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Influence of climate on the fishery recruitment of a temperate, seagrass-associated fish, the King George whiting *Sillaginodes punctata*

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ABSTRACT: The King George whiting fishery in Victoria, Australia, is based on sub-adult fish of 3 to 5 yr old in bays and inlets. Previously, Zonal Westerly Winds (ZWW) and the El Niño southern oscillation index (ENSO) cycle have been found to influence the larval stages and subsequent catches of some fishery species in southeastern Australia. Offshore spawning and long larval life, together with a fishery based on a few year classes of sub-adult fish, led to the hypothesis that the fishery would be strongly influenced by climatic conditions in the larval stage. A significant positive correlation was found between the strength of ZWW in the region and the catch 3 to 5 yr later. These conditions may have influenced larval transport rates, or alternatively may have led to increased plankton productivity and therefore larval food supply. The ENSO cycle, however, was found to have a positive influence on catch at 0 lag. This positive correlation suggested that La Niña conditions may have led to increased catchability of King George whiting. Post-larval abundances at a seagrass site in Port Phillip Bay were strongly correlated with ZWW, confirming that the effect of these winds occurred in the larval to post-larval stages. Overall, results suggest that climatic conditions exert a strong influence on the larval to post-larval stages that subsequently affect the catch in the fishery.

KEY WORDS: Climate · Zonal Westerly Winds · ENSO cycle · King George whiting · Catch trend · Southeast Australia · *Sillaginodes punctata*

INTRODUCTION

Recruitment is recognised as a dominant process determining population structure and abundance of marine organisms (Roughgarden et al. 1988, Doherty & Fowler 1994, Caley et al. 1996), including many commercially important fish. Recruitment can be strongly influenced by climatic and hydrographic variables (Attrill & Power 2002). In many exploited populations, recruitment may be the primary determinant of catch, for example, where species are short-lived or the fishery is concentrated on young individuals (Rodhouse 2001). In terms of fisheries management, correlations between environmental variables and recruitment have the potential to lead to forward predictions of catch.

Environmental variables that have been shown to correlate with recruitment include rainfall (Crecco et al. 1986), sea surface temperatures (Francis 1993, Rutherford & Houde 1995), winds and currents (Harris et al. 1988, Thresher 1994), river flow (Salen-Picard et al. 2002) and the El Niño southern oscillation index (ENSO) cycle (Harris et al. 1988, Pearce & Phillips 1988, Kope & Botsford 1990, Jordan et al. 1995). In southeastern Australia, the frequency of Zonal Westerly Winds (ZWW) and the ENSO cycle have been found to correlate with catches of a number of freshwater and marine fishery species (Harris et al. 1988). Catches of spiny lobsters (Harris et al. 1988, McGarvey & Matthews 2001), and possibly some other species (Harris et al. 1988), were correlated with these variables, acting at lags consistent with the effects occur-

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ring in the larval stages. Such effects were suggested to be either a direct influence on larval transport or an indirect influence on plankton productivity (Harris et al. 1988).

The King George whiting *Sillaginodes punctata* forms one of the most important inshore fin fisheries in southeastern Australia (Kailola et al. 1993). This fishery has the potential to be strongly influenced by recruitment variability, because although the species can live up to 20 yr, exploitation is primarily concentrated on sub-adults of 3 to 5 yr old. These sub-adults occur in protected bays and inlets, while adults occur on the exposed open coast. Spawning occurs offshore in autumn/early winter and post-larvae enter bays and inlets in the spring at a size of approximately 16 to 20 mm (Jenkins & May 1994, Jenkins et al. 2000). Post-larvae are defined as having a full compliment of fin elements, but are yet to take on juvenile characteristics of pigmentation, gut coiling and scale formation (Bruce 1995). Within bays and inlets, post-larvae are mainly found in shallow seagrass and reef/algae (Jenkins & Wheatley 1998). The larval period is long (3 to 5 mo), and there is potential for interannual variation in factors such as current strength and plankton productivity to influence survival between coastal spawning, and settlement to bay and inlet habitats (Jenkins & May 1994, Jenkins et al. 2000).

