Estuarine, Coastal and Shelf Science 313 (2025) 109102

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Offshore wind farms could impact coastal marine heatwaves in eastern boundary upwelling systems

Michael Dalsin [a], Ryan K. Walter [a,*], Piero L.F. Mazzini [b]

[a] Physics Department, California Polytechnic State University, San Luis Obispo, CA, USA
[b] Virginia Institute of Marine Science, William & Mary, Gloucester Point, VA, USA

ARTICLE INFO

Keywords:
Coastal upwelling
Marine heatwaves
Offshore wind energy
Wind energy area
Eastern boundary current upwelling systems
Central California

ABSTRACT

Analysis of ecosystem impacts from offshore wind (OSW) farm development has primarily focused on localized effects. However, in Eastern Boundary Current Upwelling Systems (EBUS) like the California Current, OSW farms can modify the intensity and spatial structure of wind-driven upwelling, inducing non-local (tens of kms away) changes to seawater temperature. Recent numerical modeling research determined that a hypothetical upper bound full buildout of OSW farms in central California could warm coastal waters through a reduction in upwelling. Here, we examine the sensitivity of coastal marine heatwaves (MHWs), which are prolonged extreme seawater temperatures that are among the greatest threats to marine ecosystems, to seawater temperature increases motivated by OSW-induced warming. Using a novel long-term coastal water temperature record spanning over four decades, we find that there is the potential for significant increases in MHW days, with individual MHWs becoming more intense and prolonged. Although the exact nature of OSW-induced changes to MHWs are uncertain, this is the first investigation into the potential impacts of OSW development on coastal MHWs, with important implications for marine ecosystems in EBUS globally where OSW is being considered. Despite the potential impacts, OSW remains a critical component to combat the much more pervasive issue of global climate change.

1. Introduction

Marine heatwaves (MHWs), discrete and prolonged periods of anomalously warm ocean temperatures, are among the greatest threats to marine biodiversity on Earth (Smale et al., 2019). MHWs affect marine ecosystems in a multitude of ways: alteration of species range with the potential to introduce invasive species, mass mortality of marine organisms, habitat loss, and MHW-associated multi-stressor events, including harmful algal blooms, hypoxia, and low pH conditions (Smith et al., 2023a; Shunk et al., 2024). In the California Current System (CCS), MHWs and their associated stressors have resulted in the loss of large areas of species-rich kelp forests, the collapse of valuable fisheries, and persistent range shifts of marine organisms (Rogers-Bennett and Catton, 2019; Sanford et al., 2019).

Due to human greenhouse gas emissions and the resultant warming, global averages of MHW frequency, intensity, and duration have all increased since the early to mid-1900s (Oliver et al., 2018). Compared to the global trend, MHWs in highly productive Eastern Boundary Current Upwelling Systems (EBUS), including the CCS, have changed to a lesser degree (Oliver et al., 2018; Varela et al., 2018; Izquierdo et al., 2022). In the strong upwelling region of the CCS, where alongshore equatorward winds drive upwelling of cold, nutrient-rich waters from below the thermocline into coastal surface waters, positive trends in MHW frequency and intensity are more muted (Oliver et al., 2018). Based on analysis from nearshore, in-situ measurements, long-term trends in MHW characteristics are only detectable over time spans greater than approximately fifty years (Oliver et al., 2018; Dalsin et al., 2023). In the nearshore coastal environment along EBUS, wind-driven upwelling has been observed to act as a buffer against MHWs in a warming ocean, providing a cold-water reprieve for marine organisms (Dalsin et al., 2023; Varela et al., 2021; García-Reyes, 2023).

In an effort to combat the accelerating threat of global warming and reduce greenhouse gas emissions, California passed Senate Bill 100 (SB-100) in 2018, requiring the state to produce 100% of its electricity from renewable sources by 2045. To meet these targets, California has ambitious plans to build 25 GW of offshore wind-power capacity. In December of 2022, the Bureau of Ocean Energy Management (BOEM) held the first ever offshore wind (OSW) energy lease sale along the US

---

* Corresponding author.
E-mail address: rkwalter@calpoly.edu (R.K. Walter).

https://doi.org/10.1016/j.ecss.2024.109102
Received 31 May 2024; Received in revised form 14 December 2024; Accepted 16 December 2024

West Coast in two Wind Energy Areas (WEAs) located in northern California (Humboldt WEA) and central California (Morro Bay WEA) with high-value power generation potential (Bureau of Ocean Energy Management, 2022; Wang et al., 2022; Wang et al., 2019). Both of these WEAs are located in regions of moderate to strong upwelling, experiencing a combination of wind-driven coastal upwelling (Ekman transport near a coastal boundary) and wind stress curl-driven upwelling also known as Ekman suction (Checkley and Barth, 2009; Jacox et al., 2018). Thus, it is critical to understand how OSW development might impact MHWs via modification to the wind field, and consequently upwelling and seawater temperatures.

