Potential influence of a marine heatwave on range extensions of tropical fishes in the eastern Indian Ocean—Invaluable contributions from amateur observers

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A B S T R A C T

Global changes to fish distributions are expected to continue in coming decades with predicted increases in ocean temperatures and the frequency of extreme climatic events. In the eastern Indian Ocean during the 2010/11 summer, sea surface temperatures 4–5 °C above average and an unseasonal, anomalously strong, Leeuwin Current (LC) triggered a "marine heatwave" along the west coast of Australia, with elevated water temperatures persisting for a further two years. Peak LC flows in summer/autumn transported pelagic early life history stages of summer-spawning coastal subtropical and tropical fishes southwards. This study examined whether the heatwave enabled the arrival, persistence and reproduction of such species in waters $\geq \sim 32°$S using a range of available datasets. Juveniles of *Chaetodon assarius*, *Trachinotus botla*, *T. baillonii*, *Polydactylus plebeius*, *Psammoperca waigiensis* and *Siganus* sp. recruited into nearshore waters at $\geq \sim 32°$S in 2011. *Polydactylus plebeius* survived until the summer of 2012/13. *Trachinotus* spp., *P. waigiensis* and *Siganus* sp. survived over consecutive winters, with *Siganus* sp. establishing a self-recruiting, breeding population two years later. A return to more typical summer water temperatures by 2013/14 was associated with an apparent recruitment failure of *Siganus* sp. This is a rare example of a tropical vagrant surviving to breed in temperate regions. Confirmation of range extension beyond existing limits of this and other tropical species will be primarily dependent on either continuous or intermittent recruitment from this recently established southern breeding population. Commercial fisheries catch and effort data were of limited use in this study because they were not designed to record small catches of unusual and/or non-target species. In contrast, fisheries-independent recruitment surveys recorded tropical juveniles and validated amateur observations provided important information on unusual species. The study confirmed the emerging contribution of 'citizen scientists' working with researchers to document climate related impacts in the marine environment.

1. Introduction

The distributions of marine fishes are predicted to change over coming decades in conjunction with the effects of changing climates, such as increasing ocean temperatures and frequency of extreme events. Numerous distribution shifts have already been reported (e.g. Cheung et al., 2012; Montero-Serra et al., 2015; Simpson et al., 2011). A rare and extreme marine heatwave event (Hobday et al., 2016) during the summer of 2010/11 on the west coast of Australia produced sea surface temperatures (SST) 4–5°C greater than average, generated by an unseasonal and

anomalously strong poleward-flowing Leeuwin Current (LC) and an atmospheric heat flux (Feng et al., 2015, 2013; Pearce and Feng, 2013; Zinke et al., 2015). Short-term effects included marine fish and invertebrate deaths, re-distribution of species beyond their historically 'normal' ranges, unusual variations in recruitment of a range of coastal fishes and impacts on trophic relationships and community structure (Pearce et al., 2011a). During the four years after the heatwave, SST anomalies matching those of 2011 have occurred and coastal tropical species e.g. sand bass (*Psammoperca waigiensis*) and rabbitfish (*Siganus* sp.) that prior to the marine heatwave had only occasionally been recorded well south of their respective historical southern limit, have both persisted.

The marine coastal region of the southern half of Western Australia (WA) has been characterised as comprising tropical (67%), warm temperate (24%), and sub-tropical (5%) fishes, with
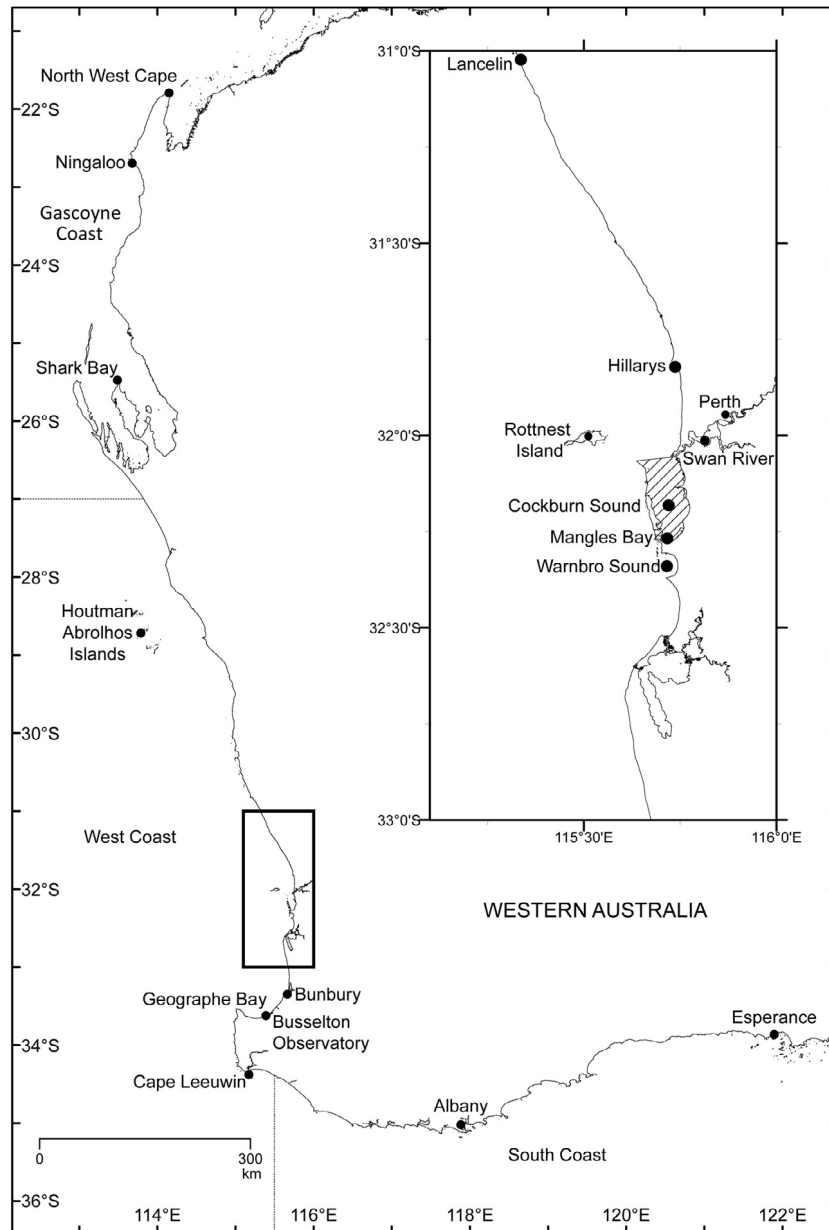
Fig. 1. The southern half of Western Australia showing the extent of the Leeuwin Province, the location of the main temperate operating areas of the Marine Aquarium Fishery, and the source of the samples of the tropical and subtropical finfish discussed in this investigation.

tropical species being more abundant north of ∼26°S (Fig. 1; Hutchins, 1994). Occurrence of sub-tropical and tropical species further south is attributed to the transport of their pelagic larvae by the LC (Hutchins, 1991; Lenanton et al., 2009; Pearce and Hutchins, 2009). This poleward flowing current has its origins in the south-eastern Indian Ocean as a result of the transport via the Indonesian Throughflow of warm waters from the equatorial western Pacific Ocean (Cresswell and Golding, 1980). For most fishes, water temperature influences the spatial and temporal extent of breeding and survival of recruits (Feary et al., 2014; Sunday et al., 2015). However, the poleward dispersal of early life history stages of tropical fishes is also heavily dependent on the strength and timing of large-scale coastal currents, such as the LC.