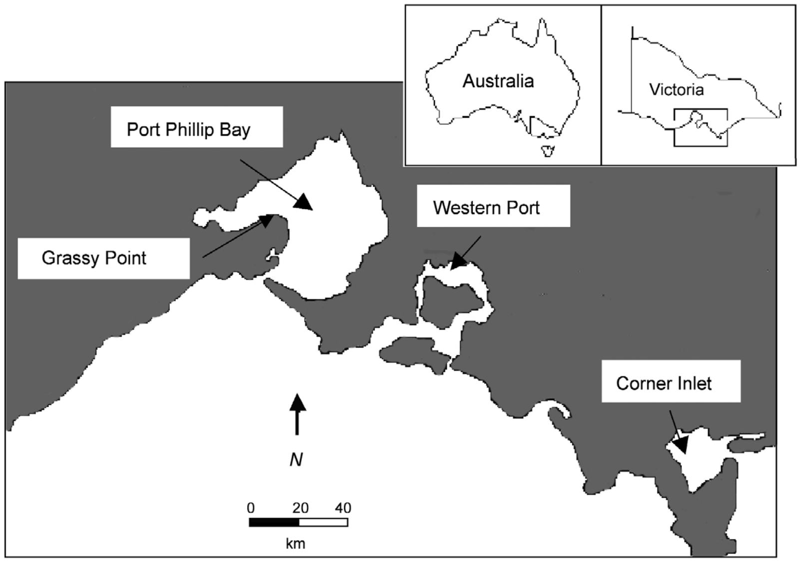

Fig. 1. Primary locations of fishing for King George whiting on the Victorian coast: Port Phillip Bay, Western Port and Corner Inlet, and the post-larval monitoring site at Grassy Point in Port Phillip Bay. Insets: location of the study area on the Victorian coast and location of Victoria within Australia

I hypothesise that the King George whiting fishery may be strongly influenced by climatological factors, because the larval stage is prolonged and occurs in the open ocean, and the fishery is based on only a few year classes of sub-adults. In this study, I test this hypothesis by analysing time series of climatological and catch data for significant correlations at biologically meaningful lags. I also examine the effect of these variables on data on abundance of post-larvae to verify possible effects occurring in the larval/post-larval stages that eventually translate to variation in catch.

MATERIALS AND METHODS

Catch and effort. Historical catches of King George whiting from the 3 main fisheries in Victoria — Port Phillip Bay, Western Port and Corner Inlet (Fig. 1) — were collated from commercial fishing catch returns as annual landings by weight. Landings were recorded annually from 1945 to 1963 but subsequently for financial years (July to June) from 1964 to the present. This change is not seen as an impediment to the present analysis because the primary interest was in low frequency variation where comparisons would be little affected by a 6 mo phase shift. From 1978, information on fishing effort was available in terms of number of net shots. This analysis was restricted to seine nets (beach, haul, ring and garfish) that account for most of the King George whiting catch.

Climate variables. ENSO is based on the air pressure difference between Darwin and Tahiti. Negative values represent El Niño or ocean warming in the Pacific, while positive values represent La Niña or ocean cooling in the Pacific. This cycle is thought to influence recruitment of fishery species in southeastern Australia (Harris et al. 1988, Thresher 1994, Jordan et al. 1995). ENSO values were obtained from the Bureau of Meteorology, Australia, and were calculated as the Troup SOI.

Also implicated in variation in recruitment of southeastern Australian fishery species, is the strength of westerly winds (Harris et al. 1988, Thresher 1994). Westerly winds were quantified by calculating the number of 'Zonal Westerly Wind (ZWW)' days in each year. Criteria for ZWW are detailed in Harris et al. (1988) and include isobars mostly aligned east–west, at least 1 cold front embedded in the westerly stream, and total duration of the weather system of more than 1 d.

Sampling of post-larvae. Post-larvae were sampled in 1991 and then annually from 1993 to 2003. Sampling was conducted at Grassy Point in Port Phillip

Bay at approximately monthly intervals during spring (mid-late August to mid-late November). Sampling was conducted on shallow sub-tidal *Zostera tasmanica* seagrass beds. Four replicate hauls were taken with a fine-mesh (1 mm) seine net (10 m × 2 m). Details of the study area and sampling method are described by Jenkins et al. (1997). From 1994 to 2001, five 2 × 1 m artificial seagrass units (ASUs) were deployed on sand patches within the *Zostera* beds over spring and were sampled fortnightly for post-larvae with a small seine net. Details of ASU construction and sampling are described in Jenkins et al. (1998).

