RR 2016/0809 | 2017

Australian Government
Australian Fisheries Management Authority

Improving the location and targeting of economically viable aggregations of squid available to the squid jigging method and the fleet's ability to catch squid

Matt Koopman, Ian Knuckey and Madeleine Cahill

2018

ISBN: 978-0-9954122-6-2

Improving the location and targeting of economically viable aggregations of squid available to the squid jigging method and the fleet's ability to catch squid

Matt Koopman, Ian Knuckey and Madeleine Cahill

AFMA Project 2016/0809

Executive Summary

Sources of variation in catches and catch rates of Gould's squid (*Nototodarus gouldi*) were examined in fisheries off southeast Australia. Fisheries included trawl fisheries: Commonwealth trawl sector (CTS), the Great Australian Bight trawl sector (GABTS), Danish Seine (DS). These fisheries targeted species other than squid but caught squid as a by-product. Dedicated squid fisheries included the historical squid fishery (HistSJ: an exploratory fishery involving mainly Japanese vessels in the 1980s), the Tasmanian squid jig fishery (TasSJ, a state-managed component of the Tasmanian scale fishery) and, the main focus of this study, the Southern Squid Jig Fishery (SSJF).

A literature review included evaluation of environmental factors and their influence on squid fisheries more generally. The review also considered the influence of technology (i.e. technical innovations) on squid jigging, the method used to catch squid in the SSJF. Insights on factors affecting squid catches were also derived from an Industry workshop including participants from various squid fisheries. These insights assisted in the development of hypotheses for factors affecting catch rates of squid particularly for the SSJF: an aim was to improve targeting and catch efficiency for the SSJF. Environmental factors evaluated and modelled for Australian squid fisheries included: sea surface temperature (SST), ocean colour (Chl a), coastal oceanography (currents), sea level, barometric pressure, and moon phase. Broader scale oceanographic events driven by the southern oscillation index (SOI) were also examined and modelled against catch rates of squid. Of the fisheries examined, the CTS had the most comprehensive data set. Examination of the SSJF was compromised by a limited time series and the spatial concentration of effort in one location: Western Victoria.

Peak catches and catch rates of squid occurred at the same time of the year for all fisheries (summer months). This suggests that the factors driving abundance and / or availability of Gould's Squid are consistent or linked between fishing areas. However, since records have been taken, the timing of peak catches has become earlier in the year (February, March) particularly off Western Victoria.

The SSJF operates off the continental shelf in waters ranging in depth from 60 to 105 m. There is no evident pattern of interannual change in depth of fishing for the SSJF although squid are caught in greater depths from the CTS. Catch rates of squid in the trawl fisheries were highest during the waning gibbous and full moon, but lowest during those moon phases in the squid jig fisheries. This is likely due to an increase in availability of squid to trawl methods caused by reduced diel vertical migration during those moon phases. Catch rates for the squid jig fisheries (which only operate at night) are highest around the new moon. This, and clear, calm sea conditions are more likely to yield higher catches and catch rates for the SSJF.

Catch rates of squid for trawl fisheries varied with depth and with time of day most likely as a function of surface feeding migration characteristics. The concentration of fishing by the SSJF off Western Victoria (Portland) focused attention on environmental factors specific to the region: the Leeuwin current, the Bonney upwelling, and related factors which affect primary productivity and the availability/abundance of prey for Gould's squid. Peaks and troughs in catch and catch rates in the trawl sector occurred at the same time possibly because of variation

in the strength of the Leeuwin Current. However, there was no apparent influence of the Bonney upwelling on catch or catch rates of squid in either trawl fisheries or the SSJF. Similarly, there was no apparent relationship of sea surface temperature or of chlorophyll a concentration on catches or catch rates of squid. Nonetheless, modelling with lagged data (- 1 year) for Western Victoria showed correlation of peak catch rates in the SSJF with current strength (or sea level at Portland), SST and chlorophyll a.

No clear, or obviously important source of variation were identified which could potentially improve targeting in the Southern Squid Jig Fishery. This is most likely due to confounding variables affecting squid distribution and abundance. Factors which influence growth and survival of squid (e.g. SST, currents) may be confounded with factors which influence prey abundance (e.g. primary/secondary productivity). Under conditions of chlorophyll a/high productivity e.g. with the Bonney upwelling, waters are more turbid. This limits the effectiveness of surface lights on SSJF vessels used to attract and catch squid. Evidence from industry participants suggest that squid accumulate at thermal or nutrient fronts, attacking prey in turbid waters from clear water. Thus, taking a more focused spatial approach, variation in coastal oceanographic productivity associated with the Bonney upwelling and the abundance of prey species (particularly krill) is an important driver of squid population abundance. Accordingly, seasonal catches are optimal during summer when oceanic processes favour squid accumulation off Western Victoria. Changes in the frequency and intensity of upwelling due to, for example, ENSO events and climate change will influence squid abundance. More specifically, advances in technology associated with jigging and squid/prey attraction appear promising. Targeting squid around the new moon, in clear water, with lights (including blue wavelengths) and automated jigging machines (to account for sea state and squid depth) reflect our findings both for the SSJF and for squid jig fisheries more generally. Adoption and development of such technology improve catch rates in the SSJF.

List of Tables

List of Figures

Introduction

The Gould's Squid (*Nototodarus gouldi*) is an important fishery in southern Australia. Historically, the first significant jig catches of arrow squid occurred in the Derwent estuary, Tasmania in 1972/73 but more substantial catches were taken during the late 1970's and 1980's during feasibility fishing by jigging vessels from Japan, Korea and Taiwan in western Bass Strait and off northern Tasmania (Kailola *et al.*, 1993) see also (Winstanley *et al.*, 1983, Smith, 1983, Machida, 1983). The Japanese Marine Fishery Resources Research Centre (JAMARC) conducted four surveys during the seasons from 1977/78 to 1980/81 covering most of the waters of the continental shelf off Tasmania, Victoria and south-eastern South Australia. During this period there were also a number of joint venture fishing operations by Australian and foreign companies. During 1979/80, 68 jigging vessels caught a record 7914 tonnes of squid.

After exclusion of foreign fishing, catches by the domestic fleet have been far less. The domestic squid jig fishery for arrow squid started in the 1986/87 fishing season with a single vessel and developed into a fishery of 84 Commonwealth Southern Squid Jig entitlements during 2001, although many of these were not active every year. The fishery now consists of a number of specialised squid jigging vessels, but a significant amount of the catch is also taken by fisherman using Danish seine and trawl gear in the CTS and GABTS sectors of the Southern and Eastern Scalefish and Shark Fishery (SESSF). Catches over the last 30 years have rarely exceeded 2500 t of which the trawl sectors regularly take 100 – 500t. The jig catch is highly variable from 2000t to virtually nothing depending on the year.

There is renewed interest in the potential of the jig fishery to produce product for both the domestic and international market, with industry members optimistic about potential expansion in the near future and improved prices. The difficulty for industry is the "boom and bust" nature of the jig sector and how this may negatively impact on such commercial opportunities. There is a perception that the small active fleet that now operates has limited potential to explore, find and target the dense aggregations of squid as they migrate around southern Australia.

Earlier work in Australia and overseas has shown relationships between oceanographic and environmental factors and squid migration and aggregation. Related research on the SSJF was last conducted during 2001 (Knuckey *et al.*, 2001). With 15 years of further data on the fishery and the extensive amount of new and more detailed oceanographic information now available, industry believes the time is right to re-examine correlations between squid catches and oceanographic conditions to improve targeting by the jig sector.

Gould's Squid Catch by Commonwealth Fisheries

Gould's Squid are considered to be one of Australia's largest under-exploited fisheries (Jackson and McGrath-Steer, 2003). They are widely distributed in waters across southern Australia south of latitude 27° 13'S and off New Zealand. They inhabit shelf and slope waters generally shallower than 500 m depth. Their ubiquitous distribution results in them being caught by multiple fisheries using selective and non-selective fishing gears in Commonwealth and State waters.

The Southern Squid Jig Fishery (SSJF) targets Gould's Squid using automatic jigging machines in shallow shelf waters across south east Australia, generally between 60 and 120 m depth (Patterson *et al.*, 2017). The area of the fishery is bound in the west by the longitude 129° E, and on the east cost the northern limit is at latitude 24° 30'E (Figure 1). Effort in the fishery is sporadic both temporally and spatially. Seasonally, it is focussed on peak times between January and June, whereas it changes annually in response to variable biomass or availability of the stock, high costs relative to return and market forces. In 2016 there were 7 active vessels in the fishery, who landed 384 t of Gould's Squid from 1,733 jig hours (Patterson *et al.*, 2017). Despite the stock being widely distributed and the large area of the fishery, effort is concentrated in specific locations, with most effort recorded off Portland in Western Victoria. Because t large aggregations of Gould's Squid are targeted at particular times of the year, effort is highly aggregated both spatially and temporally, resulting in a lack of consistent fisheries dependent time-series of data. Furthermore, the fine spatial scale of squid aggregations and the behaviour of squid in response to jigging (sensing, attacking and grabbing the jig) can reduce the utility of catch or CPUE as an indicator of abundance.

Gould's Squid are also caught by Commonwealth managed trawl fisheries including the Commonwealth Trawl (CTS) and Great Australian Bight (GABTS) sectors of the SESSF. The two main gear types used in both sectors are demersal trawl and Danish seine. There were 34 active demersal trawl vessels and 16 active Danish seine vessels in the CTS during the 2016–17 season, which together caught 542 t of Gould's Squid in 2016 (Patterson *et al.*, 2017). The 4 active demersal trawl and 1 Danish seine vessel operating in the GABTS in 2016-17 together landed 55 t of Gould's Squid in 2016 (Patterson *et al.*, 2017). Because Gould's Squid is a bycatch in these sectors, the distribution of fishing effort is more regular than that of the SSJF. However, the Danish seine fleet of the CTS operates mostly off eastern Victoria. Because Gould's Squid are not targeted by the trawl fisheries, fishing effort is distributed more widely than that for the SSJF. Thus, catch or CPUE data from the trawl sector may be a more useful indicator of abundance than that from the SSJF.

Gould's Squid are listed as 'permitted species' in state managed commercial fisheries in Tasmania, South Australia and New South Wales, and they are also caught by Victorian commercial fisheries (Patterson *et al.*, 2017). State catches are generally small (less than 10 t). However, catch in Tasmania's Scalefish Fishery has in some years reached more than 100 t. Although catch and effort data from most state-managed fisheries have not been used here, data from squid jiggers operating in Tasmania's Scalefish Fishery are used (titled SJTas throughout).

