CSIRO PUBLISHING

Marine and Freshwater Research, 2009, **60**, 912–923 www.publish.csiro.au/journals/mfr

Short-term climate variability and the commercial barramundi (*Lates calcarifer*) fishery of north-east Queensland, Australia

Jacqueline Balston[A,B,C]

[A]Queensland Climate Change Centre of Excellence, PO Box 937, Cairns, Qld 4870, Australia.
[B]School of Earth and Environmental Sciences, James Cook University, PO Box 6811, Cairns, Qld 4870, Australia.
[C]Email: jacqueline.balston@jbalston.com

Abstract. The sustainable productivity of estuarine fisheries worldwide is threatened by over-fishing, habitat destruction and water impoundment. In some cases, the natural variability of freshwater inputs has been shown to affect catch when low flows reduce nutrient input and inundated nursery habitats. Historically, the annual commercial catch of barramundi (*Lates calcarifer*) in Queensland has been highly variable for reasons not fully understood. In conjunction with a life-cycle model, statistical analyses of climate variables and barramundi catch data from the Princess Charlotte Bay area identified several significant relationships. Warm sea surface temperatures, high rainfall, increased freshwater flow and low evaporation (all measures of an extensive and productive nursery habitat) were significantly correlated with barramundi catch 2 years later and suggest that young barramundi survival is enhanced under these conditions. Catchability was significantly increased with high freshwater flow and rainfall events in the year of catch. A forward stepwise ridge regression model that included a measure of rainfall and evaporation 2 years before catch explained 62% of the variance in catch adjusted for effort. It is recommended that the impact of climate variability be considered in the management of wild barramundi stocks and possibly other species not yet examined.

Additional keywords: ENSO, MJO, SOI, sustainable management.

Introduction

Wild fisheries worldwide are under increasing threat from the pressures of over-fishing, habitat destruction and water quality degradation. As the natural variability of atmospheric and oceanic systems is increasingly affected by climate change, species are forced also to adapt to rapidly changing environments. Large-scale climate changes such as those generated by El Niño have been known for some time to affect the catch of both inshore and offshore species including hake, flounder, scallops, bass, herring, cod and anchovy (e.g. Klyashtorin 1998). Local changes to water temperatures and river flow have also been shown to affect species such as shrimp, halibut and prawns (Sutcliffe 1973; White and Downton 1991). However, research on the relationship between climate variability and catadromous species that are dependant on suitable estuarine nursery habitats and reliable freshwater flows to provide nutrient pulses is more limited. These species are at particular risk because they are affected by both changes in natural flow regimes driven by changes in the climate and those generated as a result of water impoundment and extraction (Robins *et al*. 2005).

The barramundi (*Lates calcarifer*) is a high-value, catadromous fin-fish species distributed across much of the tropical developing world where it supports commercial, recreational and indigenous fishers. In Australia, the species ranges from the Noosa and Mary Rivers on the east coast (26°30′S) to the Ashburton River in Western Australia (22°30′S) (Dunstan 1959) and inhabits coastal waters, estuaries, tidal creeks and lagoons, ponded pastures, supralittoral saltpans, flood plains and rivers in both clear and turbid water that ranges in temperature from 15 to 39°C (Russell and Garrett 1983). Although temperature appears to limit overall distribution of the species, populations are absent in areas without permanently flowing rivers (Dunstan 1959). The barramundi has a typical perch shape, grows to up to 2 m and over 70 kg over a lifespan of some 20 years and has a complex life cycle (Fig. 1). A catadromous species, the fish spawn in marine waters before and during the summer wet season, migrate into wetland nursery habitats as post-larvae, move further upstream to fresh water as fingerlings for 2–4 years of growth as males, and then return downstream to the marine environment to mature and pair with resident females. After spawning, males undergo a sex inversion to become mature females and take up residence in the estuary (Moore 1979).

Successful recruitment of barramundi to the commercial fishery depends on the ability of post-larvae, juveniles and adults to migrate between the wetland, freshwater and marine environments suitable for each stage in the life cycle (Moore and Reynolds 1982). Research to date has identified an increase in the survival of barramundi eggs and larvae in high-salinity environments (Moore 1982), increased dispersal of eggs, larval stages and adults during extreme flood events (Keenan 1994),

 10.1071/MF08283 1323-1650/09/090912

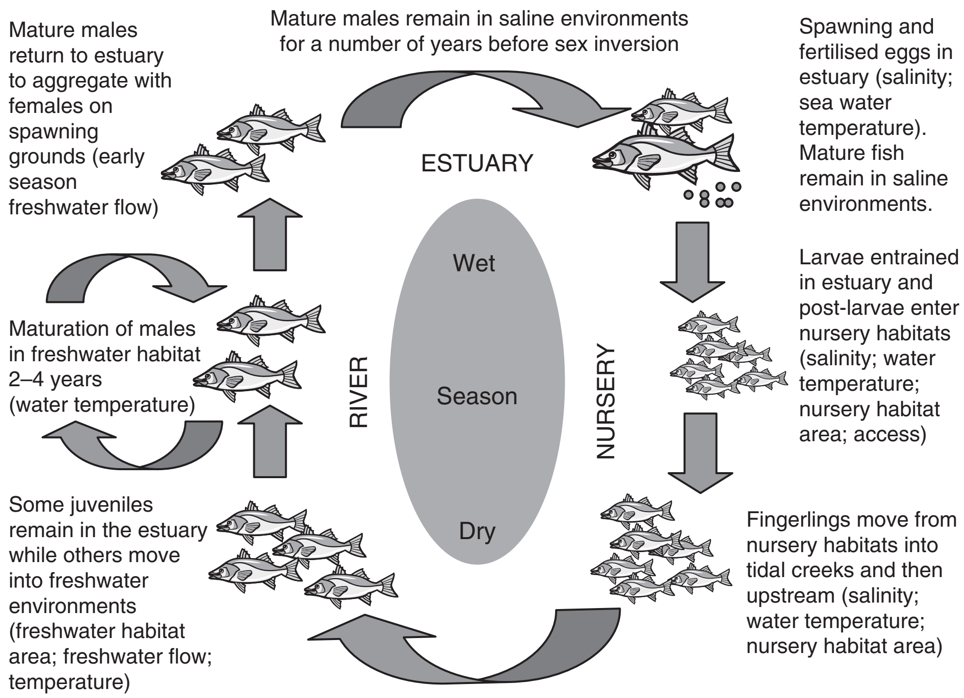

Fig. 1. Life-cycle model of the barramundi including known influences from climate at each stage in the development of the fish (Balston and Williams 2005).

increased growth rates in years of high freshwater flows (Davis 1982; Sawynok 1998; Robins *et al*. 2006), and an increase in barramundi landings (catch) in response to high flows in the year of catch (Dunstan 1959; Robins *et al*. 2005).

In Australia, the barramundi is an important commercial fish species worth approximately AU$8.8 million (ABARE 2006), and also supports valuable tourism and recreational fishing industries. Commercial catch in Queensland displays a high degree of interannual variation that has ranged, for example, from 35 tonnes (liveweight) in the 1966–67 financial year up to 110 tonnes in 1976–77 – a characteristic that many fishers believe is the result of the highly variable climate in the region. However, the impact of various climate parameters on the commercial fishery is poorly understood and existing management strategies do not consider climate variability. This study examined the relationships between short-term (intra and interannual) climate variability as measured by a selection of climate parameters and the commercial barramundi catch in north-east Queensland, Australia. It aims to determine if climate does have a significant impact on the species and if the inclusion of climate parameters in barramundi models may improve the prediction of annual catch and hence the sustainable management of the resource. The study was focussed on the variable catch of barramundi in the Princess Charlotte Bay area of north-east Queensland, where anthropogenic impacts on the environment have been minimal over the history of the fishery.

Materials and methods

Study area

Princess Charlotte Bay lies 340 km north of Cairns on the east coast of Cape York Peninsula (14°30′S, 144°E) in the 'North-East Cape York Catchment Area' (DPI 1993) (Fig. 2). Rainfall for the study area is highly variable (400–2000 mm per annum) as a result of influences from both the monsoon, which contributes up to 80% of the annual rainfall, and the El Niño Southern Oscillation (ENSO), which is responsible for up to 40% of the rainfall variability in eastern Australia (Cordery 1998). July and August are the driest months (4 mm each on average) and February the wettest (292 mm average) (Clewett *et al*. 2003). Temperature ranges from a minimum of 13°C in July up to a maximum of 35°C in December (BOM 2005).

