SCIENTIFIC COMMITTEE
NINETEENTH REGULAR SESSION

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ECOSYSTEM AND CLIMATE INDICATORS

WCPFC-SC19-2023/EB-WP-01

SPC-OFP

Executive summary

This Working Paper updates SC19 on progress regarding development of the candidate ecosystem and climate indicators for the Western and Central Pacific Ocean (WCPO).

The ecosystem and climate indicator recommendations of SC18 were:

i. making "Ecosystem and Climate Indicators" a standing agenda item of the Ecosystem and Bycatch Mitigation theme session. This would provide a mechanism for the Scientific Committee to annually consider adopting candidate indicators presented to the Committee but also review and respond to existing trends/triggers identified in adopted indicators.
ii. the development and testing of "Ecosystem and Climate Indicators" as a project of the Scientific Committee. This would provide a mechanism for the Scientific Committee to easily track its progress towards evaluating and adopting candidate indicators.
iii. that available information and updates on the impacts of climate change be included or combined with status of stocks reporting.

This working paper specifically addresses recommendation (ii) and provides SC19 with a workplan and budget for the Scientific Committee project for the period 2024-2027.

An initial screening of three candidate indicators, ENSO Variability, Ocean Productivity and Warmpool Area is provided. An update to the report card on potential ecosystem and climate change indicators (as provided since SC17) is also provided as an Annex to the report.

Recommendations

SC19 is invited to:

- note that the SSP has completed a first screening of a subset of potential indicators for adoption, and based on this experience recommends that while the criteria identified at SC12 are appropriate for the initial screening of candidate indicators, a more specific set of criteria/process is needed for testing and adoption;
- consider and adopt the proposed workplan for the development and testing of ecosystem and climate indicators for the period 2024-2027;
- consider and adopt the proposed budget to support expert workshops, later re-validation of adopted indicators and communication components of the proposed workplan;
- explore the approaches developed for indicator communication and provide feedback to the SSP (either formally or informally) on options for improvement.

Background

The Scientific Committee has been considering the application of ecosystem indicators to assist with advice generation on the impacts of fisheries targeting tuna and tuna-like species on the broader pelagic ecosystem since SC11 in 2015. The rationale and potential design and testing criteria for ecosystem indicators were agreed at SC12 (including a provisional workplan for their development – see Annex 1). Candidate indicators have subsequently been presented to the Science Committee since SC15, including those proposed for application in other ocean basins (see SC15-EB-WP-12 and SC16-EB-IP-07, SC17-EB-IP-09, SC18-EB-WP-01).

Once adopted, key ecosystem and climate indicators will provide the Scientific Committee with the capability to report on ecosystem and climate change impacts in its annual reporting to WCPFC. Hence, adopted ecosystem and climate indicators are expected to be regularised as standard tools for monitoring the status of WCPFC fisheries and ecosystems. The regular reporting of adopted indicators could form the basis of a report card on WCPO ecosystem and climate states. Such report cards would assist WCPFC with the provision of information that supports its application of the EAFM and implementation of the WCPFC climate resolution.

Process for adopting indicators

SC12 noted that developing a thorough understanding of how to interpret potential indicators, their appropriate reference levels and baselines, and how reliable they are for prediction were critical steps for indicator adoption by the WCPFC Scientific Committee (SC). Criteria for developing and testing candidate indicators has subsequently been proposed to the Scientific Committee:

- science and data based;
- characterize the states and trends of WCPFC marine ecosystems with respect to fishing activity and/or climate (including reference levels and baselines);
- reflect well-defined processes underlying fishing activity and fishery responses to climate;
- responsive to changes attributable to fishing pressure and climate (i.e. having minimal time-lags and capability to provide early warning);
- estimable on a routine basis with a historical data time-series available;
- cost-effectiveness;
- scalable across national, sub-regional and regional scales;
- linked to existing WCPFC models and decision-making processes (for inclusion in MSE scenarios, validation of predictions and testing of model assumptions);
- can be routinely estimated by members without reliance on the Science Service Provider.

Terms of Reference: Ecosystem and Climate Indicators project (SC18-EB-WP-01)

A drafted terms of reference for the Ecosystem and Climate Indicators project was provided as Annex 3 to SC18-EB-WP-01 with the following specified objectives and scope of work:

Objectives

- Develop and test candidate ecosystem and climate indicators to track the impact of climate and ecosystem changes on WCPFC fisheries and ecosystems.
- Provide technical advice to the Scientific Committee on the suitability of criteria used for testing and evaluating the performance of candidate indicators.
- Support the Scientific Committee in developing tools to communicate ecosystem and climate change impacts to WCPFC and external stakeholders and interest groups.

Scope of Work

- Technical analyses to develop and test candidate indicators.
- WCPFC member and expert workshops to refine indicators.
- Scientific Committee reporting.
- Routine preparation of adopted indicators.
- Development of tools for communication to WCPFC and wider stakeholders.

The SSP was tasked by SC18 to develop a workplan for this project to be endorsed by SC19 and to develop an associated budget.

Proposed Workplan

Technical analyses to develop and test candidate indicators

The SSP has completed a first screening of a subset of potential indicators for adoption (Annex 1). Based on this experience the SSP recommends that while the criteria identified at SC12 are appropriate for the initial screening of candidate indicators, a more specific set of criteria/process is needed for testing and adoption.

Scientific Committee reporting & Routine preparation of adopted indicators

A process for subsequent review and validation by the SC should be developed to ensure that the indicator continues to reflect a well-defined process that is relevant for the management of WCPFC fisheries.

WCPFC member and expert workshops to refine indicators

The FAO administered and GEF funded Common Oceans II project has agreed to provide resources for WCPFC member workshops to refine the indicators. Expert workshop(s) to assist the SSP with testing candidate indicators remains unfunded.

Development of tools for communication to WCPFC and wider stakeholders

The Government of New Zealand through an initiative to update the vulnerability assessment of

Pacific Island communities and economies to the impacts of climate change is supporting the development of communication tools. An example report card format is provided in Annex 2 and potential dashboard format is available on this link (https://ofp-sam.shinyapps.io/ofp-FEMA-climate-dashboard/). Participants at SC19 are invited to explore these styles of communication and provide feedback to the SSP (either formally or informally) on options for improvement.

A workplan for adoption is proposed in the Table below.

Task	Activity	Schedule			
		SC20	**SC21**	**SC22**	**SC23**
Initial screening of candidate indicators	Apply criteria endorsed at SC12 to candidate indicators that are relevant for monitoring impacts on purse seine and long-line fisheries and tuna species productivity	■			
Test candidate indicators	Fully develop methodology for developing and testing candidate indicators	■			
	Test candidate indicators	■	■		
	Expert Workshop	■	■		
	Adoption Workshop		■		
Indicator validation	SC review and evaluation that adopted		■	■	■
Communication tools	Report cards	■	■	■	■
	Dashboards	■	■	■	■
	TFAR (see https://fame1.spc.int/resources/documents/tuna-fisheries-assessment-report)	■	■	■	■

Budget

A total budget of USD70,000 over four years is required to support expert workshops in 2024 and 2025 and support re-validation analyses and communications in 2026 and 2017. All other activities are co-financed through contributions by partner organisations to the SSP.