Statistical analysis. Similarity between time series of environmental and catch variables were tested using cross-correlation analysis that tests both direct and lagged correlations. The correlation statistic used was Pearson's *r*. The modified Chelton method (Pyper & Peterman 1997) was used to adjust the sample size N_A used in correlations to account for the inflated probability of a type 1 error due to autocorrelation within time series. This method was preferred over first differencing because the primary interest was in low frequency variation (Pyper & Peterman 1997). Where necessary, time series were log-transformed and/or trend-transformed (the residuals of a linear regression were used to remove trend) to make the time series stationary.

RESULTS

Catch

Catch of King George whiting in Port Phillip Bay has been steadily increasing since 1945 but also shows cyclic variability with approximately 5, quasi-decadal cycles discernible over the period (Fig. 2A). Catch in Western Port increased from 1945 to the early 1970s, but then decreased to a level much lower than in the other bays in recent years (Fig. 2B). Superimposed on this trend was a cyclic pattern that was similar to Port Phillip (Fig. 2B). Like Port Phillip, the underlying trend in catch in Corner Inlet was upward (Fig. 2C). In Corner Inlet, the general cyclic pattern of the other bays was recognisable; however, shorter cycles of a few years period were also present (Fig. 2C). Catches of King George whiting in the 3 bays were significantly correlated, with a particularly close relationship between Port Phillip Bay and Western Port (Table 1).

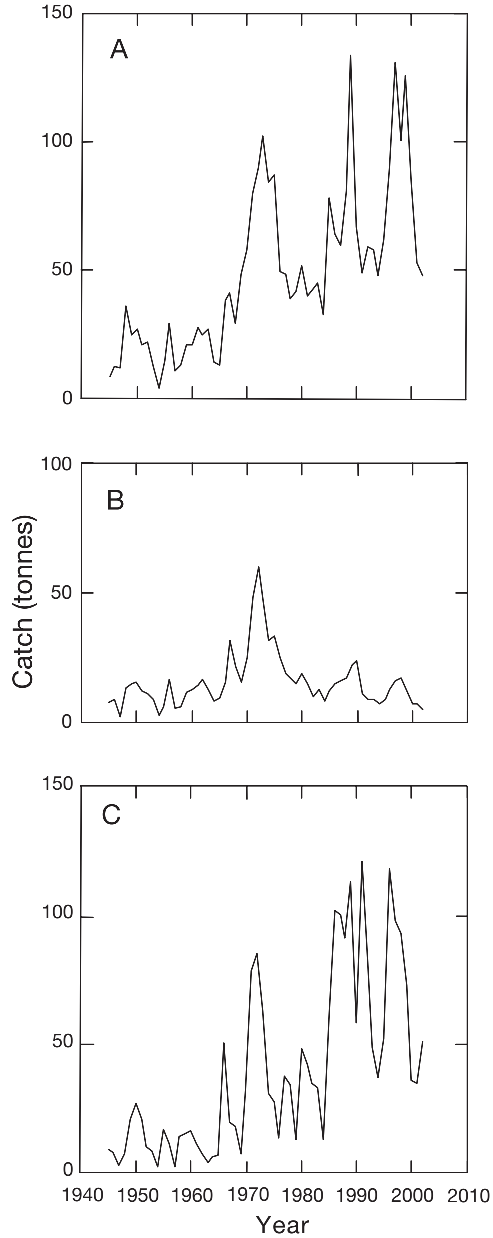

Fig. 2. *Sillaginodes punctata*. Annual catch by weight from 1945 to 1998 for (A) Port Phillip Bay, (B) Western Port and (C) Corner Inlet

Table 1. *Sillaginodes punctata*. Cross correlations between catch (tonnes) from 3 bays between 1945 and 1998. Maximum positive and negative correlations are presented with associated time lags in years. N_A: adjusted N (no value indicates adjustment not required). **: p < 0.001; ns: not significant

