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ECOSYSTEM AND CLIMATE INDICATORS OF THE WESTERN AND CENTRAL PACIfiC OCEAN

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Executive Summary

This Working Paper updates SC22 on progress regarding the development of ecosystem and climate indicators for the western and central Pacific Ocean (WCPO). An ecosystem and climate indicators report for the WCPO was presented for the 22nd Regular Session of the WCPFC in November, 2025 (Hill et al. 2025). The key advancement of that report consisted of assigning a regional structure to the WCPO that better captures the oceanographic and climate drivers of the WCPO and the spatial and temporal scales they operate at. This facilitated better detection of where climate and climate change impacts in the WCPO are most evident. Several further updates have been made to this report for SC22 including:

- Addition of data for 2025 for each of the indicators including El Niño Southern Oscillation Index, sea surface temperature, warm pool area, and ocean heat content. The marine heatwaves indicator was not updated.
- Further update of the regional structure of the WCPO to include an additional three regions to represent the oceanographic dynamics of the West Pacific East Asia (WPEA) area as per a request from the 22nd Regular Session of the WCPFC (in progress).
- Further development of the ocean heat content indicator.
- Exploration of trend in median phytoplankton size as an indicator of ecosystem trophic change (as per the request of WCPFC-SC21).

Recommendations

SC22 is advised of the following:

- The "Ecosystem and climate indicators" report to be prepared for the 23rd Regular Session of the WCPFC will be finalised using the indicators described in this Information Paper.
- The regional structure has been expanded to include the WPEA. The SSP requires notification of any further revision to the reports area structure (by WCPFC members) by closure of the WCPFC-SC22 meeting.
- After exploration of median phytoplankton size as a 6th indicator, it is suggested it should not be monitored at this stage and be revisited in future years once the data stream lengthens or other data streams become available. This is due to a significant discontinuity in satellite sensors in 2016.

Contents

Introduction

Climate change is driving long-term shifts in ocean conditions such as warming sea surface temperatures, changes in ocean circulation, and increased stratification of the upper ocean (Bindoff et al. 2019). This is impacting marine ecosystems and their associated fisheries in a range of ways such as shifts in the ranges of species and ecosystems (Pecl *et al.,* 2017; Pinsky *et al.,* 2020), changes in species physiology (Agarwal *et al.,* 2024), and in community compositions (Johnson *et al.,* 2011; Poloczanska *et al.,* 2016, 2013). Superimposed on this long-term trend is natural climate variability patterns such as El Niño–Southern Oscillation (ENSO), which strongly influences regional ocean conditions on seasonal to interannual timescales. Tropical tuna biomass is currently projected to respond to climate change with an increase in biomass towards the central and eastern Pacific Ocean with concurrent declines in the western Pacific, having implications for species productivity and broader food security for the region (Bell et al. 2021). Monitoring ocean climate indicators therefore provides an essential tool to improve the adaptive capacity of fisheries decision-making and management (Brodie et al. 2026; Griffiths and Fuller, 2019; Juan-Jordá *et al.,* 2018; SPC, 2025; Von Schuckmann et al. 2026).

For this report, six climate indicators are presented for the Western and Central Pacific Ocean (WCPO) up to 2025 including:

1. El Niño Southern Oscillation (ENSO)
2. Sea Surface Temperature (SST)
3. Warm pool area
4. Ocean heat content
5. Marine heatwaves (MHW)
6. Trend in median phytoplankton size

These indicators were selected to provide a summary of the state of oceanographic features of the WCPO. These indicators monitor ocean variability and trend, and could also provide a comparison against climate models used for management decisions going forward. Comprehensive summaries of the climate are provided elsewhere (Johnson and Lumpkin 2025; WMO 2025a; WMO 2025b).

This report represents a 2025 update of Hill et al. (2025). Updates made to this report include:

- Addition of 2025 data.
- Addition of three more regions to the regional structure of the WCPO to capture the oceanographic dynamics of the West Pacific East Asia (WPEA) area as per a request from the 22nd Regular Session of the WCPFC (in progress). This is still ongoing.

- Improved analysis and exploration of the ocean heat content indicator.
- Marine heatwaves (MHW) indicator is not updated in this report as other data sources and presentation formats are currently being explored from Copernicus Marine Services and Mercator International.
- Exploration of median phytoplankton size as an indicator of ecosystem trophic change.

The World Meteorological Organisation reported 2025 as the 2nd-3rd warmest year on record, slightly cooler than the record setting year 2024, with the transition from El Niño in 2024 to neutral/La Niña conditions in 2025 (WMO, 2025b). Despite this, the past 11 years were considered the 11 warmest on record from a 176-year observational period (WMO, 2025b). For ocean heat content (0-2000 m), 2025 was the highest on record globally for a 9th consecutive year, illustrating the continued accumulation of heat in the earth's system. El Niño Southern Oscillation (ENSO) varied between neutral and weak La Niña conditions for the year 2025 with recent sea surface temperatures and ocean heat content indicating movement to El Niño conditions as of May 2026 (WMO, 2026).

Regional structure

The circulation of the WCPO is driven by alternating eastward and westward zonal currents both at the surface and subsurface, and the shallow subtropical overturning circulation (Figure 1). These currents and their variability strongly influence the horizontal and vertical distribution of ocean properties such as temperature, salinity, oxygen and nutrients in the region. Further, the rate at which these features change varies in time across intra-annual, inter-annual and longer (i.e. decadal) timescales. Thus, there was a need to define distinct regions of the WCPO that characterize the regional ocean conditions and variability both at the surface and subsurface ocean. This area also reflects the main fishing grounds of WCPO tuna fisheries for both purse seine which is restricted to the equatorial region (10°S - 10°N), and longline which is distributed more uniformly throughout the WCPO and off-equator (Hare et al., 2025).

For this report, an additional three regions (regions 9, 10, 11) were added to this structure to capture the oceanographic dynamics of the far-western Pacific adjacent to Indonesia, the Philippines and Vietnam. The characteristics of each region are:

- Regions 1 and 8 encapsulate the circulation of the north and south subtropical boundaries encompassing the north and south Equatorial Currents (NEC and SEC). The ocean variability of this region is driven by large basin changes of the north and south Pacific Ocean gyres. Climate variability in this region is dominated by longer timescales (multiyear, decadal and longer) than regions closer to the equator.

- Regions 2, 6 and 7 encapsulate the ocean circulation of the off-equatorial WCPO, including the north and south equatorial counter current (NECC and SECC), the southern branch of the South Equatorial Current (SEC), and the meridional shallow subtropical overturning circulation. In these regions, the ocean is influenced by fast (intra-annual) equatorial processes and the ENSO climate mode (3-4 year cycle). ENSO influences oceanographic conditions and variability, particularly longitudinally across the south Pacific, and therefore we define two boxes south of the equator.
- Regions 3, 4 and 5 encapsulate Pacific equatorial circulation and variability of the Lower Equatorial Intermediate Current (LLICs) and Equatorial Counter Current (EUC). Major oceanographic features of these regions include the western Pacific warm pool, the westward expansion of the cold tongue, and the dynamic boundary of those two features. Conditions in these regions are principally driven by ENSO-related variability and the position and extension of the warm pool and cold tongue.
- Regions 9, 10, and 11 encapsulate the low latitude western boundary Mindanao Current and the western and eastern pathways of the Indonesian Throughflow within the Indonesian Seas. The extraction of data for these additional three regions is underway and will not be presented in this report.