Item	Calendar Year			
	2024	2025	2026	2027
Initial screening of candidate indicators	SSP is able to utilise complementary funding			
Testing Methodology	SSP is able to utilise complementary funding			
Testing	SSP is able to utilise complementary funding	SSP is able to utilise complementary funding		
Expert Workshop	20,000	20,000		
Adoption workshop		SSP is able to utilise complementary funding		
Validation		SSP is able to utilise complementary funding	10,000	10,000
Communication tools	SSP is able to utilise complementary funding	SSP is able to utilise complementary funding	5,000	5,000
Total	**20,000**	**20,000**	**15,000**	**15,000**

Recommendations

SC19 is invited to:

- note that the SSP has completed a first screening of a subset of potential indicators for adoption, and based on this experience recommends that while the criteria identified at SC12 are appropriate for the initial screening of candidate indicators, a more specific set of criteria/process is needed for testing and adoption;
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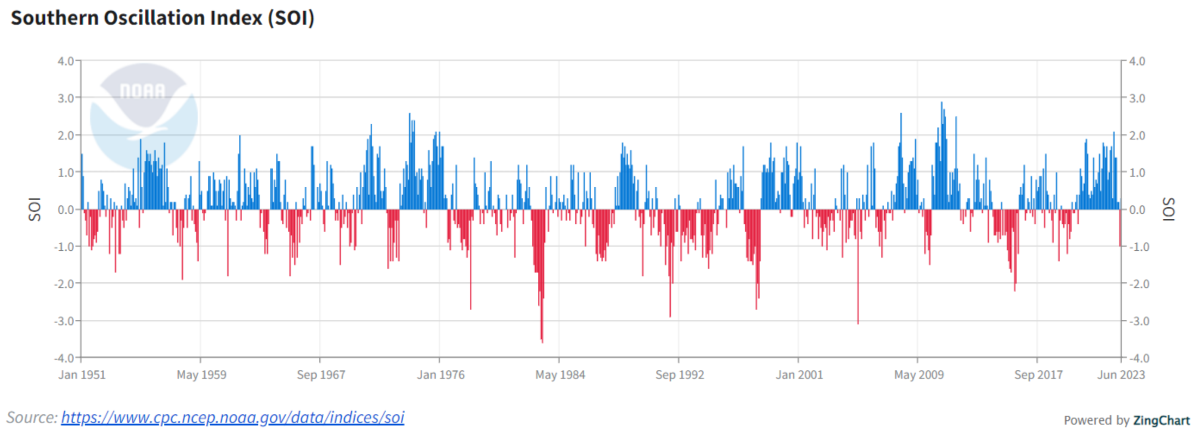
Annex 1 Initial Candidate Indicator Screening

ENSO variability

There are several indicators of the ENSO state, either based on atmospheric pressure (SOI: https://www.ncei.noaa.gov/access/monitoring/enso/soi) or Sea Surface Temperature (https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni). All are available on the web.



Recent events:

2015-16. A very intense El Niño occurred, characterized by an unprecedented warm temperature anomaly in the central equatorial region, while it had limited extension to the far east Pacific. Unlike most previous El Niño events, this one was not followed by a strong La Niña phase, depriving this region of a strong subsequent recovery of the equatorial upwelling and high productivity associated with it. The biological consequences of this 2015–16 El Niño event were dramatic on the ecosystems of Pacific islands in this central region. For instance in Jarvis Island (0°22’S, 160°01’W), on the equator south of Hawaii, the longest and most widespread coral bleaching event was recorded, with massive mortality, i.e. 95% of Jarvis corals were killed. In the meantime, the biomass of planktivore and reef fishes significantly declined, as did seabird abundance (Brainard et al., 2018)[1].

Sep 2020- Apr 2023. An exceptional series of 3 consecutive La Niña years occurred. It was the third time since 1950 that there has been a triple-dip La Niña. These events took place against a background of climate warming (cf below), which make this series of events unique and without equivalent in the past few centuries, at least.

2023-2024. Since June 2023, the dynamics of key oceanic and atmospheric variables are consistent with the onset of El Niño. Almost all the models used for ENSO forecast an **El Niño event developing** during boreal summer and **continuing up to the winter and spring in 2024**.

Impacts on tunas

In addition to the well described redistribution of skipjack tuna and associated purse seine fisheries in the WCPO in relation to ENSO, its variability is thought to also have an impact on recruitment of tuna. A correlation between the **South Pacific albacore** tuna recruitment variability and ENSO has been proposed with La Niña being favourable and El Niño unfavourable. An exceptional low recruitment peak estimated in 2016-17 with the last stock assessment study (independent of

[1] Brainard R. E., Oliver T., McPhaden M. J., Cohen A., Venegas R., Heenan A., Vargas-Angel et al. (2018). Ecological impacts of the 2015-16 El Niño in the central equatorial Pacific. In “Explaining Extreme Events of 2016 from a Climate Perspective.” *Bulletin of American Meteorological Society*, *99* (1), S21 –S26. doi:10.1175/BAMS-D-17-0118.1

environmental or climate data) coincides well with the powerful 2015-16 El Niño event, given that age of recruitment in the fisheries is likely around 2 years (Figure 1). This seems to support the proposed relationship. If it is robust, the 2020-23 series of La Niña can be expected to be very favourable to the recruitment of South Pacific albacore, and effects could be detected in the fisheries in the coming years.

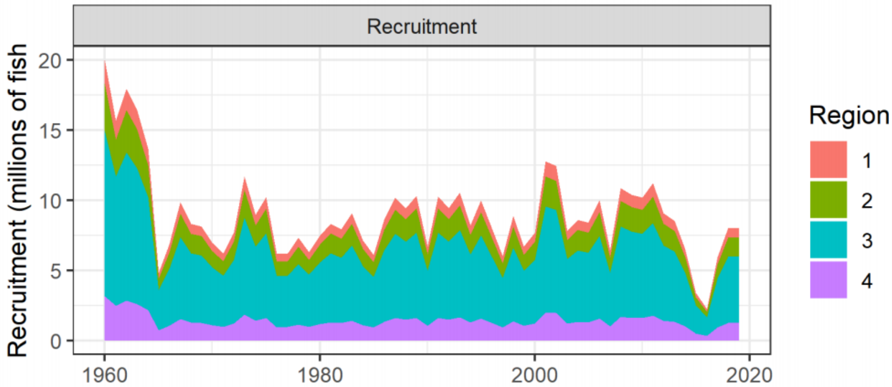


Figure 1 Last estimate of South Pacific Albacore recruitment showing low peak recruitment in 2016 (Castillo-Jordan et al., 2021)

An opposite relationship has been also proposed for skipjack (Lehodey et al. 2000; 2021), El Niño (La Niña) being favourable (unfavourable) for recruitment. While the last recruitment time series for skipjack remains correlated with the ENSO SOI index, the relation is shown only after an increasing trend is removed in the recruitment time series. This trend seems correlated to the expansion of the warm pool (see below). This could suggest that though La Niña remains less favourable than El Niño to skipjack recruitment, the long-term trend in ocean warming may modulate and dampen the negative effect of La Niña. Although difficult to demonstrate in the absence of large-scale sampling of tuna larvae/juveniles, the mechanisms at play that influence recruitment success are likely related to changes in temperature and productivity in the spawning grounds of the tuna species. Therefore, in addition to indicators for monitoring the change in temperature (see below), productivity of the WCPO needs to be monitored and observation and trends compared to ocean and climate model projections.

Ocean productivity indicators

The phytoplankton (microscopical algae in the water column) is the basis of ocean productivity. Thanks to photosynthesis, it produces the organic matter composed of carbon and other chemical elements. **Phytoplankton is used by zooplankton that are prey of tuna larvae. Therefore, these two variables are key indicators to monitor and predict with ecosystem models**. Phytoplankton abundance is monitored by satellite ocean colour sensors. However, converting this information to total primary production over the water column is not straightforward especially in tropical waters where maximum phytoplankton abundance occurs in sub-surface waters up to 100m depth. **There is no evidence that primary production has decreased in the Pacific tropical region over the last decade, contrary to the trend that would be expected due to continuous warming**, leading to vertical thermal stratification and expansion of the warm pool. In fact, one oceanographic station north of Hawaii (HOT) that has been monitored since 1989 shows either **multi-decadal regimes or an increasing trend** (Figure 2). The multi-decadal regimes would coincide with the Interdecadal Pacific Oscillation (IPO).