The fate of such tropical fishes that may have experienced significant displacement as a result of the heatwave event is of particular interest (e.g. Wernberg et al., 2013). However, one of the requirements for detecting the effects of extreme events, such as the dispersal and survival of tropical fishes and possible range extensions, is the availability of appropriate datasets that can be used to demonstrate changes over time (Bates et al., 2015). Furthermore, there are a number of challenges associated with the detection of range extensions of coastal marine species (Bates et al., 2015; Przeslawski et al., 2012). They include the need for uniform or random distribution of adequate levels of sampling effort. Thus, species targeted and reported by commercial and recreational fisheries often provide good examples, with the capture of legal-sized individuals of displaced species, often represented by highly mobile adults, being immediately identifiable in their catch data. Further, non-migratory or sedentary species that occupy shallow nearshore habitats rather than demersal or pelagic habitats located further offshore (Department of Fisheries, 2011), are more likely to react to abnormal coastal environmental conditions by either contraction or extension of their range, rather than movement offshore. With this in mind, species that exhibit life history characteristics conducive to range extension, such as dispersal capacity (Sunday et al., 2015), are likely to provide the best examples of range shifts. It is also widely acknowledged that

physiological and ecological factors are important. For example, the availability and/or competition for habitat and food at settlement may constrain the establishment of vagrant tropical species (Bates et al., 2015, 2014; Beck et al., 2014; Feary et al., 2014). Also, photoperiod needs to be appropriate to enable displaced species with photoperiod sensitive life stages to undergo developmental phases and/or reproduce (Grevstad and Coop, 2015).

While a variety of fish species occupying all of the above three broad habitats were reported off the lower west coast of WA during the marine heatwave (Pearce et al., 2011a), and during the two years following (Caputi et al., 2014), ongoing availability of data from the reported occurrence of nearshore species with good dispersal capacity enabled the longer-term consequences of the heatwave for these species to be explored in more detail.

Off the lower west coast of Australia, the newly-settled juveniles of coastal tropical and subtropical fish species that recruit into regions south of their normal range may fall into three categories. (1) Survival in the settlement year until the advent of the cooler inshore winter water temperatures (Pearce et al., 2011b; Pearce and Hutchins, 2009; Ben Mitchell Western Australian Marine Aquarium Fishery, pers. comm.), (2) successful over-wintering and survival into the year after settlement, or (3) survival in several consecutive years after settlement which, for many species, may be long enough to allow sexual maturation and establishment of viable breeding populations. The latter two scenarios presumably could only occur during conditions of persistent warmer winter water temperatures.

Since the advent of the marine heatwave, records have reconfirmed the presence of nearshore species that fit category (1), e.g. western butterflyfish, *Chaetodon assarius* (Wernberg et al., 2013). However records have also revealed evidence of a further five tropical species in shallow coastal waters off the temperate lower west coast of Australia south of ~32°S that fit category (2), e.g. common dart *Trachinotus botla*, black-spotted dart *T. baillonii*, and northern threadfin *Polydactylus plebeius* (Caputi et al., 2014), and potentially category (3), e.g. *Psammoperca waigiensis* and *Siganus* sp. Available evidence also suggests that an extreme event, such as the marine heatwave (Pearce et al., 2011a,b) has the potential to extend the range of these tropical finfish southwards at a much greater rate than predicted by Cheung et al. (2012). However, because such events are infrequent and difficult to predict, wide scale and long-term research targeted at measuring their impact is difficult to mount. Thus, the principal aim of this investigation was to identify the potential for selected sub-tropical and tropical species to undergo range extension south of their historical distributions along the temperate west coast of Australia using a variety of available data sources not specifically designed to monitor climate-related impacts. Datasets containing records of the chosen species were analysed from before, during and after the marine heatwave. They included data from commercial and recreational fishery catches, fishery-independent nearshore fish recruitment monitoring, underwater fish surveys, and validated items of information from commercial and recreational fishers, divers and other users. These data were related to observed patterns of SST and LC strength. Biological analysis provided additional worthwhile information on the age and reproductive state of volunteered fish specimens.

2. Materials and methods

2.1. Environmental data

The mean monthly Fremantle sea level (FMSL, cm above zero datum) provides an index of the strength of the LC (Feng, 2003; Pearce and Phillips, 1988). FMSL data for 1900–2014 were obtained from the Australian Government Bureau of Meteorol-

ogy website (http://www.bom.gov.au/ntc/IDO70000/IDO70000_62230_SLD.shtml). To avoid bias from rising sea level over time, mean monthly FMSL readings were linearly de-trended then used to identify years of strong LC. These are defined here as years when de-trended monthly FMSL (Pearce and Feng, 2013) exceeded 75 cm during three months of the year. SSTs for nearshore marine waters off the Metropolitan WA coast (~32°S) were collected from both satellite-derived and *in situ* sources. (1) The satellite-derived continuous daily SSTs from the NOAA OIv2 dataset from 1982 onwards at ¼° (~28 km) resolution were used for analyses (Reynolds et al., 2007) of mean monthly SST for four locations, two immediately north and two south of Rottnest Island (Fig. 1). These locations provided a good representation of the nearshore SST of ~32°S, as they were adjacent to, but far enough off the coast not to be adversely affected by terrestrial influences. Mean winter (June to August) and summer (December to March) SST anomalies for waters around Rottnest Island from 1982 to 2016 were calculated against the 1982–2009 mean (representing preheatwave years). (2) The *in situ* self-recording temperature loggers (Onset TidBit Model TB132-05 + 37 and/or Hobo model UA-011-64 loggers were located in Warnbro Sound Pearce et al., 2016; Pearce and Feng, 2013; Fig. 1). Monthly averaged SSTs were derived from hourly values (Pearce et al., 2016; Pearce and Feng, 2013). Average austral summer and winter SSTs were determined from data for December–February and June–August, respectively.

2.2. Records of fish occurrences

Available data sources that comprise both long and short time series were evaluated. They included scientific information from WA state government-based compulsory commercial fishing records (administered by the Department of Fisheries, DoF), a fisheries-independent nearshore fish recruitment monitoring programme (RMP), dive-based surveys and a boat-based recreational Fisher survey (all undertaken by DoF); together with records of validated 'items' of information volunteered by amateur observers, i.e. commercial and recreational fishers, divers and observers (e.g. Redmap sightings) (Table 1). 'Items' of information included contributed specimens and records of the presence of the species being studied. These were collected on a single sampling occasion, usually a trip or excursion on a given day (1). Species-specific size frequency data for *P. waigiensis, T. botla*, *T. baillonii*, *P. plebeius* and *Siganus* sp. sourced from different locations off the WA coast were presented for the following three regions; Mid-west, 29–31°S (~30°S), Metropolitan, 31–33°S (~32°S), and Lower west, ≥33°S. Results from the Reef Life Survey (RLS) (Edgar and Stuart-Smith, 2014), and other relevant published scientific surveys (Atlas of Living Australia, 2016; Hutchins, 2001a, 1995, 1994, 1990) were also reviewed.

