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A stakeholder-guided marine heatwave hazard index for fisheries and aquaculture

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Abstract

Marine heatwaves pose an increasing threat to fisheries and aquaculture around the world under climate change. However, the threat has not been estimated for the coming decades in a form that meets the needs of these industries. Tasmanian fisheries and aquaculture in southeast Australia have been severely impacted by marine heatwaves in recent years, especially the oyster, abalone, and salmon industries. In a series of semi-structured interviews with key Tasmanian fishery and aquaculture stakeholders, information was gathered about the following: (i) the impacts they have experienced to date from marine heatwaves, (ii) their planning for future marine heatwaves, and (iii) the information that would be most useful to aid planning. Using CMIP6 historical and future simulations of sea surface temperatures around Tasmania, we developed a marine heatwave hazard index guided by these stakeholder conversations. The region experienced a severe marine heatwave during the austral summer of 2015/16, which has been used here as a reference point to define the index. Our marine heatwave hazard index shows that conditions like those experienced in 2015/16 are projected to occur approximately 1-in-5 years by the 2050s under a low emissions scenario (SSP1-2.6) or 1-in-2 years under a high emissions scenario (SSP5-8.5). Increased frequency of marine heatwaves will likely reduce productivity by both direct (mortality) and in-direct (ecosystem change, greater incidence of disease) impacts on target species. The illustrative hazard index is one step towards a marine heatwave risk index, which would also need to consider aspects of exposure and vulnerability to be of greater utility to stakeholders.

Keywords Marine heatwaves · Hazards · CMIP6 · Stakeholders · Aquaculture · Fisheries

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1 Introduction

Whilst marine heatwaves occur as part of natural variability, their increased intensities, frequency, and duration over the past century (Oliver et al. 2018) exemplify the threat to oceanic and coastal ecosystems from long-term climate change (Hughes et al. 2018; Oliver et al. 2018; Smale et al. 2019; Eakin et al. 2019; Marin et al., 2021b). Critically, marine heatwave impacts are being increasingly experienced by regional fisheries and aquaculture businesses (Mills et al. 2013; Caputi et al. 2016; Cavole et al. 2016; Oliver et al. 2017; Galli et al. 2017). Efforts to adapt to these changes and manage risks are building (Metcalf et al. 2014; van Putten et al. 2014; Pershing et al. 2018; Fogarty et al. 2020), as is demand for continued, refined, and targeted information and services by stakeholders (Dunstan et al. 2018; Fogarty et al. 2021; McInnes et al. 2021).

The fishery and aquaculture industries in Tasmania, Australia, had a gross value of production (GVP) of $1.18b in 2020–2021, predominantly from aquaculture (Tuynman & Dylewski 2022). Exacerbated by the strong long-term warming trend in the Tasman Sea (Holbrook and Bindoff 1997; Ridgway 2007), which is presently 2–3 times greater than the global average rate, fisheries and aquaculture in the region have been severely impacted by marine heatwaves in recent years. For instance, during the austral summer of 2015/2016, sea surface temperatures were 2 °C warmer than the seasonal mean over an area approximately seven times the size of Tasmania (Oliver et al. 2017). The anomalous warm water stretched along the east coast of Tasmania and extended across the continental shelf into the Tasman Sea. At that time, it was identified as the longest marine heatwave on record, persisting for 251 days (Oliver et al. 2017). Aside from the appearance of marine species that would otherwise normally reside farther north, the heatwave caused major ecological impacts. There was an outbreak of the virus *Ostreid herpesvirus 1* (OsHV-1) in Pacific oysters, also known as Pacific Oyster Mortality Syndrome (POMS) in Australia, which led to the closure of local hatcheries, and a decimation of juvenile Pacific oyster stocks (Ugalde et al. 2018). Poor blacklip abalone condition was also recorded during the event, with approximately 5% mortality (Oliver et al. 2017), and reduced performance in cultured Atlantic salmon resulted in a limited supply to seafood markets (Oliver et al. 2017; Hobday et al. 2018a). The region experienced a more intense marine heatwave, but of shorter duration (221 days), during the austral summer of 2017/2018 (Perkins-Kirkpatrick et al. 2019). The warming spanned the entire Tasman Sea between Australia and New Zealand (Perkins-Kirkpatrick et al. 2019; Salinger et al. 2019; Kajtar et al. 2022), with impacts to aquaculture and fisheries in both countries (Perkins-Kirkpatrick et al. 2019; Salinger et al. 2019). Every year between 2014 and 2020 in the Tasman Sea experienced more than 100 marine heatwave days (Kajtar et al. 2021), and a short marine heatwave in January and February 2022 (~30 days duration) resulted in some low-level abalone mortality near Bruny Island, Tasmania (C.N. Mundy, personal communication, 23 March 2023).

This study focuses on projected future hazards to Tasmania's salmon, oyster, and abalone industries from marine heatwaves. The species that are farmed or caught in Tasmania are as follows: Pacific oysters (*Magallana gigas*, previously known as *Crassostrea gigas*), blacklip abalone (*Haliotis rubra*), greenlip abalone (*Haliotis laevigata*), and Atlantic salmon (*Salmo salar*). Their typical locations are indicated in Fig. 1. There are other hazards and impacts associated with climate change such as declining productivity (Watson et al. 2013; Thompson and McDonald 2020) and range extensions (Johnson et al. 2011), amongst others (Fogarty et al. 2021), but only the direct hazard of warm ocean temperature extremes is considered here.

A key part of the study was to engage with stakeholders, to help provide targeted and specific information regarding marine heatwave futures which could assist in assessing

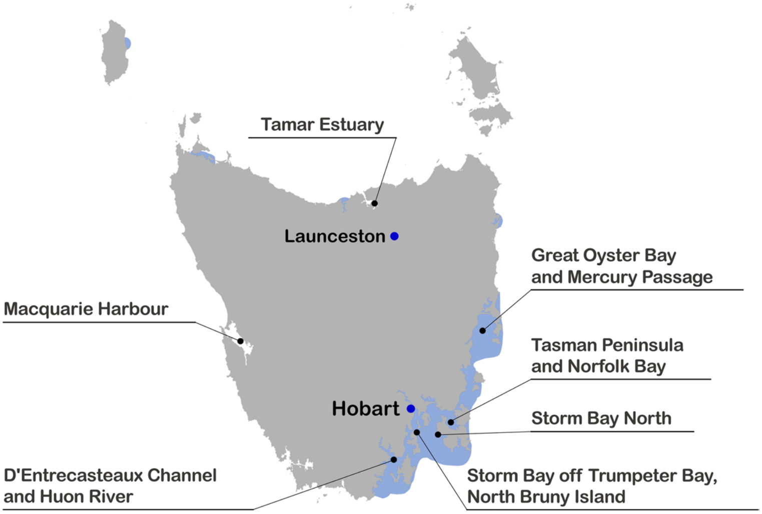

Fig. 1 Fishing and aquaculture regions in Tasmania. Salmon farming areas are indicated with labels (source: https://salmonfarming.nre.tas.gov.au). Oyster farms are generally located in the blue shaded regions, spanning the far north-west coast through to the southern part of the D'Entrecasteaux Channel (source: http://www.oysterstasmania.org/ourindustry.html). Blacklip abalones can be found along the entire coast of Tasmania, whereas greenlip abalones are found along Tasmania's northern coast (Mundy and McAllister 2021)

potential risks to their industries over the coming decades. The emphasis was on marine heatwave projections to guide long-term strategic decisions, rather than short-term forecasts or predictions which support operational decisions (Hobday et al. 2018b; Spillman et al. 2021; Hartog et al. 2023). We directly engaged with stakeholders to understand the impacts they have experienced to date, the level of future planning they already conduct, and the type of scientific information they desire to aid further planning and risk assessment (Sections 2.1 and 3.1). This stakeholder engagement was then used to guide the subsequent analysis of observed sea surface temperature extremes and state-of-the-art CMIP6 climate model projections (Sections 2.2, 2.3, and 3.2), which then led to the development of an illustrative marine heatwave hazard index (Sections 2.4 and 3.3).

2 Data and methods

2.1 Stakeholder inquiry

The broad aim of the project was to assess and communicate the hazards to Tasmanian aquaculture and fisheries from marine heatwaves. The stakeholder inquiry focussed on Tasmania's salmon, oyster, and abalone industries, which are three of the four most valuable seafoods in the state (Department of Natural Resources and Environment Tasmania 2021), and each of which have experienced marine heatwave impacts (e.g., Oliver et al. 2017). The goal of the engagement was to gain a deeper understanding from stakeholders in three areas (or discussion themes):

1. Observed impacts: the impacts from marine heatwaves that they have experienced to date.
2. Future planning: the level of future planning or risk assessment they currently undertake.
3. Desired information: the types of scientific information they desire to aid future planning for marine heatwave associated hazards.

Interviewees were sought with the aim of gathering a range of perspectives. After compiling a list of potential stakeholders, with assistance from fellow researchers, 18 representatives were contacted from peak industry agencies, businesses, state government, and academia by telephone and/or email. Ultimately, a total of 8 meetings were held involving 13 participants, garnering representation from a broad cross-section of stakeholders from the Tasmanian salmon, oyster, and abalone industries. The 8 meetings were conducted between April and June 2021 via recorded videoconferences with representatives from state government, peak bodies, business, and academia (two meetings with different representatives from each of these groups). The stakeholder engagement was conducted under Human Ethics approval granted by the University of Tasmania's Research Integrity and Ethics Unit (Project ID 24303).

