## General oceanography of the WCPO

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### Introduction

Oceanographic variables (e.g. water temperatures, currents, productivity, etc) and climate dynamics have major influences on population dynamics of pelagic fishes and fisheries (Lehodey *et al.*, 2006). Ocean-climate systems have been shown to strongly influence tuna fisheries in the Western and Central Pacific Ocean (WCPO) at various spatio-temporal scales and in different ways (Bour *et al.*, 1981, Lehodey *et al.* 2003, Lehodey *et al.*, 2006). Changes in oceanography influence vertical and horizontal movements of tunas and other species, larval survival and recruitment strength, with individual tuna species having different preferences (e.g. preferred temperature) and responding differently to changes in oceanography and climate (Fromentin and Fonteneau, 2001). While beyond the control of fishery managers, it is important to take into account the influence of oceanography and climate in order to better manage and sustainably exploit fisheries. This chapter presents an overview of the oceanographic context of the WCPO at both regional and domestic scales and highlights the impacts of ocean-climate dynamics on tuna species and fisheries.

I- Global wind circulation and majors currents in the WCPO

The western Pacific is subject to seasonal monsoons (rain-bearing winds), associated with the heating of the Asian and Australian land-masses in summer and cooling in winter. The principal effects of monsoon winds are to reduce the general trade winds regime along the equator and to introduce a strong seasonality over the region: South East Trade winds are strengthened at the equator and in the southern hemisphere in the austral winter (May-November) and reduced, or even replaced by North West Monsoon winds in austral summer (December-March). The monsoon also has an impact on the distribution and intensity of the atmospheric convergence zones which control rainfall.

Ocean currents in the WCPO are driven mainly by the action of the trade winds and north-west monsoon winds (Figure 1). The main current systems of the Pacific Ocean include two westward-flowing currents (North and South Equatorial currents, NEC and SEC) and two eastward-flowing counter-currents (North and South Equatorial Counter Currents, NECC and SECC). The NEC and SEC flow across the entire Pacific Ocean under the influence of trade winds in each hemisphere. Along the Philippine coast, the NEC bifurcates near latitude 14°N with one branch turning into the northward flowing Kuroshio Current (KR), which becomes the western boundary of the north Pacific subtropical gyre, and the southward flowing Mindanao Current (MC), which feeds the NECC (Toole *et al.*, 1990).

The NECC flows between the NEC and SEC at 5–10°N, counter to the direction of the easterly trade winds. The SECC is only well 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 and direction than the equatorial branch. The equatorial branch enters the Coral Sea south of the Solomon Islands and becomes the East Australian Current (EAC), which defines the western boundary of the south Pacific subtropical gyre.

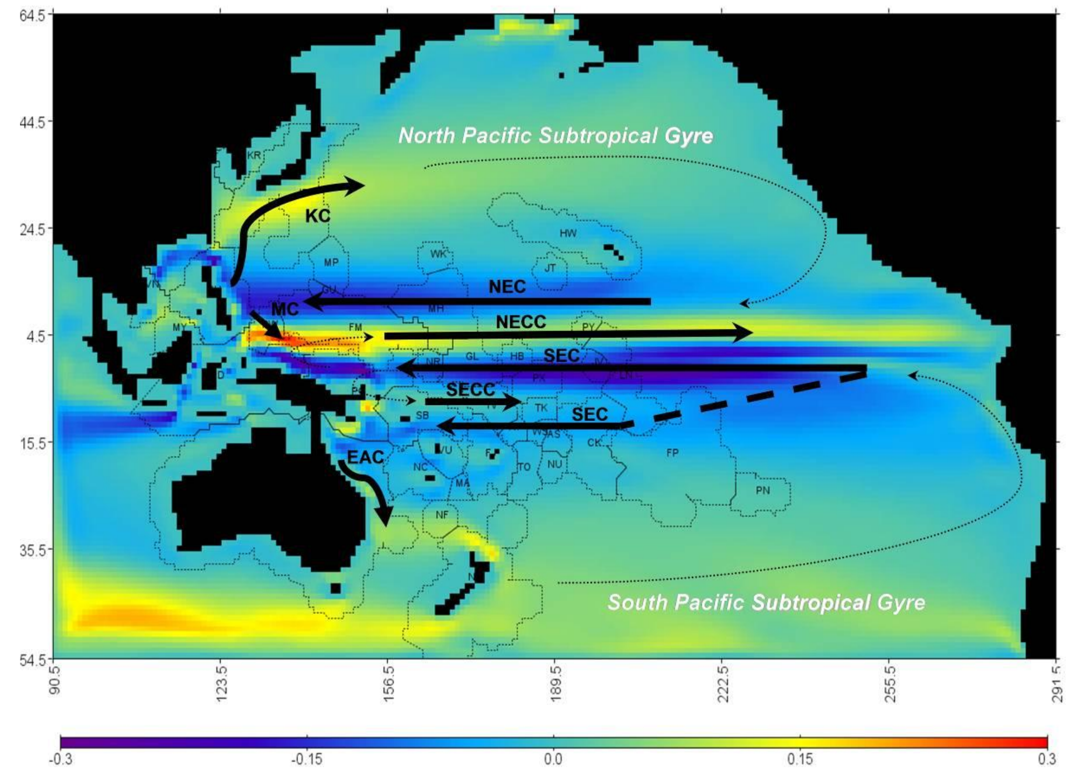


**Figure 1. Surface water circulation velocity (colour scale) and direction (arrows) highlighting the major currents of the Pacific Ocean. The location of Exclusive Economic Zones are also provided.**

Major shifts in regional currents occur with the changes between the South East Trade Wind and North West Monsoon seasons (see Appendix 1A). During the South East Trades (austral winter), the major subsurface flows into the region are the SEC moving from east to west. The SEC is usually strongest during the third and fourth quarter of each year, however it sometimes reverses early in the austral winter (Yu and McPhaden, 1999). During the North West Monsoon (austral summer), the NECC moves to its southernmost position (around 0°) and encounters the SEC flux in the western area near the equator. The intrusion of the NECC causes a reversal in the sub-surface current along the north coast of Papua New Guinea. The other major change in subsurface currents during the North West Monsoon is the intensification of both the eastward flowing SECC (which reaches a maximum during March–April) and the southward flowing EAC.