2.3. Biological sampling

Specimens of *P. waigiensis, T. botla*, *T. baillonii*, *P. plebeius* and *Siganus* sp. were acquired from the RMP, commercial fishers and/or recreational fishers, and their lengths measured to the nearest 1 mm (total length; TL). The gonads of each fish were examined macroscopically when possible to determine sex and stage of reproductive development according to the criteria of Laevastu (1965). Sagittal otoliths of each *P. waigiensis* and *Siganus* sp. to be aged were extracted, cleaned, dried and stored in paper envelopes. The annual periodicity of otolith increments has previously been validated for *P. waigiensis* and *Siganus* sp. (Grandcourt et al., 2007; Katayama et al., 2009; Lee et al., 2014; Shimose and Tachihara, 2006). One whole otolith from each fish was placed in a small black dish and covered with methyl salicylate, then viewed under a Nikon SM2745T dissecting microscope with reflected light. Images
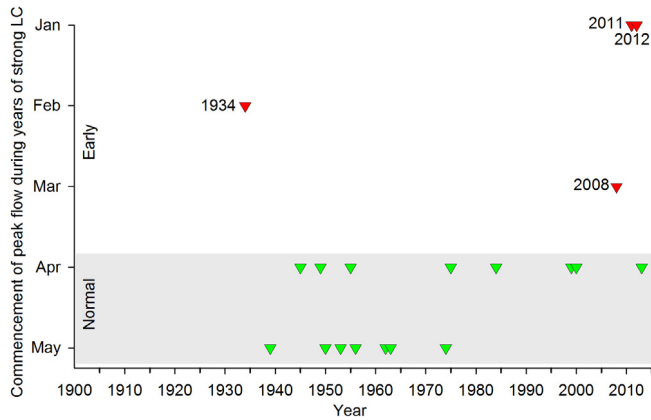
Fig. 2. The first month of each of the years between 1900 and 2013 deemed a strong Leeuwin Current, when the detrended FMSL exceeded 75 cm.
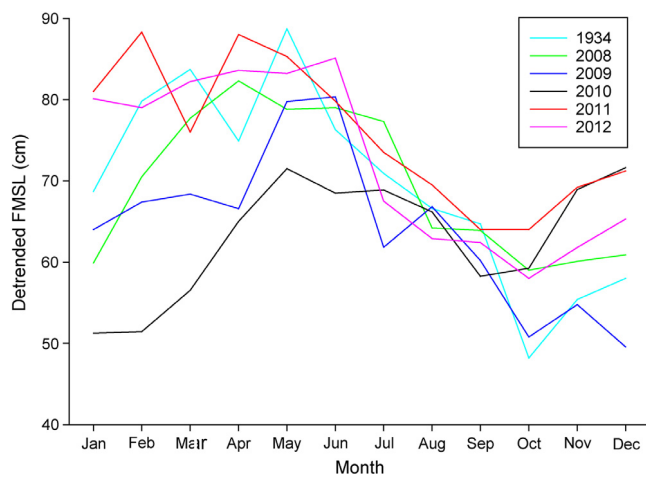
Fig. 3. Comparison of the mean monthly FMSL (cm) during the four years between 1900 and 2013, that experienced an unusually early onset of a strong Leeuwin Current, with two typical years (2009 and 2010).
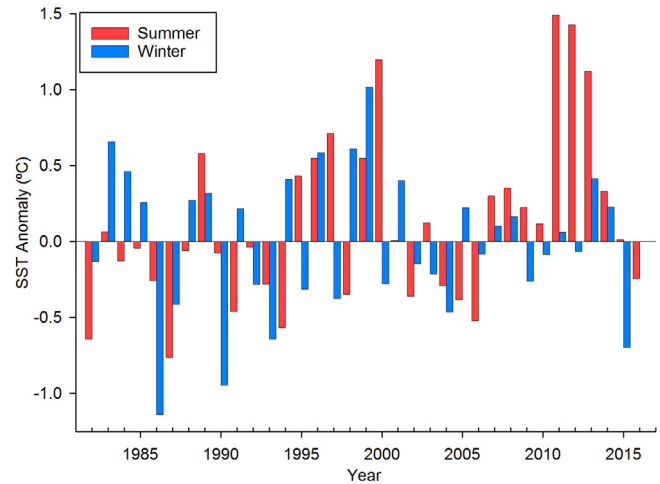

Fig. 4a. Mean winter (June to August) and summer (December to February) satellite-derived monthly SST anomalies for four locations around Rottnest Island, each of $^1/_4°$ resolution, and presented from 1982–2016, were calculated against the 1982–2009 mean that represented pre-heatwave years.

Fig. 4b. The mean *in situ* summer (December–February) and winter (June–August) nearshore water temperatures (°C) measured at the Warnbro Sound temperature logger site each year since 2002.

of otoliths were captured using JenoptikProgRes® Model C7 digital camera and ProgRes® software. The numbers of opaque annuli (increments) were then counted, enabling each fish to be assigned to a probable age class.
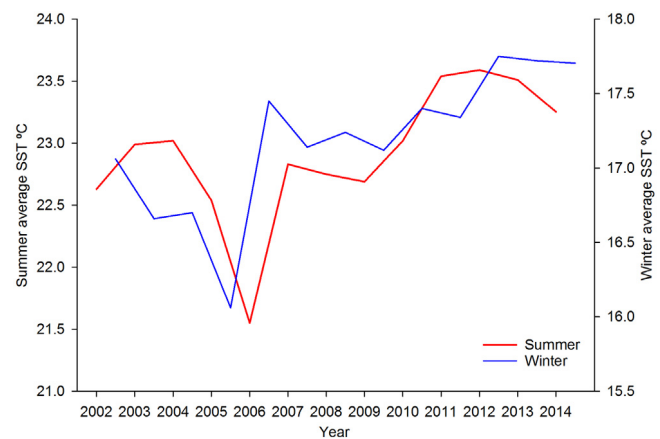
3. Results

3.1. Leeuwin Current and SST

Historically, LC flow peaked typically during late autumn and mid-winter, i.e. May–July (Smith et al., 1991). Strong LC flows were recorded during 22 of the years between 1900 and 2013. In each of the strong LC years prior to 1975, the onset of the LC occurred between April and June, except in 1934, when it occurred in February (Fig. 2). However, in each of the eight strong LC years since 1975, the onset was never later than April. Furthermore, in 2008, it commenced in March, while in 2011 (the year of the marine heatwave) and 2012, it commenced even earlier, i.e. January (Fig. 2). In 2011 and 2012, the de-trended FMSL revealed consistently high LC flows (>75 cm) during mid-late summer and autumn, in comparison to 2009 and 2010, which were 'typical' of those months, and relatively weak (Fig. 3). However, by 2013, the onset of a strong LC reverted back to later in the year (April) and by 2014 a strong LC was not recorded (Fig. 2).

Mean monthly SST anomalies revealed a significant elevation in water temperatures during the summer months, together with

a consistent increase during the winters of the marine heatwave years (2011–2013; Fig. 4a). This trend was also apparent in the mean monthly *in situ* water temperatures in Warnbro Sound (Fig. 1), during the summers of 2011/12–2013/14 and winters of 2012–2014, with maxima approximately 0.6 and 0.4°C above the maxima in the several years preceding the heatwave (Fig. 4b).

3.2. Survival only within the settlement year

Chaetodon assarius

Historically, taxonomic surveys have recorded *C. assarius* from coastal waters between North West Cape and Cape Leeuwin, i.e. ~22–34°S (Fig. 1; Hutchins, 2001a). During these surveys, *C. assarius* was considered rare between ~31–34°S. However, although catches of *C. assarius* by the Marine Aquarium Fishery (MAF) at ~32°S were low in years immediately preceding the marine heatwave (2011), large catches were obtained during 2011 and 2012 (Fig. 5). Records from the RLS (Edgar and Stuart-Smith, 2014) at Rottnest Island during these years comprised the first recorded presence of this species since the inception of the survey in 2008. Catches were also taken from the more southerly location of Geographe Bay at ~34°S, and off the south coast as far east as Albany (Figs. 1 and 5). This pattern of catches is very similar to the

Table 1
Data-sources queried for evidence of range extension of selected tropical fish species.

