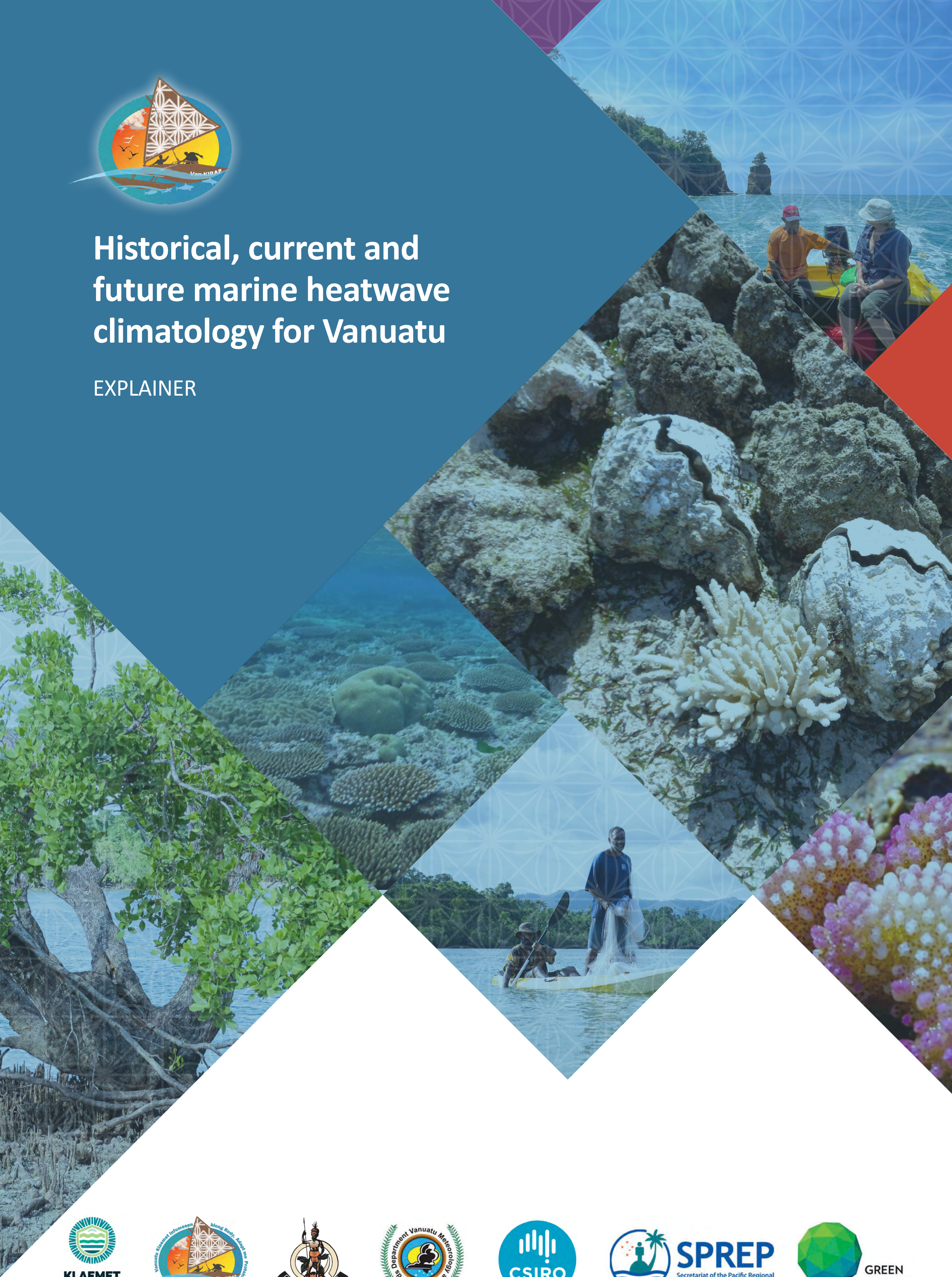

Historical, current and future marine heatwave climatology for Vanuatu

EXPLAINER

KLAEMET SAVE
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CSIRO

SPREP
Secretariat of the Pacific Regional Environment Programme

GREEN CLIMATE FUND

This publication should be cited as:

CSIRO, SPREP and VMGD (2023). Historical, current and future marine heatwave climatology for Vanuatu. A report to the Van-KIRAP project. Commonwealth Scientific and Industrial Research Organisation (CSIRO), Secretariat of the Pacific Regional Environment Programme (SPREP) and Vanuatu Meteorology and Geo-hazards Department (VMGD), CSIRO Technical Report, Melbourne, Australia.

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The project team would like to acknowledge Kevin Hennessy (Climate Comms), Alistair Hobday and Geoff Gooley (CSIRO) for providing helpful comments.

The project team would like to acknowledge Ellian Bangtor, Geoff Gooley, Gina Ishmael and Rebecca Gregory for images used on the front cover.

Contents


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Summary

- Marine heatwaves (MHWs) are defined as 'discrete, prolonged anomalously warm water events which last for five or more days, with sea surface temperatures (SSTs) warmer than the 90th percentile relative to climatological values'.
- The most common drivers of MHWs include ocean currents which can build up areas of warm water and air-sea heat flux, or warming through the ocean surface from the atmosphere. Winds can enhance or suppress the warming in a marine heatwave.
- MHWs can have a very different temperature profile depending on the seasonal, regional-scale background ocean temperatures.
- Across Vanuatu historically there has been an increasing frequency of MHWs (1982–2021), mostly in the 'Moderate' to 'Strong' category.
- Broadly speaking, northern Vanuatu has experienced more frequent, longer duration and higher intensity MHWs than southern Vanuatu for the period 1982–2021.
- Across all sites, historically the typical number of MHWs is around 25 days per year (20-year average centred on 1995). Under the low greenhouse gas emissions scenario (SSP126), this is projected to increase to about 80–150 days per year by 2050. Under the high emissions scenario (SSP585) this increases to about 170–310 days per year by 2050, with many days in the 'Strong' and 'Severe' MHW categories.
- Degree heating weeks (DHW), a related MHW metric, provide a measure of coral stress.
- Using DHW estimates, more exposed reefs are found in northern Efate, west Epi, east Malekula and south-west Ambrym islands. Less exposed reefs, identified as historical refugia, are in Tanna, southern Efate, Ambrym, north Pentecost and west Maewo islands.
- Some of these refugia are projected to experience delayed impacts such as annual severe bleaching seven or more years later than the average for Vanuatu in 2040.

Introduction

Marine heatwaves (MHWs) are episodes of prolonged and anomalously high ocean temperatures [1, 2]. They can have devastating impacts on aquaculture and marine ecosystems, including many that provide critical habitat and ecosystem services (e.g. coral reefs, seagrass, kelp beds). MHWs can be caused by a whole range of factors, and not all factors are important for each event. The most common drivers of MHWs include ocean currents which can build up areas of warm water, air-sea heat flux or warming through the ocean surface from the atmosphere. Winds can enhance or suppress the warming in a MHW, and climate variability drivers like ENSO can change the likelihood of events occurring in certain regions [3]. MHWs are often associated with periods of clear skies and more settled conditions, and consequently less wind-driven mixing of the surface ocean which enhances surface heating.