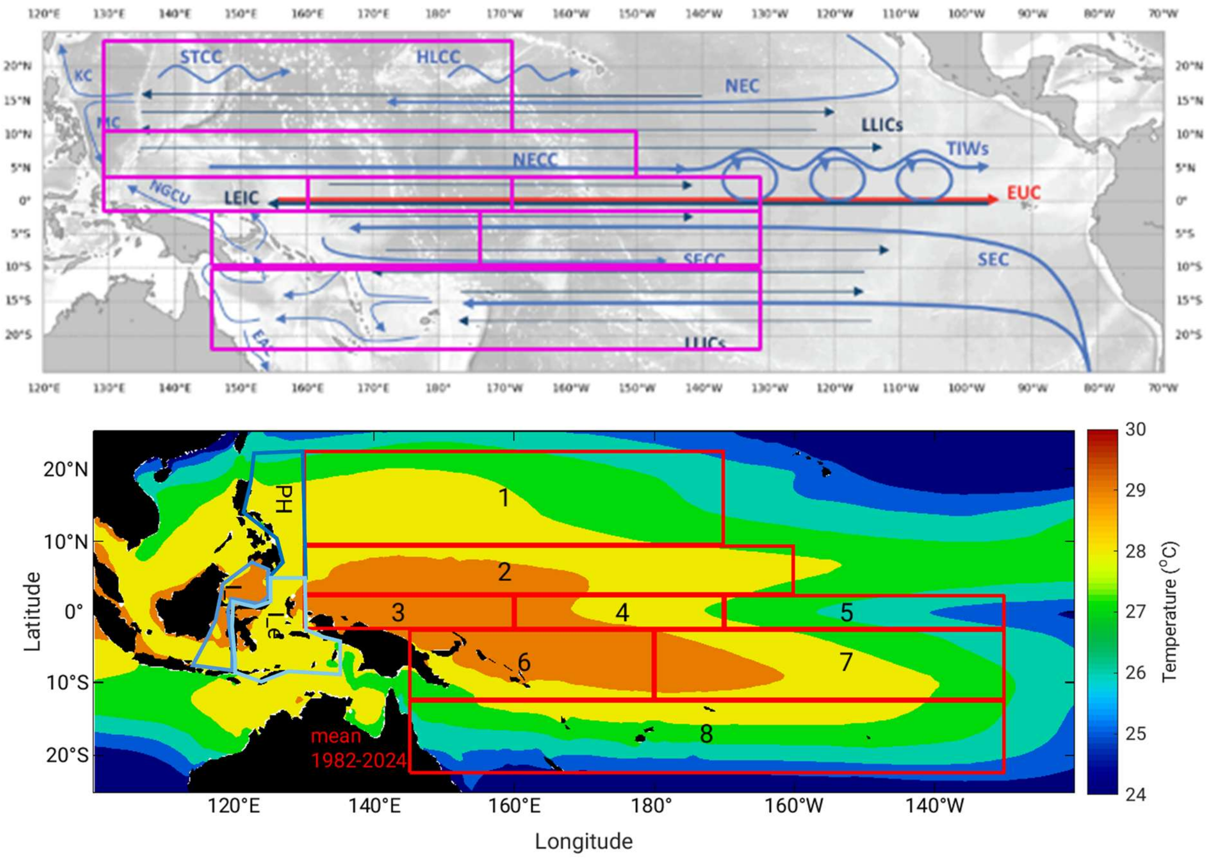


Figure 1: Schematics of the tropical Pacific Ocean circulation and dominant currents. The pink rectangles denote the eight western and central Pacific Ocean (WCPO) regions that capture the dominant oceanographic features of the WCPO. The arrows identify the major currents; light blue: surface currents, red: thermocline currents, deep blue: deep currents. EUC, Equatorial Undercurrent; HLCC, Hawaiian Lee Countercurrent; LEIC, Lower Equatorial Intermediate Current; LLICs, Low-Latitude Intermediate Currents; NEC, North Equatorial Current; NECC, North Equatorial Countercurrent; SEC, South Equatorial Current; SECC, South Equatorial Countercurrent; STCC, Subtropical Countercurrent; TIWs, tropical instability waves (source: Delpech et al. 2020; Hill et al. 2025). Bottom panel: The updated Western and Central Pacific Ocean regional structure with 8 regions overlaid on country exclusive economic zones in red. Blue bold lines show the new regions 9,10 and 11 for the far-western Pacific adjacent to Indonesia, the Philippines and Vietnam.

Indicators

El Niño Southern Oscillation

El Niño Southern Oscillation (ENSO) is the main driver of climate interannual variability in the tropical Pacific, influencing weather, ocean circulation, and ecosystems

(McPhaden et al. 2006; Timmerman et al. 2018). ENSO shifts at irregular intervals between El Niño and La Niña conditions every 2-7 years. Typically, La Niña events drive increased warm water in the western Pacific with a deepening of the warm surface layer, and relatively cooler sea surface temperature in the eastern and central Pacific. During El Niño events, the western Pacific warm pool moves eastward to the central and eastern Pacific, resulting in an anomalously cooler western Pacific and anomalously warmer central and eastern Pacific. These shifts in ocean conditions have been shown to be a major driver of the distribution of tunas and purse seine fishing effort and catch in the WCPO (Lehodey et al. 1997), making it an important indicator to monitor.

The Oceanic Niño Index (ONI) tracks three-month averaged SST anomalies of the central tropical Pacific (i.e. between 120°-170°W) relative to a 30-year moving average temperature to identify El Niño or La Niña events (Figure 2) (NOAA Global climate dashboard, www.climate.gov/climatedashboard). From 2020-2023, the WCPO experienced near continuous La Niña conditions, an anomalously long-term ENSO event. A short, intense El Niño event occurred between May 2023 and April 2024. Since this time, ENSO has been neutral to weak La Niña like conditions with above average SST in the western Pacific and average to below average SST in the central and eastern Pacific.

ENSO varied between neutral and weak La Niña conditions for the year 2025 (WMO 2025b). As of May 2026, recent sea surface temperature and ocean heat content anomalies indicate movement towards El Niño conditions by the end of 2026 (WMO, 2026). El Niño conditions could result in below average sea surface temperatures in the west with an eastward extension of the warm pool to the central and eastern Pacific, that could drive a shift in purse seine catch and effort to the same region of the central and eastern Pacific.

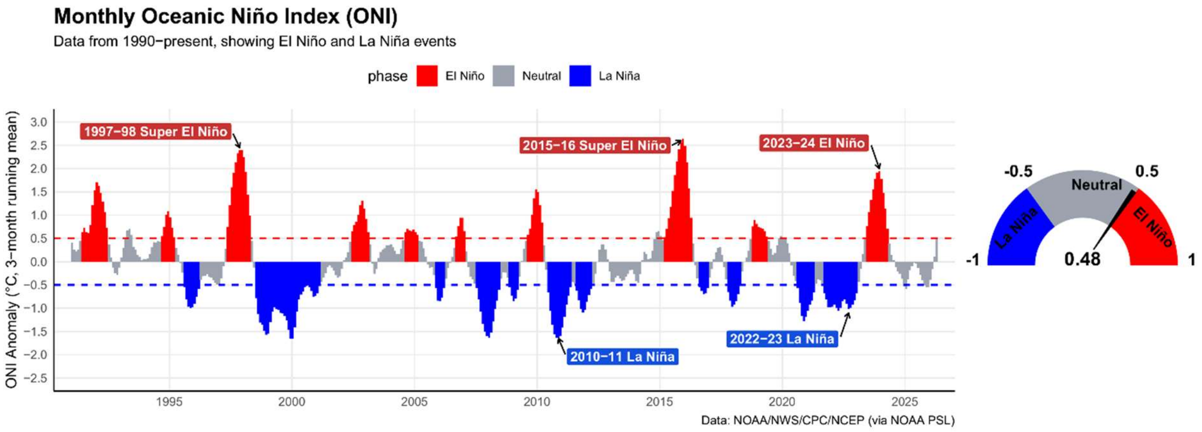


Figure 2: Oceanic Niño Index (ONI) from 1990-April 2026 showing a timeline of El Niño Southern Oscillation (ENSO) events (NOAA Global climate dashboard, www.climate.gov/climatedashboard).

Sea surface temperature

Sea surface temperature (SST) is a key index of the ocean climate and impacts a range of ecological processes such as species distribution and growth (Bindoff et al. 2019). It is also one of the most observable measures of tracking the marine environment and a key indicator of anthropogenic climate change (Johnson and Lumpkin 2025; Von Schuckmann et al. 2026). Tracking both variability and long-term trends in SST throughout the WCPO helps identify ocean changes that may impact WCPFC fisheries.

The WCPO is a large and complex region and how climate change and variability impact the region will be variable. For this reason, the WCPO was divided into eight regions which are each influenced by different underlying oceanographic dynamics and conditions (Figure 1). Monthly SSTs and their anomaly relative to the climatological mean (1982-2024) from the NOAA OISST (Huang et al., 2021) product are presented for eight regions from 1982-2025.

There were two overarching SST patterns across the eight regions in the WCPO (Figure 3-4). Firstly, those regions that intersect with the warm pool boundary (i.e. region 4, 5, 7) are largely driven by ENSO-related inter-annual variability (Figure 4). In these regions, the large SST variability is driven by periodic east-west ENSO movement of the warm pool and cold tongue, which drives an inter-annual variability of 1.5-4°C (Figure 4). This large inter-annual variability masks any evidence of a longer-term climate signal that may be present. For these regions, 2025 was close to the climatological mean.

The second over-arching pattern was that those regions that do not intersect with the warm pool boundary (i.e. region's 1, 2, 3, 6, 8) show a long-term climate signal (Figure 4). The SST of the WCPO northern and southern regions (region1, 8) ranged from ~25-29°C over the seasonal cycle and were ~0.5°C warmer than the climatological mean. There is evidence of an ocean warming trend overlain on this seasonal cycle with each decadal average warmer than the previous one. For regions 1, 2, 3, 6 and 8, the top 10 hottest years have all occurred since 2010.