The coastal zone and catchment of Princess Charlotte Bay are classified near pristine and relatively undisturbed (Heap *et al*. 2001) and consist of extensive (3920 km^2), shallow (<1 m), freshwater swamps vegetated by *Melaleuca* forest and sedge (*Eleocharis* species) that usually dry out in the autumn and winter (Garrett and Russell 1982), and gently undulating alluvial plains and old stream channels now in-filled (ANCA 1996). The large meandering rivers and numerous small streams that enter Princess Charlotte Bay are near-natural, with only a few small weirs and minimal extraction of water for grazing stock and national park requirements (DPI 1993). The estuaries of the study area are dominated by extensive saline flats (Bucher and Saenger 1994) that range from fresh water through to 44 psu (Russell and Garrett 1985).

Previous studies of barramundi on the east coast of Australia have shown that the migration of adults is usually restricted to only 50–100 km (Garrett and Russell 1982). The barramundi in the Princess Charlotte Bay study area are genetically different from other populations, a result of isolation by distance (Shaklee *et al*. 1993).

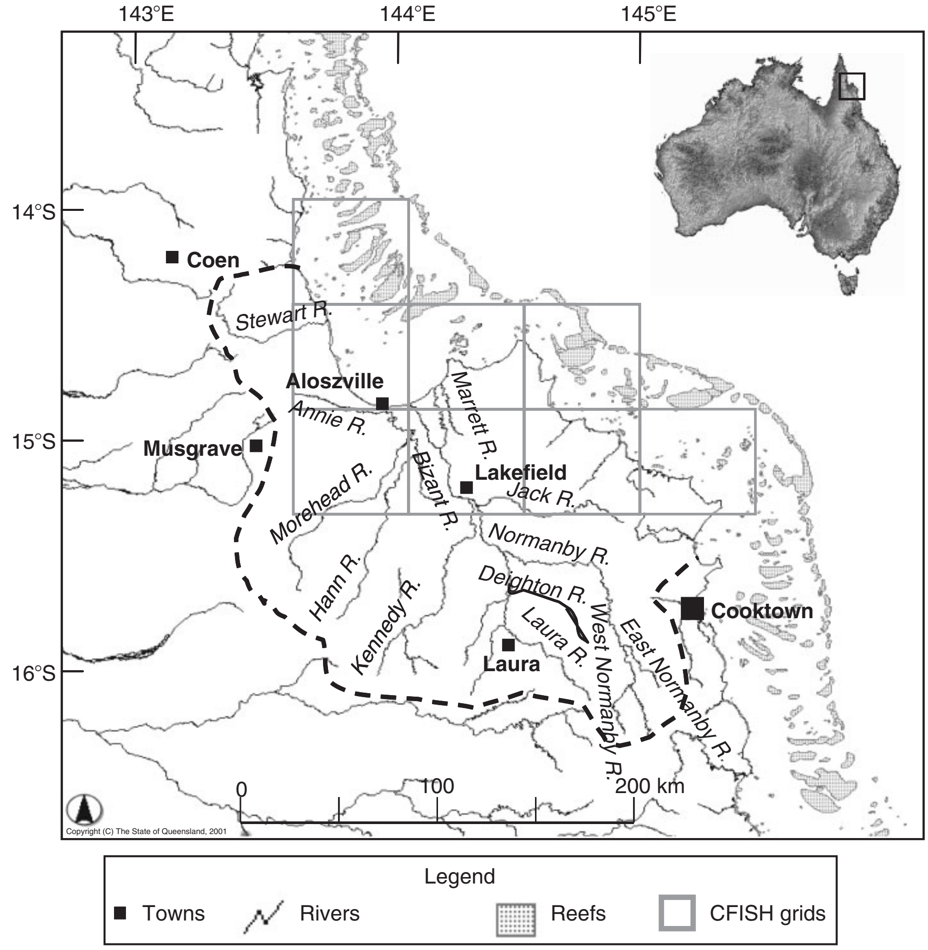

Fig. 2. The Princess Charlotte Bay study area (adapted from the Queensland Fisheries Service CHRIS website at http://chrisweb.dpi.qld.gov.au/chris/, November 2006). The study area covers land and inshore areas to the north-east of the dashed line. Barramundi catch data were sourced for the CFISH grid squares marked on the map.

Commercial fisheries data

Within Princess Charlotte Bay, commercial barramundi fishing is undertaken using set nets and is limited to the tidal waters in the bay. Monthly catch-and-effort data recorded as part of the mandatory CFISH program was extracted from the Queensland Department of Primary Industries and Fisheries logbook for all the grid squares in the study area that reported barramundi catch (D10, D11, D12, E11, E12, F11, F12, G12) for the years 1989–2002 from the northern edge of Princess Charlotte Bay to Cape Flattery (Fig. 2). Fishing effort in the database is recorded as the number of net days (i.e. the number of days the nets were set and for which fish were caught). Catch is recorded in kilograms by individual fishers each day (Magro *et al*. 1996). The barramundi fishing season is closed over the summer wet season while fish are spawning, so to include all of the individuals spawned in a single year, total catch and effort for each *financial* year (1 July–30 June) was calculated (Fig. 3). Growth rates for the species have been shown to vary considerably between genetic stocks (Shaklee *et al*. 1993) and even from one river to the next. An analysis of sagittal otoliths to age the fish has identified 1- and 2-year-old fish in the Fitzroy River area commercial fishery in central Queensland, although some were as old as 32 years (Staunton-Smith *et al*. 2004). The majority of fish in the Princess Charlotte Bay area grow to commercial size in 2–4 years (R. Garrett, QPDI&F, pers. comm.). In support of this, male barramundi in river systems north of 15°S on both the east and west coasts of Cape York Peninsula were found to be breeding as young as 1 or 2 years old (Garrett 1986). As selectivity for certain-sized fish has remained the same (commercial gear has not changed over the period of the study), it can be assumed that the majority of fish caught in the commercial Princess Charlotte Bay fishery are 2–4 years old. To ensure there was no signal from effort in the catch data, residuals from the regression of catch and effort, the catch adjusted for effort (a regression between catch and effort – CAE), was calculated for each year and used for all analyses.

Climate data

Rainfall

As a measure of coastal wetland availability, monthly rainfall was sourced from the Bureau of Meteorology (BOM) SILO database (http://www.bom.gov.au/silo) and averaged for

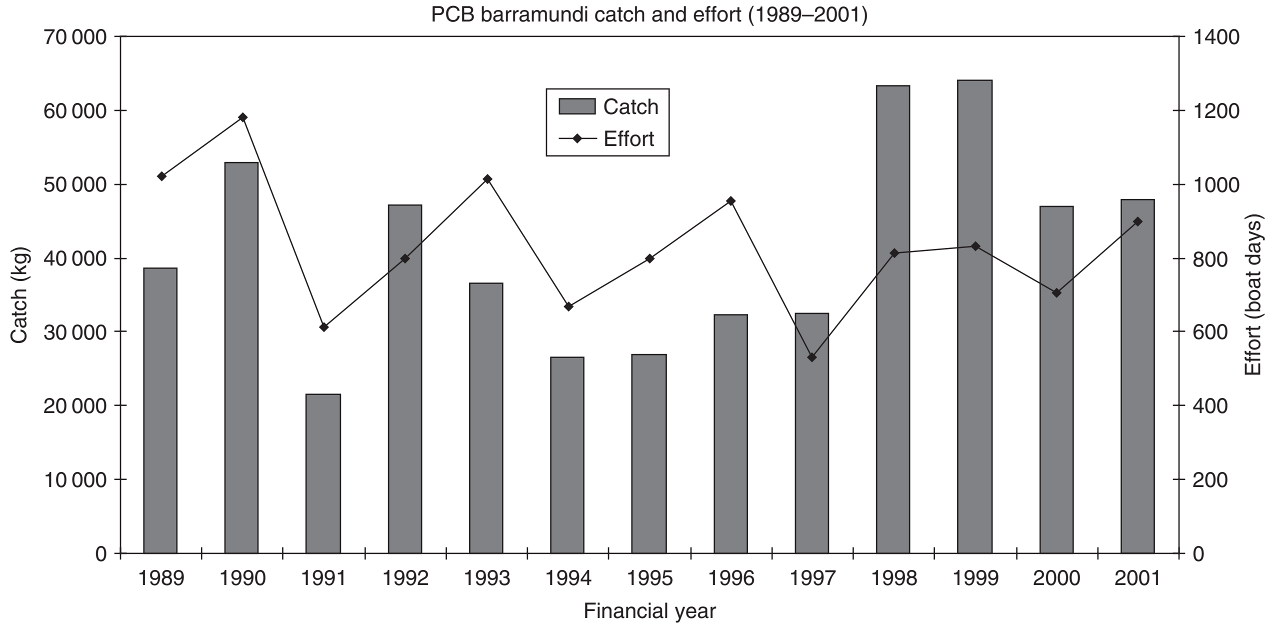

Fig. 3. The Princess Charlotte Bay study area commercial barramundi catch and effort (1989–2001).

five splined locations within the study area that corresponded with the mouth of the Annie (14°30′S, 143°42′E), Normanby (14°24′S, 144°12′E) and Stewart Rivers (14°06′S, 143°42′E), Aloszville Station (14°24′S, 144°00′E) and Lakefield National Park headquarters (14°57′S, 144°12′E). High rainfall during the spawning and early life-cycle stages of the barramundi (wet season and early dry season) would be expected to increase both the extent of wetland habitat available for fingerlings and juveniles and upstream habitats for maturing males – and lead to an increase in year-class size and subsequent catch.

