FISHERIES OCEANOGRAPHY

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Entrainment of larval fish assemblages from the inner shelf into the East Australian Current and into the western Tasman Front

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ABSTRACT

Entrainment and transport of larval fish assemblages by the East Australian Current (EAC) were examined from the coastal waters of northern New South Wales (NSW) to the western Tasman Front, via the separation of the EAC from the coast, during the austral spring of 2004. Shore-normal transects from the coast to the EAC off northern NSW revealed an inner shelf assemblage of near-shore families (Clupeidae, Engraulidae, Platycephalidae and Triglidae), an EAC assemblage dominated by Myctophidae and Gonostomatidae, and a broadly distributed assemblage over the continental shelf dominated by Scombridae and Carangidae. Further south and after the EAC had separated from the coast, we observed a western Tasman Front assemblage of inner shelf and shelf families (Clupeidae, Engraulidae, Serranidae, Scombridae, Carangidae, Bothidae and Macroramphosidae). The abundance of these families declined with distance from the coast. Surprisingly, there was no distinctive or abundant larval fish assemblage in the chlorophyll- and zooplankton-enriched waters of the Tasman Sea. Water type properties (temperature-salinity, T-S), the larval fish assemblages and family-specific T-S signatures revealed the western Tasman Front to be an entrained mix of EAC and coastal water types. We found an abundance of commercially important species including larval sardine (*Sardinops sagax*, Clupeidae), blue mackerel (*Scomber australasicus*, Scombridae) and anchovy (*Engraulis australis*, Engraulidae). The entrainment and transport of larval fish from the northern inner shelf to the western Tasman Front by the EAC reflects similar processes with the Gulf Stream Front and the Kuroshio Extension.

Key words: East Australian Current, entrainment, inner shelf water, larval fish, temperature-salinity, transport, western Tasman Front

INTRODUCTION

The transport of larval fish assemblages within western boundary currents and their extensions is well documented for the Gulf Stream (Churchill and Berger, 1998; Govoni and Spach, 1999; Hare *et al.*, 2001, 2002; Grothues *et al.*, 2002) and Kuroshio Current (Watanabe, 2002; Sassa *et al.*, 2006). In contrast, the role of the East Australian Current (EAC) in larval fish transport can only be surmised from parallel studies with other western boundary currents. Larval fish identified within the Gulf Stream Front, for example, have originated from the southeast US continental shelf (Hare *et al.*, 2001, 2002), the Cape Hatteras Confluence (Churchill and Berger, 1998; Grothues *et al.*, 2002) and the northeast US continental shelf (Ford *et al.*, 1952; Fisher, 1972; Lillibridge *et al.*, 1990).

In shelf areas adjacent to western boundary currents, life cycle strategies often include winter spawning in subtropical regions followed by larval transport poleward to temperate juvenile habitats. For example, *Pomatomus saltatrix* larva are transported poleward from spawning grounds to nursery habitats via the Gulf Stream and by warm-core rings and swimming (Hare and Cowen, 1996). Larval *Sardinops melanostictus* (Watanabe, 2002) and *Trachurus japonicus* (Sassa *et al.*, 2006) are transported poleward in the Kuroshio Current from spawning grounds to Oyashio juvenile habitats. Off the east coast of Australia, temperate pelagic species, such as *Sardinops sagax*, *Etrumeus teres*, *Engraulis australis* and *Scomber australasicus*, are

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primarily winter/spring spawners in subtropical northern New South Wales (NSW) and southern Queensland (QLD) (Ward and Staunton-Smith, 2002; Ward *et al.*, 2003; Keane and Neira, 2008; Neira and Keane, 2008; Syahailatua *et al.*, 2011a) but the processes governing poleward transport of their larvae are not fully known.

The EAC is a poleward-flowing western boundary current that originates in the Coral Sea and flows parallel to the east coast of Australia. The EAC is closest to the coast in northern NSW and flows over the narrowest section of the continental shelf off Smoky Cape (31°S) (Ridgway and Dunn, 2003). It separates from the NSW coast between 30°S and 34°S, where the main component meanders east towards New Zealand, forming the Tasman Front between the EAC and Tasman Sea waters (Godfrey *et al.*, 1980; Ridgway and Dunn, 2003; Baird *et al.*, 2008). Larval fish within the western Tasman Front may have originated from coastal NSW and southern Queensland through entrainment into the EAC.

To assess this potential entrainment and identify the role of the EAC in larval fish transport, we compared temperature, salinity, larval fish assemblages and family-specific T-S signatures north and east of the EAC separation zone during the productive austral spring. We first characterized the larval fish assemblages of the EAC and adjacent coastal waters off northern NSW prior to the EAC separation. We then compared these assemblages with those found in the western Tasman Front and in the Tasman Sea after separation to infer entrainment and transport in the early life history of some important pelagic species. During our voyage, there was at least a 2°C difference in surface temperature in approximately 10 km across the Tasman Front, associated with a 3–8 fold increase in depth integrated chlorophyll and zooplankton from the EAC to Tasman Sea-dominated waters (Baird *et al.*, 2008). We wished to determine whether the more productive waters of the Tasman Sea had an effect on larval fish assemblages.

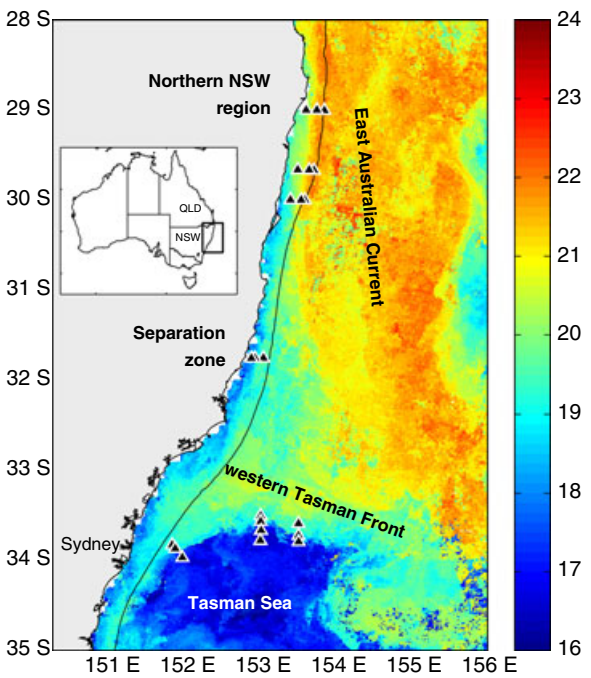
Of particular interest were the larval sardine (*S. sagax*), blue mackerel (*S. australasicus*) and anchovy (*E. australis*). These species are commercially targeted in NSW, and the early life history strategies of spawning in southern Queensland and northern NSW and the use of the EAC for southward transport have recently been examined (Keane and Neira, 2008; Neira and Keane, 2008). However, the significance of the western Tasman Front during the larval and post larval stages is not fully understood. Studies of pelagic fishes in the Gulf Stream (Hare and Cowen, 1996) and the Kuroshio Current (Watanabe, 2002; Sassa *et al.*, 2006) are compared to transport mechanisms in the EAC.