Globally, MHW frequency, intensity, and duration have increased over the last four decades [4], and climate projections indicate that this trend is set to continue for decades to come in many regions, including the Pacific [5]. This will have serious impacts on marine species and aquatic ecosystems over the coming decades [6], along with the coastal communities dependent on these natural resources for coastal protection, livelihood and environmental amenity (ecosystem services), with the rate of change depending on the global greenhouse gas emissions pathway followed in future [7]. This report describes what MHWs are, observed changes and how MHWs may increase in future (also see the Seagrass infobyte).

Observed sea surface temperature, seasonal cycle and trends for Vanuatu

Across the Vanuatu archipelago annual average sea surface temperatures (SSTs) range historically from about 25.5 °C to 28.5 °C from south to north (Figure 1). Through the 1993–2021 period, monthly-average SSTs at the Port Vila tide gauge ranged from around 29 °C in February–March to 25.5 °C in August (Figure 1, top right) [8], with individual monthly SSTs varying within 2 °C of the monthly average.

As part of the Van-KIRAP project case studies, SST observations taken from the NOAA daily Optimum Interpolation Sea Surface Temperature v2-1 data set[1] (hereafter called OISST v2-1; [9]), have been averaged over the Vanuatu Exclusive Economic Zone, revealing a historical warming trend of 0.23 °C per decade during 1981–2021 (Figure 1, bottom right) [8]. SSTs are now reaching record high levels globally [10] driven by global warming due to increases in greenhouse gases [11].

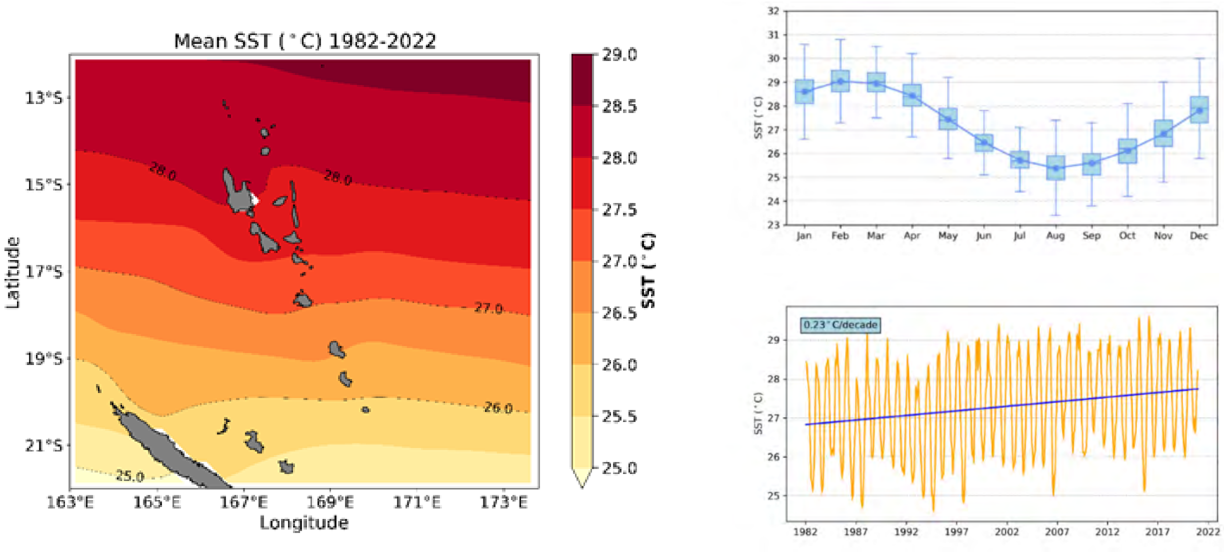

Figure 1 (left) Vanuatu annual average SST (°C) (1982–2022). (Top right) SST (°C) measured at the Port Vila tide gauge (1993–2021), with blue dots showing the monthly average, shaded boxes show the median (middle 50 % of observations) and lines showing the top and bottom 25 % of observations. (Bottom right) SST from satellite observations averaged across the Vanuatu region, with annual averages shown as the orange line. The blue line shows the linear regression trend [8]. Data source for left and bottom right plots: [9].

[1]Daily OISST data are constructed by combining observations from different platforms (satellites, ships, buoys, and Argo floats) on a regular 0.25 ° global grid (around 27 km between data points) with interpolation to fill any data gaps. Full year data are available from 1982–2022.

Definition of marine heatwaves

Marine heatwaves are defined as 'discrete, prolonged anomalously warm water events which last for five or more days, with SSTs warmer than the 90th percentile relative to climatological values' [1, 2] where:

- 'discrete' implies a well-defined start and end date, and separated from a previous MHW by more than two days
- 'anomalously warm' is warmer than the 90th percentile (top 10 % of events) in a 30-yr baseline period
- 90th percentile accounts for seasonal differences as it is uniquely computed for each calendar day.

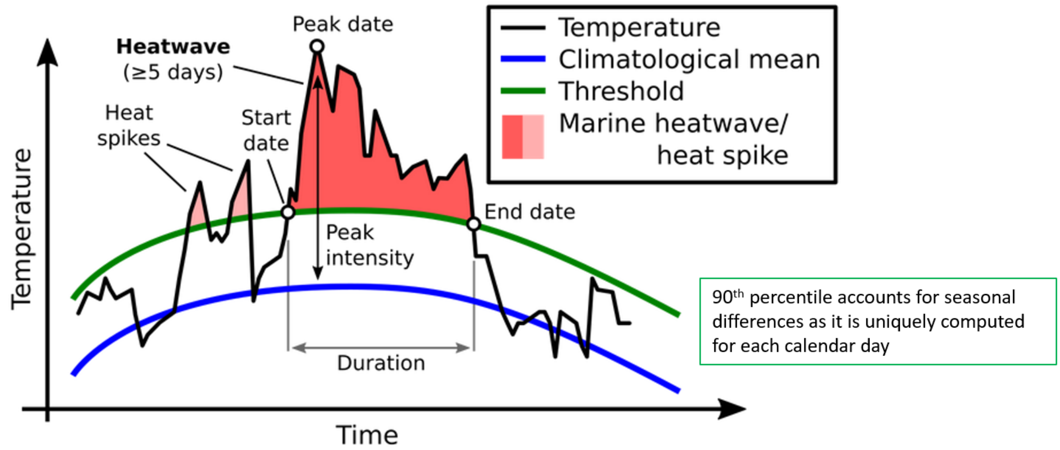

Figure 2 Diagram illustrating MHW definition: SST (°C) timeseries (black line) overlaid on the average SST (blue line) and the 90th percentile threshold (green line). When the SST exceeds the threshold for more than five days, it is defined as a MHW (red shading) [1, 2]. Heat spikes (pink shading) are not classified as a MHW because they are shorter than five days and are separated from the MHW by more than two days.