In the northern hemisphere, the monsoonal winds along the low-latitude western Pacific induce a large northward extension of the NEC's bifurcation in early austral winter. The KC has a seasonal minimum transport at this period when the NEC bifurcates at its northernmost latitude (Qiu and Lukas, 1996). KC and MC have inverse phases in the seasonal variation.

Understanding patterns in wind-driven surface currents is of major importance in understanding the distribution, abundance and movements of highly migratory fishes including tunas. Areas where currents converge or diverge (fronts) tend to have concentrations of prey species for large pelagic fishes. In addition, divergence of currents brings nutrient-enriched water from underlying cold layers to surface waters. This creates local areas of high productivity with high concentrations of planktonic organisms. Under the influence of convergent currents, the organisms from the divergence zone remain aggregated in large zonal bands usually associated with a thermal front. These features create zones of high food availability in otherwise low productivity tropical oceans (Grandperrin, 1978). Therefore, seasonal and annual variations in current patterns and the associated variation in location and timing occurrence of upwellings, convergences and divergences, have a major effect plankton communities and therefore tuna distributions.

In the equatorial Pacific, it has been shown that the highest purse-seine catches per unit of fishing effort (CPUE) of skipjack were strongly related to the position of convergence zones, especially where the westward advection of cold saline water (i.e. the SEC) from the eastern Pacific encounters the eastward advection of warm, low salinity water from the western Pacific (Lehodey *et al.*, 1997). This oceanographic feature is also known as the cold tongue-warm pool pelagic system (see part II).

A recent study in the American Samoa EEZ has shown that seasonal and interannual variability in eddy activity (circular movement of water associated with a current),induced by the interaction between the SECC and the SEC, seems to play an important role in regulating albacore availability and therefore longline catch rates (Domokos *et al.*, in press). Similarly, other studies on other domestic longline fisheries in sub-equatorial EEZs of the WCPO have also highlighted the importance of spatio-temporal variability in current direction and strength and the influence on albacore catch rates (Langley, 2004; Briand, 2005).

II- The cold tongue-warm pool system

In the eastern and central Pacific Ocean, an upwelling extends westward along the equator from the coast of South America. The water mass is characterised by cold nutrient-enriched waters that rise to the surface in the EPO. This results in the formation of a large zonal band in which there is high primary production. This band is commonly referred to as the “cold tongue” (Figure 2). In contrast, the western equatorial Pacific is characterised by low primary production and high (greater than 29° C) sea surface temperatures (SST). The surface equatorial layer west from 160°E has the warmest surface temperatures of any ocean in the World. In addition, the seasonal variation of SSTs in this region is less than 1°C. The intermittent eastward surface current in the western Pacific generated by wind bursts encounters the westward advection of the equatorial circulation and induces a convergence zone on the eastern edge of the warm pool, identified by a salinity front and the 29 °C isotherm (see Figure 2).

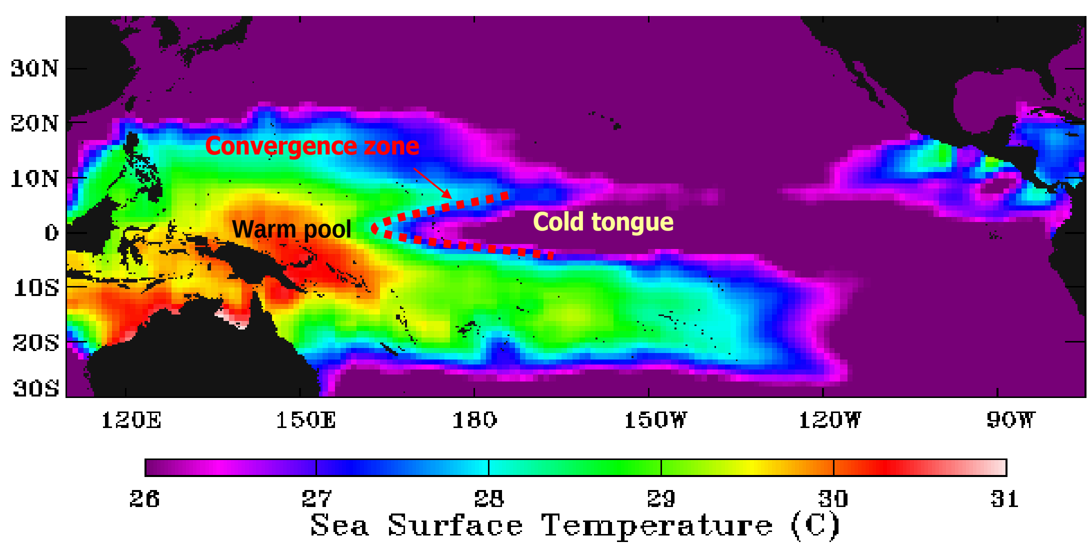


**Figure 2. Sea surface temperatures and location of the warm pool–cold tongue system and the convergence zone in the equatorial Pacific.**

The maintenance of high SSTs in the "warm pool" area (figure 2) is due to several processes. Initially, intense atmospheric convection in the western Pacific associated with weak trade winds results in rainfall greatly exceeding evaporation. Consequently, the balance between precipitation and subsurface water of higher salinities (and densities) results in haline stratification, producing the 'barrier layer' lying between the bottom of the mixed layer and the top of the thermocline (depth at which the rate of decrease of temperature with increase of depth is the largest) (Figure 3).

One of the effects of this haline stratification is to prevent the vertical mixing of nutrients from deep, cooler waters to the surface, maintaining warm SSTs in the region. The low surface saline waters from the warm pool move seasonally eastwards under the influence of westerly winds (Figure 4).