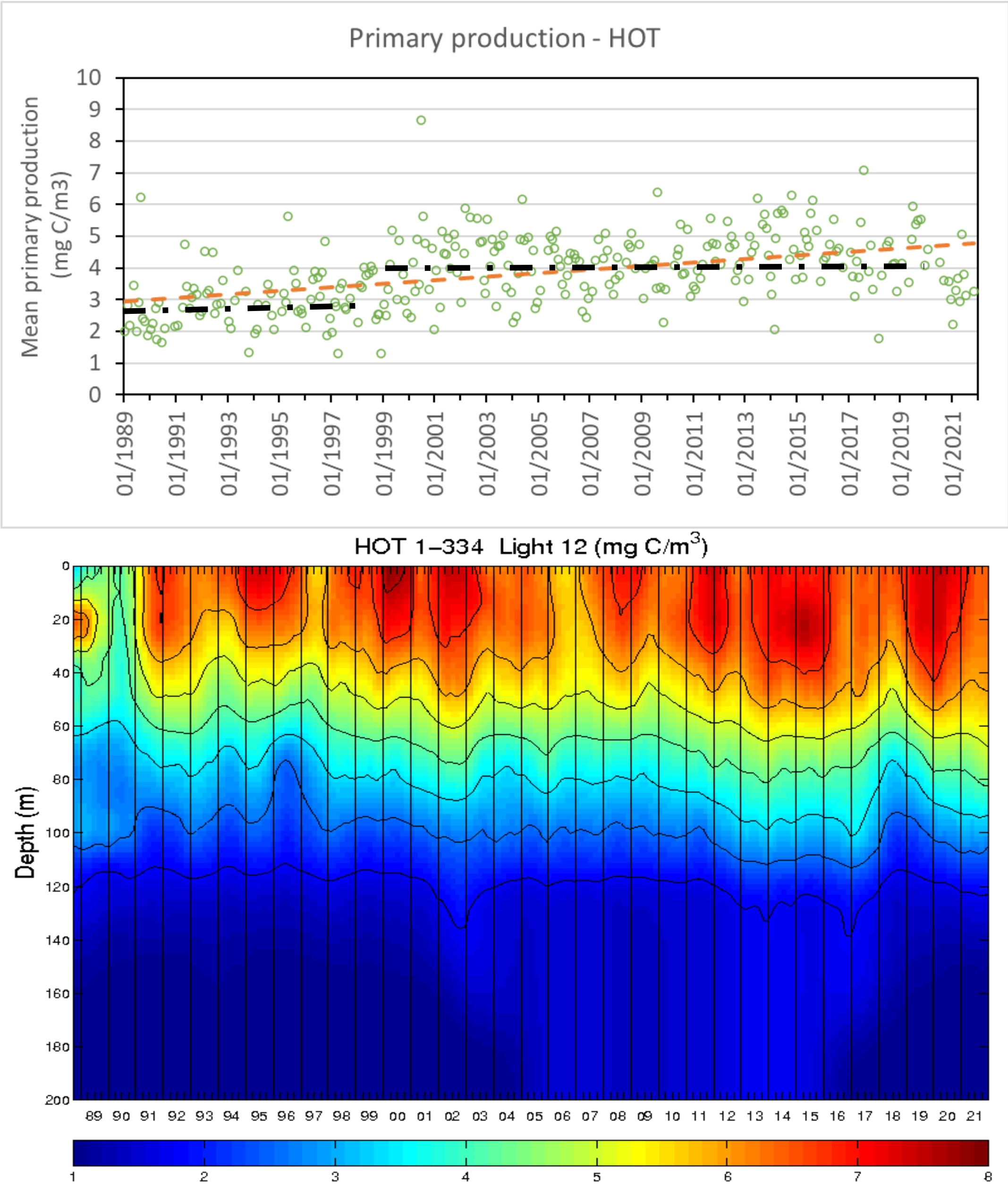


Figure 2 Top: Observed primary production at station HOT, north of Hawaii, since 1989. Orange line shows increasing linear trend. Black dotted line shows possible two-regime phases linked to IPO. Data available at HOT-DOGS: Primary Production Time-series (hawaii.edu). Bottom: Contour plot of 14C-based primary production (mg C m^{-3} d^{-1}) at station ALOHA north of Hawaii 1989-2021. https://hahana.soest.hawaii.edu/hot/hot-dogs/ppcontour.html

The Interdecadal Pacific Oscillation (IPO)

The IPO is a long period climate oscillation that operates at a multi-decadal scale, with phases lasting roughly 20–30 years. Since 1920, the IPO had positive phases from 1922 to 1946 and 1978 to 1998 and **negative phases** between 1947 and 1976 and **since 1999**. An index of IPO is the tripole index (TPI) based on the difference between the average SST anomaly over the central equatorial Pacific and the Northwest and Southwest Pacific (https://psl.noaa.gov/data/timeseries/IPOTPI/). IPO phases are associated to changes with abrupt shifts in North Pacific sea level pressure (SLP) and contrasting anomaly patterns in temperature, precipitation and atmospheric circulation over the eastern and western Pacific. The positive (negative) phase of the IPO is associated with anomalously warm (cool) sea surface temperatures (SSTs) in the tropical Pacific Ocean and anomalously cool (warm) SSTs in the subtropical North and South Pacific Oceans. IPO is strongly correlated to the Pacific Decadal Oscillation (PDO) that occurs in mid-latitudes of the northern hemisphere. Accelerated warming periods in the long-term rise of global mean surface temperature have been associated with the IPO (e.g. Henley and King 2017; Bordbar et al., 2019). **The negative IPO phase since 1999 may have provided a temporary buffer for global warming.**

The intensity of trade winds is tightly coupled to the east-west SST gradient over the equatorial Pacific. A strengthening of the trade winds is observed since the 1950s, part of it likely linked to the IPO shift to a negative phase in 1999. The influence of negative phases of IPO on both north-east and south-east trade winds is highlighted by indices computed from their core zone by Yang et al. (2022) (Figure 3). The enhancement of northeast trade wind has been particularly intense since the establishment of the last negative phase in 1999 and could explain part of the increase in primary production at the HOT station.

After 23 years of negative IPO, the probability of a shift to a positive phase in the coming few years is becoming high. The future shift of the IPO to a new positive phase should have strong consequences in terms of temperature and productivity in the WCPO for the following decades. This needs to be closely monitored.

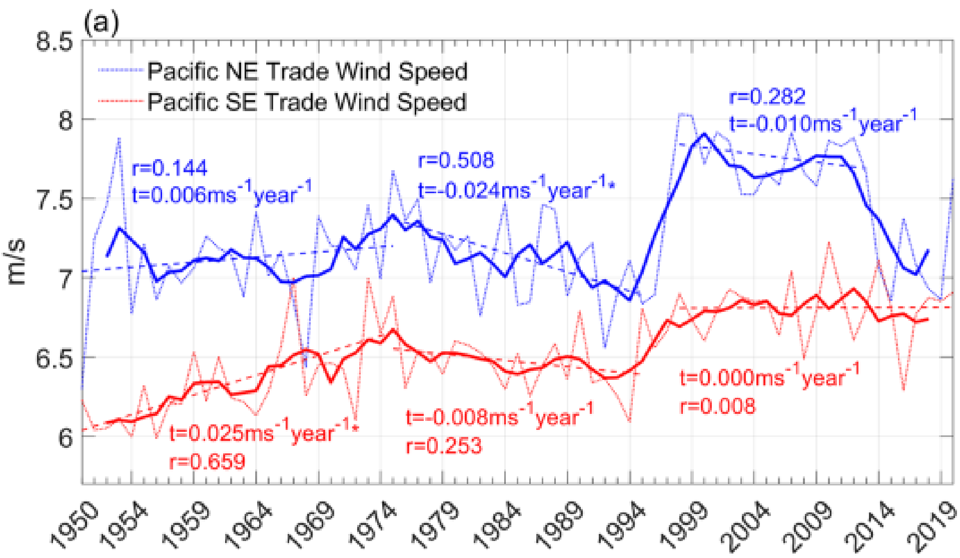


Figure 3. Reproduced from Yang et al (2022). The decadal variations in wind speed in the trade wind core zone of the Pacific from 1950 to 2020. (Thick lines indicate 5-year running averages of wind speed and dashed lines are the linear regression result of the trade wind area in the corresponding period. “t” and “r” are the regression/correlation coefficient of the corresponding period respectively. ‘*’ indicates that the trend passes the 95% significance test.