MHWs are categorised into four intensity categories, defined by multiples of the difference between the mean SST across a defined period and the 90th percentile threshold i.e. the difference (D) between the blue and green lines in Figure 3. For example, an event with moderate intensity is 1–2 x D. Intensity is defined as 'Moderate' (Category I, 1–2 x D), 'Strong' (Category II, 2–3 x D), 'Severe' (Category III, 3–4 × D), and 'Extreme' (Category IV, greater than 4 x D) [2].

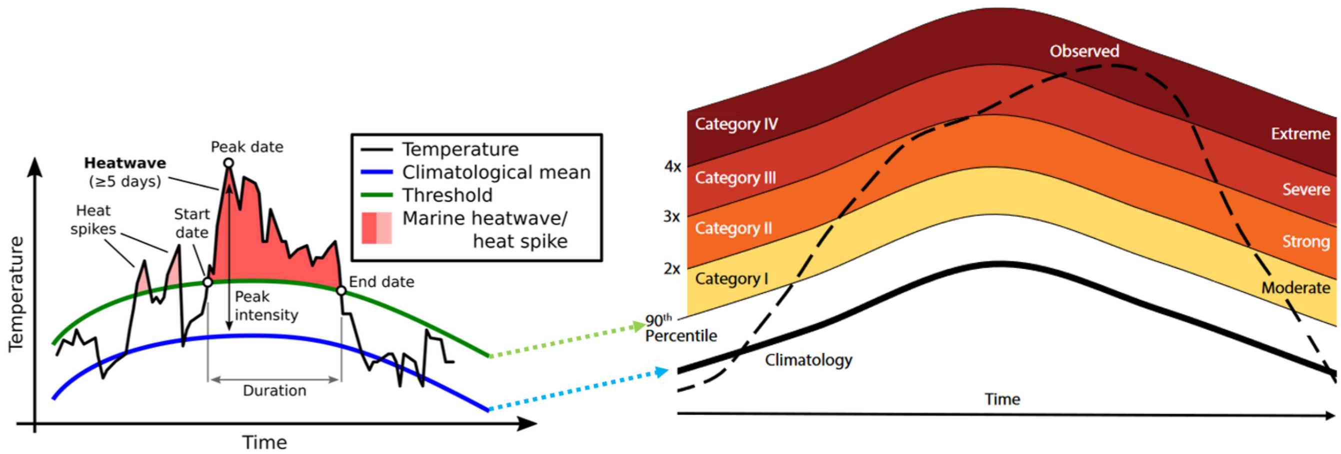

Figure 3 Multiples of the 90th percentile difference (2×D, 3×D, etc.) from the mean climatological value define each of the MHW categories I–IV, with corresponding descriptors from moderate to extreme. This example (dashed line) peaked as a Category IV (extreme) MHW [2].

Detecting and measuring marine heatwaves from global gridded data sets

To measure MHW occurrence, SST timeseries are extracted from the OISST v2-1 data for the closest grid cell best representing the location of interest. It is noted grid cells may not be centred on the exact location (Figure 4). Recent analysis undertaken for Fiji, Samoa, Palau, [5] and Cook Islands [12] indicates OISST v2-1 SST is usually very close to actual temperatures recorded in coastal areas and reef systems. Similarly, recent work in Vanuatu indicated that the OISST v2-1 data were very close to SST observations from marine Spotter wave buoys deployed around the coastline by the Van-KIRAP project (see Ocean monitoring factsheet).

In Figure 4, timeseries for the period 2002–2021 are shown for Pango (adjacent to Port Vila, Efate), in which a significant MHW event occurred, resulting in thousands of fish being killed [13]. The MHW in mid-February 2016 reached the 'Strong' category with SST between 1.75–2.0 °C above normal.

