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## Monitoring and predicting marine heatwaves in Vanuatu

To cite this article: Jessica Bhardwaj and Yuriy Kuleshov 2024 *Environ. Res. Commun.* **6** 125005

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## PAPER

## Monitoring and predicting marine heatwaves in Vanuatu

## OPEN ACCESS

RECEIVED  
17 October 2024

REVISED  
19 November 2024

ACCEPTED FOR PUBLICATION  
25 November 2024

PUBLISHED  
10 December 2024

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**Keywords:** marine heatwaves, satellite monitoring, sub-seasonal to seasonal prediction

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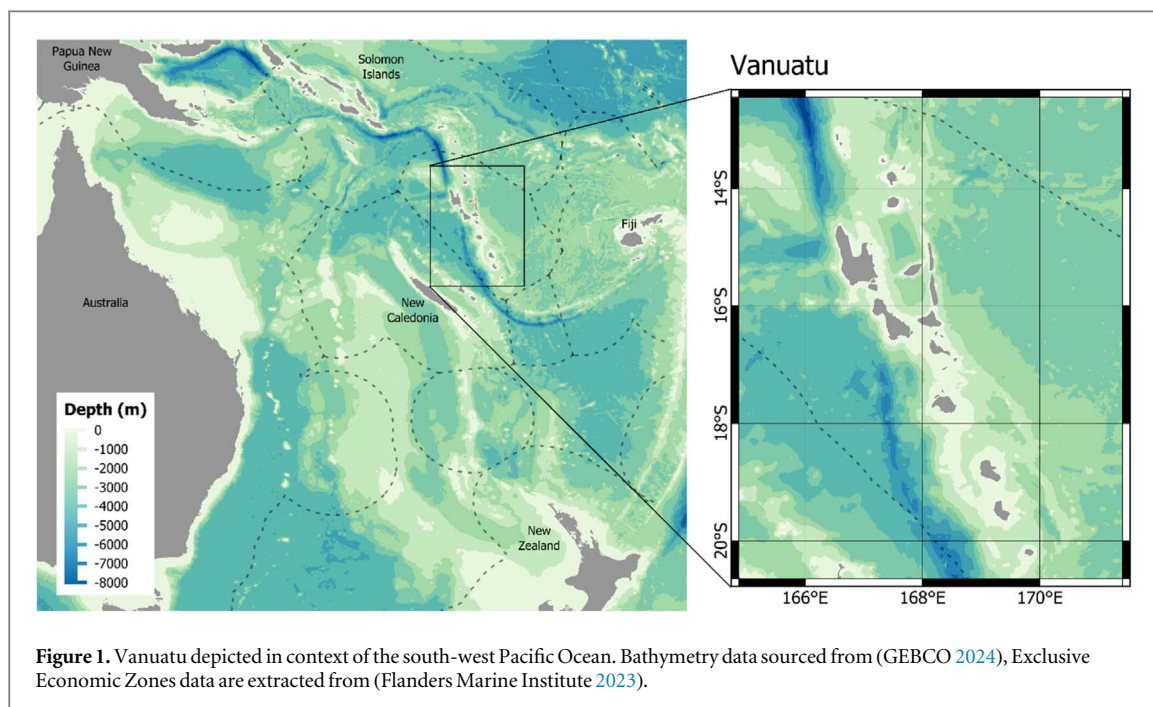
### Abstract

Marine Heatwaves (MHWs) have disastrous impacts on ecosystems and communities in the south-west Pacific but there is limited research investigating their onset and evolution in this region. In collaboration with local fisheries and marine sectors, this study applied a MHW framework to define and categorize MHW events in the waters around Vanuatu. A range of events amongst the most intense and longest were investigated, as well as an anecdotally notable event from February 2016. This event was neither in the top five longest, nor the most intense of events, highlighting how impacts in marine ecosystems are non-linear and have cascading interactions with a region's exposure and vulnerability. In analysing these events, we also explore how sub-seasonal to seasonal (S2S) prediction can be used to forecast MHW events. Hindcasts from the Bureau of Meteorology's operational coupled ocean-atmosphere model were used to create weekly and monthly forecasts for each MHW event in the period from 1980 to 2018. We found that chance above 90th percentile hindcasts had promising accuracy with average hit rates highest for lead 0 weekly and monthly hindcast but conclude that hindcast accuracy is not always indicative of real time forecast accuracy as real time forecasts use a larger set of model ensembles. We also investigated an event outside the hindcast study period (May 2022) due to its notably 'off the charts' impacts. This event was the longest and most intense event on record, surpassing the previously longest and most intense event by 144 days and 0.56 °C. As climate change intensifies, such extreme events will become more frequent and will likely compound with other extremes, making the use and uptake of monitoring and prediction services critical to the long-term resilience of marine-reliant communities and sectors.

## 1. Introduction

Marine Heatwaves (MHWs) are episodes of prolonged anomalously warm Sea Surface Temperatures (SSTs). These events can have catastrophic impacts on marine ecosystems, coastal communities, and fisheries in any region, particularly for Pacific Island nations (Holbrook *et al* 2022). Common ecological impacts include coral bleaching, biomass decrease, spatial shifts in fish stock locations, depressed catch rates, declines in extent and quality of habitats, toxic algal blooms, changes in species abundance, reduced reproductive success and survivorship of marine animals (Cheung and Frölicher 2020, Holbrook *et al* 2022). These ecological impacts cascade forward into sectoral and community impacts such as catch quota restrictions, fishery closures, decreased nutrition, increased travel for local fishing, reduced employment and less product for local markets (Hartog *et al* 2023). Vanuatu is a Pacific Island nation in the southwestern Pacific Ocean (figure 1). In Vanuatu, around 94% of the population resides within five km of the coast which makes such cascading impacts of MHWs particularly detrimental to community wellbeing and productivity (Andrew *et al* 2019).

Analyses of South-Pacific nutritional demand indicate that rising per capita fish consumption in Vanuatu may outpace local fish supplies due to decreased catch rates from warming induced shifts in fish distributions by 2050 under certain high emissions scenarios (Bell *et al* 2009, 2021, Morgan *et al* 2023). This will have significant



implications for coastal habitation as marine ecosystems sustain and modulate the financial abundance of local communities and have even been found to factor into individual self-reported wellbeing (Vanuatu National Statistics Office and Malvatumauri National Council of Chiefs 2012, Vanuatu National Statistics Office 2021). Given the symbiotic relationship of marine resources to livelihoods in Vanuatu, it is evident that MHWs pose a considerable threat to the economic, socio-cultural, and physical wellbeing of Vanuatu communities.