METHODS

Study area

The EAC originates in the south Coral Sea and flows south along the 200-m isobath before separating from the continental shelf around 31–33°S (Ridgway and Dunn, 2003) (Fig. 1). Approximately half the current heads east towards Lord Howe Island, forming the Tasman Front; the rest flows south towards the Tasmanian coast as a series of eddies (Suthers *et al.*, 2011). A research cruise onboard the RV *Southern Surveyor* was undertaken during the austral spring, September 2004. During this period, the EAC separated from the coast of New South Wales (NSW) at approximately 31°S and meandered southeast between 32°S and 34°S (Fig. 1). At 34°S the EAC headed east, forming the Tasman Front between the EAC (north) and the Tasman Sea (south). The Tasman Front is a

Figure 1. Transects and stations for northern NSW located at 29°S, 29.7°S and 30°S, for the separation zone located at 31.8°S and for the Tasman Front region located at 152°E, 153°E and 153.5°E. Unbroken line represents the 200-m isobath. SST data provided by the Australian Bureau of Meteorology and the Integrated Marine Observing System (IMOS).



physically dynamic region that separates two major water types with very different biological regions. During our voyage there was a decrease in surface temperature from 19 to 17°C from the northern to the southern end of our transect, associated with a 3–8 fold increase in depth integrated chlorophyll-*a*, and an order of magnitude increase in zooplankton (Baird *et al.*, 2008). The warmer, oligotrophic, EAC–Coral Sea waters are in stark contrast to the Tasman Sea water.

Our study area was separated into two regions, northern NSW and the western Tasman Front (Fig. 1). In northern NSW, four cross-shelf transects from the coast to the EAC were occupied at latitudes 29°S, 29.7°S, 30°S and 31.8°S. Water depths at the inshore stations were 65, 75, 50 and 55 m and at the offshore stations were 210, 200, 780 and 100 m for transects 29°S, 29.7°S, 30°S and 31.8°S, respectively. The water type at each tow location was identified by using data from the vessel's underway thermosalinograph at 4 m depth, particularly temperature, except along transect 31.8°S, where the temperature gradient was too diffuse to identify water types and was indicative of upwelling and cross-shelf mixing. The boundary between each water type was identified by a change in temperature as each transect was traversed. It was not possible to identify the water types beforehand as this is a dynamic region where the physical properties of the EAC, the Tasman Front and coastal water are seasonally dependent and not constant in time, as they would be for a water mass (Pickard and Emery, 1990).

In the Tasman Front region, three north–south transects crossed the Tasman Front at 152°E, 153°E and 153.5°E (transect 153°E was sampled twice). Along each transect, three stations were sampled; the western Tasman Front to the north, a middle station, and the Tasman Sea to the south, separated by approximately 12 km. Ocean depth ranged from 600 to 1700 m for transect 152°E (northwest to southeast) and was approximately 4800 m for transects 153°E-a, 153°E-b and 153.5°E. The distance from the shelf break to the mid-way point of the Tasman Front transects was approximately 20 km (transect 152°E), 90 km (for both transects at 153°E) and 130 km (transect 153.5°E).

Sampling methods

At each station two replicate 15-min mid-water oblique tows were conducted. The rectangular mid-water trawl (RMT) was a 1-m^2 net, 1-mm mesh, with a two-point bridle and a 40-kg depressor. The upper mixed layer was sampled by gently lowering the RMT to approximately 40 m depth and slowly raised to 5 m depth over the 15-min duration, to evenly sample the water column, at speeds of 4–5 km h^{-1}. All tows were carried out at night to avoid daytime stratification of the larval fish community and net avoidance (Gray and Kingsford, 2003). A General Oceanics flow meter recorded the volume of water sampled and a Vemco TDR data logger recorded trawl depth. Temperature and salinity, from the vessel's thermosalinograph, were recorded every 5 min.

All samples were preserved in a 5% formalin/seawater solution and approximately 3 g of $NaCO_3$ (buffer) was added. Within 6 weeks all larval fish were removed under a dissecting microscope and stored in 95% ethanol. All fish were identified to family where possible and to species for the more common, commercially valuable taxa, using larval fish identification texts (Moser, 1996; Neira *et al.*, 1998; Leis and Carson-Ewart, 2000). Fewer than 2% of larvae were too damaged to be identified. Concentration was standardized to number of larvae 1000 m^{-3}, as the average volume of water sampled with each tow was 930 m^3.

Data analysis

Temperature-salinity (T-S) properties differentiated the water types along each transect. Total taxa and concentration (individuals 1000 m^{-3}) were compared among water types and transects and significant differences were determined from analysis of variance (ANOVA), with both 'water type' and 'transect' being orthogonal and fixed factors. Multidimensional scaling (MDS) ordination on standardized Ln(x + 1) transformed data and a Bray–Curtis dissimilarity matrix, using PRIMER v6, were used to distinguish the larval fish assemblages. Similarity percentages (SIMPER) analysis identified the contribution of each family to the observed differences between the water types and was performed on standardized Ln(x + 1) transformed data. Monte Carlo P values of pairwise comparisons from permutational multivariate analysis of variance (PERMANOVA) performed on the assemblages identified the stations that were significantly different. The PERMANOVA involved a two-way crossed orthogonal design with 'water type' and 'transect' being fixed factors on standardized Ln(x + 1) transformed data and used a Bray–Curtis dissimilarity matrix and 9999 permutations. The PERMANOVA was performed on the 43 families that composed 99% of the community.

The abundance-weighted T-S signatures for the common families were calculated as the summed product of each station's family concentration by temperature (Eqn 1), or salinity (Eqn 2), divided by that family's total larval concentration. Standard error

around each weighted average is also included (Syahailatua *et al.*, 2011a).

$$T_{(\mathrm{aw})} = \sum_{i=1}^{n} (T_i \times \mathrm{C}_i) \Big/ \sum_{i=1}^{n} \mathrm{C}_i \qquad (1)$$

$$S_{(\mathrm{aw})} = \sum_{i=1}^{n} (S_i \times \mathrm{C}_i) \Big/ \sum_{i=1}^{n} \mathrm{C}_i \qquad (2)$$

where $T_{(\mathrm{aw})}$, abundance weighted temperature; $S_{(\mathrm{aw})}$, abundance weighted salinity; T_i, temperature at station i; S_i, salinity at station i; C_i, concentration at station i.

