SPC factsheet

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This fact sheet provides SPC members with a gentle introduction to the oceanography of the western and central Pacific Ocean and how it influences the distribution and abundance of tuna and tuna fisheries.

Tuna

Yellowfin tuna in a purse-seine net

Photo: Jeff Muir, University of Hawaii

Oceanographic characterisation of the Pacific Ocean and potential impact of climate variability on tuna stocks and their fisheries

Background

The way that ocean-climate systems impact tuna population dynamics in the Western and Central Pacific Ocean (WCPO) varies at different spatial and temporal scales (Bour et al. 1981; Lehodey et al. 2003). Changes in oceanic conditions (sea temperature, current speeds, direction, location, depth, upwellings, convergences, etc.) create a mosaic of different physical habitat conditions that influence tuna vertical and horizontal migrations as tuna continually move into preferred habitats. Because individual tuna species display different habitat preferences and different physiological adaptations, they respond differently to oceanographic and climate changes (Fromentin and Fonteneau 2001). Within species, the habitats exploitable by tuna are also influenced by animal size, with larger adults often able to exploit a greater range of habitats than juveniles (Brill 1994). Oceanographic variability also impacts the biological and environmental conditions affecting larvae survival and the subsequent quantity of recruitment into juvenile and adult ages (Lehodey 2000; Rotschild 2000; Govoni 2005; Lehodey et al. 2006).

The tuna industry in the WCPO extends beyond the enterprise of fishing by Pacific Island nations. Economic wealth is generated through the sale of fishing licenses to foreign fleets, servicing of domestic and foreign vessels and land-based processing of tuna catch into value-added products for sale on global markets (e.g. canned tuna; loins/steaks, fish meal, fertiliser, omega 3 oils). As an example, in Papua New Guinea tuna represents approximately USD 1.5 billion annually in fish value and potentially over USD 4 billion annually in retail value. The industry annually generates about USD 8 million in salaries and wages from over 15,000 jobs and about USD 14 million in direct domestic commerce, and significantly more in indirect commerce. Changes in tuna distribution and abundance may lead to changes in fishery distribution and catch rates, which could have potential impacts on regional and national economies, food security and social implications for Pacific Island countries and territories.

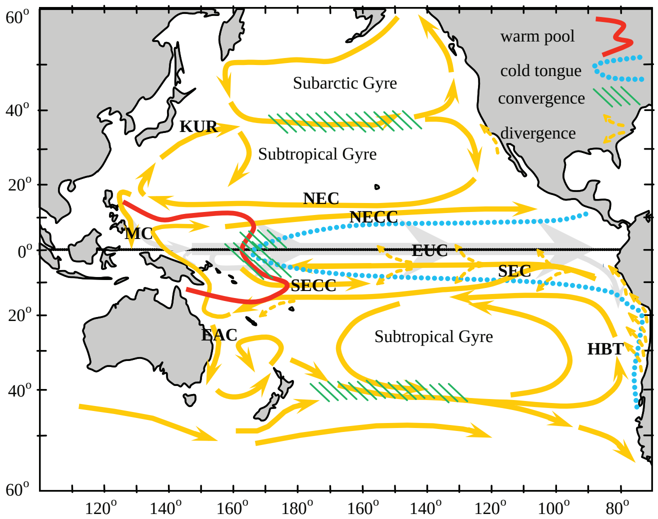

Figure 1. Direction of major currents in the Pacific Ocean. NEC – North Equatorial Current, SEC – South Equatorial Current, NECC – North Equatorial Counter Current, SECC – South Equatorial Counter Current, MC – Mindanao Current, EAC – East Australian Current, EUC – Equatorial Under Current, HBT Humboldt Current, KUR Kuroshio Current.

The following description presents an oceanographic characterisation of the Pacific Ocean and a review of the potential impacts of ocean-climate dynamics on tuna species and their fisheries. Included are inter-annual changes in regional oceanography that are related to natural climatic phenomena such as El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), and how tuna and fisheries are likely to respond to these periodic climatic episodes. We include discussion on the vulnerability of tuna species and fisheries to future climate scenarios. Comprehending available information on climate variability and change and its impacts on fisheries is important for fishermen, fishery managers and stakeholders. It is necessary for the development of tuna fishery management plans that guide government decision-making over the short term. It is also needed to build and adapt strategies that minimise the disruption that changes in tuna availability may have on national economies and the subsequent ability of Pacific Island countries to achieve their development aspirations.

Major currents in the Pacific Ocean

Surface water circulation in the Pacific Ocean is dominated by two large gyres centred at approximately 30°N and 30°S (**Figure 1**). Between these two gyres is the Pacific equatorial current system, which includes two westward-flowing currents, the North and the South Equatorial Currents (NEC and SEC) and two eastward-flowing counter-currents, the North and the South Equatorial Counter Currents (NECC and SECC). The NEC and SEC flow at approximately 15–20 cm/s across the Pacific Ocean under the influence of trade winds in each hemisphere. Along the Philippine coast, near the latitude 14°N, the NEC bifurcates, with one branch turning into the northward flowing Kuroshio Current (KUR) and the southward flowing Mindanao Current (MC). The KUR forms the western boundary of the north Pacific subtropical gyre and the MC feeds the NECC (Toole et al. 1990). Surface velocities of the MC are approximately 120 cm/s. Current speeds of the KUR can vary between 60 and 120 cm/s. The NECC flows between the NEC and SEC at 5–10°N, counter to the direction of the easterly trade winds. At depths of 100–250m part of the MC flows directly to the equator. The SECC is developed in the western Pacific typically at a latitude of 10°S, and divides the SEC into two branches. The sub-equatorial branch of the SEC is more variable in strength (~ 10 cm/s) and direction than the equatorial branch, which can reach up to 50 cm/s in the eastern Pacific. The equatorial branch of SEC dissipates at the eastern edge of the warm pool and weak eastwards currents are observed in the warm pool. The sub equatorial branch enters the Coral Sea south of Solomon Islands and divides into the southward flowing East Australian Current (EAC) and the northward flowing NQC (North Queensland Current). The EAC defines the western boundary of the South Pacific Subtropical Gyre. The NQC flows into the Hiri current entering the Solomon Sea and toward the equator through the Solomon and Vitiaz straits and eventually feeds the NECC. In the western Pacific the deepest parts of the equatorial and sub-equatorial SEC (100–250 m) as well as the deepest parts of the MC that flows to the equator converge to form the Equatorial Under Current (EUC). The EUC is a tube of eastward flowing current centred around 150–200 meters below the surface in the western Pacific and 30–75 meters in the eastern Pacific with velocity of 100 cm/sec. These currents are not constant over time; their strength typically changes seasonally. Currents also vary from year to year depending on climatic conditions and especially under the influence of El Niño Southern Oscillation (ENSO).