Vanuatu is home to vast culturally significant, and nutritionally vital marine ecosystems which are expected to face increased damages as anthropogenic climate change intensifies. Globally, MHWs have been increasing in their frequency, intensity and duration due to anthropogenically-forced increases in air and ocean temperatures with such changes projected to intensify into the future (Oliver *et al* 2018). In reviewing historical MHW metrics and trends in the waters around Australia, Kajtar *et al* (2021) found this global trend to also apply to the south-west Pacific. Vanuatu lies in the north-east of their study area, over which they found a consistent increase in the linear trend of annual MHW frequency and duration, as well as a weak negative trend in annual MHW intensity (significance of trends is unreported) (Kajtar *et al* 2021). Oliver *et al* (2019) further investigated MHW trends and projections in this region using outputs from global climate model simulations which culminated in the authors coining the term ‘permanent MHW state’. This state is a circumstance in the future when ocean temperatures will exceed the MHW threshold continuously over a whole calendar year. For a high emissions scenario, it was found that the date of a first permanent MHW state could be reached as early as 2040 for parts of the south-west Pacific (Oliver *et al* 2019). This is particularly notable for a country like Vanuatu, which, according to the 2020 World Risk Report was found to have the highest disaster risk index in the world (Behlert *et al* 2020). Thus, in a warming future climate, more frequent, variable and longer MHW events are likely to contribute to complex multi-hazard scenarios that will require meticulous proactive planning, management and mitigation efforts.

The El Niño-Southern Oscillation (ENSO) is a primary driver of MHWs in the south-west Pacific. Holbrook *et al* (2019) found that, in general, the horseshoe-like pattern of ENSO events leads to stronger MHWs near the equator during El Niño and to the south, north and west during La Niña. Aside from ENSO, other climate modes such as the Indian Ocean Dipole (IOD) and Madden-Julian Oscillation can also influence the onset, occurrence and cessation of MHW events (Holbrook *et al* 2019). MHW predictability is dependent on these key drivers, where longer lead times are usually influenced by regional climate modes (Benthuisen *et al* 2021). These drivers modulate conditions like surface warm pool presence, cloud cover, reduced latent ocean loss, enhanced insolation, suppressed winds, reduced upwelling and enhanced warm-water advection (Holbrook *et al* 2020). For this reason, forecast accuracy tends to vary depending on the region and the time of year (Stevens *et al* 2022). Despite this, there are very few studies of MHWs and their impacts in Pacific Island countries. Holbrook *et al* (2022) note that there are relatively limited reports of MHW impacts in this region, and also found that MHW occurrence likelihoods may be predictable several months in advance for regions of the tropical south-west Pacific. A study by Dunstan *et al* (2018) found that such model guidance has the potential to improve the sustainability of coastal fisheries in Pacific Island countries. Given this ability to provide proactive

decision-making guidance to disaster management and fisheries sector stakeholders, it is critical to investigate sub-seasonal to seasonal (S2S) MHW forecasts from dynamical climate models.

In this study, observed and forecasted MHW events in the period of overlap between the satellite record and hindcasts from the Bureau of Meteorology's (BoM's) operational climate model were analysed. To understand the severity and extent of past events as well as to examine how S2S forecasts performed in predicting events, a universal MHW framework was applied. Such analysis has not been conducted for Vanuatu before and aims to provide local fisheries and climate sectors with guidance and insight into key features and patterns of past MHW events in Vanuatu. We conclude our analysis with a set of recommendations for climate outlook products that these sectors already disseminate and provide indications of other products that could be used to bolster increased stakeholder and user engagement. Ultimately, understanding past MHW events and deepening predictive and observation capacity for relevant communities and sectors will be key to preparing proactively for MHW events as climate change contributes to intensified extremes for Vanuatu.

## 2. Data and methods

### 2.1. Observational SST datasets

SST data from the U.S. National Oceanic and Atmospheric Administration (NOAA) 0.25° daily Optimum Interpolation Sea Surface Temperature (dOISST) v2.1 dataset were used for our analysis. The dOISST data is compiled from a range of satellite, ship, buoy and Argo float observations that are interpolated on a 0.25° global grid (Banzon *et al* 2014, Banzon *et al* 2016, Huang *et al* 2021). As recommended by Hobday *et al* (2018), an 11-day window centred on each calendar day and smoothed with a 30-day moving window was applied to calculate the daily 90th percentile threshold and climatological mean for a 30-year baseline (1982–2012). For February 29 climatology, both the mean and 90th percentile SST values were calculated using an average of the SST values from February 28 and March 1 (Hobday *et al* 2018).

### 2.2. MHW definitions and metrics

In this study, we adopt the widely accepted definition of Hobday *et al* (2016, 2018) who define a MHW event as a 'discrete, prolonged anomalously warm water event' such that SSTs exceed the 90th percentile threshold for five or more days with no more than two below-threshold days in between. Following precedent, we use a 30-year base period of 1982–2012 that is also consistent with the base period used for our forecasting datasets. In this way, Hobday *et al* (2018), define MHW categories as multiples of the difference between the climatological mean and the 90th percentile. This definition allows for consistent identification and categorisation of the key features of a MHW. Based on this definition, the following metrics were calculated:

- **Duration:** number of days above the 90th percentile threshold.
- **Maximum Intensity:** maximum temperature above the climatological mean during the event.
- **Mean Intensity:** average temperature above the climatological mean during the event.
- **Cumulative Intensity:** sum of daily intensities above the climatological mean for the duration of the event.

For each event day we compare the dOISST observations to the daily 90th percentile climatology and accordingly derive the MHW categories. Observed SST Anomalies (SSTAs) were also calculated using the climatological mean. The observed SSTAs and event categories were used to investigate the intensity and duration of each event.

### 2.3. S2S forecast approach

For analysing S2S forecasts for MHW events in our study period, the BoM's operational climate model, the Australian Community Climate Earth-System Simulator—Seasonal, version 2 (ACCESS-S2) was used. The oceanic component of this model has a horizontal resolution of 0.25°, further model details are provided in Wedd *et al* (2022), where authors find ACCESS-S2 to have improved skill compared to version 1. Over ocean domains, ACCESS-S2 improves on the data assimilation regime of ACCESS-S1 by assimilating *in situ* temperature and salinity profiles, allowing for an improved ocean analysis (Wedd *et al* 2022). For real-time forecasts, ACCESS-S2 uses a 99-member time lagged approach. Real-time forecasts are only available from October 2021, thus for our study we use the publicly available raw model hindcasts that have temporal coverage from 1980–2018. A hindcast strategy using 27 members is employed (3-time lagged runs from 9 ensembles) to produce lead 0 and lead 1 monthly and weekly forecasts for the events analysed in this study. The runs of these

27 ensemble members are compared to model climatology to produce SSTA and chance of exceeding the 90th percentile forecasts.

For the SSTA forecasts, daily timeseries for each weekly/monthly forecast were correlated with observed timeseries. For the chance above 90th percentile forecast, stippling where observed SSTs were above the 90th percentile were overlaid on the forecast. In this way, hit-miss grid cells were derived as per:

- Hit (SST > 90th percentile observed and forecasted).
- Miss (SST > 90th percentile observed but not forecasted).
- Correct Rejection (SST > 90th percentile not observed nor forecasted).
- False Alarm (SST > 90th percentile not observed but forecasted).

Using these metrics, the Hit Rate (HR), the False Alarm Rate (FAR) and the Critical Success Index (CSI, also sometimes referred to as a Threat Score) were derived, equations (1)–(3).