Overall, 2025 was an anomalously warm year for the off-equatorial regions of the WCPO relative to the climatological mean (1982-2025), but generally below the record setting year of 2024 (Figure 3-4). Linked to the 2025 neutral/La Niña conditions, equatorial waters in the western pacific (region 6) were approximately 0.5-1°C warmer than the long-term mean and at or above ~30°C for significant periods, while the central equatorial Pacific (region 5) were at or below the climatological mean showing the western contraction of the warm pool and expansion of the equatorial cold tongue (Figure 4).

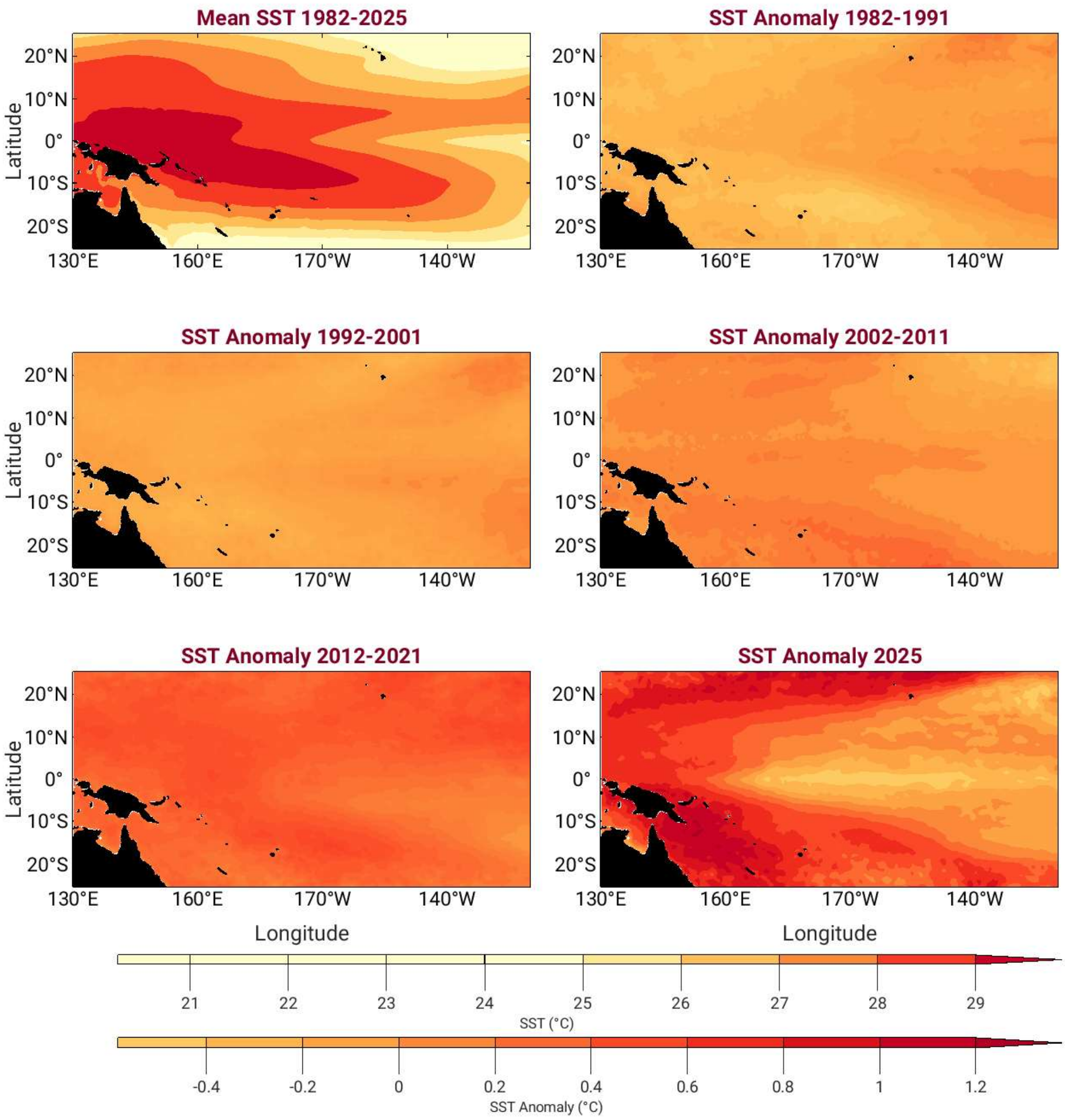
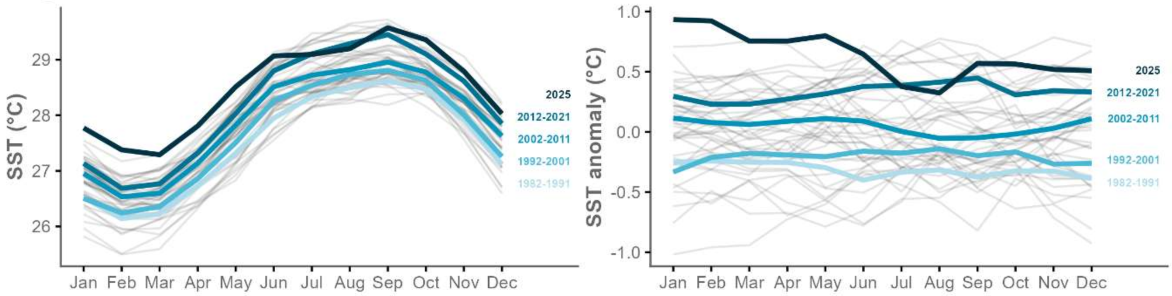
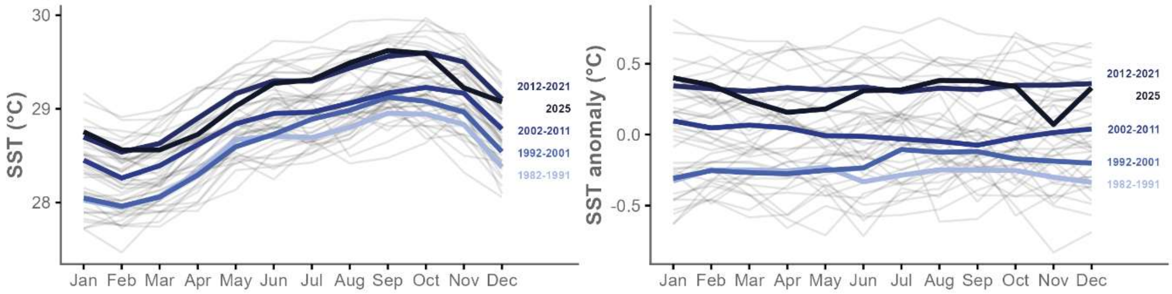


Figure 3: Mean sea surface temperature of the western and central Pacific Ocean for 1982-2025, and sea surface temperature anomaly for 10-yearly periods and 2025 relative to the climatological mean (1982-2025).

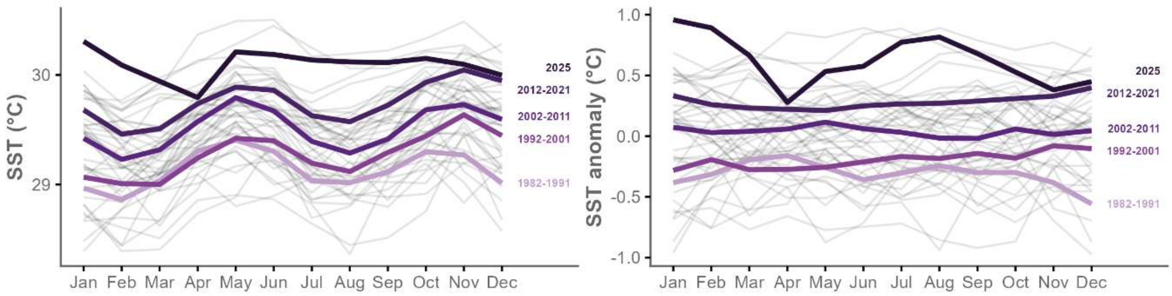
Region 1



Region 2



Region 3



Region 4

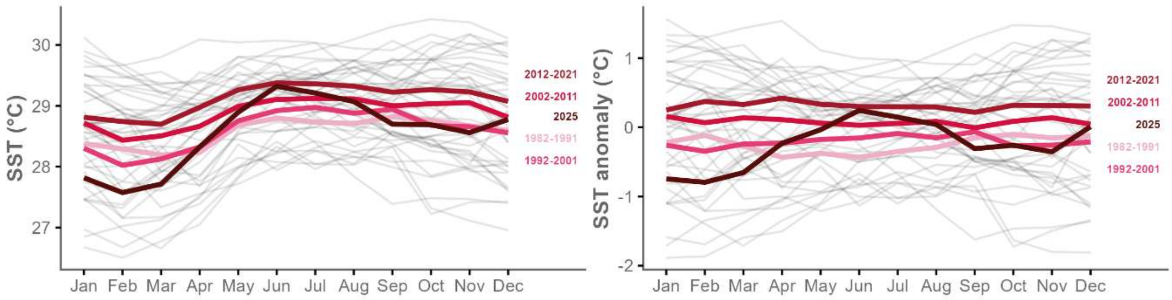


Figure 4: Monthly sea surface temperature from 1982-2025 (left panels) and sea surface temperature anomaly (right panels) for the same time period relative to the climatological mean (1982-2025) for Regions 1- 8. Coloured lines represent decadal

averages, 2025 is the annual mean and grey lines represent individual years to show inter-annual variability.

