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The 2011 marine heat wave in Cockburn Sound, southwest Australia

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Abstract. Over 2000 km of Western Australian coastline experienced a significant marine heat wave in February and March 2011. Seawater temperature anomalies of +2–4 °C were recorded at a number of locations, and satellite-derived SSTs (sea surface temperatures) were the highest on record. Here, we present seawater temperatures from southwestern Australia and describe, in detail, the marine climatology of Cockburn Sound, a large, multiple-use coastal embayment. We compared temperature and dissolved oxygen levels in 2011 with data from routine monitoring conducted from 2002–2010. A significant warming event, 2–4 °C in magnitude, persisted for > 8 weeks, and seawater temperatures at 10 to 20 m depth were significantly higher than those recorded in the previous 9 yr. Dissolved oxygen levels were depressed at most monitoring sites, being $\sim 2\,\mathrm{mg\,l^{-1}}$ lower than usual in early March 2011. Ecological responses to short-term extreme events are poorly understood, but evidence from elsewhere along the Western Australian coastline suggests that the heat wave was associated with high rates of coral bleaching; fish, invertebrate and macroalgae mortalities; and algal blooms. However, there is a paucity of historical information on ecologically-sensitive habitats and taxa in Cockburn Sound, so that formal examinations of biological responses to the heat wave were not possible. The 2011 heat wave provided insights into conditions that may become more prevalent in Cockburn Sound, and elsewhere, if the intensity and frequency of short-term extreme events increases as predicted.

1 Introduction

The frequency and intensity of short-term thermal events (i.e. “heat waves”) is very likely to increase as a consequence of anthropogenic climate change (Solomon et al., 2007). A recent analysis showed that, in the last 30 yr, the number of days of anomalously high seawater temperatures has increased along 38 % of the world’s coastlines (Lima and Wethey, 2012). As such, documenting, predicting and managing the effects of such events has (and will continue to) become increasingly important. In marine ecosystems, anomalous warming events are often concurrent with observations of mass mortalities of a range of taxa, from macrophytes and invertebrates to fish (Harvell et al., 1999; Garrabou et al., 2009). These marine organisms are generally ectothermic (and are therefore strongly influenced by ambient water temperature), so that heat waves can have major physiological and ecological implications (Harley et al., 2006).

In early 2011, a large-scale marine heat wave affected > 2000 km of the southwestern Australian coastline (Pearce et al., 2011). This warming was associated with one of the strongest La Niña events ever recorded, which caused a stronger than usual Indonesian Throughflow (Pearce et al., 2011). This, in turn, fed warm tropical waters into the poleward flowing Leeuwin Current, which strongly influences the oceanography and biology of southwestern Australia as it flows along its coastline (Gaughan and Fletcher, 1997; Koslow et al., 2008). Increased flow of the Leeuwin Current was evidenced by anomalously high sea level readings in temperate regions (e.g. Fremantle Port, see Gaughan and Fletcher, 1997 for further details) and resulted in increased transport of warm water along the coastline of Western Australia (Fig. 1). Moreover, these strong La Niña conditions

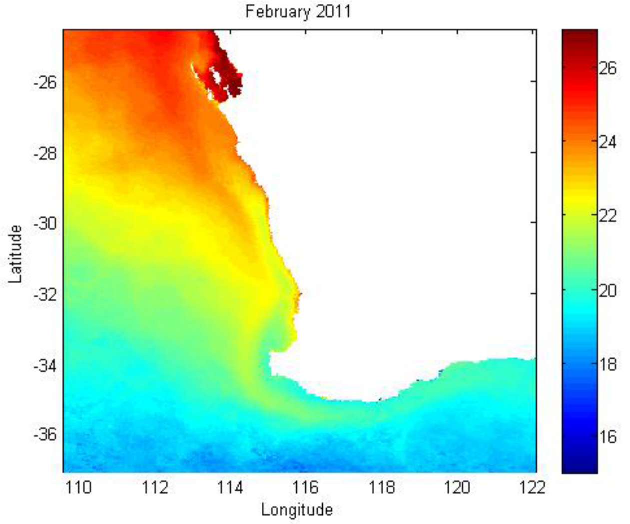

Fig. 1. Mean SST for February 2011 along the southwest Australian coastline. SSTs generated from NASA's MODIS Aqua 4 km dataset, scalebar indicates SSTs in °C.