Variable	Western Port catch[a]			Corner Inlet catch[a]		
	Lag	N_A	*r*	Lag	N_A	*r*
Port Phillip catch[a]	0	30	0.814**	0	40	0.611**
Western Port catch[a]				0	43	0.563**

[a]Data log- and trend-transformed

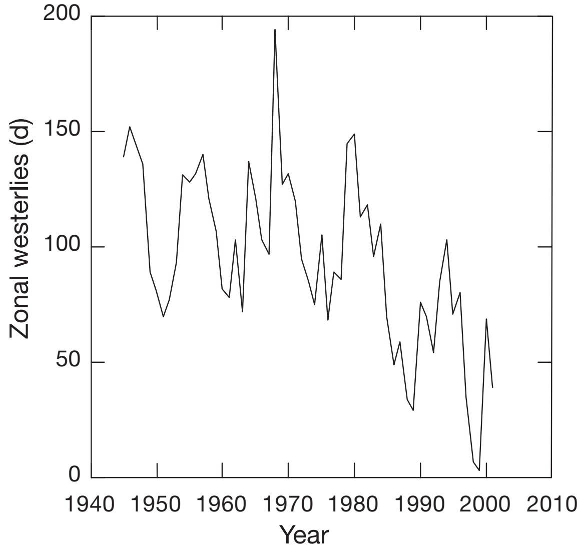

Fig. 3. Time series of the annual number of days of Zonal Westerly Winds in the southeast Australian region

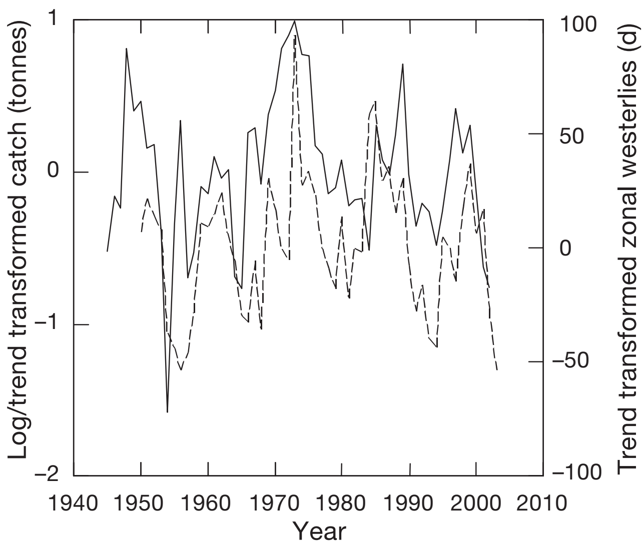

Fig. 4. *Sillaginodes punctata*. Relationship between trend-transformed annual number of days of Zonal Westerly Winds (ZWW) and log-/trend-transformed Port Phillip Bay catch lagged by 5 yr. Solid line: catch; dashed line: ZWW

Correlation between environmental variables and catches

ZWW have exhibited strong, quasi-decadal cyclic variability with approximately 5 cycles occurring over the period (Fig. 3). This variability is superimposed on a very marked downward trend in the number of days of ZWW (Fig. 3). Long-term catches were significantly correlated with ZWW at lags of 3, 4 and 5 yr in Port Phillip, 3 and 4 yr in Western Port, and 3 yr in Corner Inlet (Table 2). Fig. 4 shows the relationship with the highest correlation: Port Phillip Bay catch lagged by 5 yr and ZWW.

The ENSO showed high variability at the scale of approximately 2 to 7 yr superimposed on a slight downward trend (Fig. 5). Long-term catch for Port Phillip showed a significant positive correlation with the ENSO at 0 lag (Table 2). No significant correlation was found between ENSO and catches in Western Port or Corner Inlet (Table 2).