Major ocean surface currents are wind-driven and contribute to the transportation of heat, dissolved oxygen, salts, carbon dioxide and nutrients. Hence, large water masses often have differences regarding temperature, salinity, and oxygen. Ocean processes inducing movement of water masses such as upwelling are also particularly involved in phytoplankton production. Its growth rate is known as primary productivity and constitutes the amount of food and energy available to higher trophic levels. Areas of high productivity with high concentrations of planktonic organisms are usually found in strong upwelling regions which bring nutrient-enriched water from underlying cold layers to surface waters. Conversely, areas of downwelling are areas of low primary production. Consequently, areas of divergence or convergence of currents (**Figure 1**) are important because these result in downwelling and upwelling areas as well as smaller features (fronts, eddies, turbulence) that enhance local productivity and may create zones of forage availability that are attractive for tuna (Grandperrin 1978).

Thermal structure of the Pacific: the warm pool and cold tongue system

The eastern and central equatorial Pacific Ocean is characterised by cold nutrient-enriched waters rising to the surface via an upwelling process and forming a band with high primary production, commonly known as the 'cold tongue' (**Figure 2**). This upwelling area may support up to 30% of the world's primary production (Chavez and Barber 1987). In contrast, the western equatorial Pacific is characterised by low primary production and high sea surface temperatures (SST> 29° C). The surface equatorial layer west from 160°E (~0–200 m of depth) has the warmest surface temperatures in the world and is commonly known as the 'warm pool'. The eastern edge

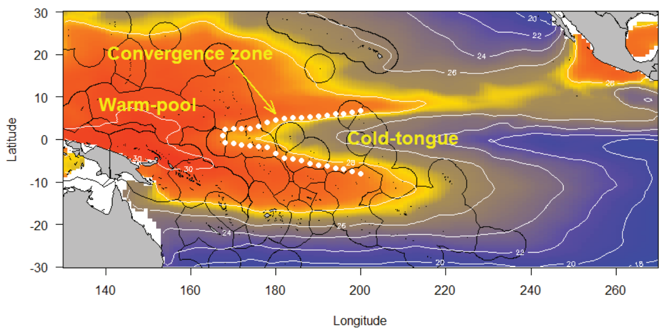

Figure 2. Mean sea surface temperature distribution in the Pacific Ocean in October 2007. The location of the warm pool, cold tongue and the convergence zone in the equatorial Pacific are highlighted. Temperature isotherms are separated by 2-degree intervals.

of the warm pool is identified by a salinity front (at about 34.8 psu) and the 28.5° C isotherm (**Figure 2**). The weakening of the SEC following the weakening of the trade winds as they enter the western Pacific, as well as the contrast between the high precipitation region in the warm pool and the dry eastern Pacific induce a convergence zone between the cold tongue and warm pool (**Figure 2**).

The intense atmospheric convection in the western Pacific and resulting weak trade winds mean rainfall greatly exceeds evaporation, which maintains the contrast between the fresh western Pacific waters and the high salinity waters in the east. The surface warm pool waters move seasonally to the north during boreal summer and to the south during austral summer following the course of the sun (**Figure 3**). At the equator, the seasonal variations of the warm pool are weak. Tuna migrations in the western central equatorial Pacific have been hypothesised to correlate with the position of the warm pool–cold tongue convergence zone (Lehodey et al. 1997). The eastern Pacific nutrient-rich zone supports high forage abundance, which concentrates in a band several hundred kilometres wide along the eastern edge of the warm-water pool. Tuna are likely to follow the movements of this convergence zone due to the high prey species concentrations (Lehodey 2001). Tuna fisheries, particularly purse-seine fisheries targeting skipjack, appear also to track the position of the warm pool–cold tongue convergence zone.

Oxygen distribution

The dissolved oxygen levels in surface waters of non-coastal areas are mainly determined by the rate at which oxygen is transferred from the atmosphere, which is dependent on temperature and surface mixing. Consequently, the oxygen distribution at the surface is not homogeneous throughout the Pacific. The richest areas of surface dissolved oxygen are found at higher latitudes, where the water is colder and oxygen is more soluble. In contrast, the equatorial and western areas of the Pacific (especially the warm pool) are regions with lower surface oxygen concentration, around 4.5 ml/L (**Figure 4**).

Dissolved oxygen concentration is also determined by phytoplankton production and the rate at which the oxygen rich surface waters are submerged via ocean currents and mixing. At high latitudes, some cold and dense surface waters rich in O_2 are pushed below the lighter and oxygen poorer subtropical area via a subduction process (mid-latitude