Freshwater flow

Monthly freshwater-flow data were collected from the Queensland Department of Natural Resources and Water stream gauge website database (http://www.nrm.qld.gov.au/watershed/index.html) for the eight gauged rivers flowing into Princess Charlotte Bay. The gauge with the most reliable downstream data was selected for each river. Data are not available for all rivers after 1988 and there is no end-of-system flow model for Princess Charlotte Bay. For these reasons, it was necessary to generate the missing data statistically. As the flow data were gamma-distributed, a non-parametric rank-order gamma correlation matrix of flows for each river was generated. Every river was significantly and positively correlated with every other river ($P < 0.05$). Those rivers with the longest and highest quality monthly data available were selected to generate a gamma-distributed logarithm link function model (Chandler and Wheater 2002) for the years 1971–1987 to estimate total basin flow for the years 1988 onwards. Validation of the monthly modelled basin flow against the observed basin flow for the base period gave an $R^2 > 0.9$ for each of the three equations used (based on data from the Normanby, East Normanby and Laura Rivers). Increased freshwater flows provide connectivity to the estuary, so could be expected to increase the number of fish available for catch in the commercial fishery. Additionally, freshwater flows contribute to wetland nursery habitat area, so an increase in flow may increase subsequent catch by improving survival of early life-cycle stages.

Terrestrial temperature and evaporation

As a measure of the habitability of shallow nursery wetlands, interpolated maximum and minimum monthly average terrestrial temperature and monthly total pan evaporation data were extracted for Lakefield (14°57′S, 144°12′E) from the BOM SILO database. Warm water temperatures were expected to improve the survival of young fish, although beyond a certain threshold, very high water temperature in shallow wetlands may have been detrimental. Warm water temperatures were also expected to increase growth rates of males in freshwater environments. Cold winter water temperatures below a certain threshold have been shown to reduce the survival of even adult barramundi (Agcopra *et al.* 2005), so the relationship between catch and minimum temperature was expected to be positive.

Evaporation is a climate parameter that has not been linked to barramundi catch in any previous study. However, as it is the shallow wetland habitat that creates a nursery environment for fingerlings and juveniles, high evaporation would be expected to reduce the available area and increase the likelihood of predation from older barramundi and other species including birds.

Sea surface temperatures

As there was no *in situ* recording of sea surface temperatures (SST) in Princess Charlotte Bay, monthly averaged SST data were extracted for a 1° point (−14°S, 114°E) from the National Centre for Environmental Prediction Physical Oceanography Distributed Active Archive Centre. These satellite-derived SSTs measure ambient heat from the surface and have an accuracy to within 0.5°C (http://podaac.jpl.nasa.gov/DATA_CATALOG/sst.html). Warm SSTs are associated with increased egg and larvae survival, so a positive relationship between SSTs and subsequent catch was predicted.

Indices of the Southern Oscillation

The two extremes of the El Niño Southern Oscillation (ENSO) bring very different climatic conditions to north-east Queensland. During a La Niña event, stronger than average low-level easterly winds and warm SSTs in the western Pacific basin bring an increased probability of above-average rainfall to the region, whereas the other extreme, El Niño, is characterised by a migration of the warm SSTs eastward along the equator and associated atmospheric changes that tend to increase the probability of drought (Allan 1988). The Southern Oscillation Index (SOI) referred to in this study is a calculation of the difference in air pressure anomalies between Tahiti and Darwin and is the standard measure for the state of ENSO (Troup 1965). Monthly average values of the SOI were extracted from the 'Long Paddock' website (http://www.longpaddock.qld.gov.au/SeasonalClimateOutlook/SouthernOscillationIndex/SOIDataFiles/index.html). As positive values of the SOI are generally associated with a La Niña and above-average rainfall across the study area, and negative values of the SOI are associated with El Niño conditions and below-average rainfall, it was predicted that there would be a positive correlation between CAE and the SOI.

Indices of the Madden–Julian Oscillation

The 40–50-day wave, or Madden–Julian Oscillation (MJO), in its simplest form is an oscillation of atmospheric pressure that migrates eastward along the equator from Africa and is considered to be the strongest intra-seasonal signal in the tropical atmosphere (Anyamba and Weare 1995). Pulses of the MJO are associated with increased convection and modulation of monsoonal westerlies and often result in increased rainfall and 'active bursts' of a few days in the north Australian monsoon followed by a strong stabilising and drying influence after passing (Hendon and Liebmann 1990). The MJO reaches maximum intensity over the Indonesia–New Guinea region in the austral summer (December–February), and weakens towards the International Date Line (Madden and Julian 1972). The MJO appears to influence the timing (but not the intensity) of monsoon active periods, the likelihood and timing of extreme rainfall events (Jones *et al*. 2004) and rainfall totals across much of northern Australia (Hendon and Liebmann 1990).

All-season real-time multivariate MJO indices were taken from the BOM Research Centre website and include longitudinal position of the centre of the oscillation (phase) and the number of days in each phase (http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/RMM/index.htm). The variable used in the analysis was a summation of the number of days for phases 1, 4 and 6 from 1 November to 30 April (northern wet season). Each of these phases has a significant effect on rainfall in the Princess Charlotte Bay area and is calculated for a time of the year when the MJO has the strongest influence on the east coast of Australia. This period also corresponds with the migration, spawning and early juvenile development of the barramundi.

MJO phase 1 is associated with a significant suppression of rainfall for the Princess Charlotte Bay area during the pre-wet and wet season (Wheeler and Hendon 2004), so it was predicted that the variable would be negatively correlated with CAE. On the other hand, phases 4 and 6 of the MJO are both associated with significant enhancement of rainfall over the same period (Wheeler and Hendon 2004), so these variables were expected to be positively correlated with CAE.

Data preparation

To align with the climate patterns of north-eastern Queensland, seasonal variables were calculated as defined by Vance *et al.* (1998): pre-wet (October–December); wet (January–March); early dry (April–June); and dry (July–September). Climate variables that were not normally distributed before statistical analysis were transformed (freshwater flows, rainfall, temperature, evaporation and sea surface temperatures), checked for normality using histograms and the Shapiro–Wilk test (Shapiro *et al*. 1968) and plotted against barramundi CAE. Often in the case of fisheries and climate analysis, there are issues of collinearity between independent variables (e.g. freshwater flow correlated with rainfall). For this reason, a correlation matrix of independent climate variables was generated to determine cases of collinearity (Table 1).

Autocorrelation within a single variable (e.g. September rainfall correlated with October rainfall) can also be a problem with such datasets, so variables were calculated at a seasonal scale to reduce this risk. As the removal of autocorrelation through processes such as prewhitening (removal of red noise from a times series) can increase the risk of a Type II error (by removing an authentic significant relationship between the variables), or bias results if the source of autocorrelation is due to covariance (Pyper and Peterman 1998), the analyses were undertaken without adjusting either the fisheries or climate data for autocorrelation (e.g. Robins *et al*. 2005).

Regression analysis

A linear regression analysis was used to test the relationship between each selected climate variable and commercial barramundi CAE for lags of up to 3 years. To reduce the risk of spurious relationships that did not have a likely causal link to barramundi production, results of the regression analysis were viewed in context of the life-cycle model. Those relationships that had no known causal link on the basis of previous physiological or tagging studies were considered to be not relevant (Table 2).