Each meeting was 1–1.5 h in duration. The project aim, objectives, and important background scientific information were outlined at the commencement of each meeting in a 10-min presentation by the project team. It was explained, for example, that the subsequent analysis would focus on climate projections, rather than forecasts. A preliminary figure was also shown to interviewees, illustrating the observed, historical, and future projected annual counts of days exceeding 19.5 °C in eastern Tasmanian sea surface temperature. The figure was used as a prompt for discussions around the critical temperature thresholds for oyster, abalone, and salmon in Tasmania. The presentation was followed by a semi-structured discussion around the three themes outlined above, including questions such as whether they were aware of marine heatwaves. The sets of questions in the three discussion themes are given in Table S1. Some interviewees were better able to respond to particular groups of questions than others, so the lines of questions and discussion were tailored for each interview.

Following interviews, transcripts were generated from the recordings using transcription software, and manually checked and corrected with reference to the original recording. The corrected transcripts were then reformatted and summarised in a dot-point format and sent to the interviewees for verification. Edits and clarifications to the meeting summaries were made upon request from the interviewees. From the verified meeting summaries, each dot point was then tagged as a response under one of the three discussion themes (either directly or indirectly). The questions and responses were then further clustered into several subgroups (Table S2), forming the basis for the stakeholder engagement synthesis and analysis report (Kajtar, Holbrook & Lyth 2021). The key point summaries at the end of each subsection of the report were used to guide the subsequent analysis of observed and simulated temperatures around Tasmania.

2.2 Observational and model temperature data

Sea surface temperature (SST) is analysed in both observational data and model outputs. The observational SST are from the daily Optimum Interpolation Sea Surface Temperature (OISST), version 2.1, distributed by the National Oceanic and Atmospheric Administration (NOAA; Huang et al. 2021a). The OISST product is a combination of observations from satellites, ships, buoys, and Argo floats mapped onto a regular global 0.25° grid, with interpolation used to fill gaps (Reynolds et al. 2007). The dataset commences from 1 September

1981, but here only the period 1 January 1982 to 31 December 2020 is analysed. This period ending in 2020, representing the timespan of complete-year data availability at the time of analysis, is denoted as the observational period. OISST v2.1 is a robust observational product (Huang et al., 2021b; Yang et al. 2021), but in a study focusing on cataloguing marine heatwaves around Australia (Kajtar et al. 2021), some limitations of the dataset are discussed.

SST is also analysed in output from models participating in the Coupled Model Intercomparison Project, phase 6 (CMIP6; Eyring et al. 2016). Daily SST fields (variable name: *tos*) from native model grids (grid label: *gn*) are analysed from three CMIP6 experiments: historical, SSP1-2.6, and SSP5-8.5. The historical experiments represent simulations forced by observed fluxes over the period 1850–2014 (Eyring et al. 2016). SSP1-2.6 and SSP5-8.5 are two future shared socioeconomic pathways (SSPs) from the Scenario Model Intercomparison Project (ScenarioMIP; O'Neill et al. 2016). SSP1-2.6 is a low emission pathway, following a sustainable socio-economic future and resulting in 2.6 W/m^2 of effective radiative forcing from greenhouse gases at year 2100. SSP5-8.5 is a high emissions scenario, with heavy future fossil-fuel development, and 8.5 W/m^2 of effective radiative forcing at year 2100. Although they are not the most extreme scenarios, SSP1-2.6 and SSP5-8.5 represent low- and high-end plausible futures, corresponding closely with the best- and worst-case scenarios. SSP1-2.6 was selected over SSP1-1.9 since it has been simulated by a greater number of models (IPCC 2021). The analysis of historical experiment data herein commences from the year 1982, aligning with the start date of the observational analysis. At the end of the historical experiments, i.e., from the beginning of 2015, the future scenarios are appended, resulting in a set of two time series for each model: historical with SSP1-2.6 extension, and historical with SSP5-8.5 extension. The resultant time series thus span the years 1982 to 2100. Our aim was to maximise the number of models in the analysed ensemble, but a requirement of daily SST availability from each of the three experiments was imposed. This requirement is to ensure that the same model set is represented in the two future pathways, and it resulted in a set of 25 models with available data at the time of analysis (August 2021; Table 1). Only one ensemble member from each model and experiment is analysed.

All the SST data, both observational and simulated, were first cropped to a broad region around Tasmania, Australia (138–155°E, 49–35°S; Kajtar and Holbrook 2021). Then, after appending the model future scenario data to the historical data, the time series were trimmed to the required timespan, i.e., 1 January 1982 to 31 December 2020 for the observational data, and 1 January 1982 to 31 December 2100 for the model data. For subsequent analyses, area weighted means were computed for five subdomains in the Tasmanian region (Fig. 2):

- Whole Tasmanian subdomain: 142–151°E, 45–39°S (index name: *tas_all*)
- Southeast subdomain: 146.5–149.5°E, 44.5–42°S (*tas_se*)
- Northeast subdomain: 146.5–149.5°E, 42–39.5°S (*tas_ne*)
- Southwest subdomain: 143.5–146.5°E, 44.5–42°S (*tas_sw*)
- Northwest subdomain: 143.5–146.5°E, 42–39.5°S (*tas_nw*)

The CMIP6 models have various grid resolutions (Table 1), and thus different numbers of ocean grid cells in each subdomain. The numbers of ocean grid cells in the smaller subdomains vary from as few as two (MPI-ESM1-2-LR), to as many as 144 (CNRM-CM6-1-HR and HadGEM3-GC31-MM), but 19 models have at least 9 ocean grid cells of data in the smaller subdomains. Grid resolution and grid cell counts are

Table 1 List of CMIP6 models analysed, along with their global oceanic grid resolutions. For a given model, ensemble members with the same variant identifiers are used across each of the three experiments (historical, SSP1-2.6, and SSP5-8.5). These variant labels are used by modelling groups to denote the specific configurations of their simulations. The model calendar type is also listed: Gregorian, No leap (365-day calendars with no leap years), or 360-day (twelve 30-day months each year)

	Institute	Model	Nominal ocean grid (lon × lat)	Variant	Calendar
1	BCC	BCC-CSM2-MR	360 × 232	r1i1p1f1	No leap
2	CCCma	CanESM5	361 × 290	r1i1p1f1	No leap
3	CMCC	CMCC-CM2-SR5	362 × 292	r1i1p1f1	No leap
4	CMCC	CMCC-ESM2	362 × 292	r1i1p1f1	No leap
5	CNRM-CERFACS	CNRM-CM6-1-HR	1442 × 1050	r1i1p1f2	Gregorian
6	CNRM-CERFACS	CNRM-CM6-1	362 × 294	r2i1p1f2	Gregorian
7	CNRM-CERFACS	CNRM-ESM2-1	362 × 294	r1i1p1f2	Gregorian
8	CSIRO	ACCESS-ESM1-5	360 × 300	r1i1p1f1	Gregorian
9	CSIRO-ARCCSS	ACCESS-CM2	360 × 300	r1i1p1f1	Gregorian
10	EC-Earth-Consortium	EC-Earth3-Veg-LR	362 × 292	r1i1p1f1	Gregorian
11	EC-Earth-Consortium	EC-Earth3-Veg	362 × 292	r1i1p1f1	Gregorian
12	EC-Earth-Consortium	EC-Earth3	362 × 292	r11i1p1f1	Gregorian
13	IPSL	IPSL-CM6A-LR	362 × 332	r1i1p1f1	Gregorian
14	MIROC	MIROC6	360 × 256	r1i1p1f1	Gregorian
15	MOHC	HadGEM3-GC31-LL	360 × 330	r1i1p1f3	360-day
16	MOHC	HadGEM3-GC31-MM	1440 × 1205	r1i1p1f3	360-day
17	MOHC	UKESM1-0-LL	360 × 330	r1i1p1f2	360-day
18	MPI-M	MPI-ESM1-2-HR	802 × 404	r1i1p1f1	Gregorian
19	MPI-M	MPI-ESM1-2-LR	256 × 220	r1i1p1f1	Gregorian
20	MRI	MRI-ESM2-0	360 × 364	r1i1p1f1	Gregorian
21	NCAR	CESM2-WACCM	320 × 384	r1i1p1f1	No leap
22	NCAR	CESM2	320 × 384	r4i1p1f1	No leap
23	NCC	NorESM2-LM	360 × 384	r1i1p1f1	No leap
24	NCC	NorESM2-MM	360 × 384	r1i1p1f1	No leap
25	NOAA-GFDL	GFDL-ESM4	720 × 576	r1i1p1f1	No leap

important because, generally, higher resolution of spatial features, such as coastlines or topography, and of small-scale processes such as convective precipitation, result in more realistic simulations (e.g., Flato et al. 2013). For the calculations of the model area weighted means, the native model grid cell areas (variable name: *areacello*) were utilised. To ensure temporal consistency, models with non-Gregorian calendars (Table 1) had some adjustments applied. For models with 365-day calendars, data for each leap day (29 February) were linearly interpolated from 28 February and 1 March data. For models with 360-day calendars, the 360 days of data in each year were linearly interpolated to the appropriate 365- or 366-day temporal grid in each year. Such regridding for 360-day calendars is not optimal, since it may smooth some extreme temperature days, but testing showed that the effect is small (figure not included).