Warm-pool Surface Area/Volume

As noted above, a relationship is proposed for skipjack recruitment that is linked to ENSO variability but also likely impacted positively by the expansion of the warm pool since the mid-1980s (Figure 4).

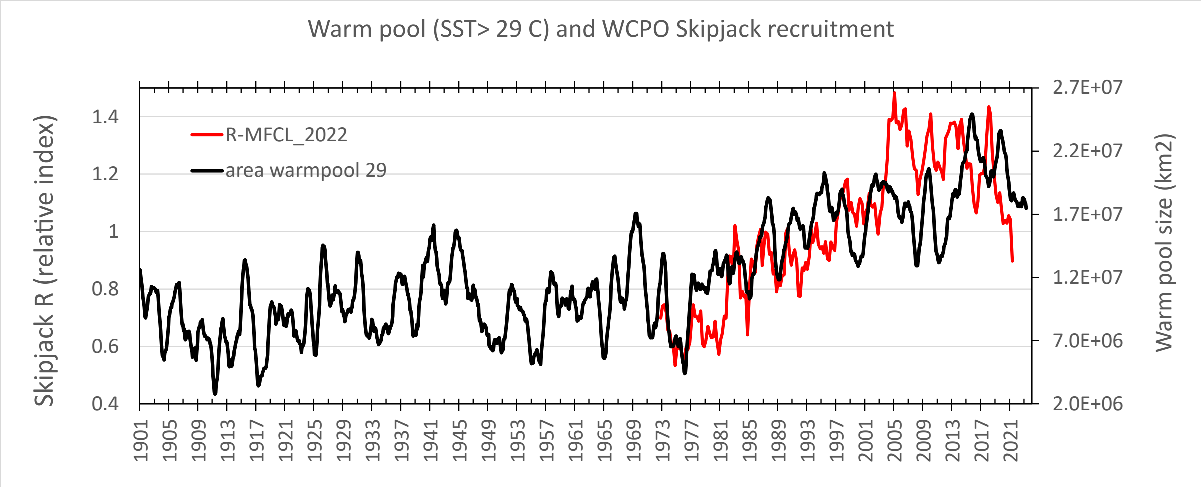


Figure 4 Skipjack recruitment time series from last stock assessment study and evolution of the size of the western tropical warmpool defined by SST> 29°C.

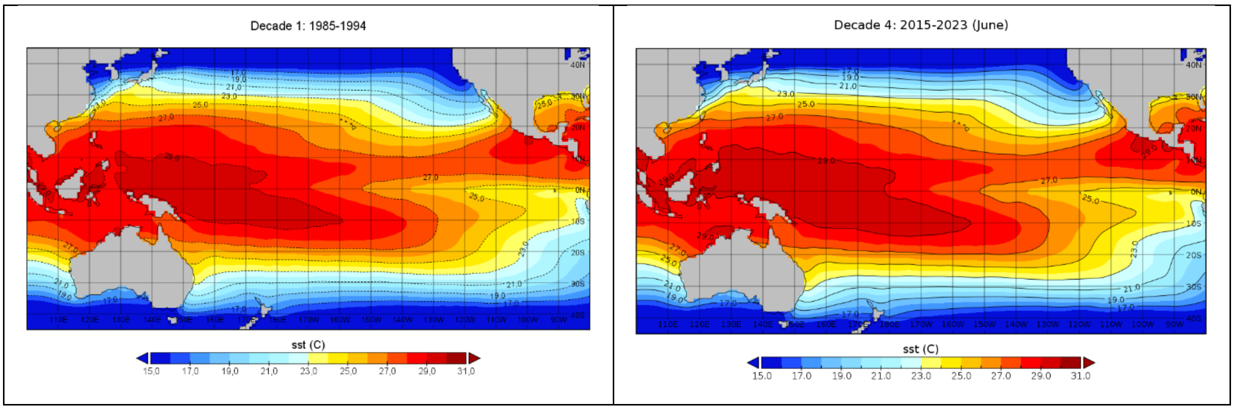


Figure 5 Mean observed SST temperature per decade (based on HadISST dataset: Met Office Hadley Centre observations datasets)

Therefore, it is important to monitor the dynamic changes of the warmpool (Figure 5) and evaluate if the observed change is following expectations according to climate change IPCC scenarios and climate model projections, and then if observed change can be attributed to climate change or is still in the range of natural variability (i.e., interannual ENSO and interdecadal IPO) (e.g. Figure 6). Several indicators can be proposed to monitor these changes, combining observations and model projections: the size of the warmpool, the mean positions of the 28 or 29°C isotherms and the average mean decadal position of the warmpool front (Figures 7).

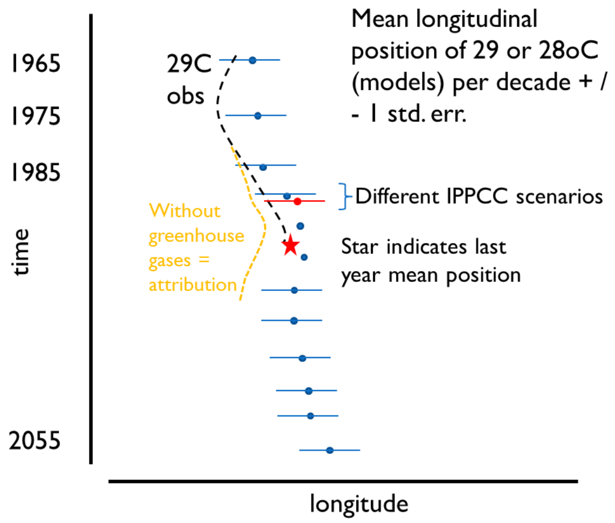


Figure 6 Proposed indicator to monitor long term change in the warmpool longitudinal convergence zone with observation and climate model projections. Dashed line is for observations; dots and bars are for model's mean position with 1 standard error.

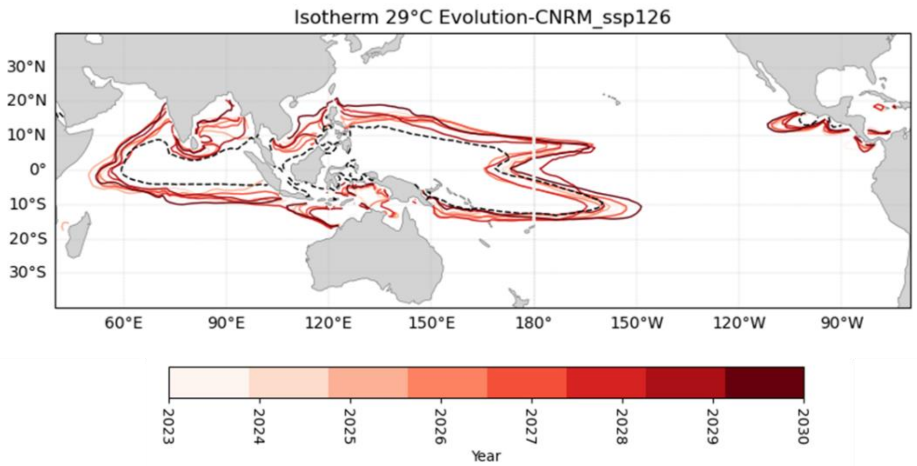


Figure 7 Change over time of the Indo-Pacific warmpool defined by SST>29°C predicted by one climate model (CNRM) under the IPCC SSP 1.6

Assuming that the expansion of the warmpool is favourable to the spawning of skipjack, it is interesting to monitor the size frequencies of catch by the fisheries in the central region where surface waters are warming over time (Figure 8) with SST above 27-28°C becoming more favourable to spawning and recruitment of juvenile fish. In that case the median size for the recent decade should be shifted to smaller sizes compared to the historical warmpool area. A preliminary plot of median size (Figure 9) suggests this is effectively the case.