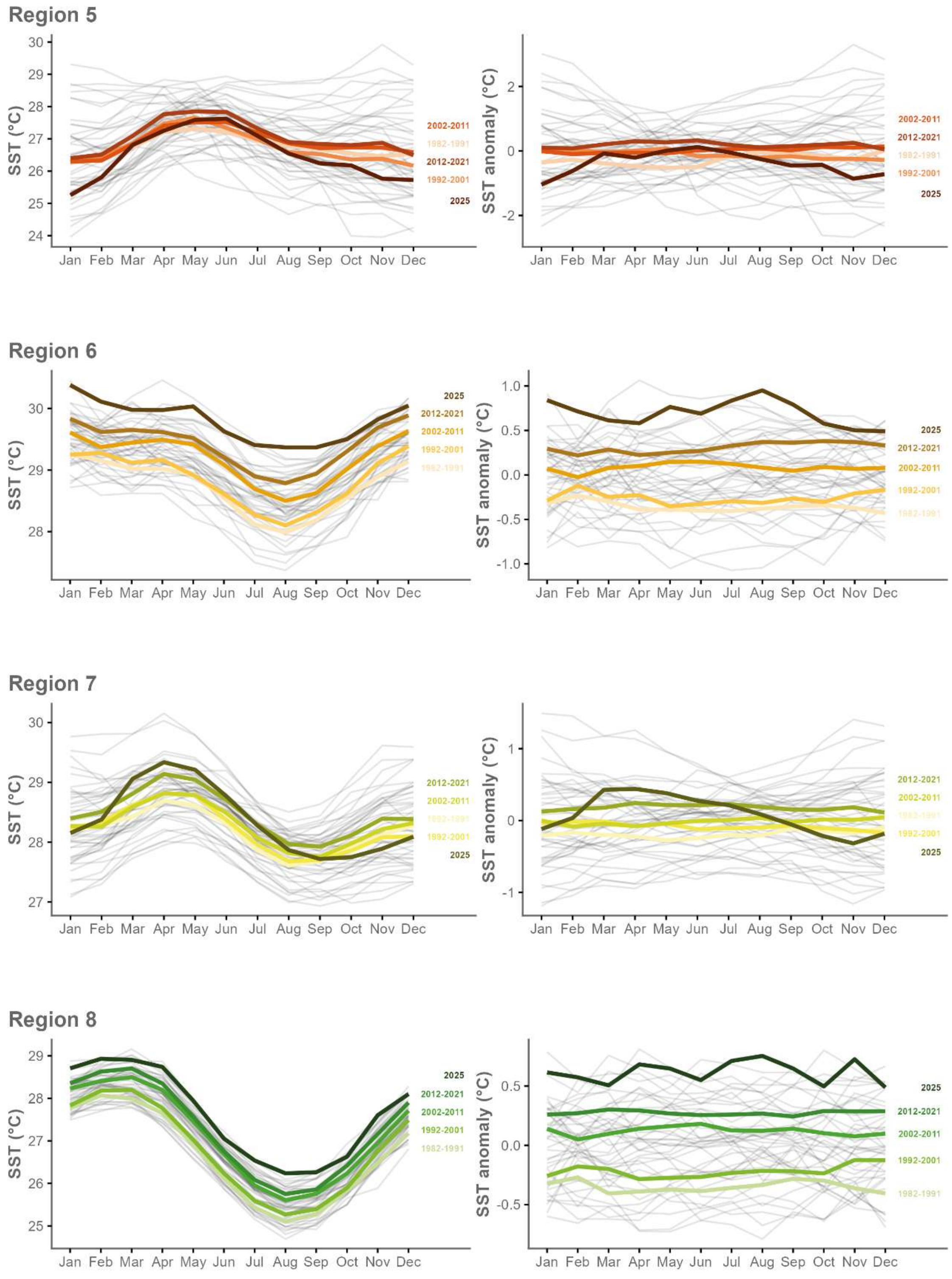


Figure 4 (continued): Monthly sea surface temperature from 1982-2025 (left panels) and sea surface temperature anomaly (right panels) for the same time period relative to the climatological mean (1982-2025) for Regions 1- 8. Coloured lines represent decadal averages, 2025 is the annual mean and grey lines represent individual years to show inter-annual variability.

Ocean heat content

The world's oceans have stored more than 90% of the excess heat trapped in the Earth's climate system from excess greenhouse gases (Bindoff et al. 2019; Gulev et al. 2021). Ocean heat content (OHC) is a measure of the amount of heat (temperature) stored in the sub-surface ocean and provides a more consistent, reliable indicator of climate change and variability than SST alone which is more susceptible to short-term atmospheric forcing. Subsurface changes also often precede SST anomalies associated with ENSO and other large-scale climate fluctuations, providing an early indication of shifts in the ocean–climate system. Therefore, OHC provides an improved long-term indicator of change in marine ecosystems that is important for WCPO fisheries, as well as a potential early warning system relative to using SST alone. Here, we present OHC indices for 0-300m for the eight regions of the WCPO using the Roemmich and Gilson Argo gridded dataset from 2004-2025 (Figure 5, 6). Monthly 0-300 m mean layer ocean temperature and OHC anomalies and maps of key OHC trends in the WCPO are also presented.

The spatial distribution of OHC in the WCPO differs markedly from that of SST, highlighting the importance of monitoring subsurface ocean processes (Figure 5, 6). OHC is highest off-equator centred near 10-15^{o} north and south, with lower OHC in equatorial regions. For regions 1 and 3, 2025 had the highest 0-300 m layer temperature and largest OHC anomaly across the observational time period of 2004-2025. Similar to SST, there was regional variability in OHC trends across the timeseries, highlighting the need for a regional structure to capture variability throughout the WCPO. Like SST, regions (regions 1, 2, 6,8) not directly influenced by the movement of the warm pool boundary generally showed a long-term warming trend and increased OHC, with each 5-year period warmer than the previous. In 2025, OHC in the equatorial regions (Regions 3, 4 and 5) shows the impact of the transition from neutral/weak La Niña to more La Niña like conditions during the year with subsurface heat slowly moving eastward (Figure 6).