RESULTS

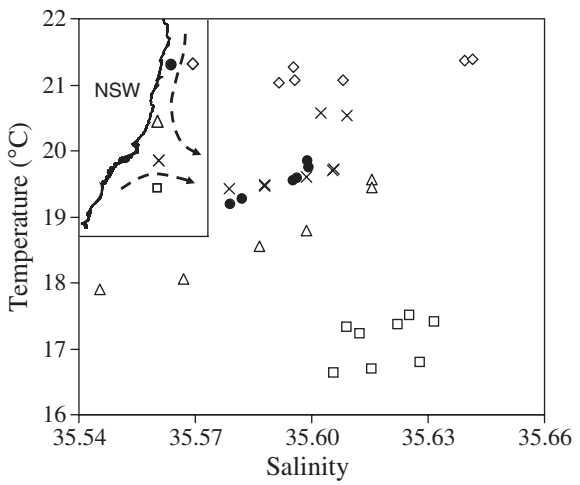
T-S properties of the study region

Temperature differences, rather than salinity, mostly defined the water types in this region (Fig. 2). The inner and outer stations for the three northern-most transects (29°S, 29.7°S and 30°S) were identified as northern NSW coast and northern NSW EAC water types. The water types sampled at the inner stations were <20°C, while the outer water types were >21°C.

All three stations from transect 31.8°S were <20°C and coastal (west) of the EAC. This region is therefore referred to as the separation zone (sepn). The T-S properties of stations in this region were different from all other water types and indicate uplifting and mixing of cooler water. The separation zone was included as a separate water type for all analyses.

The T-S properties from the Tasman Front region separated the Tasman Sea waters (<18°C) from the western Tasman Front (≥19°C). Importantly, the western Tasman Front stations were very similar in their T-S properties to the coastal stations from northern NSW (Fig. 2).

Figure 2. Water type T-S properties showing the well defined EAC in northern NSW (◇) and Tasman Sea (□), the overlapping coastal region (•) with the western Tasman Front (x) and a distinct yet more dynamic separation zone (**Δ**). Insert shows the study region and symbol locations.



Larval fish concentrations from the north coast to the Tasman Front

There was a greater concentration of larval fish in the northern coast than in the EAC for transect 29°S (ANOVA and Tukey's *post hoc* test, $P = 0.048$), a lower concentration in the coast than the EAC for transect 29.7°S ($P = 0.003$) and no difference between the coast and the EAC for transects 30°S and 31.8°S ($P = 0.50$ and 0.45). A similar result was obtained for the number of families (Fig. 3c), with more families near the coast than the EAC for transects 29°S ($P = 0.005$), fewer families in the coast than the EAC for transect 29.7°S ($P = 0.03$) and no difference between the coast and the EAC for transects 30°S and 31.8°S ($P = 0.99$ and 0.74). The middle stations had significantly greater concentrations compared with the EAC for transect 29°S ($P = 0.04$), significantly greater concentrations than the coast for transect 29.7°S ($P = 0.02$) and, conversely, significantly smaller concentrations for transect 29.7°S ($P = 0.02$).

For the Tasman Front region there was a sevenfold greater mean concentration of larval fish in the warmer western Tasman Front water than in the cooler Tasman Sea. There was also a decline in larval fish concentration and number of taxa eastwards, with distance from the coast (Fig. 3b,d). For example, mean larval fish concentrations were 730, 524 and 98 larvae 1000 m^{-3} for the western Tasman Front, the middle and the Tasman Sea stations, respectively (Fig. 3b). The middle station of transect 152°E had a significantly greater larval fish concentration ($P = 0.048$) than the western Tasman Front station, even though this station was primarily located within the western Tasman Front based on T-S properties. Larval fish concentrations were also significantly greater in the western Tasman Front than the Tasman Sea for transects 153°E-b and 153°E-a ($P = 0.02$ and 0.01). For the eastern-most transect, 153.5°E, there was no significant difference between the western Tasman Front and the Tasman Sea ($P = 0.10$), which had the lowest mean concentration and number of taxa. In general, the trends in number of taxa were similar to concentration.

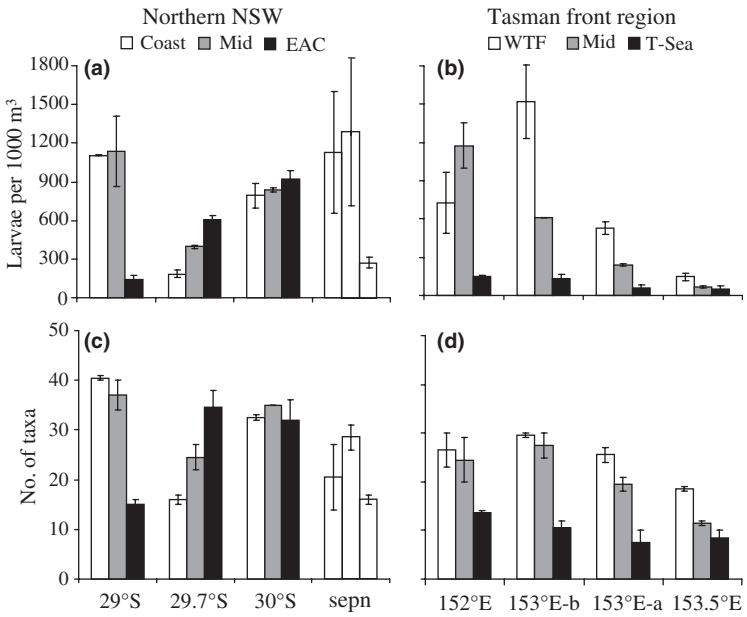


Figure 3. Larval fish concentrations (a,b) and number of taxa (c,d) for northern NSW (a,c) and the Tasman Front region (b,d). Results are averaged over two replicate tows for coast, middle (mid), East Australian Current (EAC) and the separation zone (sepn) in northern NSW and the western Tasman Front (WTF), middle (mid) and Tasman Sea (T-Sea) sites in the Tasman Front region. Error bars depict standard error. All three sites within the separation zone (transect 31.8°S) were located on the coastal side of the EAC.