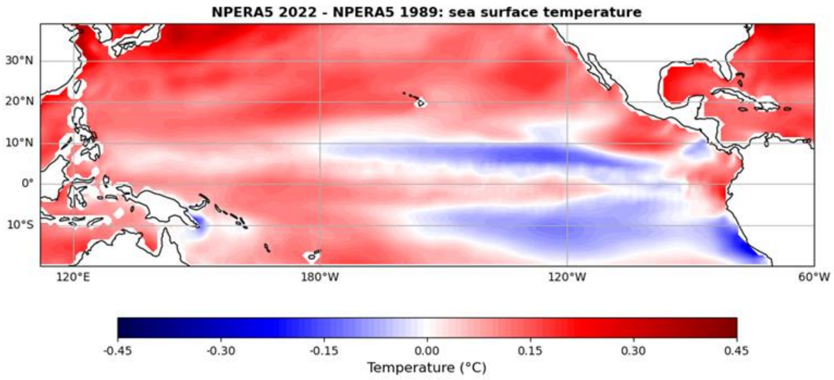


Figure 8 SST anomaly (difference between 2022 and 1989), using mean rate of change to remove interannual variability.

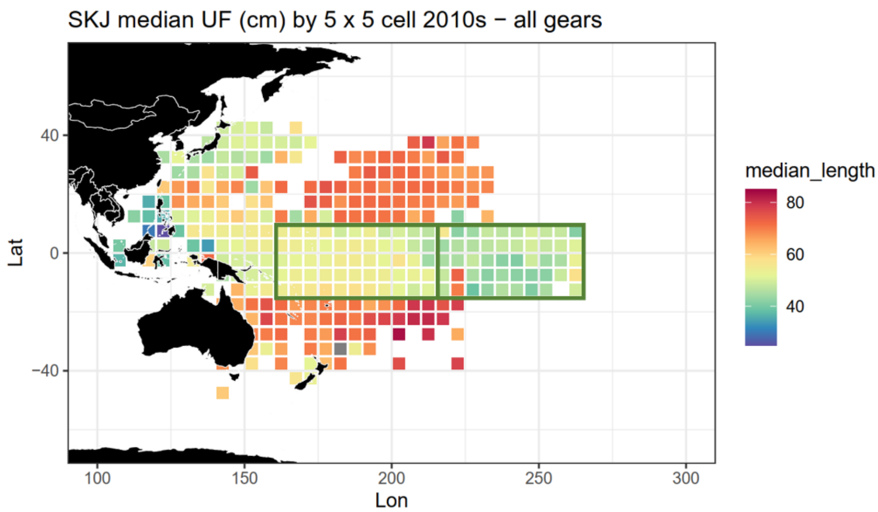


Figure 9 Median size of skipjack caught by WCPFC fisheries, temporally aggregated for the 2010-2019 decade in 5 x 5 longitude and latitude cells

As noted above, it is critical to monitor past and future trends in ocean primary production together with the change in temperature. A recent study (Kwon et al 2022) has suggested a possible mechanism that could explain the increasing trend observed at the oceanographic station ALOHA, and at larger scale, based on ocean colour data (Sharma et al 2019; Cael et al, 2023). They tested the mechanisms in an Earth Climate model and showed that a flexible utilization of phosphorus by phytoplankton under phosphate-stressed conditions can overcompensate the previously projected 21st century declines due to ocean warming and enhanced stratification.

References

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Screening against SC12 Criteria

Using the above information an initial screening of ENSO variability, Ocean Productivity and Warmpool Area was undertaken against SC12 criteria. All three indicators met the criteria, except for criteria 7 (scalability) as they were basin scale only indicators.

Indicator	SC12 Criteria*								
	1	2	3	4	5	6	7	8	9
ENSO Variability	✓	✓	✓	✓	✓	✓	×	✓	✓
Ocean productivity	✓	✓	✓	✓	✓	✓	×	✓	✓
Warmpool Area/Volume	✓	✓	✓	✓	✓	✓	×	✓	✓

*SC12 Criteria:

1. science and data based;
2. characterize the states and trends of WCPFC marine ecosystems with respect to fishing activity and/or climate (including reference levels and baselines);
3. reflect well-defined processes underlying fishing activity and fishery responses to climate;
4. responsive to changes attributable to fishing pressure and climate (ie. minimal time-lags and capability to provide early warning);
5. estimable on a routine basis with a historical data time-series available;
6. cost-effectiveness;
7. scalable across national, sub-regional and regional scales;
8. linked to existing WCPFC models and decision-making processes (for inclusion in MSE scenarios, validation of predictions and testing of model assumptions);
9. can be routinely estimated by members without reliance of the Science Service Provider.

Annex 2 Ecosystem and Climate Indicator Report Card

Details on the calculations for each indicator in Report Cards 1 to 3 are provided below. Code, data, and associated figures and results for each indicator are available in the GitHub repository for the paper: github.com/PacificCommunity/OFP-FEMA-ecosystem-indicators.

Report Card 1. Environment Indicators

All environmental indicators were calculated from outputs of the Bluelink Ocean ReANalaysis 2020 (Chamberlain et al. 2021), a three-dimensional, physical ocean model with a spatial resolution of 1/12°. Monthly outputs were used to allow averaging over seasons, when required by an indicator. The code used to generate indicators from pre-processed netcdf output files from BRAN2020 can be found at the GitHub repository for this paper (see link above).

A.1 *Sea Surface Temperature Anomalies*

Sea surface temperature (SST) anomaly was calculated across three spatial extents. In all three cases, the annual value was the mean anomaly of all cells within the spatial extent, from a baseline mean across the period 1993-2021. For the WCPO SST anomaly, this spatial extent was bounded by a square with corners at 50°N, 130°E and 50°S, 150°W (see Figure 1 in SPC-OFP 2021). The WCPO equatorial SST anomaly included only cells bounded by the box with corners at 5°N, 130°E and 5°S, 150°W. In the case of the warm pool extent SST anomaly, the spatial extent of cell anomalies changed each year. Following a typical characterisation of the warm-pool extent, only those cells that exceed a mean sea surface temperature of 29°C during the period November to April were included in anomaly calculations for each year (e.g. Roxy et al. 2019; Hu and Federov 2017). The mean anomaly of cells included in this extent, from their respective 1993-2021 baseline, was then calculated annually for the period November to April.

A.2 *Warm Pool Indices*

Each year, the extent of the warm pool was calculated using the method described above. In the case of the mean warm pool size, the number of cells with a mean sea surface temperature greater than 29°C during November to April was used to provide the approximate area encompassed by the warm pool each year. The eastern boundary of the warm pool was calculated following a similar methodology to Qu and Yu (2014) and others, where strong changes in sea surface salinity (SSS) across the equator were used to indicate the presence of a barrier layer between increased fresh water in the warm pool meeting colder, high salinity water from the east. Mean SSS between 2°S and 2°N was calculated during the November to April period, and the centre of the largest longitudinal change across a 10° window identified as the eastern limit of the warm pool. The mean warm pool mixed layer depth (the depth at which water mixing results in uniform buoyancy of a particular value) was simply taken directly from BRAN2020, and averaged over the extent of the warm pool during the period November to April each year.

A.3 *Climate Indices*

Here, we have presented two climate indices which relate to changes in the WCPO ecosystem. The Oceanic Niño Index (ONI) tracks three-month averaged SST anomalies across regions of the equatorial Pacific from a moving 30-year average temperature, and one method of identifying likely El Niño or La Niña events. The Interdecadal Pacific Oscillation index (IPO) measures longer-term climate cycles affecting the extent of the Pacific basin, and switches phases roughly each 15-30 years. Positive phases are associated with increased warming in the tropics and cooler northern Pacific climate, and negative phases are associated with cooler temperatures in the tropics and increased temperatures in the higher latitudes.