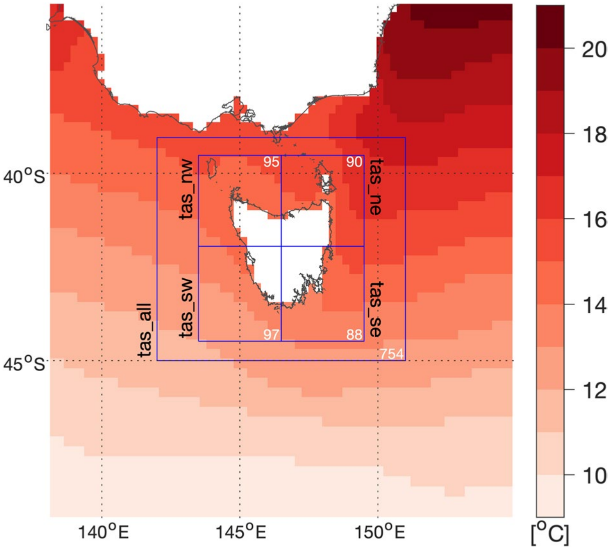

Fig. 2 Tasmanian region subdomains analysed in this study. Colour shading denotes mean sea surface temperature over 1983–2012 in the observational OISST product. The five subdomains analysed in this study are indicated by blue boxes: *tas_all*, *tas_nw*, *tas_ne*, *tas_se*, and *tas_sw*. The numbers of ocean grid cells, excluding land cells, within each subdomain are indicated by white numbers

The processing steps outlined above resulted in 10 daily SST time series for each CMIP6 model: five for each of the subdomains, with two future scenario pathways (appended to the common historical pathway).

2.3 Bias corrections

The CMIP6 SST outputs were bias corrected for two aspects: mean temperature, and seasonal cycle amplitude. Models sometimes simulate mean temperatures with biases relative to observations, with some being cooler, and others warmer (Grose et al. 2020; Zelinka et al. 2020; Carvalho et al. 2022). Since absolute temperatures are analysed herein (for example, counts of days with temperature greater than 19 °C), the model SSTs are corrected for biases in the mean temperature. Without such a correction, models that run with a cooler mean temperature may not exhibit any days warmer than 19 °C around Tasmania, whereas models that are too warm may exhibit too many. Model SSTs are mean bias corrected to match the observational SST over the reference period of 1983–2012, which aligns with a typically used climatological period for marine heatwave analysis (Hobday et al. 2018a). Note that this period of 1983–2012, which is used as the reference or baseline climatology, is distinct from the 1982–2020 observational period described in Section 2.2. After computing the mean SST difference between models and observations over 1983–2012, the bias was subtracted from the whole time series (i.e., 1982–2100). Each subdomain was mean bias corrected separately. The mean temperature bias was up to ± 2.5 °C amongst all models, but the multi-model mean temperature agreed well with the observed.

A second bias correction was applied to the amplitude of the SST seasonal cycles. Starting with the mean bias corrected SST, seasonal cycles were computed for observations and models over the baseline reference period 1983–2012. The climatological seasonal cycle was computed over an 11-day window centred on each calendar day, sampling each year within the baseline period. After computing the mean for each calendar day, the seasonal cycle was further smoothed by applying a 31-day moving mean. This process is identical to that of Oliver et al. (2018) for calculating climatologies and seasonally varying thresholds for marine heatwave detection. After computing the smoothed seasonal cycles for observations and models, the means were subtracted (to represent cycles as anomalies), and the standard deviations were computed. The model seasonal cycle amplitude biases were then computed by dividing the model standard deviation by the observational standard deviation. Matching the amplitude to observations was then achieved by dividing the model seasonal cycle anomalies by the amplitude bias. After restoring the mean temperature of the adjusted seasonal cycle, the seasonal bias correction was applied to the entire time series, for each model and each subdomain separately.

2.4 Construction of a marine heatwave hazard index

The marine heatwave hazard index developed here is motivated not only by the stakeholder engagement but also by other recent studies. Firstly, one of the intentions with the index was to combine more than one marine heatwave metric. Such metrics may include the following: the temperature exceedance above seasonal climatology (i.e., the intensity), the consecutive days above the threshold (i.e., duration), the accumulation of temperature excess over multiple days (i.e., cumulative intensity), or the regularity (or frequency) of recurrence (Galli et al. 2017; Frölicher and Laufkötter 2018; Oliver et al. 2019; Smale et al. 2019; Gruber et al. 2021). Oliver et al. (2019) analysed marine heatwave intensity together with duration as an indicator of potential ecological impacts. In the marine heatwave intensity-duration phase space, the projected range in probable marine heatwaves moves entirely outside the present-day domain by 2050–2080 under a high emissions scenario (Oliver et al. 2019; their Fig. 5). The second intention for the index was to use a particular level as the marine heatwave hazard benchmark. Russo et al. (2019) considered the projected future return interval of one-in-500-year heatwaves, albeit for atmospheric heatwaves occurring over land. They also went beyond simply estimating heatwave hazard, considering exposure and vulnerability in developing an ‘illustrative heatwave risk index’. The two key elements of the marine heatwave hazard index developed here are thus that (i) it makes use of temperature magnitude (or intensity) and time of exposure (akin to duration), and (ii) the observations are utilised to identify a benchmark occurrence, and then the climate projections give an estimate of likelihood for future occurrence. Further details on the calculation of the index follow here.

The first step is to identify a threshold temperature. The threshold should represent an approximate temperature at which impacts might be first experienced. For example, oyster farmers have reported that they usually observe disease and mortality with temperature > 18 °C in Tasmania (Ugalde et al. 2018). In this study, two choices for the threshold temperature are tested: a region-dependent 99.5th percentile temperature, based on observations, and a fixed temperature of 19 °C (Section 3.2). The former choice may be more suitable where the critical temperature is unknown (or not known precisely) for the species of interest. The second step in the hazard index calculation is to compute annual cumulative intensities. Starting with daily temperature time series, the days on which the threshold temperature is exceeded and by what amount (i.e., the exceedance anomaly) are recorded. The exceedance anomalies are then summed annually, but instead of summing over calendar years, they are summed over year-long periods centred on the climatologically warmest month of the year. In Tasmania, the warmest time of year is early March, and hence, annual periods of September 1 to the following August 31 are used. This is done so that days belonging to a single (austral) summer period are counted together, rather than in separate years. The resulting annual cumulative intensities, with units °C.days, is unlike that from the commonly used marine heatwave definition by Hobday et al. (2016) in two ways: (i) the chosen temperature threshold here does not vary seasonally, and (ii) the anomalies need not be over consecutive days. In the first regard, our definition is more akin to the ‘degree heating week’ metric used for measuring the thermal stress experienced by coral (Liu et al. 2003). On the second point, it was recognised that consecutive days of temperature exceedance are likely more impactful than several isolated days, but this choice was made to simplify the analysis. It was not immediately clear how to include information on consecutive days into the annual time series. The annual cumulative intensity time series are computed for observations, as well as for each model realisation.

The third step in computing the hazard index is to determine an appropriate hazard level. Here, an annual cumulative intensity value of 10 °C.days is chosen, since it is close to the maximum value observed in the whole Tasmanian domain (Section 3.3). This maximum occurred during 2015/2016 (i.e., in the period September 2015 to August 2016), coincident with an impactful marine heatwave on the relevant species in this study. The fourth and final step is then to estimate the likelihood of occurrence of a year with the selected hazard level from the model data. The index value for a given year, again centred on the climatologically warmest month, is computed from a 10-year window of model data (i.e., the year of interest, the five years prior, and the four years after). With 25 models, and using 10-year windows, there are thus 250 model-years to determine the index value for a single given year. All years in which the hazard level (i.e., an annual cumulative intensity of at least 10 °C.days) is reached is added to the tally, and the index value is thus the proportion of such years from all 250 model-years. For example, if the hazard level is exhibited in 125 of the model-years, then the hazard index value is 0.5 and is taken to represent 50% likelihood of experiencing hazardous marine heatwave conditions for the selected year.

The marine heatwave hazard index, after making appropriate choices for threshold temperatures and hazard levels, can in principle be computed following the steps outlined above for any region of interest around the world.

3 Results

3.1 Stakeholder engagement synthesis and analysis

Stakeholders in the Tasmanian fishery and aquaculture industries outlined valuable perspectives from their experiences with general ocean warming and extreme events in recent years. Detailed analysis of those responses is presented elsewhere (Kajtar, Holbrook & Lyth 2021). The key findings pertinent to this study are summarised here, which are drawn from the summary boxes at the end of each sub-section in the report by Kajtar, Holbrook & Lyth (2021).

It was apparent that warm water extremes affected the three species in different ways. For example, the primary concern for oyster growers was the virus *Ostreid herpesvirus 1* (Pacific Oyster Mortality Syndrome, POMS), which is typically activated by warm temperature extremes (de Kantzow et al. 2016; Rodgers et al. 2019), and usually at >18 °C in Tasmania (Ugalde et al. 2018). For abalone, extreme warmth directly affects their metabolism and reproduction rates, leading to smaller populations and some mortality (Shepherd and Breen 1992; Gilroy and Edwards 1998; Harris et al. 2005; Fordham et al. 2013). On the other hand, the warm temperature extremes experienced in Tasmania in recent years have not necessarily led to salmon mortality, but rather to reduced growth rates and higher levels of disease (Battaglene et al. 2008; Tassal Group Limited 2016; Zarkasi et al. 2016).