were superimposed onto a gradual warming trend in the southeast Indian Ocean over the past few decades (Pearce and Feng, 2007). As a result, seawater temperature anomalies of up to 5 °C were recorded at restricted locations (e.g. Jurien Bay, 30.3° S), while anomalies of at least 2 °C were observed along > 2000 km of coastline (Pearce et al., 2011). The heat wave persisted for > 8 weeks, during which time satellite-derived SSTs (sea surface temperatures) for much of the coastline were the highest since records began some 30 yr ago (Pearce et al., 2011). Here, we present detailed in situ environmental data collected from the semi-enclosed embayment of Cockburn Sound (32.1706° S, 115.7239° E) to characterise the heat wave event in an important, multiple-use coastal system.

2 Method

2.1 Study area

Cockburn Sound and its surrounding coastline form one of the most commercially and recreationally exploited embayments in Australia, contributing > $20 billion to the Australian economy each year (Botting et al., 2009). This revenue is primarily generated from heavy coastal industry (e.g. through the manufacture of alumina, nickel and cement), although sea-based activities, including commercial and recreational fishing (e.g. for Blue Swimmer Crabs, herring and whiting), aquaculture (e.g. of mussels) and tourism, are also important. Cockburn Sound comprises a large, low-gradient basin bounded by a shallow (5 m) sand bank to the north, the West Australian coastline to the east, Cape Peron to the south and Garden Island to the west (Fig. 2). The main basin gradually slopes to a maximum depth of 22 m. The sound is approximately 22 km long and up to 15 km wide, encompassing an area of 124 km^2. Cockburn Sound comprises a range of marine habitats – primarily seagrass meadows and unvegetated sediments but also isolated patches of hard rock and coral – which support considerable abundances of commercially important fish and invertebrate species (Wells and Threlfall, 1980; Potter et al., 1983), as well as ecologically important non-target organisms (such as the sea star, *Archaster angulatus*).

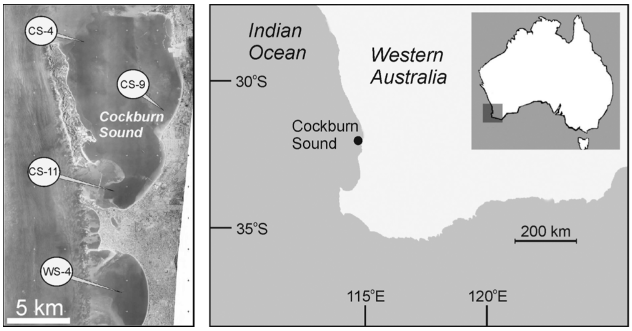

Fig. 2. Left: Long-term monitoring sites in Cockburn and Warnbro Sounds. Right: Location of the Cockburn Sound study area in southwestern Australia.

The ecosystem represents a complex, multiple-use embayment, with similar management issues and threats to other coastal systems both in Australia and internationally (e.g. nutrient run-off, coastal development, and species introductions; see Lotze et al., 2006). In particular Cockburn Sound is influenced by intense coastal industry, shipping and fishing practices, which pose ecological threats through run-off of nutrients and pollutants, introduced species and over-exploitation. Moreover, the system is susceptible to pronounced seasonal and short-term variability in environmental factors, such as temperature, salinity, dissolved oxygen and water movement (CSMC, 2009). Cockburn Sound supports extensive seagrass meadows, which provide a wealth of ecosystem services but are sensitive to environmental stressors and have suffered degradation in the past (Cambridge et al., 1986; Orth et al., 2006). Between the 1950s and 1970s, poor industrial practices led to highly nutrient-enriched waters, which in turn caused a 78 % decline in seagrass cover in the sound. The environment has improved considerably since then, although the marine embayment has also been affected by extensive industrial, defence, recreational and fringing urban development since the 1970s (Kendrick et al., 2002).

