Distribution and Migration—Southern Bluefin Tuna (Thunnus maccoyii)

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CHAPTER 8

Distribution and Migration—Southern Bluefin Tuna (*Thunnus maccoyii*)

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Introduction

Southern bluefin tuna (*Thunnus maccoyii*, SBT) are a highly migratory tuna species that occur in waters of the eastern Atlantic, Indian and South-west Pacific Oceans between 30°S and 50°S (Caton 1991). Mature fish migrate to a single spawning ground located in the North-east Indian Ocean between Java and Australia (Farley and Davis 1998; Patterson et al. 2008). After a larval stage, juveniles leave the spawning ground, move down the west coast of Australia and reach the south coast by age one where they spend the austral summer. Up until approximately five years of age, juvenile fish undertake annual cyclical migrations in which they generally spend austral summers in the Great Australian Bight (GAB), and move east as far as New Zealand or west as far as South Africa during the winter (Bestley et al. 2008; Basson et al. 2012). Fish older than five years rarely return to the GAB and disperse widely across the southern oceans from the western Atlantic across the Indian Ocean to the Tasman Sea. SBT are estimated to reach maturity at 10–12 years and can live to more than 40 years (Shimose and Farley this volume).

Although the species is long-lived and highly fecund, characteristics such as slow growth, late onset of maturity, the presence of a single spawning ground and a highly migratory behaviour (exposing the stock to national and international commercial

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fishing fleets) led to overexploitation and dramatic reductions in population size (Anon 2011). Between 1960 and the present, the global stock of SBT declined to less than 10% of its unfished biomass, leading to successive reductions in commercial quotas for fishing nations (Anon 2011). Today, SBT are fished commercially by Australia and Japan, with smaller catches taken by vessels from New Zealand, Taiwan, Indonesia, Korea, South Africa, the European Union and the Philippines. Commercial fishing for SBT is managed internationally by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), which determines global total allowable catch and allocates national quotas to member nations (http://www.ccsbt.org/site/commission_role.php). Within Australia, the species is listed as threatened both federally and within a number of states and is listed as critically endangered by the International Union for Conservation of Nature (IUCN). Recent assessments suggest the population may be recovering, and under the CCBST, harvest strategies are in place to ensure more robust population sizes by 2020 (Anon 2013).

Broad scale information on the distribution of the species has traditionally been based on catch data, fishery-dependent tagging programs, and larval surveys. More detailed insights into the horizontal and vertical movements of individuals have come from recent studies using a variety of electronic tags. In this chapter we describe the global and regional distribution and migration patterns relative to the life cycle of SBT, including information on how these patterns have been determined. We discuss management of the species in the context of the spatial dynamics of the species and potential changes to population distributions and movements in relation to climate change. We conclude with a discussion of the remaining uncertainty regarding distribution and movement patterns, and research required to address these uncertainties.

Distribution and Movement of Early Life Stages

Larval distributions

Genetic studies suggest that there is a single SBT population (Grewe et al. 1997). Larval studies support this understanding, with larvae collected from a single region in the Indian Ocean between Java and North-west Australia (Nishikawa et al. 1985; Davis et al. 1989) (Fig. 8.1). The spawning area is large, but has not been precisely surveyed or defined, and a lack of data from Indonesian territorial waters results in substantial uncertainty on the northern limits of the spawning area. The surface ocean characteristics in the general region have been shown to be particularly stable compared to the rest of the Indian Ocean in terms of consistent sea surface temperatures (SST), low eddy kinetic energy and low chlorophyll *a*, with a high frequency of low intensity SST and chlorophyll fronts (Nieblas et al. 2014). These characteristics are consistent with the loophole hypothesis of Bakun and Broad (2003) in which poor larval feeding conditions are balanced by reduced predation. Recent comparative work shows that tuna larvae feeding success is low in this region (Llopiz and Hobday 2014), supporting earlier work that suggested that food is limiting for SBT larval growth in the region (Young and Davis 1990). Net sampling of larvae in the spawning region has shown that SBT larvae (4–7 mm) are largely restricted to the mixed layer, and move towards

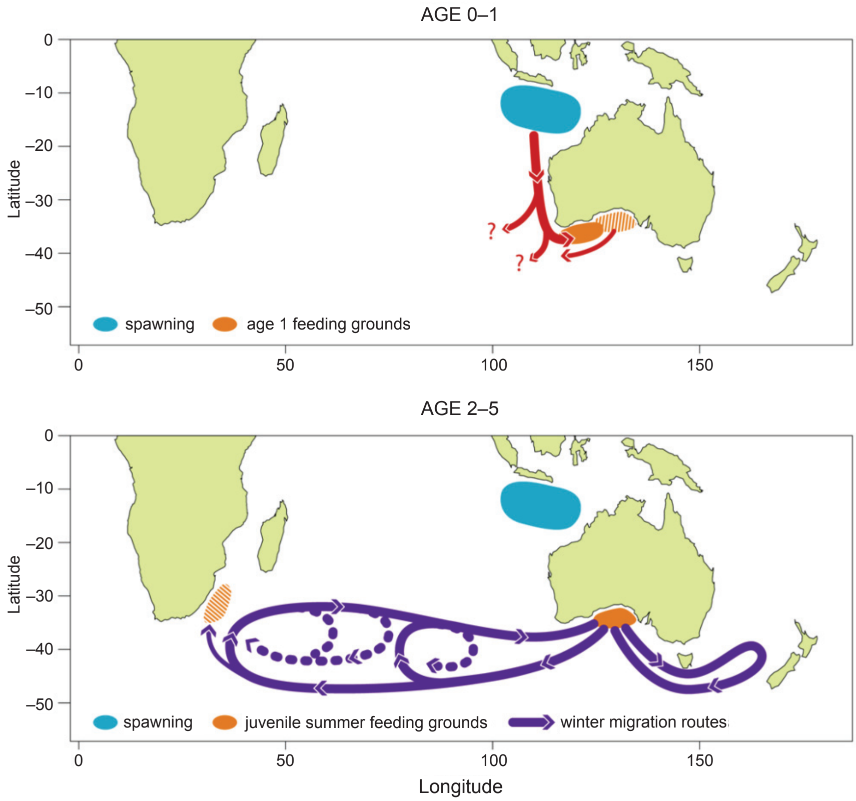

Figure 8.1. General migration patterns and distribution of juvenile southern bluefin tuna with age one movements from the spawning ground (upper panel) and age two–five movements from the Great Australian Bight (lower panel).

the surface during the day (Davis et al. 1990), probably to feed. These small larvae are passive and drift with surface water masses (Davis et al. 1991). As larvae grow (the larval stage is estimated to last 20 days—Jenkins and Davis 1990) and become capable of independent movement, an unknown fraction is entrained in the poleward flowing Leeuwin Current (Fig. 8.1).