Despite the differing impacts of extreme warmth, interviewees agreed that temperatures near 18–20 °C were close to the level of greatest concern for each of the three species. Some interviewees commented that the numbers of days exceeding such temperatures each year (as shown in the preliminary figure to interviewees; Section 2.1) were a more informative way of illustrating projected changes, as opposed to simply plotting mean or anomalous temperature changes over time. Furthermore, near-term projections over the coming 2–3 decades are of most interest since businesses do not tend to plan to 2100. The salmon industry also expressed interest in projected changes to optimal temperatures, and some studies have started exploring such aspects (Meng et al., 2022).

From our interviews, we found that Tasmanian fishery and aquaculture industry stakeholders have a strong understanding of marine heatwaves, largely because they have directly experienced their impacts and observed changes first-hand. The marine heatwave concept was discussed with stakeholders, and all were familiar with the term, as well as the potential impacts to their industries. There was less familiarity with specific definitions of marine heatwaves (e.g., Hobday et al. 2016), but that was not seen as a barrier to understanding the scientific concerns regarding possible future changes to their frequency and intensity.

The Tasmanian industry and government have already started some level of adaptation to the changing climate, with reduced quotas on abalone harvesting in areas affected by marine heatwaves, selective breeding for disease-resistant oysters, and active planning and temperature monitoring over 12–24-month time scales by salmon businesses. However, not all of these actions are necessarily in direct response to climate change, since, for example, reduced quotas on abalone harvesting are also a response to over-fishing. Extreme temperature projections were considered a useful addition for planning and risk assessment by all.

Thus, some of the key suggestions that we inferred from the stakeholder discussions, summarised in the preceding text and in a stakeholder engagement synthesis and analysis report (Kajtar, Holbrook & Lyth 2021) are as follows: focus on temperature extremes exceeding 18–20 °C, provide the counts of days with such temperatures, and focus on projections only to 2050. These suggestions do not necessary represent the most important to the industry, but rather we considered them the most pertinent to the analysis we could undertake with the model temperature projection data. They helped to develop the marine heatwave hazard index (Section 2.4).

3.2 Past and projected future extreme temperatures

Following the inferred suggestions made through stakeholder engagement, we investigated the annual counts of days with mean temperatures exceeding 19 °C in both the observations and models (Fig. 3). The data are analysed separately for the five Tasmanian regions (Fig. 2). The days exceeding 19 °C are tallied over September 1 to the following August 31, rather than over the calendar year, so that days belonging to a single austral summer period are counted together (Section 2.4). The area-averaged SST in the whole Tasmanian domain only exceeded 19 °C in two summers in the observations: 2015/2016 and 2017/2018, and for fewer than 5 days in each case (Fig. 3a). The model data are plotted to show the multi-model mean, the range of the central ~ 67% of models, and the full model range. The model means and 67% ranges were smoothed using a 10-year moving mean. There is clearly a range of possible outcomes amongst the models, with some years comprising 80 days or more exceeding 19 °C, even under SSP1-2.6. Following the multi-model mean, a typical approach to interpreting the model projections (e.g., Flato et al. 2013), indications are that

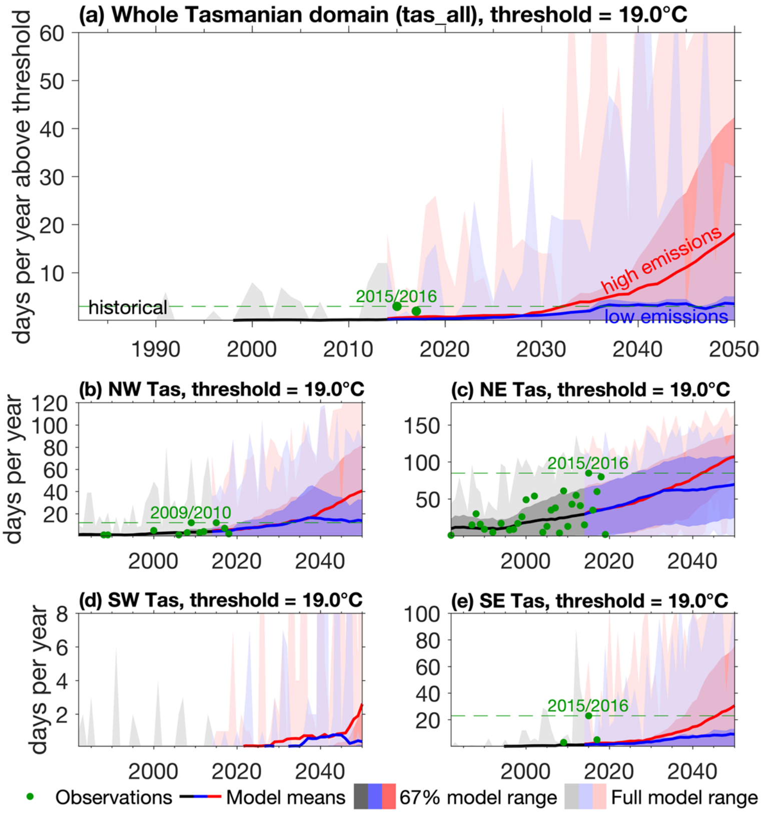

Fig. 3 Historical and projected changes in counts of days per year exceeding 19 °C. The analysis is for SST averaged over **a** the whole Tasmanian domain (*tas_all*) and **b**–**e** each of the smaller subdomains (*tas_nw*, *tas_ne*, *tas_sw*, and *tas_se*). The excess days are tallied over full years from September to August, and the x-axis label for the year 2000 denotes the 2000/2001 data, for example. The year of the observed maxima are labelled in green in each panel, and also denoted by a green horizontal dashed line. CMIP6 model means are indicated by solid curves: black for the *historical* period, up to the year 2014, and then branching to the two scenarios in red (SSP5-8.5) and blue (SSP1-2.6). Darker shading denotes the smoothed range of the central ~ 67% of models (17 out of 25), and lighter shading denotes the range of all models

an average year by 2050 will experience 5 days exceeding 19 °C, as observed in 2015/2016, under SSP1-2.6 (Fig. 3a). Under SSP5-8.5, however, a typical year is projected to have almost 20 days exceeding 19 °C.

In other regions, the counts of days exceeding 19 °C vary dramatically. In the northeast Tasmanian region, which is the warmest on average due to the influence of the East Australian Current Extension, more than 80 days warmer than 19 °C were experienced in 2015/2016, and 19 °C is exceeded in most years (Fig. 3c). On the other hand, the daily mean temperature, averaged over the southwest Tasmanian region, has never exceeded 19 °C, and there is only a small likelihood of doing so out to 2050, even under the high emission scenario (Fig. 3d).

The multi-model means of the two emission scenarios tend to be similar up to 2030–2035 (Fig. 3), after which they diverge substantially. The observed maxima of days warmer than 19 °C are exceeded in the projected model mean under SSP5-8.5 by 2050 in all domains, suggesting that the most extreme observed year is likely to be a typical year under such a scenario. However, such occurrences are less likely under SSP1-2.6, particularly in the eastern domains (Fig. 3c,e).

An alternative investigation of extreme temperature changes in each domain is to determine region-dependent thresholds, rather than using the fixed value of 19 °C. Since the historical mean temperatures are different in each region, the ranges of the extremes also differ. Therefore, an alternative threshold was determined by computing the temperature which has been exceeded on 0.5% of days over the observational period of 1982–2020, or in other words, the 99.5th percentile. This is a stricter threshold than the 90th percentile (Hobday et al. 2016), since here only a small fraction of the most extreme temperature days is sought. The 99.5th percentile equates to the temperature exceeded on the 71 warmest days in the observational period. The observed and model simulated counts of days exceeding the region-dependent thresholds are shown in Fig. 4. For the whole domain, 0.5% of days have exceeded 18.3 °C in the observational record (Fig. 4a). The threshold temperature is warmer for the northeast subdomain (20.3 °C; Fig. 4c), and it is coolest for the southwest (17 °C; Fig. 4d). For the whole domain and the two eastern domains (Fig. 4a,c,e), the greatest counts of days in excess of the threshold temperature occurred in the summer of 2015/2016, aligning with the Tasman Sea marine heatwave occurring at that time (Oliver et al. 2017). In the western domains (Fig. 4b,d), the highest counts are more evenly spread across several years, but the greatest numbers of days occurred in 2009/2010.

The projected counts of excess days under the two scenarios are similar for each domain, which is a result of the choice of the threshold definition (Fig. 4). However, there are some differences and variations that indicate that the mean temperature change projected over the coming decades is not entirely independent of location. It is also important to note that mean SST tends to be lower in near-coastal regions in southeast Tasmania (Meng et al., 2022), and shelf temperatures tend not to be increasing as fast as offshore temperatures (Marin et al. 2021a). At the larger scale, which the models represent, some of the small-scale dynamics are necessarily not captured.

3.3 Marine heatwave hazard index

As described in Section 2.4, the marine heatwave hazard index is computed from model simulations of the annual cumulative intensity exceeding a given temperature threshold. The annual cumulative intensity in each of the Tasmanian domains using the observed 99.5th percentile threshold is shown (Fig. 5a,c,e,g,i). The time series for observations and models show similar patterns to those seen in Fig. 4, such that the annual cumulative intensity increases over time, and more so for the high emissions pathway. One of the steps in the marine heatwave hazard index calculation is to determine an appropriate hazard level. Here, an annual cumulative intensity value of 10 °C.days was chosen. The choice was made as it is close to the level observed region-wide (Fig. 5a) and southeast domain (Fig. 5g) during 2015/2016, corresponding to the austral summer in which an impactful marine heatwave to the relevant species occurred. In all other observed years, the annual cumulative intensity was less than 10 °C.days.