Data source	Owner	Location	Years queried	Description	Usefulness as source of valid records
Compulsory monthly commercial catch and effort statistics (CAES)	Department of Fisheries WA (DoF)	West Coast Bioregion (27°S–115°30′)	2009–2016	Monthly reporting of legal-sized target and byproduct species. Less useful because the database is designed to record catches of economically important species, not small catches of unusual species. However, during early 2013, a commercial Fisher from Cockburn Sound agreed to record his *Siganus sp.* catches in CAES. His subsequent monthly catches of *Siganus sp.* demonstrate that this species has persisted in this embayment.	Potentially high
Compulsory monthly commercial Marine Aquarium Fishery (MAF)	DoF	WA, 31–34°S, e.g. Cockburn Sound, Geographe Bay	1996–2014	Monthly reporting of diver catches of small juveniles of targeted tropical, sub-tropical and temperate species (>250 spp.; Newman et al., 2012). Consistent spatial and temporal distribution of effort likely to provide indication of species relative abundance over time. Targeting bias is a potential issue.	Medium
Boat-based recreational catch surveys (ISurvey)	DoF	All WA	2011/12	Single integrated survey estimate of recreational catch of Western Australian boat-based fishers (Ryan et al., 2013). Less useful because the database is designed to record catches of popular target species, not small catches of unusual species.	Low
Nearshore recruitment monitoring program (RMP)	DoF	WA coast, 32°S to 123°E	1994–2015	Annual shore-based beach seine fishery-independent time-series of occurrence of newly settled juveniles in shoreline habitats (Gaughan et al., 2006; Smith et al., 2008). Data examined from 32–33°20′S at Hillarys, Cockburn Sound, Warnbro, and Bunbury (Fig. 1).	High
Diver roaming visual survey	DoF	Hillarys marina rock wall, 31°49′S (Fig. 1)	2010–2015	Annual opportunistic validated records from research diver survey of fishes.	High
Southwest Artificial Reef Monitoring	DoF—Research	Geographe Bay, 33°30′S	2013–2015	Annual quantitative data from diver operated video and baited remote underwater video (BRUV) surveys of fishes inhabiting artificial reefs and adjacent natural habitats.	High
Cockburn Sound juvenile snapper monitoring program.	DoF—Research	Cockburn Sound, 32°11′S	2005–2015	Annual quantitative BRUV survey of fishes in representative habitats (Wakefield et al., 2013).	High
Specimens submitted directly from the community	DoF, WA Museum	WA	2011–2015	Reports commenced during 2011 heatwave. Provided validated records of the initial capture of unusual species by the recreational fishing community	Medium to high
Community anecdotal reports to DoF	DoF official record management system	WA	2011–2015	Reports commenced during 2011 heatwave. Provides information on capture/observation of fishes in support of scientifically validated records (see above).	Medium
Records on recreational fishing forum websites	Community—Web-based records	WA	2011–2015	Provided records (often validated with photographs) of the initial appearance of unusual species captured by the recreational fishing community (e.g. www.fishwrecked.com.au ; www.wafishaman.com.au). However once species are more frequently observed, there may be a tendency to cease reporting them.	Medium
Range extension database and mapping project (Redmap)	Community/ Redmap	WA	2012–2015	Australia-wide since 2012. Community observations of marine species beyond typical ranges, validated by scientists. However once species are more frequently observed, there may be a tendency to cease reporting them. (http://www.redmap.org.au/)	Medium to high
Records from the Busselton Underwater Observatory (BUWO)	Local Government—Busselton Shire Council	Geographe Bay 33°37′S	2004–2015	Commenced in 2004. Time series of daily records of occurrence of fishes from underwater observatory.	High

catches taken immediately following the strong La Nina years of 1999 and 2000 (Fig. 5). This species was not recorded in any of the other datasets examined (Tables 1 and 2).

3.3. Survival beyond settlement year

Polydactylus plebeius

Small *P. plebeius* (~90 mm) were first caught by the RMP at ~30°S in May 1998 and at ~32°S in May 1999 and 2000. Observations of juvenile *P. plebeius* at ~30°S by shore-based recreational fishers and divers were first reported to Redmap in March 2012 (~100 mm) and April 2012 (~50–60 mm) and validated via digital images (Fig. 6a). Larger individuals (185–200 mm) were also caught at ~32 and ≥33°S during April 2012 by recreational fishers

and at ~32°S by the RMP in September 2012 (205 mm; Fig. 6a, Table 2). Recreational catches of large individuals were also received at ~32°S in February 2013 (~200 mm), ~35°S 117°E in March 2013 (~200 mm), and at ~34°S in April 2013 (280 mm). Other validated reports of larger individuals were received during late 2012 at Esperance (~34°S, 122°E) on the south coast (Fig. 1), but specimens were not able to be examined.

Trachinotus botla and *T. baillonii*

The ranges of *T. botla* and *T. baillonii* are considered to extend south to Bunbury (≥33°S) and Lancelin (~30°S), respectively, on the west coast of Australia (Hutchins and Swainston, 1986) (Fig. 1). Small *T. botla* (78–119 mm; $n = 7$) were first recorded by the RMP in nearshore waters at ~32°S in September 2011, while larger individuals were sampled at the same location in April 2012

Table 2
The source of items of validated information used in this investigation to identify potential range extension of the five key tropical finfish species.

Species	Scientific observation	Amateur observations
Polydactylus plebeius	1	7
Trachinotus spp.	4	9
Psammoperca waigiensis	3	16
Siganus sp.	18	16
Total	26	44
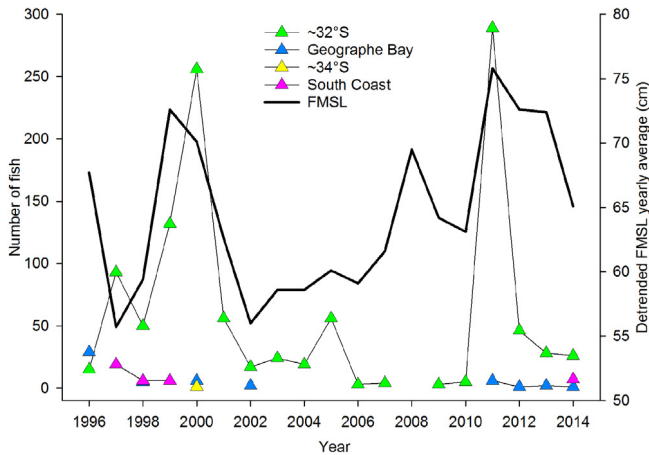
Fig. 5. The monthly catches (numbers) of *Chaetodon assarius* by the MAF between January 1996 and December 2014 from each of the main fishing areas off the lower west coast of Western Australia.

(268 mm) and September 2012 (275 mm; Fig. 6b). One *T. botla* of 150 mm was captured by a shore-based angler at 32°S in February 2012, while individuals of 300–360 mm were caught between February 2013 and April 2015 at several locations between 32°S on the west coast and ~35°S, 117°E on the south coast and reported either to DoF or Redmap (Fig. 6b, Table 2). The gonads of two relatively large specimens (320, 322 mm) from January 2014 contained no evidence of reproductive development. Other *T. botla* of ~300 mm were observed during DoF dive surveys at Hillarys (~32°S) in February 2013, but specimens were not available for examination. In April 2012, a single *T. baillonii* (191 mm) was captured by the RMP at ~32°S, while another (~300 mm) was captured by a recreational fisher at ~34°S (Fig. 6b).

3.4. Survival to sexual maturity

Psammoperca waigiensis

Since the onset of the marine heatwave in early 2011, a commercial fisher has regularly reported *P. waigiensis* in haul net by-catch in Cockburn Sound (~32°S) (Fig. 1), with "reasonable numbers" caught in the summer of 2012. However, until early 2015, this species was not commercially marketed under its accepted common name and did not appear in official catch records.

Individuals from these catches ranged from 250 mm (age 1+ year) in March 2012 to 333 mm (age 3+ years) in February and April 2014 and 294–329 mm (age 4+ years) in January–March 2015 (Fig. 6c). Gonads from the age 3+ females and males were in pre-spawning, spawning or post-spawning condition, while the 4 year old individuals were in pre-spawning, post spawning, and resting condition.