Report Card 2. Annual Tuna Catch & Fishing Effort indicators

A.4 ***Annual Tuna Catch***

These indicators describe trends in annual catch estimates (in metric tonnes) of the four main tuna species (skipjack, yellowfin, bigeye and albacore) targeted within the WCPFC Convention Area (WCPFC-CA), between 1990 and 2022, inclusive. Data for the calculations were extracted from SPC's 'a_model' database, a collation of S_BEST, L_BEST, and P_BEST catch data aggregated at 5° x 5° resolution for all fishing gears, and S_BEST and L_BEST containing aggregated, raised catch data from the purse-seine fishery at 1° x 1°, and the longline fishery at 5° x 5°, respectively. See Hare et al. (2023) [SC19/SA-WP-06] for a compilation of all fishery indicators for these target tunas.

A.5 ***Fishing Effort***

Data to characterize trends in fishing effort were extracted from SPC's S_BEST and L_BEST databases from 1990-2033, inclusive, for purse seine (PS) and longline (LL) catch and effort data, respectively. These databases contain aggregated, raised fishing effort across the WCPFC-CA. We focused on purse seine and longline data as they represent the major gear sectors for the region. For the purse seine fishery, the individual fishing set was considered the metric of effort, while for longline, effort was defined as the number of hooks fished.

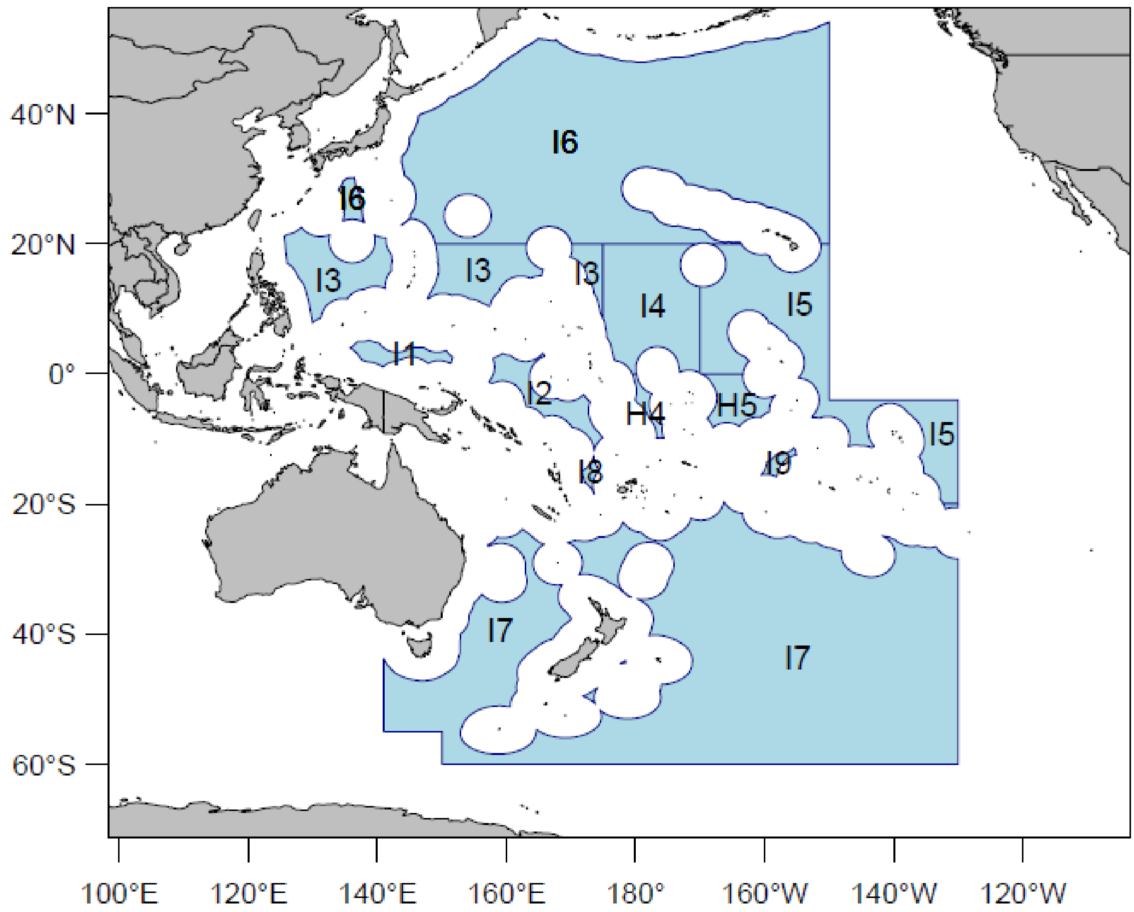
The central tendency of purse seine fishing effort was defined here by the 'centre of gravity', i.e. the mean location (latitude and longitude) of fishing effort. This was calculated by year for each fishing mode i.e. 'unassociated' free-school sets (UNA) versus 'associated' sets (ASS). We present only the annual longitudinal centre of gravity for purse seine, as the fishery remains relatively stable latitudinally year on year. It should be noted that for this analysis, associated sets refers to sets made on drifting FADs and drifting logs or debris; this does not include sets made around whales or whale sharks, nor does it include anchored FAD sets.

The central tendency indicators were not calculated for the longline fishery because of the diversity in targeted species and the areas associated with different targeting behaviours. At this time, a measure of central tendency for the longline fishery was not expected to be an informative indicator of ecosystem dynamics.

In addition to the central tendency of fishing effort, area occupied by the purse seine and longline fisheries was calculated. Area occupied is a measure of the distribution of effort across the spatial domain of the WCPFC and was calculated as the sum of the area (in km^2) of unique 1° x 1° cells fished by the purse seine fishery and 5° x 5° cells fished by the longline fishery, in each year evaluated.

With growing interest in tracking changes in the distribution of purse seine effort inside and outside EEZs within the WCPFC-CA, we include a new effort indicator this year, representing the proportion of purse seine sets made in High Seas areas, disaggregated by fishing mode. High Seas areas included in the calculations comprise the I1, I2, I3, I4, I5, I6, I7, I8, I9, H4, H5 regions (Figure A1).

Figure A1. WCPFC-CA High Seas regions and boundaries.



Report Card 3. Biology & Bycatch Indicators

A.6 *Tuna Condition*

The mean fork length (cm) of skipjack tuna was calculated annually from all length measurements recorded for longline, purse seine and pole-and-line catches made in the WCPFC-CA between 1990 and 2022, inclusive. Length data were drawn from observer and port sampling records, in this case contained in SPC's 'BioDaSys', 'OBSV_MASTER' and 'Tufman2' databases. Following the methods used for the fishing effort indicators (see section A.5) we focussed our attention on the purse seine and longline data as they represent the major fisheries in terms of catch, and were available across the full 33-year time series. Where required, published 'conversion factors' were used to convert length measurements to fork length (UF) in cm. These conversion factor equations are updated as new data comes to hand, and are housed in an online database managed by SPC. We refer readers to Macdonald et al. 2023 [SC19/ST-IP-04] for an update on progress on this conversion factor work.

The mean fork length (cm) of yellowfin and bigeye tuna caught in the longline fishery was calculated annually from all length measurements recorded for each species within the WCPFC-CA between 1990 and 2022, inclusive. The length data were again drawn from observer and port sampling records contained in SPC's 'BioDaSys', 'OBSV_MASTER', 'FISH_MASTER' and 'Tufman2' databases. We focussed on the longline data for yellowfin and bigeye, as this gear typically selects for larger individuals than purse seine, placing a lower bound on the length range considered. This allowed us to maximise precision, while minimising potential gear-related bias in tracking shifts in mean length through time. As for skipjack, length measurements were converted to fork length (UF) in cm where required using published conversion factors for each species.

Mean fish condition, defined by the average relative condition factor $K_{\text{rel}} = WW/aUF^b$ (where WW is an individual's whole weight (kg) and aUF^b is the model predicted whole weight at fork length UF (cm)) was calculated annually for skipjack, yellowfin and bigeye tuna separately, based on length and weight data from longline catches made across the WCPFC-CA between 1990 and 2022, inclusive. The data were drawn from observer and port sampling records contained in SPC's 'BioDaSys', 'OBSV_MASTER', 'FISH_MASTER' and 'Tufman2' databases.

Published conversion factors were again used to convert length measurements to fork length (UF) in cm, and weight measurements to whole weight (WW) in kg.