2.2 Monitoring data

Bottom water temperatures and dissolved oxygen (DO) concentrations (0.5 m from the bottom) were recorded at three Cockburn Sound water quality monitoring sites (sites CS4, 9 and 11) and an additional site in the adjacent Warnbro

Sound (WS4). Site CS4 is located in the north central area of Cockburn Sound in a deep basin with a depth of 20 m, site CS9 is on a shallow eastern shelf site between industrial areas with a depth of 10 m, while site CS11 is in a deep southern basin with a depth of 17 m (Fig. 2). The Warnbro Sound site is in the central eastern sound with a depth of 18 m (Fig. 2). Temperature and DO were measured in situ each week (at approximately the same time of day) by deploying a YSI 6600 multiparameter sonde. Data for 2011 were plotted against mean values for the preceding 9 yr (2002–2010, means ± standard error, "SE"). Data collected during the event, from early January through to late March (weeks 4–16, inclusive), were selected for statistical analysis. For each site, a one-way Analysis of Variance (ANOVA) was used to detect differences in temperature and DO between years, and, where a significant difference was observed (at $P < 0.05$), post-hoc Student-Newman–Keuls (SNK) tests were used to determine which year(s) were statistically distinct (data were first tested for normality and homogeneity of variance, using Shapiro–Wilk and Levene's tests, and were left untransformed for analysis). F-ratios and degrees of freedom associated with the numerator and denominator for ANOVA are provided for each test. Thermal Stress Anomalies (TSAs) were also calculated from the temperature data. TSAs were defined as weekly measurements that were $\geq 1\,^{\circ}\mathrm{C}$ higher than the warmest climatological week (means of 2002–2010). TSAs represent deviations from the maximum expected summertime temperatures and may therefore be of high ecological relevance (Selig et al., 2010). Moreover, as Degree Heating Weeks (DHWs) – a cumulative measure of thermal stress – are calculated in a similar way, it was possible to examine cumulative thermal stress at the monitoring sites. Here, DHWs refer to the number of cumulative weeks where temperatures were $\geq 1\,^{\circ}\mathrm{C}$ higher than the maximum expected summertime temperatures; one DHW is equivalent to one week of warming anomalies of 1 °C or half a week of warming anomalies of 2 °C, and so forth (see Mumby et al., 2004 for further discussion).

3 Results and discussion

Monitoring data indicated that water temperatures were anomalously high at the four study sites during the sampling period, with notable warming persisting from late January through to April (weeks 4–16) in both Cockburn and Warnbro Sounds. During this warm water event, a maximum bottom temperature of 26.62 °C was recorded. Historical records (2002–2010) indicate that bottom water temperatures at these monitoring sites typically range from 21.0 to 23.5 °C during these months. Plots of 2011 data against the 2002–2010 mean indicated a warming anomaly of 3–4 °C (Fig. 3). ANOVA tests showed that temperature varied significantly between years at all four sites ($F_{9,\,120}$ ranged from 4.7 to 7.1, $P < 0.001$ in all tests). Post-hoc tests showed that temperatures in 2011 were statistically higher than those recorded in all previous years at all sites. The magnitude of the warming event was ∼ 2–4 °C and persisted for ∼ 12 weeks. Thermal Stress Anomalies (TSAs) showed that temperatures exceeded the expected summer maximums at all monitoring sites, for a total of 4–12 weeks (Fig. 3). A maximum TSA of 3.3 °C was recorded at CS9. In terms of cumulative stress, Degree Heating Weeks ranged from 5 at WS4 to 17 at CS9 (Fig. 3). It is very likely that the Cockburn Sound warming event was driven, at least in part, by the regional-scale oceanographic processes associated with the anomalously strong La Niña conditions. In addition, Cockburn Sound experienced unusually warm air temperatures and weak winds during the summer of 2010/2011, which would have maximised local transfer of heat from the air to the sea to further warm the surface waters of the sound (Pearce et al., 2011).