Post-larval juvenile movement and distribution

Post-larval, juvenile SBT move down the west coast of Australia, carried in part by the Leeuwin Current. On reaching the south-west coast they are generally restricted to the continental shelf (Hobday et al. 2009a) where they predominately occur in warm waters adjacent to colder upwelling cells (Fujioka et al. 2010). Nutrient-rich and cool sub-Antarctic water periodically intrudes onto the southern Western Australian shelf, leading to elevated chlorophyll concentrations and prey densities (Ward et al. 2006). By December and January each year, age-one fish (approximately 50 cm in length) are found off southern Western Australia, with some age-two fish (mean size 79 cm) also present (Itoh and Tsuji 1996; Hobday et al. 2009a). Recent results from tagging programs in the region found that in some years two size modes of age-one fish are present while in other years only one size mode is present (Fig. 8.2A). Two modes of age-one fish is consistent with two peak periods of spawning (see: Migration of adults to the spawning ground). However, one mode suggests that either successful spawning does not occur in both periods every year, or that movement into southern Australia varies for post-larval fish from the two spawning periods, perhaps due to oceanographic influences on entrainment into the Leeuwin Current.

It has been suggested that not all juveniles move directly south from the spawning region to South-west Australian waters, but that some larvae and juveniles are carried from the spawning ground towards the west, perhaps in the south equatorial current (Harden-Jones 1984). Alternatively, juveniles may swim west from southern Western Australia into the Indian Ocean (Murphy 1977; Murphy and Majkowski 1981; Hobday et al. 2009a).

In South-west Australia, SBT generally form schools with similarly sized conspecifics, although as the overall population size declined from the 1960's to the 1990's (Polacheck and Preece 2001), schools containing mixed sizes became more prevalent with larger juveniles associating with schools of smaller fish (Dell and Hobday 2008). The association of larger juveniles with smaller juveniles that remain in the west has been hypothesized to contribute to lower numbers of these larger juveniles moving to the east and a measure of school size similarity may be of use as a potential population indicator (Dell and Hobday 2008). Small age-two fish consistently occur in the waters off southern Western Australia, likely members of the smaller age-one cohort, with the larger age-one fish having moved into the GAB by their second year (Fig. 8.2B).

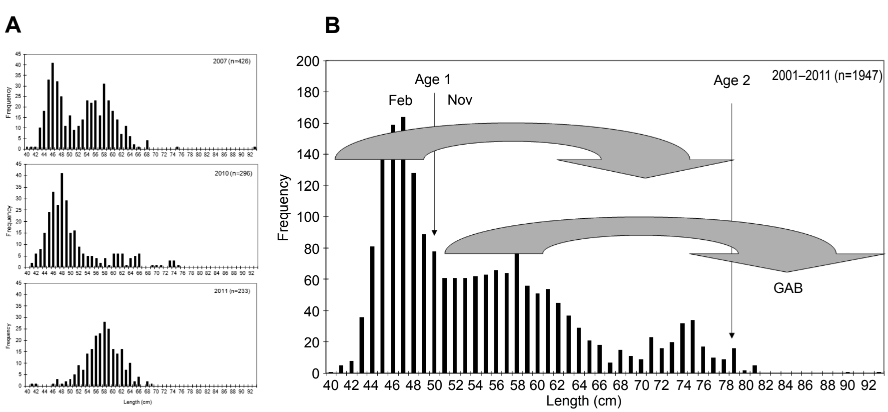

Figure 8.2. Size distribution of juvenile southern bluefin tuna in southern Western Australia collected during tagging studies in the austral summer (A) for three years showing two age-one cohorts in 2007, a small age-one cohort in 2010 and a large age-one cohort in 2011, and (B) all fish collected across the years 2001–2011. The average size for age-one and age-two fish is shown, together with an inferred spawning month (Feb or November). Note the absence of a large age-two cohort in southern Western Australia, which may have moved to the Great Australian Bight (GAB). Hobday, unpubl. data.

Whilst in waters off South-west Australia, schools of SBT can be free-swimming or associated with topographic features (termed 'lumps') distributed on the continental shelf (Hobday and Campbell 2009). Interestingly, habitat partitioning between several pelagic species seems to occur at these features, with yellowtail kingfish occurring closest to the feature, followed by bonito, and then SBT occurring in the outer radius. Skipjack tuna in the region showed avoidance of features. Such fine scale distributional information may inform spatial management, and allow fishers to avoid or target particular species over small spatial scales (Hobday and Campbell 2009).

Due to their small size, the movements of age-one SBT have generally been studied with conventional tags and via acoustic tags and subsequent monitoring with large numbers of listening stations running across the continental shelf and around topographic features in the South-west Australian region (Hobday et al. 2009a). Data collected over almost 10 years has demonstrated that both the residence time and migration routes inshore and offshore across the continental shelf of age-one and age-two SBT along the south coast varies between years (Hobday et al. 2009a; Honda et al. 2010). The strength of the warm Leeuwin Current into southern Western Australia may influence the movement timing and foraging habitat of juvenile SBT in this region (Hobday et al. 2009a; Fujioka et al. 2012). Seasonal and interannual changes in the strength of the Leeuwin Current lead to thermal differences and potential changes in food availability between tropical and temperate waters. Movements of juvenile SBT into waters further east have been observed to increase as temperatures increase, with fish leaving the region when temperatures exceeded 20°C, a temperature indicative of the leading edge of the Leeuwin Current in this region (Fujioka et al. 2012). When the Leeuwin Current was narrow and restricted to the shelf edge, the distribution of SBT in inshore waters was not affected. In contrast, long distance eastward movements frequently occurred when the Leeuwin Current intrusion was spread wide over the continental shelf. This suggests that juvenile SBT move quickly out of local foraging habitats defined by cool, sub-tropical and temperate waters ahead of the tropical Leeuwin Current intrusion, despite these waters not being physiologically limiting. Movements are likely driven instead by changes in prey availability resulting from changes in oceanographic conditions (Fujioka et al. 2012).

