Pelagic Fishes and Sharks

Alistair J Hobday[1], Shane Griffiths[2], Tim Ward[3,4]

[1]CSIRO Climate Adaptation Flagship, Hobart, Tas, 7001, Australia.
[2]CSIRO Marine and Atmospheric Research, PO Box 120, Cleveland Qld 4163, Australia
[3]South Australian Research & Development Institute, PO Box 120, Henley Beach, SA 5022, Australia; School of Biological Sciences, Flinders University, SA, Australia
[4]School of Earth and Biological Sciences, Adelaide University, SA, Australia.

Hobday A.J., Griffiths S. and Ward T. (2009) Pelagic Fishes and Sharks. In *A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009* (Eds. E.S. Poloczanska, A.J. Hobday and A.J. Richardson), NCCARF Publication 05/09, ISBN 978-1-921609-03-9.

Lead author email: Alistair.Hobday@CSIRO.au

Summary: Pelagic fishes occupy the surface waters from the coast to the open ocean. There are approximately 260 pelagic species around Australia. While some of the most well known are the large offshore apex predators such as tunas, billfish and sharks, the mid-trophic level small pelagic species, such as sardines, anchovies, and squids, are critical to ecosystem function. Pelagic fishes of all sizes have high ecological, economic and social value. The observed impacts of climate change are restricted to changes in local abundance and distribution, particularly southward range extensions. Little is known regarding changes in phenology, physiology or community structure. In future, general ocean warming around Australia and in particular on the east coast, in combination with predicted strengthening of the East Australia Current, is likely to see the distribution of a range of pelagic species extend southwards from present limits. On the west coast, changes in the strength of the Leeuwin Current are likely to have major implications for the distribution and abundance of some species, including western Australian salmon and Australian herring in waters off South Australia. Changes in productivity, for example due to increased coastal upwelling, may lead to increases in abundance of some species, particularly of small coastal pelagic fishes, such as sardines and anchovy, in the large upwelling system between Cape Otway and the central Great Australian Bight. Confidence in observed impacts is generally low to medium as observed changes are limited. Similarly, confidence in future impacts is also generally low to medium, as lack of data on observed impacts makes prediction difficult. Knowledge gaps include an absence of information on species habitat tolerances and empirical models for future prediction of species ranges and abundances. With regard to species, impacts on sharks are poorly known compared to the teleost fishes, and impacts in southern Australia have been better reported than in northern Australia. The adaptation potential is high for many species because of significant opportunity for large scale movements of most pelagic species, and thus the main impacts are likely to be localized changes in composition of pelagic fish community. The impact of change in community composition is unknown. To address the knowledge gaps, focused regional studies on the relationship between climate variables and the distribution and

abundance of species of high interest are one way to improve understanding of the potential impacts of climate change. Predictive modelling at appropriate scales is also reliant on downscaled climate model which can generate a range of environmental variables at the scale of individual fish movements.

Introduction

Pelagic species occupy the open ocean which is the largest ecosystem on earth, comprising around 70% of the planet's surface. Wide ranging iconic species including tuna, billfish (swordfish and marlin) and sharks are the best known pelagic fishes. However, smaller species, such as sardines and anchovies, are also crucial elements of the pelagic realm and are particularly sensitive to the impacts of climate variability and climate change (e.g. Jacobsen et al. 2001, Chavez et al. 2003).

Pelagic fishes can be categorised in several ways. For example, small pelagic species, with adult body size less than 50 cm, and large pelagic fishes, with adult body sizes greater than one metre, have been distinguished. Species with adults between these sizes, such as skipjack tuna, have been typically grouped with the large pelagic species. Offshore (oceanic) and coastal (neritic) groups are also often identified, with small pelagic fishes most commonly being found in shallow embayments and shelf waters and large pelagic fishes ranging widely offshore, including both continental shelf waters and the open ocean. Small pelagic fishes typically occupy intermediate trophic levels, whereas large pelagic species are typically high-level or apex predators (Hunt and McKinnell 2006).

In Australian waters, there are distinct tropical and temperate Australian assemblages, with the dynamic line of integration between the two groups located approximately between Shark Bay and Exmouth Gulf on the west coast and Hervey Bay and Moreton Island on the east coast. In the tropics, different assemblages of small pelagic fishes occur in the Great Barrier Reef, Gulf of Carpentaria, across Northern Territory and the North West Shelf. In temperate Australia, the pelagic fish assemblages can be best divided into eastern, southern and western groups, where the dominant oceanographic features are the East Australia, Flinders and Leeuwin Currents, respectively.

Offshore large pelagic fishes

The oceanic pelagic fishes that occur in waters overlying the Australian continental shelf include tunas (e.g. *Thunnus spp., Katsuwonus pelamis*), swordfish (*Xiphias gladius*), billfish (i.e. marlin, sailfish and spearfish) and pelagic sharks (e.g. blue shark, *Prionace glauca* and white shark, *Carcharodon carcharias*). Many of these species occur throughout the southern hemisphere and have the ability to reach depths of 1000 m, but are generally found in the upper waters of the ocean (0-200 m). The east coast of Australia between southern Queensland and Lord Howe Island been identified as a biodiversity 'hotspot' for large pelagic fishes (Worm et al. 2003, Figure 1**)**. Unlike most of the world's hotspot regions, where catch rates are relatively low, the Australian biodiversity hotspot for pelagic fish on the east coast of Australia is located in an area of high catch rates and fishing effort (Campbell and Hobday 2003, Campbell 2008).

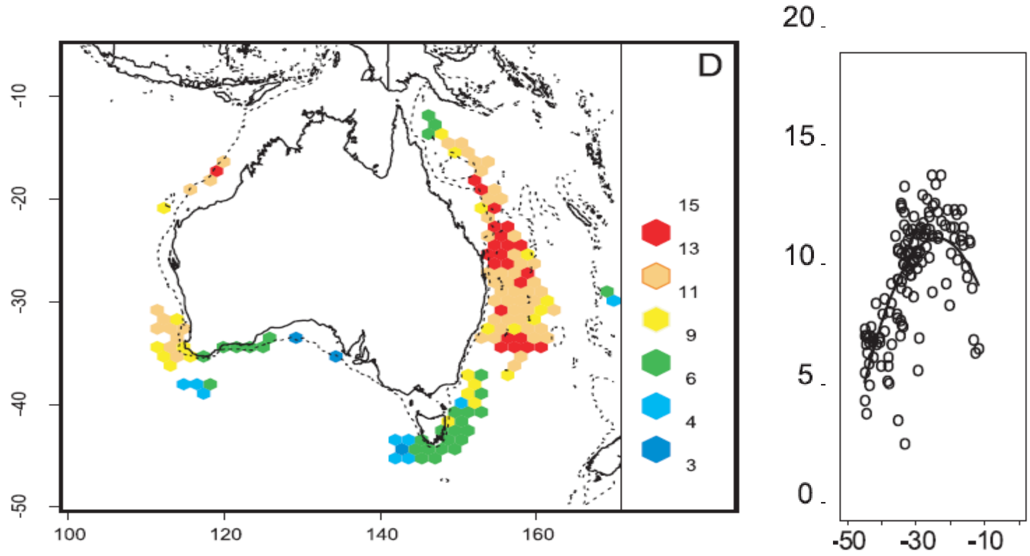

Figure 1: Diversity patterns in large pelagic fish predators (from Worm et al. 2003). Left hand panel: Predator diversity in the ocean predicted from Australian observer data. Color codes indicate levels of species diversity calculated by rarefaction and expressed as the expected number of species per 50 individuals. Red cells indicate areas of maximum diversity, or hotspots. The dotted lines represent 1,000-m isobaths, identifying the outer margins of continental slopes. Right hand panel: Predator diversity (species per 50 individuals) as a function of latitude for Australia.

Coastal large pelagic fishes – tropical species

In tropical waters of Australia, the large coastal pelagic fish fauna comprises around 50 species of tunas, mackerels, billfishes and sharks. The most abundant tropical species tend to utilise pelagic habitats within the confines of the continental shelf in waters less than about 200 m. These include longtail tuna (*Thunnus tonggol*), mackerel tuna (*Euthynnus affinis*), Spanish mackerel (*Scomberomorus commerson*), Indo-Pacific sailfish (*Istiophorus platypterus*) and black tip sharks (*Carcharhinus tilstoni* and *C. sorrah*). Several other species are reasonably common, including cobia (*Rachycentron canadum*), grey mackerel (*Scomberomorus semifasciatus*) and dogtooth tuna (*Gymnosarda unicolor*). However, these species are more commonly associated with deepwater reefs, rather than open water.