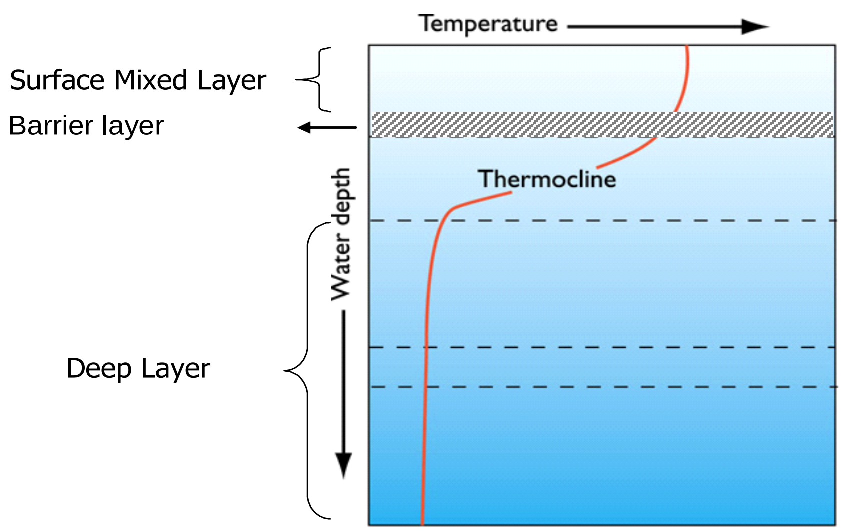


**Figure 3 Vertical profile showing the thermal structure of the water column and the position of the different layers**

The largest proportion of the tuna catch (mainly skipjack) in the Pacific Ocean is taken within the warm pool area. This area produces almost 80% of the tuna caught by purse-seine and other surface gears, while catches of deep water tuna by longline is more widely distributed over the tropical and sub-equatorial areas of the western Pacific Ocean. Surface tuna fisheries, particularly purse-seine fisheries targeting skipjack, appear to respond to the seasonality of the warm pool (Figure 4). Large scale movements of tropical tuna in the western central equatorial Pacific have been correlated with the position of the oceanic convergence zone, produced where the warm pool meets the cold tongue (Lehodey *et al.*, 1997). This nutrient-rich zone supports high concentrations of secondary productivity (small fishes) in a band several hundred kilometres wide along the eastern edge of the warm-water pool. Tuna are likely to seasonally follow this convergence zone to remain in waters with relatively high concentrations of prey species(Lehodey, 2001) in conditions suitable for reproduction.

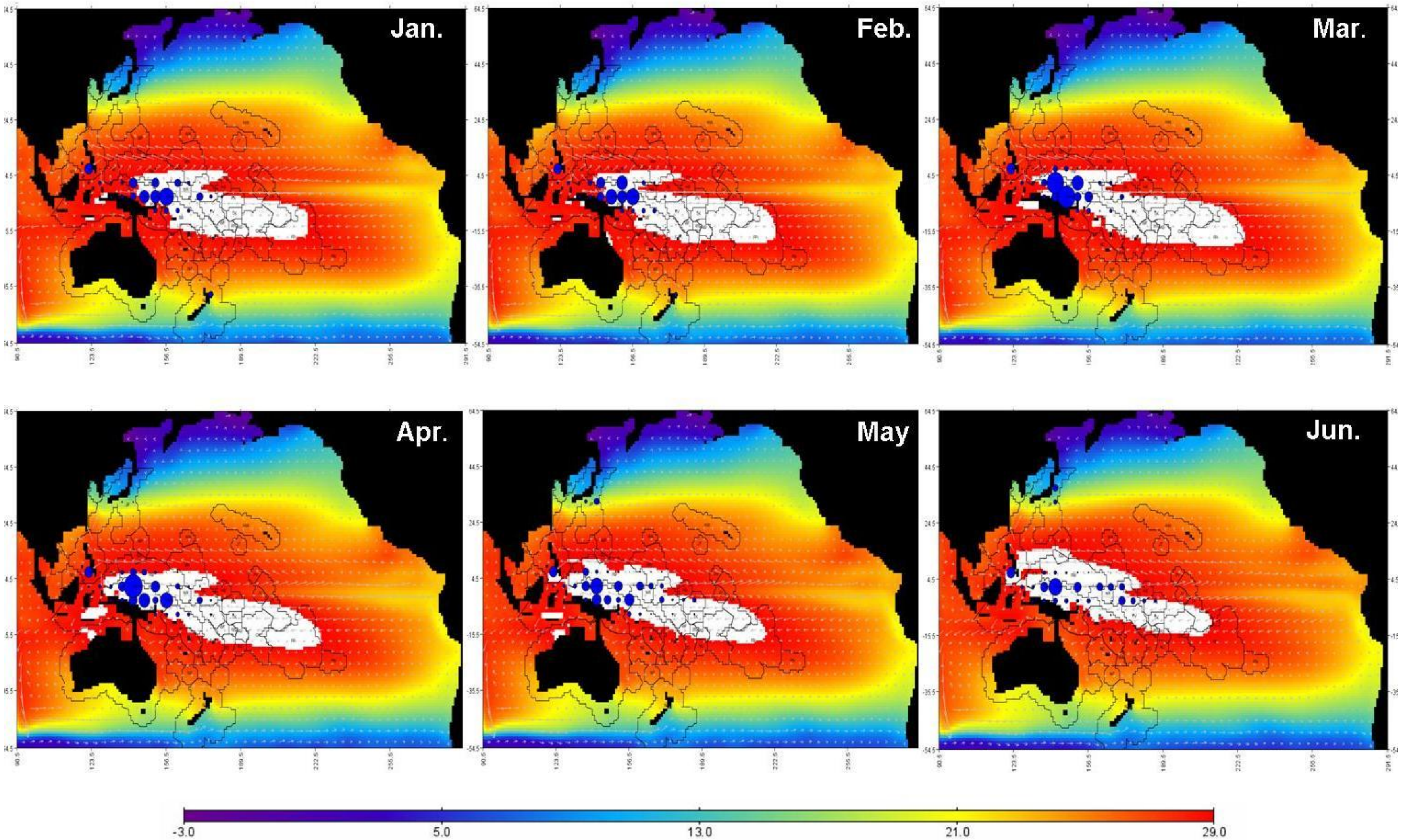


**Figure 4A. Seasonal evolution of the warm pool averaged over 1980–2004 period and skipjack catches in the WCPO. Blue circles represent the sum of skipjack catches aggregated by 5° degrees of latitude and longitude. White area represents the region where sea surface temperatures are > 29°C. Source: Temperature data were derived from a biogeochemical model developed at the Earth System Science Interdisciplinary Center (http://essic.umd.edu/) and aggregate logbook data were held by the SPC.**