Exploratory fishing for squid was undertaken by the Japanese-owned Gollin Gyokuyo Fishing Company around Tasmania in 1969/70 revealing extensive squid stocks around Tasmania (Willcox *et al.*, 2001). Two years later, a vessel owned by the same company returned, carrying 20 automatic jig machines and targeted squid commercially (Wolfe, 1972; cited by Willcox *et al.*, 2001). Although stimulating a local fishery for squid, foreign (Taiwanese, Koran and Japanese) vessels fished Australian waters throughout the 1970s and 1980s, catching large quantities of squid (Willcox *et al.*, 2001) from eastern, southern and western Australia. In the 1979-80 season, 64 Japanese vessels took 8,000 t of Gould's Squid from around Bass Strait from December to May (FAO, 1982). Data from this fishery are referred to as HistSJ throughout this report.

The HistSJ Fishery covered a wide area, with the highest catches from South-east King Island, South-west Flinders Island, Central Victoria and South-west Victoria (Figure 56, Figure 67 and Figure 68). Large catches were reported from some areas not regularly fished by the SSJF, despite being within the boundaries of the current fishery. These locations include in Bass Strait east of King Island and off Port Sorell, Tasmania (e.g. Figure 70).

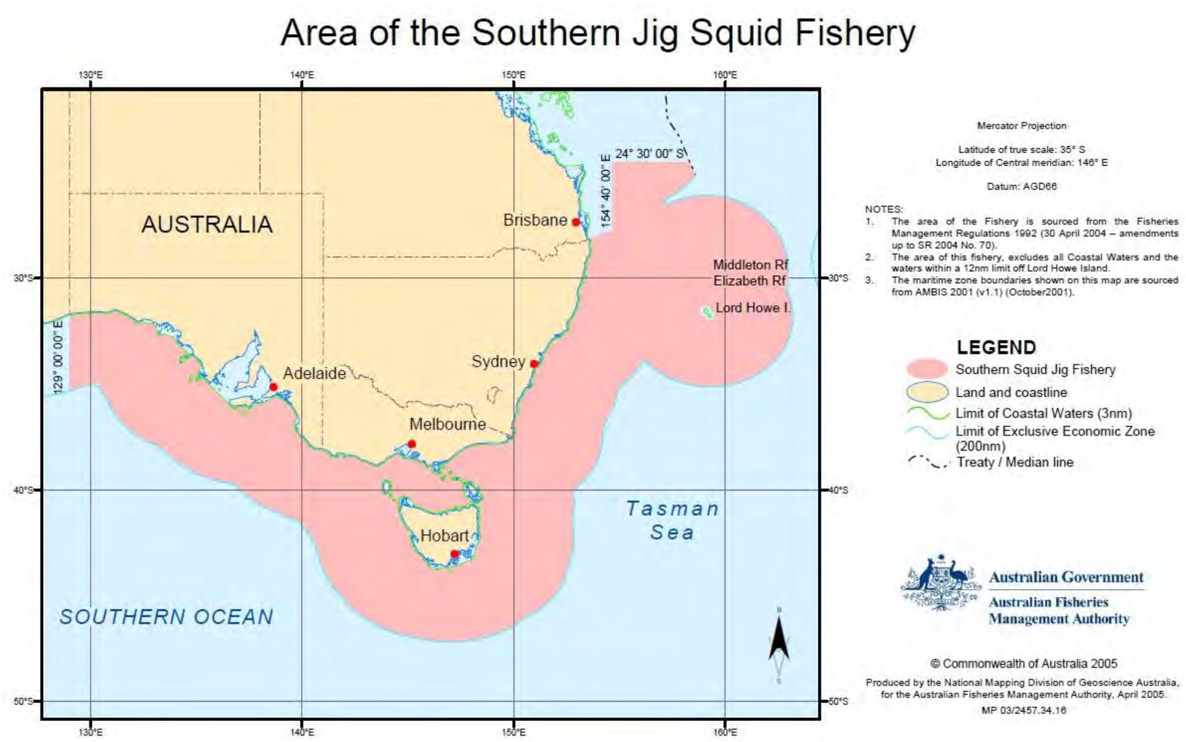


Figure 1. The area of the Southern Squid Jig Fishery (Reproduced from http://www.afma.gov.au/wp-content/uploads/2014/02/Southern-Squid-Jig-Fishery-map.jpg)

Objectives

1. Hold a workshop with major stakeholder groups to develop hypotheses about the major environmental drivers and their potential influence of gross fishery characteristics (catch composition, seasonal variations, recruitment pulses, etc).
2. Review international research on environmental effects on squid fisheries catches
3. Examine trends in Arrow Squid catch, effort and catch rates from fishery logbooks, observer data and fishery independent surveys in the area of the SSJF for both trawl and jig fisheries.
4. Examine trends between Arrow Squid catch, effort and catch rates by the SSJF, CTS and Tasmanian squid fishery and measured and modelled environmental data.
5. Review international literature describing squid jig fishing techniques and practices and recommend improvements to improve the ability of the SSJF to catch squid.

Materials and Methods

Industry workshops

A scoping workshop was held to canvas Industry's ideas on which environmental and oceanographic factors they think are most important in affecting squid availability and/or abundance, and fisheries indicators to be calculated from catch and effort data. Industry members from a range of different fisheries (SSJF, CTS, GABTS, SJTas), scientists and oceanographers were invited to participate in the workshop. Using the combined knowledge of workshop participants, a range of hypotheses were developed to correlate major environmental factors with key characteristics of the fisheries. Outcomes from the workshop were used to inform data used and analyses undertaken in objectives 3 and 4.

A second workshop was also held to present results to industry members and management.

Review of international research on environmental effects on squid fisheries catches.

There is a large volume of international literature available describing environmental effects on catches, recruitment and migration of squids. Some of the environmental factors that have been linked to squid catches and CPUE include sea surface temperature (Cabanellas-Reboredo *et al.*, 2012; Pierce *et al.*, 2006; Roberts and Sauer, 1994; Robin and Denis, 1999; Sims *et al.*, 2001; Wang *et al.* 2010; Alabia *et al.* 2016a;Yu *et al.*, 2015, 2016a, 2017;), wind speed (Cabanellas-Reboredo *et al.*, 2012), atmospheric pressure (Cabanellas-Reboredo *et al.*, 2012), sea surface height anomaly (Yu *et al.*, 2015, 2016b); moon phase (Cabanellas-Reboredo *et al.*, 2012), turbidity (Roberts and Sauer, 1994), chlorophyll (Hurst *et al.*, 2012), salinity (Yu *et al.*, 2015) and large scale climate predictors such as the Southern Oscillation Index (SOI) and the North Atlantic Oscillation (NAO) (Waluda *et al.*, 1999; Morales-Bojorquez *et al.* 2001; Pierce *et al.*, 2006; Roberts and Sauer, 1994; Sims *et al.*, 2001).

In the first stage of this project, an extensive literature review was conducted. The review focussed on environmental factors linked to different species of squid, fishery abundance indicators, sources of variation for squid abundance and/or catches, and statistical methods used. The review was used to guide inclusion and analyses of fisheries and environmental data for objectives 3 and 4.

Catch and effort data

Although the SSJF is the main fishery that targets Gould's Squid, other fisheries catch significant quantities of Gould's Squid. The Commonwealth Trawl Sector of the SESSF landed nearly 4 times more Gould's Squid by weight than the SSJF (663 t vs 166 t) in 2013, whereas in the same year, the GABTS caught 61 t and the SJTas fishery caught 976 t (Noriega *et al.*, 2014). The focus of this study was initially on the SSJF, data from those other fisheries were examined, and where appropriate were analysed to investigate the influence of environmental variables on Gould's Squid catches. In fact, comparison of the data sources reveals that the

CTS logbook data are likely to be the most comprehensive in terms of spatial and temporal coverage (Table 1).

Daily logbook and observer data were obtained from AFMA for the SSJF, CTS and GABTS, and logbook data for the SJTas from Institute for Marine and Antarctic Studies, University of Tasmania. AFMA also provided catch and effort data from the HistSJ from the 1970 and 1980s. The range of dates of catch and effort data received is shown in Table 2.

Data grooming procedures were applied to ensure accuracy of the data to be used, including range checks and missing values. It is noted that there are some issues with reporting of other species such as cuttlefish, octopus and Southern Calamari under Gould's Squid CAAB code, reporting of Gould's Squid under the "other species code" (see for example Knuckey *et al.*, 2001; Noriega *et al.*, 2014). Catches of Gould's Squid in fishing logbook could be recorded as the generic "Squid" (CSIRO Code 23615000) or Gould's Squid (CSIRO Code 23636004). The composition of each of those codes varies between fisheries, with generic "Squid" recorded for 99.9% of the catch by the SSJF, 78% for the CTS and 92% for the GABTS (Table 3). While Gould's Squid are the dominant "Squid" caught by all three sectors, other squid species are caught, and this increases with depth. The challenge for this project was to decide on a rule for use of both species codes. We considered that depth would be an appropriate variable to filter data to retain as much Gould's Squid as possible, while excluding other squid species. Fisheries observer data are generally considered to contain more accurate species identifications than logbook data. However, observer data also include the generic "Squid". A comparison of catch composition of the two codes by depth revealed that more than 95 % of the Gould's Squid recorded by observers was taken in less than 500 m depth, whereas only about 85% of "Squids" was taken from 500 m or less (Figure 2). Thus, while we can't be certain that all "Squids" reported by observers as coming from less than 500 m are Gould's Squid, we can be confident that "Squids" reported from depths greater than 500 m comprise mostly other species. We therefore combined logbook records for catches of "Squid" and Gould's Squid, but excluded those records from depths greater than 500 m.

Table 1. Preliminary summary of likely usefulness of different sources of fisheries data.

	Logbook					Observer			FISs
	SSJF	CTS	GABTS	HistSJ	SJTas	SSJF	CTS	GABTS	
Catch / no catch									
Location – as high a resolution as possible									
Depth									
Date/time – as high a resolution as possible	But no time					But no time			
Effort									
Wide spread									
Continuous									
Quantity									

Table 2. Date range of catch and effort data provided for each fishery, and acronyms used throughout this report.