Dissolved oxygen (DO) concentrations were markedly reduced within Cockburn Sound in early March, with a minimum value of $3.12\,\mathrm{mg\,l^{-1}}$ recorded at site CS11 (Fig. 4). The lowest bottom DO concentration previously recorded from Cockburn Sound was $4.9\,\mathrm{mg\,l^{-1}}$ (both at site CS11 in late February 2003 and site CS4 in March 2006). Statistically, DO concentrations varied significantly between years at all sites ($F_{9,120}$ ranged from 5.6 to 20.7, $P < 0.001$ in all tests). We recorded differences between sites in the magnitude of interannual variability, and DO levels in 2011 were not consistently lower than in previous years. Post-hoc tests showed that at site CS9, DO levels during 2011 were significantly lower than those recorded during all 9 previous years, whereas at sites CS4 and WS4 they were statistically lower in 2011 compared with 4 previous years (2002–2005, inclusive), while at site CS11 they were lower in 2011 than 2 previous years (2004 and 2005). Although DO trends during the event were less defined than temperature trends, they were still atypically low, especially at the Cockburn Sound sites, where DO concentrations decreased to about $2\,\mathrm{mg\,l^{-1}}$ lower than the norm in March. A range of factors influence water mixing and oxygen diffusion in Cockburn Sound, including bathymetry, seawater temperature, water density differences, local currents, surface winds, biological and sedimentary oxygen demand and phytoplankton activity (Rabalais and Turner, 2001). The coastal waters off Western Australia are typically oligotrophic, but due to historical influences, the Cockburn Sound system is considered mesotrophic with healthy oxygen levels (CSMC, 2009). As such, extensive hypoxic "dead zones" generally do not persist in the region, although episodic, localised hypoxia following algal blooms do occasionally occur (Diaz and Rosenberg, 2008). The low DO levels observed in early 2011 were most likely a consequence of increased stratification (driven by minimal surface mixing), perhaps in conjunction with increased biological activity during the warming period (Diaz and Rosenberg, 2008).

The Cockburn Sound Management Council received few reports of detrimental environmental events or incidents that

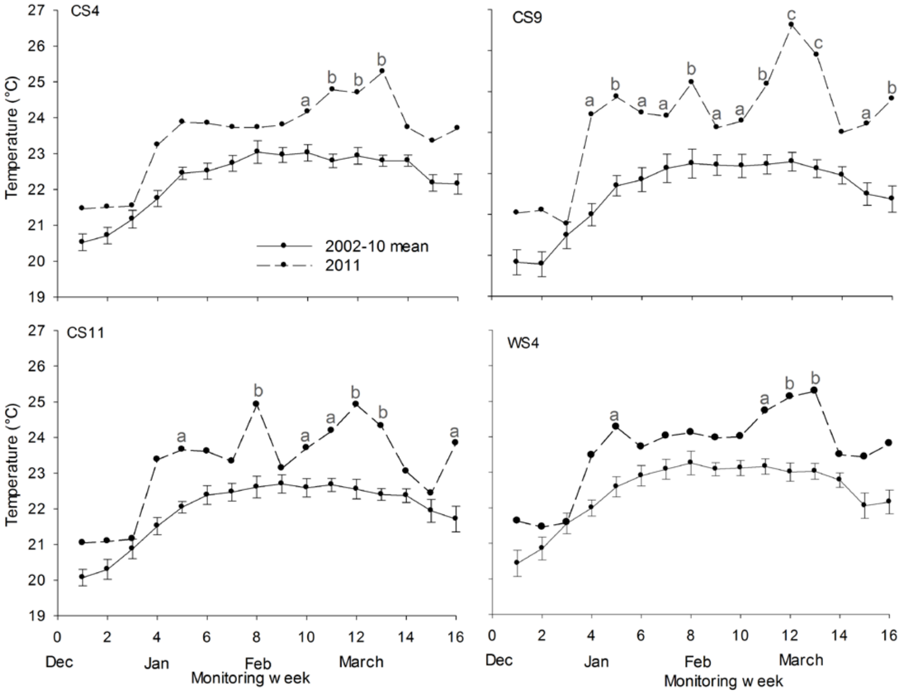

Fig. 3. Weekly bottom temperatures recorded during 2011, plotted against 2002–2010 mean temperatures (±SE) at each monitoring site ("monitoring week 1" relates to the first week in December). Thermal Stress Anomalies (TSAs) where weekly temperatures were ≥ 1 °C higher than the warmest climatological week (i.e. mean summer maximum, 2002–2010) at each site are indicated by lower case letters; a = TSA of 1.00–1.49 °C, b = TSA of 1.50–2.49 °C and c = TSA of ≥ 2.50 °C.