For each species, we elected to model predicted weight from the longline records only. This decision was based around two points. i) Data coverage: the broad spatial and temporal extent of coupled length and weight measurements available from the longline fishery provide the most reliable estimates for calculating K_{rel}. ii) Mismatch in scales: given the different size selectivities, areas fished and length of time series available for longline, purse seine and pole-and-line gears, there is potential for the shape of the length-weight curve to differ among gears/areas/time periods fished. Therefore, by fitting our models to the longline data only we aimed to reduce these possible biases in monitoring changes in fish condition across the 1990 to 2022 time series. We note that new sampling initiatives are being developed to enhance data collection on purse seine vessels, and as further data becomes available, gear-to-gear comparisons could be reported in future iterations of these Report Cards.

Fat content represents the percentage of lipids in the tuna flesh, and we consider this a potentially useful second indicator of tuna condition that complements the measurement of K_{rel}. The percentage of fat is measured using the Distell's fish 'fatmeter' model 692 by a simple contact of the instrument's sensor on the skin of the fish. Collection of fat content data on tropical tunas is now part of routine biological sampling tasks during PTTP tuna tagging cruises, and the dataset is growing steadily. Fat content is dependent on fish size; hence to avoid introducing bias, only skipjack, yellowfin and bigeye tuna measuring 40-60cm fork length were used to calculate annual mean fat content by species.

A.7 *Bycatch Species*

The observer and aggregate effort datasets used to estimate the amount of catch for the bycatch species were extracted from SPC data holdings. The overall approach was to estimate stratified catch rates using a combination of presence/absence models and bootstrap sampling for catch when present, and then to use these catch rates to estimate bycatch for unobserved sets. Recorded catches were used directly for observed sets, and assumed to be known without error.

For purse seine, the methods are fully described in Peatman and Nicol (2021), and a summary of the approach is provided here. The estimates cover the large-scale equatorial purse seine fishery operating in the WCPFC-CA. Bycatch estimates were not generated for purse seine fleets for which SPC holds limited representative observer data, namely small-scale domestic fisheries of Indonesia, Vietnam and the Philippines, and purse seiners operating in temperate waters. Bycatch estimates were generated in units of individuals for billfish, sharks and rays, with finfish bycatch estimated in units of metric tonnes. These units match those most commonly used by observers when recording catch volumes of the respective species groups and were considered to provide the most accurate dataset of observed catches in SPC's purse seine observer data holdings.

Presence/absence models were fitted to observer data using Generalised Estimating Equations (GEEs) with year, sea-surface temperature (SST – Reynolds et al. 2002), and categorical variables for quarter and school association as explanatory variables. The fitted presence/absence models were used to estimate the probability of presence for a given estimation group and strata (combinations of year, quarter and school association). The volume of catch when present was estimated by bootstrap sampling from sets with observed captures, stratified by association type. Estimates of the overall bycatch rate were then obtained for each estimation group and strata by taking the product of the probability of presence and the volume of catch when present. As such, the units of bycatch rate were numbers or metric tonnes per set. The estimated catch rates were then applied to the number of unobserved sets in each strata, to calculate unobserved bycatch. The estimates of unobserved bycatch were then combined with recorded bycatch from observed sets to give estimates of total bycatch.

For longline, the methods are fully described in Peatman and Nicol (2020), and a summary of the approach is provided here. The estimates cover longline fishing from 2003 to 2018 in the WCPFC-CA, including the region overlapping the IATTC Convention Area. Catch estimates do not include catches from the domestic longline fisheries of the Philippines, Vietnam and Indonesia, referred to in this report as 'west-tropical domestic fisheries', as SPC holds little representative observer data for these fisheries. Catch estimates also do not include former shark-targeted longline fisheries in the Papua New Guinea (PNG) and Solomon Islands (SB) EEZs as these fisheries are not included in aggregate longline catch and effort data held by SPC.

Hooks between float (HBF) specific aggregate catch and effort data, i.e. 'L_BEST_HBF' data, were used to estimate the proportions of aggregate effort data by HBF categories. K-means clustering was applied to aggregate longline catch data to partition longline effort into groups with similar species compositions.

GEEs were again used to model catch rates with year, sea-surface temperature (SST), HBF, and categorical variables for flag, and the species composition cluster for the 'L_BEST' strata as explanatory variables. A simulation modelling framework was used to estimate catches. First, the effort dataset for catch estimation was generated by aggregating HBF-specific effort surfaces to a resolution of year, SST, HBF, catch composition cluster, flag and region. Then estimated catches were obtained by taking the product of the catch rates and the effort.

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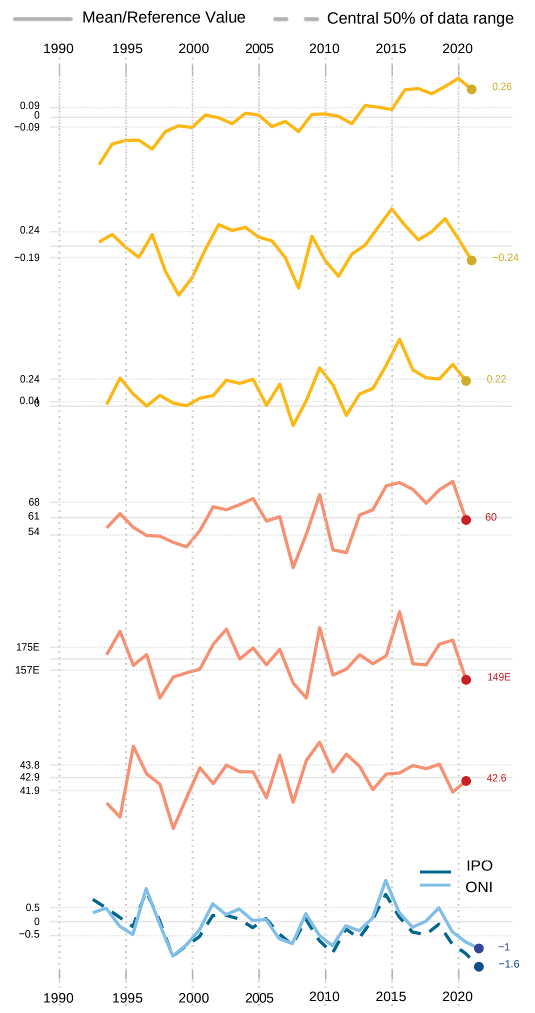
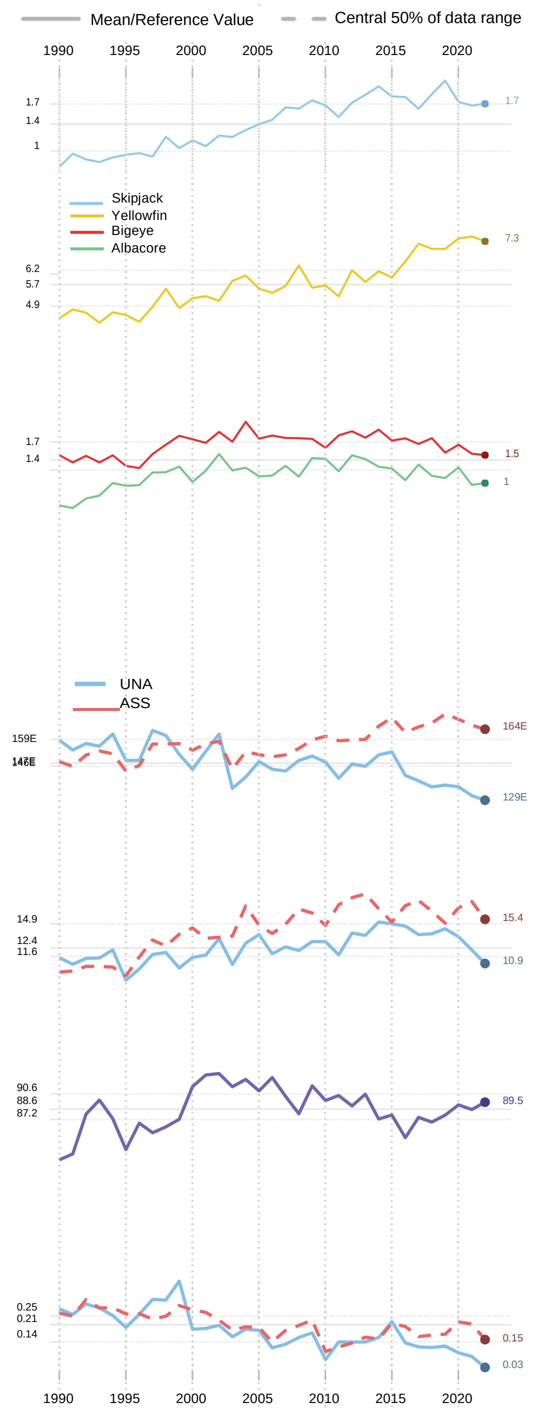
Indicator	Description	Notes	Time-series
Sea Surface Temperature Anomalies (ANNEX 1 - A.1)			
Annual SST Anomaly	Mean annual SST anomaly (°C) across **WCPO area**	• Derived from ocean models • WCPO area western limit of 130°E • Anomaly from mean temperature 1993-2021	
	Mean annual SST anomaly (°C) across **WCPO equatorial zone**	• Derived from ocean models • Equatorial zone 5°S-5°N • Anomaly from mean temperature 1993-2021	
Nov-Apr Warm-pool SST Anomaly	Mean annual SST anomaly (°C) within warm-pool extent	• Derived from ocean models • Warm-pool defined by mean Nov-Apr temperature > 29°C	
Warm-pool Indices (ANNEX 1 - A.2)			
Mean Size of Warm-pool	Approximate size of warm-pool in millions of km^2	• Derived from ocean models • Warm-pool defined by mean Nov-Apr temperature > 29°C	
Eastern Limit of Warm-pool Boundary	Longitude of strongest sea surface salinity boundary	• Derived from ocean models • Boundary defined as largest change over 10° distance	
Mean Warm-pool Mixed Layer Depth	Mean depth (m) of the mixed layer within warm-pool	• Derived from ocean models • Layer over which water temperature is homogenous	
Climate Indices (ANNEX 1 - A.3)			
Oceanic Niño (ONI) and Interdecadal Pacific Oscillation (IPO) Index	ONI indicates SST anomalies in the Niño 3.4 region during Nov-Jan each year IPO represents long-term oscillation between El Niño favourable and La Niña favourable phases	• ONI values > 0.5 indicative of El Niño events, values < -0.5 indicative of La Niña • IPO values > 0 indicative of more El Niño events, < 0 indicative of more La Niña events • Time series from 1993-2021	