Coastal large pelagic fishes – temperate species

The large coastal pelagic fish fauna of Australia includes several species that are the sole or main local representative of their family including tailor (*Pomatomus saltatrix*, Pomatomidae), eastern and western Australian salmon (*Arripis trutta* and *A. truttaceus*, Arripidae), barracouta (*Thyrsites atun*, Gempylidae), snook (*Sphyraena novaehollandiae*, Sphyraenidae) and silver trevally (*Pseudocaranx dentex*, Carangidae). Although there are, or at least have been, significant commercial fisheries for these species in several locations, they are now taken mainly by recreational fishers. Patterns of distribution and relative abundance vary among species. Tailor (*Pomatomus saltatrix*) is common along the east and west coasts of Australia, where there are significant recreational fisheries, but is rare along the south coast (Kailola et al. 1993). There is evidence to suggest that tailor makes a northward migration along the east coast each winter-autumn to spawn which is analogous to the migration-dispersal model that has been established for the east coast of the USA

(Ward et al. 2003). In contrast, off Western Australia the eggs and larvae of tailor appear to be transported northwards into coastal nursery areas by winds that prevail during the spring and autumn spawning period (Lenanton et al. 1996).

The eastern Australian salmon (*Arripis trutta*) occurs along the east coast of Australia and as far west as Cape Otway (Vic) and the western Australian salmon (*A. truttaceus*) occurs along the west and south coasts, occasionally extending into southern NSW. The western Australian salmon spawns in Western Australia and larvae are advected eastward by Leeuwin Current. The year class strength of western Australian salmon in South Australia is positively correlated with the strength of the Leeuwin Current (Li and Clark 2004). Significant commercial fisheries for western Australian salmon still occur off Western Australia and South Australia, mainly for use as bait in rock lobster pots, but overall both species of Australian salmon are now more important to recreational fishers than to commercial fishers.

Barracouta (*Thyrsites atun*), snook (*Sphyraena novaehollandiae*) and silver trevally (*Pseudocaranx dentex*) are patchily distributed throughout temperate Australia and are taken mainly by recreational fishers (Kailola et al. 1993). However, in the 1800s and early 1900s, barracouta was the second most important species in the Australian fishing industry, after the sea mullet (*Mugil cephalus*). In the 1960s and 1970s important State-based commercial fisheries for barracouta were conducted in Bass Strait out of Victorian and Tasmanian ports. The rapid decline of this fishery in the mid-1970s has been variously attributed to the level of demand for this species (e.g. Kailola et al. 1993) and to a reduction in local abundance associated with a change in ecosystem structure (i.e. a reduction in the abundance of krill in Bass Strait) and/or the effects of fishing on the population (Dr Keith Jones, SARDI, pers. comm.).

Small pelagic fishes (temperate and tropical)

Australia's coastal small pelagic fishes, which are often surface-schooling, includes several families which are often each represented by several species (see Allen 1997, Randall et al. 1997, Gomon et al. 2008), including the Clupeidae (sardines, herrings and sprats), Engraulidae (anchovies), Carangidae (scads, jack mackerel), Scombridae (short mackerels), Atherinidae (hardyheads, silversides), Arripidae (Australian herring) and Emelichthidae (redbait). There are distinct tropical and sub-tropical assemblages of small pelagic fishes, and differences within each of these regions in the patterns of distribution and relative abundance (Kailola et al. 1993).

In temperate Australia, as elsewhere in the world, one species of small pelagic fish (commonly one with a worldwide distribution) often dominates the fish biomass in shelf waters. In many locations, the globally distributed species, sardine (*Sardinops sagax*), is the most abundant species in shelf waters. Several thousand tonnes of sardine have been taken in a single year from waters off the east coast (NSW and Victoria), South Australia and southern Western Australia (e.g. Kailola et al. 1993, Ward et al. 2006). Several other species with broad global distributions, including redbait, blue mackerel, jack mackerel, and yellow tailed scad, are also abundant in shelf waters in some parts of temperate Australia (Jordan 1994, Jordan et al. 1992, 1995, Lyle et al. 2000, Neira et al. 2008, Ward et al. 2009). During different time periods, large biomasses and fisheries for jack mackerel and redbait have occurred off the east coast of Tasmania (Jordan et al. 1992, Kailola et al. 1993, Neira et al. 2008).

A suite of very small pelagic species, including Australian anchovy (*Engraulis australis*), whitebait (*Hyperlophis vittatus*) and blue sprat (*Spratelloides robustus*), usually dominate temperate, shallow-water embayments, such as South Australia's two gulfs and Port Phillip Bay (Hoedt and Dimmlich 1995, Dimmlich et al. 2004; Rogers et al. 2003, Rogers and Ward 2007). These species typically have more restricted distributions than the larger shelf species. For example, while the anchovy genus *Engraulis* occurs globally, *E. australis* is only found in Australian waters. Similarly, the genus *Hyperlophus* (two species) is endemic to temperate Australia. Although the Australian anchovy is usually found in inshore embayments, when the abundance of sardine in shelf waters of South Australia was reduced by two mass mortality events in the 1990s, anchovy quickly expanded its distribution and increased its abundance in shelf waters (Ward et al. 2001b). This change in the species composition of the pelagic fish assemblage in shelf waters is comparable to the decadal fluctuations in the relative abundance of anchovy and sardine that have occurred in the eastern boundary current systems off the Americas and southern Africa (e.g. Luch-Belda et al. 1992).

In contrast to temperate waters, the biomass and fisheries of small pelagic fishes in tropical environments are not usually dominated by one or two highly abundant species. For example, Scombrids (*Rastrelliger*, *Decapterus*, *Scomberomorus*), carangids and tropical sardines (*Sardinella*) all contribute significantly to commercial landings in the South East Asia (FAO 1997). Many species such as short mackerels (*Rastrelliger*), scads (*Decapturus*) and tropical herrings (*Herklotsichthys*) are widespread in shelf waters throughout the Australian tropics. Similarly, several species of tropical herrings, *Herklotsichthys,* occur throughout the Australian tropics, mainly in inshore waters. In contrast, several species of tropical sardine, *Sardinella*, and two species of *Amblygaster* only occur in coastal and shelf waters between the Gulf of Carpentaria and the North West Shelf. Similarly, several species of hardyheads (atherinids) are found only on Great Barrier Reef.

Observed Impacts

The expected impacts of anthropogenic climate change on pelagic fishes can mainly be gleaned from known relationships with historical climate variability. No Australian studies have considered the potential changes in the phenology, physiology or community structure of pelagic species therefore only the limited evidence of that has been gathered to link to climate variability to changes in the abundance and distribution of Australian pelagic fishes are discussed below.

Changes in distribution of pelagic fishes

The known relationships between the distribution and abundance patterns of some large pelagic species on the east coast suggest that changes in the strength of the East Australian Current (EAC) would have dramatic effects on the distribution of a variety of pelagic species. The seasonal expansion and contraction of the EAC is linked to the local abundance of species such as yellowfin (*Thunnus albacares*) and bigeye tuna (*T. obesus*) captured in the east coast longline fishery (Campbell 2008). An increased southward penetration of the EAC may increase the suitable habitat for these species (Hobday 2009). At a finer scale the distribution of yellowfin tuna has been linked to the distribution of mesoscale environmental features such as eddies generated by the EAC (Young et al. 2001). Again, an increase in the strength of the EAC may result in increased eddy formation; these are productive feeding grounds for a suite of species.

Few studies have examined the movements of coastal large pelagic fishes in northern Australia from which the effects of climate change can be inferred with respect to potential changes in species distributions. Stevens et al. (2000) showed that carcharhinid sharks (mainly *Carcharhinus tilstoni*, *C. sorrah* and *C. macloti*) have limited movement in northern Australia, with most animals moving less than 50 km after being at liberty for up to 18 years (CSIRO 2002). Similarly, stock structure and movement studies of Spanish mackerel (*Scomberomorus commerson*) (Lester et al. 2001, Moore et al. 2003, Newman et al. 2007) show there is limited movement and the presence of several stocks in the region. In contrast, length-frequency and limited tagging data indicates that longtail tuna (*Thunnus tonggol*) uses waters off northwestern Australia as a juvenile 'nursery' habitat and undertake an ontogenetic movement southward, where they exist as adult fish along the east and west coasts of Australia (Serventy 1942, Stevens and Davenport 1991, Griffiths In Review). Here it is believed fish undertake seasonal movements moving north and south with the expansion and contraction of the East Australia and Leeuwin currents (Serventy 1956, Wilson 1981). Evidence from these movement studies indicates that the effects of climate change are likely to be species-specific. The most obvious effects are likely to be detected in species that move large distances with seasonal changes in water masses (e.g. longtail tuna). Ocean warming may increase the strength of coast currents and extend the distribution of highly mobile fish southward.