An overall habitat utilization model for the southern Western Australia shelf, termed the productivity-distribution hypothesis, has been proposed for juvenile SBT on the basis of movements observed in age-one and two individuals (Honda et al. 2010). As oceanographic conditions vary between years, driven by varying Leeuwin Current strength and coastal upwelling, environmental quality (i.e., food availability) in the region also varies, with the greatest variability observed at the shelf edge. When the environmental quality for SBT is good, higher prey densities occur at the shelf edge, and subsequently SBT are distributed to a greater extent at the shelf edge (Honda et al. 2010). In poor quality years, the inshore environment represents improved foraging relative to the shelf environment (Fig. 8.3). There is a suggestion that small fish may always be more common at the shelf edge as they are excluded from the inshore waters in the poor years (Honda et al. 2010), but this hypothesis remains unresolved. In order to establish if this productivity-distribution hypothesis is reflective of drivers for juvenile SBT movements and distribution in the waters of

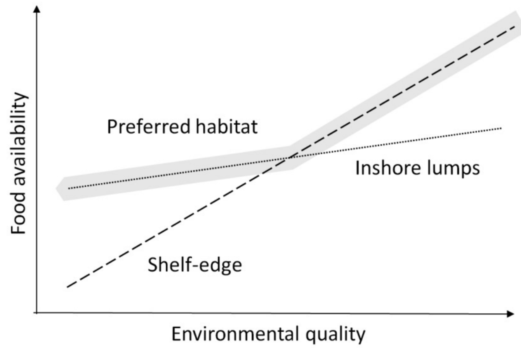

Figure 8.3. Proposed productivity-distribution hypothesis explaining distribution of juvenile SBT in southern Western Australia. Food availability varies more strongly as a function of environmental quality at the shelf edge (dashed line) compared to inshore lumps (dotted line). The preferred habitat across the range of environmental conditions is shaded.

South-western Australia, detailed distribution and behavioural data for both predator and prey species is required (e.g., Itoh et al. 2011).

Collectively, data from conventional and electronic tagging experiments have shown that at the end of the austral summer, juvenile SBT of age-one either remain in waters off South-western Australia, move east and into the GAB, or move west and into the Indian Ocean, although the proportion for each pathway has not been determined. It has been assumed that the majority of juvenile SBT move to the GAB by the following summer.

Juvenile SBT in the GAB

The waters of the GAB are an important summer feeding ground for juvenile SBT aged two–five years (Basson et al. 2012; Bestley et al. 2009; Fig. 8.1). The GAB region comprises a very wide (up to 260 km) and shallow (<160 m) continental shelf which extends some 1300 km along the coastline of southern Australia and covers an area of approximately 150,000 km^2.

Shelf circulation in the GAB is dominated by the Leeuwin Current and the west wind drift in the winter, and by the Flinders Current and winds from the south-east in the summer. By some descriptions, the waters of the GAB are oligotrophic with low productivity (Condie and Dunn 2006), which seems paradoxical given the high density of many predators, including SBT, in the region (see a review of the GAB ecosystem in Rogers et al. 2013). During winter, the Leeuwin Current extends into the western GAB and spreads across the shelf of the GAB as a body of warm water (~20°C), with relatively low salinity. The Leeuwin Current reinforces the wind-driven geostrophic coastal current directed to the east and interaction with the offshore Flinders Current results in a series of eddies in the eastern GAB enhancing local cross-shelf water exchange (Rogers et al. 2013). During the summer, the Leeuwin Current weakens, resulting in little to no penetration of waters associated with the current into the GAB. Winds from the east drive small upwelling cells, particularly in the eastern and far western GAB, bringing cold nutrient-rich waters onto the shelf (Middleton and Bye 2007) and support pelagic food webs in the GAB (Rogers et al. 2013).

Considerable effort has been expended on understanding the abundance, distribution and migration patterns of juvenile SBT in the GAB, motivated in part by the large surface fishery that operates there, relatively easy and reliable access to part of a widely spread population, and also broader scale declines in the population. A number of programs involving the deployment of conventional tags on juvenile SBT in the GAB have occurred since the 1950's providing information on movements and distribution of juveniles both within and outside of the GAB, as well as providing estimates of mortality and growth rates of individual SBT (Fig. 8.4). In the early 1990's, to better understand the movements of juvenile tuna, CSIRO initiated extensive development of archival tags that could provide quantitative data on how fish use the environment (Gunn et al. 1994). This work, in conjunction with related research developments elsewhere in the world, has resulted in the availability of highly efficient archival tags for marine species (e.g., Gunn and Block 2001; Nielsen et al. 2009) and has provided important insights into SBT movements (Gunn 1999; Bestley et al. 2008; Bestley et al. 2009; Basson et al. 2012). A large multi-nation multi-region archival tagging study has revealed even more variation in the movements of juvenile SBT (Basson et al. 2012). Some 568 tags were released on age two–four SBT in five ocean regions (from the western Indian Ocean to New Zealand) and over 75 tags (13%) have been recaptured to date, and demonstrated the potential power of these tags to provide the data necessary to start integrating spatial patterns into the assessment of pelagic resources (e.g., Nielsen et al. 2009).

Archival tags have been critical to understanding the timing of juvenile SBT migrations, showing that juveniles start to appear in the GAB around November/ December (Bestley et al. 2009; Basson et al. 2012). Whilst in the GAB, juvenile SBT aggregate in large schools, which spend substantial time in the upper 100 m of the water column mostly during the day with deeper average depths observed in individuals

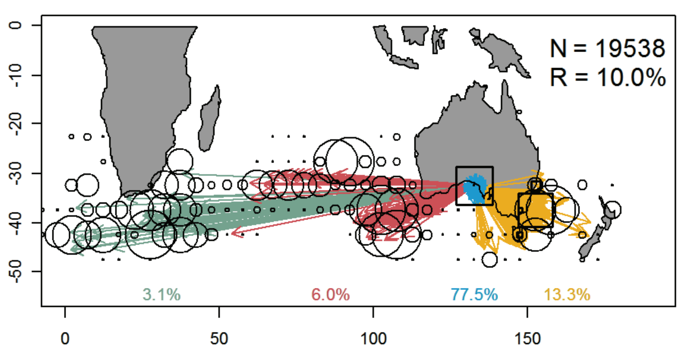

Figure 8.4. Movement of juvenile (age two) southern bluefin tuna from the Great Australia Bight as determined from recapture of 19,538 conventional tags released in the 1990's. The colours correspond to regions in which the recapture occurred, with percentages showing the recovery of tags in each area. A total of 10% of tagged fish were recaptured as age three or four year old fish. Circles show fishing effort in the southern ocean by all fleets.

during the night (Bestley et al. 2009). It is this surfacing behaviour that commercial purse seine operations take advantage of by using spotter planes to locate and target schools of juvenile SBT.