Fishery / sector	Acronym used throughout report	Earliest date	Latest date
CTS (demersal trawl)	CTS	03/08/1985	02/12/2016
CTS (Danish seine)	DS	04/08/1985	01/12/2016
GABTS (demersal trawl)	GABTS	26/03/1986	29/11/2016
Historical Squid Jig Fishery	HistSJ	04/10/1977	06/04/1987
Tasmanian Scalefish Fishery (Squid Jig)	SJTas	12/07/1995	25/06/2016
Southern Squid Jig Fishery	SSJF	16/09/1995	16/06/2016

Table 3. Percent of species reported in daily catch and effort logbooks that could represent Gould's Squid.

CSIRO code	Scientific name	Common name	% in SSJF	% in CTS	% in GABTS
23 615000	Order Teuthoidea - undifferentiated	Squid	99.9%	78%	92%
23636004	*Nototodarus gouldi*	Gould's Squid	<0.1%	22%	8%
23636000	*Ommastrephidae* - undifferentiated	Flying squids		In observer data only	

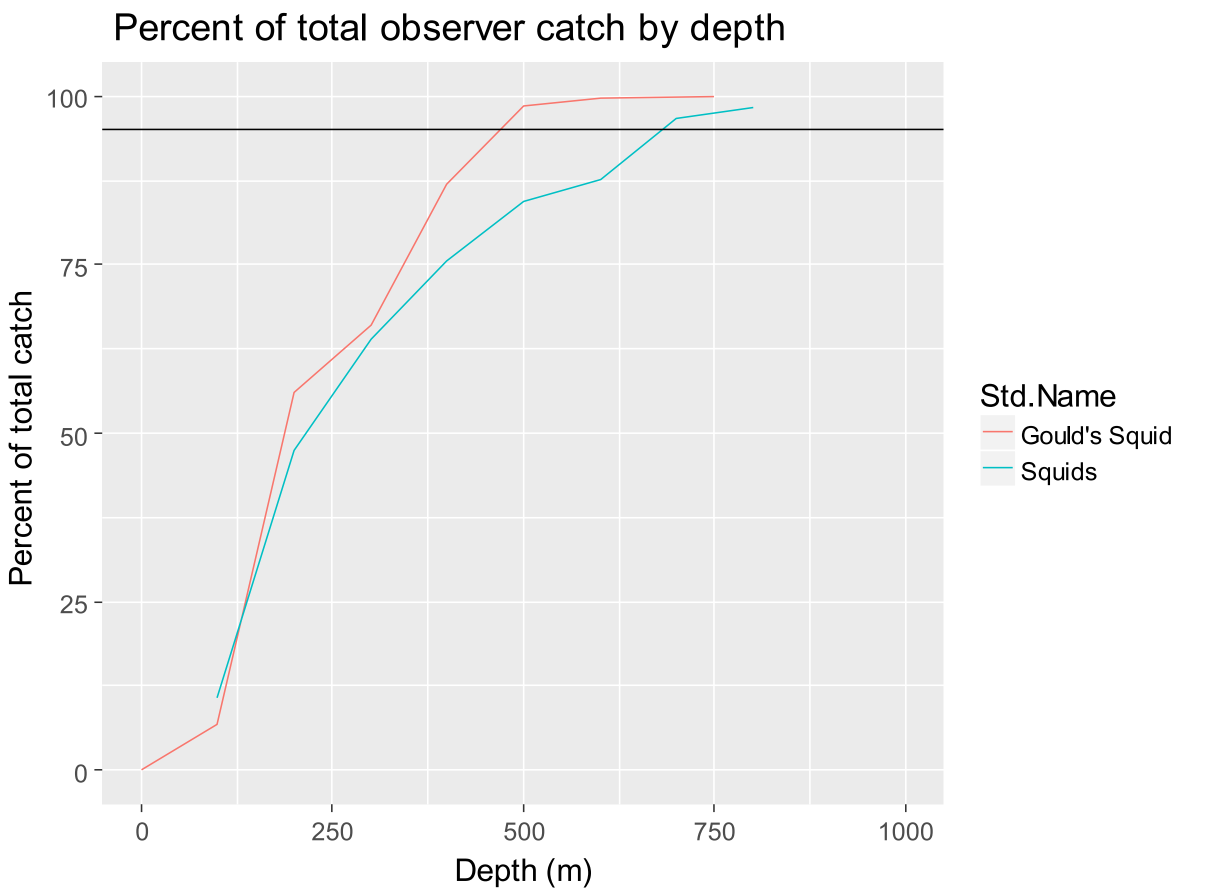


Figure 2. Cumulative percent of catch recorded by observers from the CTS by otter trawl gear. Horizontal line is at 95%.

Trends between Arrow Squid catch, effort, and catch rates and environmental data

Data used

Environmental variables used were chosen based on the literature review, data availability, and advice and outcomes from the first workshop. Ideally, variables selected should be ecologically relevant and sources of variation in catch rates (Dormann *et al.*, 2012). However, for squid fisheries examined, there are no clear environmental effects on CPUE: the fisheries cover a wide range of habitats and oceanographic forces (e.g. currents, upwelling events). Furthermore, the locations and timing of reproduction vary considerably. Ommastrephid squid have a pelagic egg stage (Puneetae *et al.*, 2015). Thus, movement of large egg masses is influenced by currents,, stratification and/or mixing in the water column. These factors and other uncertainties in the life history of Gould's Squid limit the development of testable hypotheses. Therefore,, a wide range of variables was used during this project. These are listed in Table 6.

Remotely measured sea surface temperature (SST) is correlated with in situ measurements of SST across southern Australia (Stobart *et al.*, 2015). SST also corresponds to subsurface ocean temperature to at least 400 m depth off south-eastern Tasmania (Sokolov and Rintoul, 2003). Thus, it appears likely that the measure of SST used is appropriate for investigating potential drivers of changes in the abundance of Gould's Squid. Remote-sensed data comprise relatively fine spatial scale. However, at such a fine scale, data can be influenced by interference from, for example, cloud cover or missing data. The following range of spatial scales was used to generate environmental data:

- Representative locations (points) in each area of interest located about 20 nm off shore (Table 4, Figure 3). A single point was chosen for New South Wales, Bass Strait and Eastern Victoria. Two points were selected for Western Victoria, one in the region of the Bonney Upwelling, and another off Portland representing the main fishing grounds in that area. Two points were also selected from Eastern Tasmania, one from within Storm Bay representing the main area of Tasmanian State catches, the other representing the zone in general. Analyses revealed that there was no benefit from using points as well as lines (because results were so similar) and so, for brevity, only data from lines are presented in this report.
- Representative "lines" running perpendicular to the coast line from about the 40 m depth contour to the 200 m depth contour (80 m for Bass Strait) (Table 5, Figure 3). The same locations as for points were used for lines.
- Location (points) of "Start position" in effort data for each fishery. Start position was used because end position was often missing, and so calculation of a centre position would have resulted in the loss of significant amounts of data.
- Polygons of SEF Zones.

Environmental data were matched to the points, lines, and polygons using the "extract" function from the sp package (Pebesma and Bivand, 2005). For points, the mean value within a 5000 m buffer was calculated. For lines, the mean value along the length of the line was calculated, and for polygons, the mean value within each polygon was calculated. The buffer was used for points to reduce the number of missing values.

Table 4. Positions of points used to extract remote sensed data for each area. Points are shown in Figure 3.

Point	Lon1	Lat1
Bonney_Upwelling	139.87	-37.61
West_Vic	142.08	-38.71
Bass_Strait	144.42	-38.48
East_Vic	148.06	-38.12
Tas_Maria_Island	148.25	-42.75
Tas_Storm_Bay	147.5	-43.25
Southern_NSW	150.148	-36.82

Table 5. Extent of lines used to extract remote sensed data for each area. Lines are shown in Figure 3.

Line	Inshore longitude	Inshore latitude	Inshore depth	Offshore longitude	Offshore latitude	Offshore depth	Zone
Bonney_Upwelling	139.985	-37.491	40	139.701	-37.725	200	West Vic
West_Vic	142.155	-38.407	40	142.048	-38.843	200	West Vic
Bass_Strait	144.351	-38.365	40	144.489	-38.6	>80	Bass Strait
East_Vic	147.952	-37.935	40	148.42	-38.647	200	East Vic
Tas_Maria_Island	148.1444	-42.7025	40	148.3711	-42.7987	200	East Tas
Tas_Storm_Bay	147.48	-43.2332	40	147.942	-43.584	200	East Tas
Southern_NSW	150.338	-36.857	40	150.009	-36.792	200	South NSW

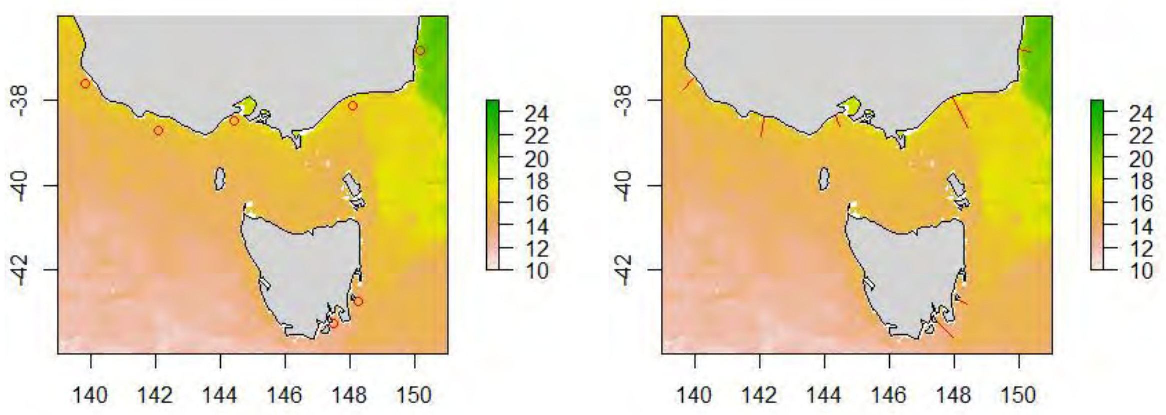


Figure 3. Left panel: Locations of points used to extract remote sensed data (Table 4). Right panel: locations of lines used to extract remote sensed data (Table 5). Background is SST from February 2016.

Calculation of thermal and Chl a gradients

The presence of a thermal or chlorophyll a (Chl a) gradient has been shown to influence squid CPUEs. Such gradients were noted by industry at the squid workshop as a part of this project, and also during Knuckey *et al.*, (2010). These measures are not directly available and so were calculated from remote-sensed data as described below.