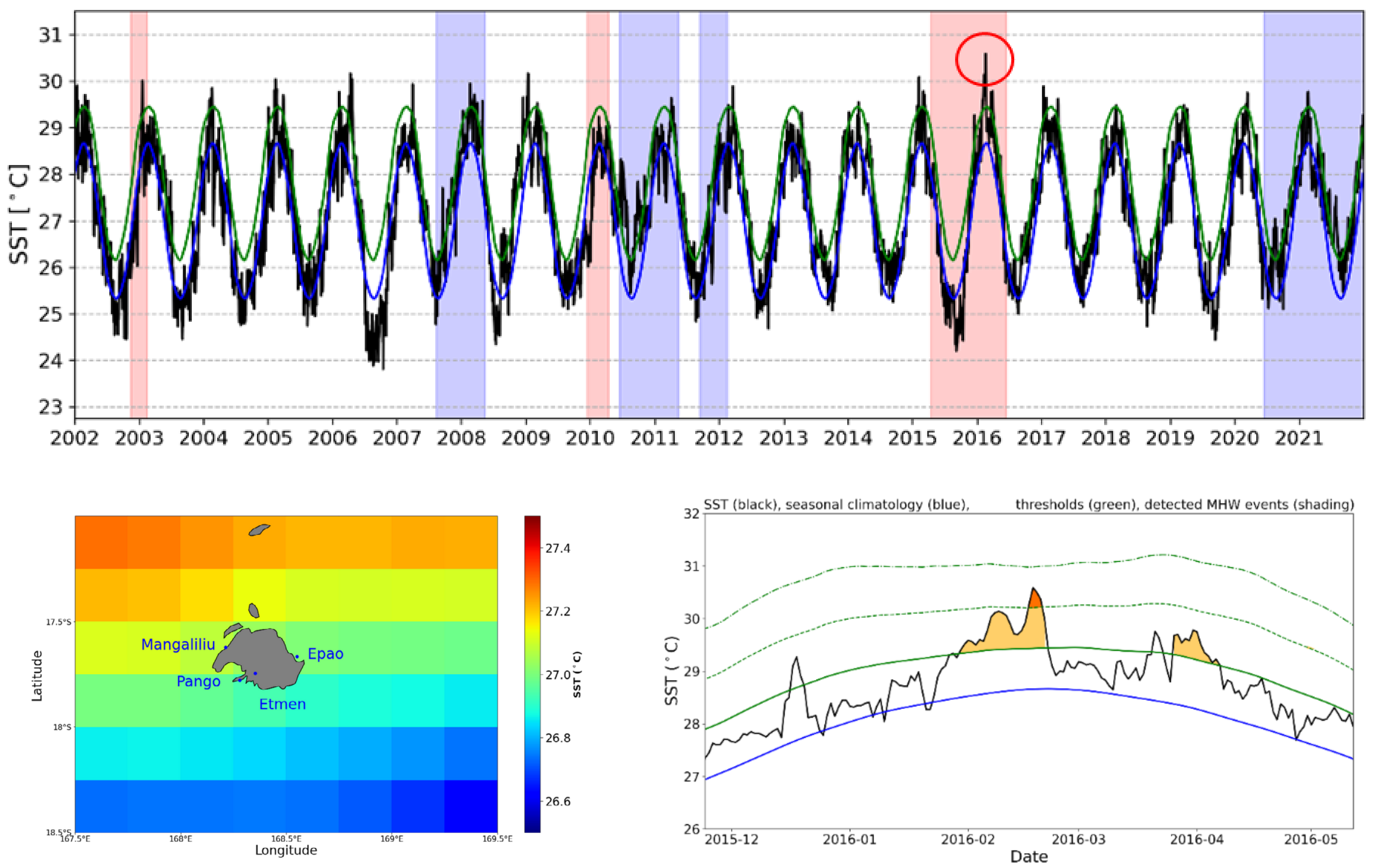

Figure 4 (top) SST (°C) timeseries from 2002–2021 for Pango region showing the observed daily values (black line), the seasonal mean climatology (blue line; based on 30-year baseline, 1986–2015), and the 90th percentile threshold (green line). Coloured bars denote strong El Niño (pink) and La Niña (blue) events. The February 2016 heatwave is highlighted with a red circle. (Bottom left) NOAA OISST v2-1 grid focused on Efate, noting the relative size of the grid cell from which each timeseries and MHW analysis is taken. (Bottom right) SST timeseries of the February 2016 event for Pango showing observed daily values (black line), seasonal mean climatology (blue line), 90th percentile threshold (green solid line), 2× threshold (dashed line), and 3× threshold (dash-dot line).
Data source: [9].

Analysis of the longest MHW duration and cumulative intensity for Pango indicate the largest MHWs have occurred in the last 15–20 years (Figure 5), with cumulative intensity being the sum of the daily intensities through the duration of the MHW event.

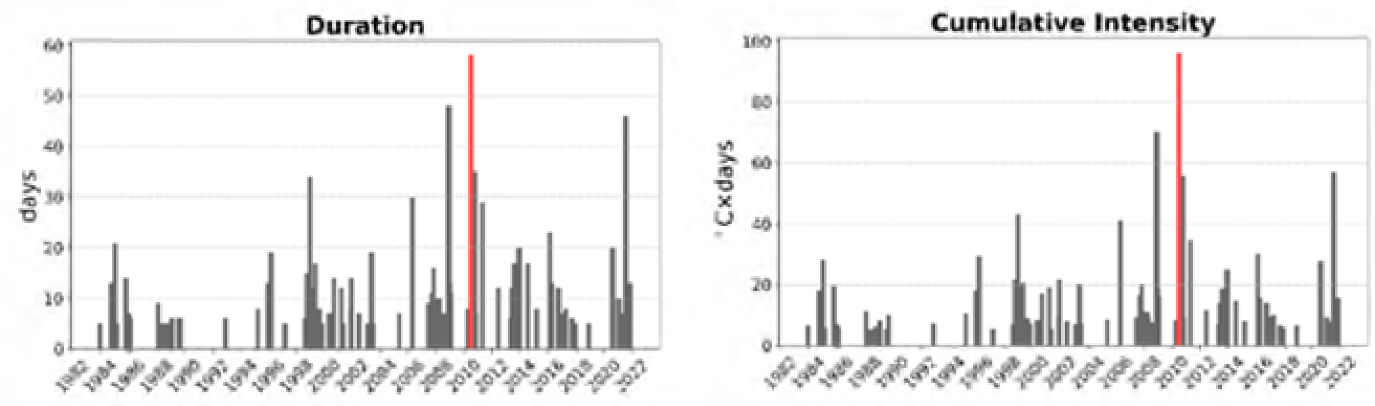

Figure 5 MHW duration (days) and cumulative intensity (°C x days). Data source: [9].

Observed marine heatwaves for sites of interest for Vanuatu's fisheries sector

Timeseries of MHW observations have been assessed for Vanuatu's fisheries sector. At eight sites of interest there has been an increasing frequency of MHW's during 1982–2021, mostly in the 'Moderate' to 'Strong' category (Figure 6).

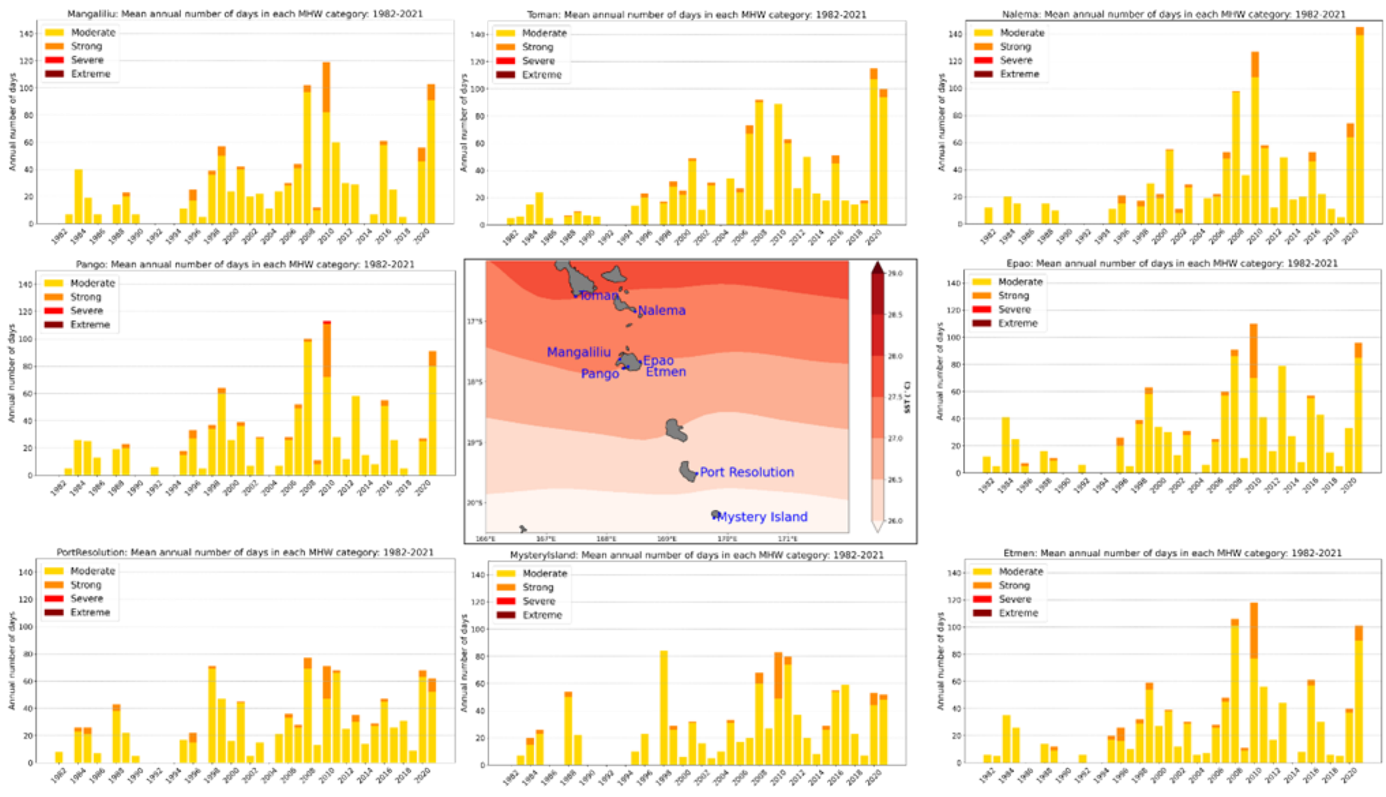

Figure 6 Mean SST (°C) (1982–2021) for Vanuatu fisheries sector sites of interest from north to south: Toman, Nalema, four sites on the coast of Efate, Port Resolution and Mystery Island (central map). For each site, the annual number of MHW days (1982–2021) is shown in each category [1, 2]. Data source: NOAA OISST v2-1 [9].

