperature events. We partially deal with this by filling gaps of ≤ 2 days. However, this filled data represents $< 2.5\%$ of the time period when considering, for example, surface data at all sites, and there are many instances of gaps > 2 days (Fig 2).

We use daily climatology thresholds incorporating temperature data over the entire record, which is between 70 and 80 years at the four sites. We acknowledge that using a climatology of approximately 30 years is recommended (Hobday et al., 2016; WMO, 2018), and is commonly used for MHW studies (e.g. Frölicher et al. (2018); Oliver et al. (2018); Elzahaby and Schaeffer (2019)). Schlegel et al. (2019) showed that using a climatology period > 30 years may effect MHW detection in a similar way as using a climatology period < 30 years, dependent on environmental multi-decadal variability. We use daily climatologies calculated using the entire temperature record at the long-term sites because of data availability challenges. We acknowledge that the number of extreme temperature events and their metrics may differ if a 30-year daily climatology was used instead, and will vary depending on which 30-year period is used.

4 Usage

The AMDOT-EXT data products described here can be used to analyse extreme ocean temperature events at the four sites, at / or below the surface and over time. For example, the 'MHW_EVENT_CAT' variable could be used to select 'Strong' MHWs at a particular depth and site. Applying this information to variables 'TIME' and 'MHW_INTENSITY_MEAN' would select the timings and mean intensities of 'Strong' MHWs. Further, exporting the data during such events might be useful for working with other data sets, for example phytoplankton data, for investigating the biological impact of MHWs. Code written in Python, MATLAB, and R demonstrating how to load and slice the AMDOT-EXT data products is available here:*OneDriveLink*, and further details are provided in Appendix sections A2 and A3.

5 Marine Heatwaves and Cold-spells

As shown in Table 1, MHWs and MCSs were detected at each site and depth that had continuous temperature data. In Figure 4 we explore the most intense events (based on cumulative intensity) at the long-term sites: PHB/PH100, MAI, and ROT. The most intense MHWs were at approximately 22 m depth at sites PHB/PH100 and MAI in 2015 and 2015/16, respectively (Fig 4a,b). At ROT the most intense MHW was at 38 m in 2011 (Fig 4c) at the time of the well-documented 'Ningaloo' La Niña MHW (Wernberg et al., 2013; Pearce and Feng, 2013). On average the intensity of the 2015 MHW at PHB/PH100 was 2.36 ° C above the mean climatology and lasted 50 days, while the MAI and ROT MHWs were on average 2.24 and 1.83 ° C above the mean climatology, and lasted 138 and 60 days, respectively.

The most intense MCSs were in 2010 and 2018 at PHB/PH100 and ROT, respectively (Fig 4d,e). At PHB/PH100 and ROT, these events were 3.00 and 1.86 ° C cooler than the mean climatology on average, and lasted 23 and 29 days, respectively. We detected no MCSs at MAI.

Information relating to the longest MHWs at sites PHB/PH100, MAI, and ROT is provided in Table 3. The longest MHW detected lasted 138 days at MAI (same as in Fig 4) between 28/12/2015 and 13/05/2016, while the longest MHWs at PHB/PH100 and ROT lasted 54 and 60 days, respectively. Their cumulative intensities were between 116 and 309 $^\circ$C day^{-1}. The longest MCSs lasted 24 and 34 days in 2010 and 2018/2019 at PHB/PH100 and ROT, respectively. The cumulative intensities at PHB/PH100 and ROT were -60.8 and -53.1 $^\circ$C day^{-1}, respectively. As mentioned above, no MCSs were detected at MAI. All of the longest MHWs and MCSs were classified as a 'Strong' event, and were at various depths below the surface.

6 Summary

Extreme temperature events have been identified and characterised at multiple depths between the surface and the bottom at four long-term oceanographic sites: PHA, PHB/PH100, MAI, and ROT using long-term ocean temperature records. We provide four data products - one data product per oceanographic site - including indices for identifying extreme temperature events, their characteristics, and corresponding temperature time series and daily climatology statistics. We refer to these new data products as the Australian Multi-Decadal Ocean Time series EXTreme (AMDOT-EXT) data products.