Larval fish assemblages from the north coast to the Tasman Front

A total of 92 families and 25 694 individuals were identified from this study (Table 1). Six families, Clupeidae, Scombridae, Carangidae, Myctophidae, Bothidae and Engraulidae composed over 75% of the larval fish assemblage. In northern NSW, Clupeidae comprised *S. sagax* (91%), *E. teres* (7%) and preflexion larvae of either *S. sagax* or *E. teres* that were too small to differentiate (2%). In the Tasman Front region, Clupeidae were composed of *S. sagax* (99%) and *E. teres* (1%). Engraulidae were all identified as *E. australis*, Scombridae were all *S. australasicus* and Carangidae were an unidentified mix of *Pseudocaranx*, *Trachurus* and *Decapterus* spp.

Overall, the MDS plot of larval fish assemblages (Fig. 4) showed an association with the distinct coastal, EAC and Tasman Sea water types, and showed all stations within the separation zone as being similar to the northern coastal stations. It also showed the western Tasman Front was a mixture of the coastal, EAC and Tasman Sea assemblages. In particular, the assemblages were significantly different between the north coast and north EAC stations for transects 29°S, 29.7°S and 30°S (from PERMANOVA; $P = 0.02$, 0.04 and 0.03). There was no similar difference among stations for transect 31.8°S (within the homogeneous separation zone, $P = 0.07$). In the Tasman Front region the larval fish assemblages in the western Tasman Front and the Tasman Sea were distinct (Fig. 4) but not as well defined as the northern NSW region. PERMANOVA only found differences between the western Tasman Front and the Tasman Sea assemblage for transect 153°E-b ($P = 0.04$).

Distribution of key families from the north coast to the Tasman Front

In northern NSW, Clupeidae, Triglidae, Engraulidae, Bothidae, Labridae, Platycephalidae and Acropomatidae contributed more to the coastal assemblage than the EAC assemblage (Table 2). The concentration of Clupeidae was an order of magnitude greater than most other coastal families (Table 1). Clupeidae also dominated the separation zone, accounting for 68% of all larvae in this zone (Table 1). Clupeidae and Engraulidae were the most abundant, distinct coastal families found in the western Tasman Front (Fig. 5a,b) with highest concentrations of 1127 and 216 ind. 1000 m^{-3} (and similar to that from coastal NSW) but the Clupeidae was only present in these high concentrations within one station along 153°E-b in the Tasman Front region. Triglidae, Labridae, Platycephalidae and Acropomatidae were consistently found in the north coast of NSW but not in the EAC, western Tasman Front or Tasman Sea (Table 2). On the other hand, Bothidae, Macroramphosidae and Anthiinae were prominent in the western Tasman Front but absent or in very low concentrations in the Tasman Sea, the EAC and north coast NSW (Fig. 5h–j). The concentration of all coastal families found in the western Tasman Front diminished with distance from the coast.

Table 1. Mean larval fish concentrations (ind. 1000 m^{-3}) from northern NSW, the separation zone and the Tasman Front region.

	Northern NSW				Tasman Front		
Taxon	Coast	Mid	EAC	Sepn	WTF	Mid	TSea
Clupeidae	280	49	22	583	206	32	2.1
Scombridae	28	172	155	40	169	198	2.0
Carangidae	35	300	148	104	18	31	0.6
Myctophidae	5	63	108	1	37	39	61
Bothidae	22	6	1	18	104	89	7.0
Engraulidae	72	12	9	25	73	35	0.6
Serranidae	0.5	3	2	3	46	42	1.4
Triglidae	79	30	1	4	0.3	0.2	–
Gonostomatidae	1	11	24	1	10	5.7	5.4
Macroramphosidae	–	0.2	–	7	18	17	4.9
Acropomatidae	26	40	–	1	–	–	–
Labrinae	39	4	4	5	1.7	–	–
Platycephalidae	14	2.2	1.5	5	0.4	0.2	–
Notosudidae	1.1	11	13	–	2.8	1.0	0.2
Scorpaenidae	1.3	2	1	8.7	5.3	4.2	0.5
Mullidae	3.6	1.6	4.8	2.4	0.9	0.7	–
Bramidae	–	0.7	0.5	–	7.4	5.1	0.2
Lethrinidae	1.4	13	6.3	0.8	–	–	–
Anguilliformes	0.7	3.3	3.6	–	1.0	0.9	2.3
Synodontidae	8.5	0.7	0.8	0.7	0.4	–	–
Gempylidae	0.5	1.7	6.4	0.5	1.2	0.6	–
Callanthiidae	–	0.4	–	–	3.7	3.6	0.3
Microcanthidae	0.3	–	–	2.7	2.6	2.4	–
Sillaginidae	4.4	0.9	–	6.3	0.1	–	–
Gobiidae	5.4	0.8	0.7	1.4	0.5	–	–
Nemipteridae	5.8	2.2	0.4	0.3	–	–	–
Cynoglossidae	5.8	1.4	0.9	1.3	–	–	–
Paralichthyidae	4.6	2.2	0.3	2.2	–	0.1	0.2
Howellidae	–	2.8	3.9	–	0.9	0.8	0.3
Sparidae	4.7	0.5	0.4	4.4	–	–	–
Callionymidae	4.5	–	2.0	1.5	0.4	0.7	–
Astronesthinae	–	0.2	0.6	0.2	2.7	1.5	0.5
Trachichthyidae	4.7	1.0	0.2	1.9	–	–	–
Scorpididae	0.2	–	0.2	0.7	2.9	0.8	–
Phosichthyidae	0.2	2.0	4.2	–	0.1	0.1	–
Melanostomiidae	–	1.2	4.4	–	0.1	0.1	0.1
Bregmacerotidae	1.7	2.8	0.7	0.3	0.2	–	–
Lutjanidae	0.8	1.9	2.2	–	0.1	0.3	–
Pseudochromidae	4.6	–	–	–	1.0	–	–
Pomacentridae	0.4	1.1	0.6	–	0.6	1.2	–
Aplodactylidae	–	–	0.2	–	0.6	0.3	2.5
Monacanthidae	0.3	1.4	0.8	2.7	0.2	–	–
Tetraodontiformes	0.3	0.2	–	0.2	0.8	1.4	–
Chiasmodontidae	–	–	–	–	1.6	0.1	1.3
Trichiuridae	–	0.4	0.2	–	0.5	1.3	0.2
Pomatomidae	0.7	3.2	0.2	–	–	–	–
Champsodontidae	0.3	1.3	0.9	–	0.4	0.2	–
Paralepididae	0.1	0.5	1.0	–	0.5	0.3	0.2
Moridae	0.3	0.6	0.2	–	1.1	–	–
Chironemidae	–	0.2	–	–	–	0.7	0.5
Nomeidae	–	0.6	0.2	–	0.6	0.2	0.2

