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Nearshore and offshore co-occurrence of marine heatwaves and cold-spells

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ABSTRACT

A changing global climate places shallow water ecosystems at more risk than those in the open ocean as their temperatures may change more rapidly and dramatically. To this end, it is necessary to identify the occurrence of extreme ocean temperature events – marine heatwaves (MHWs) and marine cold-spells (MCSs) – in the nearshore (<400 m from the coastline) environment as they can have lasting ecological effects. The occurrence of MHWs have been investigated regionally, but no investigations of MCSs have yet to be carried out. A recently developed framework that defines these events in a novel way was applied to ocean temperature time series from (i) a nearshore *in situ* dataset and (ii) $\frac{1}{4}°$ NOAA Optimally Interpolated sea surface temperatures. Regional drivers due to nearshore influences (local-scale) and the forcing of two offshore ocean currents (broad-scale) on MHWs and MCSs were taken into account when the events detected in these two datasets were used to infer the links between offshore and nearshore temperatures in time and space. We show that MHWs and MCSs occur at least once a year on average but that proportions of co-occurrence of events between the broad- and local scales are low (0.20–0.50), with MHWs having greater proportions of co-occurrence than MCSs. The low rates of co-occurrence between the nearshore and offshore datasets show that drivers other than mesoscale ocean temperatures play a role in the occurrence of at least half of nearshore events. Significant differences in the duration and intensity of events between different coastal sections may be attributed to the effects of the interaction of oceanographic processes offshore, as well as with local features of the coast. The decadal trends in the occurrence of MHWs and MCSs in the offshore dataset show that generally MHWs are increasing there while MCSs are decreasing. This study represents an important first step in the analysis of the dynamics of events in nearshore environments, and their relationship with broad-scale influences.

1. Introduction

Over the past three decades, anthropogenically mediated warming has negatively affected marine and terrestrial ecosystems with far reaching consequences for humanity and natural ecological functioning. Although climate change is generally understood as a gradual long-term rise in global mean surface temperature (Stocker et al., 2013), which will continue for decades or centuries, it is generally the associated increase in frequency and severity of extreme events that affects humans and ecosystems in the short-term (Easterling et al., 2000). Impacts of extreme events such as floods, wind storms, tropical cyclones, heatwaves and cold-spells are often sudden with catastrophic consequences. The recognition to focus more on the extremes and less on the background mean state has emerged as a critical direction of climate change research (Jentsch et al., 2007).

'Heatwaves' usually refer to atmospheric phenomena where vague definitions such as "a period of abnormally and uncomfortably hot [...] weather" are invoked (Glickman, 2000), but there are also precise definitions based on statistical properties and other metrics of the temperature record that are relative to location and time of year (e.g. Meehl, 2004; Alexander et al., 2006; Fischer and Schär, 2010; Fischer et al., 2011; Perkins and Alexander, 2013). As the definitions for heatwaves have increased, so too have the investigations of heatwaves in the ocean (e.g. Mackenzie and Schiedek, 2007; Selig et al., 2010; Sura, 2011; Lima and Wethey, 2012; DeCastro et al., 2014). Well-known marine heatwaves (MHWs) have occurred in the Mediterranean in

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2003 (Black et al., 2004; Olita et al., 2007; Garrabou et al., 2009), off the coast of Western Australia in 2011 (Feng et al., 2013; Pearce and Feng, 2013; Wernberg et al., 2013), in the north west Atlantic Ocean in 2012 (Mills et al., 2012; Chen et al., 2014, 2015) and more recently the "Blob" in the north east Pacific Ocean (Bond et al., 2015). The extreme temperatures from these events have had negative impacts on the local ecology of the regions in which they occur. For example, the 2003 Mediterranean heatwave may have affected up to 80% of the gorgonian fan colonies in some areas (Garrabou et al., 2009), and the 2011 event off the west coast of Australia is now known to have caused a 100 km range contraction of temperate kelp forests in favor of seaweed turfs and a tropicalisation of reef fishes (Wernberg et al., 2016).

Although the consequences of these anomalously warm events have been widely publicized, the events themselves have until recently not been objectively characterized. In part, this has been due to the lack of a consistent definition and metrics. In response to this need, Hobday et al. (2016) developed a definition of a MHW as "a prolonged discrete anomalously warm water event that can be described by its duration, intensity, rate of evolution, and spatial extent," and in doing so have derived statistical metrics that quantify these properties. For example, the count of MHWs within a time series and their maximum and cumulative intensity are quantifiable parameters that can be calculated in an objective and consistent manner irrespective of geographical location. The focus of this paper is on marine thermal events that are anomalous with respect to the seasonal climatology as per the Hobday et al. (2016) definition. They may be anomalously warm events, or anomalously cold (marine cold-spells, MCSs; introduced here). While MHWs are becoming reasonably well known by virtue of their increasing count and intensity, MCSs have received less recognition. Whereas extreme hot events may be demonstrably damaging to organisms and ecosystems, extreme cold events also have the potential to negatively impact organisms and ecosystems (Lirman et al., 2011). In both cases their drivers and dynamics, offshore as well as in the nearshore (<400 m from the coastline), remain poorly understood.