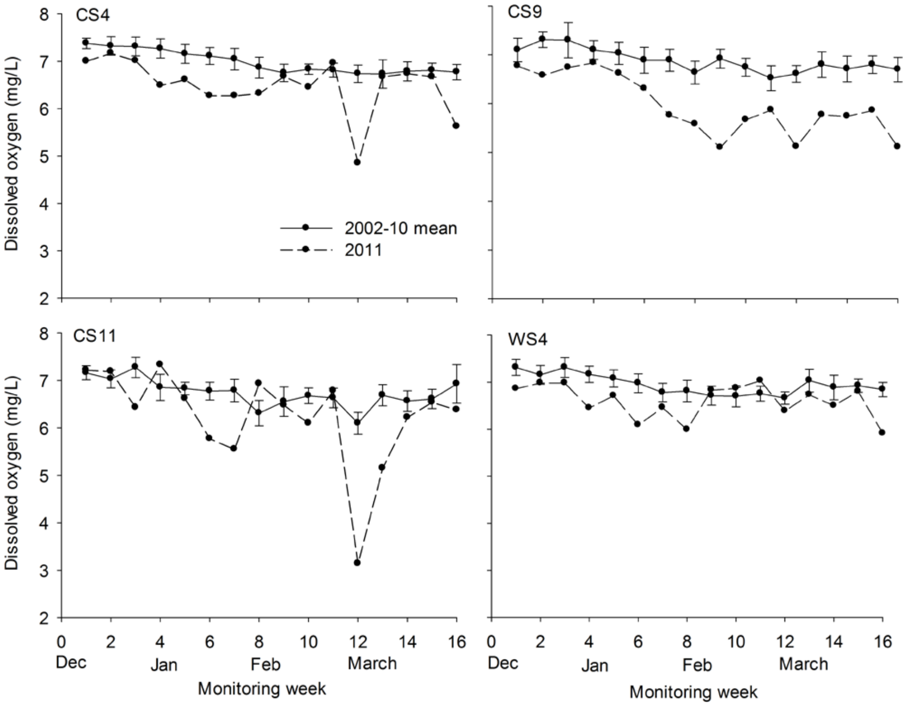

Fig. 4. Weekly dissolved oxygen (DO) recorded during 2011, plotted against 2002–2010 mean DO (±SE) at each monitoring site ("monitoring week 1" relates to the first week in December).

could be directly attributed to elevated temperatures or lower DO levels in Cockburn and Warnbro Sounds. Even so, confirmed reports of high invertebrate mortality (the starfish, *Archaster angulatus*) and algal blooms were probably associated with the warmer conditions. It is important to note, however, that these observations are not unusual for this time of the year, with occasional starfish kills and algal blooms typical in autumn. However, Cockburn Sound and surrounding waters support sensitive marine habitats, including isolated hard coral patches, which may have been affected by the heat wave but are not routinely monitored. Hard corals at Rottnest Island (20 km northwest of Cockburn Sound) exhibited high rates of bleaching in May 2011 (Thomson et al., 2011), while high levels of fish and invertebrate mortalities, widespread coral bleaching, shifts in benthic community structure and extensive algal blooms elsewhere along the coastline were attributed to the warming event (Pearce et al., 2011; Smale and Wernberg, 2012; Wernberg et al., 2012). As such, it is possible that the heat wave in Cockburn Sound had ecological consequences that went undetected and warrant further investigation. The 2011 heat wave event also provided an insight into conditions that may become more prevalent in Cockburn Sound, and elsewhere, if short-term warming events become more frequent and extreme, as predicted.

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