#### Hit Rate, HR

*Ideal value = 1*

What fraction of all observed events were correctly forecast?

$$\frac{\text{hits}}{\text{hits} + \text{misses}} \quad (1)$$

#### False Alarm Rate, FAR

*Ideal value = 0*

What fraction of all forecasted events were incorrectly forecast as an event?

$$\frac{\text{false alarms}}{\text{hits} + \text{false alarms}} \quad (2)$$

#### Critical Success Index, CSI

*Ideal value = 1*

What fraction of all observed and forecasted events were correctly forecasted?

$$\frac{\text{hits}}{\text{hits} + \text{misses} + \text{false alarms}} \quad (3)$$

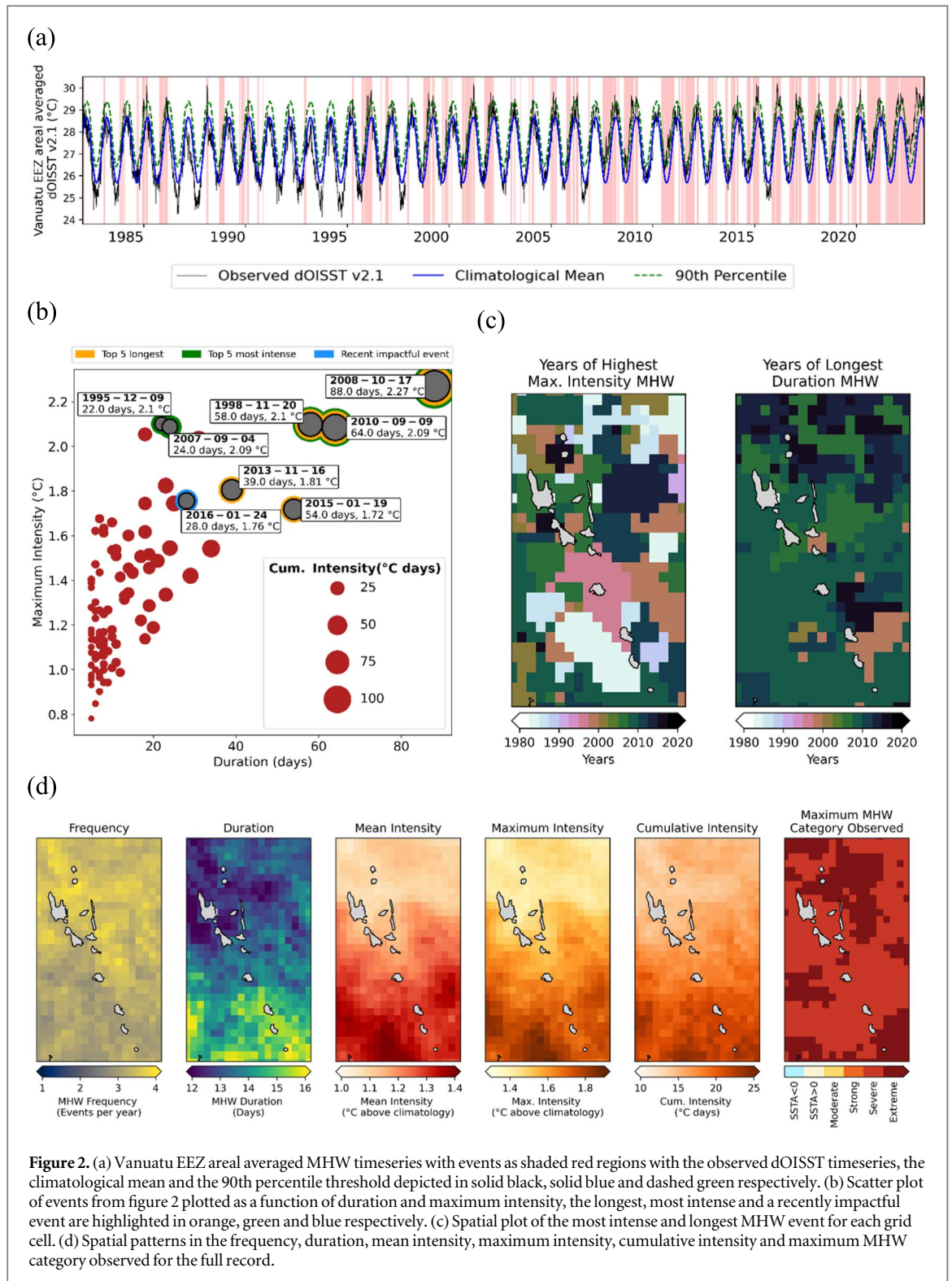
A caveat of using hindcasts in this context is that hindcast performance is not always indicative of real time model skill. In a real time context, there are significantly more ensemble members and model climatology are also calculated according to lead time. However, despite this caveat, hindcast outputs can still provide insight into signal detection ability and provide some gauge of how an S2S forecast preceding an extreme event can be used to provide hazard management guidance.

### 3. Results and discussion

In applying the definition of a MHW event as exceeding the 90th percentile SST for five or more days (with no more than two below threshold days in between), a total of 98 events in Vanuatu's Exclusive Economic Zone (EEZ) were identified within our study period. This is consistent with analysis by Holbrook *et al* (2022) who analysed MHW events in the waters around Palau, Samoa and Fiji and found a similar total number of events (~90) in their record between 1982 to 2019. Figure 2(a) depicts these events as shaded red regions with the observed dOISSST timeseries (solid black), the climatological mean (solid blue) and the 90th percentile threshold (dashed green).

Interestingly, a recently impactful MHW event (January 2016) was not in the top five longest or most intense events. To extend upon this national event analysis, the most intense and longest duration event for each grid cell in the study domain was also visualised (figure 2(c)) similar to analysis done by Kajtar *et al* (2021) for a larger study region. We note how each MHW event impacted different regions of Vanuatu differently. The nationwide longest or most impactful events from figure 2(b) are not necessarily the same between different regions or provinces. Impacts from each event vary depending on onset time, ecological and socioeconomic vulnerability of impacted area/s, exposed assets, cumulative impacts of any past events and the ocean/wind currents present in the region at the time. This means that the felt impacts as well as the regional severity of each event can differ from the national average. For example, in parts of Vanuatu, the 2016 event was the most intense and longest event on record (black colours in figure 2(c)), but this detail would be missed from the national overview analysis alone. Average event frequency, duration, mean intensity and maximum MHW category observed for each grid cell were also visualised (figure 2(d)).

It was found that across Vanuatu there is a spatially consistent average of 2–4 events per year (figure 2(d)). Kajtar *et al* (2021) similarly analysed mean MHW frequency and duration in the Pacific region; Vanuatu lies in the north-east of their study area. Our findings of a frequency of 2–4 events per year and duration between 10–15 days are also consistent with their findings (figure 2 in Kajtar *et al* 2021). Our analysis also found that MHW



**Figure 2.** (a) Vanuatu EEZ areal averaged MHW timeseries with events as shaded red regions with the observed dOISST timeseries, the climatological mean and the 90th percentile threshold depicted in solid black, solid blue and dashed green respectively. (b) Scatter plot of events from figure 2 plotted as a function of duration and maximum intensity, the longest, most intense and a recently impactful event are highlighted in orange, green and blue respectively. (c) Spatial plot of the most intense and longest MHW event for each grid cell. (d) Spatial patterns in the frequency, duration, mean intensity, maximum intensity, cumulative intensity and maximum MHW category observed for the full record.

events were tend to be longer and more intense in the south of Vanuatu’s EEZ. Some explanations for MHWs being more intense in the south of Vanuatu’s EEZ could be:

- (i) Ocean currents: a range of complex currents flow through the region around Vanuatu, a notable north-south current is the South Equatorial Current (SEC) that flows in toward Vanuatu from the East and pushes surface water southward (Hu *et al* 2015). Such currents can transport warm water and lead to the accumulation of anomalous warmth in certain areas, prologing the duration of an extreme event.