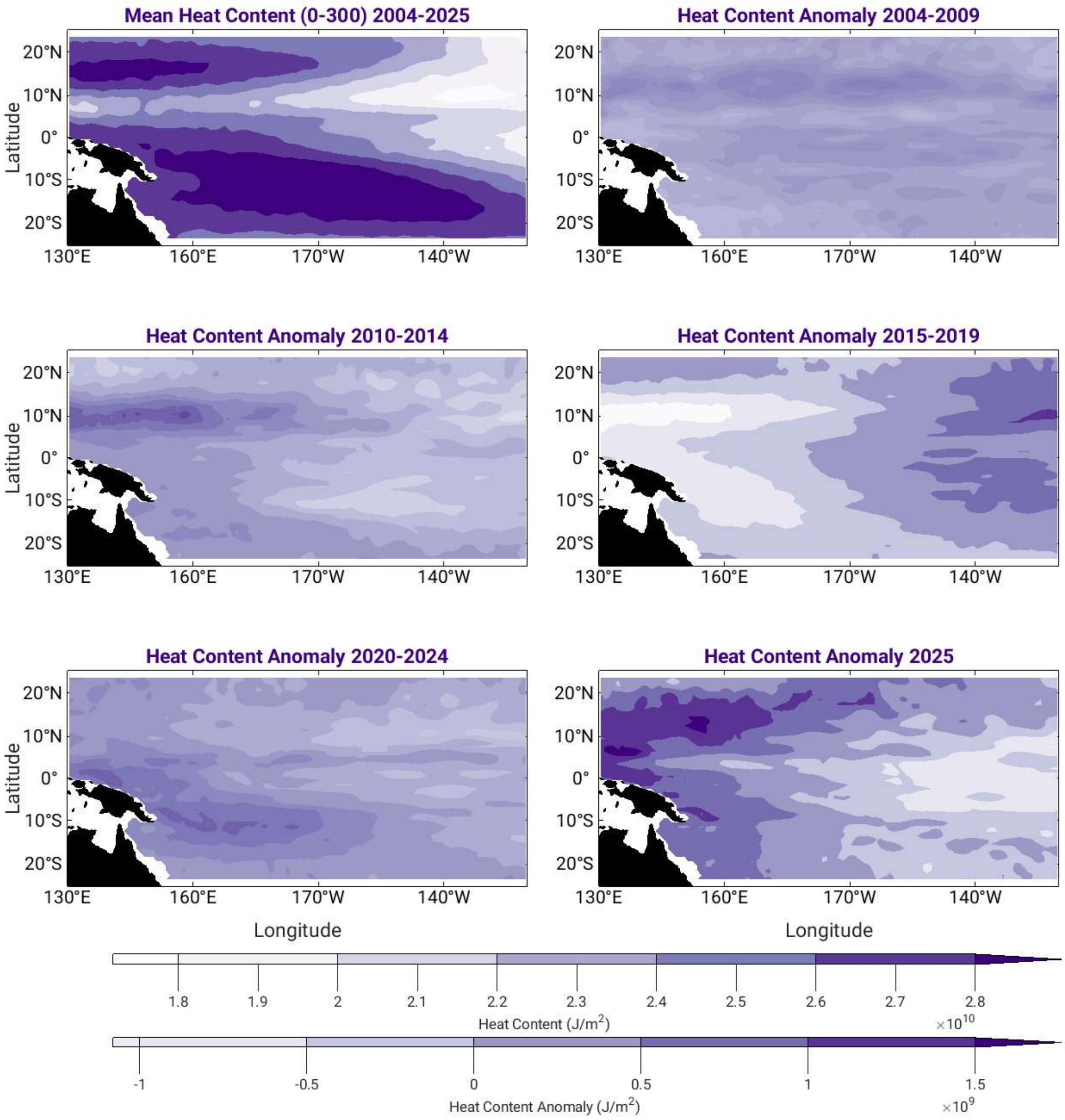


Figure 5: Mean ocean heat content (0 – 300 m) of WCPO for 2004-2025 and sea surface temperature anomaly for 5-yearly periods, and 2025 relative to the climatological mean (2004-2025).

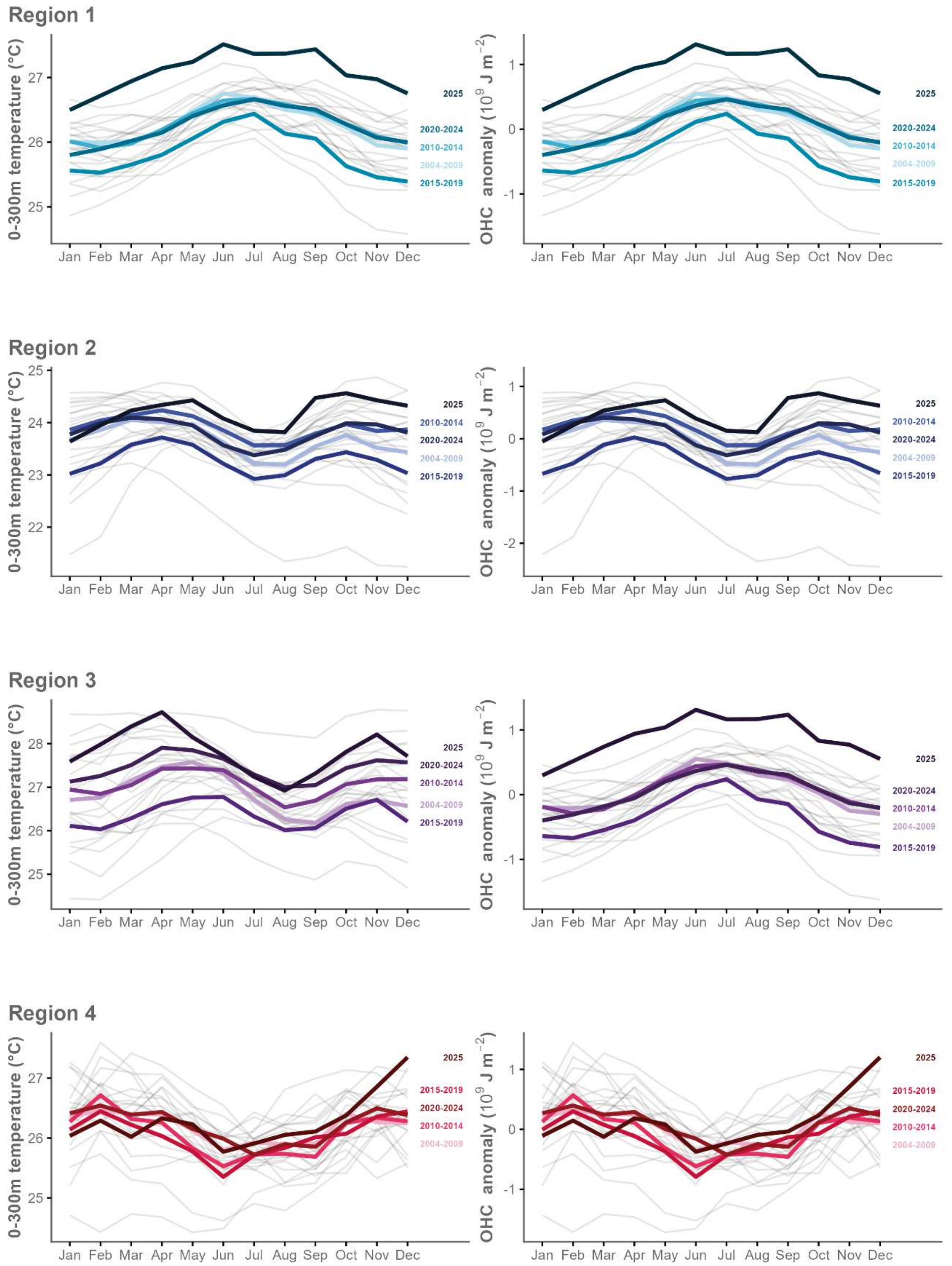


Figure 6: Monthly ocean mean layer temperature (0-300 m) from 2004-2025 (left panels) and ocean heat content anomaly (right panels) for the same time period relative to the

climatological mean (2004-2025) for Regions 1- 8. Coloured lines represent 5-year averages, 2025 is the annual mean and grey lines represent individual years to show inter-annual variability.