For SST matched to the location of individual fishing effort from 1992–2016, SST data could not be matched in 1.6% of records. Unrealistic values for SST were also obtained, ranging from 0.5˚C for minimum SST within a buffer area, to 34.3˚C for maximum SST (Figure 4). Mean SST ranged 6.2˚C – 30.7˚C, whereas the greatest difference between minimum SST and maximum SST within a buffer area was 19.7˚C. To remove data (as shown by unrealistic values), an arbitrary decision was made to exclude all data with a difference between minimum and maximum values of 5˚C or greater within a buffer with a radius of 5,000 m. This resulted in the omission of about 0.8% of shots. The large buffer was chosen to reduce drop-outs from missing SST data and was considered appropriate given the scale of the positions reported by fishers in logbooks.

Another arbitrary decision made was the range of SSTs that constitutes a "front". Waluda *et al.* (2001a) in their study in Falkland Islands (Islas Malvinas) in the South-west Atlantic, defined "thermal gradients" as areas with a range in values of 0.4–1°C within an area of about 10.9 km^2., Given the large area covered in the present study and the numerous influences of SST in this region (e.g. the East Australian Current, Leeuwin Current, eddies and upwelling), we considered a thermal gradient to be where the difference in minimum and maximum SST within a buffer area is 1.3–5°C. The arbitrary choice of temperatures that define a thermal gradient was considered to be a trade-off between over- and under- identifying thermal gradients. This choice resulted in about 13% of SSJF and 21% of CTS effort being classified as occurring in the area of a thermal gradient. The influence of a thermal gradient of fisheries was examined in two ways: catch and catch rates were compared between shots classified categorically as having a thermal gradient and those that were not; and the trend in temperature difference against catch and catch rates.

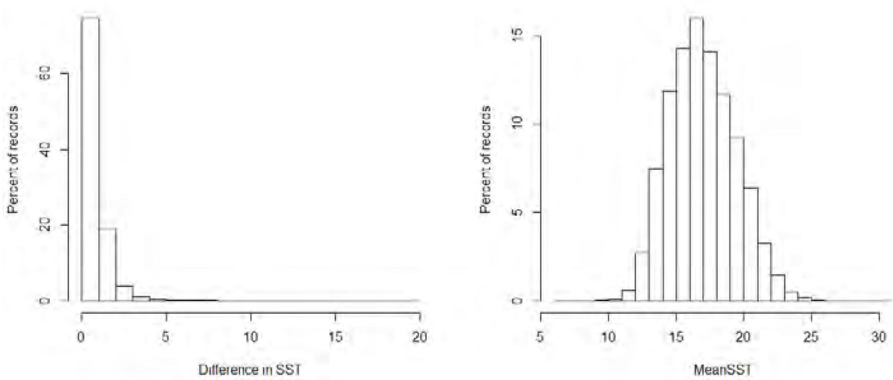


Figure 4. Histograms of the difference between minimum and maximum SSTs (˚C) in buffer zones around individual fishing locations (left panel) and of the mean SSTs (˚C) within each buffer zone (right panel).

Remote sensing data for ocean colour (chlorophyll a, OC3) (O'Reilly *et al.*, 2000) were available for the years 2003–2016. Even when a 5000 m buffer is applied, 1-day OC3 data have many gaps caused by cloud cover (Blondeau-Patissier *et al.*, 2017). To reduce "drop-outs", a seven-day rolling average was calculated for the mean, minimum, and maximum Chl a levels from each shot. This resulted in a dropout rate of only 1.2%.

As for SST, some anomalously high values were present in the data. Chl a in turbid coastal waters can be overestimated in the OC3 data because of the presence of non-algal particulate matter and coloured dissolved organic matter (Brando *et al.,* 2006), particularly during large discharge events. However, whereas the highest value obtained for the maximum Chl a in a buffer was 467 mg/m^3, only 5% of maximum Chl a values, and 2% of mean Chl a values were above 5mg/m^3 (Figure 5). The scale of IMOS (http://oceancurrent.imos.org.au/oceancolour.php) daily ocean colour figures is restricted to just over 4 mg/m^3, and to avoid outliers having a large influence, records with a value greater than 5 mg/m^3 were excluded.

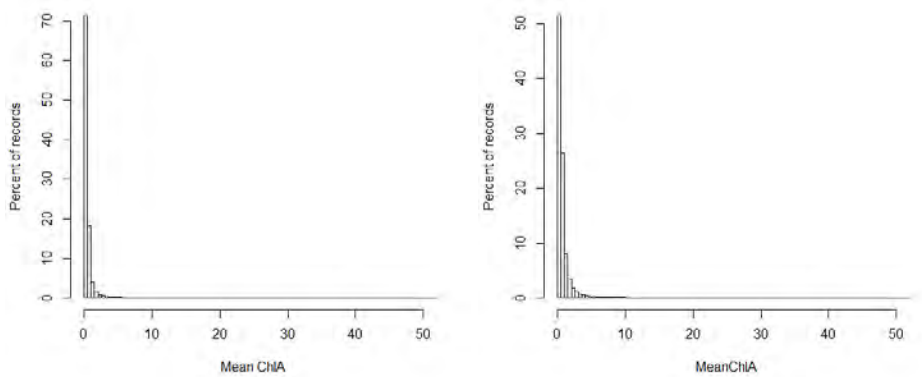


Figure 5. Histograms of the mean Chl a (mg/m^3) in buffer zones around individual fishing locations (left panel) and of the maximum Chl a (mg/m^3) within each buffer zone (right panel). The x-axis has been restricted to 50 mg/m^3 in both cases.

Table 6. Environmental data used in this project.

Variable	Description	Source	Location	Years obtained	Whole years	Time steps	Transformation
Latitude and longitude	Where latitude and longitude were used as predictor variables (e.g. for inclusion in standardised CPUEs, the presence of collinearity was examined, and where present, removed with principal component analysis, which produces orthogonal axes (Dormann *et al.*, 2013)	Logbook effort data	Shot start location	See Table 2	SSJF: 1997-2016 DS: 1987-2016 CTS: 1987-2015 GABTS: 1987-2015 SJTas: 1995-2015 HistSJ: 1978-1986		NA
8 phase Moon Phase	Previously downloaded 4 phase, but at industries request calculated an 8-phase moon phase	Calculated for each date in the R package lunar (Lazaridis, 2014)	Calculated within R	All years in time series			NA
Fishing_depth	Depth in metres recorded in daily logbooks	Logbook effort data	During the shot	All years in time series			
Diel period	AdjtimeDec>=15 & AdjtimeDec<21,"dusk", ifelse(AdjtimeDec>=3 & AdjtimeDec<9,"dawn",ifelse(AdjtimeDec>=9 & AdjtimeDec<15,"day","night"))	Calculated from data	Calculated within R	All	All	Four categories: 3-9, 9-15, 15-21, 21-3	
Shot SST	L3S - 06 day composite - night time	http://thredds.aodn.org.au/thredds/catalog/IMOS/SRS/SST/ghrsst/L3S-6d/ngt/		Mar 1992–Dec 2016			
SST_Monthly	L3S – 1-month composite - night time	http://thredds.aodn.org.au/thredds/catalog/IMOS/SRS/SST/ghrsst/L3S-1m/ngt/	F:\RworkingDirectory\Data\EnvironmentalData\data\MonthlySST	Jan 1993–Dec2016	1993-2016		None
Maria Island Water Temp	Maria Island National Reference Station combined long-term	http://thredds.aodn.org.au/thredds/dodsC/IMOS/ANMN/NRS/NRSMAI/aggregated_products/	H:\EnvironmentalData\Maria Island water temp	1944–2016	1946-2013 – but random months missing in years		log
Daily Chl a	IMOS - SRS - MODIS - 01 day - Chlorophyll-a concentration (OC3 model)	http://thredds.aodn.org.au/thredds/catalog/IMOS/SRS/OC/gridded/aqua/P1D/catalog.html	H:\EnvironmentalData\Chl_a\ChlaShot	5/7/2002–17/11/2016			
Monthly Chl a	Chl a	http://rs-data1-mel.csiro.au/thredds/dodsC/imos-srs/oc/aqua/1m	H:\EnvironmentalData\Chl_aMeanmonthly	July 2002–Sept 2015	2003-2014		Log
Average annual and monthly Chl a from SeaWIFS for the	With 3 nm buffer along coast	http://thredds.aodn.org.au/thredds/catalog/IMOS/SRS/OC/gridded/seawifs/P1H/catalog.html	H:\EnvironmentalData\SeaWifs	1997-2010	1998-2010	Annual – Financial Year, Calendar Year	Log

Variable	Description	Source	Location	Years obtained	Whole years	Time steps	Transformation
area of the Bonney upwelling						Monthly	
Relative La Nina and El Nino strength	Qualitative strength of ENSO events scaled from 1-5. 1=weak, 5 = Strong	http://www.bom.gov.au/climate/enso/index.shtml	D:\Fishy business\RworkingDirectory\Data\Squid targeting\data\processed\el nino la nina.xlsx			Annual	
SOI	The SOI is defined as the normalized pressure difference between Tahiti and Darwin. There are several slight variations in the SOI values calculated at various centres. Here we supply the SOI (from CRU) which is based on the method given by Ropelewski and Jones (1987).	https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/SOI/	H:\EnvironmentalData\SOI	1866-2016	1866-2016	Annual – Financial Year, Calendar Year Monthly	None
Sea level	Monthly and annual sea level data from Portland, Storm Bay and Eden	http://www.psmsl.org/data/ Holgate *et al.*, 2013; PSMSL, 2017	H:\EnvironmentalData\Portland Tide data	1992-2016	1992-2016	Annual – Financial Year, Calendar Year Monthly	log
NINO3.4	Average equatorial SSTs across the Pacific from about the dateline to the South American coast. Or see https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni	https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/	H:\EnvironmentalData\NINO3.4	1870-2016	1866-2016	Annual – Financial Year, Calendar Year Monthly	None
Trans Polar Index Monthly and Annual	The TPI is defined as the normalized pressure difference between Hobart and Stanley. The index was first suggested by Pittock (1980,1984) and has been updated and analysed further by Jones *et al.* (1999).	https://crudata.uea.ac.uk/cru/data/tpi/	H:\EnvironmentalData\Trans Polar Index	1895 - 2014	1895 - 2014	Annual – Financial Year, Calendar Year Monthly	None
OT-HP JAS-OT-HB-BP	The JAS-OT-HB-BP is the barometric pressure difference between Cape Otway and Hobart during July, August and September. It was proposed as an alternative to Zonal Westerly Winds by Hamer *et al.* (2010)	The index was provided by Paul Hamer (Victorian Fisheries Authority).		Up until 2013	1948-2013	Annual – Fin Year, Calendar Year, July, August, September Monthly	None
Zonal Westerly Winds	Annual ZWW averaged over fiscal Calculated by John Morrongiello	John R. Morrongiello	H:\EnvironmentalData\ZWW	1972–2015	1972–2015	Annual – Fin Year	None
GLSA	Gridded (adjusted) sea level	http://thredds.aodn.org.au/thredds/catalog/IMOS/O	H:\EnvironmentalData\GLSA	1993–2016	1993–2016	Monthly	None