- (ii) Bathymetry: underwater surface depth can impact the circulation and mixing of seawater in an area. To the west of Vanuatu, lies the Vanuatu ridge and to the east lies the North Fiji basin. Ocean trenches are often associated with subduction zones and can influence the upwelling and downwelling of water in the region. Such processes could influence the retention of warm surface water in southern parts of Vanuatu and contribute to the observed result.
- (iii) Wind/weather interactions: Wind and cloud patterns can also work to promote or suppress the presence of warm water in certain areas. Prevailing winds, like the southeast trade winds can reinforce surface currents and influence the throughflow of warm water in the south of Vanuatu. When this compounds with localised cloud cover, the amount of solar radiation reaching the ocean surface can be greatly impacted. Historically Vanuatu experiences above average cloudiness during the Wet Season (November to April), it is possible that MHW events in this period can interact with surface wind and weather patterns to promote the pooling of warmer water in the south of Vanuatu's EEZ.

Further research is needed to determine a specific attributable cause. To understand how the patterns observed in figure 2 may have changed over time, we repeated this exercise for events from 1980 to 1999 (Appendix A) and then again for events from 2000 to 2018 (Appendix B). The 2021 Pacific Climate Change Monitor (PCCM) similarly analyses MHW duration, severity and frequency variation across the four decades from 1980 to 2020 (figure 21, Marra *et al* 2022). Vanuatu is discernible within their broader study domain, albeit requiring careful examination due to the study's larger scale. Authors similarly use dOISST 2.1 for their analysis, and they have consistent findings with ours—noting, for Vanuatu, an increase in median duration and frequency as well as similar maximum MHW category observed across the different decades.

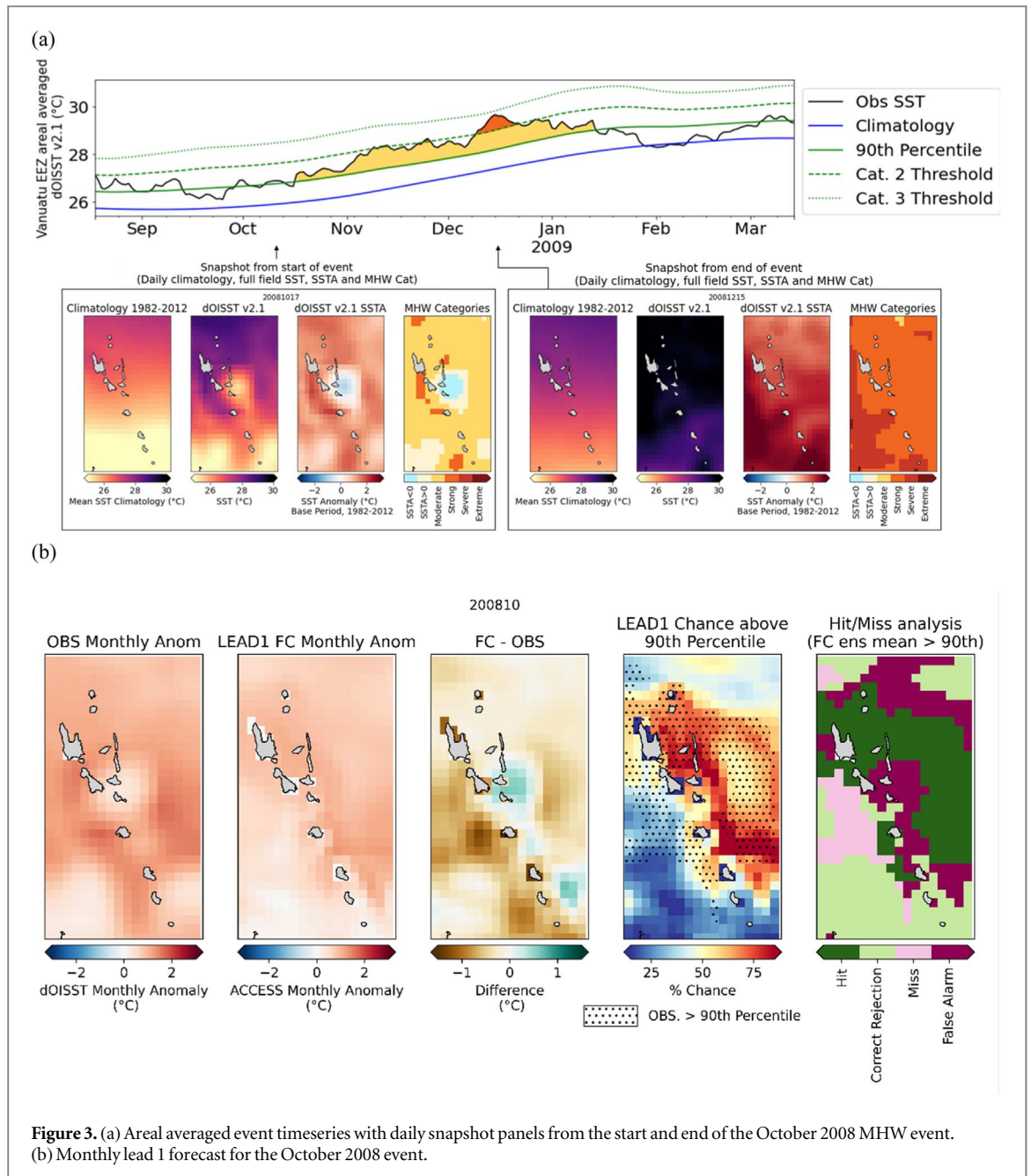
Combining analysis from figure 2 with anecdotal evidence based on discussions with climate staff from the Vanuatu Meteorology and Geohazards Department (VMGD) some key events were selected for further analysis.

### 3.1. October 2008 - Longest and most intense MHW event during the study period from 1980 to 2018

Within the study period of this analysis (1980–2018), the October 2008 was the longest and most intense of all MHW events with an event duration of 88 days and a maximum intensity of 2.27 °C. The area-averaged event timeseries and two key panels showcasing the beginning and peak of this event are presented in figure 3(a). A weak to moderate La Niña event dominated the beginning of 2008 (BoM 2023). Despite being a globally cooler year for the Pacific Ocean basin on average, SSTAs in the waters around Vanuatu were warmer than average due to the presence of the canonical La Niña horseshoe SSTA pattern. By the end of the year, warm anomalies around Vanuatu began surpassing the 90th percentile threshold subsequently peaking to a category II MHW (figure 3(a)) in mid-December and dissipating in the weeks following that peak. In analysing MHW events in tropical western and central Pacific island countries, Holbrook *et al* (2022) also detected a MHW event for this period in the waters around Palau. Despite these elevated SSTs, Palau only experienced mass coral bleaching in 1998 and 2010 (Holbrook *et al* 2022). Bleaching incidence is a complex phenomenon involving many factors, it is unclear for this event in Vanuatu if anomalously warm waters contributed to widespread bleaching and coral coverage reduction. NOAA coral bleaching products available over Vanuatu indicate that coral bleaching thresholds were surpassed for early 2008 and 2009, which may indicate the time lagged bleaching impacts of this event (NOAA Coral Reef Watch, 5 km *Regional Bleaching Heat Stress Maps and Gauges*, Vanuatu 2008–2009, dataset reference: Liu *et al* 2006).