Spatial analyses of trends in observed marine heatwaves for Vanuatu

Spatial analyses of MHWs occurring in the Vanuatu region for 1982–2019 are presented in Figure 7. Note that MHWs are considered as separate events if a period of more than two days elapses since the occurrence of a previous MHW [1, 2]. Qualitative interpretation of trends in, and numbers of, observed MHWs are listed:

- Trends in annual MHW frequency are positive across the archipelago, with more occurring in the north than south (Figure 7, top left).
- The trend in annual MHW duration is mostly positive in the north, particularly around Sola and Avire, and negative in some sites in the south (Figure 7, top right).
- The trend in annual maximum MHW intensity is mostly positive in the north, and less in the south, with Aneityum (Mystery Island) having a trend to shorter duration MHWs through the specified time period (Figure 7, bottom left).
- The total number of MHW events over the period 1982–2019 varies across the region, mostly above 50, with more in the east (Figure 7, bottom right).

Regarding the fisheries sector sites of interest (Figure 6), Toman and Nalema were more exposed to MHWs, whereas the southern regions of Port Resolution and Mystery Island were less exposed.

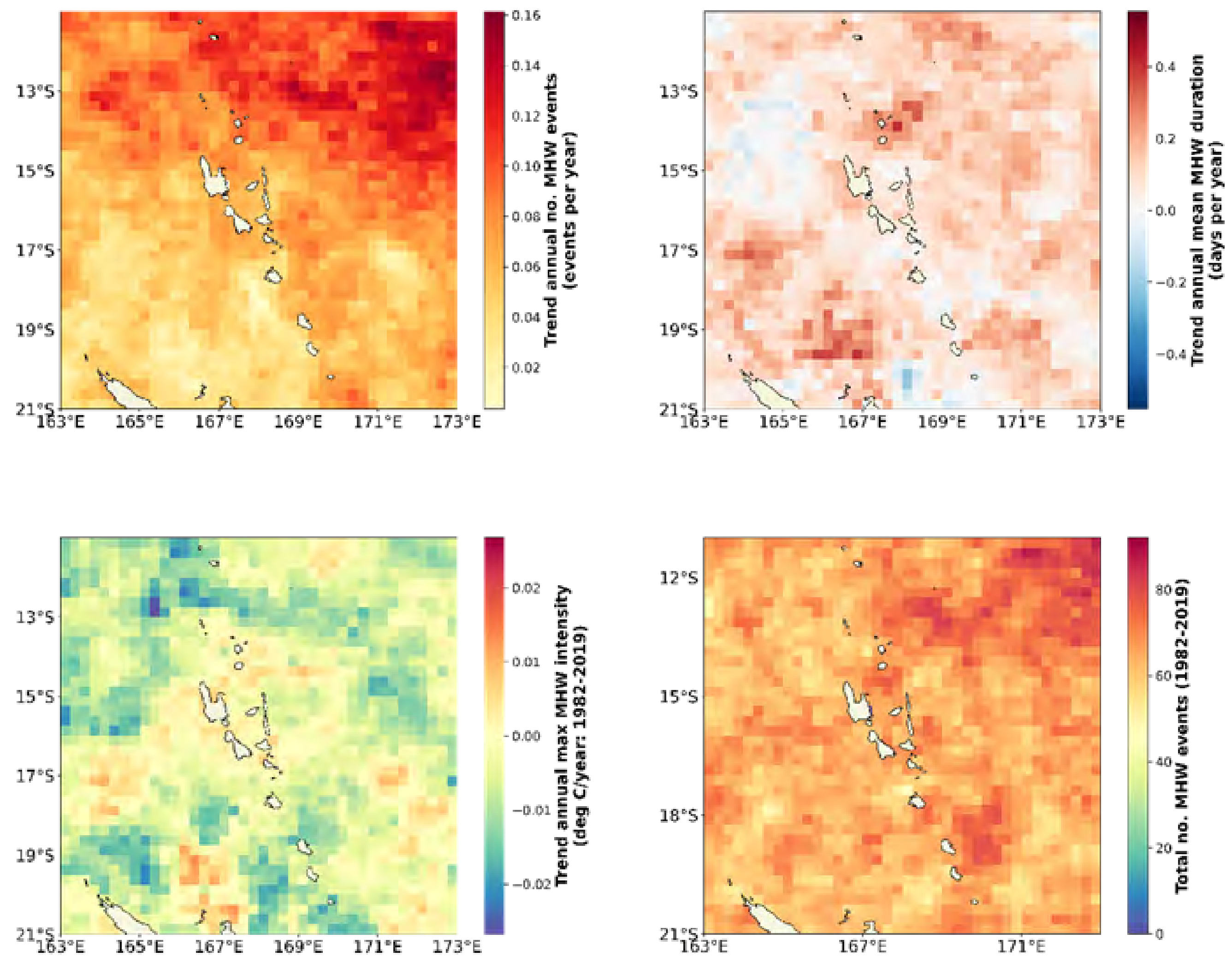

Figure 7 Trend in annual number of MHW events (top left), annual mean MHW duration (top right), annual maximum MHW intensity (bottom left), and total number of MHW events (bottom right). Source data: NOAA OISST v2-1 SST [9].

Marine heatwaves and ENSO

The incidence and intensity of MHWs is naturally influenced by the El Niño-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO), as well as local factors such as circulation patterns and processes that affect air-sea heat fluxes [14]. During El Niño events, higher SST, rainfall and sea level are clearly apparent in the central tropical Pacific. For Vanuatu, in the western tropical Pacific, El Niño events are normally associated with cooler and drier conditions [14] (also see Climate variability explainer). There is a higher likelihood of MHWs in La Niña periods, but they can occur during any ENSO phase (e.g. the 2016 MHW occurred during an El Niño event, Figure 4).