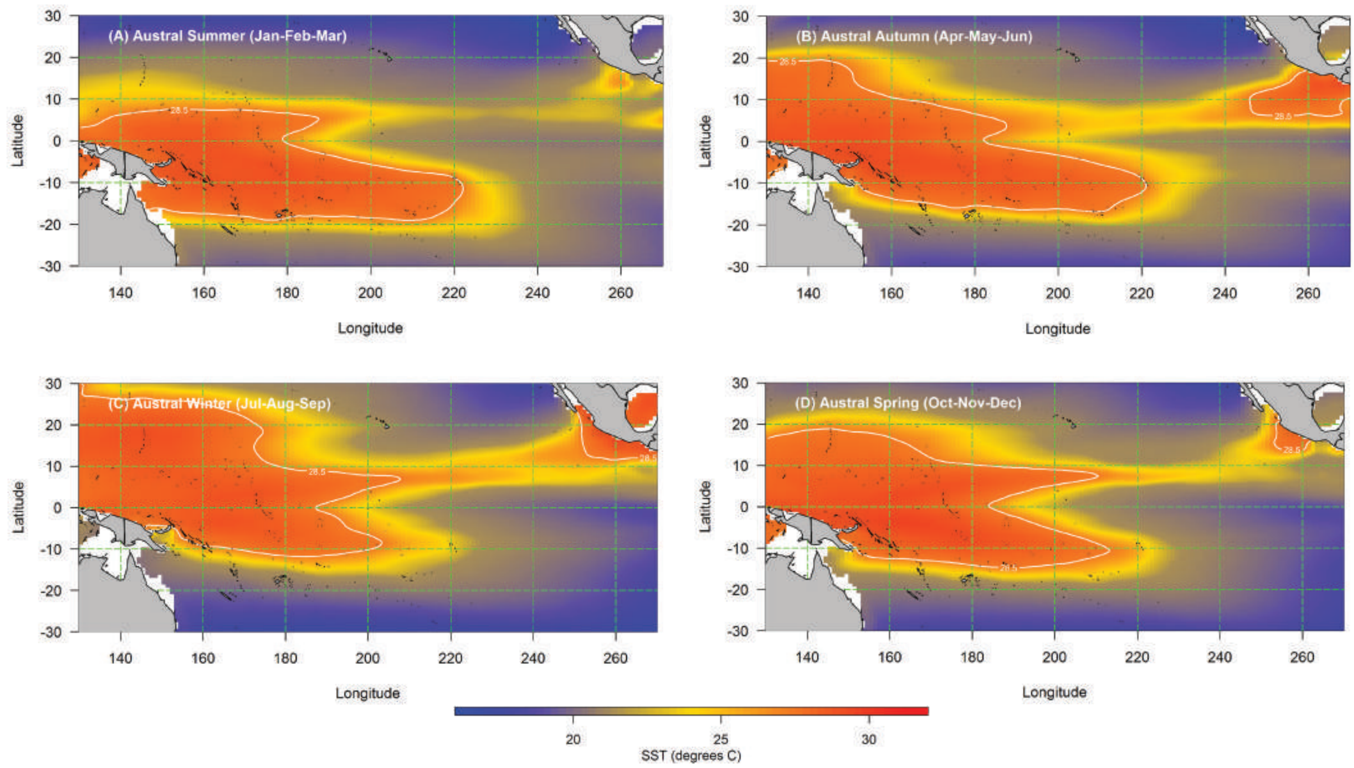

Figure 3. Seasonal variability of the warm pool–cold tongue system in the Pacific Ocean: a) austral summer, b) austral autumn, c) austral winter, d) austral spring. Data are averaged over the period 1990-2012 with El Niño and La Niña phases removed. The 28.5 ^{0}C temperature isotherm is highlighted to indicate the warm pool boundary. Source: SODA (http://www.atmos.umd.edu/~ocean/).

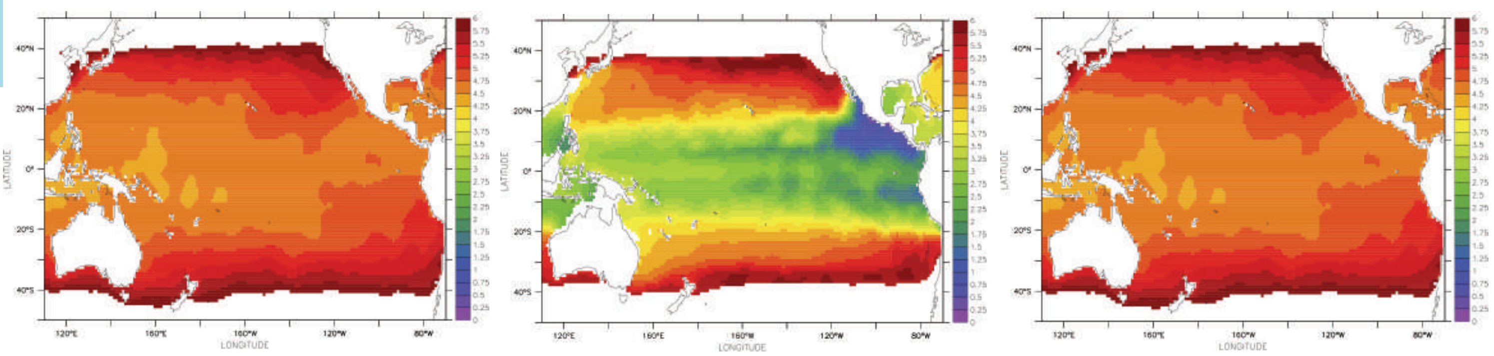

Figure 4. Annual distribution of dissolved oxygen (mg/l) in the Pacific Ocean at (left panel) surface; (middle panel) 16^0C thermocline; and (right panel) depth of the 16^0C thermocline meters. Source: http://iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94/.ANNUAL/.O2/ .

convection). These waters gradually lose O_2 as it is utilised in the remineralisation of organic matter by bacteria. Dissolved oxygen at any point in the water column is a balance between the original O_2 content, the effect of remineralisation of organic matter, and the rate at which water is replaced through ocean circulation. In regions of high remineralisation, consumption of O_2 can exceed replenishment from ocean circulation, causing part of the water column to become oxygen depleted, resulting in hypoxic to anoxic conditions. Areas of strong oxygen depletion usually occur in strong biological production areas. Figure 4 plots the concentration of dissolved oxygen at the surface and at the 16 ^{0}C thermocline. There is small variation in O_2 concentration across the surface layer of the Pacific Ocean, however at the 16 ^{0}C thermocline the higher productivity of the eastern Pacific is evident.