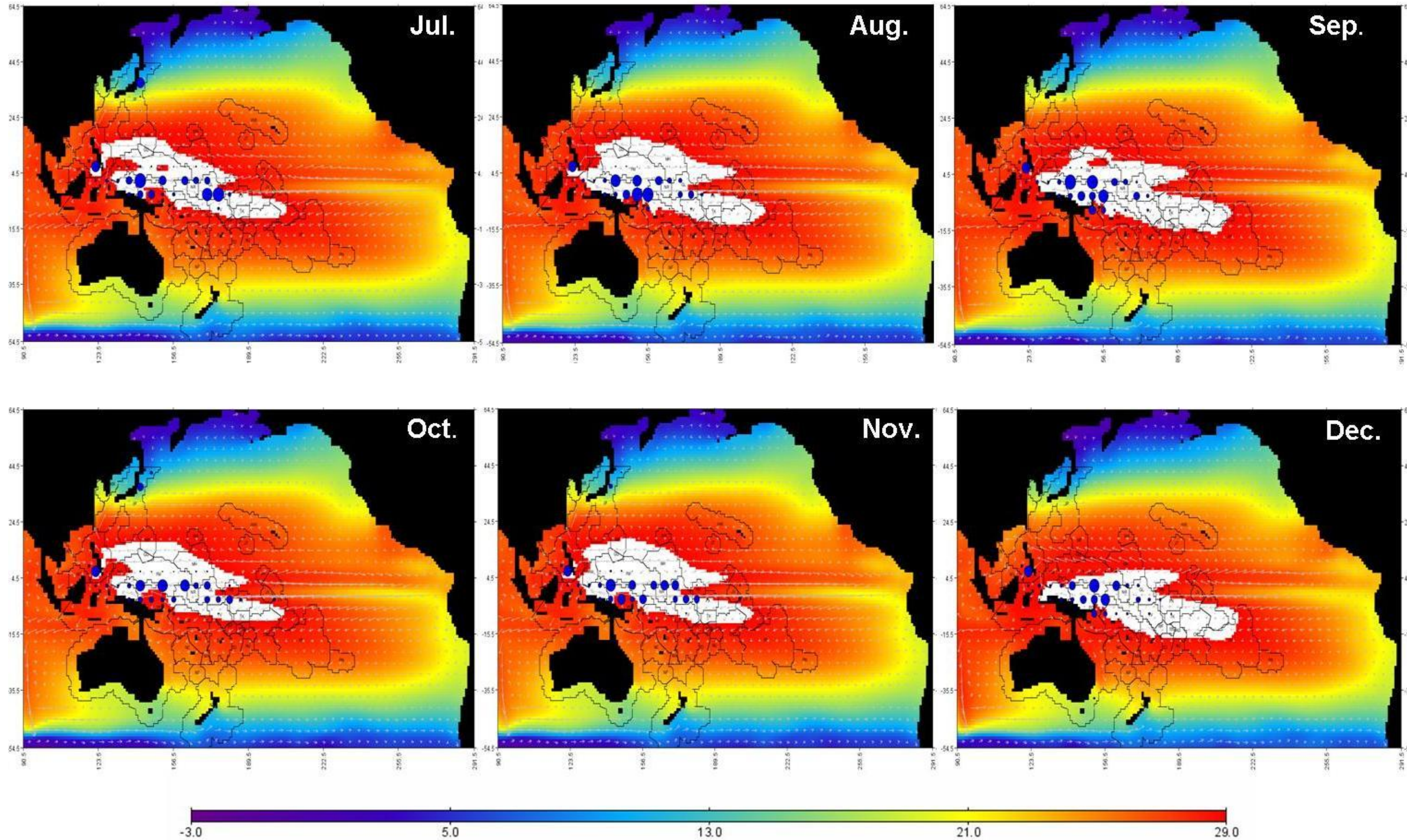


**Figure 4B. Seasonal evolution of the warm pool averaged over 1980–2004 period and skipjack catches in the WCPO. Blue circles represent skipjack catches aggregated by 5° degrees of latitude and longitude. White area represents the region where sea surface temperatures are > 29°C. Source: Temperature data were derived from a biogeochemical model developed at the Earth System Science Interdisciplinary Center (http://essic.umd.edu/) and aggregate logbook data were held by the SPC.**

III- Inter-annual variability

In addition to seasonal patterns in ocean-atmosphere dynamics in the WCPO, there are a number of additional processes which contribute to the natural variability in climate over longer and less predictable time-scales. The most widely known is that referred to as the *El Niño*–Southern Oscillation (ENSO) phenomenon. ENSO refers to the large-scale ocean-atmosphere climate phenomenon linked to a periodic warming in SSTs across the central and east-central equatorial Pacific (between approximately the date line and 120$^{o}$W). ENSO is an irregular climatic oscillation of 3–7 years involving warm (*El Niño*) and cold (*La Niña*) phases (in regard to the central and eastern Pacific) that evolves under the influence of the dynamic interaction between atmosphere and ocean (Philander 1990).

The Southern Oscillation Index (SOI) is an index used to quantify the strength of an ENSO event (Figure 5). It is calculated from the difference between the standardized sea level pressure (SLP) at Tahiti and Darwin. Prolonged periods (usually more than 3 months) of increasingly negative SOI values (below-normal air pressure at Tahiti and above-normal air pressure at Darwin) coincide with *El Niño* episodes whereas prolonged periods of positive SOI values coincide with *La Niña* episodes.