Numerous studies throughout the world have shown that small pelagic fishes are particularly sensitive to climate variations (e.g. Jacobsen et al. 2001, Chavez et al. 2003). Both the geographical boundaries between species distributions and the dominant species within an ecosystem have been shown to vary at decadal scales and be correlated with environmental variability (Lluch-Belda 1992, Stenseth et al. 2004). Anthropogenic climate change will have different effects on the small pelagic fish assemblages that occur in tropical and temperate Australia. Alterations to the East Australian, Leeuwin and Flinders Currents will be key drivers for small pelagic fishes off the eastern, western and southern coasts, respectively. Along the top-end (effectively the NT), in the Gulf of Carpentaria and in other shallow embayments around Australia, the most significant climate change impact is likely to be a direct increase in water temperature.

Increased sea surface temperatures associated with the increased southward intrusion of the boundary currents along the east and west coasts, may have resulted in the increased southward extension of the distribution of tropical and sub-tropical small pelagic fishes. For example, *Sardinella* became more prevalent in catches of purse-seine fishers of the south-western WA in late 1990s. It was hypothesised that this change could reflect a southward extension of the distribution of this species due to an increased strength of the Leeuwin Current associated with climate change and mediated by a local decline in the abundance of sardine due to the combined effects of over-fishing and mass mortality events (Gaughan and Mitchell 2000). Similarly, off eastern Tasmania in the 1990s the cold-water species jack mackerel was replaced by the East Australian Current species, redbait, which is consistent with the warming trend observed in temperature records (Ridgway 2007). However, the declines in the growth rates and age structure of fishery catches of jack mackerel could have had both environmental and anthropogenic components (Lyle et al. 2000). Changes in the fishing method (purse-seine to mid-water trawl) also confounded detection of environmental relationships (Lyle et al. 2000).

The most likely effect of climate change on tropical species is the southward extension of their current distributions. The increases in water temperatures that may occur in shallow temperate embayments are likely to favour species with tropical affinities, such as the blue sprat, *Spratelloides robustus* (Rogers et al. 2003). However, many species that occur in these environments, e.g. anchovy and sandy sprat, are eurythermal (e.g. Ward et al. 2003, Dimmlich et al. 2004) and may be able to cope with even quite large increases in water temperature. To date there is no evidence available to suggest that small pelagic fishes of tropical Australia have been adversely impacted by climate change.

Changes in local productivity

In southern Australia, juvenile southern bluefin tuna (SBT) have been the subject of several studies investigating distribution and abundance relationships to mesoscale environmental variability (Hobday 2001, Cowling et al. 2003) or to prey (Young et al. 1996). In general, the environmental linkages to abundance are not strong at the mesoscale, although problems with the spatial resolution of some biological data have confounded analyses (Hobday et al. 2004). Seasonal changes in the abundance of juvenile SBT (ages 1-5) in southern Australia are well documented. SBT are resident along the shelf during the austral summer (Cowling et al. 2003) and then migrate south during the winter. Interannual variation in SBT abundance within the main fishing grounds in the Great Australia Bight has not been linked to the environment, although variation in the arrival time of schools has been attributed to unspecified environmental factors (Cowling et al. 2003). Finally, the impact of climate change on the winter SBT feeding grounds in the Southern Ocean may be more dramatic than those in temperate coastal Australia waters (e.g. Sarmiento et al. 2004).

No increase in productivity has been observed in tropical Australia and no changes in structure or function of assemblages of pelagic fishes that could be related to climate change have been observed. No major changes in productivity are predicted for tropical Australia under most climate change scenarios.

In southern Australia, the most important current is arguably the Flinders Current, which is a cold, current that flows westward along the continental slope and is upwelled during summer-autumn between Cape Otway and the head of Great Australian Bight (Middleton and Cirano 2002). It is predicted that anthropogenic climate change may result in increases in the strength and frequency of the south-easterly winds that prevail during summer and autumn and drive upwelling. The increase in nutrient enrichment that results from upwelling supports the highest levels of primary, secondary production and fish production in Australian waters (Ward et al. 2006). The strongest upwelling events recorded in the Flinders Current system have occurred during the last decade (Neiblas et al. 2009). The rapid increase in sardine biomass that has occurred in this region since the mass mortality event in 1998 could be in part related to enhanced productivity of this system due to increased upwelling.

Variation in the availability of prey (sardines and anchovies), which are likely if climate change affects the strength of upwelling favourable winds in southern Australia (Hertzfeld and Tomczak 1997, Dimmlich et al. 2004, Ward et al. 2006; Nieblas et al. 2009), may also affect the distribution and abundance of large pelagic predators, such as SBT. Another example of how changes in oceanography can affect productivity and propagate upwards to effect predators can be seen in the effects of the change in relative dominance of the East Australian Current and the sub-Antarctic water masses off the east coast of Tasmania in 1989 (Young et al. 1996). In this warm (La Niña) year the krill, (*Nyctiphanes australis*) disappeared from the shelf ecosystem as did the key predator, jack mackerel (*Trachurus declivis)* (Young et al. 1996). This krill species is a critical component of most Tasmanian shelf foodwebs and persistent warming of the regional oceanography would have a profound effect on pelagic fishes (Young et al. 1996), cephalopods (Pecl and Jackson 2008) and seabirds (Bunce 2004). Similarly, observations of the effects of variations in oceanographic conditions on the distribution of krill have been made off southern Australia. In years of strong upwelling, krill swarms that occur normally confined to the Bonney Coast between Cape Jaffa and Cape Otway, extend westward into the eastern GAB in years. During these years, the distribution of blue whales, which come to Bonney Coast each summer to feed on krill, appears to extend further west into the eastern Great Australian Bight than in weak upwelling years (Ward unpublished data).

The expansion of habitat favoured by tropical small pelagic fishes along the eastern and western coasts would be associated with a concomitant reduction in the habitat available for temperate species, with the northern extent of the distribution of these taxa contracting southward. An increase in the strength of Leeuwin Current could increase intrusion of tropical species into GAB. Increased strength of upwelling favourable winds could increase upwelling of Flinders Current and enhance productivity in waters between the head of the bight and western Tasmania. This could results in increased production and abundance of existing species of small pelagic fishes or could cause a major shift in ecosystem structure.

Potential impacts by the 2030s and 2100s

The expected impacts of climate change will be seen first on the distribution and abundance of pelagic species. Water temperature is a key variable with regard to distribution, and around Australia the range of many species will expand to the south (Hobday et al. 2008, Hobday 2009). The impact of changes in other environmental variables, such as salinity, UV, pH and sea level are expected to be minor, based on the known relationships. Due to limited knowledge, predictions to 2030 or 2100 for particular climate change scenarios are not considered possible or realistic at this time, and so here information on the likely direction of change is the focus, unless otherwise specified.

The timing and extent of the migrations of pelagic fishes may be impacted if the timing of expansion or contraction of seasonal currents, such as the Leeuwin or East Australian Current, changes. For example, southern bluefin tuna (SBT) have a seasonal presence along the east coast of Australia (Hobday et al. 2009), which may be restricted further if Tasman Sea warming continues (Hartog et al., in review). Preliminary analyses indicate that changes may have already occurred, with fewer SBT moving to the east coast in the Austral winter (Polacheck et al. 2006). Hobday (2009) described the preferred water temperature for a suite of large pelagic fishes (tuna, billfish, sharks) and then predicted that by 2100 suitable habitat would move further south by an average of 4 degrees (~ 450 km) on the east coast and 3.5 degrees (~ 390 km) on the west coast. The area of suitable habitat was also predicted to decline on the east coast due to warming, while on the west coast, the area of suitable habitat would be similar due to an expansion into southern Australia (Hobday 2009).