Table 2. *Sillaginodes punctata*. Cross correlations between environmental variables and long-term catch from 3 bays. Zonal Westerly Wind (ZWW) and ENSO series are from 1945 to 2001. Maximum positive and negative correlations are presented with associated time lags in years. N_A: adjusted N (no value indicates not significant before adjustment). *p < 0.05; ns: not significant

Variable	Sign	Port Phillip catch[a]			Western Port catch[a]			Corner Inlet catch[a]		
		Lag	N_A	r	Lag	N_A	r	Lag	N_A	r
ZWW[b]	+ve	3	28	0.428*	3	31	0.430*	2	38	0.305 ns
	+ve	4	29	0.434*	4	31	0.374*	3	36	0.336*
	+ve	5	29	0.442*	5	32	0.332 ns	4		0.247 ns
ENSO[b]	+ve	0	50	0.309*	0		0.233 ns	0		0.106 ns

[a]Log- and trend-transformed; [b]trend-transformed

Catch per unit effort (CPUE)

Although the catch and effort time series is insufficiently long for statistical analysis of correlation with environmental variables, examination of these series could indicate whether variability in catches could, in part, reflect variability in fishing effort. The time series of CPUE in Port Phillip (Fig. 6A) and the raw catch (Fig. 2) were very strongly correlated (Pearson's $r = 0.930$, $N_A = 13$, $p < 0.001$, $r^2 = 0.86$); the cyclic variability in the time series was apparently not a function of variation in effort. CPUE for Western Port was lower than for the other 2 bays and showed no trend over time (Fig. 6B), showing that the declining trend in catch (Fig. 2B) was partly related to declining effort. Peaks in catch around 1980, 1990 and in particular the late 1990s for Western Port (Fig. 2B) were also apparent in CPUE (Fig. 6B). In general, the CPUE for Corner Inlet showed similar variability to raw catch (Fig. 6C). The lack of an increasing trend in the data (Fig. 6C), which was apparent in the raw catch (Fig. 2C), is a reflection of increasing effort in Corner Inlet over time. Like raw catch, time series of CPUE for the 3 bays were highly correlated (Table 3).

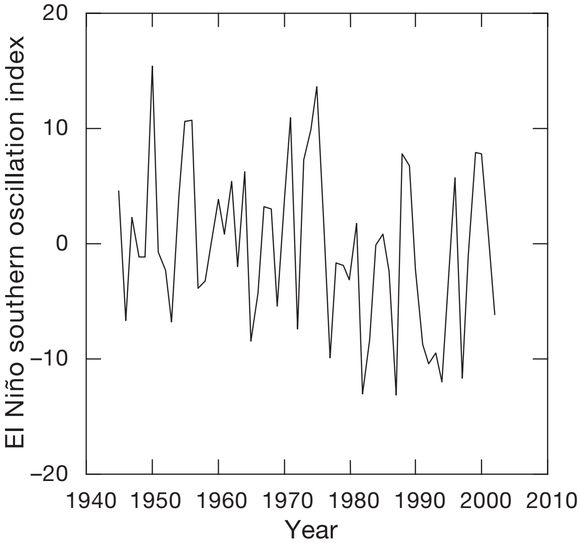

Fig. 5. Time series of the annual average El Niño southern oscillation (ENSO)

Correlation between westerly winds and recruitment at Grassy Point

The positive correlation between ZWW and catch lagged by 3 to 5 yr suggests that the positive effect of these winds occurred in the larval to post-larval stage. I examined a time series of sampling of post-larval abundances at Grassy Point to test this hypothesis. Abundances of post-larvae in artificial seagrass units and natural seagrass were very highly correlated (natural seagrass [log trans] versus ASU [log trans]: $r = 0.981$, N = 8, $p < 0.001$, no adjustment for autocorrelation required), suggesting that abundances in natural seagrass were not affected by variation in seagrass characteristics at the site through time (Fig. 7). The time series of post-larval abundance was highly correlated with ZWW at 0 lag (zonal westerly [trend trans]/recruitment [log trans]: $r = 0.795$, N = 10, p = 0.006, no adjustment for autocorrelation required), with peaks in 1994 and 2000, and a trough in 1998 and 1999 occurring for both variables (Fig. 8).