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 5 strong *El Niño* episodes (1982/83, 1986/87, 1991/93, 1994/95, and 1997/98) and 2 strong *La Niña* episodes (1988/89, 1998/99) occurring. This period also featured two of the strongest *El Niño* episodes of the century (1982/83 and 1997/98), as well as two consecutive periods of *El Niño* conditions during 1991–1995 without an intervening *La Niña* episode. The beginning of 2000s also recorded two moderate *El Niño* episodes (2002/2003 and 2006/2007). 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).

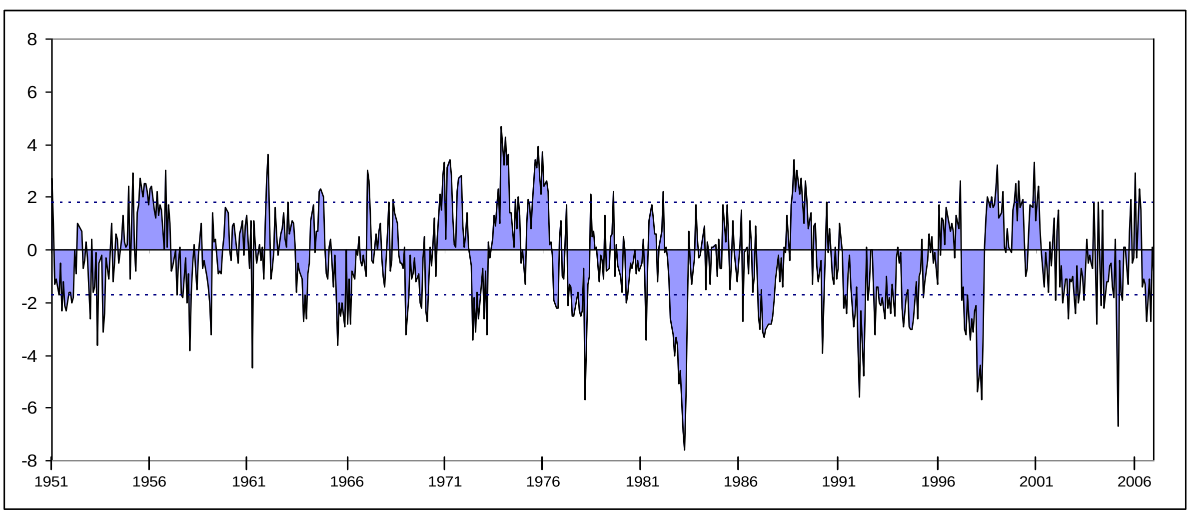


**Figure 5. Southern Oscillation Index (SOI) based on the differences in air pressure anomaly between Tahiti and Darwin, Australia. Dashed lines correspond to +/- one standard deviation over the 1951–2006 period. Source: http://www.cpc.noaa.gov/data/indices/**

ENSO phenomena are associated with major changes in wind regimes and current direction, influencing the eastern extension of the warm pool (Figure 6). Under average conditions, the convergence zone on the eastern edge of the warm pool oscillates around longitude 180°, but very large zonal displacements occur with changes in the ENSO signal, sometimes resulting in the movement of the convergence zone by more than 50° of longitude (~5,560 kms). These displacements can occur rapidly (i.e., exceeding more than 10 $cm.s^{-1}$, or 0.35 $km.h^{-1}$). The equatorial divergence that occurs within the SEC induces a shallow thermocline (~50 m) in the eastern Pacific that deepens progressively towards the west (~150 m in the warm pool). However, during the eastward displacement of the warm water masses accompanying an *El Niño*, the thermocline deepens in the central and eastern Pacific, while rising in the western Pacific. Conversely, during *La Niña* the warm pool is confined to the extreme west of the equatorial Pacific (Picaut *et al.*, 1996), resulting in a deeper thermocline in this area. Major fluctuations are observed in Pacific tuna fisheries correlated with ENSO events.

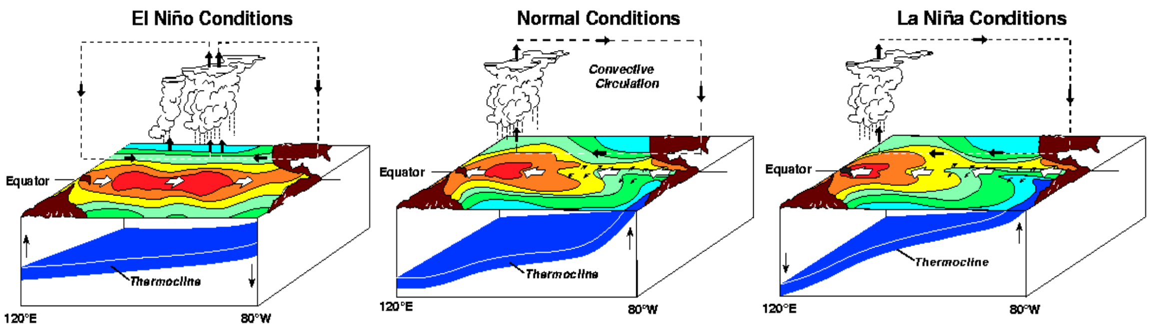


**Figure 6. Changes of the warm pool under the different ENSO conditions in the equatorial Pacific. Source: http://www.pmel.noaa.gov/tao/proj\over/diagrams/index.html.**

Spatial extension of the skipjack habitat during the 1997 *El Niño* had a negative effect on catchability in the western countries, but increased catchability in the warm pool-cold tongue convergence zone during the eastward displacement (Figure 7A). It is likely that skipjack tuna follow the convergence zone (indicated by 29°C isotherm) to the east to feed on prey species associated with the cold tongue, resulting in higher purse-seine catches in Central Pacific countries such as Kiribati (Line Islands).

However, the eastward development of the *El Niño* is also associated with the shallowing of the thermocline in the warm pool and stronger wind stresses than usual in the western Pacific, leading to a increase of primary production in the western equatorial Pacific (due to mixing of the water and increasing upwelling events). In time, the eastern edge of the warm pool becomes less attractive to skipjack tuna as more prey are available in more western areas of the equatorial Pacific resulting in the dissipation of skipjack (Lehodey, 2001), before the actual westward movement of the warm pool itself. This could explain increasing catches in western countries like the Solomon Islands or PNG, late in an *El Niño* period.