Timing of marine heatwaves

MHWs can have a very different temperature profile depending on the seasonal and regional-scale background temperatures in the ocean. MHWs can occur in summer or winter – they are defined based on differences with expected temperatures for the location and time of year. For example a heatwave occurring in August, a cooler month in Vanuatu, is unlikely to reach temperatures as high as those occurring in February. However there may be other biological, hydrological and physical and chemical processes (e.g. fish spawning and recruitment, food web and critical habitat relationships, diurnal feeding and distributional patterns, nutrient cycling etc.) that would still be sensitive to MHWs in winter [15]. Winter MHWs on top of long-term warming can also enable establishment of invasive species in some instances where previously cool winters would have killed them off [16].

Tracking marine heatwaves

The Marine Heatwave (MHW) Tracker shows the occurrence of MHWs around the world in near-real-time (roughly a one-two day delay). The tracker also shows daily the historic records for the whole planet going back to 1 January 1982. There are several other data layers offered in the tracker [3]. The February 2016 MHW event can be selected on the tracker interface as depicted in Figure 8.

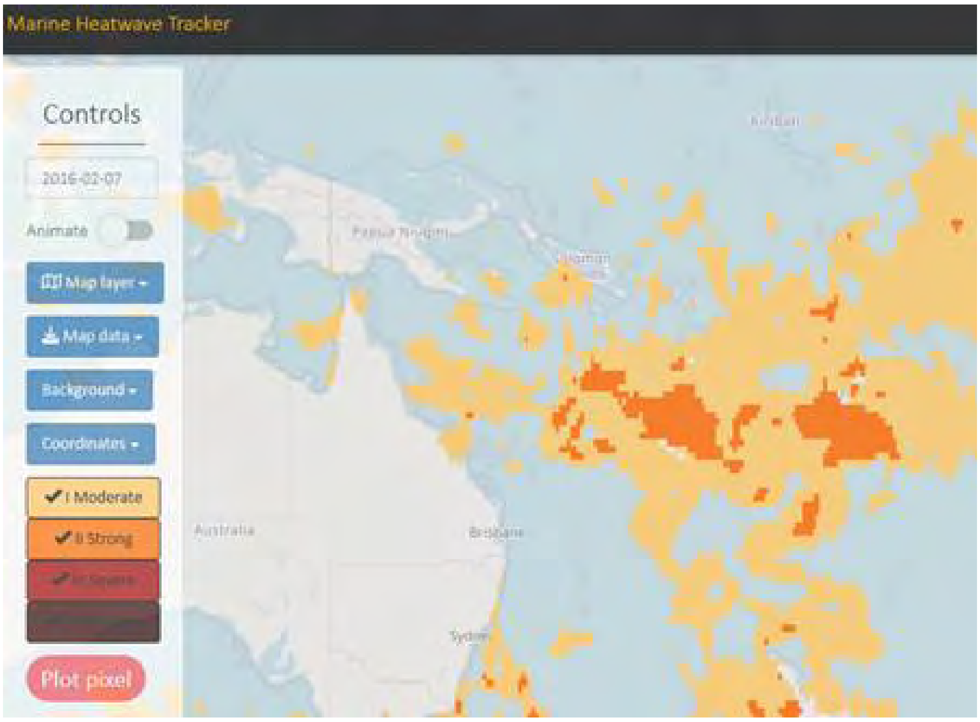

Figure 8 Marine Heatwave Tracker visualisation of the 7th of February 2016 'Strong' heatwave event (categories described here: [2]) that resulted in fish kills in Fiji and Vanuatu. http://www.marineheatwaves.org/tracker.html

Projected marine heatwaves

Projected MHWs out to the end of the century have been calculated for a lower-warming climate model (NorESM2-MM) and a higher-warming climate model (CanESM5), under low (SSP126) and high (SSP585) emissions scenarios, to capture the projected range of possible future change (Figure 9). To account for large interannual variability, data are averaged for 20-year periods centred on the years 2030, 2050, 2070 and 2090. The 20-year average (centred on the year 2005) from the OISST v2-1 observations are also plotted in Figure 9 by the left bar in each plot, denoted with an 'x'. Across all sites, the typical number of MHWs historically is around 25 days per year (20-year average centred on 2005; Figure 9). Under the low emissions scenario (SSP126) this increases to about 80–150 days per year by 2050 (20-year average centred on the year 2050; Figure 9). In Epao, under the high emissions scenario (SSP585) this increases to about 170–310 days per year by 2050, with many days in the 'Strong' and 'Severe' MHW categories (Figure 9).

By 2090, larger increases in MHWs are projected, more so in the north of Vanuatu. For a low emissions scenario the number of MHW days is 110–190, with a substantial increase in 'Strong' events. For a high emissions scenario the number of MHW days is 320–360, with a big increase in 'Severe' and 'Extreme' events (Figure 9).