Specific future habitat modelling for coastal and small pelagic fishes has not been conducted, but in a similar way, the apparent annual northward migration of sardine, blue mackerel and tailor along the east coast to spawn and/or the transportation of larvae southwards into nursery grounds and adult habitats (Ward et al. 2003) could be affected by changes in the EAC. For example, if winter water temperatures in southern increased, the extent of these northward migrations may be reduced and these species may not migrate into waters off southern Queensland to spawn. The strong positive correlation between the strength of the Leeuwin Current and the year class strength of western Australian in South Australian waters, suggests that changes in the Leeuwin Current could have major implications for the abundance of this species off South Australia.

Too little is known to speculate on changes in physiology or morphology that might be driven by climate change. A single example from the tropical Atlantic and Pacific regions indicates how physiology, changes in climate, and fishing pressure may stress fish populations (Prince and Goodyear 2006). Prince and Goodyear (2006) demonstrated that large areas of cold hypoxic water in the eastern tropical Pacific (ETP) and Atlantic oceans, occurring as a result of high productivity initiated by intense nutrient upwelling, restricts the depth distribution of tropical pelagic marlins, sailfish, and tunas. The acceptable physical habitat is compressed into a narrow surface layer. This in turn makes them more vulnerable to over-exploitation by surface fishing gears. They showed that the long-term landings of tropical pelagic tunas from areas of habitat compression have been far greater than in surrounding areas. If climate change further compresses the habitat, or the area of habitat compression increases, many tropical pelagic species could be quite sensitive to increased fishing pressures. In Australia habitat compression or expansion may occur as a result of climate-forced ocean changes. In the following sections, the impact of change in particular environmental variables is considered.

Sea Surface Temperature (ocean temperature)

Change in ocean temperature, especially in the surface layers, is expected to have an impact on the distribution of many pelagic species. Southern bluefin tuna (*T. maccoyii,* SBT) are restricted to the cooler waters south of the East Australian Current and range further north when the current contracts up the New South Wales coast. This response to climate variation has allowed real-time spatial management to be used to restrict catches of SBT by non-quota holders in the east coast fishery by restricting access to ocean regions believed to contain SBT habitat (Hobday and Hartmann 2006, Hobday et al. 2009).

Along the eastern and western coasts of Australia, the distribution of large neritic tropical pelagic species is likely to extend further southward. For example, along the east and west coasts the abundance of longtail tuna and various mackerels (*Scomberomorous* spp.) could increase in temperate locations off NSW and southern WA. Conversely, the habitat available and hence the population size for temperate species such as tailor, Australian salmon, snook, barracoutta, may contract as warm water from the tropics extends further south. In parts of NSW, this could result in the suite of large pelagic fishes changing from temperate to sub-tropical. Off Tasmania, warm temperate species could become even more prevalent.

Off the south coast of Australia, the increased strength of Leewuin Current and level of intrusion into the central GAB could introduce additional sub-tropical and sub-tropical species into this region. Reduction in sea surface temperatures during summer and autumn in waters between head of Great Australian Bight and western Tasmania could enhance the environment for cool temperate species.

Rainfall/Coastal runoff/Salinity

Changes in rainfall and salinity are not likely to influence the large pelagic species in southern Australia, as the change in salinity in the open ocean is expected to be negligible.

In contrast, changes in rainfall and salinity are likely to have a detectable effect on the distribution of pelagic fishes in northern Australia. This is due to numerous large rivers discharging large volumes of low salinity, turbid water into coastal regions where sediment plumes may extend tens of kilometres offshore (Vance et al. 1998). Considering that large pelagic fish rely heavily on their eyesight to feed, they are likely to be forced further from the coast to feed in clearer waters (Griffiths et al. 2007). Because neritic pelagic fishes are restricted to a narrow coastal habitat, constriction of an already small habitat may increase density-dependent mortality within species and increase competition among species that normally spatially partition resources (see Potier et al. 2004). Sharks primarily use their sense of smell and electroreception to locate prey (Moss 1977), so movement of larger teleost fish to offshore waters during the monsoonal season may benefit shark populations as a result of decreased competition for common prey, such as small pelagic fish.

Reduction in rainfall in eastern Australia could have implications for assemblages that occur in shallow embayments, especially in southeastern Australia where reductions in rainfall may be most significant. Most species that inhabit shallow water embayments are relatively well adapted to coping with significant variations in temperature and salinity. However, runoff is significant input of nutrients in some regions reduced rainfall could result in decreases in estuarine productivity.

Wind and upwelling

Wind indirectly impacts pelagic species through mixing of the surface waters (Cury and Roy 1989), although the direction of productivity changes is hard to predict. Pelagic regions may become more or less productive, depending on the relative balance of nutrients and light and stability for phytoplankton production (Cury and Roy 1989, Bakun and Weeks 2004). It is possible that wind may increase mixing of turbid surface waters and have the same effect on fish in northern Australia as rainfall and coastal runoff in that it may affect the ability of fish to locate prey.

Off southern Australia, an increase in the strength or persistence of southeasterly winds between the head of the Great Australian Bight (GAB) and western Tasmania and northeasterlies along east coast could increase upwelling (Neiblas et al. 2009), which could enhance pelagic production and abundance of some species of small pelagic fishes. However, large increases in wind-forced upwelling can also result in catastrophic consequences for coastal pelagic systems (Bakun and Weeks 2004).

The largest upwelling system in temperate Australia extends from the head of the GAB to western Tasmania (Ward et al. 2006, Nieblas et al. 2009). There is also a smaller upwelling system on the east coast, around Smoky Cape. Increases in the strength of winds and boundary currents that drive upwelling in both locations are likely to increase (Nieblas et al. 2009). Some species, such as sardines, blue mackerel and redbait, may benefit if this increase in wind speed lead to increased seasonal upwelling and local productivity. The species and location where an increase in abundance is most likely, is sardine off South Australia where spawning dynamics is strongly linked to upwelling (Ward et al. 2006). However, increases upwelling can also have negative impacts (Bakun and Weeks 2004), including changes in community structure (e.g. phytoplankton and zooplankton) that could in turn affect small pelagic fishes.

Upwelling regions in southern Australia are important foraging grounds for some large pelagic fishes, such as bluefin and yellowfin tuna. If upwelling becomes more intense, and production of small pelagic fishes increases, then aggregation of the large species may increase. In northern Australia, coastal upwelling is a minor process, with no expected impact on the pelagic fishes of the region.

Mixed layer depth

Some large pelagic species are constrained by physiology to remain in the warmer mixed layer (e.g. skipjack tuna). The anticipated changes according the CSIRO Mk3.5 model are minor in the regions around Australia (Tony Hirst, CSIRO pers. comm), and impacts on open ocean pelagic fishes and sharks may not be detectable, or significant. If the changes in mixed layer depth do result in changes in available habitat, such as surface compression, then impacts such as changes in fish catch are expected (e.g. Prince and Goodyear 2006). Negligible impacts for coastal pelagic fish, both large and small, are expected since they occupy shallow waters (<100 m) where mixed layer effects are minimal.

Key Points

- The main climate drivers that will impact pelagic fishes around Australia are water temperature and winds leading to changes in upwelling-generated productivity.
- The main impact of change in these drivers on large temperate pelagic species will be on their distribution. The impact on overall population size is less certain. Exploring climate relationships in offshore waters will be challenging, due to the short and patchy time-series of species abundance data.
- Increased strength of south-easterly winds during summer and autumn is likely to increase seasonal upwelling along southern coast between the head of the Great Australia Bight (GAB) and western Victoria. This region supports Australia’s largest population of sardines, which is supported by enhanced productivity associated with upwelling. If upwelling increased the size of the sardine population could increase. However, an increase in upwelling could also have significant negative impacts on community structure and function.
- Increased pelagic productivity and sardine abundance off southern Australia could be beneficial for the southern bluefin tuna that aggregate each year in feeding grounds of the central GAB. Similarly, increased upwelling off Smoky Cape (NSW) could enhance productivity and aggregation of small and large pelagic fishes off Australia’s east coast.
- The distribution of Australia temperate pelagic species is likely to move southward as water temperatures warm on both coasts, and could result in reductions in available habitat and population size for some species dependent on the continental shelf. Conversely, suitable habitats and hence population sizes,

could increase for some tropical species as more of temperate Australia becomes suitable.

- The tropical assemblage of pelagic fishes is likely to extend further southward along the eastern and western coasts. Availability of some species at particular locations may change. For example, sardine, blue mackerel and tailor are currently present in southern Queensland and northern NSW mainly during winter and autumn due to the northern spawning migration. If winter water temperatures increased significantly the extent of these migrations may be reduced and these species may no longer spawn in waters off southern Queensland.