Field surveys are the only ground-truthed assessment tool to ascertain coral bleaching extent and damage. There are limited such surveys in Vanuatu for this event. In surveying coral recovery and damage from the 1998 MHW event, Maynard and Done (2008) noted 30% of hard coral colonies in Santo Reef to be bleached by April 2008, indicating slow recovery from previous bleaching events. Limited reporting in the aftermath of this event constrains the impact analysis of this event but the surveys of Maynard and Done (2008) highlights the vulnerability and ecosystem threat the late 2008 event may have had as it onset on already bleached and decaying local shelf and branch coral species. These impacts cascaded forward to the few reports of other marine disturbances in the region. By early 2009, there was reporting that anomalously warm SSTs were contributing to crown of thorns starfish outbreaks and large phytoplankton blooms (Houk and Raubani 2010). Crown of thorns starfish (*acanthaster planci*) are a species of coral feeding starfish that can weaken and kill the corals they feed on (Dutra *et al* 2021). MHWs are often associated with an increase in reproduction rates of crown of thorns starfish, contributing to increased population sizes. In the aftermath of this event, Houk and Raubani (2010) noted increased upwelling and large phytoplankton blooms that subsequently increased starfish populations in January 2009 leading to removal efforts for dive points near Efate Island.

Beyond these ecological impacts, we would also expect local fisheries, communities and marine stakeholders to have observed impacts (Weinberg *et al* 2024). Our hindcast analysis indicates that monthly and weekly forecasts could have been used by such stakeholders to prepare and respond to the event. Our analysis found that



**Figure 3.** (a) Areal averaged event timeseries with daily snapshot panels from the start and end of the October 2008 MHW event. (b) Monthly lead 1 forecast for the October 2008 event.

lead 0 monthly hindcasts performed best in detecting this event with a HR, FAR and CSI of 67%, 38% and 47% respectively for lead 0 monthly forecasts. This compared to poorer overall lead 1 monthly forecast performance with a HR, FAR and CSI of 37%, 40% and 30% respectively. We also note an overall reduced CSI indicating that there is a lower proportion of hits detected when considering both false alarms and misses. Both of these observations could be an artefact of using hindcasts where there are only 27 ensemble members used unlike real time runs that use 99 members. Despite poorer lead 1 monthly performance overall during this event, we found that the lead 1 monthly forecast prior to the event to have promising detection of the MHW. The monthly lead 1 hindcast for this event is included in figure 3(b). For a forecast issued on the 1st of September 2008, a lead 1 forecast would depict the forecast period of October 2008 similar to figure 3(b). A real time forecast would evolve 99 members unlike the 27 evolved by hindcast analysis and thus may have improved skill compared to a hindcast. Nonetheless, it is evident even with hindcast analysis, that the signal of this event is able to be detected with promising hit and correct rejection capability at a one-month lead time. It is in this period where local stakeholders may consult a forecast, evaluate their resources and activities and plan accordingly.

### 3.2. September 2010 –Impacts on cultural fish festival

Vanuatu is a diverse and culturally heterogenous nation, where local fish festivals are often held to celebrate the confluence between abundant food supply and local tradition. The September 2010 event had severe impacts for

cultural festivals and practices in local Vanuatu communities. The beginning of 2010 was categorised by a decaying weak to moderate El Niño event which was quickly followed by a strong La Niña event that was one of the strongest on record (BoM 2023). According to our applied MHW framework, we found that this event had a nationwide peak of Category II or a ‘Strong’ event with a duration of 64 days and a maximum intensity of 2.09 °C. Holbrook *et al* (2022) similarly found this event to reach Category II thresholds in the waters around Fiji. Similar to the 2008 event, monthly lead 1 forecasts were not as successful in detecting the onset of this event, with an overall lower number of ‘hits’ registered in comparison. This may be another artefact of hindcast analysis—whereby both lead 0 and lead 1 forecasts are analysed in context of the same climatology (similar to the hindcast approach of Wedd *et al* (2022)). A real-time forecast, however, uses lead-time specific climatologies that may account for biases that can compound for longer lead times. In all the lead 1 monthly forecasts the magnitude of the forecasted SSTA is smaller in comparison to the magnitude of the observed anomaly. At longer lead times, hindcasts can start drifting back towards median climatology which can make it increasingly difficult for the model to surpass 90th percentile thresholds.

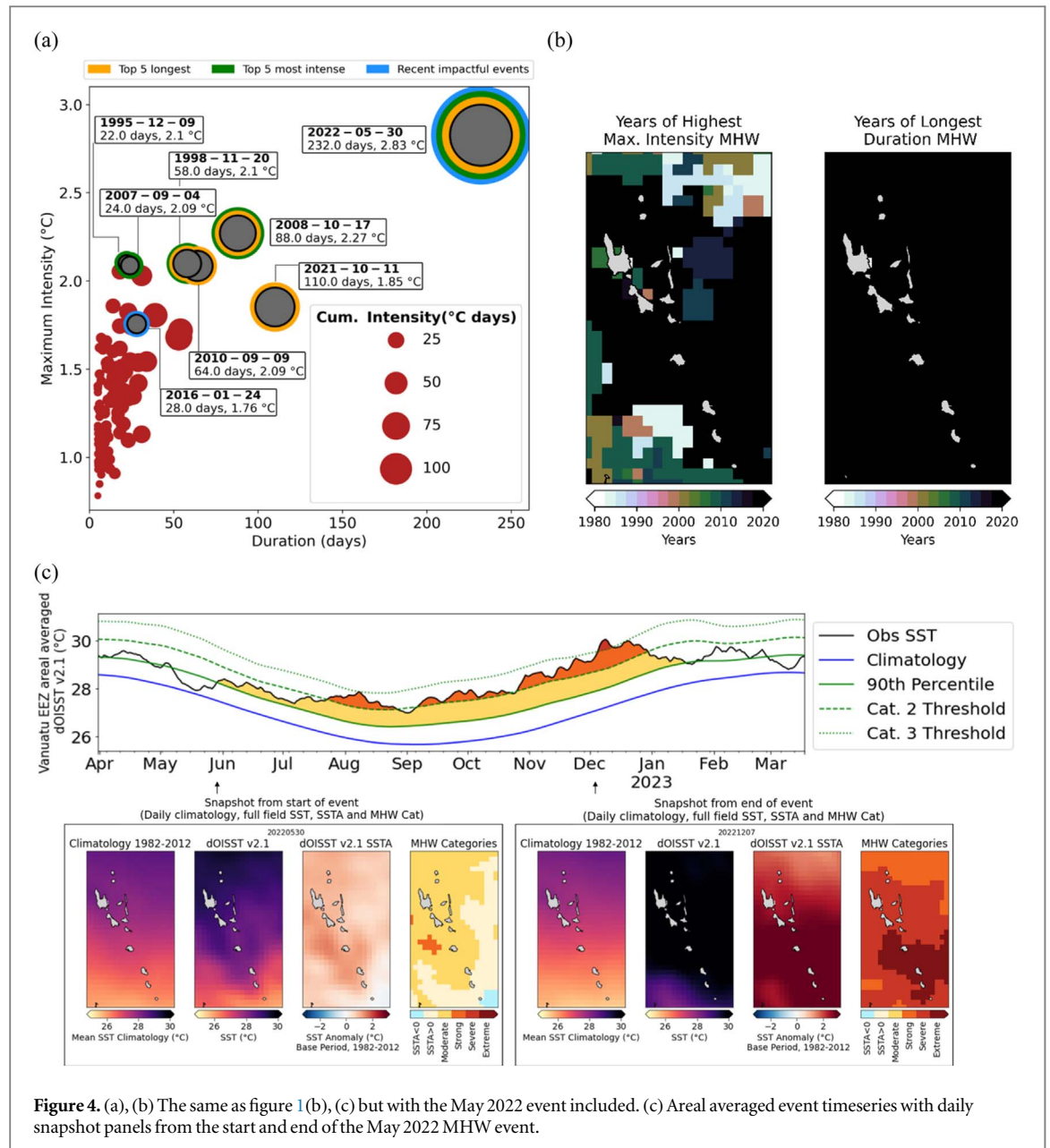
Literature analysis of the 2010 El Niño event found little reports of coral bleaching (NOAA’s coral watch tool didn’t detect any above threshold days unlike for the 2008 event). However, Holbrook *et al* (2022) report dead/dying fish and invertebrates washing up on beaches along Fiji. Elsewhere in the region, along the Western coast of Australia, there were reports of dead fish washing up on beaches from MHW events in the eastern Indian Ocean (Pearce *et al* 2011). Whilst there are little official records of biological impacts in Vanuatu, VMGD staff recounted memories of fish poisoning incidence that lingered from this event. This event also coincided with a local fish festival celebrated in November (St Andrews and Leaf Fishing festival). VMGD staff recounted how fish poisoning impacted on festival celebrations leading to complaints of smell and poisoned fish (VMGD staff, pers. comm.). Similar to the 2008 event, early warning of the 2010 event could have helped impacted communities respond differently. Forecasted areas above 90th percentile thresholds could factor into festival management and planning to avoid celebrating in areas where warmer waters may have contributed to fish death.