The performance of pelagic fishes, such as tuna, is related to the dissolved oxygen availability and the capacity of their respiratory and circulatory systems. Tuna cannot maintain their metabolic rate when oxygen decreases to 1 mg/l but the lower lethal level varies considerably among species (Brill 1994). As a result, dissolved O_2 distribution in the water column also influences the horizontal and vertical distribution of tuna because they require adequate levels of dissolved oxygen for their survival and growth.

Inter-annual variability

The ENSO phenomenon is a climatic process contributing to most of the strong interannual variability observed in ocean-atmosphere dynamics in the WCPO. The ENSO's strongest signature is measured between 10°N and 10°S in the ocean of the tropical Pacific but its climate consequence extend worldwide. ENSO is an irregular climatic oscillation of 3–7 years involving warm (El Niño) and cold (La Niña) phases evolving under the influence of the dynamic interaction between atmosphere and ocean (Philander 1990). ENSO phenomena induce major changes in wind regimes and current direction, influencing, in particular, the eastern extension of the warm pool (**Figure 5**). Under average conditions, the convergence zone of the warm pool oscillates weakly around 180° E, but very large displacements occur with ENSO signal changes. In addition, during normal conditions, a shallow thermocline is found (~15 to 50 m) in the eastern Pacific that deepens progressively towards the west (~150 m in the warm pool). During an El Niño event there is an eastward displacement of the warm water mass of the warm pool and the thermocline deepens in the central and eastern Pacific, while shallowing in the western Pacific (**Figure 5**). In some extreme cases, this results in the relocation of the convergence zone to the east by more than 50° of longitude. During La Niña, the warm pool is displaced westwards and is typically confined to the extreme west of the equatorial Pacific (Picaut et al. 1996), resulting in a deeper thermocline in this area (> 200 m). The dynamics of an El Niño and La Niña phase usually start in the western Pacific at the beginning of the year and peak in the central Pacific or in the eastern Pacific during the following austral summer, typically 9–15 months later.

Historically, there is considerable variability in the ENSO cycle from one decade to the next. The 1980s and 1990s featured a very active ENSO cycle, with 2 extreme El Niño episodes (1982/1983, and 1997/1998) and two strong La Niña episodes (1988/1989, 1998/1999). This period also featured two consecutive periods of El Niño conditions during 1991–1995 without an intervening La Niña episode. Since the beginning of the 2000s, three moderate El Niño episodes (2002/2003, 2006/2007 and 2009/2010) and two moderate La Niña episodes (2007/2008 and 2010/2011) have been recorded. How El Niño impacts the WCPO is not always consistent in latitudes outside of the 10^0 S–10^0 N equatorial zone. For example during the 1997–1998 El Niño, there were few climate impacts observed in the South Pacific in the higher latitudes (i.e. > 10° S) in comparison to the 1986–1987 El Niño. By contrast, both the 1986–1987 and 1997–1998 events had catastrophic impacts in the 10^0 S–10^0 N band.

Several indices are used to quantify the strength of ENSO events; among them, the Southern Oscillation Index (SOI) is defined as the difference between the standardized sea level pressure at Tahiti and Darwin. As convective masses are displaced to the east during El Niño events the atmospheric pressure decreases in the eastern Pacific and increases in the western Pacific (and vice versa during La Niña events). Hence SOI is negative during El Niño and positive during La Niña. Prolonged periods (usually more than 3 months) of increasingly negative SOI values define El Niño episodes whereas prolonged periods of positive SOI values coincide with La Niña episodes. Another commonly used method is based on the NINO 3.4 Index, which is the departure in monthly SST from its long-term mean averaged over the NINO 3.4 region (5°N–5°S, 120°–170°W) as shown in **Figure 6**. By contrast with the SOI, that index is positive during El Niño events (temperatures are warmer than usual in the central Pacific) and negative during La Niña events. Regular monitoring and short-term predictions of ENSO signal are available from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/enso/index.shtml) and a climate forecast discussion of world model predictions is available on http://www.pmel.noaa.gov.

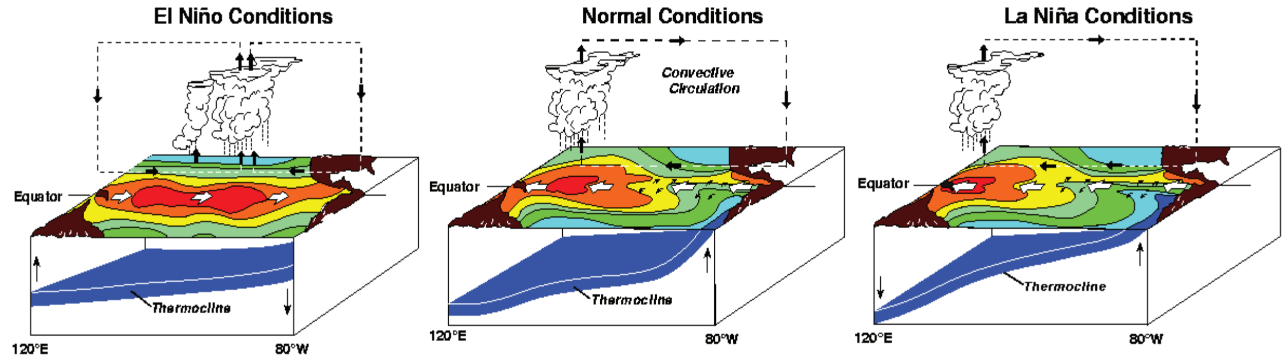

Figure 5. Interaction ocean/atmosphere in the equatorial Pacific and variability in trade winds, warm pool, convection and thermocline depth under the different ENSO climatic conditions. Source: http://www.pmel.noaa.gov/tao/elnino/nino-home.html.