Variable	Description	Source	Location	Years obtained	Whole years	Time steps	Transformation
	Altimeter and tidegauge estimates of adjusted sea level anomaly mapped onto a grid using optimal interpolation (OI).	ceanCurrent/GSLA/DM00/catalog.html				Annual	
UCUR	Eastern Component velocity from GLSA data	http://thredds.aodn.org.au/thredds/catalog/IMOS/OceanCurrent/GSLA/DM00/catalog.html	H:\EnvironmentalData\GLSA	1993–2016	1993–2016	Monthly Annual	None
VCUR	Northern Component velocity from GLSA data	http://thredds.aodn.org.au/thredds/catalog/IMOS/OceanCurrent/GSLA/DM00/catalog.html	H:\EnvironmentalData\GLSA	1993–2016	1993–2016	Monthly Annual	None
TOTVEL	Total velocity= sqrt (UCUR^2+ VCUR^2)	http://thredds.aodn.org.au/thredds/catalog/IMOS/OceanCurrent/GSLA/DM00/catalog.html	H:\EnvironmentalData\GLSA	1993–2016	1993–2016	Monthly Annual	Sqrt

CPUE standardisation

Annual and monthly CPUE standardisations were performed on data for each sector combined, and for main zones within each sector.

Before undertaking the standardisations, data were filtered to remove any obvious outliers. The following filters were applied:

- CTS data - Fishery= CTS & year > 1985 & Depth < 501
- DS data - Fishery = DS & year > 1985 & Depth < 501
- GABTS data - Fishery = GAB & year > 1986 & Depth < 501
- SSJF data - Fishery= SSJ & year > 1995 & Depth < 301 & month > 1 & month < 7 & CPUE < 8000 & moonphase != Full & moonphase !=Waning gibbous)
- SJTas data - Fishery=SJTas & year>1986 & Depth <501

Contrast between months was largely removed by filtering out data from July to December, whereas the effect of the moon was removed by filtering out records from the full moon and waning gibbous. Longitude and Latitude were also highly correlated (e.g. for the SSJF for all zones combined: r=0.14, p<0.0001). Thus, the principle components of latitude and longitude were used to describe position for all sectors (PC1 and PC2).

Models used to calculate CPUE differed between fisheries depending on the availability of explanatory variables. Of the range of transformations examined, the log transformation consistently provided the most normal distribution of CPUE, while examination of model diagnostics (Nelder and McCullagh 1989, Ortiz and Arocha 2004) suggested that a GLM with a Gaussian error distribution was most suitable, and accordingly used for all fisheries. Variables includes in standardised CPUEs are as follows: year, month, vessel name (trawl fisheries only), PC1, PC2, depth, moon phases, diel period (trawl fisheries only), moon phases x diel period interaction (trawl fisheries only), depth x diel period interaction (trawl fisheries only), and moon phases x depth. Models were fitted using the glm function in R (R Core Team, 2017). Models followed the general form:

log(CPUE)~year

Variables were iteratively added to the base model and retained if inclusion of a particular variable improved the deviance by more than 1%. The influence of SST and Chl a on standardised CPUE deviance was examined by adding each to the final CPUE model separately.

Timing of highest CPUE

Preliminary analyses revealed that the seasonality of CPUE of Gould's Squid varied between years. To examine the influence of environmental variables on the seasonality of squid catches, the month of peak CPUE was calculated for each year using unstandardised log CPUEs. Because of the prevalence of peak catch rates late in the year (November and December), months were rescaled to begin the 'season' in October. For those analyses, October has the value of 1, with the value of each month increasing by 1 to September which has the value of 12.

Similarities in CPUE trends between sectors / zones

Cluster analysis was used to identify similarities in attributes (time series of annual catch rates). Similarity was measured using the Ward method using the R software with the Cluster package (Maechler *et al.* 2014). This cluster analysis treated the CPUE index as scatter points and identifies which time series of CPUE for each sector/zone are most similar (Castillo-Jordán *et al.*, 2016). Grouping the time series into clusters allows inferences to be made about the spatial scale over which drivers might affect CPUE or recruitment (e.g. Castillo-Jordán *et al.*, 2016).

Time series analysis on SST

Apparent increasing SST off Portland warranted further analyses of the time series. The non-parametric Mann-Kendall tests were used to detect monotonic trends in SST time series for each month separately, whereas a seasonal Mann-Kendall test was used for the entire data set (month by year). The magnitude of the trend was calculated using Sen's method for each month individually and the seasonal Sen's slope for the entire data set. Presence of a change point was examined using Pettitt's test. These tests were implemented using the trend package (Pohlert, 2018) implemented in R version 3.4.3 (R Core Team, 2017).

Results

Project Workshop

A workshop was held in Melbourne on 27th January 2017. Seventeen people were invited to the workshop, 11 attended, 5 of whom were industry members. The agenda is shown in Appendix 1. The positives and negatives of different fisheries data sources were described in relation to their potential use in this project as an indicator of squid abundance or availability. It became clear that despite not targeting Gould's Squid, CTS data would be particularly useful because of the long, continuous time series, covering a large area and range of depths. Furthermore, the CTS data are less seasonal than other data sources and data records include start and end time, date, and location for every fishing operation.

Industry members provided advice on analysis of fisheries catch and effort data including:

- the importance of adjusting for daylight savings;
- using catch composition from observer records of CTS shots to set a maximum depth for "Gould's Squid";
- the importance of obtaining data from the SJTas;
- to split the moon cycle into 8 phases rather than 4;
- that including number of hooks in CPUE calculations is not important;
- years of good squid catches appear to coincide with large numbers of moths and crickets appearing on vessels while fishing;
- the main factors limiting catches of squid; and
- catches are affected by catchability – sometimes they just don't bite.

International research on environmental effects on squid fisheries catches

It has been well documented that environmental conditions affect catches, growth, recruitment, and the distribution and abundance of squid (Roberts and Sauer 1994). Examples of the influence of environmental factors on squids is presented below, and a summary of examples is shown in Table 7.

Effects of environment on squid catches

Pierce (1995) found correlations between the squid *Loligo forbesi* catches and CPUE with sea surface temperature in a number of areas in the North Sea relating to interannual variation in the strength of the Gulf Stream. Similarly, Robin and Denis (1999) found a strong correlation of squid catches and water temperatures in the previous winter suggesting that survival and growth of early life stages was involved.

Roberts and Sauer (1994) suggested that fluctuations in annual catches of *Loligo vulgaris reynaudii* appeared to be related to the presence of spawning aggregations. They found that "meso- to large-scale environmental fluctuations" affect catches in the South African fishery relating to the Southern Oscillation Index. During times of La Niña there are enhanced summer easterly winds that cause low inshore water temperatures, whereas during El Niño events, there are enhanced westerly winds during winter that causes high levels of turbidity inshore. Both of these conditions reportedly influence the spawning behaviour of *L. vulgaris reynaudii*.

Hurst *et al.* (2012) found that ocean colour (Chl a) may be useful as a pre-season predictor of CPUE of *Nototodarus gouldi* and *N. sloanii* in New Zealand's southern fisheries. They found that whereas pre-season colour was potentially useful as a predictor, the in-season correlations between CPUE and ocean colour were higher and may be used in CPUE analyses.

Chen *et al.* (2010) developed a habitat suitability index (HIS) model of *Ommastrephes bartramii* using fishery indicators of effort (where fishing effort can be considered an index of squid occurrence). The most parsimonious HIS model included three variables: sea surface temperature, sea surface height anomaly, and Chl a concentration. Reporting on the same fishery, Yu *et al.* (2015) concluded that HIS was strongly associated with ENSO-induced variability in oceanic conditions on the fishing grounds including SST, chlorophyll-a concentration, and sea surface height anomaly.

In the recreational fishery for the European squid (*Loligo vulgaris*), Cabanellas-Reboredo *et al.* (2012) found CPUE to be seasonal: highest during the colder months. They found that CPUE was maximised when there was a low SST, low windspeed, low atmospheric pressure and on days close to the new moon.

An effect of water temperature on catches of squid have also been described for *Loligo pealei* (Brodziak and Hendrickson, 1999), *Nototodarus sloanii* (Kato and Mitani, 2001) and *Illex argentines* (Portela *et al.*, 2005; Chang *et al.*, 2015).

Effects of environment on squid growth

Temperature has been linked to growth in a number of squid species and is usually found to be most important early in the life cycle. Moreno *et al.* (2004) found that exposure to a SST of about 16.5˚C during the first 3 month of life had a positive effect on length-at-age on *L. vulgaris* from Portuguese waters, but there was no apparent benefit with higher SSTs. They also found that hatching month and year were also significant factors influencing growth.

Effects of environment on squid recruitment

Although recruitment is often considered to be density-dependent in fish stocks, stock-recruitment relationships are less evident for squid. Challier *et al.* (2005) suggested that recruitment of *Loligo forbesi* in the English Channel was probably density-dependent at high stock sizes, but that recruitment is also negatively correlated with SST. Recruitment in squid is more likely to be influenced by environmental factors. For example, lower levels of recruitment of the Japanese common squid (*Todarodes pacificus*) were found to correspond to years of lower than normal SST in winter and spring, and cold winters with strong northwesterly winds (Isoda *et al.* 2005). Bakun and Csirke (1998) presented a number of hypotheses relating to environmenatl effects on *Illex sp.* Including:

1. A convergent pattern would help squid paralarvae remain in the frontal zone at the inshore edge of the Gulf Stream, and to return them to it if they are ejected by the frontal eddy patterns in the shear zone. This zone provides for particularly favourable paralarval growth and survival; and

2. Favourable transport conditions from the Gulf Stream zone to feeding grounds on the continental shelf.

Downey *et al.* (2009) showed that formation of spawning aggregations was triggered by upwelling events . They also suggested that rapid changes in temperature, such as sudden upwelling, caused short disruptions to spawning activity. Egg development of the North-west Atlantic Squid (*Illex illecebrosus*) was found to be inhibited at temperatures below 12.5˚C (Coelho *et al.*, 1994).

