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Marine heatwaves off eastern Tasmania: Trends, interannual variability, and predictability

Eric C.J. Oliver[a,b,c,*], Véronique Lago[a,b,d], Alistair J. Hobday[d], Neil J. Holbrook[a,e], Scott D. Ling[a], Craig N. Mundy[a]

[a] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia
[b] Australian Research Council Centre of Excellence for Climate System Science, University of Tasmania, Hobart, Tasmania, Australia
[c] Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada
[d] CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia
[e] Australian Research Council Centre of Excellence for Climate Extremes, University of Tasmania, Hobart, Tasmania, Australia

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ABSTRACT

Surface waters off eastern Tasmania are a global warming hotspot. Here, mean temperatures have been rising over several decades at nearly four times the global average rate, with concomitant changes in extreme temperatures – marine heatwaves. These changes have recently caused the marine biodiversity, fisheries and aquaculture industries off Tasmania's east coast to come under stress. In this study we quantify the long-term trends, variability and predictability of marine heatwaves off eastern Tasmania. We use a high-resolution ocean model for Tasmania's eastern continental shelf. The ocean state over the 1993–2015 period is hindcast, providing daily estimates of the three-dimensional temperature and circulation fields. Marine heatwaves are identified at the surface and subsurface from ocean temperature time series using a consistent definition. Trends in marine heatwave frequency are positive nearly everywhere and annual marine heatwave days and penetration depths indicate significant positive changes, particularly off southeastern Tasmania. A decomposition into modes of variability indicates that the East Australian Current is the dominant driver of marine heatwaves across the domain. Self-organising maps are used to identify 12 marine heatwave types, each with its own regionality, seasonality, and associated large-scale oceanic and atmospheric circulation patterns. The implications of this work for marine ecosystems and their management were revealed through review of past impacts and stakeholder discussions regarding use of these data.

1. Introduction

Heatwaves are major climate extremes, in both the atmosphere and the ocean, often with devastating impacts on biota and ecosystems. In the ocean, marine heatwaves have led to observable redistributions of marine species, reconfigurations of ecosystems, and economic losses in fisheries and aquaculture industries (Perry et al., 2005; Garrabou et al., 2009; Wernberg et al., 2013; Mills et al., 2013; Oliver et al., 2017a). The surface ocean off eastern Tasmania is a global warming hotspot (Hobday and Pecl, 2014) and local ecosystems face major challenges due to changes in regional oceanography under climate change (Oliver et al., 2014, 2015; Oliver and Holbrook, 2014; Sloyan and O'Kane, 2015). It is likely that global warming has altered the frequency, duration and intensity of marine heatwaves, and will continue to do so in the future. The rate of change in the physical environment could outstrip the capacity of populations, with the exception of very-short lived species, to adapt to the new temperature regime (Visser, 2008; Hoffman and Sgro, 2011; Kelly et al., 2011). Therefore it is important, ecologically and economically, that we understand the historical context and predictability of marine heatwaves.

Marine heatwaves are extreme events in which ocean temperatures are above the normal range for an extended period of time and can cause widespread and significant damage to marine ecosystems (Johnson and Holbrook, 2014; Hobday et al., 2016a). In particular, marine ecosystems accustomed to low temperatures and which are undergoing change due to long-term increases in water temperature, including those around Tasmania, are particularly vulnerable to additional short term environmental shocks such as marine heatwaves. Increasing temperatures, including transient marine heatwaves, may push ecosystems over a "tipping point" (Lenton et al., 2008; Serrao-Neumann

* Corresponding author at: Department of Oceanography, Dalhousie University, Life Sciences Centre Room 5617, 1355 Oxford Street, Halifax, Nova Scotia, Canada. Tel: +1 902 494 2505.
E-mail address: eric.oliver@dal.ca (E.C.J. Oliver).

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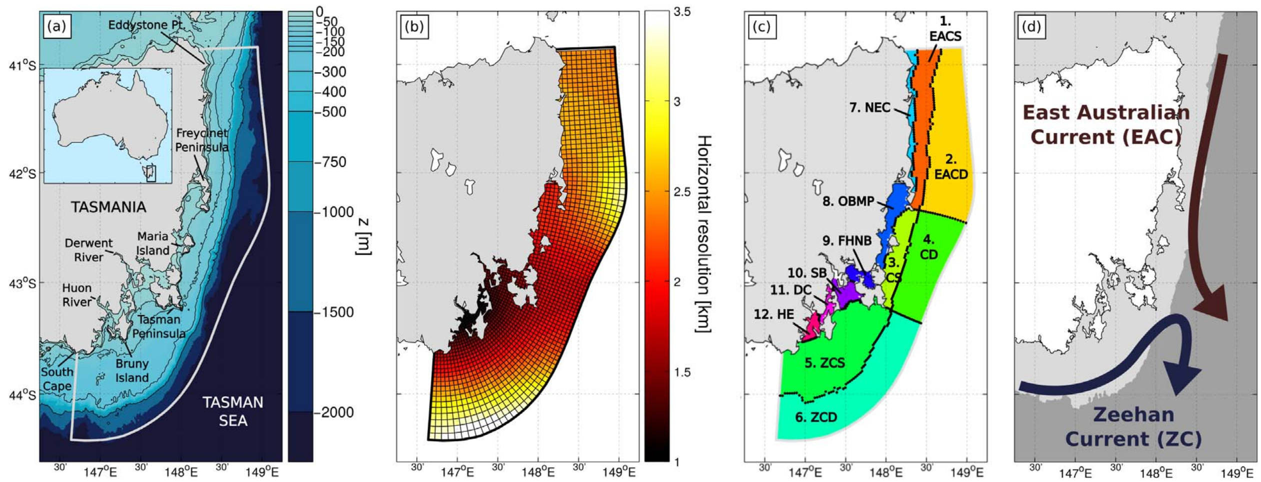