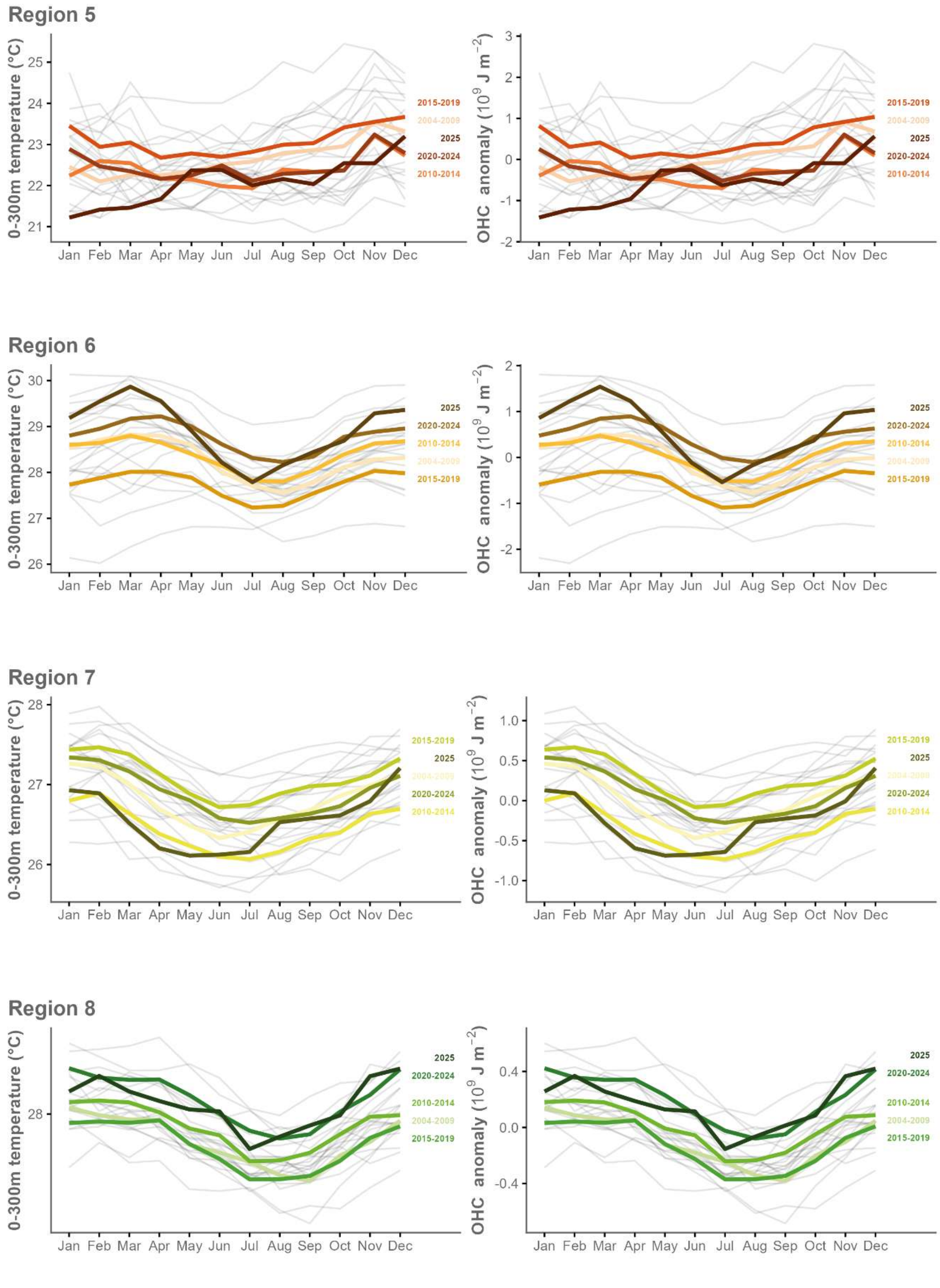


Figure 6 (continued): Monthly ocean mean layer temperature (0-300 m) from 2004-2025 (left panels) and ocean heat content anomaly (right panels) for the same time period relative to the climatological mean (2004-2025) for Regions 1- 8. Coloured lines represent 5-yearly averages, 2025 is the annual mean and grey lines represent individual years to show inter-annual variability.

Warm pool area

The Pacific warm pool is as an area of surface waters above 29°C centred in the WCPO. Warm pool size, extent, and in particular its longitudinal position varies with ENSO. With the impacts of climate change, the warm pool is predicted to increase in size and volume, contributing to a potential eastward shift in tuna biomass (Bell et al., 2021; Lehodey et al., 2013). The warm pool is also considered as an important spawning ground for tuna species, in particular skipjack tuna and so changes in its size, structure or position may also influence the productivity of tunas (Ashida 2020; Fujioka et al., 2024). The area of the warm pool was calculated using mean surface temperature (0-10 m) monthly between 2004-2025 using the Roemmich and Gilson Argo climatology product (Roemmich and Gilson, 2009). The area of water greater than 30°C was also calculated to explore changes in the temperature and structure of the warm pool.

Changes in 29°C warm pool area over the timeseries are characterised by inter-annual variability driven by ENSO events, masking any long-term trends that may be present in longer timeseries (Figure 7, 9). During El Niño events, the warm pool extends eastwards as trade winds weaken, while during La Niña events it contracts to the west and deepens the thermocline in the region. As such, despite interannual variability there is no evidence of a persistent increase in warm pool area over the observational timeseries (2004-2025). In contrast, the area of the warm pool warmer than 30°C has increased in size from 2004-2025 (Figure 8, 9). From 2004-2014, the area of waters >30°C varied between approximately 0-5 million km^2, representing on average 10% of the 29°C warm pool area. Since 2014, it has regularly been above 5 million km^2 and has recently been above 10 million km^2, representing on average 30% of the 29°C warm pool area and as high as 55% in August 2024. From 2020-2024, the area of the warm pool warmer than 30°C shifted westward when compared to the previous 5-year mean (Figure 8). This shows that the area and extent of the WCPO warm pool with waters > 30°C has increased in the last decade. However, a longer timeseries is needed to monitor the impacts of decadal climate forcings such as Pacific Decadal Oscillation (PDO).

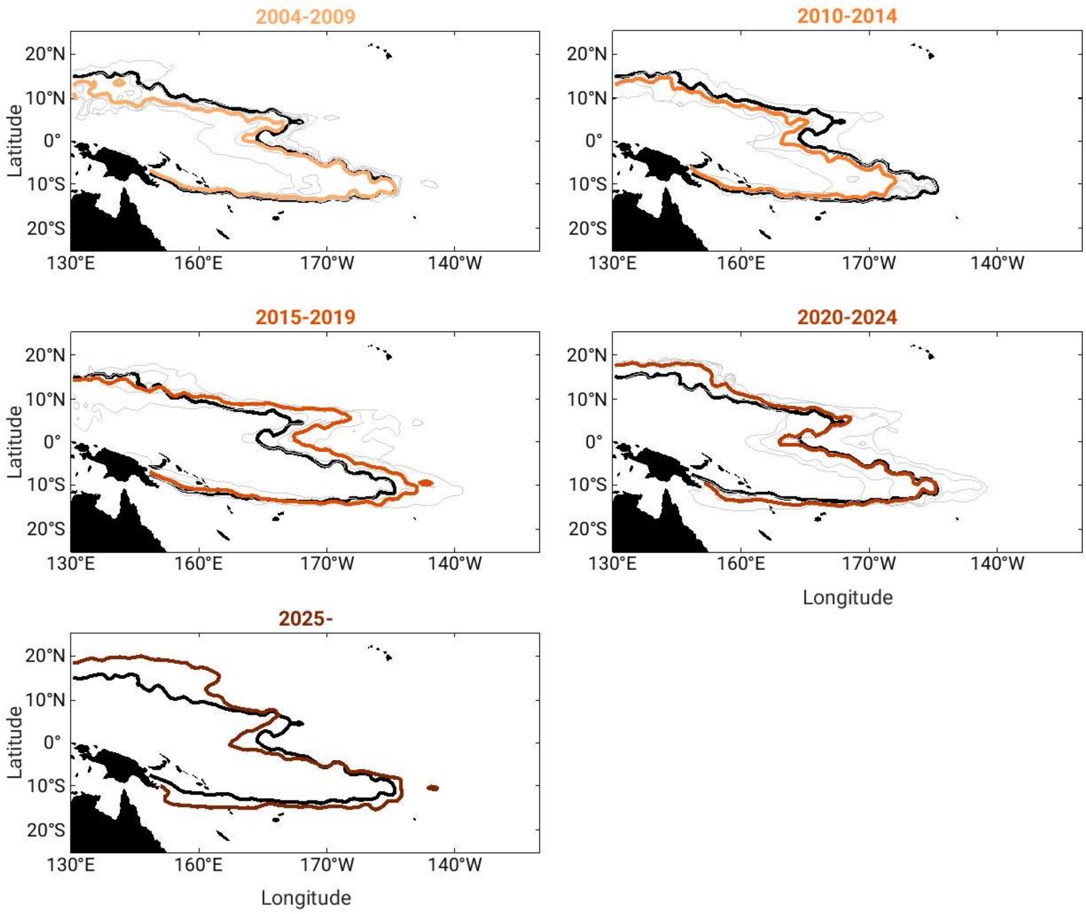


Figure 7: Area of the 29°C western pacific warm pool from 2004-2025 using mean surface temperature (0-10m). Solid black line indicates the climatological mean 29°C warm pool area for 2004-2025, grey lines represent individual years and coloured lines the mean 29°C area for each time period.