A recent study utilized an ocean-atmosphere numerical model (3 km spatial resolution regional ocean model for the inner nest) to simulate the effects of OSW development in the two California WEAs (as well as a prior area of interest near the Morro Bay WEA termed the Diablo Canyon Call Area) and found moderate changes to the wind stress curl-driven upwelling, particularly in the central California region (Raghukumar et al., 2023). Using a hypothetical upper bound full buildout scenario (e.g., max number of turbines across both the Morro Bay WEA and Diablo Canyon Call Area), the authors found moderate reductions in the wind-stress curl along the eastern (landward) side of the central California OSW farms that led to reductions in upwelling. The change in vertical transport led to an increase in average seawater temperatures of approximately 0.1–0.4 °C in the coastal regions on the eastern (landward) side of the hypothetical central California OSW farms, with consistent temperature increases across all seasons (see Figures 1 and 2 in Raghukumar et al., 2023). In this communication, we consider the potential impact of the reduction in upwelling and subsequent increases of the mean temperature due to the potential development of OSW in central California on nearshore MHWs. We utilize a novel long-term temperature record in central California previously analyzed for MHWs (Dalsin et al., 2023) and examine how a range of temperature increases, which model the potential impact of the hypothetical upper bound full buildout scenario in central California and associated uncertainties, modify MHW characteristics in the region. This study provides the first known investigation into the potential impact of OSW development on coastal MHWs, with important implications for marine ecosystems in EBUS where OSW is being considered.

2. Methods

2.1. Temperature and MHW data

We utilize seawater temperature data detailed in Dalsin et al., 2023. These data were obtained from a nearshore measurement site (~3 m nominal depth; 35.2055°N, 120.8500°W) landward from the central California OSW region (Fig. S1). The data span over four decades (1978–2020), with measurements taken at 20-min intervals. MHWs were calculated using the MATLAB MHW toolbox (Zhao and Marin, 2019) following the standard MHW definition: a period of five or more consecutive days where the daily average ocean temperature exceeds the 90th percentile threshold (Hobday et al., 2016). The climatology and 90th percentile threshold were computed using an 11-day moving average for each day of the year. We quantified the following MHW metrics: duration, mean intensity (mean temperature anomaly), cumulative intensity (time-integrated temperature anomaly), and maximum intensity (peak temperature anomaly) (Hobday et al., 2016). We also categorized the MHWs as moderate (maximum intensity that is 1–2x the 90th percentile threshold), strong (2–3x), and severe (3–4x) (Hobday et al., 2018).

2.2. Modeling mean temperature changes induced by OSW

Based on the ocean-atmosphere model projections from Raghukumar et al., 2023, upwelling was reduced on the eastern (landward) side of the central California OSW farm due to a reduction in wind stress curl. Consequently, seawater temperature averages landward of the OSW buildout were found to increase by approximately 0.1–0.4 °C (Raghukumar et al., 2023). Seasonal variations in the modeled OSW-induced ocean temperature differences were minimal and remained positive throughout the year (see Figure 1 in Raghukumar et al., 2023). In this work, we modeled the potential warming effect from the hypothetical full buildout scenario in central California. We utilized a constant temperature offset between 0 and 0.5 °C, where a 0 °C temperature offset represents the status quo with no OSW development in the central California WEA (e.g., the results from Dalsin et al., 2023).

On the other extreme, the temperature offset of 0.5 °C accounts for a hypothetical full buildout of both the Morro Bay WEA and previously considered Diablo Canyon Call Area (as modeled by Raghukumar et al., 2023) as well as various uncertainties that could push this warming higher (e.g., increased turbine sizes, changes in turbine density, OSW area expansions, upwelling changes, unresolved processes, etc. – see Discussion for additional details). We note that the Diablo Canyon Call Area is not currently under consideration for OSW development and was not included in the December 2022 lease sale with the Morro Bay WEA. As a result, reductions in upwelling, and therefore seawater temperature changes of up to 0.4 °C modeled by Raghukumar et al. (2023) represent an extreme development scenario. However, California has ambitious plans to build 25 GW of OSW capacity by 2045, and thus, expansions into the Diablo Canyon Call Area and beyond are possible (but also dependent on the proposed Chumash National Marine Sanctuary). Thus, we analyzed the effect of a range of temperature offsets, from 0 to 0.5 °C in 0.1 °C increments, effectively conducing a sensitivity analysis, representing seawater temperature increases resulting from varying degrees of OSW development and inherent uncertainties in the modeled changes and assumptions made here. While a constant temperature offset does not model time-variable changes associated with OSW development and the consequent upwelling and seawater temperature response, the range of constant offsets is meant to bound the range of possible warming scenarios, with the understanding that changes to MHWs would likely be variable in time and space (these caveats are further detailed in the Discussion).