Fig. 1. ETAS ocean model (a) domain and bathymetry, (b) curvilinear grid and horizontal resolution, and (c) sub-domain regional definitions. (d) A schematic of the summer (Dec-Jan-Feb) mean surface circulation with the Zeehan Current (ZC) and East Australian Current (EAC) indicated (adapted from Fig. 15 in Oliver et al. (2016)). Region names are East Australian Current-Deep (EACD), East Australian Current-Shelf (EACS), Zeehan Current-Deep (ZD), Zeehan Current-Shelf (ZS), Confluence-Deep (CD), Confluence-Shelf (CS), Northeast Coast (NEC), Oyster Bay & Mercury Passage (OBMP), Frederick Henry and Norfolk Bays (FHNB), Storm Bay (SB), D'Entrecasteaux Channel (DC) and Huon Estuary (HE).

et al., 2016) whereby they enter into a new state which is entirely different from its previous state. This type of tipping point change has been observed in Tasmania whereby marine ecosystems in some regions have changed from habitat-forming highly biodiverse kelp forests to a predominance of low biodiversity sea urchin barrens (Ling, 2008; Johnson et al., 2011). In addition, short-term winter warm spell events, i.e. heatwaves during wintertime, will enable high survival of urchin larvae in the region (Ling et al., 2009b).

Marine heatwaves have occurred off Tasmania's east coast in the past decades and have included impacts on marine ecosystems. A major marine heatwave was observed off southeastern Australia, including coastal Tasmania, in the summer of 2015/16 (Oliver et al., 2017a). This event lasted for 251 days and reached a peak intensity of 2.9 °C above climatology. Apparent impacts included the first outbreak of Pacific Oyster Mortality Syndrome, regional above-average abalone mortality, die-back of bull kelp *Durvillea potatorum* and localised bleaching of crayweed *Phyllospora comosa* (S. Ling, pers. obs.), and out-of-range fish observations. This event was driven by an anomalously strong southward extension of the East Australian Current and its occurrence was at least 6.8 times more likely due to anthropogenic climate change. It has also been noted that a complete die-back of giant kelp (*Macrocystis pyrifera*) occurred in the coastal waters off eastern Tasmania during a warm weather event in 1988 (Sanderson, 1990) and an extreme ocean temperature event in 2000/2001 caused extensive die-back of kelp beds formed by the crayweed *Phyllospora comosa* off eastern Tasmania (Valentine and Johnson, 2004). More recent events caused mass deaths of Tasmanian Abalone in March 2010 (Craig Mundy, IMAS, pers. comm.) and deaths in Atlantic Salmon aquaculture populations in 2012 (Alistair Hobday, CSIRO, pers. comm.).

This study performs a systematic analysis of marine heatwaves off eastern Tasmania over the 23-year period from 1993 to 2015. A numerical ocean model is used to reconstruct the historical marine heatwave record in the region as well as high-resolution estimates of the associated water temperatures and circulation. We quantify the mean state and long term trends of marine heatwave properties, which are particularly strong off the southeast of Tasmania. The interannual variability of annual marine heatwave days is decomposed into two modes of variability and the East Australian Current is associated with nearly half of the observed variability. Finally we organise each of the detected marine heatwaves into one of 12 types, using an automated neural network approach. Each type has a unique combination of marine heatwave properties, spatial and seasonal distribution, and associated oceanic and atmospheric circulation patterns. This typology may be used to inform analysis of trends in different types of marine heatwaves, and to prepare management responses based on event types.

2. Data and methods

The data and methods are presented as follows: the high-resolution ocean model output for the continental shelf off eastern Tasmania (Section 2.1), the coarse-resolution estimates of the atmospheric and offshore ocean states (Section 2.2), the definition of marine heatwaves (MHWs) and their properties (Section 2.3), the calculation of annual MHW time series (Section 2.4), the Empirical Orthogonal Function analysis technique for the decomposition of the annual time series into modes of variability (Section 2.5) and the Self-Organising Maps analysis technique for the organisation of MHWs into a set of distinct types (Section 2.6).

2.1. ETAS ocean model

The historic ocean record off eastern Tasmania is derived from daily three-dimensional ocean temperatures and currents from the Eastern TASmania (ETAS) coastal ocean model which covers the 23-year period from 1993 to 2015 (Oliver et al., 2016). The ETAS model data provide an unprecedented high-resolution record of the marine climate variations off eastern Tasmania and represent our best estimate of the ocean state off eastern Tasmania. The ETAS model is based on the Sparse Hydrodynamic Ocean Code (SHOC; Herzfeld, 2006), a numerical ocean model well-suited to complex curvilinear grids with a large proportion of "land cells". The ETAS model covers the eastern continental shelf of Tasmania from South Cape in the south to just north of Eddystone Point in the northeast and seaward to just beyond the shelf break (~ 2500 m, Fig. 1a; Oliver et al., 2016). The model has a curvilinear grid, in a 200×120 grid cell configuration, with a horizontal resolution of ~ 1.9 km on average (Fig. 1b) and 43 z-levels in the vertical. Boundary forcing includes National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) Reanalysis (CFSR, 1993–2010, Saha