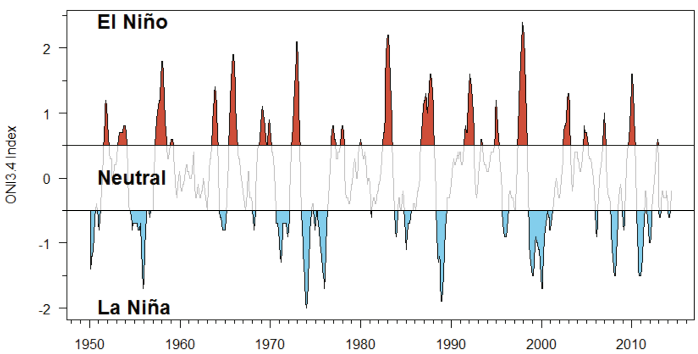

Figure 6. Evolution of Niño 3.4 Index from 1950 to 2014, corresponding to the 3 months running mean SST anomalies from Niño 3.4 region. Above 0.5 values correspond to El Niño periods, while below -0.5 correspond to La Niña periods. Source: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears_1971-2000_climo.shtml.

El Niño events affect tuna habitat and their distribution in the Pacific Ocean. For example, the longitudinal distribution of the catch of skipjack tuna in the equatorial Pacific has been associated with ENSO events (Lehodey et al. 2011). The spatial extension of skipjack preferred habitat toward the east during El Niño results in higher fishing effort in the central Pacific as the warm pool-cold tongue convergence zone moves eastwards (**Figure 7**). However, El Niño eastward development produces a shallowing of the thermocline in the warm pool and stronger wind stresses than usual in the western Pacific, eventually leading to an increase of primary production in the western equatorial Pacific (due to mixing of the water and increasing upwelling events). Tuna habitat in the western Pacific improves with this addition of primary productivity and this may explain the increasing catches in western countries (Solomon Islands or PNG) during the later part of an El Niño event (Lehodey 2001). In contrast, during La Niña events, a chlorophyll-rich cold tongue extends as far west as 160°E and the skipjack habitat retracts; consequently fishing effort decreases in the central Pacific (**Figure 7**).

Changes in the thermocline depth in the warm pool due to ENSO events also potentially affect catchability. The habitat of adult bigeye and yellowfin includes the thermocline and deeper layers. In the western Pacific, El Niño produces the shallowing of their preferred thermal and feeding habitats (Lehodey 2004). The opposite effect happens during La Niña periods, with a deepening of the thermocline which extends the yellowfin and bigeye tuna vertical habitat. Hence the optimal fishing depths for longline fisheries which target adult bigeye and yellowfin may be squeezed during El Niño and expanded during La Niña. For South Pacific albacore, higher catch rates are recorded from the southern subtropical areas of the Pacific Ocean six months before, or at the onset of El Nino episodes (Lu et al. 1998). This pattern could be linked to the shallowing of the mixed layer depth in the equatorial waters, and a reduction in extent of the 18° to 25°C isotherms in the water column, which are the preferred temperature range of adult albacore. Impacts on catchability for skipjack appear less likely. Skipjack inhabits the epipelagic layer (0–100 m depth) and consequently changes in thermocline depth produced by ENSO events are probably negligible for this species.

In addition to impacts to tuna migration and local availability, ENSO-related variability also affects recruitment and therefore total abundances of tuna populations. Previous studies based on predictions from the statistical population dynamics model Multifan-CL (Fournier et al. 1998) suggests a potential link between tuna recruitment and climatic fluctuations and indicate that tuna species respond in a different way during ENSO events. Results from the model SEAPODYM (Lehodey et al. 2008; Langley et al. 2009) suggested increasing skipjack and yellowfin recruitment in the central and the western Pacific during El Niño events that might be a result of four mechanisms:

1. The extension of warm surface waters (26°–30°C) further east, resulting in favourable conditions for spawning of these two species;
2. Enhanced food for tuna larvae due to higher primary production in the west;
3. Lower predation of tuna larvae; and
4. Larvae retention in these favourable areas as a result of ocean currents.

The situation is reversed during La Niña events, when westward movement of cold waters reduces spawning success of yellowfin and skipjack in the central Pacific. During La Niña events the bulk of recruitment is centred in the warm waters of the western equatorial Pacific. A study also shows that the extent of the warm pool might be a good indicator for monitoring the effect of environmental variability on yellowfin recruitment (Kirby et al. 2007). The extension of the warm waters in the central Pacific during El Niño events that extends the tropical tuna spawning grounds may conversely reduce those of albacore (Lehodey et al. 2003).

On larger time scales, variations in the strength of the mid-latitude westerly winds produce climate 'regime shifts', like those recorded in 1925, 1947, 1976–1977, 1989 and possibly 1997–1998 in the Pacific ocean, that had a major impact on the ecosystem and fisheries (Beamish et al. 1999; Hare and Mantua 2000; Peterson and Schwing 2003; Polovina 2005; Chavez et al. 2003). Regime shifts are characterised by abrupt