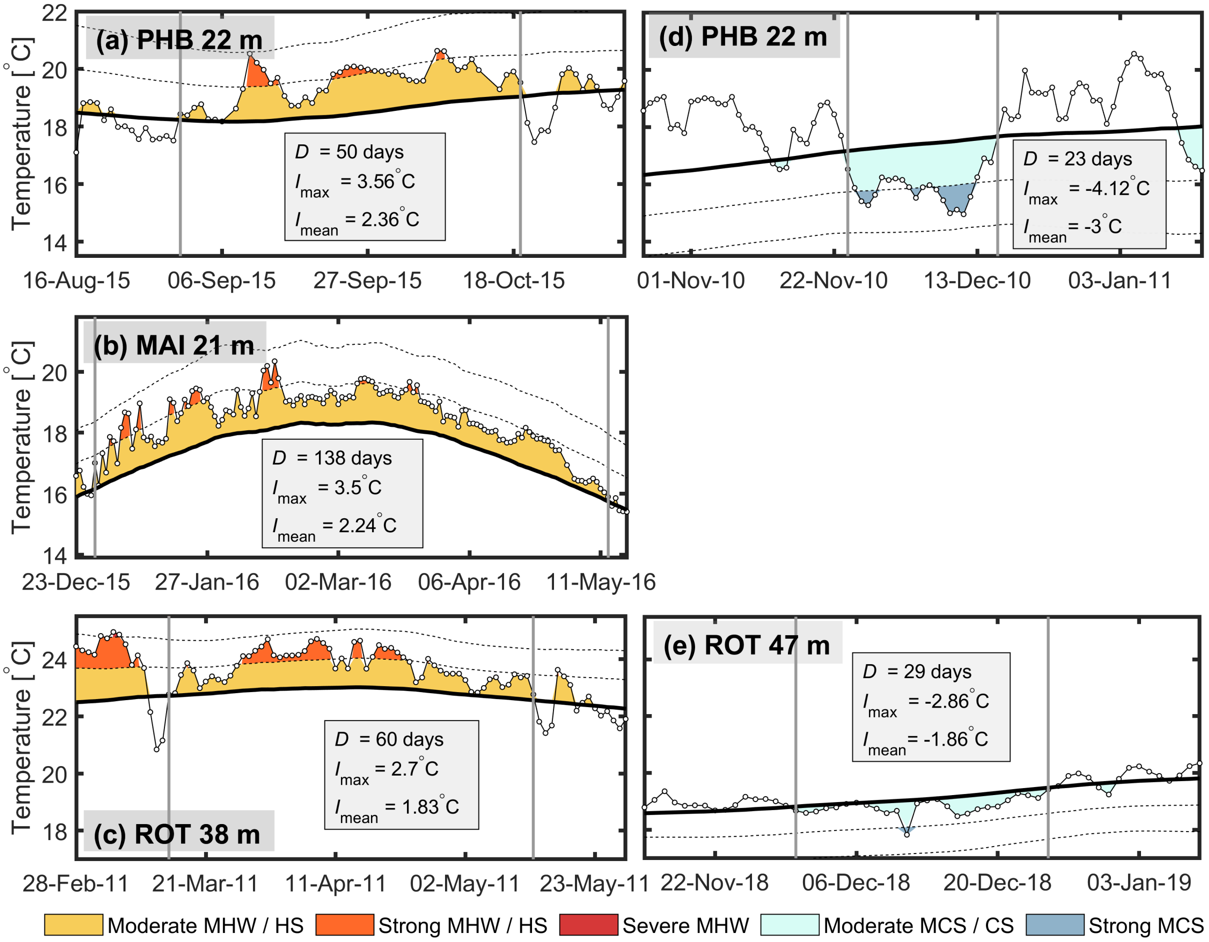

Figure 4. Examples of a)-c) Marine HeatWaves / Heat Spikes (MHWs/HS) and d)-f) Marine Cold-spells / Cold Spikes (MCSs / CSs,) with the maximum cumulative intensity at the long-term sites PHB/PH100, MAI, and ROT. The area underneath the portion of the time series experiencing an extreme event is filled according to the category: 'Moderate MHW / HS' (yellow), 'Strong MHW / HS' (orange), 'Severe MHW' (red), 'Moderate MCS / CS' (light blue), and 'Strong MCS' (dark blue). The metrics shown are duration ('D'), maximum intensity ('I_{max}'), and mean intensity ('I_{mean}'). The time period of each MHW or MCS is indicated by vertical grey lines. Each panel covers a different time period, hence the x-limits are not the same in each panel.