In contrast, during the *La Niña* event of 1998–1999 a chlorophyll-rich cold tongue extended as far west as 160°E and the skipjack habitat retracted. Catches increased over the period in the western Pacific, particularly in countries around the cold tongue area (Kiribati, Marshall Islands, FSM) (Figure 7B).

As skipjack inhabit the epipelagic layer (i.e. 0–100 m depth layer), changes in catchability due to changes in vertical structure seem negligible for this species. This is not the case for bigeye and yellowfin, as the adults are also caught by deeper fishing gears (longline). In the western Pacific, the vertical change in the thermal structure during *El Niño* events results in the shallowing and vertical extension of their temperature habitats. This change would increase surface (purse-seine and pole-and-line) catch rates of yellowfin (Lehodey, 2004). The opposite happens during *La Niña* periods, with a deepening of the thermocline which extents the vertical habitat of yellowfin tuna and bigeye, reducing the concentration of fish as habitat increases, decreasing the availability of this species to surface gears.

Lu et al. (2001) showed that relatively high longline CPUEs of both bigeye and yellowfin were found in regions where sea surface temperature (SST) increased during *El Niño* or *La Niña* periods; low CPUEs were associated in regions where SSTs declined during *La Niña* years. Lu et al. (2001) speculate that changes in the thermal structure of the water affects fish availability, resulting in changes in hook rates. For example, it seems that bigeye hook rates in the western Pacific (130–160°W) are significantly higher during *El Niño* periods because of east-west displacement of bigeye as their preferred part of the water column is expanded in the west and compressed in the east. The raised thermocline during ENSO events may also make fish more accessible to longline fisheries and less accessible to surface fisheries.

For South Pacific albacore, it has been shown that higher CPUEs by the Taiwanese distant-water longline fishery were recorded in the southern Pacific region at the beginning of, or up to six months prior to the occurrence of ENSO episodes (Lu *et al.*, 1998). This phenomenon is linked with a shallowing of the mixed layer depth in the equatorial region and a reduction in extent of the 18–25°C isotherms in the water column, which comprise the preferred temperature range of adult. In the New Caledonia EEZ, Briand (2005) showed that *El Niño* episodes could have a positive impact on SEC which favours tuna migration and prey concentration within the New Caledonia EEZ.

In addition to the impacts to tuna movement, migration and local availability, ENSO-related variability also affects recruitment and therefore total abundances of tuna populations. Results from statistical population dynamics modelling point to a clear link between tuna recruitment and climatic fluctuations and indicate that not all tuna species respond in the same way during ENSO periods (Lehodey *et al.*, 2004).

Recruitment of tropical tunas (such as skipjack and yellowfin) increase following *El Niño* events. Sub-equatorial tunas (e.g. south Pacific albacore) show the opposite pattern, with low recruitment after *El Niño* events and high recruitment after *La Niña* events (Lu et al. 1998, Lehodey et al. 2003). Model simulations resulted in increased skipjack and yellowfin recruitment in both the central and western Pacific during *El Niño* events, a result of four mechanisms;

- the extension of warm surface waters (26°–30°C) further east, resulting in conditions conducive for spawning for these two species
- enhanced food for tuna larvae due to higher primary production in the west
- lower predation of tuna larvae and
- retention of larvae 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 recent study also shows that the extent of the warm pool is a good indicator for monitoring the effect of environmental variability on yellowfin recruitment (Kirby et al., submitted). The extension of the warm waters in the central Pacific during *El Niño* events that extends the tropical tuna spawning grounds may also conversely reduce those of albacore (Lehodey, 2003).