### 3.3. January 2016—MHW event with mass fish deaths

The January 2016 event was not identified in the top five most longest or most intense events in figure 2(b) but was associated with the deaths of hundreds of marine fin fish and invertebrates (Holbrook *et al* 2022). The beginning of 2016 was categorised by a decaying strong El Niño event which was followed by La Niña-like conditions (La Niña Watch, no event, BoM 2023). This MHW event was comparatively short lived—with a duration of 28 days (and a maximum intensity of 1.76 °C). However, its rapid onset led to a rapid decline in dissolved oxygen leading to significant biological deaths in lagoon regions (Marra *et al* 2022). Our applied MHW framework found that this event had a nationwide peak of Category I or a ‘Moderate’ event. Another factor that may have exacerbated the impacts of this event could be the various preceding MHWs, most notably a 54 day event in January 2015, appendix C).

Overall, the lower intensity and shorter duration of this event may have contributed to decreased hindcast detection at longer lead times. The monthly lead 0 February hindcast had a hit rate of 95.5% compared to the monthly L1 February of 6%. Similar to the 2010 event, the lack of lead time specific climatology could be contributing to decreased event detection at longer lead times particularly as forecasted anomalies seem to be reduced in magnitude to observed ones. Literature analysis of this event found widespread reports of sudden fish death and coral bleaching in Pango Village, Port Vila and Aneityum Island (Holbrook *et al* 2022). Unlike the 2008 and 2010 events, the 2016 MHW event saw anomalously warm waters for the majority of the tropical south-west Pacific. This may have also influenced the rapid onset and extreme impacts of this event. In previous events, cooler water in the south-west Pacific may have been transported by jets, currents and upwelled through a variety of different processes. However, in 2016 the lack of cooler surface waters in the region may have offered little relief to stressed ecosystems and local species. Similar to the 2008 event, and unlike the 2010 event, NOAA coral bleaching products indicate that coral bleaching thresholds were surpassed for early 2016 and 2017, which may indicate the time lagged coral bleaching impacts of this event (NOAA Coral Reef Watch, 5 km Regional Bleaching Heat Stress Maps and Gauges, Vanuatu 2016–2017, dataset reference: Liu *et al* 2006).

Despite the 2008 event being the empirically longest, and most intense, and even the 2010 event having more extreme nation-wide averages, the impacts from the 2016 event were widespread and non-linear in their relation to empirical metrics. In unpacking the non-linear impacts of this event, we conducted concurrent analysis into the region’s exposure and vulnerability (Aitkenhead *et al* 2024). We found moderate to high exposure values (exposed assets, ecosystems and infrastructure) for Sanma province and high vulnerability values (susceptible communities and socioeconomic factors) in Malampa province. The 2016 event manifested primarily around Torba, Sanma, Penama and Malampa provinces. The event onsetting on a backdrop of highly exposed vulnerable provinces could explain the severity of impacts observed in the region (Aitkenhead *et al* 2024).



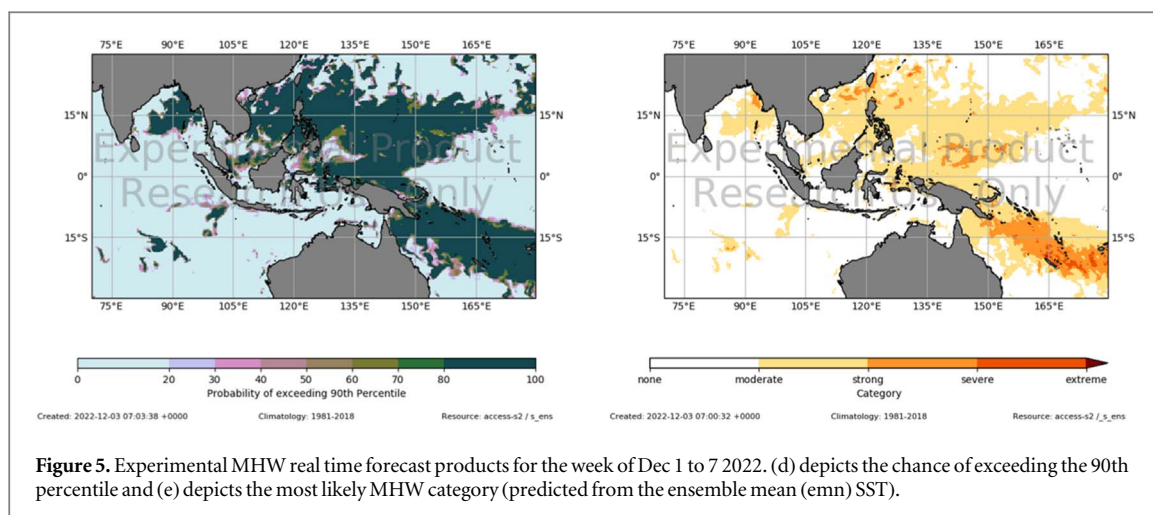
**Figure 4.** (a), (b) The same as figure 1(b), (c) but with the May 2022 event included. (c) Areal averaged event timeseries with daily snapshot panels from the start and end of the May 2022 MHW event.