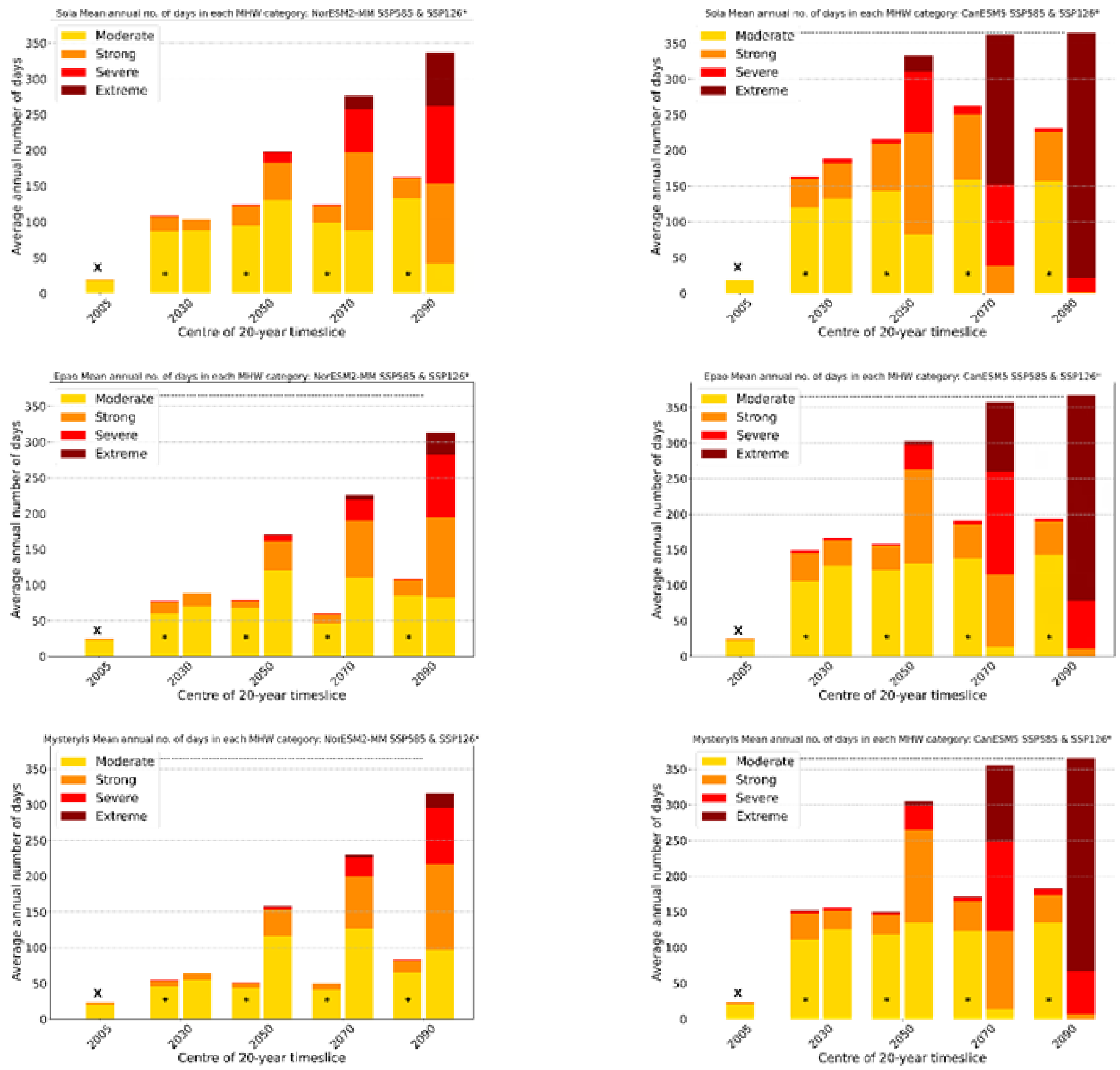

Figure 9 Projected average annual number of MHW days for an area-averaged domain encompassing northern through to southern regions of Vanuatu: (top) Sola, (middle) Epao, and (bottom) Mystery Island. The far left bar on each plot 'x', indicates historical MHWs for a 20-year period centred on 2005 (1995–2014) (x). Projections based on CMIP6 climate modelling indicate future MHW frequency for 20-year periods centred on 2030, 2050, 2070, and 2090. These are plotted for a lower warming model (NorESM2-MM; left panel) and higher warming model (CanESM5; right panel). For each future timeframe the low emissions scenario (SSP126) has an asterisk included in the bar (*), while the high emissions scenario (SSP585) has no asterisk. For all periods MHWs are categorised: moderate, strong, severe, and extreme [2]). (Data source: OISST v2-1 SST [9]: and CMIP6 climate models).

Impact of ocean temperatures on corals: degree heating weeks

Degree heating weeks (DHW) is another measure of ocean temperatures which also provides a useful measure of coral stress [17-19] (see Coral bleaching infobyte). Corals become stressed when SSTs are warmer than the bleaching threshold (solid blue line in Figure 10). This threshold is defined as 1.0 °C above the maximum of the monthly mean (MMM) SST climatology (indicated by the dashed blue line in Figure 10). Heat stress builds up the longer SST stays above the bleaching threshold. Both the magnitude of threshold exceedance and length of the exceedance are important factors in measuring stress, and thereby DHW. See Donner et al. [20] for a discussion of the metrics used.

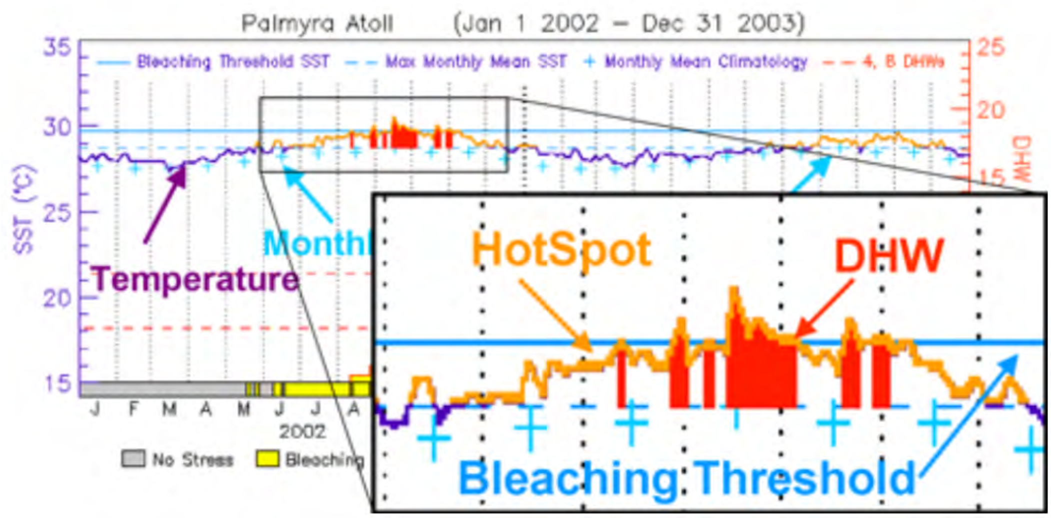

Figure 10 Simulated SST (°C) timeseries. A HotSpot is included in the DHW calculation when SST reaches or exceeds the bleaching threshold temperature. DHW (red region) is accumulated from HotSpot occurrence as the magnitude of exceedance above the MMM for a period of 12 weeks.

The term 'HotSpot' indicates the extent (in °C) that SST is above the MMM each day. DHW indicates how much heat stress has accumulated[2] and is calculated by summing the HotSpot values, over the previous 12 weeks, whenever the SST reached or exceeded the bleaching threshold. It is calculated as a running sum over a 12-week window (i.e. as you advance each day, you lose a day off the start of the 12-week window). The sum is divided by 7 to obtain the unit of '°C-weeks'. In that way a DHW of 2 is equivalent to one week of HotSpot values persistently at 2 °C (i.e. 2 °C x 7 days/7 =14/7 = 2), or two weeks of HotSpot values persistently at 1 °C (i.e., 1 °C x 14 days/7 =14/7 = 2) etc. (see : https://coralreefwatch.noaa.gov/product/5km/methodology.php#dhw). The United States National Oceanic and Atmospheric Administration (NOAA) monitors world SST and releases warnings for bleaching based on DHW (e.g. Figure 11).