Using this selected hazard level, the illustrative marine heatwave hazard index is computed from the model projections (Section 2.4; Fig. 5b,e,f,h,j). The index represents the likelihood of experiencing hazardous conditions from extremely warm SST each year, under both low and high emissions scenarios. An index level of 0.5 denotes a 50% likelihood of experiencing hazardous marine heatwave conditions, and values close to 1.0 denotes near certainty.

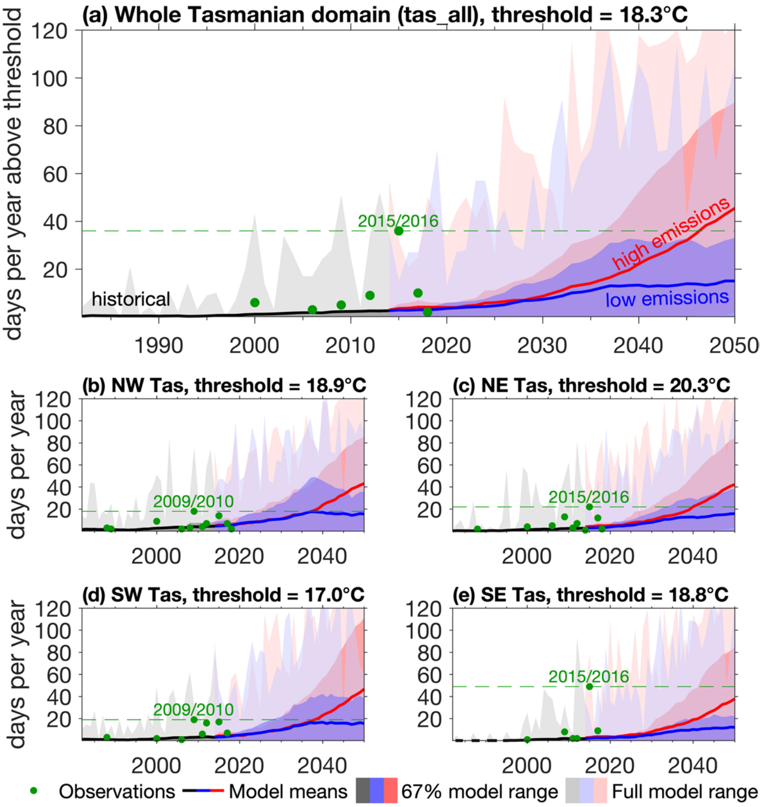

Fig. 4 As in Fig. 3, but instead using region-dependent threshold temperatures. The thresholds are the 99.5th percentile of SST during the period 1982–2020 in observations. The computed region-dependent threshold temperature is denoted in each subpanel title

Since the projected annual cumulative intensity pathways are somewhat similar for each domain, the marine heatwave hazard index evolutions are similarly uniform (Fig. 5b,d,f,h,j). In each region, the hazard level reaches approximately 0.2 by 2050 under SSP1-2.6, and 0.5 under SSP5-8.5. In other words, approximately 1-in-5 years by 2050 are projected to be like 2015/2016 under the low emission scenario, whereas it is projected to be closer to 1-in-2 years under the high emission scenario.

The region-dependent temperature threshold, or one based on the local climatology, is an appropriate choice if the critical temperature for a marine species of interest is unknown. An alternative to using region-dependent thresholds for the hazard index is to use a fixed temperature threshold, and 19 °C is used here as an example (Fig. 6). In this case, the marine heatwave hazard index levels are different across the regions. In the northeast, the index rapidly approaches 1.0 under both scenarios by 2050 (Fig. 6f), whereas in the southwest, it remains close to zero (Fig. 6j). If 19 °C is close to the critical temperature for impacts in all regions around Tasmania in reality, at least to oysters, abalone, and salmon, then this marine heatwave hazard index is informative. It indicates that the southwest of Tasmania will continue to have very low levels of marine heatwave hazard for many years to come, regardless of the future scenario.

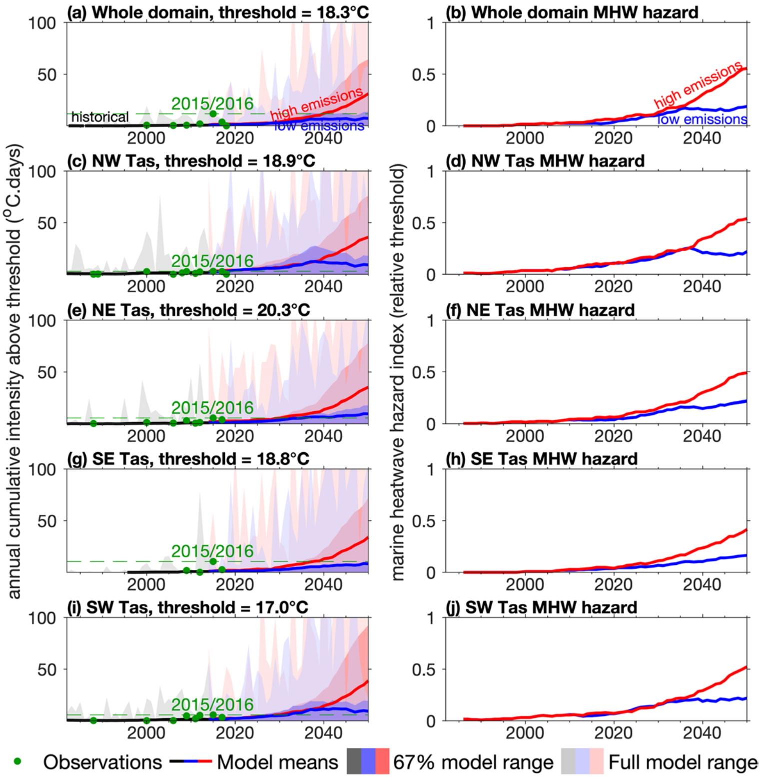

Fig. 5 Historical and projected changes in annual cumulative intensity exceeding region-dependent temperature thresholds, and their associated projected hazard levels. The analysis is of SST over **a**, **b** the whole Tasmanian domain (*tas_all*) and **c**–**j** each of the smaller subdomains (*tas_nw*, *tas_ne*, *tas_sw*, and *tas_se*). The left panels show annual cumulative intensity, which is the sum of all daily SST anomalies exceeding region-dependent thresholds each year, summed over September to August. The observed maxima are labelled in green in each panel, and also denoted by a green horizontal dashed line. Green data points are not shown for years in which the observed value is zero. The right panels show the marine heatwave hazard index, estimated from CMIP6 models. The index represents the likelihood of occurrence of a year with 10 °C.days of cumulative intensity, where an index value of 0.5 represents 50% likelihood, and approaching 1.0 represents high likelihood

4 Discussion and conclusions

The marine heatwave hazard index introduced here is a step towards developing a marine heatwave risk index across both fishery and aquaculture sub-sectors spatially and temporally. Whilst this is an example of how the hazard component of risk can be computed and presented, a complete risk assessment would also need to consider the exposure and vulnerability aspects, including the adaptative capacity of the industry sectors and species (Cardona et al. 2012; IPCC 2012, 2014; Russo et al. 2019; Boyce et al. 2022). This would form the next step in any sector specific risk assessment process and would require further engagement with stakeholders.

There are some caveats and limitations associated with the present study, which are discussed here. Firstly, it is often challenging to secure time with key stakeholders (e.g., Luyet et al. 2012; Röckmann et al. 2015). Whilst the Tasmanian stakeholder landscape is relatively contained and networks are readily identifiable (Lyth et al. 2016), this project

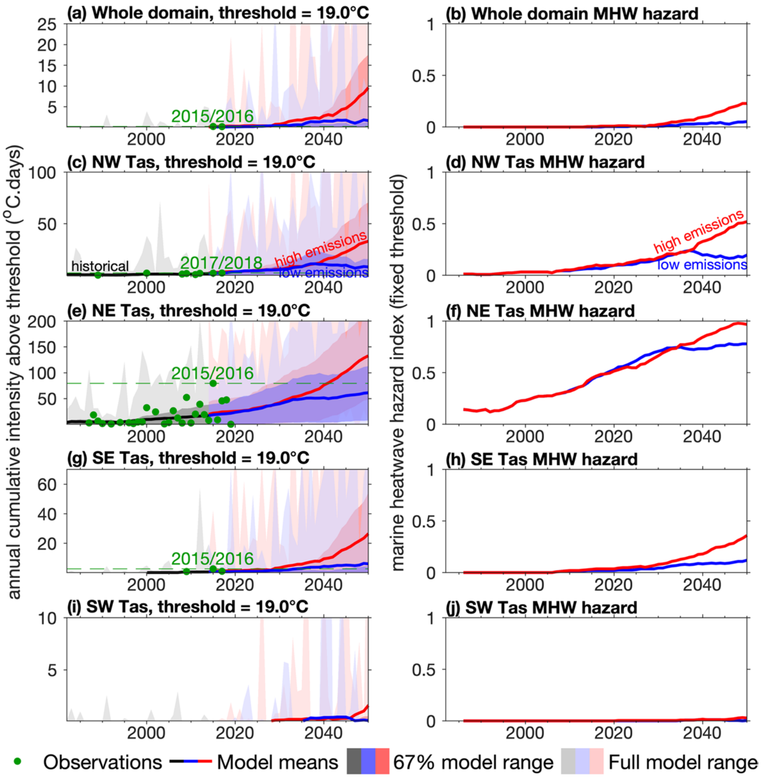

Fig. 6 As in Fig. 5, but instead using a fixed temperature threshold of 19 °C

nevertheless faced some challenges in stakeholder engagement. The two primary challenges were as follows: (i) the willingness of stakeholders to engage, which was hindered by other consultation demands and international trade issues at the time, and (ii) the reduced ability or wariness to meet in person or in large groups due to COVID-19 measures during the time of the study.