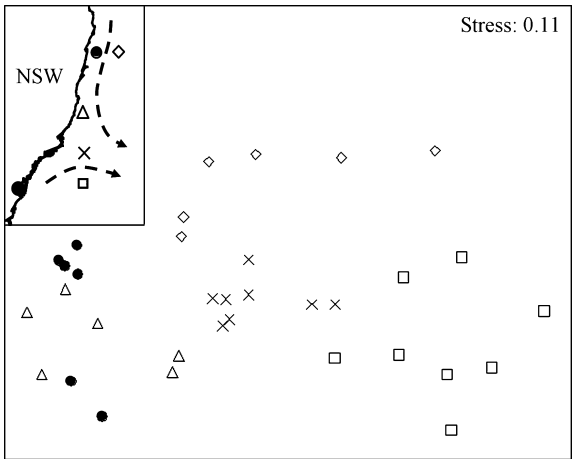
Table 1. (Continued)

	Northern NSW				Tasman Front		
Family	Coast	Mid	EAC	Sepn	WTF	Mid	TSea
Pinguipedidae	1.4	–	–	–	0.2	–	–
Stromateidae	0.1	0.2	1.3	–	–	0.3	–
Apogonidae	0.3	0.6	0.4	0.3	–	–	–
Centrolophidae	–	0.2	0.2	–	0.1	0.4	0.1
Cepolidae	0.8	–	–	0.2	–	–	–
Stomiinae	–	–	–	–	–	0.1	0.9
Terapontidae	0.7	0.5	0.2	–	–	–	–
Ammodytidae	0.4	–	–	–	0.3	0.1	–
Melamphaidae	–	–	–	–	0.8	0.1	–
Pegasidae	0.3	0.3	0.5	0.2	–	–	–
Bathylagidae	–	–	–	–	–	–	0.9
Evermannellidae	–	0.5	–	–	0.2	0.1	–
Exocoetidae	–	–	0.8	–	–	–	–
Ophidiidae	–	–	–	–	0.5	0.9	–
Schindleriidae	0.7	–	0.2	–	–	–	–
Aulopidae	–	0.2	–	0.7	–	–	–
Girellidae	–	–	–	0.9	–	–	–
Malacosteidae	–	–	0.7	–	–	–	–
Scarinae	0.2	0.2	0.4	–	–	–	–
Scomberesocidae	–	0.2	0.3	–	0.1	–	–
Chaetodontidae	–	0.3	0.2	–	0.2	–	–
Gonorynchidae	–	–	0.2	–	0.1	0.1	–
Percophidae	–	–	–	–	0.1	0.2	–
Scopelarchidae	0.2	0.2	0.2	–	–	–	–
Blenniidae	0.1	–	0.2	–	–	–	–
Cirrhitidae	–	0.4	–	–	–	–	–
Uranoscopidae	–	–	0.2	–	–	0.1	–
Caracanthidae	–	–	0.2	–	–	–	–
Carapidae	–	–	–	–	1.0	–	–
Ceratiidae	–	–	0.2	–	–	–	–
Creediidae	–	–	0.2	–	–	–	–
Diretmidae	–	–	–	–	1.0	–	–
Epinephelinae	–	–	0.2	–	–	–	–
Hoplichthyidae	–	0.3	–	–	–	–	–
Idiacanthinae	–	–	–	–	1.0	–	–
Lampridiformes	–	–	0.2	–	–	–	–
Lophiiformes	0.2	–	–	–	–	–	–
Ogcocephalidae	–	–	0.2	–	–	–	–
Samaridae	–	–	0.2	–	–	–	–
Soleidae	–	–	0.2	–	–	–	–
Sternoptychidae	0.2	–	–	–	–	–	–
Damaged	23	20	12	17	3.8	4.1	0.9

Mid, middle; EAC, East Australian Current; Sepn, separation zone; WTF, western Tasman Front; T-Sea, Tasman Sea. All stations within the separation zone are in coastal water.

Two broadly distributed families in northern NSW were Carangidae and Scombridae (Table 2). The concentrations of these families were not significantly different between coastal and EAC water types and often dominated the middle station (Fig. 5d,e). They also accounted for 20% of the larvae in the separation zone (Table 1). The concentration of Scombridae was greatest at 30°S in the EAC (459 ind. 1000 m^{-3}), whereas the highest concentration of Carangidae (564 ind. 1000 m^{-3}) was found in the middle station

Figure 4. MDS plot of larval fish assemblages grouped by dissimilarities of family abundance. Greater distance between symbols indicates greater dissimilarity. All sites within the separation zone (**Δ**) were located between the coast and the EAC, ◇ = north EAC, • = north coast, × = western Tasman Front and □ = Tasman Sea. Insert shows the study region and symbol locations.



at 29°S. The commercially important species *S. sagax* and *E. australis* dominated the coastal assemblage entrained into the EAC, whereas Carangidae and *S. australasicus* dominated the broadly distributed assemblage present in the EAC. The coastally spawned taxa within the EAC (301 individuals) were composed of *S. sagax* (50%) and *E. australis* (32%), while the broadly distributed taxa within the EAC (1965 individuals) comprised carangids (50%) and *S. australasicus* (47%).

Scombridae (*S. australasicus*) was the most abundant broadly distributed family from northern NSW also found in the western Tasman front (Fig. 5d). The highest concentration of Scombridae in the western Tasman Front was 751 ind. 1000 m^{-3}, nearly twice that found in northern NSW (459). On the other hand, the concentration of carangids in the western Tasman Front was significantly less than in northern NSW (Fig. 5e). Again, the concentration of both families diminished substantially with distance from the coast.