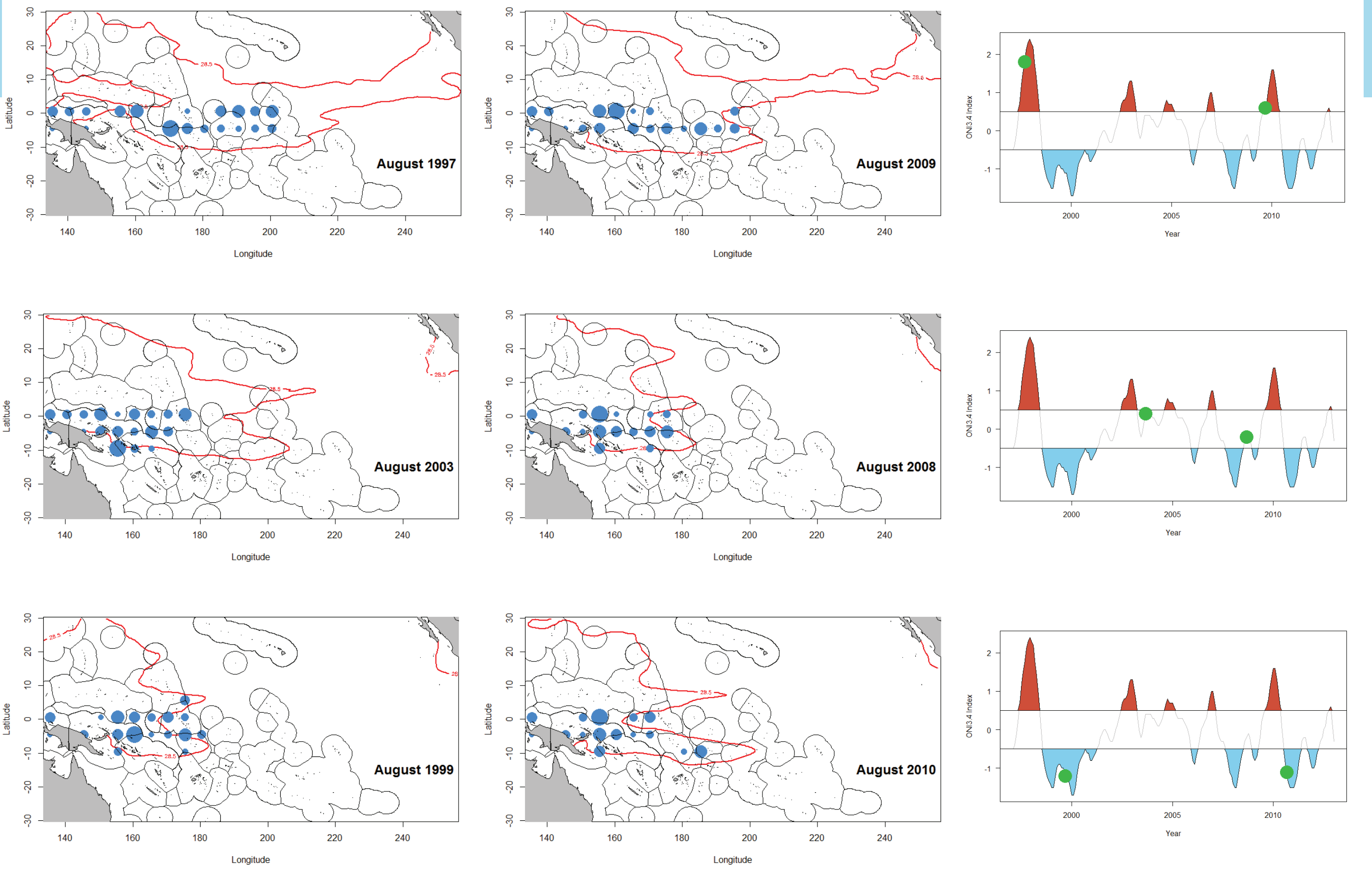

Figure 7. Examples of the distribution purse-seine effort during El Niño, neutral and La Niña phases of ENSO. Blue circles are the square root of the number of fishing days by 5 degree longitude and latitude. The 28.5°C SST isotherm as an indicator of the warm-pool boundary is represented in red. The upper plots are fishing efforts for August 1997 and August 2009 (El Niño phases), the middle plots are fishing efforts for August 2003 and August 2008 (neutral phases) and the lower plots are fishing efforts for August 1999 and August 2010 (La Niña phases). The plots on the extreme right indicate the strength of the ENSO phase (green circles). Source: WCPFC public domain fishing data, http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears_1971-2000_climo.shtml.

ENSO-like changes that can last for several decades, commonly associated with the Interdecadal Pacific Oscillation (IPO) or closely related Pacific Decadal Oscillation (PDO). The PDO may be dependent upon ENSO as it has been hypothesised that this signal is a residual of successive El Niño and La Niña events (Newman et al. 2003). Its signal is greatest in the North Pacific. It has only a weak signal in the western tropical Pacific, but is also strong in the subtropical South Pacific and in the central and eastern Pacific (Mantua and Hare 2002). It has been hypothesised that the dominance of either El Niño or La Niña events during multi-year periods, possibly in correlation with the Pacific Decadal Oscillation (PDO), could lead to regimes of high and low productivity in the tuna population (Lehodey et al. 2003; Kirby et al. 2004; Lehodey et al. 2006). However, particular strong shifts in the environment were not always detected in tuna recruitment time series (Briand and Kirby 2006), which implies that the relationship between tuna recruitment and climatic oscillations is not linear and might depend on several interrelated factors including the adaptation of spawners to environmental variability.

Potential climate change effects on tuna stocks and fisheries

Recent modelling simulations suggest that the increasing greenhouse gas effects on ocean dynamics could also affect the future distribution and abundance of the four main tuna species in response to changes in water temperature, dissolved oxygen, ocean currents and ocean acidification as well as indirect changes in food web structure (Lehodey et al. 2010; Lehodey et al. 2011; Bromhead et al. 2014). The analysis is based on the 'Institut Pierre Simon Laplace' coupled climate model (IPSL-CM4) and the multi-model means from the Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset. These state-of-the-art simulations formed the basis of the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (AR4) (Solomon et al. 2007). IPCC-AR4 often presents a multi-model average across a large number of relatively independent climate projections to account for the intermodal variability. This averaging tends to remove opposing biases in the models and is considered a suitable method for obtaining useful output, though it can also remove climate extremes that may be real. While there is uncertainty about the effect of climate change on tuna fisheries, considerable research is underway, and a number of observations and hypotheses have been proposed.

Climate effects on future temperature and oxygen

Increases in average sea temperatures have been observed around the globe. SST is estimated to have increased by 0.67°C from 1901 to 2005, especially in the warm pool area (Bindoff et al. 2007; Cravatte et al. 2009). In addition, simulations from IPSL-CM4 suggest that in the tropical Pacific, SST is projected to increase by 1.5 to 6°C under the worst (IPCC-A2) scenario by 2100. At a depth of 80 m, water temperature is expected to rise by 0.5°C in 2035 and by 1.5°C in 2100 (Ganachaud et al. 2011). SST in the central and east equatorial Pacific are expected to warm more than those in the west. The size of the warm pool is also projected to increase by 250% in 2035 and by 770% in 2100 under the worst scenario (Ganachaud et al. 2011), although there is considerable uncertainty on how the dynamics of the warm pool will change (Brown et al. 2014). Because O_2 concentration in water depends on temperature, these models also projected a minor O_2 decrease by 2100 in surface waters, due to the reduced solubility of O_2 in warmer water. In subsurface waters, the increased temperature and stratification of the ocean at higher latitudes are expected to lead to a decrease in O_2 transfer from the atmosphere to the ocean due to less ventilation and advection, resulting in lower O_2 concentrations in the tropical thermocline (Ganachaud et al. 2011). There are also considerable uncertainties on the regional patterns of predicted O_2 changes.