Effects of environment on squid distibution and abundance

Studies have found relationships between SST and the North Atlantic Oscillation (NAO) index on the abundance of *Loligo forbesi* in Scottish waters (Pierce and Boyle, 2003; Zuur and Pierce, 2004), whereas the NOA index was also linked to the timing of migration of *L. forbesi* in the English Channel (Sims *et al.,* 2001). Sims *et al.,* (2001) also reported that days of peak abundance of *L. forbesi* (as measured by trawl surveys) were correlated with sea-bottom temperatures that appear to be driven by the NOA. When warm temperatures coincided with hatching time and in the few months before migration, squid encountered much earlier than when the water was cold over the same period. These results reflect a temperature-dependent movement: temperature determines preferred t habitat and / or as a response to available food.

Roberts and Sauer (1994) found that along-shelf and mid-shelf demersal distribution of the Chokka Squid (*L. vulgaris reynaudii*) in South Africa was focussed on a “preferred zone” that fell in between areas with low bottom temperatures offshore (≤8˚C) and low dissolved-oxygen levels inshore (≤3 mg/l). The location of spawning grounds of that species was also affected increased wave action and high turbidity during winters with severe weather (Roberts and Sauer, 1994). Although Chokka squid usually prefer spawning inshore with warm water and abundant planktonic food, they spawn in deeper waters during years with bad weather.

Distribution of major prey species

Squid concentrate in oceanic waters to feed (Young *et al.* 1987, Arkhipin *et al.,* 2015). Prey abundance is strongly correlated with SST and this is a common driver of localised abundance of squid (Medellin-Ortiz *et al.,* 2016; Yu *et al.*, 2016a, 2017; Wang *et al.,* 2010; Xu *et al.,* 2016). This correlation of temperature and prey species applies to lanternfish (Brandt, 1983 a,b), crustacea (Griffiths and Brandt, 1983 a, b) and more general distribution and abundance of squid (Dunning and Brandt, 1985; Young *et al.,* 1987).

Effects of environment on Gould’s Squid in Australia

In Australia, Virtue *et al.* (2011) found that Gould’s Squid hatchlings that were exposed to warmer SST off Victoria were heavier as adults than those caught in the GAB. SST explained more than 50% of the variation in weight-at-catch of squid caught in Victoria.

Food availability has been shown to affect growth rates of some species including *Sepioteuthis lessoniana* (Jackson and Moltschaniwskyj 2001) and *Illex illecebrosus* (Hirtle and O'Dor 1981). Virtue *et al.* (2011) suggested that although Chl a is a good proxy for food availability, there is a time-lag between algal blooms and subsequent transfer of energy through the food web, and that food availability and SST may influence differences in Gould’s Squid growth compared with Chl a and SST alone. Jackson *et al.* (2003) found that sea surface colour helped to explain differences in growth rate of female Gould's Squid caught in winter, but not those caught in summer, nor males caught in any season. The diet of Gould's Squid is varied, with O'Sullivan and Cullen (1983) reporting that the diet of Gould's Squid in Bass Strait comprised mostly fish (37.9%), crustaceans (32.6%), and cephalopods (27.4%). Common prey items identified included Australian Sardine (*Sardinops sagax*; previously *Sardinops neopilchardus*), Barracouta (*Thyrsites atun*; previously *Leionura atun*), Gould's Squid, the decapods *Leptochela sydniensis* and *Macropipus corrugatus*. More recently Pethybridge *et al.* (2011) found that the diet of Gould's Squid sampled off eastern South Australia and western Victoria comprised mostly two mesopelagic planktivorous light fish, *Lampanyctodes hectoris* and *Maurolicus muller*, supplemented by cephalopods and crustaceans with an increased representation of these animals in the diet over winter.

There have been a number of studies looking at spawning and recruitment of Gould's Squid. McGrath-Steer and Jackson (2004) reported continual year-round hatching, which may be a strategy to maximise the survival of offspring in variable environmental conditions. Further, Virtue *et al,* (2011) stated that "*although year-round spawning characteristics showed peaks in hatch date frequency distributions, large overlap in cohort structure coupled with their rapid response to changes in oceanographic and environment factors suggests that forecasting N. gouldi recruitment will remain challenging*". In the Great Australian Bight, spawning peaked in February (of 2008), but peaks were less distinct in Victoria (Virtue *et al.*, 2011).

Industry members (in a workshop on potential environmental drivers of recruitment and availability of fish stocks in south-east Australia) (Knuckey *et al.,* 2010) noted the following influences on squid catches:

- "Like to sit in front of eddies at the change from warm to cold water."
- "Best temperatures are 18˚C off Queenscliff and 16.5˚C off Portland. When temperature 14˚C and below, catches decline."
- "Good catches during years of strong westerlies."
- Seem to oscillate on 10yr cycle.
- Squid are dispersed by leatherjackets.
- Squid prefer warm water, so when thermocline is deeper and warmer water through the water column, they are more likely to be caught (by trawlers).
- Squid catches coincide with Mirror Dory catches (mirror dory feed on small squid).
- Year 2000 was a very poor year, with uncharacteristically calm winter and warm water (Portland, Queenscliff, King Island). The only cold water was in Hobart (Storm Bay in 2000).
- A very good year was 1996 when water was cold (jig), with trawlers also reporting larger than average shots in that year in 150–200 fathom. Could fish a very small area.
- Jig catches are more variable than trawl catches. Catchability variable (so can have high biomass and low catch rate on a day-to-day basis, so low catch one day, but high next day). Jig seems very variable and trawls more stable, but trawl only more stable across entire fishery, do see variability at any one location.
- Possible correlation with strong westerly's = good years.

- Squid also associated with areas of high krill abundance.
- Krill and squid possibly associated with the frontal index (change of warm and cold water).
- Strong food chain links identified, e.g. abundance of krill = more squid, mackerel, and other target species, but predicting when and where these events occur very difficult!
- Should look at frontal index and relationship to catches over time, noting for jig and east coast trawl, catches would generally correlate to availability. Like sitting on fronts/eddy edges.
- Locally, squid is a good indicator for presence of other quota species.
- Best catches of squid and all else when eddy hits shelf, when it leaves again everything else goes too.
- Dedicated Victorian squid fisheries do best in clear water.
- New South Wales flathead fishers find they can target squid in dirty water where they are feeding on juvenile cardinalfish.
- Eddies full of small forage (squid, mesopelagics).
- Noted Japanese and Korean squid fishers analyse thermoclines (when do they hit the bottom?) and salinity data and know how to fish them. The Korean's caught 7000–8000 t per year when they were allowed here.
- 4 days before and after the full moon gives the lowest catches.
- January/February typically medium sized, then March/April schools of very small squid 1000s tonnes, (but too small to be marketable); April/May jiggers seeing no big fish, but trawlers were picking up spent adults on the bottom.
- Discarding high as market gets swamped easily in GAB, not in the east (where all kept and landed).
- Good time series of catches and locations kept by jiggers, so compare with last 10 years of CSIRO Atlas of regional seas (CARS) environmental data to see if can find correlates or mechanisms.
- New machines and computerising to optimise jig method and depth to maximize catch.
- Possibly conditions at depth (not surface) determining where squid are.
- Maybe tied into couta biomass too - another component of a larger species complex that cue on the same signals?
- Squid are often associated with salps.
- Squid, redfish and flathead often both found booming simultaneously as all following same forage; so if forage there, all there.
- School shark are always full of redbait, mackerel, rubyfish, blue warehou, squid – associated with schools of bait.

  On the east coast — During the summer months when water warms, the jackets move in, and many other species such as squid, cuttlefish, flathead disperse – it seems the jackets just move in and displace everything else (shark, angel shark not impacted).

Life history of Gould's Squid

Gould's Squid are endemic to southern Australia and northern New Zealand, where they are considered oceanic and neritic species (Jackson and McGrath-Steer, 2003). They have been reported to occur in water temperatures ranging from 11–25˚C (Dunning 1998) and depths shallower than 500 m, although they are more commonly found at depths from 50–200 m (Uozumi, 1998).

Male Gould's Squid transfer spermatophores to the female's buccal cavity using a hectocotylus arm, and eggs are fertilized soon after being released from the oviduct (Green, 2011). Eggs are laid in a series of small clutches (McGrath and Jackson, 2002) into large egg masses of 1–2 m diameter that contain several thousand randomly-distributed eggs (O'Shea *et al.*, 2004). Egg masses are free floating and, while there is little information regarding the distribution of egg masses, eight of the nine "gelatinous squid egg spheres" reported in O'Shea *et al.* (2004) were found in no more than 30 m depth. Jackson and McGrath-Steer (2003) suggested that reproduction is similar among ommastrephid squid, and that egg spheres are released mid-water, potentially in the region of a pycnocline as described by Sakurai *et al.* (2000). Boyle and Rodhouse (2005; cited in Green, 2011) reported that egg spheres drift in oceanic currents, probably at a pycnocline. Laboratory experiments on eggs of the ommastrephid *Todarodes pacificus* revealed that egg masses were reliant on a thermocline (17–22°C) to maintain suspension and, where the temperature was uniform (22°C), egg mases settled on the bottom of the tank, collapsed and became infested with microbes (Puneet *et al.,* 2015). These eggs resulted in non-viable or abnormal embryos. This early stage of the life cycle may be particularly important to Gould's Squid given the influence of coastal oceanography in south-east Australia including the Leeuwin Current, East Australian current, and the Bonney Upwelling.

Citing Dunning (1985), Green (2011) reported that paralarvae that are 0.8–1.0 mm dorsal mantle length (DML) were caught throughout most of the geographic distribution of the adults, and that small squid (9–10 mm) are caught during summer months and are abundant at depths between 50–200 m.