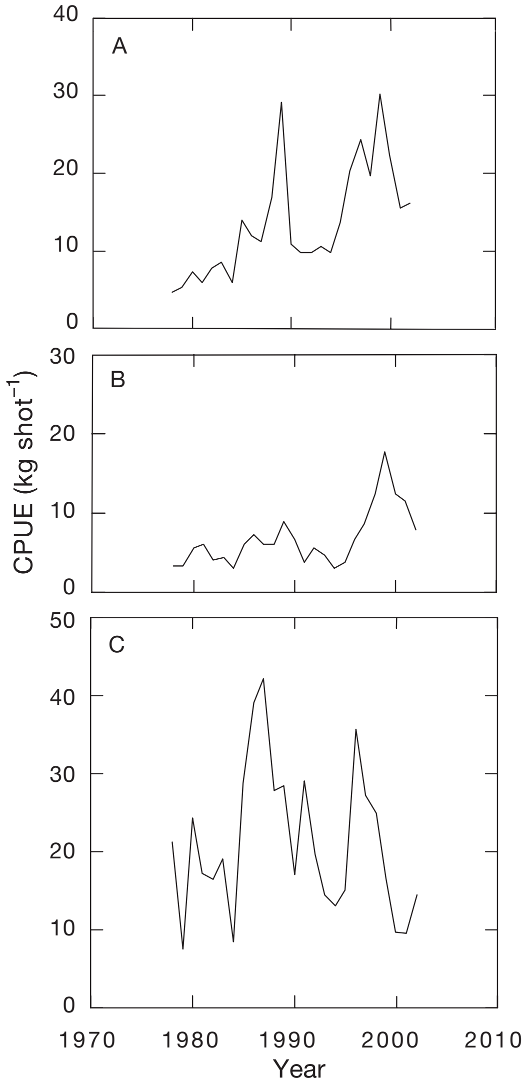

Fig. 6. *Sillaginodes punctata*. Time series of annual catch per unit effort (CPUE) for seine netting. (A) Port Phillip Bay, (B) Western Port (C) Corner Inlet

Table 3. *Sillaginodes punctata*. Cross correlations between catch per unit effort (CPUE, kg per net shot) from 3 bays between 1979 and 1998. Maximum positive and negative correlations are presented with associated time lags in years. N_A: adjusted N (no value indicates adjustment not required). *p < 0.05; **p < 0.001

Variable	Western Port CPUE[a]			Corner Inlet CPUE[a]		
	Lag	N_A	r	Lag	N_A	r
Port Phillip CPUE[a]	0	10	0.825**	0	17	0.588*
Western Port CPUE[a]				0	15	0.655*

[a]Data log- and trend-transformed

DISCUSSION

Annual catches of King George whiting were highly variable and were highly correlated amongst Port Phillip Bay, Western Port and Corner Inlet. This strongly suggests that large-scale environmental variation exerts a significant control on the abundances of whiting. Similarity of time series of catch and CPUE indicates that the strong variability observed is not simply a reflection of variable fishing effort. One source of large-scale environmental variation, the ZWW across southeastern Australia, appears to have a

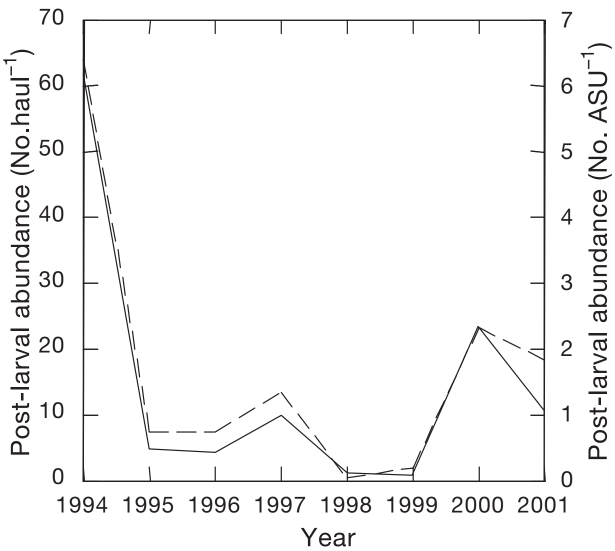

Fig. 7. *Sillaginodes punctata*. Average annual abundance of post-larvae collected from Grassy Point, Port Phillip Bay. Solid line: natural seagrass; dashed line: artificial seagrass units (ASU)

significant influence on the catch of King George whiting.