The second set of caveats relate to the analysis of sea surface temperature data. The NOAA OISST dataset was analysed for observational SST, but there are many other products available (Yang et al. 2021). OISST has been extensively used in marine heatwave studies; it also ranks highly regarding documentation, accessibility, and dissemination (Yang et al. 2021). There are some higher spatial resolution products available, which are more appropriate for studying coastal regions, but they tend to cover a shorter timespan (Huang et al., 2021b; Yang et al. 2021). An associated consideration is that CMIP6 models may not have sufficiently high resolution for small domain studies (Fiedler et al. 2021). There is some indication that CMIP6 models perform better than CMIP5 in some marine heatwave metric representation (Grose et al. 2020; Qiu et al. 2021), but marine heatwave studies utilising CMIP5 or CMIP6 would greatly benefit with further model evaluation to understand sources of biases (Plecha and Soares 2020). Recent studies show that model resolution is a crucial factor in marine heatwave representation (Pilo et al. 2019; Hayashida et al. 2020).

A key challenge in the development of a temperature-focused hazard index is that both eddy and current structures create considerable heterogeneity at small spatial scales, particularly in the Tasmanian region. The smallest domains chosen for analysis in this study span ~ 250–300 km, which is extremely large relative to the area of an oyster farm or salmon pen. The gridded observational and model datasets analysed here did not necessarily permit such small scale analyses, due to their coarse spatial resolutions. On the other hand, the average temperature over such a large domain can nevertheless be informative, since marine heatwaves sometimes span vast areas.

In analysing future projections to 2050, it was shown that the two greenhouse gas scenarios can diverge substantially. The future pathway is clearly an unknown variable and presents a source of uncertainty for planning and risk assessment. However, two possible pathways near the extreme ends were selected: a low emissions pathway and a high emissions pathway. The eventual reality over the coming decades is likely to lie somewhere in between. In addition, it was found that the two pathways did not substantially differ until after 2035, providing at least some utility for the coming 10–15 years.

Rather than using the typical definition of marine heatwaves, in which unusual warmth is measured against a seasonally varying climatology (Hobday et al. 2016), sector-relevant absolute threshold temperatures were employed for the marine heatwave hazard index presented here. This approach was taken because the stakeholder engagement indicated a clear concern for temperatures exceeding 18–20 °C in Tasmania, rather than atypical warmth in the cool seasons. Using regionally dependent temperature thresholds, the likelihood of years during which the total cumulative intensity is 10 °C.days greater than the threshold was assessed. The marine heatwave hazard index ranges between zero, representing low or no possibility of 10 °C.days above the threshold in a given year, and unity, representing virtual certainty of reaching 10 °C.days. For region-dependent thresholds, the temporal evolution of the hazard index is similar in each region, reaching approximately 0.5, or 50% likelihood, by 2050 under high emissions, with ~ 0.2 hazard level under the low emission scenario. A fixed temperature threshold of 19 °C, rather than regionally dependent thresholds, was also tested in the calculation of the hazard index. Whilst informative if the critical temperature for a species is known, a fixed threshold ignores the fact that different species may have adapted or acclimatised to different local conditions, i.e., individuals of the same species in the northeast of Tasmania may tolerate temperatures > 19 °C more readily than those in the southwest. Hence, the region-dependent temperature threshold may be more appropriate, but the choice will depend on the species of interest.

The approach to identifying hazard likelihood is somewhat akin to the ‘storyline’ approach (Shepherd et al. 2018; Shepherd 2019), whereby a particular event is used as a reference point, and plausible future scenarios are then shown. But the next step with such a marine heatwave hazard index will be to go beyond showing ‘What will happen?’, and instead ‘What is the impact of particular actions under an uncertain regional climate change?’ (Shepherd 2019). The utility of the marine heatwave hazard index for informing the risk assessment and planning of Tasmanian fisheries and aquaculture has not yet been assessed, and to do so will require more engagement. Any utility will also ultimately depend on stakeholder capacities to alter practises (Hartog et al. 2023), such as reducing or modifying harvesting, or introducing stock with higher thermal tolerances. Development of the hazard index, with extension to a risk index, will also require further iterative engagement.

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Author contribution Jules Kajtar, Neil Holbrook, and Anna Lyth conceived the study, sought funding and ethics approval, and designed the stakeholder engagement. Observational and model data analysis was performed by Jules Kajtar. Alistair Hobday, Craig Mundy, and Sarah Ugalde were members of the project advisory group. The first draft of the manuscript was written by Jules Kajtar, Neil Holbrook, and Anna Lyth, and all authors contributed to editing subsequent versions. All authors read and approved the final manuscript.

Data availability The NOAA 0.25-degree daily Optimum Interpolation Sea Surface Temperature (OISST), Version 2.1 description and metadata is available at https://doi.org/https://doi.org/10.25921/RE9P-PT57, and annual datafiles are provided courtesy of NOAA/OAR/ESRL PSL at https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html. Coupled Model Intercomparison Project, Phase 6 (CMIP6) daily sea surface temperature data were obtained from the National Computational Infrastructure (NCI) node of the Earth System Grid Federation (ESGF) at https://esgf.nci.org.au/search/cmip6-nci. The processing scripts used in this study to analyse the data are available at https://github.com/jbkajtar/sst_tasmania. The raw and processed data analysed, from both observations and models, are available to download at https://doi.org/https://doi.org/10.25959/F33G-8234. The daily sea surface temperature, including the area average timeseries for each of the subdomains and scenarios are provided for 1982–2100. The raw data, and data with common calendar, mean bias corrected, and seasonal bias corrected temperatures, are all provided.

Declarations

Competing interests The authors declare no competing interests.

References

Battaglene S, Carter C, Hobday A, Lyne V, Nowak B (2008) Scoping study into adaptation of the Tasmanian salmonid aquaculture industry to potential impacts of climate change. Natl Agric Climate Change Action Plan: Implementation Programme Report

Boyce DG, Tittensor DP, Garilao C, Henson S, Kaschner K, Kesner-Reyes K, Pigot A, Reyes RB, Reygondeau G, Schleit KE, Shackell N, Sorongon-Yap P, Worm B (2022) A climate risk index for marine life. Nat Clim Chang 12:854–862. https://doi.org/10.1038/s41558-022-01437-y

Caputi N, Kangas M, Denham A, Feng M, Pearce A, Hetzel Y, Chandrapavan A (2016) Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot spot. Ecol Evol 6(11):3583–3593. https://doi.org/10.1002/ece3.2137

Cardona OD, van Aalst MK, Birkmann J, Fordham M, Mc Gregor G, Rosa P, Pulwarty RS, Schipper ELF, Sinh BT, Décamps H, Keim M, Davis I, Ebi KL, Lavell A, Mechler R, Murray V, Pelling M, Pohl J, Smith AO, Thomalla F (2012) Determinants of risk: exposure and vulnerability. Manag

Risks Extreme Events Disasters Adv Clim Change Adapt: Special Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/CBO9781139177245.005

Carvalho D, Rafael S, Monteiro A, Rodrigues V, Lopes M, Rocha A (2022) How well have CMIP3, CMIP5 and CMIP6 future climate projections portrayed the recently observed warming. Sci Rep 12:11983. https://doi.org/10.1038/s41598-022-16264-6

Cavole LM, Demko AM, Diner RE, Giddings A, Koester I, Pagniello CMLS, Paulsen ML, Ramirez-Valdez A, Schwenck SM, Yen NK, Zill ME, Franks PJS (2016) Biological impacts of the 2013–2015 warm-water anomaly in the northeast Pacific: winners, losers, and the future. Oceanography 29(2):273–285. https://doi.org/10.5670/oceanog.2016.32

de Kantzow M, Hick P, Becker J, Whittington R (2016) Effect of water temperature on mortality of Pacific oysters Crassostrea gigas associated with microvariant ostreid herpesvirus 1 (OsHV-1 μVar). Aquac Environ Interact 8(2010):419–428. https://doi.org/10.3354/aei00186

Department of Natural Resources and Environment Tasmania (2021) Tasmanian Agri-Food Scorecard 2020–21. In Tasmanian Agri-Food. https://nre.tas.gov.au/Documents/Tasmanian%20Agri-Food%20SCORECARD%202020-21.PDF

Dunstan PK, Moore BR, Bell JD, Holbrook NJ, Oliver ECJ, Risbey J, Foster SD, Hanich Q, Hobday AJ, Bennett NJ (2018) How can climate predictions improve sustainability of coastal fisheries in Pacific Small-Island Developing States? Mar Policy 88(September 2017):295–302. https://doi.org/10.1016/j.marpol.2017.09.033

Eakin CM, Sweatman HPA, Brainard RE (2019) The 2014–2017 global-scale coral bleaching event: insights and impacts. Coral Reefs 38(4):539–545. https://doi.org/10.1007/s00338-019-01844-2

Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 9(5):1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Fiedler T, Pitman AJ, Mackenzie K, Wood N, Jakob C, Perkins-Kirkpatrick SE (2021) Business risk and the emergence of climate analytics. Nat Clim Chang 11:87–94. https://doi.org/10.1038/s41558-020-00984-6

Flato GM, Marotzke J, Abiodun B, Braconnot P, Chou SC, Collins WJ, Cox PM (2013) Evaluation of climate models. Clim Change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change 741–866

Fogarty HE, Cvitanovic C, Hobday AJ, Pecl GT (2020) An assessment of how Australian fisheries management plans account for climate change impacts. Front Mar Sci 7(December):591642. https://doi.org/10.3389/fmars.2020.591642

Fogarty HE, Cvitanovic C, Hobday AJ, Pecl GT (2021) Stakeholder perceptions on actions for marine fisheries adaptation to climate change. Mar Freshw Res. https://doi.org/10.1071/mf21055

Fordham DA, Mellin C, Russell BD, Akçakaya RH, Bradshaw CJA, Aiello-Lammens ME, Caley JM, Connell SD, Mayfield S, Shepherd SA, Brook BW (2013) Population dynamics can be more important than physiological limits for determining range shifts under climate change. Glob Change Biol 19(10):3224–3237. https://doi.org/10.1111/gcb.12289

Frölicher TL, Laufkötter C (2018) Emerging risks from marine heat waves. Nat Commun 9:650. https://doi.org/10.1038/s41467-018-03163-6

Galli G, Solidoro C, Lovato T (2017) Marine heat waves hazard 3D maps and the risk for low motility organisms in a warming Mediterranean Sea. Front Mar Sci 4 https://doi.org/10.3389/fmars.2017.00136

Gilroy A, Edwards SJ (1998) Optimum temperature for growth of Australian abalone: preferred temperature and critical thermal maximum for blacklip abalone, Haliotis rubra (Leach), and greenlip abalone, Haliotis laevigata (Leach). Aquac Res 29:481–485. https://doi.org/10.1046/j.1365-2109.1998.00241.x

Grose MR, Narsey S, Delage FP, Dowdy AJ, Bador M, Boschat G, Chung C, Kajtar JB, Rauniyar S, Freund MB, Lyu K, Rashid HA, Zhang X, Wales S, Trenham C, Holbrook NJ, Cowan T, Alexander LV, Arblaster JM, Power S (2020) Insights from CMIP6 for Australia's future climate. Earth's Futur 8:e2019EF001469. https://doi.org/10.1029/2019EF001469

Gruber N, Boyd PW, Frölicher TL, Vogt M (2021) Biogeochemical extremes and compound events in the ocean. Nature 600:395–401. https://doi.org/10.1038/s41586-021-03981-7

Harris JO, Burke CM, Edwards SJ, Johns DR (2005) Effects of oxygen supersaturation and temperature on juvenile greenlip, Haliotis laevigata Donovan, and blacklip, Haliotis rubra Leach, abalone. Aquac Res 36:1400–1407. https://doi.org/10.1111/j.1365-2109.2005.01360.x

Hartog JR, Spillman CM, Smith G, Hobday AJ (2023) Forecasts of marine heatwaves for marine industries: reducing risk, building resilience and enhancing management responses. Deep Sea Res Part II 209:105276. https://doi.org/10.1016/j.dsr2.2023.105276

Hayashida H, Matear RJ, Strutton PG, Zhang X (2020) Insights into projected changes in marine heatwaves from a high-resolution ocean circulation model. Nat Commun 11:4352. https://doi.org/10.1038/s41467-020-18241-x

Hobday AJ, Alexander LV, Perkins-Kirkpatrick SE, Smale DA, Straub SC, Oliver ECJ, Benthuysen JA, Burrows MT, Donat MG, Feng M, Holbrook NJ, Moore PJ, Scannell HA, Sen Gupta A, Wernberg T (2016) A hierarchical approach to defining marine heatwaves. Prog Oceanogr 141:227–238. https://doi.org/10.1016/j.pocean.2015.12.014

Hobday AJ, Oliver ECJ, Sen Gupta A, Benthuysen JA, Burrows MT, Donat MG, Holbrook NJ, Moore PJ, Thomsen MS, Wernberg T, Smale DA (2018a) Categorizing and naming marine heatwaves. Oceanography 31(2):162–173. https://doi.org/10.5670/oceanog.2018.205

Hobday AJ, Spillman CM, Eveson JP, Hartog JR, Zhang X, Brodie S (2018b) A framework for combining seasonal forecasts and climate projections to aid risk management for fisheries and aquaculture. Front Mar Sci 5:1–9. https://doi.org/10.3389/fmars.2018.00137

Holbrook NJ, Bindoff NL (1997) Interannual and decadal temperature variability in the Southwest Pacific Ocean between 1955 and 1988. J Clim 10:1035–1049. https://doi.org/10.1175/1520-0442(1997)010%3c1035:IADTVI%3e2.0.CO;2

Huang B, Liu C, Banzon V, Freeman E, Graham G, Hankins B, Smith T, Zhang H-M (2021a) Improvements of the daily optimum sea surface temperature (DOISST) - version 2.1. J Clim 34:2923–2939. https://doi.org/10.1175/JCLI-D-20-0166.1

Huang B, Liu C, Freeman E, Graham G, Smith T, Zhang HM (2021b) Assessment and intercomparison of NOAA daily optimum interpolation sea surface temperature (DOISST) version 2.1. J Clim https://doi.org/10.1175/JCLI-D-20-0166.1

Hughes TP, Kerry JT, Baird AH, Connolly SR, Dietzel A, Eakin CM, Heron SF, Hoey AS, Hoogenboom MO, Liu G, McWilliam MJ, Pears RJ, Pratchett MS, Skirving WJ, Stella JS, Torda G (2018) Global warming transforms coral reef assemblages. Nature 556:492–496. https://doi.org/10.1038/s41586-018-0041-2

IPCC (2021) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC (2012) Special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX). In C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley (Eds.), Managing the risks of extreme events and disasters to advance climate change adaptation. https://doi.org/10.1017/cbo9781139177245

IPCC (2014) Climate change 2014 impacts, adaptation and vulnerability: part a: global and sectoral aspects: working group II contribution to the fifth assessment report of the intergovernmental panel on climate change (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White, Eds.). https://doi.org/10.1017/CBO9781107415379

Johnson, C. R., Banks, S. C., Barrett, N. S., Cazassus, F., Dunstan, P. K., Edgar, G. J., Frusher, S. D., Gardner, C., Haddon, M., Helidoniotis, F., Hill, K. L., Holbrook, N. J., Hosie, G. W., Last, P. R., Ling, S. D., Melbourne-Thomas, J., Miller, K., Pecl, G. T., Richardson, A. J., … Taw, N. (2011). Climate change cascades: shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. Exp Mar Biol Ecol 400(1–2) 17–32 https://doi.org/10.1016/j.jembe.2011.02.032

Kajtar JB, Holbrook NJ, Hernaman V (2021) A catalogue of marine heatwave metrics and trends for the Australian region. J Southern Hemisphere Earth Syst Sci 71(3):284–302. https://doi.org/10.1071/ES21014

Kajtar JB, Bachman SD, Holbrook NJ, Pilo GS (2022) Drivers, dynamics, and persistence of the 2017/2018 Tasman Sea marine heatwave. J Geophys Res: Oceans 127:e2022JC018931. https://doi.org/10.1029/2022JC018931

Kajtar JB, Holbrook NJ (2021) Future projections of marine heatwave hazards to aquaculture and fisheries in Tasmania. http://ecite.utas.edu.au/147866

Kajtar, J. B., Holbrook, N. J., & Lyth, A. (2021). Assessment and communication of risks to Tasmanian aquaculture and fisheries from marine heatwaves: stakeholder engagement synthesis. http://ecite.utas.edu.au/147867

Liu G, Strong AE, Skirving W (2003) Remote sensing of sea surface temperatures during 2002 Barrier Reef coral bleaching. EOS Trans Am Geophys Union 84(15):137–141

Luyet V, Schlaepfer R, Parlange MB, Buttler A (2012) A framework to implement stakeholder participation in environmental projects. J Environ Manage 111:213–219. https://doi.org/10.1016/j.jenvman.2012.06.026

Lyth A, Harwood A, Hobday AJ, McDonald J (2016) Place influences in framing and understanding climate change adaptation challenges. Local Environ 21:730–751. https://doi.org/10.1080/13549839.2015.1015974

Marin M, Bindoff NL, Feng M, Phillips HE (2021a) Slower long-term coastal warming drives dampened trends in coastal marine heatwave exposure. J Geophys Res: Oceans 126:e2021JC017930. https://doi.org/10.1029/2021jc017930

Marin M, Feng M, Phillips HE, Bindoff NL (2021b) A global, multiproduct analysis of coastal marine heatwaves: distribution, characteristics and long-term trends. J Geophys Res: Oceans 126:e2020JC016708. https://doi.org/10.1029/2020jc016708

McInnes KL, Kajtar JB, Holbrook NJ, Hemer M, Hernaman V (2021) Coastal climate services: a review of needs for coastal, marine and offshore applications. Earth Syst Clim Change Hub Rep No. 18 (Issue 18)

Meng H, Hayashida H, Norazmi-Lokman NH, Strutton PG (2022) Benefits and detrimental effects of ocean warming for Tasmanian salmon aquaculture. Cont Shelf Res 246:104829. https://doi.org/10.1016/j.csr.2022.104829