Data on the surface distribution of SBT in the GAB between January and March has also been collected since 1993 as part of a scientific aerial survey. The survey uses experienced aerial tuna spotters to locate SBT schools while searching along pre-set transect lines and to estimate the biomass in each school. The primary purpose of the survey is to provide an annual index of juvenile SBT relative abundance in the GAB (Cowling et al. 2003; Eveson et al. 2014). Since 2002, data on the surface distribution of SBT in the GAB have also been collected by commercial tuna spotters whilst engaged in purse seine operations (Basson and Farley 2014). Both the aerial survey and commercial spotting data sets show that the highest densities of SBT schools are usually found in a band inside and parallel to the continental shelf break, although the precise location varies (Fig. 8.5). In recent years, the area of highest school density has moved from the central GAB (between ~130° and 133°E) to the east (~134°E) following the shelf break (Basson and Farley 2014), although inshore areas around lumps and reefs continue to be important for small/young SBT.

Data from archival tagging experiments suggest that during the summer in the GAB, feeding success of juvenile tuna is high (Bestley et al. 2010), as they take advantage of enhanced productivity supporting spawning aggregations of small pelagic fishes (Ward et al. 2006). This enhanced productivity supports high juvenile growth rates (Bestley et al. 2010). Archival tags that are internally implanted in the peritoneal cavity close to the stomach of SBT record changes in internal body temperature that can be used as indicators of feeding events (Gunn et al. 2001; Bestley et al. 2008) and can be used to estimate relative intake size (Bestley et al. 2008). Individual foraging success has been observed to be highly variable with feeding predominantly occurring during the day and in particular, around dawn (Bestley et al. 2008), supporting assumptions that SBT are visual predators. Foraging occurs both during residence and migration phases and during migrations phases particularly so during directed movement (Bestley et al. 2008; 2010). Variation observed in feeding success may reflect differences in the availability of prey or the prey type targeted by individuals. Whilst foraging in the GAB, juvenile SBT move rapidly between inshore and shelf break habitats (Davis and Stanley 2002; Willis and Hobday 2007), avoiding cool upwelled water, likely associated with prey movements. Simulations of movements based on data from acoustic tagging experiments suggest that short movements between inshore topographic features are common—likely reflecting inshore foraging (Willis and Hobday 2007). Individuals have been observed to exhibit short-term school fidelity, suggesting that in the GAB schools break up and reform relatively often (Willis and Hobday 2007). High variability in foraging success observed in juvenile SBT whilst in the GAB suggests that movements may also be driven by social factors rather than individual-based decision making (Gunn and Block 2001) and that particular topographic features may be important for resting or for use as navigational references (Cowling et al. 2003; Willis and Hobday 2007; Bestley et al. 2008).

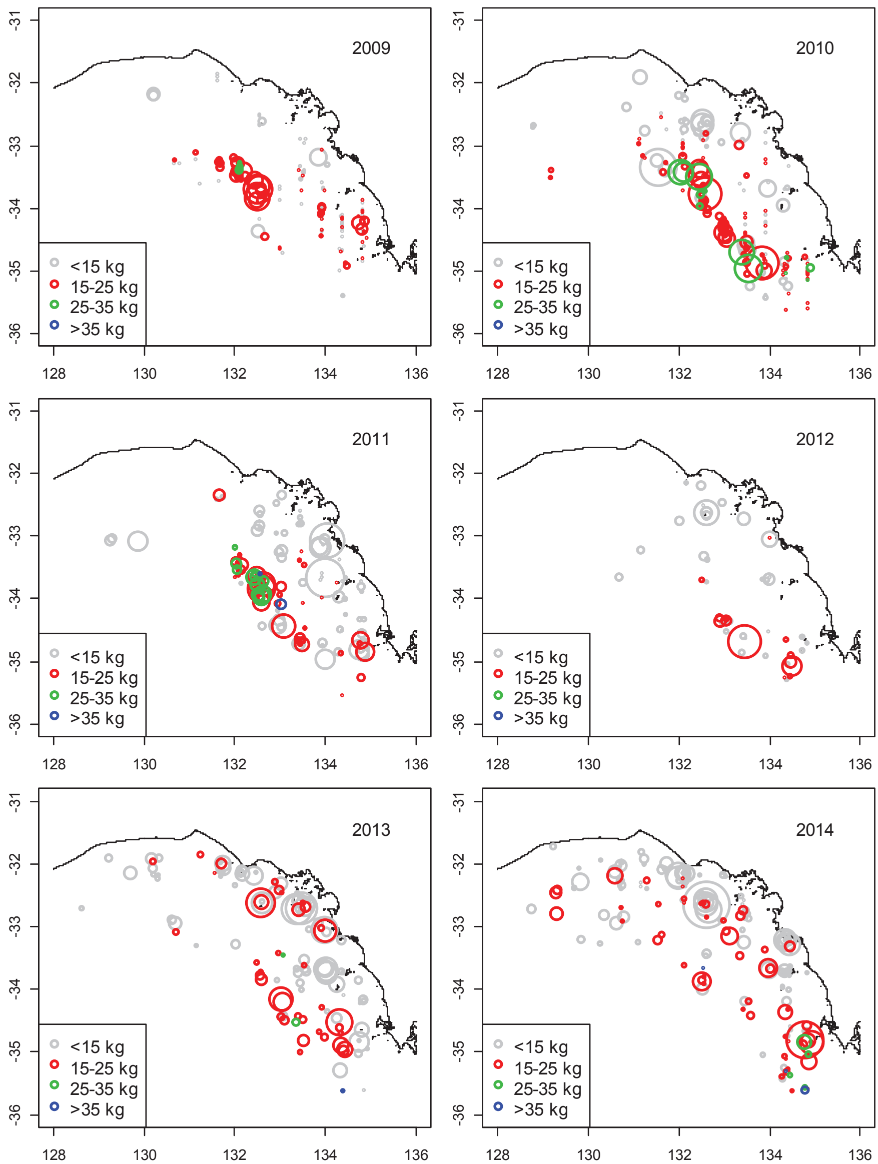

Figure 8.5. Distribution of schools of southern bluefin tuna varies over the Great Australian Bight during the austral summer (Jan–Mar) based on aerial survey data for 2009–2014.