Both the ZWW and the catch data show a quasi-decadal cycle. This quasi-decadal cycle in ZWW and fishery catches has been previously reported for south-eastern Australia (Harris et al. 1988, Thresher 2002). This variation broadly corresponds with the sunspot cycle, and reflects shifts in the latitude range each year of the sub-tropical ridge over southern Australia (Thresher 2002).

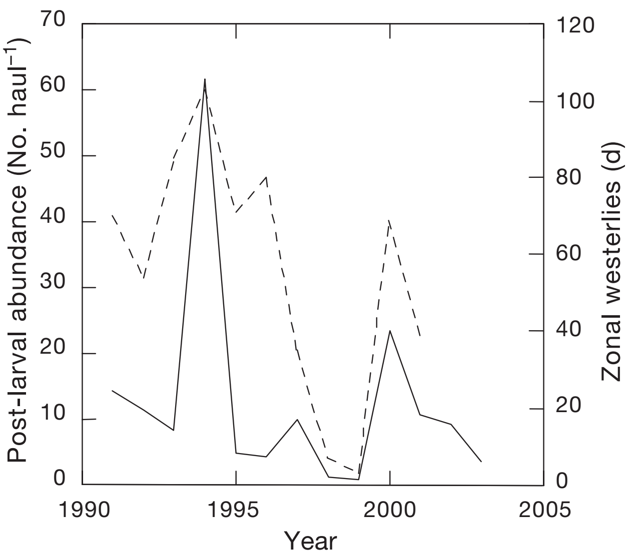

Fig. 8. *Sillaginodes punctata*. Comparison of average annual abundance of post-larvae collected from Grassy Point, Port Phillip Bay, and Zonal Westerly Winds (ZWW). Solid line: Post-larval abundance; dashed line: ZWW

As hypothesised, the lag of 3 to 5 yr between the ZWW cycle and the catch of King George whiting cycle strongly suggests that the impact of the ZWW cycle occurs in the larval to post-larval stages of King George whiting. This is because the fishery is based on only 2 to 3 year classes of sub-adults. Most whiting individuals reach legal size in their third year, and few individuals remain in the bays after their fifth year (Smith & MacDonald 1997, Fowler et al. 1999). Thus, for the lagged correlation between ZWW and catch, the strong zonal westerlies would correspond to the year of larval recruitment that resulted in a large catch 3 to 5 yr later. This result is consistent with some other fishery species in southeastern Australia where the influence of ZWW on catches appears to occur in the larval stage (Harris et al. 1988, Thresher 1994).

The larval duration in King George whiting is very long compared with most fish species (Jenkins & May 1994). Moreover, research strongly suggests that spawning occurs offshore from bays and inlets, and often a considerable distance from the settlement site (Jenkins et al. 2000). Thus, interannual variation in the current patterns carrying larvae could influence the number of larvae arriving at bays of central Victoria (Norcross & Shaw 1984, Polacheck et al. 1992, Werner et al. 1997). However, westerlies in the southern Australian region may also lead to higher planktonic productivity, and therefore survival of larvae (Harris et al. 1988, Thresher et al. 1989, Heath & Gallego 1998). The primary source of variation in larval survival and recruitment in marine fish in southeastern Australia is thought to be planktonic productivity, influencing larval feeding rates and subsequent survival (Harris et al. 1988); transport may play a subordinate role.

That years with strong westerly winds lead to higher post-larval abundance and subsequent catch, is supported by annual monitoring of post-larval abundances of King George whiting at Grassy Point in Port Phillip Bay. There appears to be a strong relationship between the strength of westerly winds and annual recruitment at this site. The high correlation between recruitment on artificial and natural seagrass shows that the inter-annual variation in recruitment at this site does not relate to inter-annual variation in seagrass characteristics. Recruitment to this site has previously shown to increase in periods of strong westerly winds and low barometric pressure, when the water level in Port Phillip Bay is increased and there is a corresponding ingress of post-larvae from Bass Strait (Jenkins et al. 1997). Thus, there is strong evidence that inter-annual variation in the westerly wind field across Bass Strait has the potential to affect annual recruitment of post-larvae. Recruitment to this site has also been shown to vary with local wind conditions; onshore winds lead to a re-entrainment of post-larvae to the plankton (Jenkins et al. 1997, Moran et al. 2003, 2004a). However, this effect is more related to winds from the north and south (onshore/offshore) rather than from the west (cross-shore) (Moran et al. 2004b).

