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Front variability and surface ocean features of the presumed southern bluefin tuna spawning grounds in the tropical southeast Indian Ocean

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ABSTRACT

The southern bluefin tuna (SBT, *Thunnus maccoyii*) is an ecologically and economically valuable fish. However, surprisingly little is known about its critical early life history, a period when mortality is several orders of magnitude higher than at any other life stage, and when larvae are highly sensitive to environmental conditions. Ocean fronts can be important in creating favourable spawning conditions, as they are a convergence of water masses with different properties that can concentrate planktonic particles and lead to enhanced productivity. In this study, we examine the front activity within the only region where SBT have been observed to spawn: the tropical southeast Indian Ocean between Indonesia and Australia (10°S–20°S, 105°E–125°E). We investigate front activity and its relationship to ocean dynamics and surface features of the region. Results are also presented for the entire Indian Ocean (30°N–45°S, 20°E–140°E) to provide a background context. We use an extension of the Cayula and Cornillon algorithm to detect ocean fronts from satellite images of sea surface temperature (SST) and chlorophyll-*a* concentration (chl-*a*). Front occurrence represents the probability of occurrence of a front at each pixel of an image. Front intensity represents the magnitude of the difference between the two water masses that make up a front. Relative to the rest of the Indian Ocean, both SST and chl-*a* fronts in the offshore spawning region are persistent in occurrence and weak in intensity. Front occurrence and intensity along the Australian coast are high, with persistent and intense fronts found along the northwest and west coasts. Fronts in the tropical southeast Indian Ocean are shown to have strong annual variability and some moderate interannual variability. SST front occurrence is found to lead the Southern Oscillation Index by one year, potentially linked to warming and wind anomalies in the Indian Ocean. The surface ocean characteristics of the offshore SBT spawning region are found to be particularly stable compared to the rest of the Indian Ocean in terms of stable SST, low eddy kinetic energy, i.e., low mesoscale eddy activity, and low chl-*a*. However, this region has high front occurrence, but low front intensity of both SST and chl-*a* fronts. The potential impact of these oceanic features for SBT spawning is discussed.

1. Introduction

The southern bluefin tuna (SBT; *Thunnus maccoyii*) is an economically valuable fish and an ecologically important apex predator, but despite its importance and a long history of research, knowledge of its early life history is limited. The larval stage is decisive for the renewal of marine populations as it has the highest mortality of all life stages (> 99%; Hjort 1914). Early life stages are highly sensitive to environmental conditions and fish larval survival is commonly influenced by retention of larvae in regions where the ocean circulation concentrates food sources (Bakun, 1996). However, the reproductive strategy of bluefin tuna is unusual, as they migrate from their temperate and productive feeding grounds to oligotrophic tropical and subtropical spawning grounds (Schaefer, 2001; Bakun and Broad, 2003). Bakun and Broad (2003) suggest that the early life stages of tuna are highly vulnerable to predation, and thus spawning adults seek regions

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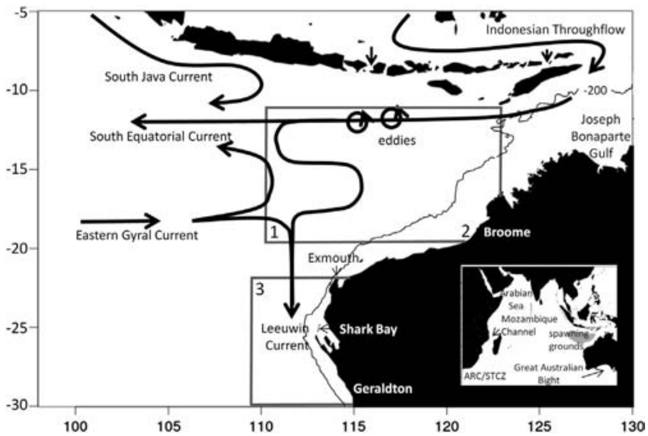

Fig. 1. Major currents of the Indo-Australian region in the tropical southeast Indian Ocean and the subregions from which time-series were derived. Boxed areas indicate the subregions investigated in this study and are described in the text as the (1) offshore, (2) coastal, and (3) southern subregions. Geographical points of interest mentioned in the text are shown here, including the Agulhas Return Current/Subtropical Convergence Zone (ARC/STCZ; inset).

where predators can be avoided, i.e., regions of low productivity where even the regular appearance of tuna larvae is not sufficient to sustain predator populations. This strategy constitutes an ecological “loophole” where the benefits of low predation outweigh the negative effects of poor feeding conditions.

An *in situ* study of tuna larvae in the tropical southeast Indian Ocean spawning grounds has shown a clear relationship between prey density and larval feeding success (Young and Davis, 1990). This suggests that regions of concentrated food resources, especially within an oligotrophic sea, may be important for larval survival. Mesoscale features such as ocean fronts play an important role in creating favourable spawning conditions, as they are a convergence of water masses of different properties (e.g., temperature, salinity, nutrients) that can concentrate productivity by forming a narrow physical barrier to planktonic particles (Belkin et al., 2009). They may act as hotspots of biological productivity even in oligotrophic ecosystems. Ocean fronts have been significantly linked to the larval distribution of the Atlantic bluefin, *Thunnus thynnus* (Mariani et al., 2010), and may also be relevant in characterising spawning habitats of bluefin tuna (e.g., Garcia et al., 2003).