Movements of juvenile SBT outside the GAB

Towards the end of the austral summer when most juveniles begin to leave the GAB, many undertake occasional exit forays before permanent departure for the winter grounds. Migration schedules are highly variable with individuals departing from the

GAB as early as March and as late as August (Bestley et al. 2009; Basson et al. 2012). The majority of fish move west to the Indian Ocean, with the remainder moving east to the Tasman Sea (Basson et al. 2012). Movements to the west or east are not always direct, with some fish spending time in the waters around Tasmania before migrating onwards (see example movement tracks in Fig. 8.6). During the austral winter-spring period, SBT that have moved into the Indian Ocean are widely distributed between about 30–45°S. Some individuals that migrate into the Indian Ocean continue to move further west toward South Africa, while others remain resident in the mid-Indian Ocean (Basson et al. 2012). Long-term archival tag deployments on juvenile SBT have shown that individuals do not always migrate to the same area or even the same ocean each winter, with some spending the winter in the Indian Ocean one year and then in the Tasman Sea the following year (Basson et al. 2012).

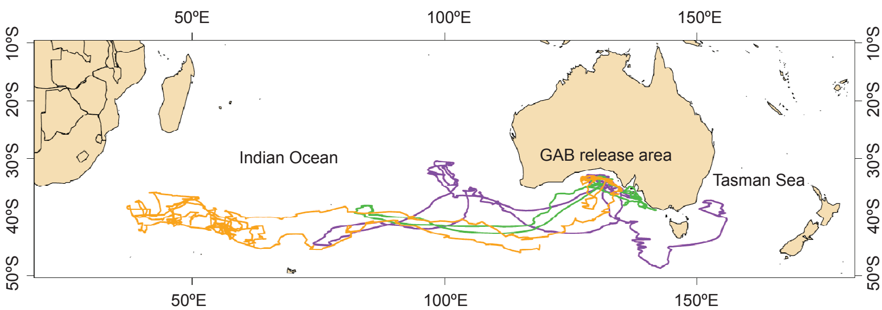

Figure 8.6. Example of three juvenile southern bluefin tuna inter-oceanic migration tracks estimated using state space models using methods described in Basson et al. (2012) and Pedersen et al. (2011).

The coldest waters inhabited by juvenile SBT lie in the most southerly latitudes where water is deeply mixed, between the southern edge of the sub-tropical front and the northern edge of the sub-Antarctic front, known as the Sub-Antarctic Mode Water (Belkin and Gordon 1996). Surface waters may be only 12°C, declining to 7°C below a sharp thermocline at ~100 m (Bestley et al. 2008). Overall, SBT do not distribute to maintain preferred depth or temperature ranges, but rather show highly plastic behaviours in response to changes in their environment (Bestley et al. 2009). In analyses of the statistical patterns of movement in relation to SST, Patterson et al. (2009) found indications that more rapid movement was associated with cooler water and that residency periods coincided with warmer phases. However this study was based on a small sample size and further investigation with data from more individuals is required to ascertain whether this pattern holds more generally.

Changes in the migration patterns of juvenile SBT have been recorded between the 1990's and 2000's, with fewer SBT moving east out of the GAB and into the Tasman Sea in the 2000's than occurred previously (Basson et al. 2012). Declining populations have been suggested as a possible driver for changes in the migration pathways used by juvenile SBT; however, changing environmental conditions may also play a role given that local environmental conditions, particularly SST and chlorophyll, have been found to influence their movement and habitat selection (Basson et al. 2012).

The long distance migrations of SBT have piqued the curiosity of many scientists, yet a mechanistic physiological explanation is lacking. Given that SBT, along with other bluefin species, undertake migrations over thousands of kilometres (Gunn and Block 2001) and can return to the same locations annually, sensory mechanisms and behavioural strategies that increase the accuracy of long-distance movements should be strongly favoured by natural selection (Willis et al. 2009). Archival tag data from the bluefin tuna species often show distinctly shaped ascents and descents at dawn and dusk known as spike dives (Gunn and Block 2001; Willis et al. 2009). Explanations that have been proposed for spike diving by tuna include (1) locating the base of the mixed layer, (2) surveying prey fields, (3) performing a geomagnetic survey for navigation, (4) undertaking a general environmental survey of the water column, and (5) foraging (Gunn and Block 2001). Willis et al. (2009) posit that spike dives may represent a behaviour related to navigation, as they are similar among fish, and are mirror images at dawn and dusk. Anatomical evidence for elaboration of the pineal organ, which is light mediated and has been implicated in navigation in other vertebrates also supports a navigational role in SBT (Willis et al. 2009). Additional experimental work is needed to determine the importance of the pineal gland and the magnetic field in tuna navigation—a difficult task given the size and physiology of these animals.

Distribution and Movement of Older Life Stages

Distribution of sub-adults and adults

Relatively little is known about movements of sub-adult SBT (ages five–10) due to their widely dispersed nature and the subsequent logistical difficulties in catching and tagging these age groups Commercial catch data suggests these fish disperse throughout southern temperate waters. In the Australian region, both sub-adult and adult SBT occur seasonally during the austral winter throughout the Tasman Sea. Sub-adults are also known to occur in the waters east of South Africa and can undertake movements around the south of Africa and into the Atlantic Ocean (CSIRO, unpubl. data). There is some evidence that sub-adults and potentially young, mature adults remain in the Tasman Sea year-round (Evans et al. 2012). In waters around Tasmania, sub-adults have been observed to forage on a high diversity of fish, cephalopods and crustaceans. Similar to juveniles, feeding has been estimated to occur predominantly during the day and in particular at dawn (Young et al. 1997).