Three donated specimens of *P. waigiensis* caught from ~30 and ~32°S off the lower west coast were reported by recreational fishers either in online fora or via Redmap. These fish ranged from 330 mm (age 8+) in March 2011, to 344 mm (age 3+) in October 2013 (Fig. 6c). The presence of this species at Rottnest

Island has consistently been reported by the RLS (Edgar and Stuart-Smith, 2014) since its inception in 2008, with numbers reported annually increasing significantly since the commencement of the heatwave in 2011. In addition, several confirmed sightings of this species were recorded at the Busselton Underwater Observatory (BUWO) in Geographe Bay (~33°30′S; Fig. 1) in April and June 2013 and June 2014 and during the southwest artificial reef monitoring survey in October 2014 ($n = 1$; no TL) and February 2015 ($n = 3$, 304–319 mm).
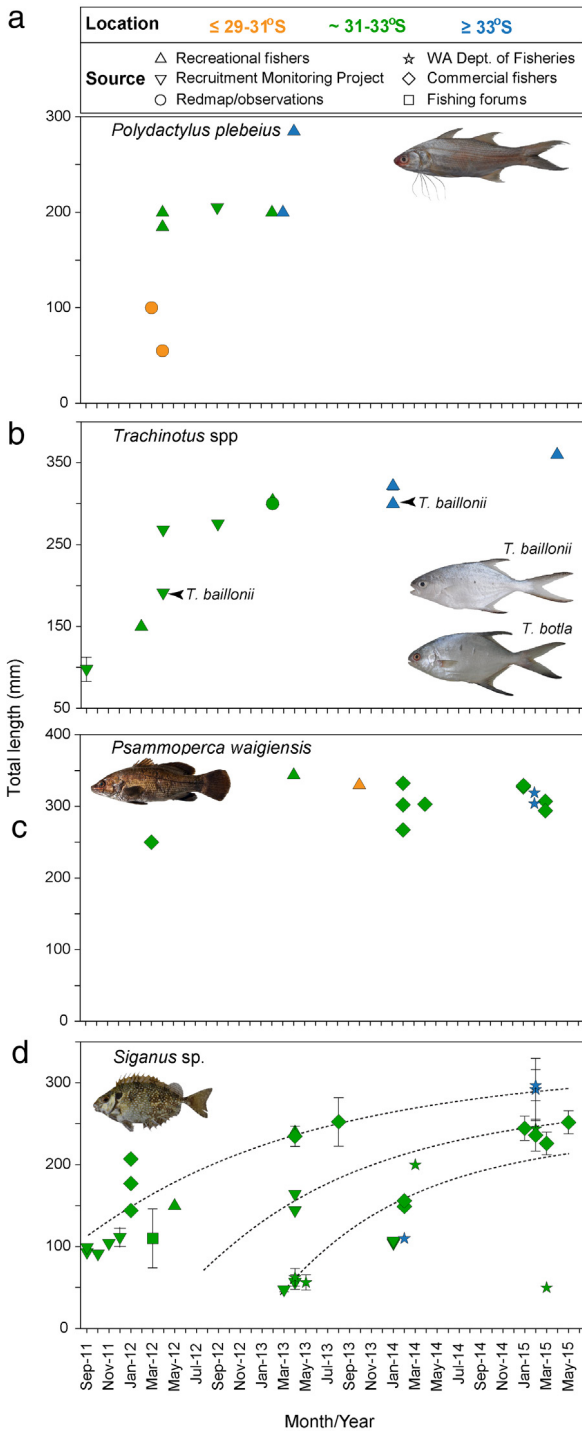
Siganus sp.

The tropical Siganidae is represented in WA by 13 species (Hutchins, 2001b). Historical records of siganids in waters off WA south of the tropics have always been attributed to either *Siganus canaliculatus*, or *S. fuscescens*. Indeed the FAO species identification guide lists both species co-occurring off the Western Australian coast south as far as the Gascoyne coast (Carpenter and Niem, 2001). However a recent review (Hsu et al., 2011) has concluded that these two species are in fact different colour morphs, and as such synonyms of a single species, subsequently referred to in this document as *Siganus* sp.

Waters off Metropolitan Perth (~32°S)

Juvenile *Siganus* sp. ($n = 11$, 90–133 mm) were first captured in nearshore waters at ~32°S by the RMP in September–December 2011 (Fig. 6d). During the summer of 2011/12, *Siganus* sp. became a by-catch species for the commercial haul net fishery in Cockburn Sound. However it was not specifically reported on DoF CAES records until 2013, when it had become well established as a minor commercial target species. In 2013 and subsequent years, regular summer catches were reported, ranging from 1 to 408 kg per month (Fig. 7). Between January and April 2012, recreational fishers also reported catching this species in nearshore waters at ~32°S (web-based forums; $n = 12$ March 2012; $n = 2$ May 2012; Fig. 6d). During March and April 2013, large numbers of newly settled juveniles were caught by the RMP at ~32°S ($n = 380$, 42–79 mm). Two larger fish were also taken during April 2013 (144 and 164 mm; Fig. 6d). Smaller numbers of this species ($n = 5$, 47–73 mm; $n = 8$, 46–71 mm) were also caught during April and May 2013 in Cockburn Sound in a DoF crab trawl net sampling program.
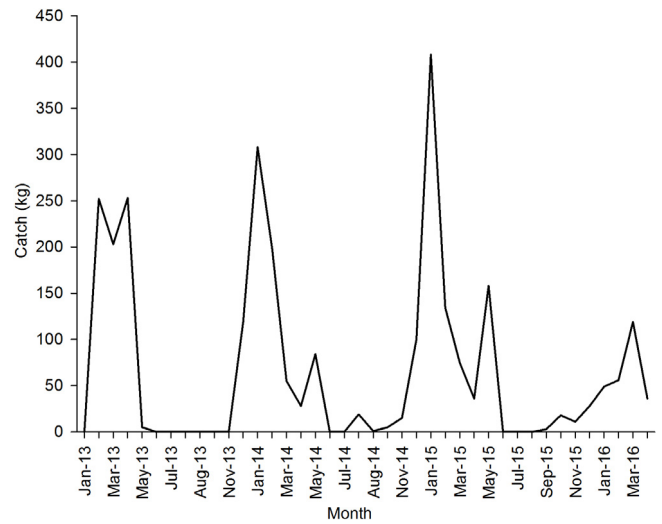
While only three commercially-caught *Siganus* sp. were obtained by DoF in January 2012 (150–210 mm; Fig. 6d), a larger sample ($n = 130$, 201–280 mm; Fig. 6d) was obtained in April 2013. Virtually all of the latter fish were age 2+ years and many were reproductively active (Figs. 8 and 9). In August 2013, the gonads of a small sample ($n = 13$; Fig. 6d) of slightly larger commercially caught individuals from Cockburn Sound were in resting condition.

During summer 2013/14, RMP surveys at ~32°S failed to capture any newly-settled age 0+ year recruits. However several individuals deduced to be from the cohort of juveniles first detected in March 2013 were captured during January 2014 ($n = 3$, 104–107 mm). Slightly larger specimens ($n = 2$, 149 and 156 mm) caught by the Cockburn Sound commercial fishery in February 2014 (Fig. 6d) were in resting condition. No further specimens were acquired during the remainder of 2014. Sampling of commercially-caught fish ($n = 123$, 190–283 mm) between January and May

Fig. 6. The five key species (a) *Polydactylus plebeius* (b) *Trachinotus botla* and *T. baillonii* (labelled) (c) *Psammoperca waigiensis* and (d) *Siganus* sp. caught or observed at three broad locations along the Western Australian coast between September 2011 and June 2015 by DoF, recreational and commercial fishers or the community. Error bars represent standard deviation. Dashed curves in Fig. 6d infer approximate growth trajectory of likely sequential cohorts of *Siganus* sp. recruited in 2011, 2012 and 2013.

Fig. 7. Commercial *Siganus* sp. catches from the Cockburn Sound fishery from January 2013 to July 2015 data obtained from the DoF compulsory monthly catch and fishing effort returns.
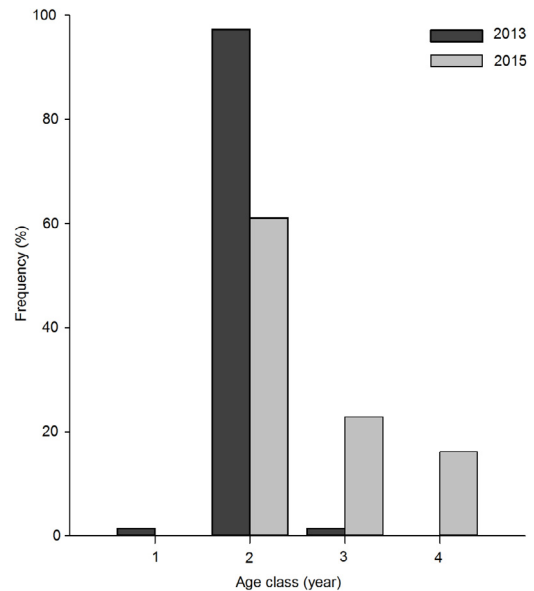

Fig. 8. Age structure of *Siganus* sp. from waters at ∼32°S in April 2013, and between January and May 2015.