Statistical modelling

Statistical modelling was employed to quantitatively determine how much of the variance in Princess Charlotte Bay barramundi CAE could be predicted using selected climate variables. Collinearity between variables was compensated for through the use of forward stepwise ridge regression (FSRR) (Statistica, StatSoft Inc., www.statsoft.com), a process that tests the residuals from each model step before selecting the next variable, therefore ensuring that only variables that improve the model are included. The ridge regression coefficient (k), selected to ensure model coefficients were stable, was set at 0.10 because

Table 1. Pearson coefficients of correlation (*r*) of climate parameters used in the Princess Charlotte Bay analyses used to indentify possible cases of collinearity between variables

Correlations ≥0.57 or ≤−0.57 are significant at the $P < 0.05$ level and correlations ≥0.48 or ≤−0.48 are significant at the $P < 0.10$ level (shown in bold). MJO, Madden–Julian Oscillation; SOI, Southern Oscillation Index; SST, sea surface temperatures

	Min temp Jul	Max temp Dec	Rainfall Jul–Sept	Rainfall Oct–Dec	Rainfall Jan–Mar	Rainfall Apr–Jun	Flow Jul–Sep	Flow Oct–Dec	Flow Jan–Mar	Flow Apr–Jun	Evaporation annual	MJO phase 1	MJO phase 4	MJO phase 6	Av Jul–Sept SOI	Av Oct–Dec SOI	Av Jan–Mar SOI	Av Apr–Jun SOI	Av Oct–Dec SST
Max temp Dec	0.21																		
Rainfall Jul–Sept	−0.01	0.19																	
Rainfall Oct–Dec	−0.47	**−0.79**	0.02																
Rainfall Jan–Mar	0.09	−0.20	**0.75**	0.35															
Rainfall Apr–Jun	0.26	−0.25	−0.20	0.11	−0.02														
Flow Jul–Sep	0.07	−0.28	−0.27	0.16	0.02	0.24													
Flow Oct–Dec	−0.40	**−0.74**	−0.04	**0.83**	0.33	0.25	0.30												
Flow Jan–Mar	−0.22	−0.37	**0.67**	**0.53**	**0.85**	0.05	0.08	**0.52**											
Flow Apr–Jun	0.11	**−0.58**	−0.16	0.43	−0.10	**0.74**	0.26	0.43	0.14										
Evaporation annual	0.24	**0.57**	−0.02	**−0.63**	−0.43	−0.34	**−0.57**	**−0.64**	**−0.69**	−0.42									
MJO phase 1	−0.11	0.37	−0.04	−0.29	−0.43	−0.01	**−0.60**	−0.19	−0.32	−0.04	**0.58**								
MJO phase 4	−0.18	−0.06	−0.08	−0.09	−0.11	0.06	−0.04	0.25	0.11	0.01	−0.13	0.09							
MJO phase 6	0.10	−0.32	0.14	0.17	0.29	**0.48**	0.14	0.08	0.35	0.45	**−0.50**	−0.25	−0.29						
Av Jul–Sept SOI	−0.02	**−0.51**	0.13	**0.59**	0.33	0.24	0.16	0.27	0.47	**0.54**	**−0.65**	**−0.53**	−0.22	**0.64**					
Av Oct–Dec SOI	−0.14	**−0.67**	−0.04	**0.54**	0.28	0.37	**0.48**	0.47	**0.52**	**0.57**	**−0.87**	**−0.66**	0.11	**0.66**	**0.82**				
Av Jan–Mar SOI	−0.19	−0.41	0.10	0.31	0.30	0.15	0.15	0.25	0.46	0.24	**−0.64**	**−0.66**	0.38	0.44	**0.66**	**0.83**			
Av Apr–Jun SOI	0.16	−0.27	−0.20	0.23	0.03	**0.94**	0.10	0.25	0.14	**0.67**	−0.44	−0.04	0.09	**0.53**	0.41	0.46	0.30		
Av Oct–Dec SST	**−0.52**	−0.12	0.19	0.17	0.22	0.31	0.22	0.38	0.33	0.03	−0.28	−0.07	0.27	−0.01	−0.24	0.12	0.14	0.23	
Av Jan–Mar SST	**−0.48**	−0.12	0.26	0.16	0.40	−0.27	0.46	0.37	0.44	−0.33	−0.44	−0.47	0.20	0.01	−0.11	0.28	0.34	−0.33	**0.61**

Table 2. Known causal relationships between climate variables and barramundi as defined from previous tagging and physiological studies
Climatic conditions that would be expected to correlate with an increased year-class size and/or subsequent catch are indicated by a '+' sign while those that would be expected to decrease year-class size and/or resulting catch are indicated by a '−' sign. Climate parameters that have not been linked to the developmental stage of the fish are marked as not applicable (n/a). MJO, Madden–Julian Oscillation; SOI, Southern Oscillation Index

Life-cycle stage climate variable	Spawning	Larvae	Fingerlings	Juveniles	Maturing males	Returning males
Minimum air temperature (°C)	n/a	+	+	+	+	n/a
Maximum air temperature (°C)	n/a	+	+	+	+	n/a
Rainfall (mm)	n/a	n/a	+	+	+	+
Freshwater flow (ML)	−	+	+	+	+	+
Evaporation (mm)	n/a	−	−	n/a	n/a	n/a
Sea surface temperature (°C)	+	+	n/a	n/a	n/a	n/a
MJO phase 1	n/a	−	−	−	−	−
MJO phase 4	n/a	+	+	+	+	+
MJO phase 6	n/a	+	+	+	+	+
Average Jul–Sept SOI	n/a	+	+	+	+	+
Average Oct–Dec SOI	n/a	+	+	+	+	+
Average Jan–Mar SOI	n/a	+	+	+	+	+
Average Apr–Jun SOI	n/a	+	+	+	+	+

a ridge trace did not indicate a significant change in adjusted R^2 values with higher values of k. Owing to the limited number of observations (12 years), the process was limited to only two steps to reduce the possibility of over-fitting the model. The model residuals were checked for normality using a probability plot and for autocorrelation using the Durbin–Watson statistic (StatSoft Statistica program, version 7.1, StatSoft Inc.).

The capacity of regression-based models to predict future catch has been questioned by several authors (e.g. Stergiou and Christou 1996; Myers 1998). If a regression model is to be used as a predictive tool, the robustness of the model needs to be tested by using cross-validation (e.g. Wilkes (1995) and the data-splitting concept recommended by Myers (1998)). For this analysis, the model was cross-validated using a 'leave-one-out' (LOO) technique (Wilkes 1995) that compares the sum of squares of the original model residuals with the sum of squares for the deleted residuals (residual value for the respective case had it not been included in the regression analysis, that is, if this case was excluded from all computations). This technique results in a cross-validated predictive R^2 value and was used as a measure of the predictive capability of the model.

When interpreting the results of these analyses, it is necessary to take into account the limitations of the data used and assumptions made. Evaporation, rainfall and air temperature are all modelled variables calculated from actual readings taken at local stations in the region. In Princess Charlotte Bay, however, recording stations are sparse, so data for the coordinates that correspond to the study area will incur a degree of spatial error. Catch data, although with a record of effort, is a measure of the number of days the nets are set and fish are caught – not the total number of days or hours of fishing. Additionally, recreational fishers may take a significant proportion of the biomass (estimated in the Northern Territory at ~23% of total catch (Griffin 1982)). Without good quality recreational catch data for Princess Charlotte Bay, this component of catch is assumed to be constant from one year to the next, although in very wet years access to the area is limited and effort would be low. As with all fisheries analyses that use CAE data as a measure of biomass, the assumption is made that landed fish represent a consistent proportion of the fishery from one year to the next and that records are accurate.

Results

Regression analysis

The regression of CAE against each selected climate variable and index (Table 3) identified five significant, relevant correlations in both the year of catch and 2 years before catch. One year before catch there was just one significant, relevant correlation, and 3 years before catch there was none. These results are summarised in a conceptual systems dynamic model that links each stage in the fish life cycle with the climate variables (Fig. 4).

Statistical modelling

To allow for a management response, a forward stepwise ridge regression model was built from variables 2 years before catch when young-of-year barramundi are spawned and in the nursery habitats. Several models were generated and the one that returned the best fit included dry season (July–September) rainfall and annual evaporation. The model explained 62.4% of the variance (adjusted R^2) in Princess Charlotte Bay (Eqn 1, Table 4). The adjusted R^2 takes into account collinearity between variables and the degrees of freedom in the model.

$$\text{CAE} = 29358.08 + 7771.86(RJS) - 0.01(E) \qquad (1)$$

where RJS is Log N(total July–September rainfall 2 years before catch + 1) and E is (total annual evaporation 2 years before catch)^2.