Positive trends in seawater temperature due to climate change have increased MHW frequency and intensity in many locations on a decadal or multidecadal time scale (Oliver et al., 2018). On these longer timescales, ecosystems can shift and adapt more easily, and thus a moving baseline climatology is recommended to better quantify the ecological impacts of MHWs (Amaya et al., 2023a). In the case of OSW development in an EBUS, warming effects will occur on short timescales relative to longer-term changes. Given the lack of adjustment time for marine organisms to adapt to these stepwise-like temperature changes, we utilize the same baseline climatology and 90th percentile MHW threshold from the 1978–2020 record. We then add a range of constant temperature offsets to the original time series and recalculate MHWs at each offset to represent the range of potential effects from OSW development and associated uncertainties. This approach aims to produce MHW metrics (e.g., frequency, intensity, duration) that would best capture potential impacts to marine organisms in the short term following OSW implementation.

3. Results

3.1. MHW metrics and trends

MHW metrics summed across the entire dataset (e.g., total number of MHWs, total MHW days, total cumulative intensity) all increased with progressively larger temperature offsets (Fig. 1). Compared to the base case (0 °C offset) the 0.5 °C upper bound temperature offset increased the number of MHWs by 58%, the total MHW days by 77%, and total cumulative intensity by 82% (Table 1). With increasing temperature offset, linear trends (e.g., slope of metric with respect to temperature offset changes) for the frequency, total MHW days, and total cumulative

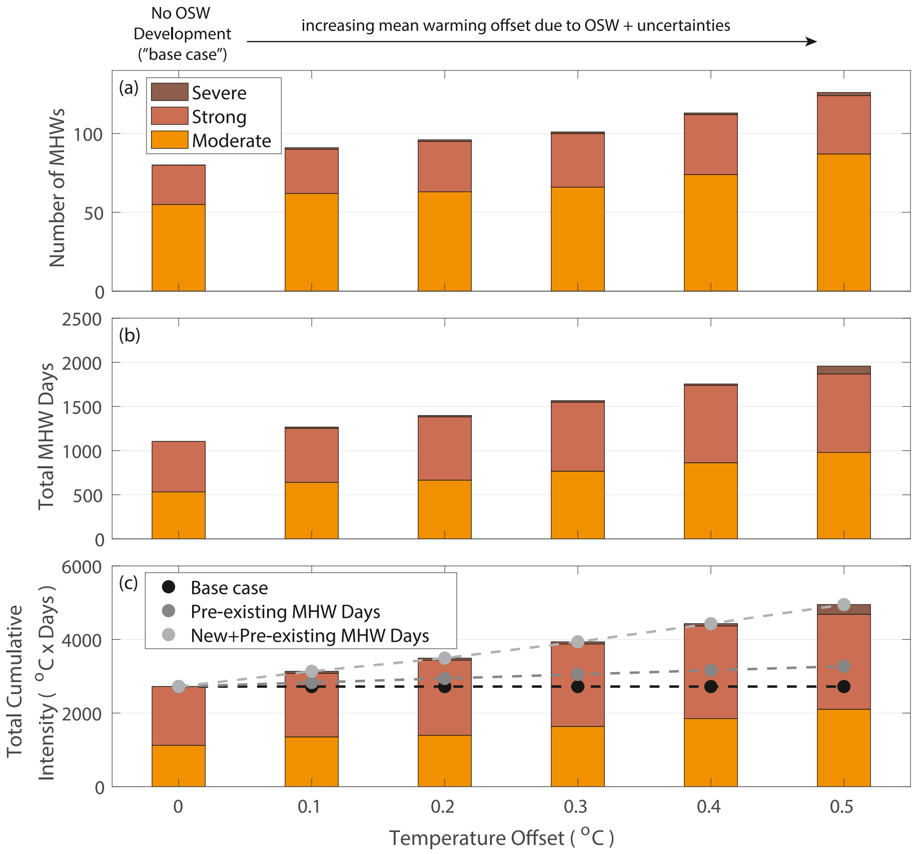

Fig. 1. Barplots of the (a) number of MHWs, (b) total MHW days, and (c), total cumulative intensity for each temperature offset from 0 to 0.5 °C over the period from 1978 to 2020. The 0 °C offset represents the base case (no OSW development and hence no temperature offset, as in Dalsin et al., 2023). Each bar is separated by the MHW category, based on the maximum intensity (e.g., maximum intensity between 1–2x the 90th percentile threshold for moderate, 2–3x for strong, and 3–4x for extreme; see Section 2.1). In panel (c), black dots denote the cumulative intensity from the base case, dark gray dots denote the cumulative intensity from pre-existing MHW days present in the base case only accounting for the increase in MHW intensity, and light gray dots denote the total cumulative intensity.

Table 1
Summary of total MHW statistics in Fig. 1 from 1978 to 2020.