2015 indicated that while the majority of the fish had developed sexually, only a single female was found to be gravid, and three females had spent or recovering ovaries (Fig. 9). While a significant number of these fish were estimated to be 2+ years of age, and thus spawned in 2013, a proportion were 3+ and 4+ years of age (Fig. 8) and likely to be survivors from earlier spawning events in 2011 and 2012 (Fig. 6d). This species was not detected by the RMP during the summer of 2015, but a single newly settled juvenile was collected in a DoF crab trawl survey in Cockburn Sound during March 2015 (Fig. 6d). Further confirmation of the establishment of this species at ∼32°S is provided by the RLS (Edgar and Stuart-Smith, 2014), where numbers of *Siganus* sp. have been reported annually from Rottnest Island since 2013. In addition, divers participating in an opportunistic roaming diver underwater "survey" conducted by DoF annually in summer since 2010 reported numbers of *Siganus* sp. at Hillarys (∼32°S; Fig. 1; P. Lewis pers. comm.) in March 2014 and February and March in 2015, which had not been recorded there in previous years (Fig. 6d).

Lower west coast ≥33°S

During the summers of 2012/13 and 2014/15, groups of adult *Siganus* sp. (up to 100 individuals) were observed at the BUWO. The southwest artificial reef monitoring survey conducted annually by DoF during the months of February, May and October each year since 2013 has also recorded large individuals of *Siganus* sp. at sites off Bunbury (February 2014 and 2015) and in Geographe Bay (February 2015).
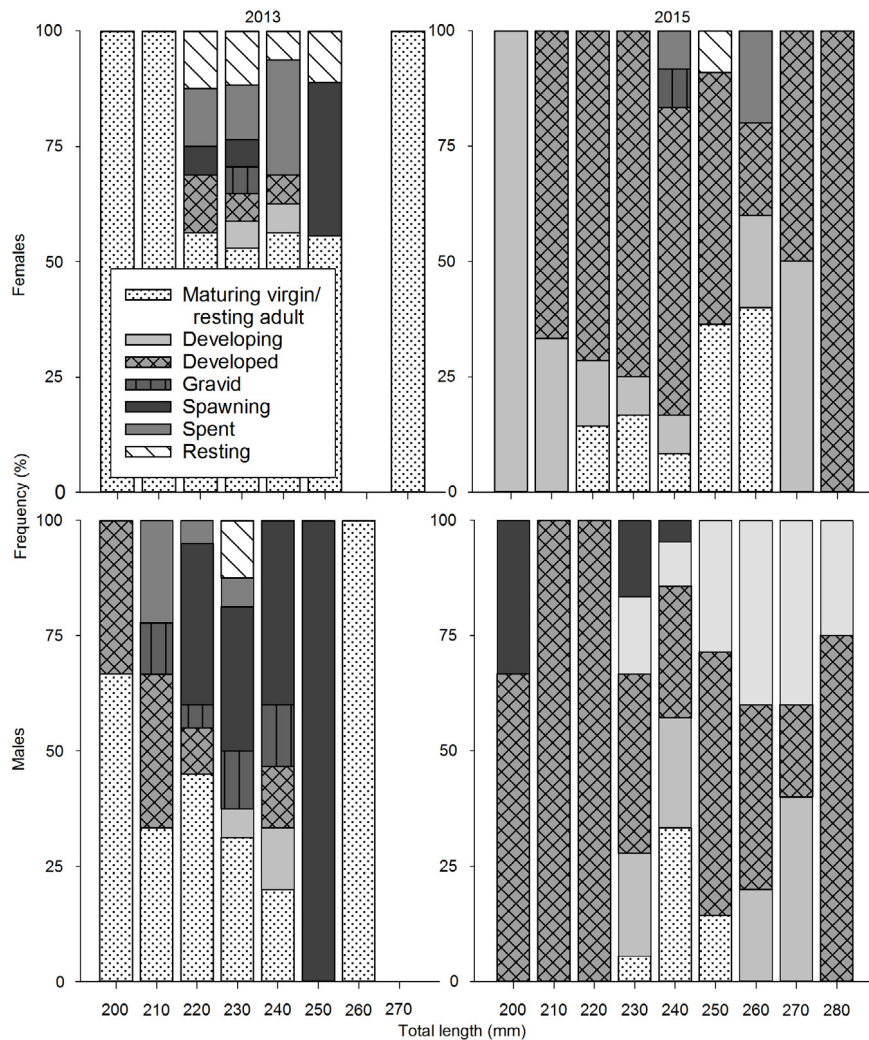
Fig. 9. Percentage frequency of *Siganus* sp. gonadal development stages from ~32°S waters in (a) April 2013, and (b) January to May 2015. Mature includes developing, developed, spawning and spent stages (see Laevastu, 1965).

3.5. Source of validated observations of selected nearshore tropical vagrants

The majority (67%) of the items of information used to evaluate the potential of the five key species to undergo range extensions in this study came from validated amateur observations and specimens volunteered by recreational and commercial fishers (Table 2), particularly for *P. waigiensis, T. botla, T. baillonii*, and *P. plebeius*. The primary source of DoF data was from specimens collected via the long-term RMP data set, which contributed almost 50% of the data on *Siganus* sp. No other useful data was derived from the other long-term datasets, e.g. commercial Catch and Effort Statistics (CAES) or iSurvey (recreational fishing survey). Additional data also came from Redmap, DoF dive surveys, and several web-based recreational fishing forums.

4. Discussion

Juveniles of the subtropical *Chaetodon assarius* and the tropical *Trachinotus botla, T. baillonii, Polydactylus plebeius, Psammoperca waigiensis* and *Siganus* sp. recruited into nearshore waters of the west coast of Australia at ~32°S in 2011 during an unseasonal, anomalously strong, poleward flowing Leeuwin Current (LC). This helped trigger a "marine heatwave" in this region, after which SSTs remained above average for a further two years. *Trachinotus spp.,*

P. waigiensis and *Siganus* sp. survived over consecutive winters, with *Siganus* sp. establishing a self-recruiting breeding population two years later. However, a return to more typical summer water temperatures by 2013/14 was associated with an apparent recruitment failure of *Siganus* sp.

4.1. Survival only within the settlement year

The southern occurrence of the subtropical *C. assarius* during the marine heatwave appears broadly consistent with results of an independent study in Jurien Bay (~30°S) that reported the first appearance of *C. assarius* in 2011 (Wernberg et al., 2013). However, detailed studies of the composition of fish communities in that region recorded *C. assarius* occasionally in the early 1980s (Hutchins, 2001a), and consistently between 2005 and 2007 (Fairclough et al., 2011). This latter study was conducted during two of the same years (2006 and 2007) as Wernberg et al. (2013). Further, Wernberg et al. (2013) did not report *C. assarius* at their more southerly sampling site (~34°S) in 2011 during the marine heatwave, while MAF records indicated catches in Geographe Bay (~33°S) in that year. The differences may be associated with low sampling intensity of Wernberg et al. (2013), given that *C. assarius* are normally site attached (Roberts and Ormond, 1992). While there is little doubt that the marine heatwave coincided with an increased presence of *C. assarius* at the southern part of its

range, care is required to ensure that the sampling effort is truly representative of the distribution of the nominated species.

The results reported in this study are consistent with those of the RLS conducted off the WA coast since 2008 (Edgar and Stuart-Smith, 2014). The southernmost records of *C. assarius* during that survey prior to the marine heatwave were from the Houtman Abrolhos Islands (~29°S; Fig. 1), while the most southerly record during the heatwave was from Rottnest Island at 32°S (Fig. 1). This was also the first record of this species at this location since the inception of this survey in 2008.