The putative migration cycle of SBT adults is to migrate between their highly productive feeding grounds in the Southern Ocean (30°S–50°S) and their oligotrophic offshore spawning grounds in the Indo-Australian region (10°S–20°S, 110°E–125°E; Box 1, Fig. 1; Shingu, 1970; Schaefer, 2001). Like other tuna, the minimum surface spawning temperature for SBT is around 24°C (Yukinawa, 1987), though can be as low as 20.5°C (Alemany et al., 2010). A potential spawning season of September to April has been inferred from catch data and larval surveys (Ueyanagi, 1969; Caton, 1991; Farley and Davis, 1998), though there is some evidence to suggest that spawning may occur in all months except July (Caton, 1991; Farley and Davis, 1998). Although several surveys have been carried out in this region (Ueyanagi, 1969; Yonemori and Morita, 1978; Yukinawa and Miyabe, 1984; Nishikawa et al., 1985; Yukinawa and Koido, 1985; Yukinawa, 1987; Davis et al., 1990), spawning and larval distributions of SBT have not been well quantified and the spatial distribution of spawning within the region is unknown (Caton, 1991).

In this paper, we investigate the surface ocean characteristics (SST, chlorophyll-*a* concentration (chl-*a*), and eddy kinetic energy (EKE)) of the presumed SBT spawning region in the tropical southeast Indian Ocean, using 30 years of satellite SST data (1981–2011), 10 years of ocean colour data (2002–2012), and 9 years of satellite altimetry data (2002–2011). We use both the gradient method (Canny, 1986) and an extension of the histogram method (Cayula and Cornillon, 1992; Nieto et al., 2012) to detect SST and chl-*a* fronts to develop indices of front intensity and occurrence. Based on these indices, we characterise the variability of surface front activity in the tropical southeast Indian Ocean SBT spawning ground and relate it to regional- and large-scale ocean dynamics.

1.1. Background oceanography

The offshore region of the tropical southeast Indian Ocean between Java and Australia (10°S–20°S, 105°E–125°E; Box 1, Fig. 1) is the only region where SBT spawning has been observed (Yukinawa and Miyabe, 1984; Yukinawa, 1987; Farley and Davis, 1998), though the northern limit of the spawning ground is uncertain due to limited sampling near the Indonesian archipelago (Farley and Davis, 1998). The tropical southeast Indian Ocean is oceanographically dynamic, with strong seasonal and interannual variability and high mesoscale activity on intraseasonal time scales (Feng and Wijffels, 2002). This region is influenced by a seasonal monsoon, which is characterised by light southwesterly winds, high temperatures and precipitation in austral summer (December–March); with stronger, more arid southeasterly winds and lower temperatures and precipitation in winter (July–November; Wyrtki, 1961; Qu and Meyers, 2005).

There are numerous interacting current systems relevant to this study region (see Fig. 1). The Indonesian Throughflow (ITF) is the flow of relatively warm, low salinity waters from the western Pacific Ocean into the Indian Ocean through the Indonesian archipelago (e.g., Gordon and Fine, 1996). The ITF feeds into the South Equatorial Current, which flows westward away from the spawning region in the latitudinal band between 10°S–15°S (Meyers et al., 1995; Potemra, 2001; Wijffels et al., 2008). The South Equatorial Current is coincident with a field of energetic westward-propagating anticyclonic eddies that likely result from instabilities associated with the ITF outflow (Bray et al., 1997; Feng and Wijffels, 2002; Nof et al., 2002; Yu and Potemra, 2006). The South Equatorial Current is also fed by recirculation of the South Java Current to the north, and the Eastern Gyral Current to the south. The South Java Current, which hugs the Java coast, reverses semiannually, with strong eastward flow during the monsoon transition seasons in May and October (Sprintall et al., 2000). It is particularly influential on northern Indo-Australian dynamics (Sprintall et al., 2009), and can affect both the mean strength of the ITF and its low-frequency variability (Wyrtki, 1987). The Eastern Gyral Current, a broad, shallow current flowing eastward at ~16°S–18°S (Meyers et al., 1995), feeds back into the South Equatorial Current as well as southward into the Leeuwin Current (LC), the poleward-flowing eastern boundary current that runs along the coast of Western Australia from ~22°S–34°S (Cresswell and Golding, 1980; Domingues et al., 2007). Part of the LC may also originate in the ITF (Wijffels et al., 2008) via a pathway along the northwest Australian coastline (Nof et al., 2002), though the coastal flows here appear to reverse seasonally (Cresswell et al., 1993; Qu and Meyers, 2005), suggesting that, on average, the direct contribution of the ITF to the LC may be weak.

On interannual time scales, variations in the Indo-Australian region are influenced by large-scale climate phenomena (Wijffels and Meyers, 2004). The El Niño-Southern Oscillation (ENSO) modulates the ITF and thus the circulation in the Indo-Australian region. For example, during El Niño events, the strength of the ITF is reduced (e.g., Clark and Liu 1994) and, accordingly, the LC is also weakened (Feng et al., 2003). The Indian Ocean Dipole (IOD) also influences the upper ocean of the Indo-Australian region on interannual time scales: during positive IOD events, temperatures