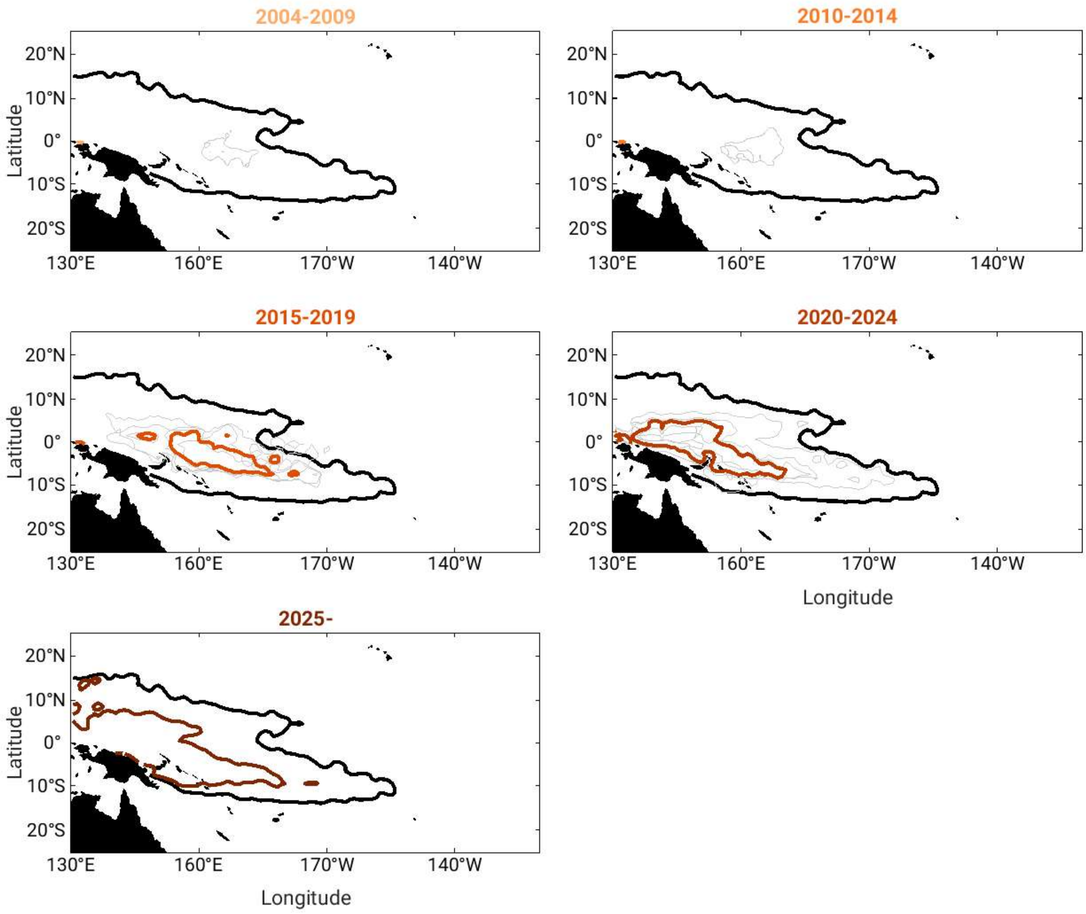


Figure 8: Area of the 30°C western pacific warm pool from 2004-2025 using mean surface temperature (0-10m). Solid black line indicates the climatological mean 29°C warm pool area for 2004-2025, grey lines represent individual years and coloured lines the mean 30°C area for each time period.

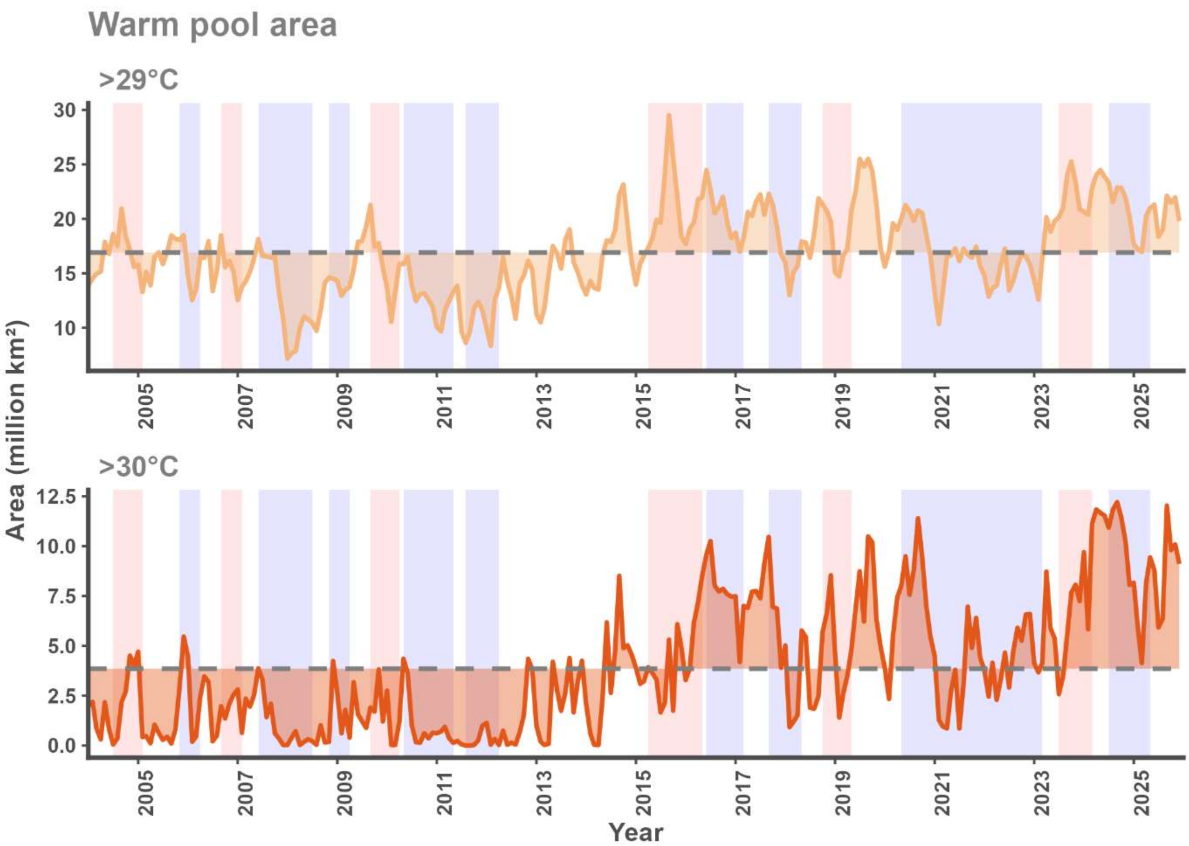


Figure 9: Western pacific warm pool area (million km^2) of the 29°C (top panel) and 30°C isotherms (bottom panel) using mean surface temperature (0-10m) from 2004-2025 relative to their mean across the same timeseries (dashed grey line). 2004-2025 mean for 29 °C = 16.8 million km^2, 2004-2024 mean for 30°C = 3.65 million km^2. Blue shading = La Niña, red shading = El Niño, white = neutral.

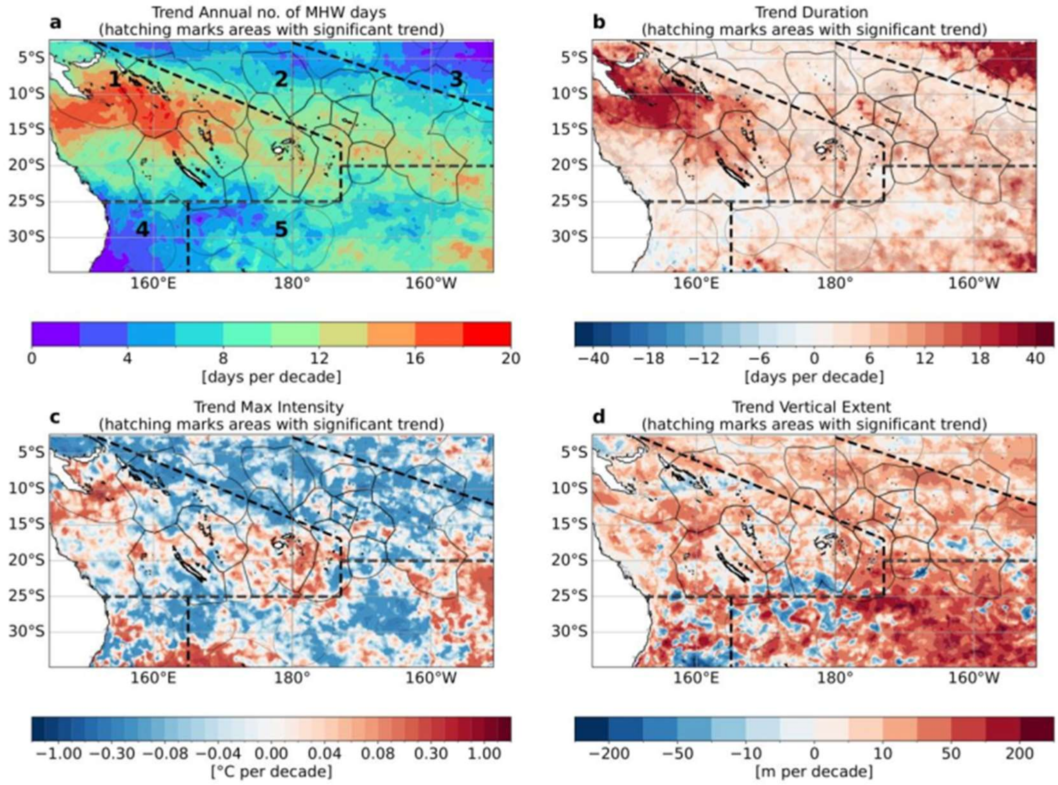
Marine heatwaves

The marine heatwaves indicator has not been updated for this report, with text below from the SC21 report (SPC, 2025). Exploration of this indicator and data products available elsewhere to update and improve the marine heatwaves indicator are currently underway (e.g. https://www.marineheatwaves.org/tracker.html).