MCSs are projected to become less frequent under future climatic scenarios, but there are also examples of them becoming more frequent in some localities (e.g. Gershunov and Douville, 2008; Matthes et al., 2015). They are frequently lethal to marine organisms (Woodward, 1987) and are known to have caused mass fish (Gunter, 1941, 1951; Holt and Holt, 1983) and invertebrate (Gunter, 1951; Crisp, 1964) kills, the death of juvenile and subadult manatees (O'Shea et al., 1985; Marsh et al., 1986) and coral bleaching (Lirman et al., 2011). Cold temperatures are very important in setting species population distribution limits, particularly limiting their range north- or southwards towards higher latitudes (Firth et al., 2011), and the timing of the onset of growing seasons (Jentsch et al., 2007). It is easy to imagine how population-level consequences might aggregate to drive whole ecosystem responses (e.g. Kreyling et al., 2008; Rehage et al., 2016). Indeed, the range contractions of ecosystem engineer species such as mussels have been shown to relate to MCSs (Firth et al., 2011, 2015).

Although we understand that the sea surface temperature (SST) of the upper mixed layer is influenced by oceanic and atmospheric processes (see Eq. (1) of Deser et al., 2010), there is by no means a good understanding of how these processes are modulated by local- *vs.* broad-scale influences, thus resulting in nearshore MHWs and MCSs. Some of the MCSs known to have impacted populations were caused by atmospheric cold-spells affecting the intertidal and coastal biota locally (Gunter, 1941; Firth et al., 2011). We hypothesise that these localized events are manifestations of extreme atmospheric cold weather phenomena situated over the coast resulting in rapid heat loss from coastal waters. On the other hand, we also hypothesize that broader-scale teleconnections may also affect the thermal properties and dynamics of coastal systems. For example, large-scale atmospheric-oceanographic coupling is being affected by global warming, which is projected to cause the intensification of upwelling favorable winds and consequently the intensification and increasing count of upwelling events (see García-Reyes et al., 2015 for a review of this and alternative hypotheses). It is therefore possible that the development of *some* nearshore MCSs may be attributed to an intensification of upwelling. MHWs at any scale likely originate directly from atmosphere-ocean heat transfer as in the Mediterranean Sea (e.g. Garrabou et al., 2009) or from advection, i.e., the transport of warm water due to currents such as what happened off Western Australia in 2011 (Feng et al., 2013; Benthuysen et al., 2014), the NW Atlantic in 2012 (Mills et al., 2012; Chen et al., 2014, 2015) and potentially off SE Australia in 2016. Because MHWs and MCSs are both able to effect ecosystem change, a mechanistic understanding of their drivers may be useful for conservation and management purposes. To this end our study serves as a constructive first step to understand the prevalence of anomalous thermal events with respect to forcing mechanisms at different scales.

Hobday et al. (2016) applied their MHW framework to the $\frac{1}{4}°$ NOAA Optimally Interpolated SST dataset (hereafter referred to as OISST; Reynolds et al., 2007), but warned users to be cognizant that different data sets would provide different kinds of information pertaining to heatwaves. Our study applied this MHW (MCS) definition to datasets of nearshore *in situ* (local-scale) and offshore gridded OISST (broad-scale) temperature time series collected at different locations along coastlines influenced by contrasting ocean currents – the Benguela Current, an eastern boundary upwelling system, and the Agulhas Current, a western boundary current – and locally modified by regional aspects of the coastal bathymetry, geomorphology and other smaller scale coastal features. Having assessed these systems within a framework that coupled local- and broad-scale features permitted us to assess how MHWs (MCSs) developed in coastal regions. Specifically, we aimed to assess the significance of MHWs (MCSs) within the context of the datasets inherent differences, and examine the various dynamical properties that then emerged out of the regional oceanographic context and out of the local-scale modifications of the regional ocean features as they approached the coast. In doing so, the aim was to provide some insights into possible mechanisms that determine the nature and origin of MHWs (MCSs) within regionally distinct ocean/coastal sections. We hypothesized that (i) nearshore local-scale MHW events are coupled with offshore broad-scale thermal patterns; (ii) MCSs originate at the local-scale in the nearshore *in situ* dataset as isolated incidents decoupled from broader-scale patterns; (iii) different coastal sections, each variously influenced by interactions between local- and broad-scale processes, display different dynamics (timing, count, duration and intensity) of MHWs (MCSs); and (iv) the count of warm (cold) events increases (decreases) with time under a regime of climate change. The effect of atmospheric forcing on nearshore events was considered but not assessed within the scope of this study.

2. Methods

2.1. Study region

The variety of oceanographic features around the *ca.* 3100 km long South African coast provides a natural laboratory for the potential effects of different ocean forcing mechanisms on the occurrence of MHWs and MCSs. Annual mean (± standard deviation; SD) coastal seawater temperatures range from 12.3 ± 1.2 °C at the western limit near the Namibian border (Site 1) to 24.4 ± 2.0 °C in the east near the Mozambican border (Site 21).