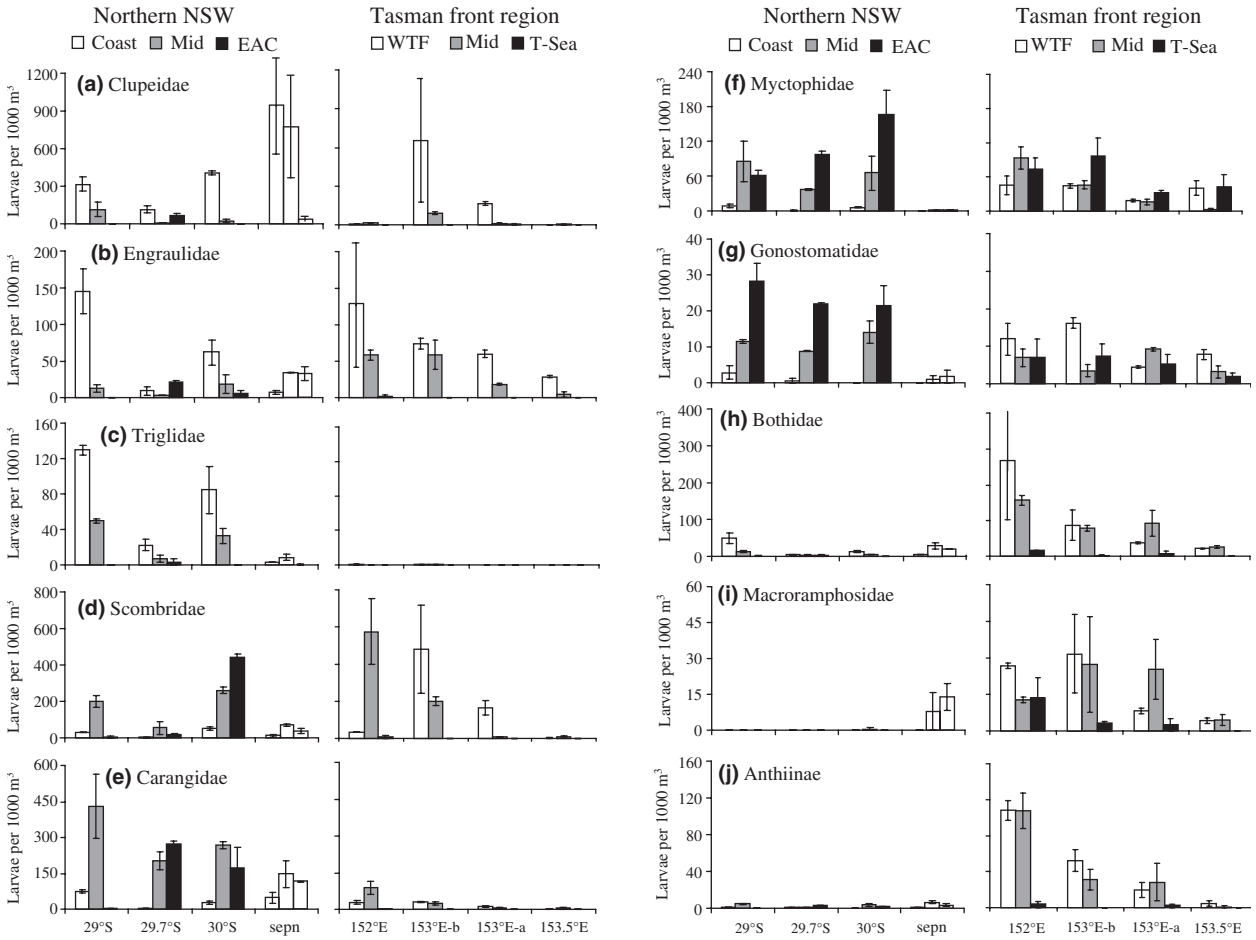
Offshore in northern NSW (transects 29°S, 29.7°S and 30°S) Myctophidae and Gonostomatidae contributed most to the EAC assemblage (Table 2) and were practically nonexistent in the separation zone (Fig. 5f,g). In the Tasman Front region, Myctophidae and Gonostomatidae were broadly distributed across the front as concentrations were similar in the western Tasman Front, middle and Tasman Sea stations (Fig. 5f,g). Myctophidae was the most common family in the Tasman Sea, with a concentration an order of

Table 2. Contributions (% similarity) of common families to each water type from SIMPER. Families were labeled as an assemblage if they registered a greater than 5% contribution from SIMPER and a minimum mean concentration of 10 from Table 1.

Family	N-coast	N-EAC	Sepn	WTF	T-sea	Assemblages
Clupeidae	16.3	1.3	18.6	6.4	5.0	N-coast, sepn, WTF
Engraulidae	8.6	2.5	11.0	12.5	<1	N-coast, sepn, WTF
Bothidae	6.4	2.0	9.5	11.8	8.1	N-coast, sepn, WTF
Carangidae	6.3	8.5	17.2	5.2	<1	N-coast, N-EAC, sepn, WTF
Scombridae	6.2	9.2	11.5	7.6	<1	N-coast, N-EAC, sepn, WTF
Myctophidae	2.6	19.0	<1	11.0	46.8	N-EAC, WTF, T-sea
Gonostomatidae	<1	13.7	<1	6.7	15.9	N-EAC, WTF, T-sea
Labridae	5.6	3.5	1.5	<1	0.0	N-coast
Platycephalidae	5.0	<1	7.2	<1	0.0	N-coast
Triglidae	11.2	<1	2.8	<1	0.0	N-coast
Acropomatidae	7.0	0.0	<1	0.0	0.0	N-coast
Gempylidae	<1	7.5	<1	<1	0.0	N-EAC
Notosudidae	<1	7.5	0.0	2.0	<1	N-EAC
Melanostomiidae	0.0	5.0	0.0	<1	<1	N-EAC
Anthiinae	<1	1.3	3.0	7.8	<1	WTF
Macroramphosidae	0.0	0.0	2.3	6.9	5.6	WTF
Bramidae	0.0	<1	0.0	4.8	<1	WTF

N-coast, north coast; N-EAC, north East Australian Current; Sepn, separation zone; WTF, western Tasman Front; T-sea, Tasman Sea.

Figure 5. Concentrations of common families from the northern NSW region (left column) and the Tasman Front region (right column). All three sites within the separation zone (sepn), along transect 31.8°S, were located on the coastal side of the EAC. Error bars are standard error, note different scales on the y axes, mid = middle, EAC = East Australian Current, WTF = western Tasman Front, T-Sea = Tasman Sea.



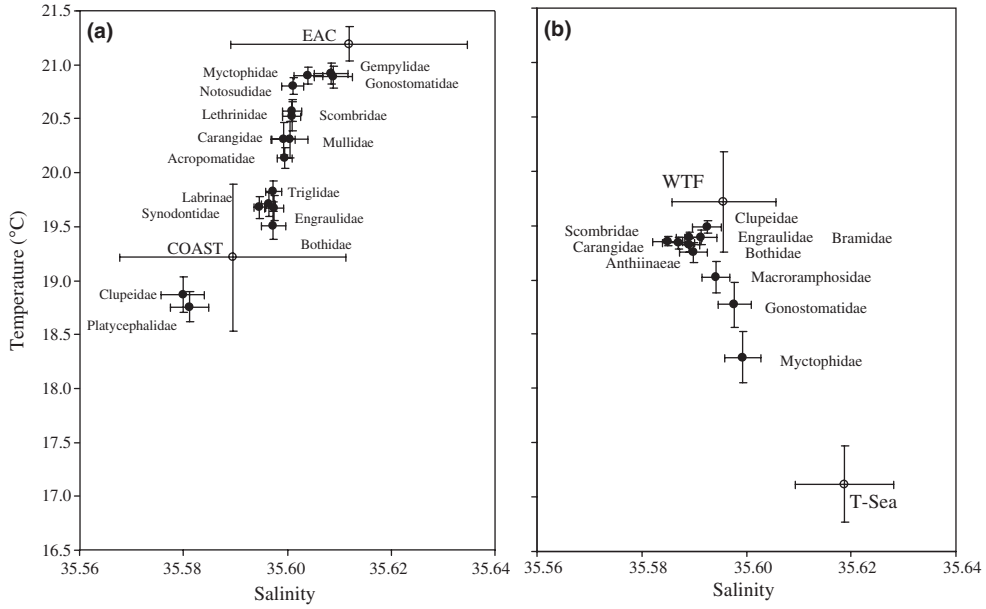
magnitude greater than the next common family (Table 1). Myctophidae and Gonostomatidae also did not diminish in concentration with distance from the coast, unlike the known coastal families found in this region.