"Marine heatwaves (MHWs) are defined as an area that has anomalously warm temperatures relative to a threshold value for an extended period of time. MHWs can have detrimental impacts on marine ecosystems and with the impacts of climate change are increasing in frequency and duration (Lal et al. 2025). Shifts in populations of

marine species, mass mortality events of non-mobile species, exacerbation of harmful algal blooms, and likelihood of extreme weather events can be expected with an increase in MHWs.

Here, analysis undertaken in Lal et al. 2025 is presented for the south equatorial Pacific Ocean (https://doi.org/10.5194/egusphere-2025-3281). MHWs were defined as daily SSTs above the 90th percentile from a 1993-2019 climatological mean using products including OISST, GLORYS12 and OSTIA. The number of MHW days, mean duration of MHWs, and their depth have all increased from 1982-2022, while their intensity has decreased (Figure 10). A significant 3.5% increasing trend in the percentage of the study region in a MHW state per decade was also observed (Figure 11). Over the past decade,



there has not been a single day when at least part of the region was not exposed to a MHW."

Figure 10: Trends in number of MHW days (a), mean duration (b), mean max intensity (c), and depth (d) for macroscale events (25-700 square degrees). Detected using NOAA-OISST from 1982-2022 (Lal et al. 2025).

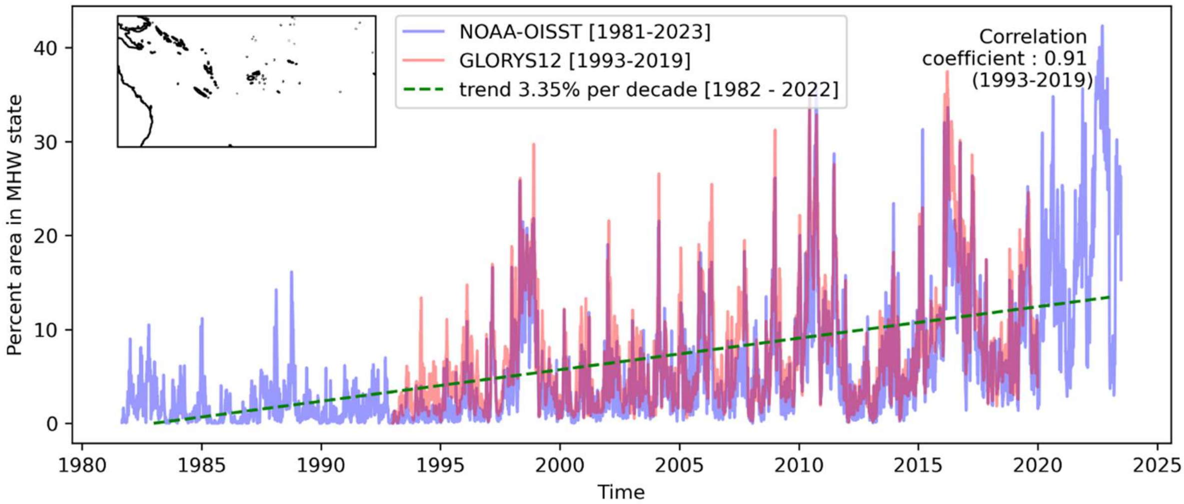


Figure 11: Timeseries showing percent of study region in MHW state, with a statistically significant trend line (p-value < 0.05) in green calculated between 1982 to 2022 for NOAA-OISST and Pearson correlation coefficient calculated between 1993 and 2019 for NOAA-OISST and GLORYS12 (p-value < 0.05). Source Lal et al. 2025.

Median Phytoplankton size

WCPFC-SC21 requested that trends in median phytoplankton size be explored as an indicator of trophic change. Past analysis of this indicator has proposed that large-sized phytoplankton (microplankton) support higher biomass of fish and mesozooplankton, and it is currently monitored as an ecosystem indicator in some other fisheries (WPRFMC, 2025). A shift toward smaller phytoplankton, potentially triggered by climate change creates less efficient food chains and reduces the total energy available to fish (Polovina & Woodworth 2012). We explored this indicator using products in the Copernicus catalogue derived from Ocean Colour. These data products are generated from merged-sensor products (SeaWiFS, MODIS, MERIS, VIIRS) for the period July 2002–April 2016, and from Ocean and Land Colour Instrument (OLCI, Sentinel 3) products from May 2016 onwards. This is a hard dataset boundary as the two products are trained separately on different algorithms. Additionally, OLCI has a different spectral configuration: the merged ocean colour products use 8 bands, while OLCI data use 10 bands. Attempts have been undertaken to calibrate the two products to provide a consistent long-term observation of surface phytoplankton functional types (Barnes et al. 2011; Xi et al. 2025). While this has provided some success at the global scale it has been less successful at localised and regional scales (Figure 12).

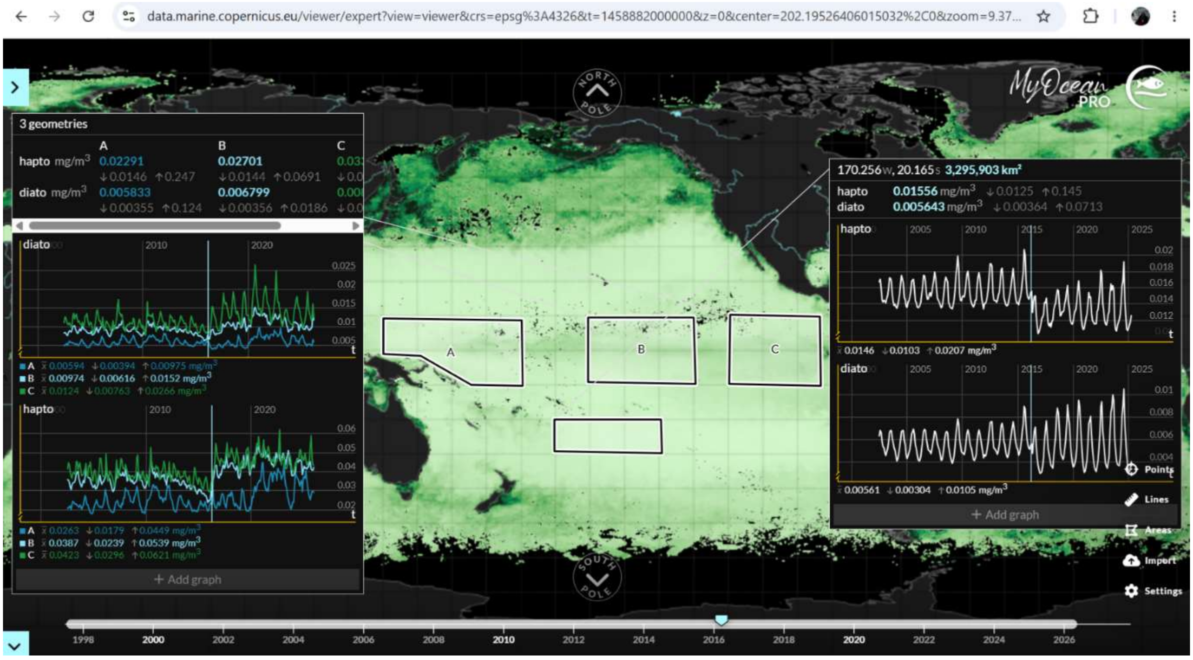


Figure 12: Examples from the surface phytoplankton functional types product provided by Copernicus Marine Services. Note the discontinuity is not spatially consistently in the Pacific Ocean: in some areas the shift in values is pronounced, while in others it is less discernible.

The satellite sensor change in 2016 and the discontinuity that remains in the time series at finer than global scales precludes treating the full record as a single, coherent dataset for long-term trend analysis. Apparent temporal patterns spanning the full time series should therefore be interpreted with caution, particularly where comparisons among regions are involved. We do not recommend using the full record for long-term trend analysis at this stage. Additionally, in the pre-2016 merged record, the sensor transitions have also introduced artifacts. Studies have found spatiotemporal patterns of discontinuities between SeaWiFS, MODIS, and MERIS remote sensing reflectance products (Barnes et al. 2021). Furthermore, VIIRS Sensor degradation has been detected. From 2016 onwards, the data product is consistent, though the resulting time series is comparatively short. This analysis could therefore be revisited in future years as the post-2016 record lengthens and as algorithms for fusing data from different sensors improve. Several research groups are currently working on this and progress could be achieved quickly (Xi et al. 2025).

Declaration of generative AI and AI-assisted technologies in the SC paper preparation process

During the preparation of this work, authors used ChatGPT to edit sections of text in this report. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the paper.

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