Confidence Assessments

Observed Impacts

Large pelagic fishes

There is LOW evidence of observed impacts in large pelagic fishes. Long-term data in temperate Australia are limited to fishery-dependent data for a small number of species. There is a LOW level of agreement that climate change is affecting large pelagic fishes; much of the evidence of fish distribution shifts is anecdotal or based on limited evidence of latitudinal changes in the sizes of fish within populations (length-frequency). Very little quantitative data has been collected to base predictions of climate change on temperate or tropical large pelagic fishes in Australia.

We have LOW confidence that climate change is affecting large pelagic fish in the open ocean. No attempt has been made to link abundance or distribution to environmental variables.

Small pelagic fishes

There is MEDIUM evidence with regard to distribution changes. Changes in fishery catches off east (redbait replacing jack mackerel) and west coasts (*Sardinella* replacing sardine) are consistent with hypothesis of southward extension in the distribution of warm water species. There is a MEDIUM consensus with regard to changes in distribution. Fishery data suggesting that southward range expansions of warm water species have occurred along both the east and west coasts of Australian are confounded by effects of fishing and changes in fishing gear.

There is LOW evidence with regard to upwelling changes. Prevalence of historically strong upwelling years over the last decade off southern Australia suggest that upwelling may have increased due to climate change. Rapid recovery of sardine population off South Australia following mass mortality events suggest that strong upwelling years are favourable for sardines. There is a LOW consensus with regard to changes in upwelling. Formal comparisons of upwelling strength over last decade in relation to historical levels have not been conduced. Ichthyoplankton samples/data have not been analysed to assess potential changes in assemblages of small pelagic fishes that may occur under increased upwelling scenarios.

There is MEDIUM confidence that some small pelagic fishes in warm waters have expanded distributions southwards along the east and west coast of Australia and that habitat suitable for cool, temperate species has been reduced. There is LOW confidence that rapid increases population size of sardine off southern Australia over last decade can be attributed to increased upwelling due to climate change.

Potential impacts by the 2030s and 2100s

Large pelagic fishes

There is a MEDIUM level of evidence and a MEDIUM consensus that oceanic fishes and sharks will be impacted by climate change. Warming along east and west coasts of Australia is predicted by a range of general circulation models. Distributional models of fish response to warming suggest that this will be associated with southward increase in the distribution of these fishes on both coasts (Hobday 2009).

There is a LOW level of evidence and LOW consensus for potential changes in large coastal pelagic species in the tropics. Very little data has been collected, especially over the long-term, in order to base predictions of climate change on pelagic fishes in northern Australia. Much of the evidence of fish movements is anecdotal or observed seasonality catches of latitudinal changes in length-frequency.

We have MEDIUM confidence for large oceanic pelagic species with regard to movements in response to a warming ocean and LOW confidence for large coastal pelagic species. Distribution models have not been developed for the present or run with climate futures.

Small pelagic fishes

There is MEDIUM evidence and a MEDIUM consensus that tropical assemblages of small pelagic fishes will expand southward and that habitat available for temperate species will contract. Oceanographic models suggest that increased intrusion of EAC and Leeuwin is likely on east and west coasts, respectively. Observations suggesting that expansion of the distribution of warm water species along east and west coasts may already have occurred are moderately robust. Models predicting southward distribution changes in distributions of large pelagic species over the coming century are also likely to apply to small pelagic species.

We have MEDIUM confidence regarding southward extension of the distribution of tropical species and contraction in the distribution of temperate species off east and west coast. There is a need to use outputs from physical models and develop and apply distributional models for key species to increase confidence in nature of changes.

There is a LOW evidence and a LOW consensus that upwelling will increase. Additional modelling is needed to investigate hypothesis that upwelling will be enhanced in parts of the south and east coasts. Effects of increased upwelling on levels of productivity are also poorly understood and responses of ecosystem and small pelagic fishes to increase in productivity are difficult to predict. Analyses of ichthyoplankton samples needed to infer likely effects of increased upwelling have not been conducted.

We have a LOW confidence in predictions regarding effects of increased upwelling on east and south coasts.

Multiple stressors

Commercial fishing is the main stressor on pelagic ecosystems around Australia. Several offshore fisheries capture species are classified as fully exploited; e.g.

southern bluefin tuna, Indian and Pacific Ocean bigeye tuna (Larcombe and McLoughlin 2007). The status of other pelagic species, such as swordfish, is uncertain, while others are classified as underfished (e.g. yellowfin tuna). As part of these legal commercial fisheries, bycatch of other pelagic species such as sharks and sunfish remains a concern, with too little known of impacts and stresses. Illegal fishing for sharks in northern Australia remains a threat. Offshore waters are relatively safe from other anthropogenic impacts such as pollution and habitat modification, although open ocean oil spills may occur and threaten pelagic species (Game et al. 2009). Finally, the impact of chronic oil spillage into the surface of the ocean as part of day-to-day boat operations is unknown.

In northern Australia, three types of fishing stressors have an impact on pelagic fish assemblages in northern Australia: domestic commercial fishing, recreational fishing, and Illegal, Unregulated and Unreported (IUU) foreign fishing. The primary commercial fisheries that target pelagic fishes are the Northern Territory and Queensland Spanish mackerel fisheries (primarily line fishing), the offshore gillnet fishery that targets sharks and grey mackerel (*Scomberomorus semifasciatus*). The recreational fishery in northern Australia is expanding at a rapid rate, primarily due to expansion of the mining industry and tourism in the region. The primary target of many recreational anglers is Spanish mackerel and longtail tuna, although there is increasing interest in sailfish in regions such as Groote Eylandt. The foreign IUU fishery is believe to have had a significant impact on the pelagic fish assemblages in the region, primarily on large sharks, which they target for their valuable fins (Salini et al. 2007, Griffiths et al. 2008). Given that the IUU fishery employ methods similar to the Taiwanese fleet that operated legally in Australian waters during the 1970’s and 80’s (Stevens and Davenport 1991), they are also likely to have a significant impact on other species that they catch as bycatch, including longtail tuna, Spanish mackerel, cobia and sailfish.

Although significant catches of Australian salmon (>1000t per annum) have been taken historically in several Australian states (Western Australia, South Australia and NSW), the current commercial fisheries for large coastal pelagic fishes in temperate Australia are generally small. Small quantities of Australian salmon, tailor, barracutta, snook, silver trevally and mulloway taken by commercial fishers in several regions, mainly for local consumption. However, these species of large temperate coastal pelagic fishes are all socially and economically important to the recreational fishing industry.

In temperate Australia, stocks of small pelagic fishes have, in the main, been exploited only lightly. However, significant fisheries for small pelagic species currently operate off South Australia (sardines, TAC of 30,000 t since 2006), Tasmania (redbait, catch of ~ 5000 t in 2007) and NSW (sardine, catch of ~1800 t in 2005/06). Declines in the abundance of sardine off Western Australia and jack mackerel off eastern Tasmania have been in part attributed to overfishing, but may also have been associated with climate change impacts. The most spectacular reductions in the abundance of a small pelagic species in temperate Australia were the mass mortalities of sardine in 1995 and 1998/99, which each killed up to 70% of the adult population, and may have been caused by the anthropogenic introduction of an exotic herpes virus (e.g. Whittington et al. 2008).

In most locations in temperate Australia, the major anthropogenic impacts on populations of small pelagic fishes are likely to be of terrestrial origin. Coastal pollution is particularly significant in many locations, especially shallow embayments adjacent to large population centres such as Moreton Bay (Queensland), Sydney Harbour (NSW), Port Phillip Bay (Victoria), Gulf St Vincent (South Australia) and the Swan River estuary (Western Australia).

Adaptation Responses

Adaptation can be with respect to the fishes or to the humans reliant on the fishes, for example through fishing or tourism businesses (Hobday and Poloczanska 2009). The adaptation response of pelagic fishes to future climate change is unknown, although based on the evidence discussed above it is anticipated that a change in distribution in response to an altered environment is most likely for a range of species. Genetic responses to climate change may also occur although the fast pace of climate change relative to the slower rate of evolutionary response may present a significant barrier to biological adaptation. In the remainder of this section we focus on the human side of adaptation to climate related changes in Australia's pelagic fishes.