Weighted T-S properties

T-S properties weighted by the abundance of individuals within a family revealed the spatial distributions at the family level between the coast and the EAC in northern NSW, and between the western Tasman Front and the Tasman Sea. The abundance-weighted T-S properties depicted the assemblage as a continuum between the coast and the EAC (Fig. 6a), and the western Tasman Front and Tasman Sea (Fig. 6b), and indicated which families are possible co-habitants during the larval stage.

In northern NSW, Platycephalidae and Clupeidae predominated in the slightly cooler, fresher inner shelf waters, more so than Triglidae, Bothidae, Engraulidae, Synodontidae and Labrinae. The EAC assemblage families of Gempylidae, Notosudidae, Myctophidae and Gonostomatidae occurred together and closer to the EAC unweighted average T-S, compared to Lethrinidae, Mullidae, Scombridae, Carangidae and Acropomatidae, which were located in the intermediate waters between the coast and the EAC and identified as broadly distributed families (Fig. 6a). Within the Tasman Front region, Clupeidae, Scombridae, Engraulidae, Carangidae, Anthiinae, Bothidae, Bramidae and Macroramphosidae were associated with the western Tasman Front. Myctophidae and Gonostomatidae were evenly distributed between the two water types (Fig. 6b).

Figure 6. Abundance weighted T-S properties for common families from northern NSW (a) and the Tasman Front region (b) with standard error. EAC, COAST, WTF and T-Sea labels (with standard deviation) represent the mean temperature and salinity values from all trawl sites within the East Australian Current, coast, western Tasman Front and Tasman Sea.



DISCUSSION

Entrainment in northern NSW

Our study identified an inner shelf, coastal larval fish assemblage which was subsequently observed off the shelf in the western Tasman front, but only out to 200 km from land. The inner shelf assemblage of northern NSW is similar to that found in other coastal studies, where inshore, offshore and transitional assemblages have been identified (Smith *et al.*, 1999; Gray and Miskiewicz, 2000; Keane and Neira, 2008; Syahailatua *et al.*, 2011a). The inner shelf taxa, *S. sagax*, *E. teres*, *E. australis*, Triglidae, Platycephalidae and Acropomatidae (*Apogonops*) have all been previously found inshore or are known shelf families (Smith and Suthers, 1999; Gray and Miskiewicz, 2000; Ward and Staunton-Smith, 2002; Smith, 2003; Ward *et al.*, 2003; Keane and Neira, 2008; Syahailatua *et al.*, 2011a). The northern EAC assemblage was primarily composed of Myctophidae, Gonostomatidae, Notosudidae, Melanostomiidae and Gempylidae. The larvae of these continental slope or ocean families have been previously found off the shelf (Griffiths and Wadley, 1986; Dempster *et al.*, 1997; Smith *et al.*, 1999; Syahailatua *et al.*, 2011a).

In total, 80% of the EAC larval fish from northern NSW were identified as either coastal or broadly distributed families, indicating a flux from the inner shelf to the EAC. Similarly, in the south Atlantic Bight, clupeids were an indicator of shelf-to-Gulf Stream flux of larval fish during winter (Govoni and Spach, 1999). This suggests the majority of the EAC larval fish have originated from either inner shelf or cross-shelf populations and therefore southward transport during the larval stage is a part of their life cycle. The most common shelf taxa found in the EAC and therefore likely using the EAC for transport were Clupeidae (*S. sagax*), Engraulidae (*E. australis*), Scombridae (*S. australasicus*) and Carangidae.

The broadly distributed families found in the EAC may be due to either entrainment or widespread spawning grounds. Although there was a peak in larval abundance at 30°S, *S. australasicus* was broadly distributed between the coastal, middle and EAC stations. Eggs and larvae of *S. australasicus* have previously been found across the entire shelf from southern QLD to mid-coast NSW, with peak abundances between 30.0°S and 33.3°S (Neira and Keane, 2008), confirming the species' widespread spawning. In contrast, larval wrasses (Labrinae) were likely to have spawned in coastal locations and larvae were entrained into the EAC. Labrinae was most abundant in the inner-most station in the northern-most transect and then more evenly distributed between the coast and the EAC in transects further south due to entrainment. The broad distribution of Carangidae was due to the presence of three common genera (*Pseudocaranx*, *Trachurus* and *Decapterus*) in high numbers, so con-

clusions around Carangidae distribution being a function of spawning dynamics or oceanographic conditions could not be drawn. However, Syahailatua *et al.* (2011b) suggest that *Trachurus* may spawn on the outer shelf but become entrained into the inner shelf waters, where they are evident as faster growing post-larvae.

Transport east into the Tasman Front

At the separation zone (31.8°S), coastal water and larval fish were being entrained further offshore as the EAC separated from the coast. The abundance of coastal taxa across all three shelf stations, the lack of oceanic taxa on the outer shelf and the similar coastal T-S properties across the three stations all indicate the movement of coastal water to the outer shelf.