Climate effects on future current and circulation patterns

SST increases affect the atmospheric pressure patterns, which are responsible for wind generation. It has been hypothesised that changes in wind might modify not only weather conditions, but also the strength and direction of major surface currents. Recent observations indicate that the South Pacific gyre has increased in strength due to a southward intensification of extratropical winds (Roemmich et al. 2007). This has altered the complex current system of the southwest Pacific and changed the structure of water temperature in the region. Simulations suggest the currents of the upper water column across most of the tropical Pacific Ocean are expected to decrease in the future, particularly as a result of weakened wind regimes at low latitudes and strengthened winds in the subtropical Southern Hemisphere (Ganachaud et al. 2011). The transport of water from the SEC at the equator is expected to decrease by 10–20% in 2100. Greater changes are predicted for the SECC, for which velocity would decline by 30–60%. Consequently, eddies and upwellings associated with the SEC and SECC are also expected to decrease due to weakening tropical circulation. Shallowing of the maximum mixed layer depth by up to 20 m is also expected in the tropical Pacific (Ganachaud et al. 2011).

Changes in circulation may also alter the timing, location, and extent of the upwelling processes upon which most oceanic primary productivity is reliant. Long-term simulations from six climate models tend to suggest a weakening of primary production in the tropics although with considerable differences in patterns and amplitude among models (Henson et al. 2013). Using one climate model (IPSL-CM4, Leborgne et al. 2011) and a detailed regional study, a 9% phytoplankton decrease is projected in the warm pool, with a 20% to 33% decrease in the archipelagic deep basins in the southwestern areas. Zooplankton is projected to decrease in these regions and nutrients will also decrease in the equatorial cold tongue. The implication is that a decline in the upwelling system in the central and eastern equatorial Pacific may lead to reduced regional productivity. This productivity currently moves with currents to the western equatorial Pacific and is a critical feature upon which tuna stocks depend. Note that modelling biological production is a major challenge because models need to integrate the projected changes in the physical and chemical features of the ocean. Globally, the upwelling in the Pacific Equatorial Divergence Province is very poorly simulated by most IPCC models over the past 50 years, so the predictions remain uncertain (Ganachaud et al. 2011). Most recently, Matear et al. (2014) constructed a higher resolution model and forecasted climate conditions in the WCPO until 2060. They noted that with the increase in model resolution and consequent ability to capture finer scale processes they did not observe significant changes in primary productivity in the warm pool.

Climate effects on future tuna distributions and fisheries

The projected warming of the tropical Pacific Ocean may have two primary effects on the spatial distributions of the four tuna species. The first involves potential changes in spawning location, timing and recruitment success. This effect will mainly depend on the phenological adaptation of each species, but the early life stages of each tuna species are expected to be more sensitive and vulnerable than adults to changes in SST and O_2 (Lehodey et al. 2011; Bromhead et al. 2014). The second potential impact relates to changes in the distribution of the fish outside the spawning season. Increased stratification of the water column may alter the vertical distribution of tuna and affect their access to deep-forage organisms. Temperature and O_2 changes in subsurface waters are expected to have less impact on skipjack, which inhabit the surface layer. In contrast, such changes are expected to have a greater impact on species swimming between the surface and subsurface (yellowfin and albacore), and to deeper layers (bigeye tuna). Bigeye tuna might be less affected due to their higher tolerance for low O_2 levels unless anoxic conditions or 'dead zones' (O_2 concentration < 1 ml/l) develop.

The expected changes in vertical and horizontal tuna distribution are likely to have consequences for fishing operations. The location of prime fishing grounds may change, and the catchability of tuna by surface and longline fisheries might be altered in ways similar to those observed during ENSO events. In particular, fishing grounds might be displaced further eastward along the equator, or shift to higher latitudes (Bell et al. 2013; Lehodey et al. 2012; Lehodey et al. 2013). Regardless of where fishing is concentrated, increased stratification could enhance catch rates of the surface-dwelling skipjack and yellowfin tuna where SST remains within their preferred ranges. Similarly, changes in O_2 would constrain yellowfin to the surface layer, leading them to be more vulnerable to capture by the surface fishery (Lehodey et al. 2011). Simulations on the future distribution of the south Pacific stock of albacore were highly dependent upon changes in O_2 with the core range moving eastwards and to higher latitudes if projected decreases in O_2 in the equatorial region occur (Lehodey et al. 2014).

Tuna are affected by the water stratification resulting from ocean circulation. The effects of changes in circulation in combination with warmer water temperatures are expected to affect the habitat and the catch of some tuna species. For example, shallowing of the thermocline in the west (like during El Niño events) implies higher yellowfin catch rates by the surface fishery in the warm pool because of the vertical habitat contraction for this species (Lehodey 2000). Tuna spawning areas are also projected to change with the decreasing trends in major currents that decrease the formation of eddies and increase the stability of water masses. Spawning tuna are expected to avoid areas where temperatures are too high to prevent overheating problems and spawning areas are expected to expand to eastern areas and higher latitudes (Lehodey et al. 2011). The spawning areas would differ among tuna species because bigeye and albacore spawn where SST is greater than 24–25°C, whereas skipjack prefer temperatures greater than 28–29°C.