Offset (°C)	0	0.1	0.2	0.3	0.4	0.5
Number of MHWs	80	91	96	101	113	126
Moderate MHWs	55	62	63	66	74	87
Strong MHWs	25	28	32	34	38	37
Severe MHWs	0	1	1	1	1	2
MHW Days	1104	1267	1398	1566	1755	1957
Cumulative Intensity (°C days)	2721	3136	3495	3937	4432	4950

intensity were all statistically different from zero ($p < 0.01$). Trends were then divided by the time span of the dataset to obtain a change in the MHW statistic per year per degree Celsius offset. There was an increase of 2 MHWs/year/°C offset, 39 MHW days/year/°C offset, and 103 °C days/year/°C offset (cumulative intensity). Additionally, with increasing temperature offset, the maximum intensity of each MHW increased, and more MHWs were categorized as strong (e.g., 25 in the base case vs. 37 with 0.5 °C offset; Fig. 1). No MHWs were categorized as severe in the base case, but one severe MHW appeared at the 0.1 °C offset and two at 0.5 °C (Table 1 and Fig. 1).

3.2. *MHW modification by temperature offset*

The increases in MHW metrics following the temperature offset can be attributed to three mechanisms: (1) emergence of new MHWs, (2) lengthened duration and heightened intensity of pre-existing MHWs, and (3) pre-existing MHWs merging to form a single MHW event with a longer duration (e.g., Fig. 2). For example, from July to September of 1998, the base case shows three distinct MHWs with durations of 10, 11, and 5 days respectively (Fig. 2a). At 0.2 °C offset, the first MHW is unchanged in duration, but the second and third MHWs are substantially lengthened to 19 and 23 days respectively (Fig. 2b). At 0.5 °C offset, the cool reprieve separating the first two MHWs was eliminated and these events merged to become a single event spanning 35 days (Fig. 2c).

When considering how temperature offset affects cumulative intensity, we examined the contribution of MHW days that emerged due to the offsets from either increasing the intensity on existing MHW days ("pre-existing MHW days") or through the lengthening of pre-existing MHW days and generation of additional MHW days not present in the base case ("new MHW days"; Fig. 1c). The emergence of new MHW days is the dominant contributor to changes in cumulative intensity at the 0.5 °C offset, accounting for 75% of the change relative to the base case (Fig. 1c). That is, only 25% of the increase in cumulative intensity is due to increasing the intensity of pre-existing MHW days (Fig. 1c).

3.3. *MHW metric distributions*

Examination of the distribution of MHW metrics across all events for the various offsets highlights an increase in the most extreme events with the longest durations and cumulative intensities. For smaller offsets, the mean and median of the respective MHW metrics (duration, mean intensity, cumulative intensity, maximum intensity) increase as the offset increases (Fig. 3). However, above the 0.3 °C offset, the means and medians begin to decrease slightly due to the emergence of new MHWs that have shorter durations along with lower mean, cumulative, and maximum intensities (Fig. 3). Even though MHWs are further

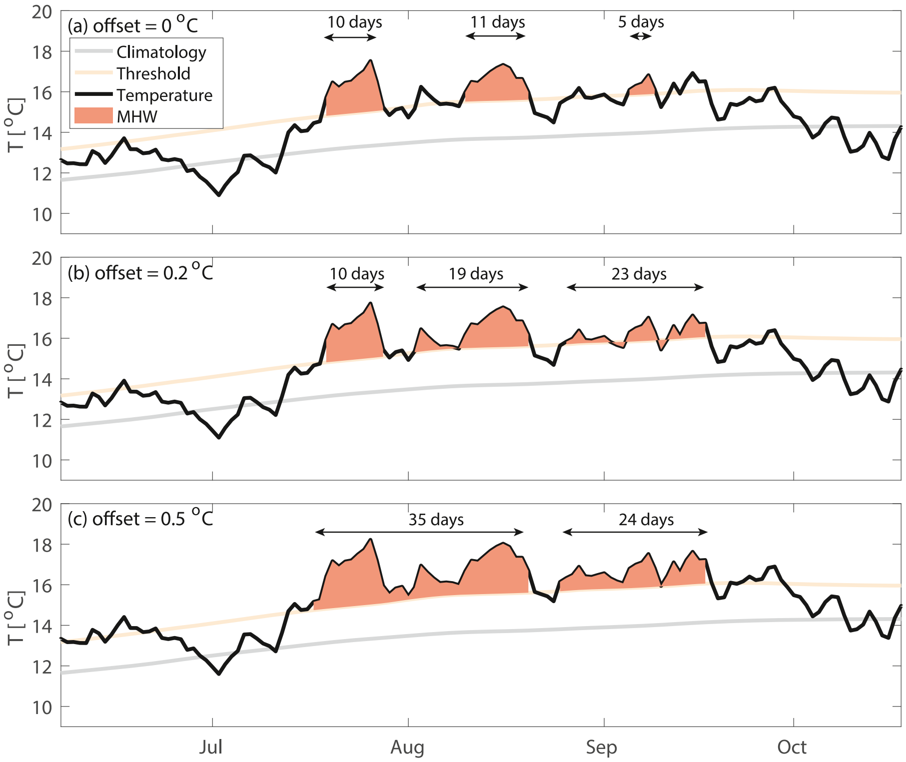

Fig. 2. Example temperature and MHW time series from June–October 1998 at (a) 0 °C offset, (b) 0.2 °C offset, and (c), 0.5 °C offset. Shown are the climatology (gray), daily-averaged temperature (black), 90th percentile threshold (light red), and MHW events shaded in dark red with arrows labeling duration. The 0 °C offset represents the base case (no OSW development and hence no temperature offset, as in Dalsin et al., 2023), from which the climatology and threshold were calculated. MHW event durations are shown in each panel with black arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