Sub-adult and adult SBT caught in the Tasman Sea and tagged with pop-up satellite archival tags demonstrate temperature preferences for waters of 18–20°C and waters <250 m, although spend time at depths >600 m and demonstrate diel variation in diving behaviour for periods of time (Patterson et al. 2008). Within this data set, significant time amounts of time spent in waters >250 m and <18°C was limited to three localized regions: the eastern Tasman Sea, the western Tasman Sea and north-west of Tasmania at 135–145°E.

Whilst in the Tasman Sea region, sub-adults and adults encounter several water masses: the southward flowing East Australia Current, sub-Antarctic water, and the Tasman Sea which is bounded to the north by the Tasman Front. Along the east coast of Australia, the seasonal cycle of SBT habitat is strongly influenced the East Australia Current (EAC; Ridgway and Godfrey 1997). The EAC is a southward flowing western boundary current between 18°S and 42°S (Tasmania), and is a region of intense eddy activity. The current is generally stronger and closer to the coast in summer (December–March) than in winter. In warmer than average years, when the EAC moves further south, thermal habitats preferred by sub-adults and adults are compressed to the south, while in cooler years, preferred thermal habitats are found further north than usual (Hobday et al. 2011).

Migration of adults to the spawning ground

Adults tagged with pop-up satellite tags (PSAT) in the Tasman Sea region have been observed to begin to move south and into waters around Tasmania towards the end of the austral spring/beginning of summer (Fig. 8.7). They then move across the south of Australia and pass around the south-west of Australia moving north along the western coastline of Australia to the spawning ground (Patterson et al. 2008; Evans et al. 2012).

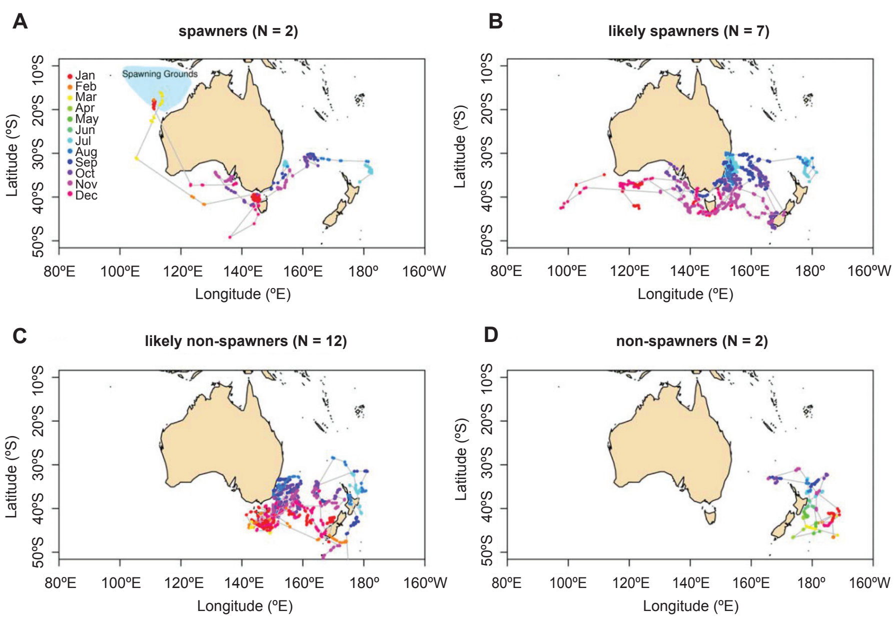

Figure 8.7. Movement paths of adult southern bluefin tuna categorized by putative spawning behaviour. (A) spawners showing movements from the tagging region to the spawning grounds (defined in blue); (B) likely spawners which made large westward migrations; (C) likely non-spawners remained in the Tasman Sea region until late in the spawning season and (D) non-spawners which remained resident in the Tasman for a full spawning cycle. Source Evans et al. 2012.

Once movement west was initiated, migration between waters around Tasmania and the spawning ground is directed and relatively quick (on the order of ~110 days).

Similar to juveniles, migration schedules of adults are highly variable, with individuals departing the Tasman Sea from September through to December (Patterson et al. 2008). Choice of winter foraging ground may, however, influence both onset of departure and subsequent arrival times on the spawning ground. Individuals tagged in the Tasman Sea have been estimated to arrive at the spawning ground in the second half of the season, potentially contributing to the second peak in abundances observed on the spawning ground (Evans et al. 2012). While SBT are captured by longline fisheries on the spawning ground in almost all months of the year, peaks in abundance have been observed to occur during October and February, also suggesting two peaks in spawning activity (Farley and Davis 1998).

While some younger fish have been captured on the spawning ground (e.g., age five), the age at which 50% of fish are mature is estimated to be around 10–12 years (Davis and Farley 2001; Gunn et al. 2008; Shimose and Farley this volume). It is unclear what proportion of sub-adult SBT migrate to the spawning ground and what proportion of young mature fish remain on winter foraging grounds rather than migrating to the spawning ground in each year. It is also unknown how long individuals remain on the spawning ground, or if adults continue to migrate annually to the spawning ground throughout their lifetime. Reproductive studies of female SBT from the spawning ground suggest that once females finish spawning, they leave the spawning ground immediately (Farley and Davis 1998). Commercial catch data suggests they move south into southern temperate waters to forage, although the pathways for this movement are unknown.

Catches of SBT in the spawning ground region suggest that individuals may vary in their vertical distributions. For example, smaller individuals are more likely to be caught deeper than larger individuals (Davis and Farley 2001). The mechanisms behind this apparent size partitioning on the spawning ground are unknown, but it is thought that a number of factors may be associated with this behaviour. It may be related to spawning activity, which is restricted to surface waters (Davis and Farley 2001). The inference is that larger fish spawn for longer than smaller fish and are likely to spend more time in shallower waters making them more susceptible to surface fishing gear than smaller fish (Davis and Farley 2001). Larger fish may also have more developed thermoregulatory capabilities than smaller fish, which might result in larger fish being able to spend more time in warmer surface waters than smaller fish (Davis and Farley 2001). Data from tagging experiments on spawning fish are limited, pop-up archival satellite tags deployed on adults have only been able to provide limited data from the regions of the spawning ground, but suggest that temperatures as high as 30°C are experienced by individuals (Patterson et al. 2008; Evans et al. 2012; Fig. 8.8). Electronic tagging on the spawning ground has also demonstrated that SBT can move rapidly back to temperate waters (Itoh et al. 2002).