With respect to the humans that rely on pelagic species, a range of adaptation responses are possible (Hobday and Poloczanska 2009). Climate change may lead to alternative species harvested when the primary species is less available. Interaction between the commercial and recreational sector and other marine users are also resulting in zoning that excludes fishing activities in some areas (e.g. recreational fishing zones, marine protected areas). Current approaches for dealing with changes in fisheries as a result of climate variability include; changes in fishing ports used, changes in fishery areas, changes in the quota allocated for harvest, and closures in some fisheries or fishing areas (Hobday and Poloczanska 2009). The adaptation responses may also differ between offshore large and inshore small pelagic fishes.

Offshore large pelagic fishes

Fishers dependent on pelagic fishes exhibit considerable fish finding skills. Their target species roam widely, and are subject to considerable interannual fluctuations in distribution and relative abundance. To counter this variability, fishers use a range of environmental products, such as satellite information and sophisticated on-board electronic equipment (Hobday and Poloczanska 2009). These help them to locate suitable conditions for the species that is being targeted. Continued use and improved availability of these products and development of new predictive tools may improve the capacity of the fishers, providing the stocks can sustain the continued or enhanced harvests. In some fisheries, spotter planes also reduce the search time by locating schools of fish (e.g. southern bluefin tuna in the Great Australian Bight, skipjack tuna on the east coast of Australia).

Coastal large pelagic fishes

The primary adaptation response that may be required in northern Australia may be the movement of fishers to more offshore fishing areas and also further south at toward the southern extremities of species current distributions. Movement of fishers offshore would be in response to increased rainfall and runoff into coastal regions, which may force both commercial and recreational fishers to incur greater economic costs to travel further offshore to target pelagic fish such as Spanish mackerel and tuna. This may decrease economic returns to commercial fishers, but also to local economies that rely heavily on recreational anglers. In contrast, if shark populations increase in inshore regions as a result of decreased competition by pelagic teleost fish, then this may provide increasing opportunity for investment in inshore shark fisheries. In the case of indigenous fisheries in northern Australia, movement of pelagic fishes further offshore may make these species (e.g. Spanish mackerel) inaccessible to fishers. This may result in a switch to species that may become more abundant as a result of reduced competition or predation pressure by predatory pelagic fishes (e.g. sharks or small pelagic fishes).

Southward expansions of distribution, and potential increases in the population size, of some coastal large tropical pelagic fishes could result in the expansion of some fisheries. For example, an increase in distribution and abundance of *Scomberomorous* spp. could benefit fishers off NSW, and potentially increase the total catch of this species along the east coast. However, this could also complicate management of the Queensland East Coast Mackerel Fishery, by increasing the need to consider catches taken in other jurisdictions. Conversely, contractions in the habitat available to temperate pelagic species could have some implications that would be difficult for fishers to resolve. For example, fishers in southern Queensland that target tailor from the land or in small boats may have limited capacity to adapt to reductions in the northward extent of this species' spawning migration that could result from climate change.

Small pelagic fishes

Expansions in distribution of tropical small pelagic fishes and contraction in habitats of temperate species could have potentially significant implications. However, localised replacement of cool water species with warm water species may be manageable in some cases. For example, the change of target species from jack mackerel to redbait that occurred off Tasmania did not have catastrophic impacts on the fishery. However, changes in target species can require costly modifications to fishing practices. Impacts of changes in distribution will have the most significant effects when replacement species is/are of lower value that original target species. This may require fishers to develop new markets for replacement species. In some cases this may not be possible. If, for example, a tropical species such as *Sardinella* expanded its distribution along east coast and effectively replaced sardine off NSW, this would have a major commercial impact on the NSW Ocean Haul Fishery as *Sardinella* is less valuable than sardine. Developing markets for *Sardinella* would be difficult. Alternatively, the fleet could travel southward to follow that change in the distribution of sardine. However, this would significantly increase fishing costs and may be logistically impractical. There are also potential jurisdictional issues as sardine is currently managed by the States except in commonwealth waters off NSW. An increase in abundance of sardine off South Australia due to increased upwelling would be relatively simple to manage. However, a change in the structure and function of the pelagic community could have catastrophic consequences.

Knowledge Gaps

Considerable knowledge gaps exist. Much of the information discussed in the earlier sections was based on (short-term) studies of species response to climate variability, rather than (long term time series) studies that demonstrate a temporal trend that is consistent with a climate change response. With regard to pelagic species, changes in distribution have been documented, although long-term data are sparse. Generation of such time series may be possible using catch records, although biases in the collection of such data continue to present obstacles. Use of proxy records, such as growth records from fish otoliths (ear bones) or scales, may help to fill some of the gaps (e.g. Thresher et al. 2007). In situ studies that record the relationship between environmental conditions and species abundance, phenology and physiological responses are needed to further understand the adaption responses of the fish to climate change. These studies, particularly if they span a range of conditions can allow inference about the likely rate of species response to future climate change. Development of habitat-based distribution models for small pelagic fishes based on ichthyoplankton data for example, can be tested with historical survey data, and then used to make future predictions. Future predictions of species responses are dependent on predictions of future environmental conditions. While sea surface temperature predictions are routinely made, additional mesoscale variables are important to pelagic fishes, particularly changes in upwelling, or the location of oceanic eddies. At this time, global climate models do not represent these features, and so downscaled models much be enhanced (e.g. Bluelink, Oke et al. 2008; Schiller et al. 2008).

Information on the response of pelagic sharks to historical changes is limited compared with the teleost fishes. Northern Australian responses are also less clear. Mesopelagic fishes (depth 200-800m) were not considered in this section, and as these species are critical prey species for almost all the offshore large pelagic fishes (Young et al. 2009), more information on these species is needed. With regard to human adaptation to changes in pelagic fishes, knowledge gaps relate mainly to how best to improve the flexibility of fishers to sustainably harvest a range of commercial and recreational species. In many cases, the adaptation responses may be autonomous and reactive, although having management considering the future changes is necessary now, and may prevent undesirable outcomes (Hobday and Poloczanska 2009).

Acknowledgements

The research of the authors has been supported by a number of funding and research agencies, including FRDC, AFMA, DCC, CSIRO, and SARDI. Comments from two reviewers and the editorial review from Elvira Poloczanska improved the flow of the information presented here.

References

Allen, R.G. (1997). Self-calibrating method for estimating solar radiation from air temperature *Journal of Hydrologic Engineering* 2: 56–66.

Bakun, A. and Weeks, S.J. (2004). Greenhouse gas build up, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems. *Ecology Letters* **7**: 1015-1023.

Bunce, A. (2004). Do dietary changes of Australasian gannets (*Morus serrator*) reflect variability in pelagic fish stocks? *Wildlife Research* 31: 383-387.

Campbell, R.A. (2008). *Summary of Catch and Effort Information pertaining to Australian Longline Fishing Operations in the Eastern Tuna and Billfish Fishery*. Background paper to ETBF Resource Assessment Group meeting, 29-30 July 2008, Hobart.

Campbell, R.A. and Hobday A. (2003). *Swordfish - Environment - Seamount - Fishery Interactions off eastern Australia*. Report to the Australian Fisheries Management Authority, Canberra, Australia.

Chavez, F.P., Ryan, J., Lluch-Cota, S.E. and Niquen, M. (2003). From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science* 299: 217-221.

Cowling, A., Hobday, A. and Gunn, J. (2003). *Development of a fishery-independent index of abundance for juvenile southern bluefin tuna and improvement of the index through integration of environmental, archival tag and aerial survey data.*, CSIRO Marine Research. FRDC Final Report 96/118 & 99/105.

CSIRO (2002) Media release: Shark tag provides long-term age and growth data. Hobart: CSIRO Marine and Atmospheric Research.

Cury, P. and Roy, C. (1989). Optimal environmental window and pelagic fish recruitment success in upwelling areas. *Canadian Journal of Fisheries and Aquatic Sciences* 46: 670-680.

Dimmlich, W.F., Breed, W.G., Geddes, M. and Ward, T.M. (2004). Relative importance of gulf and shelf waters for spawning and recruitment of Australian anchovy, *Engraulis australis*, in South Australia. *Fisheries Oceanography* 13: 310-323.

FAO (1997). *Small Pelagic Resources and their Fisheries in the Asia-Pacific region.* Proceedings of the APFIC Working Party on Marine Fisheries, First Session 13 - 16 May 1997, Bankok, Thailand, RAP Publication.1997/31, 445pp.