In Australian waters, spawning of Gould's squid occurs year-round. Virtue *et al.* (2011) found that in the area of the GABTS, the greatest number of Gould's Squid hatch in February and, whereas periods of increased hatching were not as distinct as in Victorian waters, two cohorts were observed from May 2006 and May 2007 (although this may be due to low samples sizes during November 2006 – February 2007). From samples taken from the HistSJ, O'Sullivan and Cullen (1983) concluded that peak spawning occurred during December and January, but that spawning may extend over several months. Harrison (1983) found the timing of spawning of Gould's squid differed within Bass Strait and also in neighbouring Tasmanian waters: no defined spawning period was detected. Virtue *et al.* (2011) reported higher growth rates in Gould's Squid from Victorian waters compared with those from the GABTS. There were also differences in growth rates between sexes and hatch seasons. The range of mean growth rates for female and male Gould's Squid from Victorian waters was about 1.5 g/day–3.5 g/day and 1.6 g/day–3.1 g/day over 2006–2008.

Table 7. Summary of examples of environmental variables on squid fisheries reported in international literature.

Environmental variable	Response variable/s	Lag	Family	Species	Reference	Mechanism
SST	Landings and CPUE		Loliginidae	*L forbesi*	Pierce (1995)	Interannual variation in the strength of the Gulf Stream
	Landings		Loliginidae	*L forbesi and L vulgaris*	Robin and Denis (1999)	Link between mild conditions in the previous winter and cohort success in winter / spring spawning species
	Effort (where fishing effort can be considered an index of squid occurrence)		Ommastrephidae	*Ommastrephes bartramii*	Chen *et al.*, (2010); Yu *et al.* (2015)	Habitat suitability index was strongly associated with ENSO-induced variability in oceanic conditions
	Survey catches		Loliginidae	*L. pealei*	Brodziak and Hendrickson (1999)	Preference for intermediate temperatures
	CPUE		Ommastrephidae	*Nototodarus sloanii*	Kaot and Mitani (2001)	Higher when SST 16 deg in Feb, and <14deg in March
	CPUE		Ommastrephidae	*Illex argentinus*	Portela, *et al.*, 2005	highest CPUE found at temperatures between 14 to 15º C. No cause given
	Recruitment	-1 year	Loliginidae	*Loligo forbesi*	Challier *et al.*, 2005	Negative linear relationship between recruits and average autumn SST from the previous year. Mechanism unceertain
	Recruitment		Ommastrephidae	*Todarodes pacificus*	Isoda *et al.* (2005)	Years of poor recruitment were found to correspond closely to years of lower than normal SST in winter and spring. Mechanism uncertain
	CPUE	0 to -4-7 years	Loliginidae	*L. forbesi*	Pierce and Boyle, 2003 Zuur and Pierce, 2004	Potentially many – growth, transport… The link between temperature and squid catches is most likely to reflect effects on growth.
	CPUE		Ommastrephidae	*Dosidicus gigas*	Waluda, and Rodhouse, 2006	Spawning aggregation and hatching and development
Homogeneity of water temperature	Survey catches		Loliginidae	*Doryteuthis gahi*	Arkhipkin *et al.*, 2004	Late autumn homogeneity in temperatures from inshore to 200 m depths enables the spring-spawning squid to penetrate deeper into the Transient Zone Winter cooling of the Shelf Waters and formation of the warm water layer between 150 and 250 m depths in the Transient Zone restricts squid almost exclusively to this zone, their movement being limited by colder waters situated both shallower and deeper
Water temperature in general	Migration of spawning stock		Loliginidae	*Heterololigo bleekeri*	Sato, 1990	Move south as temperatures decrease (in northern hemisphere), and north as temperatures increase to optimum water temperature of 10–12C for spawning
	Fishing effort		Loliginidae	*Uroteuthis edulis*	Takahashi and Furuta, 1988	Optimum conditions and distribution of prey - fishing grounds were found to be at temperatures between 13 and 24C and salinities of 33.4–34.8% in winter
Water temperature gradient	Catch, effort and CPUE		Ommastrephidae	*Illex argentinus*	Waluda *et al.,* 2001a	An increase in squid abundance at mesoscale fronts may be related to an increase in food availability
	Catch per vessel		Ommastrephidae	*Illex argentinus*	Waluda *et al.,* 2001b	Temperature preference. High squid abundance associated with lower proportion of frontal waters or a high proportion of favorable SST waters
Wind	Recruitment		Ommastrephidae	*Todarodes pacificus*	Isoda *et al.* (2005)	Cold winters influenced by strong northwesterly winds were also associated with lower levels of recruitment. Creates currents that upset transport to feeding grounds
Bottom temperatures	Survey catches		Loliginidae	*L. pealei*	Brodziak and Hendrickson (1999)	Preference for intermediate temperatures
	Movement / aggregation		Loliginidae	*Loligo reynaudii*	Downey *et al.*, 2010	Initial formation of spawning aggregations appears to be triggered by upwelling events
	Peak survey abundance	Mean temp over previous 12 months	Loliginidae	*L. forbesi*	Sims *et al.*, 2001	Migrate earlier when its warmer – temperature-dependent movement, and that the mechanism was either that temperature acts as a cue to ensure occupation of preferable thermal habitat and / or as a response to available food
	Survey catches		Loliginidae	*Loligo vulgaris reynaudii*	Roberts and Sauer (1994)	"Preferred zone" with low bottom temperatures offshore (<8˚C) and low dissolved oxygen levels inshore (<3˚mg/l).
Sub-surface (5m) water temperature	CPUE	none	Ommastrephidae	*Illex argentinus*	Chang *et al.*, 2015	Various – larval survival, feeding, growth
DO	Survey catches		Loliginidae	*Loligo vulgaris reynaudii*	Roberts and Sauer (1994)	"Preferred zone" with low bottom temperatures offshore (<8˚C) and low dissolved oxygen levels inshore (<3˚mg/l).
Salinity	Fishing effort		Loliginidae	*Uroteuthis edulis*	Takahashi and Furuta, 1988	Optimum conditions and distribution of prey - fishing grounds were found to be at temperatures between 13 and 24C and salinities of 33.4–34.8% in winter
SOI	Annual catches		Loliginidae	*L. vulgaris reynaudii*	Roberts and Sauer (1994)	La Niña and El Niño events enhance winds from different directions, affecting water temperature and inshore turbidity, both influencing spawning behavior.
	Survey catches		Loliginidae	*Loligo vulgaris reynaudii*	Roberts and Sauer (1994)	Influences the conditions for preferred "preferred zone" and spawning conditions.
			Loliginidae	*Loligo opalescens*	Zeidberg et al	
Antarctic Oscillation (AAO)	CPUE	-2 years in some months	Ommastrephidae	*Illex argentinus*	Chang *et al.*, 2015	Indirectly through trophic linkages
NAO	CPUE		Loliginidae	*L. forbesi*	Zuur and Pierce, 2004	Thus a tentative conclusion, to account for the

						improved fit arising from including both NAO and SST in the model, is that both the inflow of Atlantic water (with associated nutrients, prey organisms and squid) and favourable growth conditions are important in determining abundance as measured by CPUE
	Peak survey abundance	Mean temp over previous 5 months	Loliginidae	*L. forbesi*	Sims *et al.*, 2001	Migrate earlier when its warmer, temp is related to NOA. temperature-dependent movement, and that the mechanism was either that temperature acts as a cue to ensure occupation of preferable thermal habitat and / or as a response to available food
Turbidity	Survey catches		Loliginidae	*Loligo vulgaris reynaudii*	Roberts and Sauer (1994)	Spawn offshore in years with dirty water – mechanism not understood
Swell	Survey catches		Loliginidae	*Loligo vulgaris reynaudii*	Roberts and Sauer (1994)	Spawn offshore in years with big swell, dirty water – mechanism not understood
Ocean colour / Chl A	CPUE		Ommastrephidae	*N. gouldi and N. sloanii*	Hurst *et al.* (2012)	None
	Effort (where fishing effort can be considered an index of squid occurrence)		Ommastrephidae	*Ommastrephes bartramii*	Chen *et al.* (2010); Yu *et al.* (2015)	Habitat suitability index was strongly associated with ENSO-induced variability in oceanic conditions
Sea surface height anomaly	Effort (where fishing effort can be considered an index of squid occurrence)		Ommastrephidae	*Ommastrephes bartramii*	Chen *et al.* (2010); Yu *et al.* (2015)	Habitat suitability index was strongly associated with ENSO-induced variability in oceanic conditions
Upwelling (SACW)	Catches		Loliginidae	*Doryteuthis plei*	Martins *et al.*, 2004	Upwelling events that concentrate small pelagic fish prey in different bays where these schools become available for local artisanal fishing

Trends in Arrow Squid catch, effort and catch rates

Logbook catch and effort reporting

Fishers in the CTS and GABTS are required to report their catch by species for every shot, whereas those in the SSJF record their catch for each day. Logbook catch weights are usually visual estimates, based on the fisher's experience and on the number of fish bins filled. The sizes of fish bins used varies between fisheries, within fisheries, and over time. Sometimes small catches of a particular species are not recorded until a fish bin has been filled (often considered to be about 30 kg for the CTS and GABTS – although this can be smaller to maintain quality). For these reasons, catches are often rounded to regular increments. In general, logbook catches are usually estimated and are lower than accurate landed weights.

Most common catch weight increments are similar in the CTS and GABTS, and in the SSJF and SJTas for catches of less than 100 kg (Figure 6). Catches are generally rounded to the nearest 5 kg for catches up to 30 kg, and every 10 kg thereafter. In the CTS and GABTS, 30 kg is over-represented reflecting the filling of a standard fish bin, whereas in the GABTS, 25 kg is also over-represented. This may be due to packing smaller bin weights to maintain quality during the typically longer trips (10–14 days). The HistSJ fishery appears to bin their catch into lots of 8 kg or 9 kg. Furthermore, fishers in each of those fisheries often round catch estimates to 100 kg. Large catches by the SSJF are most often reported in increments of either 100 kg or 160 kg (Figure 7). Most common catch weights were 800 kg and 1,000 kg. Historically in the SSJF, fishers packed squid into standard 30 kg bins, but to improve quality they have moved to 16 kg bins in the past 15 years or so to improve the landed condition (Ian Rule, pers. comm.). This practice is reflected in the data with obvious catch records at multiples of 16 for catches less than 100 kg (Figure 6), and for larger catches (e.g. 160 kg, 320 kg, 480 kg, 640kg…) (Figure 7).

There are several implications of these reporting practices for this project:

1. If rounding of catch estimates is consistently either downwards or upwards, then catches and catch rates will be lower or higher than the true value. However, if this negative or positive bias is consistent over time, then it will not greatly affect the results of this project, i.e. a negative or positive bias cancel each other.
2. Logbooks from fishers that don't report small catches until a bin is filled will result in false positives, potentially obscuring trends between environmental variables and catch / catch rates. This practice will also increase catch and catch rates for those shots where they were recorded.