PSAT data are additionally limited because they are summarized onboard the tag prior to transmission via satellite, so identification and definition of spawning has not been established. Nevertheless, individuals migrating to the region of the spawning ground were observed to switch to more surface orientated behaviour, spending greater amounts of time in waters <150 m. Time in shallower waters was punctuated by dives

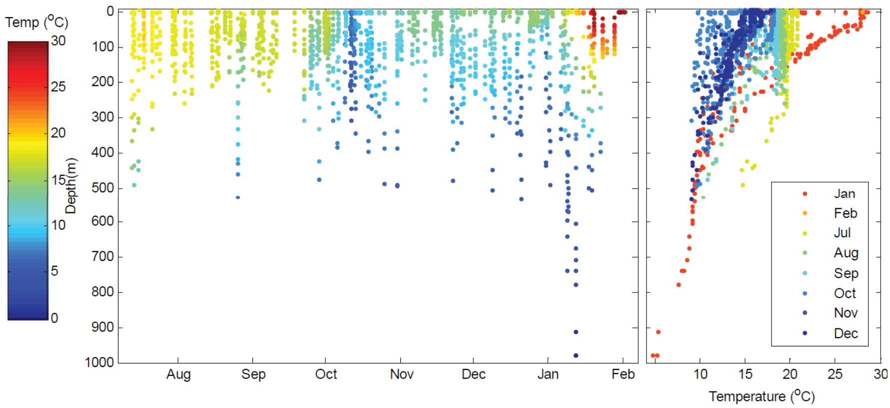

Figure 8.8. Temperature depth data from a pop-up satellite tag on an SBT which undertook a migration to the spawning grounds. The left panel shows the data through time with colours representing water temperature at depth (y-axis). The right hand panel aggregates this data by month and shows the variability in water masses encountered by this individual. Source: Patterson et al. (2008).

to >500 m, suggesting the potential for thermoregulatory behaviour (Patterson et al. 2008) in response to high surface water temperatures. Further data on the behaviour of adult SBT while on the spawning ground is needed if key descriptors of spawning, residence on the spawning ground and contributions to annual egg production are to be established.

Management Implications based on Distribution and Movements

Despite rapid advances in both electronic tagging technologies and the methods used to detail the movements of pelagic species, direct application of data from electronic tagging deployments into fishery management applications is still rare (Hobday et al. 2009b; Sippel et al. 2014). In this regard, SBT is one of the few species where information on the movement, distribution and habitat preference based on electronic tagging has supported management (Hobday et al. 2014).

In eastern Australia, information on habitat preference (surface and subsurface water temperatures) in combination with data from electronic tag deployments on sub-adults and adults is used to generate real-time habitat maps, indicating areas of high, medium and low occurrence probability (Hobday and Hartmann 2006; Hobday et al. 2009c; Fig. 8.9). Fisheries managers use this information on the likely presence of sub-adult and adult SBT to create several zones of varying access by the longline fishery. The aim of varying access to these zones is to reduce unwanted capture of SBT by fishers targeting yellowfin tuna (*Thunnus albacares*) that do not have quota to catch SBT and restricting access to areas of high SBT probability to those fishers that have quota for SBT (Hobday et al. 2009c; Hobday et al. 2010). The spatial allocation of the management zones is updated every two weeks, based on results from the model (see http://www.afma.gov.au/managing-our-fisheries/fisheries-a-to-z-index/southern-bluefin-tuna/notices-and-announcements/). Information on preferred habitat as derived

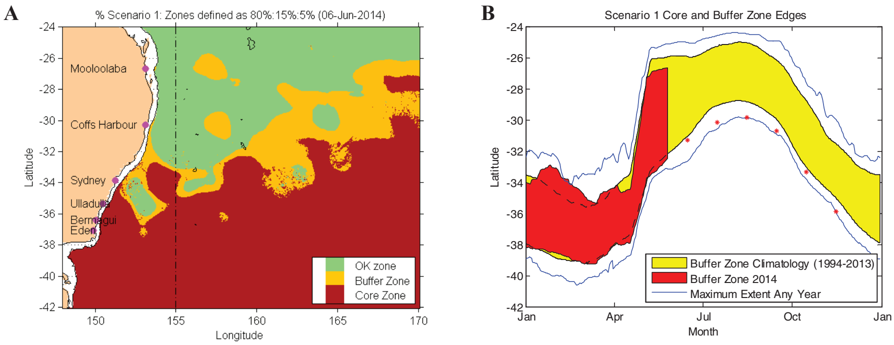

Figure 8.9. (A) Distribution of SBT habitat zones (Core = 80% probability of tuna, buffer = 15%, and OK = 5%) in eastern Australia based on the Hobday et al. (2011) habitat prediction model for June 6, 2014. (B) Annual climatology showing the mean position of the buffer zone throughout the year (yellow band) based on data from 1994 to 2013. Blue lines indicate the maximum northerly (5%) and southerly extent (5%) of buffer habitat that occurred in any year in the period considered. The position of the buffer zone in the current year is depicted by the red band. Red stars show the boundary of the core zone for the one to five month forecasts.

from electronic tag data has also been used to make seasonal forecasts of likely sub-adult and adult SBT distributions up to three months into the future (Hobday et al. 2011; Fig. 8.9). Managers use this forecast information on projected SBT distribution as a guide for future fishery interactions, rather than any direct decision making.

A similar habitat prediction approach is being implemented in the GAB, with juvenile SBT distributions forecast up to three months in advance, based on habitat preferences determined from electronic tag data (Eveson et al., in press; www.cmar.csiro.au/gab-forecasts/index.html). The forecasts aim to assist fishers to plan vessel deployments for upcoming fishing operations in an effort to improve the economic efficiency of the fishery and does not allow increased catches in this quota limited fishery.