Game, E.T., Grantham, H.S., Hobday, A.J., Pressey, R.L., Lombard, A.T., Beckley, L.E., Gjerde, K., Bustamante, R.H., Possingham, H.P. and Richardson, A.J. (2009). Pelagic protected areas: the missing dimension in ocean conservation. *Trends in Ecology and Evolution*: doi:10.1016/j.tree.2009.01.011.

Gaughan, D. J. and Mitchell, R.W. (2000). *The biology and stock assessment of the tropical sardine, Sardinella lemuru, off the mid-west coast of Western Australia*. Final Report, FRDC Project 95/037. Fisheries Western Australia Research Report No. 119, 136 pp.

Gomon, M., Bray, D. and Kuiter, R. (eds.) (2008) *Fishes of Australia's southern coast. Australia*, New Holland, Sydney, 928pp.

Griffiths, S.P. (in review) Contemporary and historic effects of fishing and efficacy of size limits for a “recreational only” gamefish, longtail tuna (*Thunnus tonggol*). *Fisheries Research*.

Griffiths, S.P., Edgar, S., Wang, Y.-G. and Salini, J. (2008) *Calculating recent foreign fishing vessel numbers using established estimators based on Coastwatch surveillance and apprehension data*. Final Report for Project 2007/836. Cleveland, Qld, CSIRO Marine and Atmospheric Research. 80pp.

Griffiths, S.P., Fry, G.C., Manson, F.J. and Pillans, R.D. (2007) Feeding dynamics, consumption rates and daily ration of longtail tuna (*Thunnus tonggol*) in Australian waters, with emphasis on the consumption of commercially important prawns. *Marine and Freshwater Research* 58**:** 376-397.

Hartog, J., Hobday, A. J., Matear R., and Feng, M. (in review). Habitat overlap of southern bluefin tuna and yellowfin tuna in the east coast longline fishery - implications for present and future spatial management. *Deep Sea Research Part II: Topical Studies in Oceanograph*.

Herzfeld, M. and Tomczak, M. (1997). Numerical modelling of sea surface temperature and circulation in the Great Australian Bight. *Progress in Oceanography* 39: 29-78.

Hobday, A.J. (2001). *The influence of topography and environment on presence of juvenile southern bluefin tuna, Thunnus maccoyii, in the Great Australian Bight*, CSIRO Marine Research, Hobart, Australia.

Hobday, A. J., Hartmann, K. Bestley, S. Tsuji S. and Takahashi N. (2004). *Integrated analysis project - environmental influences on the observed decline of southern bluefin tuna in the acoustic survey area*. Yokohama, Japan, CSIRO Marine Research, Hobart, Australia.

Hobday, A.J. (2009). Ensemble analysis of the future distribution of large pelagic fishes in Australia. *Progress in Oceanography.*

Hobday, A.J. and Hartmann, K. (2006). Near real-time spatial management based on habitat predictions for a longline bycatch species. *Fisheries Management and Ecology* 13: 365-380.

Hobday, A.J. and Poloczanska E.S. (2009). Fisheries and Aquaculture. In *Climate change adaptation in Australia: Preparing agriculture, forestry and fisheries for the future*. (eds) C. J. Stokes and S. M. Howden. Melbourne, CSIRO Publishing.

Hobday, A.J., Poloczanska, E.S and Matear, R. (2008). *Implications of Climate Change for Australian Fisheries and Aquaculture: A preliminary assessment,* Report to the Department of Climate Change, Canberra, Australia. August 2008.

Hobday, A.J., Flint, N., Stone, T. and Gunn, J.S. (2009). Electronic tagging data supporting flexible spatial management in an Australian longline fishery. *Tagging and Tracking of Marine Animals with Electronic Devices II. Reviews: Methods and Technologies in Fish Biology and Fisheries*. (eds) J. Nielsen, J. R. Sibert, A. J. Hobday et al. Netherlands, Springer. 9**:** 381-403.

Hoedt, F.E. and Dimmlich, W.F. (1995). Egg and larval abundance and spawning localities of the anchovy (*Engraulis australis*) and pilchard (*Sardinops neopilchardus*) near Phillip Island, Victoria. *Marine and Freshwater Research* 46: 735-743.

Hunt, G.L. and McKinnell, S. (2006) Interplay between top-down, bottom-up, and wasp-waist control in marine ecosystems. *Progress in Oceanography* 68**:** 115-124.

Jacobson, L.D., De Oliveira, J.A.A., Barange, M., Cisneros-Mata, M.A., Felix-Uraga, R., Hunter, J.R., Kim, J.Y., Matsuura, Y., Niquen, M., Porteiro, C., Rothschild, B., Sanchez, R.P., Serra, R., Uriarte, A. and Wada, T. (2001). Surplus production, variability, and climate change in great sardine and anchovy fisheries. *Canadian Journal of Fisheries and Aquatic Science* 58: 1891-1903.

Jordan, A.J. (1992). Interannual variability in the oceanography of the east coast of Tasmania and its effects on jack mackerel (*Trachurus declivis*) larvae. In 'Larval Biology'. Australian Society for Fish Biology Workshop, Hobart 1991. (ed). D.A. Hancock.) Bureau of Rural Resources Proceedings 15: 116-21. Australian Government Publishing Service, Canberra.

Jordan, A.R. (1994). Age, growth and back-calculated birthdate distributions of larval jack mackerel *Trachurus declivis* (Pisces: Carangidae), from eastern Tasmanian coastal waters. *Journal of Marine and Freshwater Research* 45: 19-33.

Kailola, P.J., Williams, M.J., Stewart, P.C., Reichelt, R.E., McNee, A. and Grieve, C. (1993) *Australian Fisheries Resources*. Bureau of Resource Sciences and Fisheries Research Development Corporation. Canberra, Australia. 422 pp.

Larcombe, J. and McLoughlin, K. Eds. (2007). *Fishery Status Reports 2006: Status of Fish Stocks Managed by the Australian Government.* Bureau of Rural Sciences, Canberra.

Lenanton, R.C., Ayvazian, S.G., Pearce, A.F., Steckis, R.A. and Young, G.C. (1996). Tailor (*Pomatomus saltatrix*) off Western Australia: where does it spawn and how are the larvae distributed. *Marine and Freshwater Research* 47: 337-346.

Lester, R.J., Thompson, C., Moss, H. and Barker, S.C. (2001) Movement and stock structure of narrow-barred Spanish mackerel as indicated by parasites. *Journal of Fish Biology* 59**:** 833-842.

Li, J. and Clark, A.J. (2004). Coastline direction, interannual flow, and the strong El Nińo currents along Australia's nearly zonal southern coast. *American Meteorological Society*. 34: 2373-2381.

Lluch-Belda, D., Schwartzlose, R.A., Serra, R., Parrish, R.H., Kawasaki, T., Hedgecock, D. and Crawford, R.J.M. (1992). Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report *Fisheries Oceanography* 1: 339-347.

Lyle, J.M., Morison, A.K. and Krusic-Golub, K. (2000) *Age and growth of jack mackerel and the age structure of the jack mackerel purse seine catch*. Tasmanian Aquaculture and Fisheries Institute, Hobart: 49pp.

Middleton, J.F. and Cirano, M. (2002). A northern boundary current along Australia's southern shelves: The Flinders Current. *Journal of Geophysical Research C: Oceans* 107: 3129–3143.

Moore, B.R., Buckworth, R.C., Moss, H. and Lester, R.J.G. (2003) Stock discrimination and movements of narrow-barred Spanish mackerel across northern Australia as indicated by parasites. *Journal of Fish Biology* 63**:** 765-779.

Moss, S.A. (1977) Feeding mechanisms in sharks. *American Zoologist* 17**:** 355-364.

Neira, F.J., Lyle, J.M. and Keane, J.P. (2008). Shelf spawning habitat of *Emmelichthys nitidus* in south-east Australia - Implications and suitability for egg-based biomass estimation. *Estuarine Coastal and Shelf Science* 81: 521-532.

Newman, S.J., Buckworth, R.C., Mackie, M., Lewis, P., Bastow, T.P. and Ovenden, J.R. (2007) Spatial subdivision of adult assemblages of Spanish mackerel, *Scomberomorus commerson* (Pisces: Scombridae) from western, northern and eastern Australian waters through stable isotope ratio analysis of sagittal otolith carbonate. In: *The Stock Structure of Northern and Western Australian Spanish Mackerel. Final Report 98/159.* R.C. Buckworth, S.J. Newman, J.R. Ovenden, R.J.G. Lester and G.R. McPherson (eds) Canberra: FRDC.