South of the separation, the western Tasman Front is clearly composed of EAC and coastal water types. The western Tasman Front stations were 2°C warmer than the Tasman Sea and the T-S properties were similar to the coastal sites from northern NSW. These waters were also characterized by a remarkable abundance of coastal larval fish. The western Tasman Front assemblage was identified primarily as *S. sagax*, *S. australasicus*, *E. australis*, Anthiinae, Carangidae, Bothidae, Bramidae (*Brama brama*) and Macroramphosidae. All of these except *B. brama* have been described as, or regularly found in, coastal assemblages (Dempster *et al.*, 1997; Beckley, 1998; Gray and Miskiewicz, 2000; Smith, 2003; Ward *et al.*, 2003; Neira and Keane, 2008; Syahailatua *et al.*, 2011a). Of particular interest are the larvae of the pelagic baitfish of commercial value, *S. sagax*, *E. australis* and *S. australasicus*, being as abundant in some sites of the western Tasman Front as in the coast. A recent particle-tracking experiment using an approximately 3-km regional ocean model to simulate the synoptic conditions also suggests that currents can transport larvae from northern NSW to the western Tasman Front in 2–7 days (Roughan *et al.*, 2011, their fig. 14). Furthermore, the mean body lengths of *S. sagax* and *S. australasicus* were approximately 20% larger in the western Tasman Front than in northern NSW (T. J. Mullaney, unpublished data), suggesting larvae did not spawn in the western Tasman Front.

In the western Tasman Front there were a suite of coastal families, whose source is unknown. Bothidae, Anthiinae (primarily *Hypoplectrodes* spp.) and Macroramphosidae are recognized as coastal or shelf taxa but were rare in the coastal or EAC sites from northern NSW, and yet were an order of magnitude higher in the western Tasman Front than in the Tasman Sea. A northward flowing counter current often forms south of the separation zone (Godfrey *et al.*, 1980; Tranter *et al.*, 1986) and we speculate that some taxa may have originated south of the EAC separation zone and been entrained into the western Tasman Front. Furthermore, Bothidae, Anthiinae and Macroramphosidae have previously been identified as Tasman Sea families found in an EAC-Tasman Sea mix assemblage north of the Tasman Sea (Keane and Neira, 2008). It is also suggested from particle tracking simulations that mesoscale variability can transport larvae back up north after initially leaving the shelf south of the separation zone (Roughan *et al.*, 2011). Similarly, on the northeast US continental shelf, a flux of larval fish is also observed, from north to south, towards Cape Hatteras before entrainment into the Gulf Stream (Grothues and Cowen, 1999; Grothues *et al.*, 2002).

There was a remarkable paucity of larvae in the otherwise enriched Tasman Sea water (Baird *et al.*, 2008). Total larval fish abundance in the western Tasman Front was an order of magnitude greater than in the Tasman Sea and number of families in the western Tasman Front was twice that of the Tasman Sea. The western Tasman Front assemblage included coastal families that were rarely found in the Tasman Sea water, while the Tasman Sea assemblage was composed of oceanic families, mostly Myctophidae and Gonostomatidae, which were broadly distributed between both water types. Therefore entrainment and transport of coastal larval fish by the EAC to this region had a greater influence on the larval fish assemblage and abundance when compared with resource availability.

Comparisons with other western boundary currents

In northern NSW, there is mixing of coastal and EAC water prior to EAC separation, as coastal and shelf species such as Clupeidae, Engraulidae, Scombridae and Carangidae were regularly found in the EAC. Similarly, on the southeast US continental shelf, prior to Gulf Stream separation, larvae of oceanic species such as Gonostomatidae and Phosichthyidae have been found on the shelf, and larvae of shelf species such as Clupeidae and Sciaenidae have been found in the Gulf Stream (Govoni and Spach, 1999). The high concentration of coastal species found in the western Tasman Front indicates coastal water entrainment at the separation zone. Similarly, larvae of Gulf Stream water found in the slope sea have originated south of Cape Hatteras (Hare *et al.*, 2001) and there is an intermittent offshore flow and export of larval fish to the ocean from the Cape Hatteras Confluence, where

the Gulf Stream separates from the coast (Churchill and Berger, 1998; Grothues *et al.*, 2002).

The abundance of coastal taxa rapidly declined by the eastern-most station (153.5°E) and their fate once they are entrained into the Tasman Front may be surmised from other western boundary current studies of the Gulf Stream Front and Kuroshio Extension. *Pomatomus saltatrix* spawn on the southeast US continental shelf and it is hypothesized that larvae are entrained into the Gulf Stream and transported away from the coast (Hare and Cowen, 1996), where warm core rings detach from the Gulf Stream and transport larvae back towards the shelf/slope front of the northeast US continental shelf. Here active swimming most likely allows recruitment to coastal juvenile habitats (Hare and Cowen, 1996; Hare *et al.*, 2002). *Sardinops melanostictus* (Watanabe, 2002) and *Trachurus japonicus* (Sassa *et al.*, 2006) are both winter spawners in southern Japan and the southern East China Sea, respectively. Similarly, larvae are transported northeast along the Kuroshio Current and Extension until early juveniles can actively migrate to the Oyashio nursery grounds.

The two most abundant temperate pelagic species from this study were *S. sagax* and *S. australasicus*. Both these species are known to spawn in southern Queensland and northern NSW (Ward and Staunton-Smith, 2002; Ward *et al.*, 2003; Neira and Keane, 2008) and both species are entrained into the western Tasman Front. Similar to the Gulf Stream, anti-cyclonic eddies detach from the Tasman Front (Godfrey *et al.*, 1980; Nilsson and Cresswell, 1981; Ridgway and Godfrey, 1997) and both cyclonic and anti-cyclonic eddies often form between the Tasman front and the coast (Marchesiello and Middleton, 2000; Roughan and Middleton, 2002), so both species may be retained within these eddies as the larvae develop. Our understanding of *S. sagax* and *S. australasicus* off NSW suggests they have similar adult migration to the small pelagic fish in the Gulf Stream and Kuroshio Current. This early life history strategy may result in higher larval survival through food availability, as upwelling and nutrient enrichment often occurs where the EAC flows closest to the coast in northern NSW and around the Stockton Bight (32°S, mid-coast NSW) (Roughan and Middleton, 2002; Syahailatua *et al.*, 2011a).

The larval fish assemblages off northern and mid-coast NSW are similar to those found in other coastal and shelf studies, where inshore, offshore and transitional assemblages are identified and are likely a reflection of adult habitat, spawning dynamics, oceanographic conditions and transport (Richardson *et al.*, 1980; Young *et al.*, 1986; Olivar, 1990; Cowen *et al.*, 1993; Sabatés and Olivar, 1996; Dempster *et al.*, 1997; Sampey *et al.*, 2004; Muhling *et al.*, 2008). Just as the Gulf Stream and Kuroshio Current are driving forces behind water movement and larval fish transport in other western boundary currents, the EAC plays a major role in the entrainment and transport of larval fish off NSW (Condie *et al.*, 2011). The larval fish assemblages reveal entrainment of coastal water and fish larvae into the EAC in northern NSW and the formation of a mixed water type in the western Tasman Front, south of the EAC separation, providing a key link in the life-cycle of a range of commercially and ecologically significant species.

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