Similar to other widely distributed species, information on SBT movements and distribution is important for improving population assessments (Eveson et al. 2012; Evans et al. 2014). The current operating model used by the CCSBT to develop the management procedure for SBT is non-spatial (Hillary et al. 2014); however, the CCSBT has recognized that a spatial model would be desirable, and the development of such a model has been highlighted as a future priority (Anon 2012). Spatial models require data for estimating fish movement, with tagging data often being the best or only source. Conventional tag data may not be sufficient for describing and estimating movement at the spatial and temporal scales required by the spatial model, particularly since movement can be confounded with mortality, tag reporting rates and the distribution of the fishing fleet; the more detailed information on movement provided by electronic tags can potentially be very useful in this regard. Eveson and Basson (unpublished data) found this to be true for SBT when they applied a spatial tag-recapture model for estimating natural mortality, fishing mortality and movement to data from juvenile SBT tagged in the 2000's. With only conventional tagging data, the movement estimates were inconsistent with our knowledge of juvenile SBT migration patterns and fishing mortality estimates in some regions were highly unrealistic. Including archival tag data in the model produced much more credible estimates, as well as estimates with greater precision. The current operating model for SBT only includes conventional tag-recapture data, but the results from Eveson and Basson (unpublished data) indicate that it will be important for a spatial version of the model to also include archival tag data.

Potential Changes in Movements and Distributions Under a Changing Climate

Projected changes in the physical oceanography of the ocean have the potential to alter the habitat suitability and distribution of SBT in many regions. This may result in changes to the timing of migration (phenology), dispersal of larvae, use of the continental shelf by individuals, and the spatial and temporal use of the spawning region. Changes in the Indian Ocean have been documented with waters off western Australia warming and the Leeuwin Current weakening slightly (Pearce and Feng 2007). Limited warming and southward movement of the frontal zones has also been documented in the Indian Ocean (e.g., Pearce and Feng 2007; Rolland et al. 2010). Changes in other variables, such as chlorophyll, have been reported (e.g., Boyce et al. 2010), but remain contentious (Mackas et al. 2011). The GAB has been reported to experience minor warming, however, the strength and persistence of this is difficult to discern from inter-annual variability over the same period of time (Lough and Hobday 2011). Along eastern Australia, the EAC has been observed to have strengthened and warmed, and is considered one of the fastest warming areas in the Southern Hemisphere (Ridgway 2007; Hobday and Pecl 2014).

Warmer waters on the spawning ground and changing productivity associated with changes to the vertical structure of the ocean may result in the spawning region becoming even more unproductive. Continued changes in oxygen content in deeper ocean layers have been reported from the Indian Ocean (Stramma et al. 2010) and if this area expands in the future it may also restrict SBT to shallower warmer waters on the spawning ground, which may have physiological consequences on the larger fish. In southern Western Australia, changes in the strength of the Leeuwin Current (Pearce and Feng 2007) and wind-driven coastal upwelling cells may impact on the productivity of seasonal feeding grounds for juveniles. The direction of change (positive/negative), however, is uncertain as most global climate models currently cannot conduct projections at the spatial resolutions required for regions such as the GAB (Hobday and Lough 2011), and downscaling is required (e.g., Hartog et al. 2011). If changes in productivity are negative, the spatial and temporal extent of utilization of waters off south-western Australia and in the GAB by SBT may also decline. While the GAB has warmed in recent years (Lough and Hobday 2011), climate projections suggest that winds will intensify, resulting in increased upwelling and local productivity (Hobday and Lough 2011), thereby potentially producing increased favourable conditions for SBT.

Projections based on statistically downscaled global climate models suggest that on the east coast of Australia, preferred thermal habitats for sub-adult and adult

SBT will be found further south (Hobday 2010; Hartog et al. 2011). In this region, the overlap of sub-adult and adult SBT with yellowfin tuna is projected to decrease slightly in the future (by 2060). This may result in a decrease in unwanted bycatch of SBT in the longline fishery (Hartog et al. 2011). In the southern Ocean, the frontal zone between the sub-Antarctic waters and temperate waters may move southwards, and if primary production is light-limited, the growing season may be shortened and the food chain less productive. Overall, impacts of climate change on SBT remain speculative, and are generally based on logical scenarios rather than any direct evidence. Ongoing monitoring is required to detect any response to climate change, and investigating SBT responses to climate variability may offer the greatest insight at this time (Hobday and Evans 2013).

Remaining Unknowns and Prospects for the Future

Currently, there is no single whole-of-life movement model for SBT. Spatial models for certain stages of the SBT life cycle have been developed, informed by fisheries and tagging data (e.g., Eveson et al. 2012). Integration of data on the movements and preferred habitats across different life stages will allow more holistic assessments of the impacts of external forcings on the population such as those associated with fishing and climate for example. In this chapter, we have identified a range of questions that still remain regarding the distribution and movements of SBT at different life stages. We suggest five areas that deserve additional attention as summarized here:

- Improved understanding of the movement pathways for larvae on and off the spawning ground, the spatial extent of the spawning ground, and seasonal and inter-annual variability in the spatial extent of the spawning ground. This information will be important for determining environmental influences on larval survival and in assessing spatial and temporal overlaps of fishing effort with adults on the spawning ground.
- Determination of influences on movement patterns on age one and two SBT in southern Western Australia, including resolving migration pathways after their first austral summer. This information will be important for assessing the proportion of the population entering southern Australian waters and identifying other important regions for the first year of growth and survival.
- Improved understanding of the movements and habitat use of sub-adult fish after they leave the GAB and before they reach maturity. Catch data from fisheries suggests the fish occupy a wide range of habitats, but the behaviour, physiological performance and habitat preference of SBT in these regions is unknown. This information will be important for establishing life history parameters for this component of the population, factors influencing onset of maturity and establishment of annual migrations to the spawning ground and resolving the proportion of the young, mature component of the population that skips migrations to the spawning ground (and therefore does not contribute to the spawning biomass).
- Experimental exploration of the physiological basis for navigation during the basin scale migrations performed by SBT using both captive and wild fish (see

Willis et al. 2009). While this may not be an easy task, large scale navigation is a remarkable behaviour, and will continue to stimulate the interest of many biologists, even if direct relevance to management is limited.

- Resolving physiological triggers for spawning migrations, and the behaviour of adults on the spawning ground and associated reproductive activity. This information will be important for establishing robust reproductive parameters for the population and determining robust measures of the spawning stock biomass.

Addressing these issues will require innovative data collection approaches, interdisciplinary studies, collaboration between various nations, and a commitment to long term studies. While the population of SBT is expected to recover to 20% of unfished biomass under most modelled scenarios of the current management scheme (Hillary et al. 2014), improved understanding of the movement behaviours of particular age groups and changes in the movement behaviours of the species across life stages in response to a changing climate will assist future management of this valuable and iconic species as new threats and challenges emerge.

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