Residuals for the model, although slightly curved, were normally distributed, independent (according to the Durbin–Watson statistic; $P < 0.05$) and fell within ±2 standard deviations of the mean, indicating a good fit. Predicted *v.* observed values of catch were plotted (Fig. 5). Cross-validation of the model using the LOO technique returned an R^2 value of 58.6% (Fig. 6). This demonstrates the robustness of the model and indicates that even when used in a predictive capacity, the model explained more than half the variance in Princess Charlotte Bay barramundi CAE.

Discussion

Regression analysis

Significant correlations between climate and barramundi CAE in the year of catch have most likely identified an effect on fish catchability. A study in the central Queensland Fitzroy area attributed 41% of the variability in catch to summer (December–February) freshwater flow and 45% to summer rainfall (Robins *et al.* 2005) and recreational catch rates of barramundi were found to be positively correlated with Boyne River outflow in nearby Gladstone Harbour (Platten 1999). The results from the present study were similar: pre-wet and wet season rainfall each explained 31% of the variability in annual CAE, and pre-wet season freshwater flow explained 50% of the variability in CAE. Wet season freshwater flow explained 27% of the variability in CAE. The results reinforce the observation that mature males return to the estuarine environment from the beginning of the wet season in response to the increased rainfall and freshwater flows that improve the connectivity between freshwater habitats and the ocean (Dunstan 1959). Although concurrent rainfall and flow parameters were significantly correlated (Table 1), flow is likely to have the greatest effect – both because it explains the highest proportion of variability and is the logical option when the behaviour of the fish and the habitat are considered. The pre-wet season SOI, a predictor of rainfall and freshwater flow for the region, was also significantly correlated with catch.

The regression analyses returned several significant correlations between climate parameters and barramundi CAE 2 years before catch, and suggests that barramundi in Princess Charlotte Bay are growing to commercial size within 2–3 years, depending on the time of spawning and time of catch. These results are congruent with previous observations of barramundi in the area (Garrett 1986), although there can be some individuals that may be considerably older at the time of catch (Staunton-Smith *et al*. 2004).

The high positive correlation between CAE and wet season SSTs 2 years before catch does, perhaps, most clearly identify the lag between spawning and catch, as eggs are particularly sensitive to water temperature and spawning is thought to be triggered by an increase in water temperature (Pauly and Pullin 1988). A significant positive correlation between CAE and SSTs has been shown for numerous other fish species, including Atlantic cod and herring, redfish, butterfish, alewife, hake, bass, flounder, clams and scallops (Sutcliffe *et al*. 1976). In some of these cases, the monthly average SST explained up to 76% of the variability in landings.

Both rainfall and freshwater flow in the wet season were significantly and positively correlated with CAE 2 years before catch, the time of year when fingerlings and juveniles inhabit the estuarine nursery swamps and wetland areas. The results concur with those expected from tagging and physiological studies of the species (Table 1) and confirm findings from other studies of barramundi and climate in Australia that have shown that an increase in both rainfall and freshwater flow at particular times of the year is related to an increase in the numbers of young-of-year fish in nursery habitats (Griffin 1985) and subsequent increases in catch (Staunton-Smith *et al*. 2004; Robins *et al*. 2005). In the USA, it has been estimated that over 55% of the weight of commercial fisheries landings are dependant on estuarine nursery habitats and that impediments to the natural river flows entering these environments affect estuarine species diversity and estuarine productivity (Drinkwater and Frank 1994). In other Australian research, a reduction of river flows (and changes to the timing of flows) into the estuarine environment has been shown to have a negative effect on prawns (Ruello 1973; Glaister 1978) and both recreational and commercial fisheries in central Queensland (Platten 1996).

Annual evaporation, a variable that has not been considered in any earlier studies, has a highly significant inverse relationship with barramundi CAE both 1 and 2 years before catch. Evaporation is significantly correlated with other variables, including rainfall and freshwater flow. However, it could also be that evaporation is an effective measure of the available wetland and nursery habitats in Princess Charlotte Bay, because evaporation

Table 3. Pearson coefficient of correlation (*r*) between Princess Charlotte Bay barramundi CFISH catch adjusted for effort (1989/90–2001/02) and climate variables and indices (0–3-year lag)

Highlighted correlations significant at the $P < 0.05$** and $P < 0.10$* levels. Shaded correlations were deemed not applicable according to the life-cycle model. MJO, Madden–Julian Oscillation; SOI, Southern Oscillation Index

Climate variable	3-year lag	2-year lag	1-year lag	Zero lag (year of catch)
Minimum temperature Jul (°C)	**−0.62****	−0.25	−0.16	0.10
Maximum temperature Dec (°C)	0.06	−0.02	−0.25	**−0.55***
Rainfall Jul–Sept (mm)	0.46	**0.77****	0.02	−0.01
Rainfall Oct–Dec (mm)	0.15	0.38	0.30	**0.56****
Rainfall Jan–Mar (mm)	0.12	**0.62****	0.31	**0.56****
Rainfall Apr–Jun (mm)	0.14	−0.02	0.40	0.37
Flow Jul–Sep (ML)	0.18	0.33	0.41	0.36
Flow Oct–Dec (ML)	−0.02	0.29	0.37	**0.71****
Flow Jan–Mar (ML)	0.36	**0.76****	0.35	**0.52***
Flow Apr–Jun (ML)	0.27	0.13	0.33	0.33
Evaporation annual (mm)	−0.34	**−0.62****	**−0.48***	**−0.73****
Average Oct–Dec SST (°C)	0.46	0.40	0.25	0.12
Average Jan–Mar SST (°C)	0.03	**0.58****	0.17	0.32
MJO phase 1	−0.08	−0.26	0.00	−0.55
MJO phase 4	0.05	−0.18	−0.39	0.04
MJO phase 6	0.21	0.16	**0.50***	0.38
Average Jul–Sept SOI	0.13	0.29	0.12	0.47
Average Oct–Dec SOI	0.14	0.29	0.19	**0.62****
Average Jan–Mar SOI	0.19	0.10	−0.18	0.47
Average Apr–Jun SOI	0.15	−0.04	0.26	0.41

was the only variable significantly correlated with CAE in the year before catch. Previous studies indicate that the area of available nursery habitat appears to be the strongest measure of population fluctuation in barramundi (Griffin 1985). Most of the wetlands in Princess Charlotte Bay are less than 1 m in depth, which would make them prone to drying out (Garrett and Russell 1982). Annual evaporation over the years of the study averaged 2125 mm, whereas rainfall averaged only 1142 mm. Depending on how and when the rain falls (and input from river flow), it

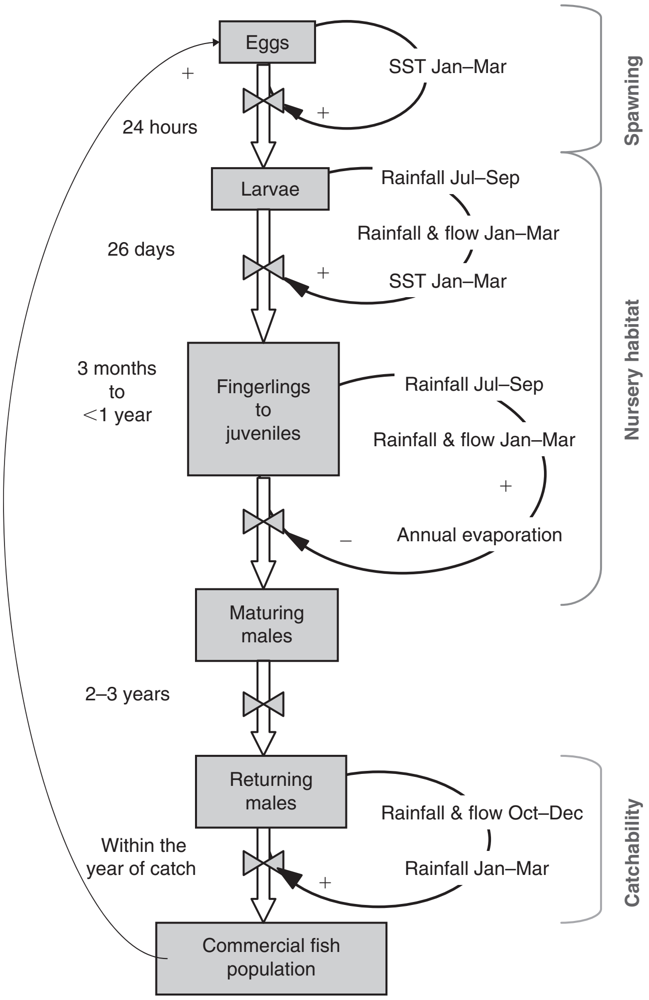

Fig. 4. A conceptual systems dynamic model of climate influences on the Princess Charlotte Bay barramundi fishery. Climate variables that show a significant correlation with barramundi catch adjusted for effort (CAE) ($P < 0.05$) are included to the right of the stock and flow chart, and time delays are shown on the left.