These AMDOT-EXT data products are freely accessible at the Australia Ocean Data Network thredds server, and we provide code tutorials in Appendix A demonstrating how to load the data products, use the NetCDF variables, and export the data as CSV files *citation to be finalised after the review phase*. We also provide CSV spreadsheets containing all of the MHW and MCS event information and characteristics at each of the four sites. Refer to the code and data availability section below for information on how to access the NetCDF and CSV files.

Using the AMDOT-EXT data products, we compare the number of extreme temperature events at the four sites, and explore the most intense and longest MHWs and MCSs, which were also often below the surface. These data products can be used for characterising and assessing the impacts of MHWs and MCSs in coastal waters around Australia.

These data products highlight the challenges faced when detecting extreme temperature events using sporadic long time series. Hence, it is vital that high temporal resolution measurements at multiple depths (i.e. moored thermistor data) continue into the future to fully understand extreme temperature events and their variability in the face of rapid environmental change.

Code and data availability. The AMDOT-EXT data products are available as NetCDF files (https://doi.org/10.26198/wbc7-8h24) (Hemming, 2023), and variables contained in the NetCDF files are listed in Table 2. Any and all use of the AMDOT-EXT data products provided here must include a citation to this paper, a reference to the data citation as written in the NetCDF file attributes, and the IMOS acknowledgements statement. Further information on these is provided in Sect A1. Any updated data products, and or potential new products (e.g. at other sites or using other ocean variables) will be hosted at the same location. Therefore it is advised that data users seek the latest data product version.

We provide basic scripts in Matlab, Python and R demonstrating how to download and load the data products, use the NetCDF variables, produce plots, and export the data as CSV files. These scripts are available online at Zenodo here:*OneDriveLink* and are available to use under a Creative Commons Attribution 4.0 International license (CC BY 4.0). Please see Appendix Sect A below for more details.

Appendix A: User Guide and Tutorials

A1 Citing AMDOT-EXT Data Products

Any and all use of the AMDOT-EXT data products or accompanying event summary spreadsheets described here must include:

- a citation to this paper,
- a reference to the data citation as written in the NetCDF file attributes and as follows: Hemming, MP. et al. (2023) "Multi-decadal time series of subsurface marine heatwaves and cold-spells in Australian shelf waters", Australian Ocean Data Network, https://doi.org/10.26198/wbc7-8h24.
- the following acknowledgement statement: Data was sourced from Australia's Integrated Marine Observing System (IMOS) - IMOS is enabled by the National Collaborative Research Infrastructure Strategy (NCRIS).

Any updated data products, and / or potential new products (e.g. at other sites or using other ocean variables) will be hosted at the same location. Therefore it is advised that data users seek the latest data product version.

A2 Loading AMDOT-EXT Data Products and Saving as CSV Files

The tutorial script 'get_DataProducts' available on Zenodo (*OneDriveLink*) demonstrates how to do the following:

- Load the MAI090 AMDOT-EXT data product using OPeNDAP,
- Select data during a MHW event,
- export the data as a Comma Separated Values (CSV) file that can be opened using Excel.

A version of this tutorial is available for use with R, Python, and MATLAB, and can be modified to use any AMDOT-EXT data product.

A3 Slicing AMDOT-EXT Data Product Variables Based on Event Characteristics

The tutorial script 'slice_DataProducts' available on Zenodo (*OneDriveLink*) demonstrates how to do the following:

- Load the PH100 AMDOT-EXT data product using OPeNDAP,
- select data during 'strong' category MHWs at a depth of 22 m,
- calculate and display mean characteristics during 'strong' category MHWs at this depth,
- save the sliced data set as either a NetCDF (Python), MAT (MATLAB) or rdata (R) file, as well as a Comma Separated Values (CSV) file that can be opened using Excel.

A version of this tutorial is available for use with R, Python, and MATLAB, and can be modified to slice any AMDOT-EXT data product based on any event characteristic.

Author contributions. MH and MR conceived the study. MH developed the data products and analysed the data, created the figures, and drafted the manuscript. MR led the project and obtained the funding. AS tested and reviewed the NetCDF files. MR and AS reviewed the manuscript.