Report Card 2. Annual Tuna Catch & Fishing Effort Indicators

Indicator	Description	Notes
Annual Tuna Catch (ANNEX 1 - A.4)		
Annual Tuna Catch	Total **Skipjack** catch for entire WCPFC-CA, in millions of tonnes	• Data from all fishing gears combined • See Hare et al. (2023) [SC19/SA-WP-06] for a compilation of all fishery indicators for skipjack
	Total **Yellowfin** catch for entire WCPFC-CA, in 100,000 of tonnes	• Data from all fishing gears combined • See Hare et al. (2023) [SC19/SA-WP-06] for a compilation of all fishery indicators for yellowfin
	Total **Bigeye** and **Albacore** catch for entire WCPFC-CA, in 100,000 of tonnes	• Data from all fishing gears combined • Data for albacore pertains to the South Pacific stock only • See Hare et al. (2023) [SC19/SA-WP-06] for a compilation of all fishery indicators for bigeye and South Pacific albacore
Fishing Effort (ANNEX 1 - A.5)		
Annual, Longitudinal Centre of Purse Seine Effort	Mean longitudinal centre of gravity of purse seine effort	• Purse seine effort is disaggregated into unassociated (UNA) and associated (ASS) sets • Associated sets include those made on drifting FADs as well as drifting logs and debris
Annual Area of Fishing Effort	Total area occupied by **Purse Seine** fleet annually, in millions of km²	• The sum of the area of 1° x 1° cells with at least one purse seine set, aggregated annually • Purse seine effort is disaggregated into unassociated and associated sets
	Total area occupied by **Longline** fleet annually, in millions of km²	• The summed area of 5° x 5° cells with at least one longline set, aggregated annually
Effort in High Seas Areas	Annual proportion of **Purse Seine** sets made in High Seas areas within the WCPFC-CA	• High Seas areas comprise the I1,I2,I3,I4,I5,I6,I7,I8,I9,H4,H5 regions • Proportions calculated relative to the total numbers of sets made, for unassociated and associated sets separately

Time-series



Report Card 3. Biology & Bycatch Indicators

Indicator	Description	Notes	Time-series
Tuna Condition (ANNEX 1 - A.6)			
Mean Length of Tuna species	Mean fork length (cm) of **Skipjack** tuna caught by WCPO purse seine and longline fisheries	• Length data sourced from purse seine and longline • Length measurements recorded at sea and in port	
	Mean fork length (cm) of **Yellowfin** and **Bigeye** tuna caught by WCPO longline fisheries	• Length data sourced from longline only • Length measurements recorded at sea and in port	
Mean Condition Factor from Longline Catch	Mean observed individual tuna weight divided by predicted weight at length	• A measure of relative tuna 'fatness' • Predicted weight modelled from longline records spanning 1990 to 2022, for each species separately	
Mean Fat Content of Sampled Tuna	Mean fat content (%) of **Skipjack**, **Yellowfin** and **Bigeye** tuna measured by fatmeter during annual PTTP research cruises informing on tuna condition - fatter fish being considered in better condition	• Second measure of tuna 'fatness' • Calculated for tuna between 40 to 60 cm fork length. • Years available: 2007-2009, 2011-2013, 2019-2021 • Sample size varies considerably by year and species, with more data in later years	
Bycatch Species (ANNEX 1 - A.7)			
Annual Finfish Bycatch	Estimated **Unassociated Purse Seine** catch of finfish bycatch in 1000s of metric tonnes	• Excluding billfish and tuna • Catch estimates based on observer data, excluding small-scale domestic fisheries of Indonesia, Vietnam, the Philippines, and temperate water purse seiners	
	Estimated **Associated Purse Seine** catch of finfish bycatch in 1000s of metric tonnes	• Excluding billfish and tuna • Catch estimates based on observer data, excluding small-scale domestic fisheries of Indonesia, Vietnam, the Philippines, and temperate water purse seiners	
	Estimated **Longline** catch of finfish bycatch in millions of individuals	• Catch estimates based on observer data, excluding domestic fisheries of Indonesia, Vietnam and the Philippines, and former shark-targeted fisheries in Papua-New Guinea and Solomon Islands	
Annual Billfish Bycatch	Estimated **Purse Seine** catch of billfish bycatch in 1000s of individuals from unassociated and associated sets	• Catch estimates based on observer data, excluding small-scale domestic fisheries of Indonesia, Vietnam, the Philippines, and temperate water purse seiners	
	Estimated **Longline** catch of billfish bycatch in millions of individuals	• Catch estimates based on observer data, excluding domestic fisheries of Indonesia, Vietnam and the Philippines, and former shark-targeted fisheries in Papua-New Guinea and Solomon Islands	
Annual Shark Bycatch	Estimated **Unassociated Purse Seine** catch of sharks in 1000s of individuals	• Catch estimates based on observer data, excluding small-scale domestic fisheries of Indonesia, Vietnam, the Philippines, and temperate water purse seiners	
	Estimated **Associated Purse Seine** catch of sharks in 1000s of individuals	• Catch estimates based on observer data, excluding small-scale domestic fisheries of Indonesia, Vietnam, the Philippines, and temperate water purse seiners	
	Estimated **Longline** catch of sharks in millions of individuals	• Catch estimates based on observer data, excluding domestic fisheries of Indonesia, Vietnam and the Philippines, and former shark-targeted fisheries in Papua New Guinea and Solomon Islands