is possible that these wetland areas dry out while larvae and fingerlings are in residence. In addition, the highest correlation between Princess Charlotte Bay barramundi CAE and climate was with dry season rainfall. Although rainfall at this time of year is minimal (0–21 mm over the period of the study), falls may maintain wetland habitats that would otherwise dry out and result in high mortalities. Also possible is that rainfall at this time of year wets the soil profile, so prepares the wetland areas for early inundation. Research in the Northern Territory (Griffin 1985) has shown that the success of early spawning significantly depends on the amount of early rain that falls to replenish water levels in supralittoral swamps. In years when the wetlands do not dry out completely, a dramatic reduction in habitat area would increase predator pressures both from larger resident barramundi (Davis 1985) and birds (Johnston 2005). This result adds weight to previous studies that have identified that conditions in the wetland nursery habitat are critical for the successful recruitment of barramundi (e.g. Russell and Garrett 1988; Garrett 1991).

As climate indices are a measure of linked atmospheric and oceanic conditions, it was expected that the climate indices may explain more of the variability in barramundi CAE than an individual climate variable. However, in this case neither of the climate indices (MJO or SOI) was significantly correlated with barramundi CAE 2 years before catch. Several studies have found that the relationship between the SOI and rainfall across north-eastern Australia has varied over time (Power *et al.* 1999) and for the years of this study the correlation between the concurrent SOI and rainfall was relatively poor. Phase 6 of the MJO (a measure of enhanced rainfall in the region) was significantly and positively correlated with barramundi CAE in the year before catch only, so may be a measure of enhanced juvenile habitats.

Statistical modelling

Results from the forward stepwise ridge regression analyses indicated that more than half of the variance in barramundi CAE in Princess Charlotte Bay may be explained by a model containing dry-season rainfall and annual evaporation ($R^2 = 62\%$, cross-validated $R^2 = 58\%$). In comparison with other regression models of barramundi catch reviewed, this is an encouraging result. A best-subsets regression of rainfall and flow in the Fitzroy area explained only 39% of the variance in Fish Board landings (summer rain in the year of catch, autumn flow 3 years before catch and summer rain 4 years before catch) before cross-validation (Robins *et al.* 2005). When effort and stocking rates were included, up to 88% of the variance in short-term barramundi catch was explained, although effort accounted for most of the improvement in fit and the predictive capacity of the model was not tested (Robins *et al.* 2005). In addition, the inclusion of variables in the year of catch precluded a management response.

Table 4. Model developed to provide an estimate of future Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from climate variables two years before catch (nursery habitats)
The adjusted R^2 takes into account collinearity between variables and the degrees of freedom in the model

Predictive model (adjusted $R^2 = 0.624$)	B	Standard error	*P*-level
Intercept	29 358.08	20 959.81	0.19
Log *N*(total rainfall July–September 2-year lag + 1)	7771.86	2370.64	0.01
(Total annual evaporation 2-year lag)^2	−0.01	0.00	0.06

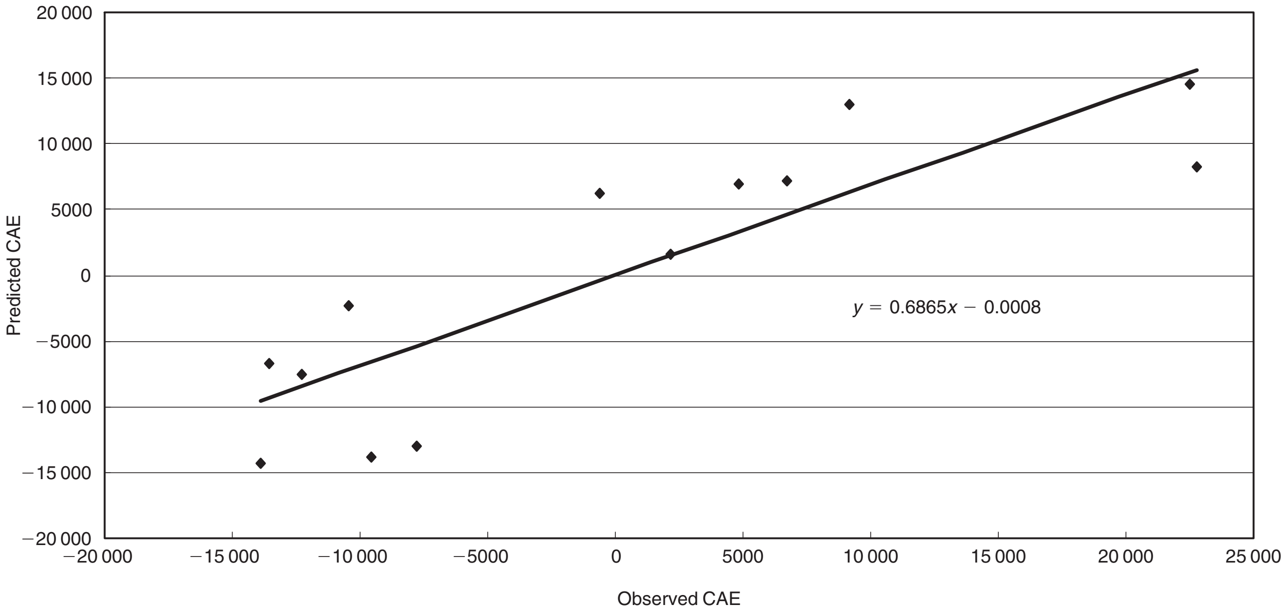

Fig. 5. Predicted values of Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from the predictive model *v.* observed CAE. Variables in the model are dry season (July–September) rainfall and annual evaporation, both two years before catch. Linear fit plotted, adjusted $R^2 = 0.62$.

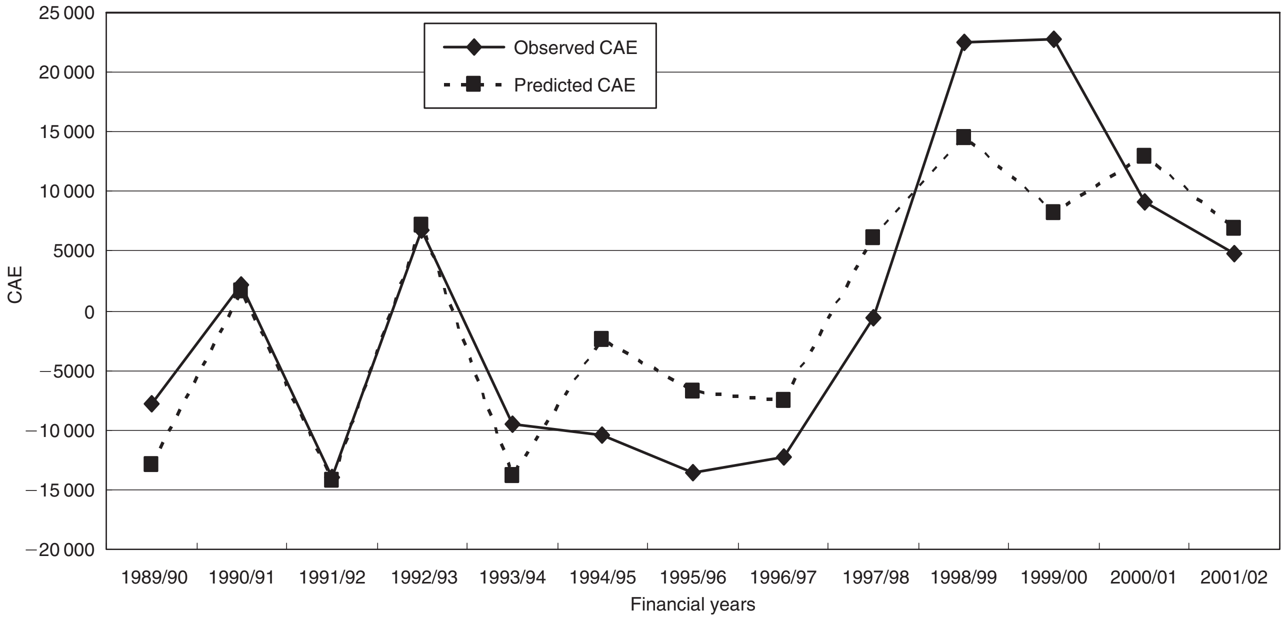

Fig. 6. Time series plot of predicted and observed Princess Charlotte Bay barramundi catch adjusted for effort (CAE) from the predictive model (1989/90–2001/02). The model contains the climate variables total rainfall July–September and total annual evaporation both two years before catch. Cross-validated $R^2 = 0.586$.