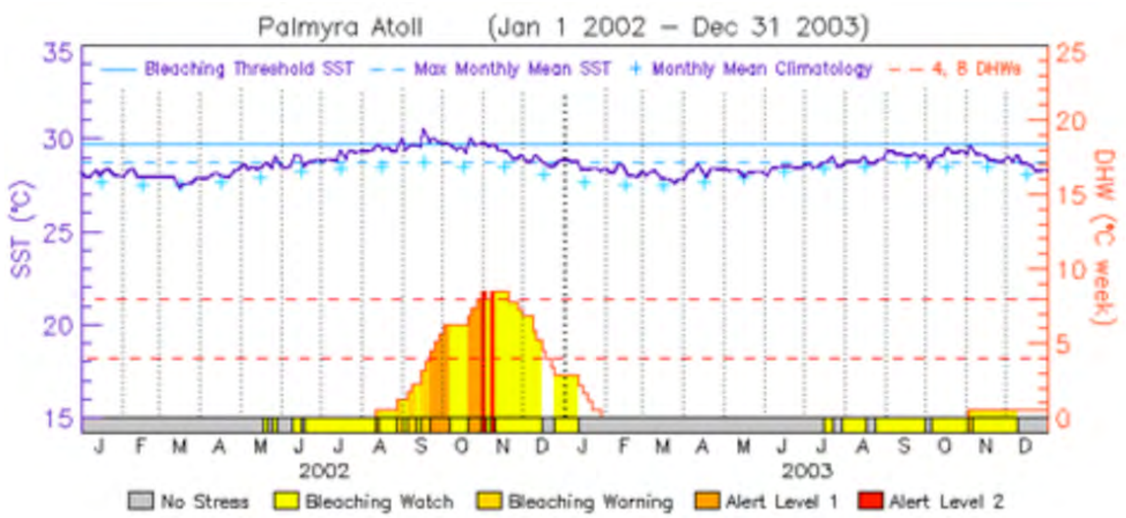

Figure 11 DHWs are plotted along the bottom of the graph, corresponding to the accumulated threshold exceedance of SST above bleaching threshold. The 4-DHW and 8-DHW thresholds are shown as dashed, horizontal red lines. The colours that fill below the DHW line correspond to established satellite bleaching alert levels (see Table 1).

A status level of 'Bleaching Watch' (Table 1) means that there is low-level thermal stress present at that location but not of sufficient magnitude to accumulate stress for corals, should they exist in that location. Alert Level 1 indicates that DHW is 4-8 and coral bleaching is likely to occur for some coral species. Alert Level 2 indicates DHW is greater than 8, so both widespread bleaching and significant coral mortality are likely. This scale has been successfully validated across historical observations at eight sites in the north-western Pacific Ocean [21].

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[2]This anomaly is summed for the preceding 12-week period to produce 'Degree Heating Days' over 12 weeks. Dividing this by seven, can change the unit to 'Degree Heating Weeks' over 12 weeks.

Table 1 Coral bleaching thermal stress levels based on the NOAA Coral Reef Watch warnings.

STATUS	INTERPRETATION	DEFINITION
No Stress	No heat stress or bleaching is present.	HotSpot of less than or equal to 0.
Bleaching Watch	Low-level heat stress is present.	HotSpot greater than 0 but less than 1; Sea Surface Temperature (SST) below bleaching threshold.
Bleaching Warning	Heat stress is accumulating; possible coral bleaching.	HotSpot of 1 or greater; SST above bleaching threshold; Degree Heating Week (DHW) greater than 0 but less than 4.
Bleaching Alert Level 1	Significant coral bleaching likely.	HotSpot of 1 or greater; SST above bleaching threshold; DHW greater than or equal to 4 but less than 8.
Bleaching Alert Level 2	Severe bleaching and significant mortality likely.	HotSpot of 1 or greater; SST above bleaching threshold; DHW greater than or equal to 8.

Degree heating weeks exposure across Vanuatu

Many of the reef locations in Vanuatu have historically been refugia from thermal stress that causes coral bleaching. Using the DHW metric, these refugia were identified [22]. For the period 1985–2012 the frequency of events greater than 4-DHW (Alert Level 1) and 8-DHW (Alert Level 2) were mapped. More exposed reefs are in northern Efate, west Epi, east Malekula and south-west Ambrym islands. Less exposed reefs, identified as historical refugia, are in Tanna, southern Efate, Ambrym, north Pentecost and west Maewo islands [22].

In the Coral bleaching infobyte produced for Van-KIRAP, DHWs were compared for Port Resolution (Tanna) and Toman Island (Malekula), with projections for low warming by 2050 which indicates a higher frequency coral bleaching, i.e. where alert levels are exceeded, in the more northern site of Toman Island (Figure 12). This result aligns with the Maynard et al. study [22], where the onset of annual severe bleaching is shown to occur much later in Port Resolution than Toman Island [22]. Under a high warming scenario by 2050, and most concerningly, Alert level 2 is exceeded in 100 % of years at Toman Island, and 95 % of years at Port Resolution (see Coral bleaching infobyte).

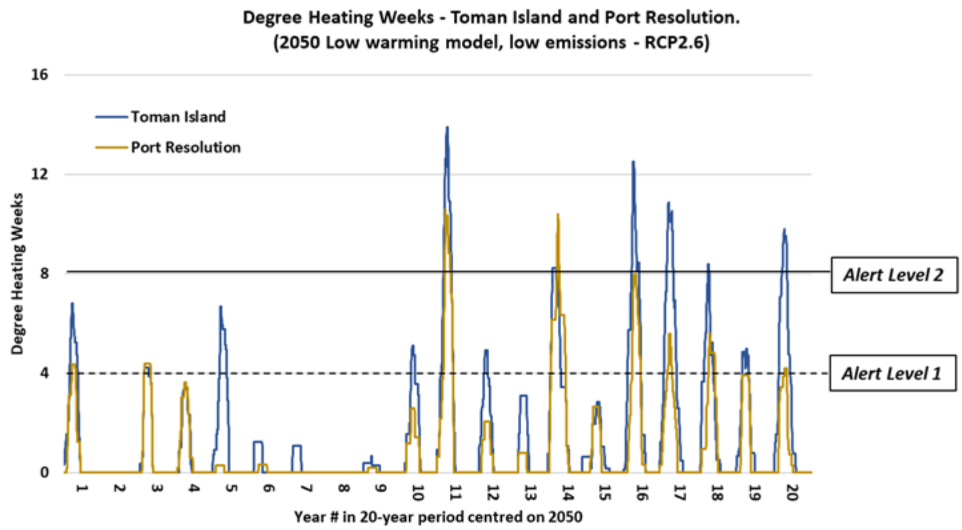

Figure 12 Regional variability of degree heating weeks (DHW) under warming. Timeseries of DHW (in °C-week) for a 20-year period centered on 2050 for 'low warming' (GISS-E2-R model, RCP2.6) for Toman Island, Malekula (blue), and Port Resolution, Tanna (brown). The horizontal lines show the risk limit: Alert Level 1, DHW >4 °C-week; significant coral bleaching is likely (dashed line) and Alert Level 2, DHW >8 °C-week; severe bleaching and significant coral mortality are likely (solid line). We assume no adaptation to thermal stress through the period. Method used here follows Langlais et al. 2017 [23]. Data source: OISST v2-1 SST [9].

This is important because, as an example, such assessments can inform adaptation planning, including opportunities for staged and prioritised management and protection of impacted reefs and other coastal resources around Vanuatu that are otherwise potentially facing severe impacts from projected changes in MHW climatology for Vanuatu over coming decades.

Climate Information Services developed by the Van-KIRAP project through the Vanuatu Climate Futures Portal are designed to facilitate such assessments and the application of the science-based evidence to inform decision making in order to build resilience to climate change in Vanuatu.

Also see Coral bleaching infobyte.

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