Metcalf SJ, van Putten EI, Frusher SD, Tull M, Marshall NA (2014) Adaptation options for marine industries and coastal communities using community structure and dynamics. Sustain Sci 9(3):247–261. https://doi.org/10.1007/s11625-013-0239-z

Mills KE, Pershing AJ, Brown CJ, Chen Y, Chiang FS, Holland DS, Lehuta S, Nye JA, Sun JC, Thomas AC, Wahle RA (2013) Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. Oceanography 26(2):191–195. https://doi.org/10.5670/oceanog.2013.27

Mundy CN, McAllister JD (2021) Tasmanian Abalone Fishery Assessment 2020. https://www.imas.utas.edu.au/__data/assets/pdf_file/0005/1455854/TasAbFisheryAssess2020.pdf

O'Neill BC, Tebaldi C, van Vuuren DP, Eyring V, Friedlingstein P, Hurtt G, Knutti R, Kriegler E, Lamarque JF, Lowe J, Meehl GA, Moss R, Riahi K, Sanderson BM (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci Model Dev 9(9):3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Oliver ECJ, Benthuysen JA, Bindoff NL, Hobday AJ, Holbrook NJ, Mundy CN, Perkins-Kirkpatrick SE (2017) The unprecedented 2015/16 Tasman Sea marine heatwave. Nat Commun 8(May):1038. https://doi.org/10.1038/ncomms16101

Oliver ECJ, Donat MG, Burrows MT, Moore PJ, Smale DA, Alexander LV, Benthuysen JA, Feng M, Sen Gupta A, Hobday AJ, Holbrook NJ, Perkins-Kirkpatrick SE, Scannell HA, Straub SC, Wernberg T (2018) Longer and more frequent marine heatwaves over the past century. Nat Commun 9(1):1324. https://doi.org/10.1038/s41467-018-03732-9

Oliver ECJ, Burrows MT, Donat MG, sen Gupta A, Alexander LV, Perkins-kirkpatrick SE, Benthuysen JA, Hobday AJ, Holbrook NJ, Moore PJ, Thomsen MS, Wernberg T, Smale DA (2019) Projected marine heatwaves in the 21st century and the potential for ecological impact. Front Mar Sci 6(December):734. https://doi.org/10.3389/fmars.2019.00734

Perkins-Kirkpatrick SE, King AD, Cougnon EA, Grose MR, Oliver ECJ, Holbrook NJ, Lewis SC, Pourasghar F (2019) The role of natural variability and anthropogenic climate change in the 2017/18 Tasman Sea marine heatwave. Bull Am Meteor Soc 100:S105–S110. https://doi.org/10.1175/BAMS-D-18-0116.1

Pershing AJ, Mills KE, Dayton AM, Franklin BS, Kennedy BT (2018) Evidence for adaptation from the 2016 marine heatwave in the Northwest Atlantic Ocean. Oceanography 31(152–161) https://doi.org/10.5670/oceanog.2018.213

Pilo GS, Holbrook NJ, Kiss AE, Hogg AM (2019) Sensitivity of marine heatwave metrics to ocean model resolution. Geophys Res Lett 46:14604–14612. https://doi.org/10.1029/2019GL084928

Plecha SM, Soares PMM (2020) Global marine heatwave events using the new CMIP6 multi-model ensemble: from shortcomings in present climate to future projections. Environ Res Lett 15:124058. https://doi.org/10.1088/1748-9326/abc847

Qiu Z, Qiao F, Jang CJ, Zhang L, Song Z (2021) Evaluation and projection of global marine heatwaves based on CMIP6 models. Deep-Sea Res Part II: Topical Studies in Oceanography 194:104998. https://doi.org/10.1016/j.dsr2.2021.104998

Reynolds RW, Smith TM, Liu C, Chelton DB, Casey KS, Schlax MG (2007) Daily high-resolution-blended analyses for sea surface temperature. J Clim 20:5473–5496. https://doi.org/10.1175/2007JCLI1824.1

Ridgway KR (2007) Long-term trend and decadal variability of the southward penetration of the East Australian Current. Geophys Res Lett 34:L13613. https://doi.org/10.1029/2007GL030393

Röckmann C, van Leeuwen J, Goldsborough D, Kraan M, Piet G (2015) The interaction triangle as a tool for understanding stakeholder interactions in marine ecosystem based management. Mar Policy 52:155–162. https://doi.org/10.1016/j.marpol.2014.10.019

Rodgers C, Arzul I, Carrasco N, Furones Nozal D (2019) A literature review as an aid to identify strategies for mitigating ostreid herpesvirus 1 in Crassostrea gigas hatchery and nursery systems. Rev Aquac 11(3):565–585. https://doi.org/10.1111/raq.12246

Russo S, Sillmann J, Sippel S, Barcikowska MJ, Ghisetti C, Smid M, O'Neill B (2019) Half a degree and rapid socioeconomic development matter for heatwave risk. Nat Commun 10:136. https://doi.org/10.1038/s41467-018-08070-4

Salinger MJ, Renwick J, Behrens E, Mullan AB, Diamond HJ, Sirguey P, Smith RO, Trought MCT, Alexander LV, Cullen NJ, Fitzharris BB, Hepburn CD, Parker AK, Sutton PJ (2019) The unprecedented coupled ocean-atmosphere summer heatwave in the New Zealand region 2017/18: drivers, mechanisms and impacts. Environ Res Lett 14(4):044023. https://doi.org/10.1088/1748-9326/ab012a

Shepherd TG (2019) Storyline approach to the construction of regional climate change information. Proc Royal Soc a: Mathematical, Physical and Engineering Sciences 475:20190013. https://doi.org/10.1098/rspa.2019.0013

Shepherd TG, Boyd E, Calel RA, Chapman SC, Dessai S, Dima-West IM, Fowler HJ, James R, Maraun D, Martius O, Senior CA, Sobel AH, Stainforth DA, Tett SFB, Trenberth KE, van den Hurk BJJM, Watkins NW, Wilby RL, Zenghelis DA (2018) Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Clim Change 151:555–571. https://doi.org/10.1007/s10584-018-2317-9

Shepherd SA, Breen PA (1992) Mortality in abalone: its estimation, variability and causes. In S. A. Shepherd, M. J. Tegner, & S. A. Guzmán del Próo (Eds.), Abalone of the world. Biology, Fisheries and Culture' (pp. 276–304). Fishing News Books, London

Smale DA, Wernberg T, Oliver ECJ, Thomsen MS, Harvey BP, Straub SC, Burrows MT, Alexander LV, Benthuysen JA, Donat MG, Feng M, Hobday AJ, Holbrook NJ, Perkins-Kirkpatrick SE, Scannell HA, sen Gupta A, Payne BL, Moore PJ (2019) Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Clim Change 9:306–312. https://doi.org/10.1038/s41558-019-0412-1

Spillman CM, Smith GA, Hobday AJ, Hartog JR (2021) Onset and decline rates of marine heatwaves: global trends, seasonal forecasts and marine management. Front Clim 3(December):1–13. https://doi.org/10.3389/fclim.2021.801217

Tassal Group Limited (2016) Annual Report 2016. http://www.tassal.com.au/wp-content/uploads/2016/08/FY2016-Annual-Report-Appendix-4E.pdf

Thompson P, McDonald K (2020) Spatial and seasonal trends in net primary production. State Trends Australia's Oceans Rep 2.2.1–2.2.5 https://doi.org/10.26198/5e16a4a749e7a

Tuynman H, Dylewski M (2022) Australian fisheries and aquaculture statistics 2021. https://doi.org/10.25814/amdt-x682

Ugalde SC, Preston J, Ogier E, Crawford C (2018) Analysis of farm management strategies following herpesvirus (OsHV-1) disease outbreaks in Pacific oysters in Tasmania, Australia. Aquaculture 495:179–186. https://doi.org/10.1016/j.aquaculture.2018.05.019

van Putten EI, Metcalf SJ, Frusher SD, Marshall NA, Tull M (2014) Transformation of coastal communities: where is the marine sector heading. Australas J Reg Stud 20(2):286–324

Watson RA, Nowara GB, Tracey SR, Fulton EA, Bulman CM, Edgar GJ, Barrett NS, Lyle JM, Frusher SD, Buxton CD (2013) Ecosystem model of Tasmanian waters explores impacts of climate-change induced changes in primary productivity. Ecol Model 264:115–129. https://doi.org/10.1016/j.ecolmodel.2012.05.008

Yang C, Leonelli FE, Marullo S, Artale V, Beggs HM, Nardelli BB, Chin TM, de Toma V, Good S, Huang B, Merchant CJ, Sakurai T, Santoleri R, Vazquez-Cuervo J, Zhang HM, Pisano A (2021) Sea surface temperature intercomparison in the framework of the Copernicus Climate Change Service (C3S). J Clim 34(13):5257–5283. https://doi.org/10.1175/JCLI-D-20-0793.1

Zarkasi KZ, Taylor RS, Abell GCJ, Tamplin ML, Glencross BD, Bowman JP (2016) Atlantic salmon (Salmo salar L.) gastrointestinal microbial community dynamics in relation to digesta properties and diet. Microb Ecol 71(3):589–603. https://doi.org/10.1007/s00248-015-0728-y

Zelinka MD, Myers TA, McCoy DT, Po-Chedley S, Caldwell PM, Ceppi P, Klein SA, Taylor KE (2020) Causes of higher climate sensitivity in CMIP6 models. Geophys Res Lett 47:e2019GL085782. https://doi.org/10.1029/2019GL085782