4.2. Survival beyond the settlement year

The tropical *P. plebeius*, *T. botla*, *T. baillonii*, *Siganus* sp. and *P. waigiensis* were all recorded from the temperate waters off the lower west coast of Australia, during and after the extreme marine heatwave event of 2011. Individuals of each of these five species tolerated the subsequent cooler winter SSTs and survived beyond the settlement year. Permanent breeding populations of these five species lie well to the north (e.g. Shark Bay at ~26°S) of the lower west coast and, prior to the heatwave, individuals of the first four of these species had rarely been recorded in temperate coastal waters ≥32°S (Hutchins, 1994, 1991, unpublished DoF records).

Polydactylus plebeius is widely distributed throughout the Indo-Pacific, with little published information on its biology and ecology (Allen, 2002; Kagwade, 1970; Motomura, 2004, 2002; Motomura et al., 2001). However, observations of small juveniles in Shark Bay during February–May (unpubl. data from DoF RMP) suggest a protracted spawning period during summer/autumn in tropical/sub-tropical waters. This spawning period overlapped with the peak LC flow in 2011. Prior to the 2011 heatwave event, the most southerly records of this species on the coast of WA were from Green Islands (30°41′S) and Geraldton (~29°S) during 1988 and 1949, respectively (Atlas of Living Australia, 2016) and from ~30°S in 1998, and ~32°S in 1999 and 2000 (RMP). Sightings of small juveniles at ~32°S in 1999 and 2000 coincided with relatively strong LC flows in those years, which presumably advected larvae southwards from their spawning areas. Similarly, larval advection by the exceptionally strong and early flow of the LC in 2011 offers a mechanism to explain the recorded appearance of juveniles of this species at ~32°S in that year and along the south coast for the first time.

Trachinotus botla has a protracted summer spawning period in north-eastern Australia (Oct–April; McPhee, 1999) and South Africa (Nov–Feb; Parker, 2012). In the Gascoyne Coast Bioregion of WA, RMP surveys between 1995 and 1998 detected 0+ fish in most months of the year, and newly settled recruits during the first 6 months of the year. Thus the very early onset of the strong LC in January could have facilitated the advection of fertilised eggs and/or larvae south of the established distribution of this species. *Trachinotus botla* matures at ~360–370 mm TL (McPhee, 1999). Individuals that recruited to nearshore sites at ~32°S during 2011 and that were subsequently captured had yet to reach that size. If they survived the 2013 winter, they may have reached the typical length at maturity by the summer of 2013/14. The two *T. botla* caught in January 2014 west of Albany (~35°S, 117°E) were yet to reach the length at maturity reported by McPhee (1999) and neither had developing gonads, suggesting that they were growing slowly at this more southerly location.

On the basis of west Australian records and the result of research undertaken on the east coast of Australia (Hutchins and Swainston, 1986; McPhee, 1999; McPhee et al., 1999), it is likely that *T. baillonii* has a more northern tropical distribution than *T. botla*. While there have been occasional records of the capture of this species at ~32°S on the west coast of Australia during the years preceding the marine heatwave, data examined during this study (see Table 1) revealed no records hitherto of the repeated capture of either of these species in this area during consecutive years.

The estimated ages of *P. waigiensis* obtained from ~32°S during 2011–2015 suggested that the majority were spawned in 2011 and other observations also indicate a significant recruitment event in this region in 2011. The source of those recruits is most likely to be a breeding population located within Shark Bay, an extensive sub-tropical marine embayment, approximately 800 km north of Perth, given the abundance of 0+ juveniles recorded in this embayment in other studies (Fig. 1; cf. Black et al., 1990; Hutchins, 1995, 1990; Jackson et al., 2007; Travers and Potter, 2002). However, the estimated ages of two fish captured in March 2011 and October 2013 were 8+ years, indicating birth years of 2003 and 2005, well before the marine heatwave. Thus it is more likely that these two fish were sourced from breeding populations located south of Shark Bay. *Psammoperca waigiensis* is reported from Fremantle (32°S) northwards (Hutchins and Swainston, 1986), and a breeding population is believed to occur in the inshore waters off Dongara (29°15′S; Howard, 1989, 1988), and perhaps the Houtman Abrolhos Islands (Edgar and Stuart-Smith, 2014). The recording of significant numbers of large individuals (>291 mm TL) during extensive reef fish surveys in Jurien Bay (~30°S) (Fairclough et al., 2011) suggests that breeding populations may also exist at least this far south. Given the ongoing presence of *P. waigiensis* in waters around Rottnest Island (Edgar and Stuart-Smith, 2014), there remains the possibility that some level of breeding has occurred this far south. Their repeated verified detection within Geographe Bay (~34°S) since the heatwave indicates a significant, at least temporary, southerly shift in their distribution. *Psammoperca waigiensis* spawns over an extended period during the warmer months of the year in other regions (Shimose and Tachihara, 2006). Hence the early onset of the LC in 2011 and 2012 would likely have resulted in a higher rate of entrainment and southwards dispersal of larvae compared to other years.

Permanent populations of *Siganus* sp. are present in the Gascoyne Coast Bioregion (north of 26°S) (Black et al., 1990; Hutchins, 1995; Travers and Potter, 2002; Travers, 1999). However, in recent years, there have been an increasing number of sightings of this species further south. In six surveys at the Houtman Abrolhos Islands (~28°S) from 1975 to 1994, *Siganus* sp. were only occasionally encountered (Hutchins, 1997). More recently, significant numbers were recorded at these islands in March 2008 and May 2010 during the RLS (Edgar and Stuart-Smith, 2014). During the early 1980s a number of specimens were caught during a survey of the nearshore fish fauna in the Dongara region (~29°S) (Howard, 1989, 1988). During 2005–2007, an intensive study of the coastal fish community off Jurien Bay (~30°S) reported both juveniles and adults of this species (Fairclough et al., 2011), which may reflect a breeding population at this location. Alternatively, juveniles and adults may have resulted from multiple recruitment events from breeding stocks further north.

The earliest records of *Siganus* sp. at ~32°S were from January to April in five separate years between 1933 and 1954 (Atlas of Living Australia, 2016), followed by those of Hutchins and Thompson (1983) and Hutchins (1994, 1979). This species was also tentatively identified at the BUWO (~34°S) during the summers/autumns of 2005–2008.

While *Siganus* sp. was not recorded in an earlier major inventory of the fish fauna of Cockburn Sound at 32°S (Dybdahl, 1979), it was recorded over seagrass by baited remote underwater video (BRUV) surveys in Cockburn Sound during June 2013, for the first time since they commenced in 2008 (Wakefield et al., 2013). Thus while there have been a number of records of individual juveniles at ~32°S, there is no previous evidence that they had persisted or matured in these waters.

In the northern hemisphere, *Siganus* sp. spawning times varied from July to August at higher latitudes, to January to May at locations close to the equator (Grandcourt et al., 2007; Woodland, 1990). There appear to be no published records of spawning times for *Siganus* sp. in the southern hemisphere. However, in Shark Bay, newly settled juveniles (26 mm mean TL) were first detected in March (RMP, DoF). As its larvae typically take 23–30 days to metamorphose (Woodland, 1990), it is probable that these juveniles were spawned in February. Thus, the cohort of *Siganus* sp. first encountered at ∼32°S in spring 2011 as 0+ individuals is believed to have been sourced from more northerly breeding populations during the unusually early LC that commenced flowing strongly during summer 2011. It was also during the summer and autumn of 2013 that both recreational and commercial fishers reported catching larger individuals (∼2+ years) in Cockburn Sound. It appears that these fish then survived the following austral winter to become the large fish obtained from commercial fishing in Cockburn Sound in April 2013, and taken by recreational fishers in the Swan River. The small juveniles sampled by the RMP at ∼32°S between March and April 2013 were likely to be the progeny of this resident older cohort at ∼32°S. While there were no sightings in 2012 of small juveniles of equivalent size to those captured between September and December 2011, it is likely that the two fish of 144 and 164 mm sampled in April 2013 were representatives of that cohort (spawned in the summer of 2012) that have hitherto remained undetected.