The projected changes in productivity could also have a potential impact on tuna spawning. Spawning areas might shift to the eastern equatorial region where primary productivity is projected to remain relatively high, bringing food supply for larvae; therefore changes in productivity might have some direct effects on the abundance/distribution of larvae and juveniles and recruitment success (Lehodey et al. 2011). Tuna populations would also appear to be affected by changes in the micronekton productivity they feed upon. Decreases in micronekton forage would likely increase natural mortality of tuna and lower their overall production in the region. Potential changes in tuna distribution are expected because these species tend to follow productive areas. It has been suggested that the eastward shift of the convergence area might lead to a decrease of the tuna population in the warm pool where primary productivity is relatively low (Lehodey et al. 2011). In addition, increasing rainfall might increase the supply of nutrients in archipelagic PNG waters and develop potential feeding areas. Where there are no physiological constraints, the highly mobile nature of tuna is expected to assist them in the adaptation to changes in the micronekton prey availability by moving to new favourable foraging grounds (Lehodey et al. 2011).

Relationships between tuna and their environment, combined with their life cycle, can lead to a complex interaction, including feedback loops and non-linear effects. However, this complexity can be modelled by the dynamic model SEAPODYM (Lehodey et al. 2008; Senina et al. 2008) that simultaneously evaluates interactions between environmental changes, biological function and spatial dynamics of tuna populations. Preliminary simulations of global warming on albacore (Lehodey et al. 2014), skipjack (Lehodey et al. 2012) and bigeye (Lehodey et al. 2010; 2013) tuna have been carried out with this model. Preliminary results suggest a declining abundance and a shift in the populations towards the eastern Pacific due to the weakening of the equatorial upwelling and equatorial current systems predicted by the IPSL model. In addition, El Niño-like conditions are hypothesised to become more frequent under some climate change scenarios (Timmermann et al. 1999; Timmermann et al. 2004), and an eastward shift in the purse-seine fisheries in the WCPO can also be expected under these conditions (Lehodey et al. 1997; **Figure 7**).

Climate change presents important challenges and implications for tuna fisheries. Fishing fleets should be able to adapt to changes in the spatial distribution and abundance of tuna stocks. Domestic fleets that do not have agreements to fish beyond national boundaries may, however, be more vulnerable to fluctuations in tuna biomass within their EEZ. For the longer term sustainability of these fleets it may be necessary to develop access agreements or capacity to fish in areas outside their current national boundaries. Land-based processing facilities are likely to be the most vulnerable to changes in tuna distribution. These facilities provide significant local employment and indirect commerce to Pacific Island countries and territories (e.g. Papua New Guinea, Solomon Islands, Marshall Islands, Fiji, American Samoa). Greater variability in the supply of tuna to these plants may have consequences for employment security and other development issues such as gender and youth (e.g. lack of employment opportunities or irregular employment may disadvantage women and youth). Developing strategies to ensure supply of tuna or encouraging industry diversification will need to be considered to 'climate proof' this aspect of the industry.

Fisheries policy will need to implement actions that minimise the impacts of environmental change on the sustainability of the industry without compromising short- and long-term development opportunities. Large scale changes to the tuna industry will incur costs. When and how future climate will alter tuna distributions and abundances however is highly uncertain. To implement appropriate and timely climate adaptations it is essential to identify early signs of change to avoid premature or unnecessary implementation of adaptations. Ongoing research has identified organisms in lower trophic levels than tuna that act as effective early warning indicators of environmental change due to their sensitivity to changes in water chemistry. As these organisms are the prey of tuna, analysing the composition of tuna stomachs has proven to be a very effective method for monitoring these lower trophic levels. This is potentially a very cheap and effective approach for government and industry to implement 'an early warning system' for climate effects as tuna stomachs are a by-product of tuna catch. Only analyses of the stomachs and modelling of the data is required.

Climate considerations for regional food security

Pacific Island countries and territories have the highest rates of diabetes and obesity on record, driven by changes in lifestyle and increasing imports of inexpensive, nutritionally-poor, energy dense food. Health agencies are promoting high rates of fish consumption to help combat the chronic non-communicable disease problems, but rapid population growth is reducing the per capita availability of coastal fish resources needed for good nutrition. Allocating more of the region's tuna resources to local food security, and facilitating access to tuna in rural and urban areas at low cost, have been prioritised as key activities to resolve this issue. Without such action, increases in the economic benefits derived from tuna fisheries may be lost to increasing health costs.

Integrating the analyses of present-day human population levels and those projected for 2020 and 2035 with the area of coral reef (as a proxy for reef fish production) in each Pacific Island country indicates that 16 of the 22 countries and territories will either increasingly fail to produce enough reef fish to meet their basic or traditional needs for fish, or have trouble distributing the fish from remote reefs to urban centres. The problem is particularly significant in Melanesia, where the great proportion of the region's people live.

To provide the fish recommended for good nutrition, or to maintain traditionally higher levels of fish consumption, tuna will need to provide 12% of the fish required by all Pacific Island countries by 2020, increasing to 25% by 2035 (Bell et al. 2011). In relative terms, the percentages of the region's tuna catch needed in 2020 and 2035 to fill the gap in domestic fish supply are small – 2.3% and 6.2% of the average present-day industrial tuna catch, respectively (Bell et al. 2011). The greatest quantities of tuna will be required in Papua New Guinea, Solomon Islands and Kiribati (Bell et al. 2011). In addition to promoting small scale artisanal tuna fisheries to supply tuna for this purpose, it will be necessary to continue to utilise small tuna and by-catch caught by industrial purse-seine fisheries. Access to this resource most effectively occurs when purse-seine vessels unload their catch to carrier vessels, which then transfer the fish to land based processing plants. The ports where this unloading occurs are typically where the greatest demand for tuna for food security occurs. If tuna distributions follow the predicted eastward expansion in core range in response to future climate scenarios, access to this resource for Kiribati may become more stable. Conversely, for western Pacific countries such as Solomon Islands and Papua New Guinea it may become more variable. Importantly, all current forecasts of tuna resources for the Pacific in association with future climate scenarios predict a decline in the total biomass of tuna. How viable offloading small tuna will be under a reduced tuna biomass scenario versus processing these size classes and returning the product as canned tuna to Pacific countries is yet to be determined.

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