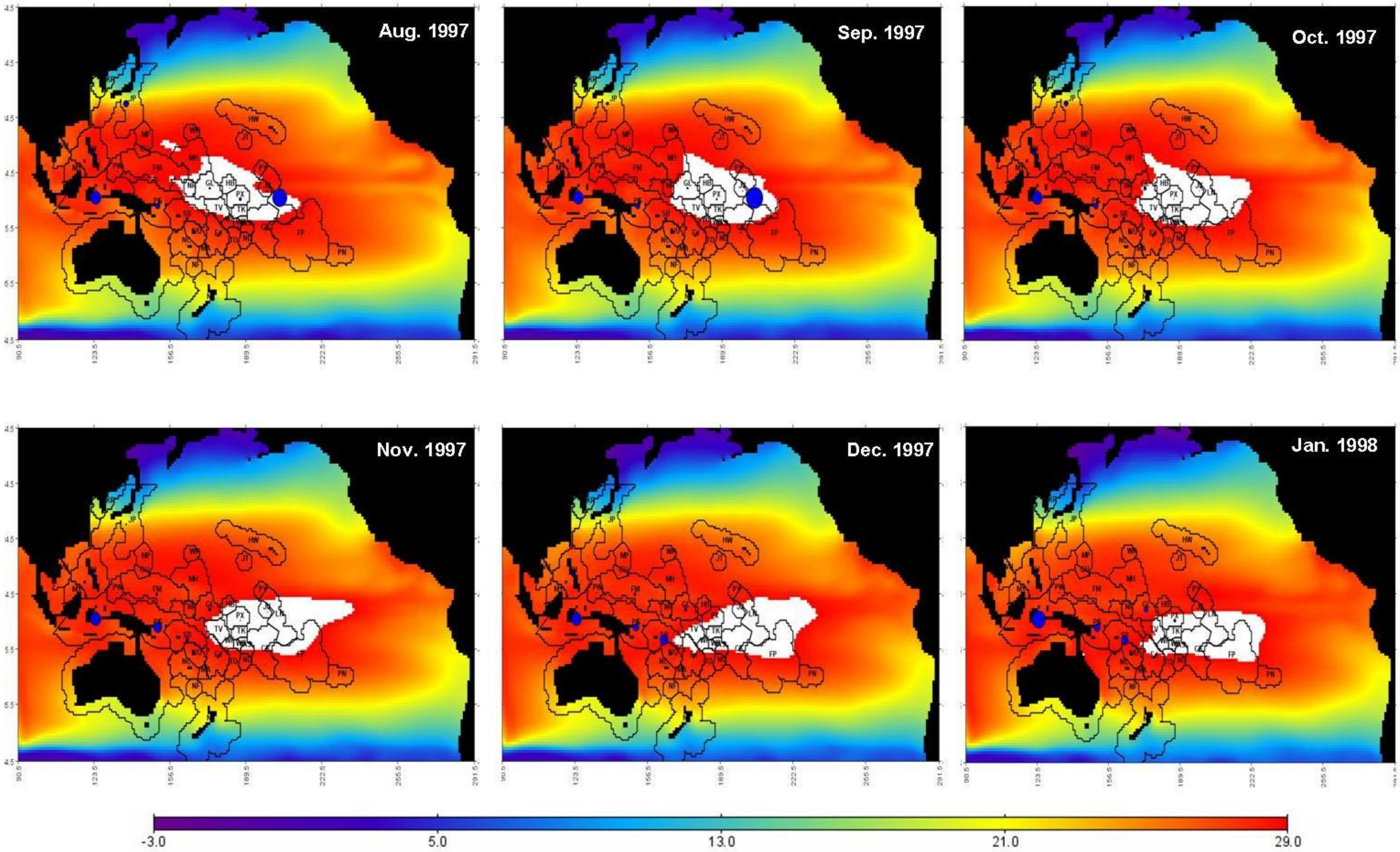


**Figure 7A. Distribution of skipjack catches during El Nino 1997–98 strongest phase (August to January). Blue circles represent total catches by EEZ. White area represents the region where sea surface temperatures are > 29°C. Source: Temperature data were derived from a biogeochemical model developed at the Earth System Science Interdisciplinary Center (http://essic.umd.edu/) and aggregate logbook data held by the SPC.**

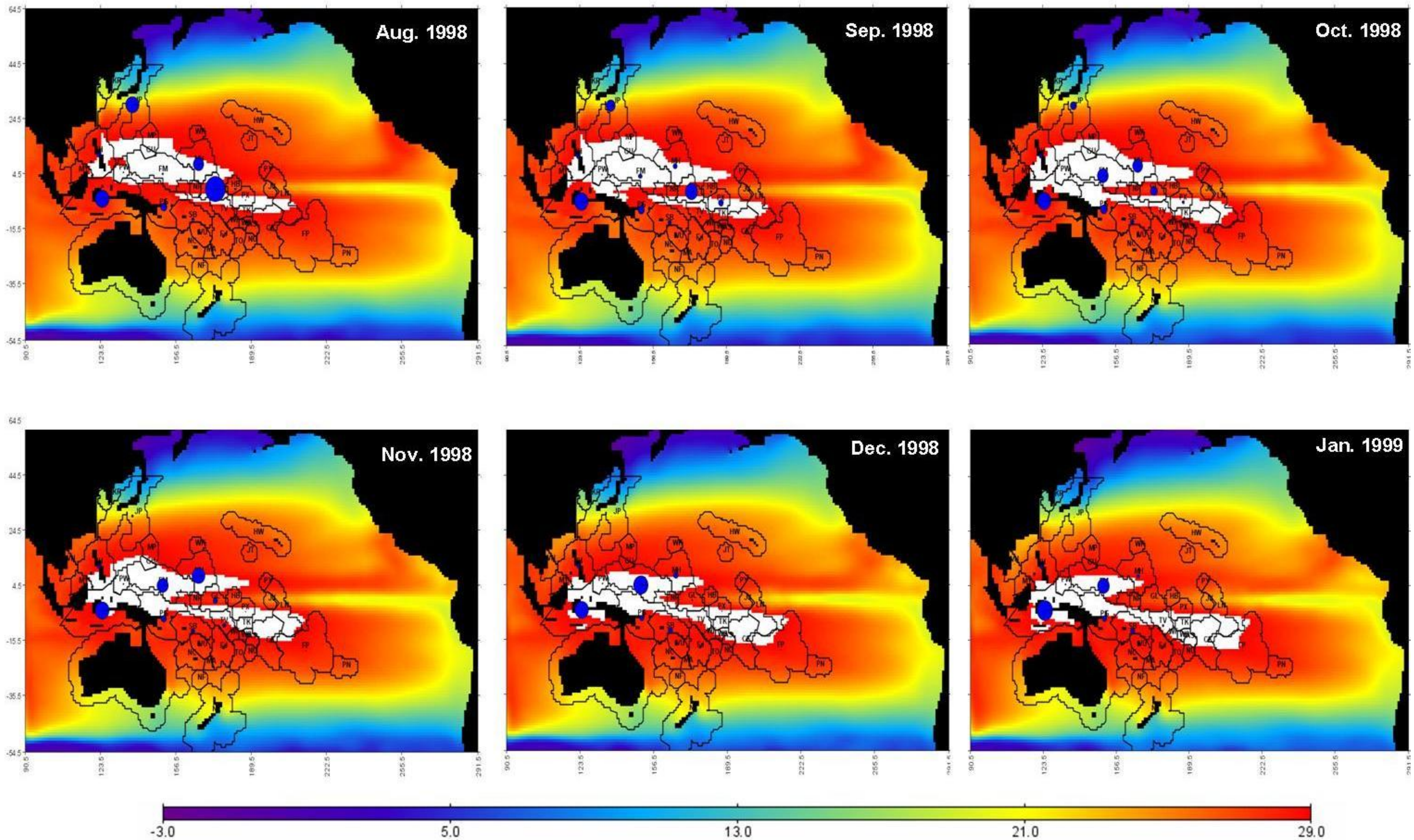


**Figure 7B. Distribution of skipjack catches during La Niña 1998–99 strongest phase (August to January). Blue circles represent total catches by EEZ. White area represents the region where sea surface temperatures are > 29°C. Source: Temperature data were derived from a biogeochemical model developed at the Earth System Science Interdisciplinary Center (http://essic.umd.edu/) and aggregate logbook data held by the SPC.**

IV- Climate change and risks

Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750. The rising in emissions of greenhouse gases and aerosols alters the energy balance of the climate system and impacts atmospheric temperature. According to the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report AR4 (http://www.ipcc.ch/), the total air temperature increase is about 0.74 °C [0.56–0.92° C] over the last 100 years from 1906-2005. Warming of the climate is also evident from observations of increases in global average SSTs, widespread melting of snow and ice, and rising global mean sea level. Sea surface temperatures affect atmospheric pressure patterns, which in turn impact patterns of wind generation. Accelerated warming of the oceans may produce stronger winds in certain areas, and increase the frequency of extreme events such as storms and cyclones. Changes in wind generated surface currents may not only modify weather conditions but also alter the timing, location and extent of upwelling processes upon which much oceanic primary productivity is reliant.