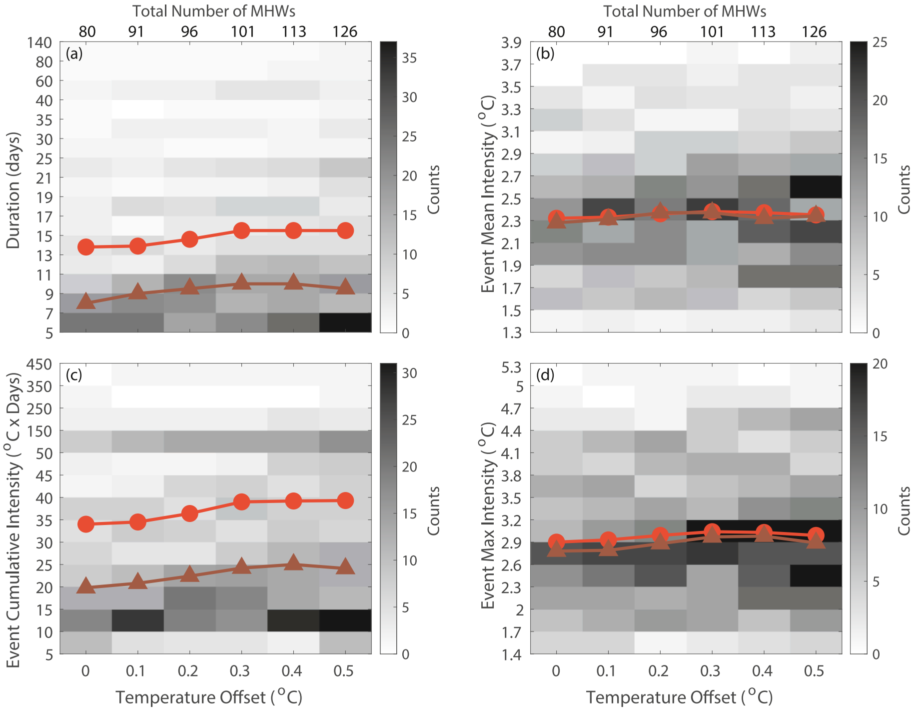

Fig. 3. Frequency/count (color bar) histograms of MHW metrics (vertical axes) across each temperature offset (horizontal axes). Quantities shown are (a) duration, (b) mean intensity, (c), cumulative intensity, and (d) maximum intensity. Mean values are plotted as red circles and median values as brown triangles. The total number of MHWs for each offset is shown across the top. In panels (a) and (c), vertical bins are not spaced proportionally to their numerical size for better visualization. The 0 °C offset represents the base case (no OSW development and hence no temperature offset, as in Dalsin et al., 2023). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lengthened and sometimes combined at larger temperature offsets (e.g., Fig. 2), generation of shorter MHWs maintain or decrease the mean and median of the distributions (Fig. 3). For duration and cumulative intensity, the means are larger than the medians because of a small number of MHWs with long durations greater than 40 days (Fig. 3a and c). Nonetheless, increasing temperature offsets generally led to increases in the frequency of the most extreme and prolonged MHWs.

4. Discussion

While previous studies have examined the impacts of OSW on local stratification (Copping et al., 2013), vertical transport (Ludewig, 2015), and air-sea heat fluxes (Akhtar et al., 2022), this is the first work to consider the implications for MHWs. Raghukumar et al., 2023 demonstrated that the hypothetical upper bound full buildout scenario in central California, which includes the newly leased Morro Bay WEA and previously considered Diablo Canyon Call Area, has the potential to reduce wind stress curl-driven upwelling, leading to warmer seawater temperatures on the eastern (landward) side of the WEA. Utilizing the projected OSW-induced temperature changes from Raghukumar et al., 2023), and accounting for other uncertainties and potential warming mechanisms (discussed below), we applied a range of constant temperature offsets (0.1, 0.2, …0.5 °C) to a novel in-situ temperature record spanning more than four decades from an adjacent nearshore site in central California and examined the sensitivity of calculated MHW metrics to these warming offsets. Under these assumptions, small changes in warming could lead to 0.2–1 additional MHWs/year, 4–20 more MHW days/year, and 10–52 more °C days/year of MHW cumulative intensity in the nearshore region adjacent to the OSW development. We find that a stepwise temperature offset increases MHW metrics in three distinct ways: (1) increasing the intensity of pre-existing MHWs, (2) lengthening and occasionally merging of pre-existing MHWs, and (3) generating new MHWs. Approximately 75% of the observed increase in cumulative intensity (similar to “degree heating days” and a measure of cumulative ecosystem stress during MHWs) was explained by the addition of new MHW days, either from new MHWs generated from the offset or the lengthening of MHWs present in the base case (no offset or OSW development).