When compared with population dynamics models, the predictive model developed in this study again performs well. The latest modelling of barramundi catch along the east coast by using CLIMPROD (a surplus production model for fisheries that incorporates climate variables) returned improved goodness-of-fit parameters when rainfall or the SOI were included (Meynecke *et al*. 2006). Results for a model that included rainfall were considered by the authors to be robust, although a jackknife R^2 varied from 0.35 (1988–2000) up to 0.85 (1988–2004), indicating a degree of instability over the time series. As with any regression-based model that is based on a limited set of climate data, to extend the model beyond the range of the original variables used in the generation of the model risks linear extrapolation of results beyond unidentified non-linear thresholds. In this instance, to introduce an extreme climate event that was not included in the range of data used in the analyses may result in a significantly different prediction to what occurs in the fishery.

Implication for management of the fishery

This and previous studies that have shown a positive correlation between freshwater flow and/or rainfall and barramundi catch highlight the importance of preserving natural environmental flows, access for fish to freshwater environments and healthy nursery wetland habitats. An estimated 50% of estuaries in Australia are now classified as degraded as a result of human pressures (DEH 2001). In some habitats, there has been a reduction of up to 70% of wetland area compared with pre-European times (DEH 2001). To preserve the quality and availability of wetland habitats, the drainage of wetlands for agricultural and other development, construction of impediments to the flow of water including dams and barrages and the creation of ponded pastures that preclude fish from entering the habitat must cease (Coates and Unwin 1991). This study also suggests that the development of catch models that include climate parameters may provide fisheries managers with the opportunity to improve the sustainable harvest of the fishery.

In conclusion, results from this study indicate that a significant proportion of the variability seen in commercial barramundi catch in north-east Queensland may be driven by variability in climate. There is the opportunity to improve both the prediction of future barramundi catch and the sustainable management of the species by considering the impacts of climate variability on the species, and by incorporating climate variables into catch models.

Acknowledgements

This study forms part of a doctoral research project funded by the Queensland Department of Primary Industries, Queensland Department of Natural Resources and Water and the Queensland Centre for Climate Change Excellence. In-kind support was provided by the James Cook University School of Earth and Environmental Sciences. Thanks to my supervisors Drs Steve Turton, Neil Gribble and Roger Stone and journal referees who all provided valuable advice in the development of this paper.

References

ABARE (2006). Australian Fisheries Statistics 2005. Australian Bureau of Agricultural and Resource Economics, Canberra.

Agcopra, C., Balston, J. M., Bowater, R., Rodgers, L. J., and Williams, A. A. J. (2005). Predictive system for aquaculture ponds. *Queensland Aquaculture News* **27**, 3.

Allan, R. J. (1988). El Niño Southern Oscillation influences in the Australasian region. *Progress in Physical Geography* **12**, 313–348. doi:10.1177/030913338801200301

ANCA (1996). 'A Directory of Important Wetlands in Australia.' (Australian Nature Conservation Agency: Canberra.)

Anyamba, E. K., and Weare, B. C. (1995). Temporal variability of the 40–50-day oscillation in tropical convection. *International Journal of Climatology* **15**, 379–402. doi:10.1002/JOC.3370150404

Balston, J. M., and Williams, A. A. J. (2005). Modelling impacts of climate variability on the commercial barramundi (*Lates calcarifer*) fishery of north-eastern Queensland. In 'International Congress on Modelling and Simulation (MODSIM): Advances and Applications for Management and Decision Making. Melbourne, Australia'. (Eds A. Zerger and R. M. Argent.) p. 456. (Modelling and Simulation Society of Australia and New Zealand Inc.: Melbourne.)

BOM (2005). 'Bureau of Meteorology Website.' Available at http://www.bom.gov.au/silo/products/cli_chg/ [accessed May 2005].

Bucher, D., and Saenger, P. (1994). A classification of tropical and subtropical Australian estuaries. *Aquatic Conservation: Marine & Freshwater Ecosystems* **4**, 1–19. doi:10.1002/AQC.3270040102

Chandler, R. E., and Wheater, H. S. (2002). Analysis of rainfall variability using generalised linear models: a case study from the west of Ireland. *Water Resources Research* **38**, 1194. doi:10.1029/2001WR000906

Clewett, J. F., Clarkson, N. N., George, D. A., Ooi, S. H., Owens, D. T., Partridge, I. J., and Simpson, G. B. (2003). Rainman StreamFlow version 4.3: a comprehensive climate and streamflow analysis package on CD to assess seasonal forecasts and manage climate risk. Queensland Department of Primary Industries, Brisbane.

Coates, M., and Unwin, L. (1991). Ponded pastures and the habitat requirements of barramundi (*Lates calcarifer*). In 'Proceedings of the Probing Ponded Pastures Workshop'. pp. 82–88. (University of Central Queensland: Rockhampton, Qld.)

Cordery, I. (1998). Forecasting precipitation from atmospheric circulation and SOI. In 'Hydrology in a Changing Environment'. (Eds H. Wheater and C. Kirby.) pp. 63–69. (British Hydrological Society: Exeter, UK.)

Davis, T. L. O. (1982). Maturity and sexuality in barramundi, *Lates calcarifer* (Bloch), in the Northern Territory and south-eastern Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research* **33**, 529–545. doi:10.1071/MF9820529

Davis, T. L. O. (1985). Seasonal changes in gonad maturity, and abundance of larval and early juveniles of barramundi, *Lates calcarifer* (Bloch), in Van Diemen Gulf and the Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research* **36**, 177–190. doi:10.1071/MF9850177

DEH (2001). Coasts and Oceans, Australia State of the Environment Report 2001. Australian State of the Environment Committee, Department of the Environment and Heritage, Canberra.

DPI (1993). The Condition of River Catchments in Queensland. Department of Primary Industries, Brisbane.

Drinkwater, K. F., and Frank, K. T. (1994). Effects of river regulation and diversion on marine fish and invertebrates. *Aquatic Conservation: Marine & Freshwater Ecosystems* **4**, 135–151. doi:10.1002/AQC.3270040205

Dunstan, D. J. (1959). The barramundi *Lates calcarifer* (Bloch) in Queensland waters. CSIRO, Melbourne.

Garrett, R. (1991). Utilization of wetland habitats by coastal fishes in northern Australia. In 'Proceedings of the Probing Ponded Pastures Workshop'. pp. 94–114. (University of Central Queensland.: Rockhampton, Qld.)

Garrett, R. N. (1986). Reproduction of Queensland barramundi (*Lates calcarifer*). In 'Management of Wild and Cultured Sea Bass/Barramundi (*Lates calcarifer*)'. (Eds J. W. Copland and D. L. Grey.) pp. 38–43. (Australian Centre for International Agricultural Research: Darwin.)

Garrett, R. N., and Russell, D. J. (1982). Premanagement investigations into the barramundi *Lates calcarifer* (Bloch) in northeast Queensland waters: a report to the Fishing Industry Research Committee. Queensland Department of Primary Industries, Brisbane.

Glaister, J. P. (1978). The impact of river discharge on distribution and production of the school prawn *Metapenaeus macleayi* (Haswell) (Crustacea: Penaeidae) in the Clarence River Region, Northern New South Wales. *Australian Journal of Marine and Freshwater Research* **29**, 311–323. doi:10.1071/MF9780311

Griffin, R. K. (1982). A survey of amateur angling for barramundi (*Lates calcarifer*) in the Northern Territory. Technical Report No. 2, Northern Territory Department of Primary Production, Darwin.

Griffin, R. K. (1985). The importance of mangrove/coastal wetland to three commercial fisheries in the Northern Territory particularly for barramundi (*Lates calcarifer*). In 'Coasts and Tidal Wetlands of the Australian Monsoon Region'. (Eds K. N. Bardsley, J. D. S. Davie and C. D. Woodroffe.) (Australian National University: Darwin.)

Heap, A., Bryce, S., Ryan, D., Radke, L., Smith, C., Smith, R., Harris, P., and Heggie, D. (2001). Australian Estuaries and Coastal Waterways:

A Geoscience Perspective for Improved and Integrated Resource Management. Australian Geological Survey Organisation, 2001/7, Canberra.