In terms of management, existing assessment methods are primarily based around analysis of catch and CPUE trends. The results of this study indicate that some of the variation in the catch trend for King George whiting can be predicted 3 to 5 yr in advance of recruitment to the fishery. This will allow managers to factor this variability into any assessment of catch trends. Although environmental correlations are significant, the proportion of variance in catch explained is relatively low. It is possible that in the future the time series of post-larval monitoring will provide a significant improvement over ZWW data in the prediction of King George whiting catches.

Other broad-scale climatic factors might also influence catches. There was a significant positive correlation between the ENSO cycle and catch in Port Phillip Bay at 0 lag. A positive relationship indicates that catches are highest during La Niña periods. La Niña years in southeastern Australia are generally associated with increased rainfall (Chiew et al. 1998) and such conditions might result in increased nutrient runoff that would stimulate benthic productivity. Such increased productivity could lead to increased weight of catch through higher growth rate, condition and survival of juvenile whiting. However, if this mechanism was occurring, a lag would be expected between the ENSO cycle and catch. An alternative explanation is that La Niña years are characterised by increased catchability of King George whiting, although the mechanism underlying this is unknown.

Affects on the juvenile stage may also be localised to specific bays or inlets depending on local environmental conditions. The decline in catch and effort in Western Port from the 1970s that was not observed in Port Phillip or Corner Inlet was most likely related to the major decline in seagrass cover that occurred at this time (Shepherd et al. 1989, MacDonald 1992). One of the triggers for this decline (Shepherd et al. 1989), and also seagrass loss in other areas (Seddon et al. 2000), was strong El Niño conditions, with associated high summer temperatures and low sea levels. This illustrates that influences on juvenile survival may affect catch in each bay more independently than effects on larvae.

The catch data in Corner Inlet showed more short-term variability at the scale of a few years compared to the other bays. This was partly due to the higher variability in effort in Corner Inlet relative to the other bays. Other possible factors that could lead to increased catch variability in Corner Inlet include variation in seagrass cover (Poore 1978), and possibly different spawning sources and associated transport pathways for Corner Inlet compared to the other 2 bays (Jenkins et al. 2000).

The possible role of variation in spawner biomass in the recruitment variation of King George whiting is difficult to assess. The commercial fishery is based on sub-adults in bays and inlets in Victoria but once fish mature at 4 to 5 yr of age and move onto the open coast, they are not targeted by the commercial fishery. This suggests that the spawning stock is largely protected from fishing impacts and is likely to maintain significant egg production. Spawning King George whiting have not been recorded in Victorian waters (Hamer et al. 2004); the only known spawning areas are in South Australia, 800 km to the west (Fowler et al. 1999), and it is possible that the spawning source for Victorian juveniles is South Australia (Jenkins et al. 2000). Catch and CPUE trends in South Australian bays and inlets are much more stable than in Victoria (A. J. Fowler unpubl. data). This may relate to the fact that the juvenile habitats in South Australia are much closer to the spawning areas (Fowler et al. 2000), and therefore environmental influences between spawning and settlement may be less likely.

CONCLUSIONS

This research has shown that the environment has a significant influence on the catch of King George whiting in bays and inlets in southeastern Australia. Strong westerly winds during the larval and post-larval stages result in increased catch approximately 3 to 5 yr later. Monitoring of post-larval abundances in Port Phillip Bay indicated that increased catch was the result of higher post-larval recruitment in years of strong ZWW. Moreover, La Niña conditions appear to have a positive effect on catches at 0 lag. Overall, results suggest that climatic conditions exert a strong influence on the larval to post-larval stages that subsequently affect the catch in the fishery. The work also emphasises the importance of juvenile habitat in underpinning this fishery in individual bays. Anthropogenic or natural effects that result in habitat loss, such as the seagrass loss in Western Port, have the potential to negatively affect the fishery. The results offer managers the prospect of forecasting trends in King George whiting catches 3 to 5 yr in advance based on ZWW.

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