While the findings in this study raise concern about nearshore impacts of the central California WEA, it is important to note that they represent an upper-bound of changes to MHWs, a worst-case scenario that may not be realized. As the authors of Raghukumar et al., 2023 note, there is inherent uncertainty in the projections made from their model, and upwelling changes were site-dependent, with the Humboldt WEA inducing much smaller changes in upwelling. Furthermore, only the Morro Bay WEA has been leased for OSW development in central California, with the Diablo Canyon Call Area no longer under consideration, the latter of which was included in the modeling study (Raghukumar et al., 2023). Excluding the Diablo Canyon Call Area from the model would reduce the area of OSW development and number of turbines in the region, thereby diminishing predicted upwelling changes and the consequent seawater temperature and MHW changes. Additionally, while regional ocean models (e.g., 3 km resolution inner nest used in Raghukumar et al., 2023) do not always accurately capture complex dynamics found in the shallow nearshore, previous studies in central California have shown that regional-scale upwelling is the dominant control on nearshore temperature variability on seasonal and intra-seasonal (1–2 week upwelling-relaxation cycles) time scales (Dalsin et al., 2023; Walter et al., 2018, 2022, 2024). Moreover, the definition of MHWs (see Section 2.1) naturally filters higher-frequency phenomena that drive warming above the 90th percentile threshold with periods shorter than five days (e.g., “heat spikes”) and thus regional-and basin-scale variability are likely more influential in shaping nearshore MHWs at this location (Dalsin et al., 2023). A constant temperature offset does not capture the exact dynamics, but rather is intended to highlight how small changes in regional upwelling due to OSW development and the resultant non-local warming could lead to non-trivial changes in coastal MHWs. Moreover, the range of warming offsets also takes into account potential uncertainties in the warming, including: 1) utilizing 10 MW turbines (as in Raghukumar et al., 2023) versus much larger 15 MW turbines currently being considered; 2) changes in turbine spacing and density; 3) vertical mixing in the ocean from the turbines (Christiansen et al., 2023) not considered by Raghukumar et al. (2023); 4) changes in upwelling and upper-ocean mixed layer dynamics (see below); 5) future expansions in OSW development not previously considered given lofty goals of 25 GW of installed capacity by 2045 in CA; 6) future climate-change-driven warming along the CA Current, the magnitude of which is highly uncertain (Pozo Buil, 2021); and 7) other uncertainties associated with the model output and assumptions made here. Future studies could develop and configure a high-resolution nearshore model, which is beyond the scope of this study, to more accurately predict detailed dynamics and spatiotemporal variability in local MHW events.

Over the last century, the California Current has warmed modestly compared to the global ocean, with trends in MHWs only observable on time scales greater than 40 years (Oliver et al., 2018; Dalsin et al., 2023). It has been shown that upwelling has helped mitigate the effects of a warming ocean in EBUS (García-Reyes, 2023), though it is uncertain if these thermal refugia will persist in the future, as stratification will likely intensify with further climate change, potentially reducing the cooling (and MHW-mitigating) effect of upwelling (Pozo Buil, 2021; Bograd et al., 2023). However, future changes in upwelling favorable winds (e.g., Bakun hypothesis), although uncertain and site-dependent, could also impact thermal refugia in EBUS (Bograd et al., 2023; Bakun, 1979). The results presented here suggest that the development of OSW in EBUS, and subsequent changes to upwelling, and consequently nearshore warming, may diminish the MHW-buffering effect typically found along coastal regions of EBUS (Dalsin et al., 2023; Varela et al., 2021).

The consistent equatorward winds in EBUS like the California Current make them appealing regions for OSW development (Wang et al., 2019). These same winds drive upwelling, the dominant mechanism of physical, chemical, biological variability in coastal regions along EBUS (Bograd et al., 2023). Extracting energy from the wind field via OSW development in EBUS therefore poses a risk to nearby ecosystems through both temperature and biogeochemical changes. To date, there has been little development of OSW in EBUS, but strong interest and future plans for development (e.g., US West Coast, Western Australia, etc.). As a result, very little is understood about the ecological impacts of OSW in EBUS. The central California WEA therefore presents a unique opportunity to study the impacts of OSW in an EBUS. While previous work has outlined potential ecological changes in the vicinity of the WEA itself (Farr et al., 2021; White et al., 2024) this study shows that there is potential for non-local (e.g., tens of kilometers from the WEA) impacts from OSW development that need to be considered.