Competing interests. We declare that no competing interests are present.

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Table 2. A table summarising the variables and their dimensions contained in each AMDOT-EXT NetCDF file with corresponding description.

Variable	**Dimensions**	**Description**
TIME	TIME	An array containing time information (days since 1950-01-01).
DEPTH	DEPTH	An array containing the chosen depth levels for deriving event statistics.
TEMP	TIME, DEPTH	An array containing the aggregated temperatures over the entire record for each depth level (Roughan et al., 2022b)
TEMP_INTERP	TIME, DEPTH	An array containing the same aggregated temperatures as in ‘TEMP’ but with gaps of ≤ 2 days filled. These temperatures are used to derive event statistics.
TEMP_EXTREME_INDEX	TIME, DEPTH	An extreme temperature event index useful for selecting specific event types. Numbers 1, 2, -1 and -2 correspond with MHWs, HSs, MCSs and CSs, respectively.
TEMP_MEAN	TIME, DEPTH	The daily mean climatology produced by Roughan et al. (2022b), and used for deriving event statistics here, for each date contained in ‘TIME’.
TEMP_PER10	TIME, DEPTH	The daily 10th percentiles produced by Roughan et al. (2022b), and used for deriving event statistics here, for each date contained in ‘TIME’.
TEMP_PER50	TIME, DEPTH	The daily 50th percentiles produced by Roughan et al. (2022b), and used for deriving event statistics here, for each date contained in ‘TIME’.
TEMP_PER90	TIME, DEPTH	The daily 90th percentiles produced by Roughan et al. (2022b), and used for deriving event statistics here, for each date contained in ‘TIME’.
<event type>_EVENT_NUMBER (e.g. ‘MHW_EVENT_NUMBER’)	TIME, DEPTH	A matrix containing the event numbers of a chosen event type (e.g. MHW or MCS) for each depth level.
<event type>_EVENT_CAT (e.g. ‘MHW_EVENT_CAT’)	TIME, DEPTH	A matrix containing the maximum event category number i.e 1 to 4: ‘Moderate’, ‘Strong’, ‘Severe’ and ‘Extreme’ for each depth level.
<event type>_EVENT_ONSET_RATE (e.g. ‘MHW_EVENT_ONSET_RATE’)	TIME, DEPTH	A matrix containing the onset rate of a chosen event type (e.g. MHW or MCS) for each depth level.
<event type>_EVENT_DECLINE_RATE (e.g. ‘MHW_EVENT_DECLINE_RATE’)	TIME, DEPTH	A matrix containing the decline rate of a chosen event type (e.g. MHW or MCS) for each depth level.
<event type>_EVENT_INTENSITY_<intensity type> (e.g. ‘MHW_EVENT_INTENSITY_MEAN’)	TIME, DEPTH	A matrix containing either the mean, max, cumulative, or variance of intensity for a chosen event type (e.g. MHW or MCS) for each depth level. Intensity is calculated relative to the mean daily climatology (Roughan et al., 2022b)
<event type>_EVENT_INTENSITY_<intensity type>_RELPERC (e.g. ‘MHW_EVENT_INTENSITY_MEAN_RELPERC’)	TIME, DEPTH	A matrix containing either the mean, max, cumulative, or variance of intensity for a chosen event type (e.g. MHW or MCS) for each depth level. Intensity is calculated relative to the daily 10th or 90th percentiles (Roughan et al., 2022b) depending on the event type.

Table 3. The date range, duration, depth, maximum classification, and cumulative intensity (I_c) for the longest marine heatwaves (MHWs) and marine cold-spells (MCSs) at sites PHB/PH100, ORS, MAI, and ROT.

	Longest MHWs					Longest MCSs				
Site	Date Range	Duration days	Depth m	Max. Classification	I_c °C day^{-1}	Date Range	Duratio days	Depth m	Max. Classification	I_c °C day^{-1}
PHB /PH100	19-Jun to 11-Aug-2017	54	59	Strong	94.3	23-Nov to 16-Dec-2010	24	40	Strong	-60.8
MAI	28-Dec-2015 to 13-May-2016	138	21	Strong	309	-	-	-	-	-
ROT	15-Mar to 13-May-2011	60	29	Strong	116	29-Nov-2018 to 01-Jan-2019	34	47	Strong	-53.1