The oceanic water column also tends to stratify with warmer water on the surface. In warm, calm conditions this stratification is intensified and becomes more resistant to mixing by surface winds (Manabe *et al.*, 1991). A recent study suggested that primary productivity in tropical oceans would decline due to increased stratification between warmer surface waters and colder deeper water, a consequence of a reduction in upwelling strength and extent (Bopp *et al.*, 2001).

It is likely that global warming may also affect the ENSO cycle. The frequency and duration of ENSO events appear to have increased over the last few decades and computer models suggest that this trend will continue with year-to-year variations becoming more extreme (Timmermann *et al.*, 1999; Timmermann *et al.*, 2004). An additional factor to consider is that 'natural' fluctuations associated with ENSO events appear to worsen against a background of rising base-line temperatures. It is possible that more frequent cold events (such as strong *La Niña* episodes) could compensate for the decrease in productivity under an *El Niño* mean state, but it is still uncertain. In addition, even though it is difficult to determine the impacts of strong *El Niño* events in the future, it is likely that such extreme events could lead to a possible decline in productivity in the eastern Pacific Ocean.

Climate change is also likely to affect regional tuna fisheries. Lehodey (2000) suggests that the observed changes in tuna fisheries during *El Niño* and *La Niña* events provide an indication of future impacts of global warming. It seems that tuna have adapted relatively easily to variations in climatic conditions by moving to new locations. It is likely that fishing fleets will also follow tunas, resulting in shifts in the areas whare large tuna catches are made. However, total tuna catches seem to be affected only to a limited degree.

Climate change may result in more-permanent *El Niño* conditions, which are likely to increase the annual fluctuations of spatial distributions and abundances of tuna. Early simulations of global warming on skipjack distribution and abundance suggest a global improvement of habitat extent east of the date line and a spatial redistribution of this species to higher latitudes. With the extension of warm waters, equatorial tuna populations spread towards presently sub-equatorial regions. Skipjack may be caught as far as Vancouver Island (48ºN), while there may be incursions of tropical tuna species and billfish into southern Peruvian waters (south of 15ºS) (Loukos *et al.*, 2003).

Distant water fishing fleets may be able to adapt to changes in the spatial distribution and abundance in tuna stocks. However, domestic fleets would be vulnerable to fluctuations of tuna fisheries in their EEZs. Moreover if the relative warming results in a general decline in the strength of the upwelling system in the central and eastern equatorial Pacific, this may lead to a reduction in productivity that is normally advected westwards, and upon which pelagic fish stocks depend. This decreasing production could lead to a decline in tuna abundance, particularly in bigeye and adult yellowfin populations (species targeted by equatorial longline fleets).

However uncertainty remains on potential changes in productivity of the western equatorial Pacific. The impact of climate change on tuna recruitment and spawning migration is also poorly understood. Nonetheless, climate change is likely to result in a change in the spatial distribution of tuna and tuna catches, as well as possible changes in productivity, total abundance and total catches.

## V- Summary and Conclusions

Tuna distributions and abundances are sensitive to environmental changes and variability. Globally, tuna catches are highest in the western equatorial Pacific warm pool, a region characterised by low primary productivity and the warmest surface waters of the world's oceans. However, the WCPO displays remarkable dynamics in oceanography, mostly linked to climatic changes (such as ENSO). In response, variations in tuna catches are reported at both regional and domestic scales both seasonally and inter-annually. The major oceanographic processes that impact on tuna distribution and abundance in the WCPO are briefly discussed below;

1) Areas of divergence or convergence of currents are of major importance as they induce physical phenomena (upwellings, eddies, thermal fronts) that enhance local productivity and create zones of prey availability. These, in turn, attract and concentrate tuna. A better knowledge of these processes and their spatio-temporal variability would be useful for fishery management.

2) Tuna movement is linked to the horizontal displacement of SST isotherms and vertical changes in mixed layer depths that determine their surface habitat. East-west migration of the warm pool-cold tongue pelagic ecosystem, especially during ENSO episodes, should be considered carefully by fisheries managers of the different countries. There is an obvious impact for the Pacific Island Nations through variations in tuna availability in EEZs and therefore tuna catches, consequently affecting economic revenues, depending to the ENSO state.

3) Contraction or extension of the warm pool also has a major impact on tuna recruitment which varies among species. For tropical species, such as skipjack and yellowfin, *El Niño* events favour recruitment through extension of warm water spawning habitat, whereas *La Niñ*a events restrict the extent of spawning areas, reducing recruitment. For subequatorial species such as South Pacific albacore, opposite trends are found. These phenomena may be taken into account to provide indication of future catches within individual EEZs.

4) Global warming is also likely to affect regional tuna fisheries by increasing average SSTs to levels currently experienced during *El Niño* periods, and increasing year to year variability. Possible changes in primary productivity in the tropical Pacific are also hypothesized. These factors would affect distribution, abundance and catchability of tuna fisheries, impacting areas and magnitude of tuna catches, but further investigations are required to validate these assumptions.

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Appendix 1A. Examples of mean quarterly ocean current directions and strengths in the WCPO region during a) 1996 neutral phase, b) 1997 *El Niño* event and c) 1998 *La Niña* event.