OSW impacts on nearshore marine ecosystems and fisheries are likely to be species-specific and site-dependent. Benthic and sessile organisms are likely to be most affected by OSW-induced warming and MHWs because of their inability to migrate out of the affected region. Similarly, highly mobile species may only be partially affected, assuming that thermal displacement distances will only be moderately affected in the regional extent of the OSW development (Raghukumar et al., 2023; Jacox et al., 2020). Over longer time scales, it is also possible that community-wide changes occur, similar (though smaller in magnitude) to what has been documented in the presence of thermal outfalls in power-generating systems (Schiel et al., 2004), and a new climatological baseline would be needed for MHW analyses (Amaya et al., 2023b). On the other hand, others have argued that a fixed climatological baseline (so called fixed-baseline definition) is more appropriate for long-term MHW analysis, even with climate-change-driven warming, since it captures increasing risks (e.g., due to climate change or an OSW farm) and maintains a consistent definition that the scientific community and policymakers have adopted (Sen Gupta, 2023). For further discussion on fixed versus shifting baselines, we refer the reader to Smith et al., 2024). While there are many documented and potential localized impacts in the immediate vicinity of deepwater floating OSW farms (Farr et al., 2021), there are limited studies that have suggested the potential for a non-local change tens of kilometers away such as the increase in nearshore MHWs documented here. Nearshore marine ecosystems like the species-rich giant kelp forests found along the California coast may not have been previously considered in impact analyses, especially for OSW development with floating turbines in deeper waters far from the coast. Strategic placement of nearshore conservation areas and marine protected areas (MPAs) in the regional extent of OSW farms could be an important management strategy to reduce potential impacts on certain fisheries (Ziegler et al., 2023), although ecosystem-wide resilience to increasing MHWs in MPAs is uncertain (Smith et al., 2023b).

While the potential ecosystem impacts discussed above are highly uncertain, and will depend on a multitude of factors include the actual changes to temperature and MHWs, given that the central California WEA will likely be the first large-scale deepwater floating development in an EBUS, careful monitoring of the region's nearshore ecosystems should be performed to help inform future development in EBUS globally. Before, after, control and impact (BACI) analyses that consider nearshore organisms and fisheries could capture changes to MHWs in the region and potential ecosystem impacts resulting from OSW development (Methratta, 2020; Livermore et al., 2023). BACI studies and others of a similar nature could provide a basis for nearshore marine management strategies for other US West Coast OSW developments and globally for OSW in EBUS (Methratta, 2020; Livermore et al., 2023). Central California represents a unique opportunity to study non-local impacts of OSW development, including changes to MHWs, with important implications for EBUS globally where OSW development is critical to reducing greenhouse gas emissions amid a warming climate.

CRediT authorship contribution statement

Michael Dalsin: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Ryan K. Walter:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Piero L.F. Mazzini:** Writing – review & editing, Investigation.

Data availability

Daily-averaged temperature data used in the marine heatwave analysis are available here: https://zenodo.org/doi/10.5281/zenodo.11052255. These data were originally used and described in Dalsin et al. (2023): https://www.nature.com/articles/s41598-023-39193-4.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge John Steinbeck from Tenera and Pacific Gas & Electric for assistance acquiring the Diablo Canyon temperature data. R. Walter was supported by NSF OCE-2242164 and P. Mazzini by NSF OCE-2242166. M. Dalsin was supported by the Santa Rosa Creek Foundation in the Bailey College of Science and Mathematics at Cal Poly.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2024.109102.

References

Akhtar, N., Geyer, B., Schrum, C., 2022. Impacts of accelerating deployment of offshore windfarms on near-surface climate. Sci. Rep. 12.

Amaya, D.J., et al., 2023a. Marine heatwaves need clear definitions so coastal communities can adapt. Nature 616, 29–32.

Amaya, D.J., et al., 2023b. Marine heatwaves need clear definitions so coastal communities can adapt. Nature 616, 29–32.

Bakun, A., 1979. Global climate change and intensification of coastal ocean upwelling. Science 247, 198–201, 1990.

Bograd, S.J., et al., 2023. Climate change impacts on eastern boundary upwelling systems. Ann. Rev. Mar. Sci 15, 303–328.

Bureau of Ocean Energy management. California activities. https://www.boem.gov/renewable-energy/state-activities/california, 2022.

Checkley, D.M., Barth, J.A., 2009. Patterns and processes in the California current system. Prog. Oceanogr. 83, 49–64.

Christiansen, N., Carpenter, J.R., Daewel, U., Suzuki, N., Schrum, C., 2023. The large-scale impact of anthropogenic mixing by offshore wind turbine foundations in the shallow North Sea. Front. Mar. Sci. 10.

Copping, A., et al., 2013. Environmental effects of marine energy development around the world. Annex IV final report. https://www.osti.gov/biblio/1069126.

Dalsin, M., Walter, R.K., Mazzini, P.L.F., 2023. Effects of basin-scale climate modes and upwelling on nearshore marine heatwaves and cold spells in the California Current. Sci. Rep. 13.

Farr, H., Ruttenberg, B., Walter, R.K., Wang, Y.H., White, C., 2021. Potential environmental effects of deepwater floating offshore wind energy facilities. Ocean Coast Manag. 207.

García-Reyes, M., et al., 2023. Most eastern boundary upwelling regions represent thermal refugia in the age of climate change. Front. Mar. Sci. 10.

Hobday, A.J., et al., 2016. A hierarchical approach to defining marine heatwaves. Prog. Oceanogr. 141, 227–238.