The establishment at ∼32°S of a self-recruiting population (i.e. category 3 permanent range extension) of *Siganus* sp., which is herbivorous, would likely have a major impact on the local algae-dominated ecological community. Indeed, *Siganus* sp. along with other tropical and subtropical herbivores have contributed to the community-wide tropicalisation of the coastal ecosystem further north off the mid-west coast of Australia, supressing the recovery of kelp forests lost during the marine heatwave (Wernberg et al., 2016). Populations of this, and other tropical siganids have also established in temperate waters of Japan and the Mediterranean, respectively (Vergés et al., 2014), and eastern Australia (Vergés et al., 2016) following rising ocean temperatures. Many of these areas have experienced major ecological changes (substantial loss of benthic habitat biomass and species richness) and economic costs as a consequence of herbivorous grazing (references in Vergés et al., 2014).

4.3. Mechanisms for southerly range extensions

The occurrence of *C assarius*, *P. waigiensis*, *T. botla*, *T. baillonii*, *P. plebeius* and *Siganus* sp. in waters ≥32°S strongly suggest that all of these summer-spawning tropical species were recruited by the atypically strong flow and early onset of the LC associated with the marine heatwave. The larvae of each of these species are assumed to be pelagic for approximately three weeks prior to settlement (Breder and Rosen, 1966; Woodland, 1990). Historically, the LC is at its strongest between May and July, limiting the potential for southward transport of summer-spawned larvae to the lower west coast. However, the LC flowed strongly from January to July during 2011 (the marine heatwave year) and 2012. While individuals of each of these species have at times been recorded at more southerly locations, this unusual and significantly earlier start to the strong LC provided the opportunity for the southward transport of their pelagic larvae. The velocity of the LC is capable of transporting larvae southwards to coastal waters at least as far south as ∼32°S, as occurs with other tropical species in the region, e.g. *Abudefduf* spp. (Pearce et al., 2011b, 2016).

It is likely that once juveniles of the different species had settled in suitable habitats in temperate waters of the west coast, the persistence of elevated temperatures, particularly during the normally cooler winter months, was a key factor in their ongoing survival. In the case of *Siganus* sp., it also enabled individuals to mature and breed during the summer of 2013. However, unlike *Siganus* sp., there was no evidence that individuals of the other species did the same.

During the summers of 2013/14 and 2014/15, nearshore SSTs had begun to decline toward pre-heatwave levels, and while the *Siganus* sp. population persisted, there was no evidence to suggest that successful breeding had occurred for a second or third year, although there was weak evidence of limited breeding in summer 2014/15. Thus, although a breeding population was established, its permanency can only be determined through ongoing monitoring. Range extension can be defined as the 'stable' extension of a population from first arrival and population increase (Bates et al., 2015, 2014). However, the persistence of such a population is dependent on ongoing (continuous or intermittent) recruitment to the newly established population via successful breeding of that population. While progeny for the original 'source' population may also contribute, it is suggested here that recruitment from this source alone would not constitute a permanent range shift.

4.4. Further responses to the marine heatwave

While the main focus of this study relates to the recruitment of nearshore (shallow water <20 m depth) species with clear dispersal capacity, evidence is mounting from verified records (via Redmap and specimens submitted to DoF) that demonstrates that since the advent of the marine heatwave, there has also been recruitment of a number of other tropical finfish species into the deeper (20–250 m depth) demersal habitats (Department of Fisheries, 2011) of the waters of 32°S and ≥33°S. Most prominent were *Lethrinus miniatus*, and *L. nebulosus*. Fewer records of *L. laticaudis* and *Epinephelus rivulatus*, and single records of *L. punctulatus* and *E. multinotatus* were also reported (unpublished DoF records).

Evidence is also available that shows the southerly displacement of larger-bodied tropical pelagic species such as billfish (*Makaita indica* and *Makaita mazara*), whale sharks (*Rhincodon typus*), manta rays (*Manta birostris*) and Spanish mackerel (*Scomberomorus commerson*) (Caputi et al., 2014; Pearce et al., 2011a, unpublished validated DoF records), together with the first record of the Japanese devilray (*Mobula japanica*) in the waters off the southwest coast of Australia (Smith et al., 2014). The reduction in abundance of a number of temperate species, such as *Aldrichetta forsteri*, *Arripis georgianus* and *Hyporhamphus melanochir* has also been recorded (RMP Database; unpublished DoF records).

While the degree of species displacement is broadly related to a combination of an appropriate temperature tolerance and intrinsic species traits, such as strong dispersal capacity and wide latitudinal range (Sunday et al., 2015), it is important to note that species that do not exhibit these characteristics are less likely to markedly alter their range in response to climate change.

4.5. The ability of severe discrete climatic events to influence ecological change

Short-term climatic events are a significant factor that influence ecological change (Jentsch et al., 2007). The consistent warming trend in temperate waters off the south-west coast of WA has influenced coastal biodiversity, and is predicted to lead to further tropicalisation of the coastal marine community (Cheung et al., 2012). However, events such as the marine heatwave superimpose additional short-term impacts on the underlying longer-term environmental changes that are influencing the abundance and distribution of marine species off the WA coast, as observed in this study (Wernberg et al., 2013, 2016).

The timing of recent LC flows is atypical, with peak flows being experienced progressively earlier in the year. Prior to 1975, peak flows commenced almost exclusively in April, May or June. After 1975, the latest they commenced was in April, with an even earlier onset on three occasions since 2007. A shift in the onset, timing and magnitude of LC flows, especially the strong flows that occur during La Niña years, has the potential to alter the composition of the suite of larvae and/or small juveniles of tropical species transported southwards, such as *Siganus* sp.

An abundant breeding population of another nearshore tropical species, *Platycephalus westraliae* (formerly *P. endrachtensis*, Imamura, 2008), is located in the Swan River estuary, and to a lesser extent, Cockburn Sound, with no evidence of this species occurring further south. While this species has also been recorded from the waters off Geraldton (~29°S), the closest breeding population to the Swan River is located to the north within the protected waters of Shark Bay (Travers and Potter, 2002). Spawning in the Swan River has been recorded between October and March (Coulson et al., 2007). If this is also the case for the Shark Bay population, it is possible that the southward extension of this tropical species to the protected waters of the Swan River and Cockburn Sound was via recruitment of progeny from Shark Bay during a similar earlier onset of a strong LC event. Since 1900, the most likely year when this may have happened was 1934, which is the only year during the 20th Century (see Fig. 2) when the early onset of the LC was experienced. Western Australian Museum records (Atlas of Living Australia, 2016) list 1937 as the earliest record of this species from the Swan River, with Imamura (2008) also citing the holotype as being collected from the Swan River in 1937.

5. Monitoring of future climatic shifts

It is important to recognise that it was only possible to document some of the southerly shifts in distribution cited in this paper because of the availability of validated items of information volunteered by the fishing community, either via specimens presented directly to DoF, or via records posted on Redmap or other web-based sites. In contrast, with the exception of the MAF, which does provide good records of those species being targeted for the aquarium fish trade in WA, most other existing 'traditional' DoF databases such as those relating to commercial catch and effort and recreational fishing surveys were not as useful as other 'fishery-independent' sources such as the nearshore finfish recruitment surveys (RMP), because they were not designed to record small catches of unusual species. The Redmap website (www.redmap.org.au) allows observational data (photographs) of marine species occurring outside their known distribution to be submitted by the public to be scientifically verified. While this has proven to be very useful, it needs to be recognised that such datasets only record the presence of a particular species and that it is a recently initiated programme (since 2012 for Western Australian sightings). While it is clear that unusual occurrences are being reported, it is presently difficult to judge how representative such observations are of the real presence/absence of the species they record. Thus, if we are to achieve maximum value from such data, then it is crucial that DoF continues to work with amateur observers and contributors to web-based datasets such as Redmap to encourage them to provide the additional required information. This can best be achieved through "citizen science" programs (Bodilis et al., 2014; Fairclough et al., 2014; Shirk et al., 2012) that are designed to provide more representative records from the community, of the changing distribution of species of interest (e.g. marine 'pest' species) into the future. Maintenance of the existing RMP is also most important, as it provides relative recruitment strength data for a wide range of nearshore finfish species over a long time period, including records of tropical and subtropical species distributed beyond their historical limits.

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