Nieblas, A.E., Sloyan, B.M., Hobday, A.J., Coleman, R. and Richardson, A.J. (2009). Variability of biological production in low wind-forced regional upwelling systems: a case study off southeastern Australia. *Limnology and Oceanography* 54: 1548–1558.

NSW Fisheries (1982). *Commercial fisheries of New South Wales*. NSW State Fisheries. 60 pp.

Oke, P.R., Brassington, G.B., Griffin, D.A. and Schiller, A. (2008). The Bluelink ocean data assimilation system (BODAS). *Ocean Modelling* 21: 46-70.

Pecl, G.T. and Jackson, G.D, (2008). The potential impacts of climate change on inshore squid: biology, ecology and fisheries. *Reviews in Fish Biology and Fisheries* 18: 373–385.

Polacheck, T., Hobday, A., West, G., Bestley, S. and Gunn, J. (2006). *Comparison of East-West Movements of Archival Tagged Southern Bluefin Tuna in the 1990s and early 2000s,* Prepared for the CCSBT 7th Meeting of the Stock Assessment Group (SAG7) and the 11th Meeting of the Extended Scientific Committee (ESC11)4-11 September, and 12-15 September 2006, Tokyo, Japan. CCSBT-ESC/0609/28.

Potier, M., Marsac, F., Lucas, V., Sabatie, R., Hallier, J.P. and Menard, F. (2004) Feeding partitioning among tuna taken in surface and mid-water layers: the case of yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) in the Western Tropical Indian Ocean. *Western Indian Ocean Journal of Marine Science* 3**:** 51-62.

Prince, E.D. and Goodyear, C.P. (2006). Hypoxia-based habitat compression of tropical pelagic fishes. *Fisheries Oceanography* doi:10.1111/j.1365-2419.2005.00393.x: 1-14.

Randall, J.E., Allen, G.E. and Steene, R.C. (1997). *Fishes of the Great Barrier Reef and Coral Sea* (revised and expanded edition) Crawford House Publishing, Bathurst, NSW and University of Hawaii Press.

Ridgway, K.R. (2007). Seasonal circulation around Tasmania: An interface between eastern and western boundary dynamics. *Journal of Geophysical Research C: Oceans* 112(C10016).

Rogers, P.J. and Ward, T.M. (2007). Life history stratergy of sandy sprat *Hyperlophus vittatus* (Clupeidae): a comparison with clupeoids of the Indo-Pacific and southern Australia. *Journal of Applied Ichthyology* 23: 583-591.

Rogers, P.J., Geddes, M. and Ward, T.M. (2003). Blue sprat *Spratelloides robustus* (Clupeidae: Dussumieriinae): A temperate clupeoid with a tropical life history strategy? *Marine Biology* 142: 809-824.

Salini, J., Edgar, S., Jarrett, R., Lin, X., Pillans, R., Toscas, P. and Wang, Y.-G. (2007) *Estimating reliable foreign fishing vessel fishing effort from Coastwatch surveillance and apprehension dat*a. Cleveland, Qld, CSIRO Marine and Atmospheric Research. 114pp.

Sarmiento, J.L., Gruber, N., Brzezinski. M.A. and Dunne, J.P. (2004). High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature* 427: 56-60.

Schiller, A., Oke, P.R., Brassington, G.B., Entel, M., Fiedler, R., Griffin, D.A. and Mansbridge, J.V. (2008). Eddy-resolving ocean circulation in the Asian–Australian region inferred from an ocean reanalysis effort. *Progress in Oceanography* 76: 334-365.

Serventy, D.L. (1942) Notes on the economics of the northern tuna (*Kishinoella tonggol*). *Journal of the Council for Scientific and Industrial Research* 15**:** 94-100.

Serventy, D.L. (1956) Additional observations on the biology of the northern bluefin tuna, *Kishinoella tonggol* (Bleeker), in Australia. *Australian Journal of Marine and Freshwater Research* **7:** 44-63.

Stenseth, N.C., Ottersen, G., Hurrell, J.W. and Belgrano, A. Eds. (2004). *Marine Ecosystems and Climate Variation The North Atlantic A Comparative Perspective*. Oxford University Press. 252pp.

Stevens, J.D. and Davenport, S. (1991) *Analysis of catch data from the Taiwanese gill-net fishery off northern Australia: 1979-1986. CSIRO Marine Laboratories Divisional Report 213.* Hobart: CSIRO, 51 pp.

Stevens, J.D., West, G.J. and McLoughlin, K.J. (2000) Movements, recapture patterns, and factors affecting the return rate of carcharhinid and other sharks tagged off northern Australia. *Marine and Freshwater Research* 51**:** 127-141.

Thresher, R., Koslow, J.A., Morison, A.K., and Smith, D.C. (2007). Depth-mediated reversal of the effects of climate change on long-term growth rates of exploited marine fish. *Proceedings of the National Academy of Sciences* 104: 7461-7465.

Vance, D.J., Haywood, M.D.E., Heales, D.S., Kenyon, R.A. and Loneragan, N.R. (1998) Seasonal and annual variation in abundance of postlarval and juvenile banana prawns, *Penaeus merguiensis*, and environmental variation in two estuaries in tropical northeastern Australia: a six-year study. *Marine Ecology Progress Series* 163**:** 21-36.

Ward, T.M., Hoedt, F., McLeay, F., Dimmlich, W.F., Jackson, G., Rogers, P.J. and Jones, K. (2001a). Have recent mass mortalities of the sardine *Sardinops sagax* facilitated an expansion in the distribution and abundance of the anchovy *Engraulis australis* in South Australia? *Marine Ecology Progress Series* 220: 241-251.

Ward, T.M., Hoedt, F., McLeay, L., Dimmlich, W.F., Kinloch, M., Jackson, G., McGarvey, R., Rogers, P.J. and Jones, k. (2001b). Effects of the 1995 and 1998 mass mortality events on the spawning biomass of *Sardinops sagax* in South Australian waters. *ICES Journal of Marine Science* 58: 830-841.

Ward, T.M., Staunton Smith, J., Hoyle, S. and Halliday, I. (2003). Spawning patterns of four species of predominantly temperate pelagic fishes in the sub-tropical waters of southern Queensland. *Estuarine, Coastal and Shelf Science* 56: 1125-1140.

Ward, T.M., McLeay, L.J., Dimmlich, W.F., Rogers, J.P., McClatchie, S., Matthews, R., Kampf, J. and Van Ruth, J.D. (2006). Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine (*Sardinops sagax*), anchovy (*Engraulis australis*) and southern bluefin tuna (*Thunnus maccoyii*) in the Great Australian Bight. *Fisheries Oceanography* 15: 191-207.

Ward, T.M., Rogers, P.J., McLeay, L.J. and McGarvey, R. (2009). Evaluating the use of the Daily Egg Production Method for stock assessment of blue mackerel, *Scomber austrasicius*. *Journal of Marine and Freshwater Research* 62: 112-128.

Whittington, I.D., Crockford, M., Jordan, D. and Jones, B. (2008). Herpesvirus that caused epizootic mortality in 1995 and 1998 in pilchard, *Sardinops sagax* (Steindachner), in Australia is now endemic. *Journal of Fish Diseases* 31: 97-105.

Wilson, M.A. (1981) The biology, ecology and exploitation of longtail tuna, *Thunnus tonggol* (Bleeker) in Oceania. MSc Thesis, Macquarie University, 195pp.

Worm, B., Lotze, H.K. and Myers. R.A. (2003). Predator diversity hotspots in the blue ocean. *Proceedings of the National Academy of Sciences, USA* 100: 9884-9888.

Young, J.W., Bradford, R.W., Lamb, T.D. and Lyne, V.D. (1996). Biomass of zooplankton and micronekton in the southern bluefin tuna fishing grounds off eastern Tasmania, Australia. *Marine Ecology Progress Series* 138: 1-14.

Young, J.W., Bradford, R.W., Lamb, T.D., Clementson, L.A., Kloser, R. and Galea, H. (2001). Yellowfin tuna (*Thunnus albacares*) aggregations along the shelf break off south-eastern Australia: links between inshore and offshore processes. *Marine and Freshwater Research* 52: 463-474.

Young, J.W., Lansdell, M.J., Hobday, A.J., Dambacher, J.M., Griffiths, S.P., Cooper, S., Kloser, R. Nichols, P.D. and Revill A. (2009). Determining ecological effects of longline fishing in the Eastern Tuna and Billfish Fishery. FRDC Final Report 2004/063. 320 pp.