Understanding these components that contribute to risk can allow for tailored communication and decision-making services for key stakeholders when an event begins or is about to begin.

### 3.4. May 2022—An ‘off the charts’ event

Despite our study period being restricted to 1980–2018 due to hindcast availability, VMGD staff notified us of an anecdotally unprecedented event in May 2022. When this event is included into the overall MHW analysis previously depicted in figure 1(b,c) the results are quite literally ‘off the charts’ with this event being the longest and most extreme on record by 144 days and 0.56 °C (figures 4(a, b)) with a total duration of 232 days and maximum intensity of 2.83 °C. We also found that spatially, this event was the longest on record for each grid cell in Vanuatu (black areas on map). This was also the first event to reach a nationwide average peak of Category III or ‘Severe’ with a significant portion of areas in ‘Extreme’ (figure 2(c)). This analysis is consistent with reports of active MHW events shared at the eleventh Pacific Islands Climate Outlook Forum (SPREP, Pacific Met Desk Partnership, and WMO 2022) and the 2022 State of the Climate in the South-West Pacific report which notes MHW events with durations longer than 180 days prevalent over Vanuatu and surrounding regions (Figure 9, WMO 2024).

Hindcast data is only available for 1980–2018 so for the 2022 event we consulted experimental real time products that began production in September 2022 (figure 5, Smith *et al* (2023)). Currently, SSTA forecast plots are issued operationally via the BoM Pacific Long Range Forecasts webpage. These products are SSTA plots



**Figure 5.** Experimental MHW real time forecast products for the week of Dec 1 to 7 2022. (d) depicts the chance of exceeding the 90th percentile and (e) depicts the most likely MHW category (predicted from the ensemble mean (emn) SST).

issued twice a week at weekly, fortnightly, monthly and seasonal timescales. Unlike our hindcast analysis, these anomaly forecasts do not provide a chance of above 90th percentile analysis, however, there is a currently an experimental product in development (Smith *et al* 2023). These products provide more detail than anomaly forecasts alone and allow for a probabilistic understanding of chance of exceeding 90th percentile thresholds (figure 5(a)). Additionally, these products also provide an indication of the most likely MHW category derived from the ensemble mean SST (figure 5(b)).

The experimental product in figure 5 only began production in September 2022 so it is not possible to analyse the other events in our study using its capability. Nonetheless, the value of such a product is evident. The experimental real time forecast depicts an ensemble mean MHW category of strong to severe in the waters around Vanuatu (left) and a greater than 80% chance of exceeding the 90th percentile SST threshold for the week of 1 to 7 Dec 2022 which was the peak of this event.

For each MHW event discussed in this study, we analysed hindcast performance on a per event basis. We extend our analysis further by averaging hindcast performance over all events (figure 6) and then also by averaging performance over the top five longest and most intense MHW events (Appendix D). Overall, hindcast performance is more skilful (higher hit rates, lower false alarm rates and higher critical success index) for lead 0 events and for the five longest and most intense MHW events. Suggesting that the model performs better for higher magnitude events. This is a model feature that is also similar for rainfall extremes whereby analysis of skill maps for quintile forecasts (rainfall extremes in the highest/lowest 20% of records) have generally higher skill than tercile forecasts and chance above median products (referred from skill maps available via the BoM Pacific Climate Outlook webpage). High magnitude extreme events often correspond to tail events in the statistical probability distribution space, by virtue of their increased severity and calibration approaches, models are generally understood to detect extreme events with greater accuracy and precision than lower magnitude events. We observed similar trends in our event-by-event analysis, whereby the lowest magnitude event analysed in this study (January, 2016) had significantly poorer performance.

When performance is averaged over all MHW events, we note relatively consistent spatial performance for lead 0 hindcasts (left column in figure 6). However, for lead 1 hindcasts, hit rates seem to be highest in the waters around Malampa and Shefa provinces. Another prevalent feature of the metrics visualised in figure 6 is the presence of white space that implies a false alarm rate of zero for lead 1 monthly forecasts. This does not necessarily mean that the model will never give false alarms in this area but rather that for this period of analysis, a limited number of false alarm grid cells could be contributing to zero values (recall FAR calculation from equation (3)). Upon inspection of lead 1 forecasts in the appendices, we note the areas of white to be mostly populated with hits/misses/correct rejections. This effect of little false alarm grid cells can also be detected in the CSI plot for lead 1 monthly forecasts. Whereby in the region where FAR values appear to be zero, CSI values are very similar to HR values. Recall CSI is hits/(hits+misses+false alarms) in the case where there are zero false alarm grid cells, CSI will converge towards the equation for HR. This is why it is valuable to consider a range of performance metrics, consulting one metric alone can give distorted insights into performance.

#### 4. Conclusion and implications

This work applied a consistent MHW methodology to analyse past events in Vanuatu and how they could have been monitored and predicted using satellite and forecast data. In analysing the dOISST satellite record for past