Hobday, A.J., et al., 2018. Categorizing and naming marine heatwaves. Oceanography 31, 162–173.

Izquierdo, P., Taboada, F.G., González-Gil, R., Arrontes, J., Rico, J.M., 2022. Alongshore upwelling modulates the intensity of marine heatwaves in a temperate coastal sea. Sci. Total Environ. 835.

Jacox, M.G., Edwards, C.A., Hazen, E.L., Bograd, S.J., 2018. Coastal upwelling revisited: ekman, Bakun, and improved upwelling indices for the U.S. West coast. J Geophys Res Oceans 123, 7332–7350.

Jacox, M.G., Alexander, M.A., Bograd, S.J., Scott, J.D., 2020. Thermal displacement by marine heatwaves. Nature 584, 82–86.

Livermore, J., Truesdale, C., Ransier, K., McManus, M.C., 2023. Small effect sizes are achievable in offshore wind monitoring surveys. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. https://doi.org/10.1093/icesjms/fsad097.

Ludewig, E., 2015. On the Effect of Offshore Wind Farms on the Atmosphere and Ocean Dynamics, vol. 31. Springer International Publishing, Cham.

Methratta, E.T., 2020. Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 77, 890–900.

Oliver, E.C.J., et al., 2018. Longer and more frequent marine heatwaves over the past century. Nat. Commun. 9.

Pozo Buil, M., et al., 2021. A dynamically downscaled ensemble of future projections for the California current system. Front. Mar. Sci. 8.

Raghukumar, K., et al., 2023. Projected cross-shore changes in upwelling induced by offshore wind farm development along the California coast. Commun Earth Environ 4.

Rogers-Bennett, L., Catton, C.A., 2019. Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. Sci. Rep. 9.

Sanford, E., Sones, J.L., García-Reyes, M., Goddard, J.H.R., Largier, J.L., 2019. Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. Sci. Rep. 9.

Schiel, D.R., Steinbeck, J.R., Foster, M.S., 2004. Ten years of induced ocean warming causes comprehensive changes in marine benthic communities. Ecology 85, 1833–1839.

Sen Gupta, A., 2023. Marine heatwaves: definition duel heats up. Nature 617, 465.

Shunk, N.P., Mazzini, P.L.F., Walter, R.K., 2024. Impacts of marine heatwaves on subsurface temperatures and dissolved oxygen in the chesapeake Bay. J Geophys Res Oceans 129.

Smale, D.A., et al., 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nat. Clim. Change 9, 306–312. https://doi.org/10.1038/s41558-019-0412-1. Preprint at.

Smith, K.E., et al., 2023a. Biological impacts of marine heatwaves. Ann. Rev. Mar. Sci 15, 119–145.

Smith, J.G., et al., 2023b. A marine protected area network does not confer community structure resilience to a marine heatwave across coastal ecosystems. Global Change Biol. 29, 5634–5651.

Smith, K., et al., 2024. Baseline matters: challenges and implications of different marine heatwave baselines. Prog. Oceanogr. https://doi.org/10.1016/j.pocean.2024.103404.

Varela, R., Lima, F.P., Seabra, R., Meneghesso, C., Gómez-Gesteira, M., 2018. Coastal warming and wind-driven upwelling: a global analysis. Sci. Total Environ. 639, 1501–1511.

Varela, R., Rodríguez-Díaz, L., de Castro, M., Gómez-Gesteira, M., 2021. Influence of Eastern Upwelling systems on marine heatwaves occurrence. Global Planet. Change 196.

Walter, R.K., Armenta, K.J., Shearer, B., Robbins, I., Steinbeck, J., 2018. Coastal upwelling seasonality and variability of temperature and chlorophyll in a small coastal embayment. Continent. Shelf Res. 154, 9–18.

Walter, R.K., et al., 2022. Seasonal controls on nearshore dissolved oxygen variability and hypoxia in a coastal embayment. Estuar. Coast Shelf Sci. 278.

Walter, R.K., Dalsin, M., Mazzini, P.L.F., Pianca, C., 2024. Compound marine cold spells and hypoxic events in a nearshore upwelling system. Estuar. Coast Shelf Sci. 300.

Wang, Y.H., et al., 2019. Spatial and temporal variation of offshore wind power and its value along the central California coast. Environmental Research Communications 1. Preprint at.

Wang, Y.H., Walter, R.K., White, C., Kehrli, M.D., Ruttenberg, B., 2022. Scenarios for offshore wind power production for Central California Call Areas. Wind Energy 25, 23–33.

White, C., et al., 2024. Spatial planning offshore wind energy farms in California for mediating fisheries and wildlife conservation impacts. Environ Dev 101005.

Zhao, Z., Marin, M., 2019. A MATLAB toolbox to detect and analyze marine heatwaves. J. Open Source Softw. 4, 1124.

Ziegler, S.L., et al., 2023. Marine protected areas, marine heatwaves, and the resilience of nearshore fish communities. Sci. Rep. 13.