Hendon, H., and Liebmann, B. (1990). The intraseasonal (30–50 day) oscillation of the Australian summer monsoon. *Journal of the Atmospheric Sciences* **47**, 2909–2924. doi:10.1175/1520-0469(1990)047<2909:TIDOOT>2.0.CO;2

Johnston, R. (2005). Discrete depth distributions of aquatic fauna within isolated pools. In 'Research for Coastal Management – Coastal CRC Conference'. p. 60. (CRC for Coastal Zone Estuary and Waterway Management: Coolangatta, Qld.)

Jones, C., Waliser, D. E., Lau, K. M., and Stern, W. (2004). Global occurrences of extreme precipitation and the Madden–Julian Oscillation: observations and predictability. *Journal of Climate* **17**, 4575–4589. doi:10.1175/3238.1

Keenan, C. P. (1994). Recent evolution of population structure in Australian barramundi, *Lates calcarifer* (Bloch): an example of isolation by distance in one dimension. *Australian Journal of Marine and Freshwater Research* **45**, 1123–1148. doi:10.1071/MF9941123

Klyashtorin, L. (1998). Long-term climate change and main commercial fish production in the Atlantic and Pacific. *Fisheries Research* **37**, 115–125. doi:10.1016/S0165-7836(98)00131-3

Madden, R. A., and Julian, P. R. (1972). Description of global-scale circulation cells in the tropics with a 40–50 day period. *Journal of the Atmospheric Sciences* **29**, 1109–1123. doi:10.1175/1520-0469(1972)029<1109:DOGSCC>2.0.CO;2

Magro, K. L., Bibby, J. M., and Gribble, N. A. (1996). Tropical Resource Assessment Program – Annual report 1996. FRDC Project 95/049, Department of Primary Industries, Brisbane.

Meynecke, J. O., Lee, S. Y., Duke, N., and Warnken, J. (2006). Effect of rainfall as a component of climate change on estuarine fish production in Queensland, Australia. *Estuarine, Coastal and Shelf Science* **69**, 491–504. doi:10.1016/J.ECSS.2006.05.011

Moore, R. (1979). Natural sex inversion in the giant perch (*Lates calcarifer*). *Australian Journal of Marine and Freshwater Research* **30**, 803–813. doi:10.1071/MF9790803

Moore, R. (1982). Spawning and early life history of barramundi, *Lates calcarifer* (Bloch), in Papua New Guinea. *Australian Journal of Marine and Freshwater Research* **33**, 647–661. doi:10.1071/MF9820647

Moore, R., and Reynolds, L. F. (1982). Migration patterns of barramundi, *Lates calcarifer* (Bloch), in Papua New Guinea. *Australian Journal of Marine and Freshwater Research* **33**, 671–682. doi:10.1071/MF9820671

Myers, R. (1998). When do environment–recruitment correlations work? *Reviews in Fish Biology and Fisheries* **8**, 285–305. doi:10.1023/A:1008828730759

Pauly, D., and Pullin, S. V. (1988). Hatching time in spherical, pelagic, marine fish eggs in response to temperature and egg size. *Environmental Biology of Fishes* **22**, 261–271. doi:10.1007/BF00004892

Platten, J. R. (1996). The influence of river freshwater discharge on fishery catch rates in Queensland waters. Department of Natural Resources, Rockhampton, Qld.

Platten, J. R. (1999). Historical trends in recreational fishing catches. Gladstone Area Waterboard, Rockhampton, Qld.

Power, S., Casey, T., Folland, C., Colman, A., and Mehta, V. (1999). Interdecadal modulation of the impact of ENSO on Australia. *Climate Dynamics* **15**, 319–324. doi:10.1007/S003820050284

Pyper, B. J., and Peterman, R. M. (1998). Comparison of methods to account for autocorrelation in correlation analyses of fish data. *Canadian Journal of Fisheries and Aquatic Sciences* **55**, 2127–2140. doi:10.1139/CJFAS-55-9-2127

Robins, J. B., Halliday, I. A., Staunton-Smith, J., Mayer, D. G., and Sellin, M. J. (2005). Freshwater flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. *Marine and Freshwater Research* **56**, 343–360. doi:10.1071/MF04087

Robins, J. B., Mayer, D. G., Staunton-Smith, J., Halliday, I. A., Sawynok, B., and Sellin, M. J. (2006). Variable growth rates of a tropical estuarine fish species (barramundi, *Lates calcarifer* Bloch) under different freshwater flow conditions. *Journal of Fish Biology* **69**, 379–391. doi:10.1111/J.1095-8649.2006.01100.X

Ruello, N. V. (1973). The influence of rainfall on the distribution and abundance of the school prawn *Metapenaeus macleayi* in the Hunter River region (Australia). *Marine Biology* **23**, 221–228. doi:10.1007/BF00389488

Russell, D. J., and Garrett, R. N. (1983). Use by juvenile barramundi, *Lates calcarifer* (Bloch), and other fishes of temporary supralittoral habitats in a tropical estuary in northern Australia. *Australian Journal of Marine and Freshwater Research* **34**, 805–811. doi:10.1071/MF9830805

Russell, D. J., and Garrett, R. N. (1985). Early life history of barramundi, *Lates calcarifer* (Bloch), in north-eastern Queensland. *Australian Journal of Marine and Freshwater Research* **36**, 191–201.

Russell, D. J., and Garrett, R. N. (1988). Movements of juvenile barramundi, *Lates calcarifer* (Bloch), in north-eastern Queensland. *Australian Journal of Marine and Freshwater Research* **39**, 117–123. doi:10.1071/MF9880117

Sawynok, B. (1998). Fitzroy River effects of freshwater flows on fish. InfoFish Services, Rockhampton, Qld.

Shaklee, J. B., Salini, J. P., and Garrett, R. N. (1993). Electrophoretic characterization of multiple genetic stocks of barramundi perch in Queensland, Australia. *Transactions of the American Fisheries Society* **122**, 685–701. doi:10.1577/1548-8659(1993)122<0685:ECOMGS>2.3.CO;2

Shapiro, S. S., Wilk, M. B., and Chen, H. J. (1968). A comparative study of various tests of normality. *Journal of the American Statistical Association* **63**, 1343–1372. doi:10.2307/2285889

Staunton-Smith, J., Robins, J. B., Sellin, M. J., Halliday, I. A., and Mayer, D. G. (2004). Does the timing of freshwater flowing into a dry tropical estuary affect year-class strength of barramundi (*Lates calcarifer*)? *Marine and Freshwater Research* **55**, 787–797. doi:10.1071/MF03198

Stergiou, K. I., and Christou, E. D. (1996). Modelling and forecasting annual fisheries catches: comparison of regression, univariate and multivariate time series methods. *Fisheries Research* **25**, 105–138. doi:10.1016/0165-7836(95)00389-4

Sutcliffe, W. H. (1973). Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence. *Journal of the Fisheries Research Board of Canada* **30**, 856–859.

Sutcliffe, W. H., Drinkwater, K., and Muir, B. S. (1976). Correlations of fish catch and environmental factors in the Gulf of Maine. *Journal of the Fisheries Research Board of Canada* **34**, 19–30.

Troup, A. J. (1965). The 'southern oscillation'. *Quarterly Journal of the Royal Meteorological Society* **91**, 490–506. doi:10.1002/QJ.49709139009

Vance, D. J., Haywood, M. D. E., Heales, D. S., Kenyon, R. A., and Loneragan, N. R. (1998). Seasonal and annual variation in abundance of postlarval and juvenile banana prawns *Penaeus merguiensis* and environmental variation in two estuaries in tropical northeastern Australia: a six year study. *Marine Ecology Progress Series* **163**, 21–36. doi:10.3354/MEPS163021

Wheeler, M. C., and Hendon, H. H. (2004). An all-season real-time multivariate MJO index: development of an index for monitoring and prediction. *American Meteorological Society* **132**, 1917–1932.

White, M. E., and Downton, M. W. (1991). The shrimp fishery in the Gulf of Mexico: relation to climatic variability and global atmospheric patterns. In 'Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impacts'. (Eds M. H. Glantz, R. W. Katz and N. Nicholls.) pp. 459–491. (Cambridge University Press: Cambridge, UK.)

Wilkes, D. S. (1995). 'Statistical Methods in Atmospheric Science.' (Academic Press: San Diego, CA.)

Manuscript received 9 October 2008, accepted 2 March 2009