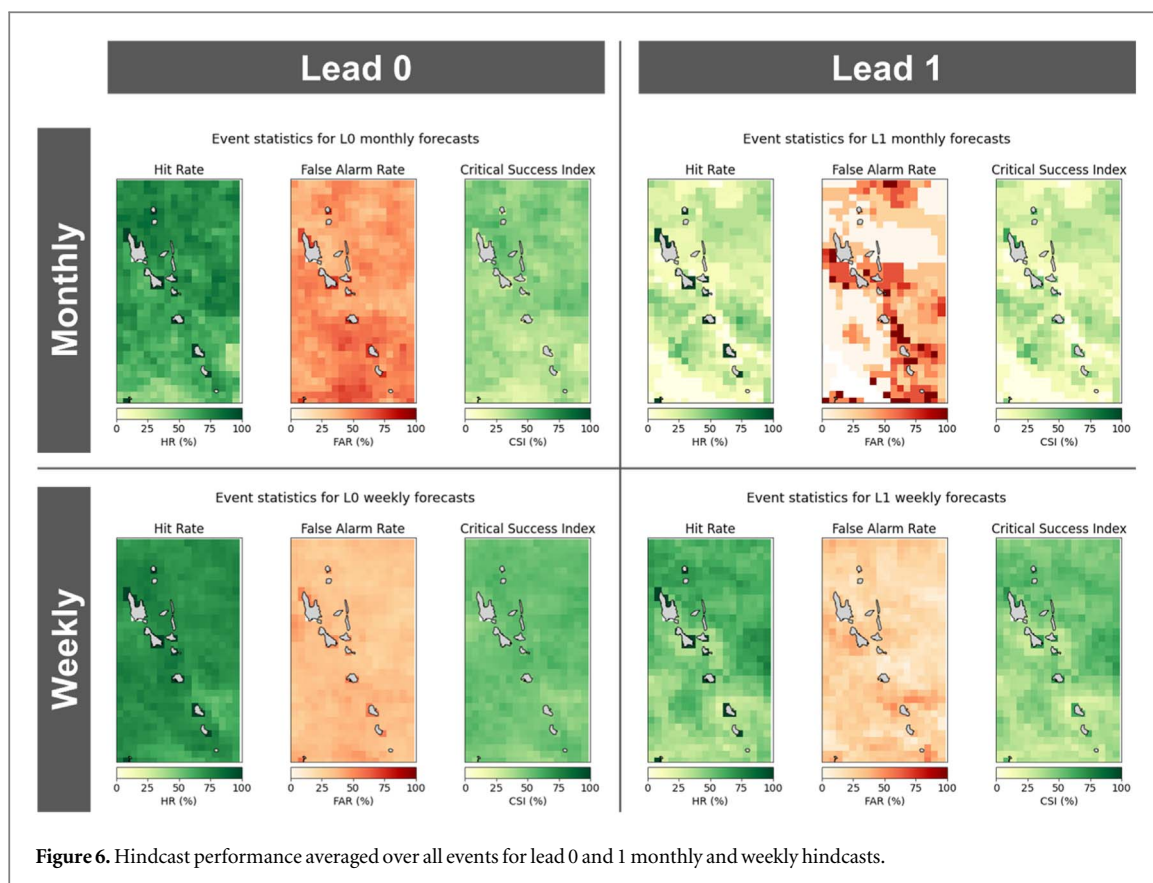


Figure 6. Hindcast performance averaged over all events for lead 0 and 1 monthly and weekly hindcasts.

MHW events in Vanuatu, we looked at some of the longest and most intense events and analysed four key events. Hindcasts with a reduced ensemble size (27 members) and real time experimental forecasts (99 members) were used to analyse the prediction of MHW events. It was found that S2S prediction of MHW events is most accurate at shorter lead times.

Earlier, we referenced the concept of a ‘permanent MHW state’, where in a warming world, oceanic baselines may be warmer than the 90th percentile threshold enduringly Oliver *et al* (2019). For a high emissions scenario, Oliver *et al* (2019) note that for the south-west Pacific this state could be reached as early as 2040. The 2022 event analysed in this study is an example of how future events are likely to surpass historical records. Our analysis of MHW characteristics in the two decades before and after the year 2000 also indicate that MHW events have gotten longer and more frequent in the waters around Vanuatu. Concurrent MHW research conducted within the Van-KIRAP project analysed the impacts of MHWs on seagrass in a warming world (CSIRO and SPREP 2023). Authors found that the mean annual number of days in each MHW category are expected to increase for 2030, 2050, 2070 and 2090 under SSP585 and SSP126 scenarios for the Pango region in Vanuatu. In a warming climate, the careful monitoring and prediction of MHWs will be critical to effective management of limited resources. Our analysis found that longer timescale forecasts indicated moderate to strong performance and can be used to provide general guidance and preparedness for at risk communities and sectors which can then be finetuned with shorter scale forecasts issued as events unfold.

The ACCESS-S2 hindcasts have been compared to observed conditions for past MHW events in Vanuatu. Such information about predicted ocean-atmosphere conditions can be used to manage risk in exposed sectors and industries. Hobday *et al* (2018) investigate a framework for combining seasonal forecasts with climate projections to provide better decision-making services for fisheries and aquaculture sectors in Australia. In their research, they investigate a decision tree to guide making informed climate dependent business decisions. In the case of the south-west Pacific, a similar approach could be adapted to categorise MHW concern into distinct categories that may have actions associated with them. A MHW decision tree may ladder through questions like:

- In the last month, have observed SSTs been above average for this region?
- Do forecasts indicate that SSTs are likely to exceed the 90th percentile for the coming week/month/fortnight/season?
- Does this region have exposed assets and vulnerable communities that are susceptible to MHW impacts?

Disaster management agencies, international development organisations, fisheries stakeholders and climate community services can tie each step of the monitoring and prediction analysis process with distinct actions.

Accompanying hazard information with exposure and vulnerability information is another key recommendation of this study. Community impacts from extreme events are often cascading and non-linear. As we unpacked with the 2016 event, the most extreme hazard does not always necessarily have the most extreme impacts if it occurs in regions where community or natural environment resilience may be higher. Thus, analysing hazard profiles in isolation from a region's exposure and vulnerability information provides very limited insight into impacts. Aitkenhead *et al* (2024) conducted a thorough analysis of such exposure and vulnerability profiles for Vanuatu. They used information such as percentage of households with income sources alternative to fisheries (i.e. cropping, livestock) as well as fisheries-specific vulnerability to create annual vulnerability profiles for each province in Vanuatu. They combined this information with exposure indices such as seagrass species richness, crown of thorns prevalence, coconut crab stock status and fish catch to devise holistic exposure-vulnerability profiles. These profiles were consulted when looking at the extreme events in this study and findings were helpful in contextualising the extent of impacts from the 2016 MHW event. Ultimately, decision makers should aim to synthesize hazard information in context of exposure and vulnerability profiles. Such information can aid management decisions into resourcing and prioritization of limited resources.

It was out of scope of this study to investigate the Traditional Knowledge (TK) systems in place for predicting and monitoring MHW events. However, this study can serve as a useful tool through which to spark discussion about how TK approaches may be consulted to better define, monitor and predict MHW events. During our time in country, we had several informal discussions about the anecdotal impacts of MHWs and how different communities prepare accordingly. The Vanuatu TK national indicator booklet created concurrently in the Van-KIRAP project provides a summary of the TK indicators used to predict and prepare for a variety of different climate hazards and phenomenon (VMGD and Van-KIRAP 2023). The information captured in this booklet was derived from TK surveys conducted at identified sites in Vanuatu's provinces (VMGD and Van-KIRAP 2023). There are a range of relevant marine TK indicators summarised in this resource and there are likely to be even more TK indicators used within communities and passed down verbally. Examples of such TK indicators include Palolo worms, flying fish, mackerel fish, dolphins and green sea turtle. The presence, abundance and timing of these species gives local communities an indicator of anomalous climatic conditions and they will often adjust their actions and decision making accordingly. We note the generations of knowledge passed down within communities that has the potential to aid in the monitoring, early warning and communication of MHW events. It would be a useful application of this report to unpack MHW definitions, adaptations and prediction tools with different communities to better understand how MHW guidance can be delivered in community-specific ways.

In a future where a permanent MHW state could be reached as early as 2040 for parts of the south-west Pacific, the careful monitoring and prediction of MHW events will be crucial. This, coupled with the integration of local knowledge systems will be essential for the resilience and well-being of symbiotic marine and human communities like the people of Vanuatu.

## Acknowledgments

This study on 'Monitoring and Predicting Marine Heatwaves in Vanuatu' was produced as part of the Climate Information Services for Resilient Development in Vanuatu (CISDRP) project also known as the Van-KIRAP (Vanuatu Klaemet Infomesen blong Redy, Adapt mo Protekt) project. The project is jointly implemented by the Vanuatu Meteorology and Geo-Hazards Department (VMGD) and the Secretariat of the Pacific Regional Environment Programme (SPREP) and funded by the Green Climate Fund (GCF). We thank Vanuatu colleagues for their collaboration and hospitality in completing this work. In particular, Sunny Seuseu, Moirah Matou, Glenda Pakoa, John Ruben as well as the extended Climate Division at VMGD. We also extend thanks to staff at the Vanuatu Fisheries Department and the Vanuatu National Statistics Department for their assistance in gathering data and scoping directions. We also thank Zhi-Weng Chua and Grant Smith at the Australian Bureau of Meteorology for their helpful feedback and reviews.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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