All sectors report effort in hours fished (or start and end time). However, for most records of Danish seine shots (54%), hours fished is not recorded. Therefore, the unit of CPUE for the Danish seine sector throughout this report shall be kg per shot.

Catch by effort

Whereas large catches (>1000 kg) have been recorded for a wide range of shot durations in the CTS, median catch increased with shot durations up until 7 hours where the median catch was 60 kg (Figure 8). In the GABTS, median catches plateaued after about 3 hours at 54 kg but, after 7 hours, continued to increase with shot duration. Both the CTS and GABTS have a spread of outliers depicting large catches. Catches in the SSJF continued to increase over a greater fishing duration than the two trawl sectors. Median catch for 5 hours fishing was 213 kg, 1120 kg after 10 hours and 1696 kg after 13 hours. Unlike the trawl sectors, some of the outliers for the SSJF depicted low catches: unusually small catches were more common than unusually large catches. Catches by hours fished by the HistSJ were more similar to those of the SSJF than the trawl fisheries. However, median catches at low levels of effort were much higher in the HistSJ (e.g. 100 kg after 1 hour, compared with just over 10kg in the SSJF). Catch by hours fished was highly variable for the SJTas at low number of hours fished, but median catch was well above 1000 kg for 7–10 hours fished.

Gould's Squid are caught by a range of gear types in the CTS (Figure 9). Catch rates are highest for bottom otter trawl gear and catch per shot is lowest for Danish seine gear. Because of this large difference in catch rate data from these two gears will be separated throughout this report, and referred to CTS (otter trawl) and DS (Danish seine).

Interannual variability

Total annual catch reported in CTS daily fishing logbooks has fluctuated between about 220 t in 2014 and 880 t in 2003 (Figure 10). The period from 2000–2013 generally had the highest catches and, despite the large decrease in the number of vessels in the fishery during the mid-2000s, catches per shot of Gould's Squid appear to have increased, possibly because of reduced discarding or improved reporting. Total catch in the GABTS increased greatly from 40 t in 2002 to 162 t in 2003 after the entry of an additional four vessels into the fishery. Catches remained at more than 100 t until 2008 when the number of vessels in the fishery dropped to six, and catches have remained below 50 t per year since then. SSJF catches have been sporadic since logbooks were introduced in 1996. More than 2,000 t was caught in 1997, whereas less than 2 t was caught in 2014. Effort in the HistSJ was sporadic, peaking at more than 8,000 t in 1980, with the next largest catch recorded from 1985 at more than 2,000 t. Similarly, catches of Gould's Squid in the SJTas have been sporadic, with relatively high catches in 1999, 2007, 2013 and 2016, peaking at more than 900 t in 2013.

CPUE of Gould's Squid by the CTS appears to fluctuate over a 5–7 year cycle (Figure 11). Peaks in CPUE range from 20–30 kg/hr, whereas the troughs were about half that at 10–15 kg/hr. Similarly, catch per shot and less so CPUE by the GABTS appears to fluctuate on an 8–9 year cycle with the peaks and troughs often coinciding with those for the CTS. CPUE steadily declined from 1986 from just below 30 kg/hr (although only one vessel reported catches of Gould's Squid in that year) to about 6 kg/hr in 2000 (Figure 11). Peaks in CPUE ranged from 15–20 kg/hr, whereas the troughs range from 5–10 kg/hr. To a lesser extent, CPUE for the DS also appeared to fluctuate in 6–8 year cycles, roughly corresponding to those in the CTS. CPUE for the SSJF increased during the early 2000s, peaking in 2009 at about 250 kg/hr (Figure 11). CPUE has fluctuated since, between less than 50 kg/hr in 2014 to about 210 kg/hr in 2015.

Over time, the HistSJ increased CPUE as the knowledge of fishers and their understanding of the fishery developed. Whereas catches were greatest in 1980, when a large number of vessels were fishing, catch rates doubled to more than 200 kg/hr in 1984 when there were only 8 vessels in the fishery, and to about 250 kg/hr in 1985. The following year there was only one vessel operating, but CPUE peaked at 350 kg/hr. CPUE in the SJTas is generally low, but was relatively high during 2007, 2013 and 2016.

Within year variability

Availability and / or catchability of Gould's Squid is clearly seasonal (Figure 12). Mean monthly catch rates are generally highest from January to June, before declining to the lowest catch rates during winter and spring. As reported by Knuckey *et al.* (2001) the seasonality is more prominent in the SSJF data than in the trawl data where lowest average monthly CPUE was only 8% of the highest CPUE. By comparison, lowest average monthly CPUEs for the CTS and GABTS were 38% and 33% of the highest.

Seasonal cycles in mean monthly CPUE appear to have become more consistent in the CTS since the mid 1990s, with clear peaks and troughs in most years (at least in comparison to the 1990s) (Figure 13). This may be due to better reporting practices or more consistent retention of Gould's Squid, both of which would align the CPUE trend with seasonal changes to abundance. CPUE in the DS is lower than in the CTS, and seasonal cycles aren't as apparent in the data. In the GABTS there was a general declining trend in mean monthly CPUE during the late 1980s and early 1990s, but this stabilised throughout the rest of the time series. Reflecting the sporadic participation in the fishery, CPUE in the SJTas is highly variable, often with catches from only a few months per year. Very high CPUEs (>400 kg/hr) were observed for the SJTas in 2007, 2013 and 2016. In the SSJF, apart from the period from the mid 2000s to 2012, there has been a general trend of increasing peaks in mean monthly CPUE each year. During the late 1990s, highest peaks were less than 200 kg/hr, in the 2000s as high as about 350 kg/hr, and in the 2010s as high as 480 kg/hour and700 kg/hr.

Of particular interest to this project is that the timing of peak catches in any year appears consistent across the CTS, SJTas, SSJF and, less so, the DS: within a year, highest monthly CPUEs generally occur in the same month (Figure 13). This occurs despite most months of peak CPUEs varying considerably between years. **This suggests that the factors driving abundance and / or availability of Gould's Squid are consistent or linked between fishing areas. The alignment of peak CPUEs between the CTS and SSJF data focuses our attention on these two fisheries and, in particular, those areas where catches by both fisheries are high.**

The month in which the highest CPUE was recorded has become earlier in the year since 2004 in the CTS (Figure 14). Before 2004, the highest mean monthly CPUEs were in either May or June in 13 of the 18 years for which a complete 12 months of data were available. Since then, highest mean monthly CPUEs were in either February, March, or April for 9 of the 12 years for which a complete 12 months of data was available (note that data for December 2016 were incomplete). Direct comparison of CPUEs from periods before and since 2004 shows a relatively consistent trend of higher CPUEs since 2004 in January, February and March, and similar CPUEs in other months with the exception of Western Victoria, where CPUEs in May to November were much higher before 2004 (Figure 15). The difference in CPUEs between time periods was significant (F (1, 248,819) = 939, p <<0.0001), as was the interaction between time period and month (F (11, 248,819) = 152, p <<0.0001) and the three-way interaction between time period, month and zone (F (55, 248,819) = 19.3, p <<0.0001).

There has been a clear change in the seasonality of catch of Gould's Squid, particularly off Western Victoria.

A similar pattern was observed for DS CPUE (Figure 16). From 1986–2002, the month with the highest CPUE was January or February in only 3 of the 17 years. However, since 2003, either January or February has been the month with the highest CPUEs in 10 of the 14 years recorded.

Trends in mean monthly CPUE for GABTS data were less apparent, but there is a much smaller sample size in that fishery (Figure 17). Lowest mean monthly CPUEs were nearly always during July–August, whereas the highest CPUEs were most commonly recorded during January, April and May. Although significantly different (F (1, 27,236) = 25.1, p <<0.0001), the most obvious pattern of change was a general decrease in CPUE for most zones (Figure 18). The main exception was in the Far West where CPUEs have generally been much higher since 2004.

Apart from 1996–2000, there has been an almost complete lack of catch and effort data during July–November in the in the SSJF, HistSJ and SJTas (Figure 19, Figure 21, Figure 22). The distribution of months with the highest mean monthly CPUE in the SSJF is evenly spread across January–May. However, as for the CTS, the month with the highest mean monthly CPUE appears to have become earlier in the year over time. The differences in CPUEs before and after 2004 (Figure 20) were significant (F (1, 10,934) = 509, p <<0.0001). This was due more to a general increase in CPUEs, particularly in January of any year.

Variability with depth

Gould's Squid are reported from across a broad depth range to greater than 1000 m by the CTS. However, because of uncertainties regarding identification of squid caught at depths greater than 500 m, data presented have been restricted to 500 m depth (Figure 23). Most of the catch came from 175–375 m depth, whereas the depth from which most was reported was 75–175 m. CPUE was highest in depths from 175–375 m.

Danish seine gear is generally used in shallow waters on the continental shelf. Most catch and effort for Gould's Squid in the DS was recorded from two depth bands: 35–85 m and 115–155 m (Figure 24). CPUE generally increased with depth and, because of the reduced effort with depth, so did variability around the mean.

The GABTS mostly operates over a relatively narrow depth range. Accordingly, nearly all of the catch (> 70%) of Gould's Squid has come from depths 125–175 m (Figure 25). CPUE by the GABTS follows a similar depth distribution to the CTS, being highest at 275–325 m, decreasing at intermediate depths, and then becoming higher and more variable at greater depths.

The SSJF operates over the shelf and most catch and effort data are reported from depths 65–105 m (Figure 26). CPUE is relatively consistent over a greater depth range (45–155 m) although variability increases with depth across that range. The HistSJ generally fished shallower than the SSJF, with most catch and effort from 65–85 m (Figure 27). CPUE was relatively stable across a wide depth range but decreased with depth. Fishing in the SJTas was even shallower with most catch and effort reported from 35–55 m depth (Figure 28). As in other fisheries, CPUE was high at depths deeper than that where most of the effort is reported: to at least 105 m.

Depth distribution of CPUE is relatively consistent throughout the year in the CTS (Figure 29), although CPUEs in shallow (<200 m) and deep (>350 m) are much lower during May–September relative to other months. Sample sizes for Danish seine CPUE are very low for depths > 200 m, but CPUEs are higher than at shallower depths (Figure 30). In most months, CPUE increases with depth to 200 m. GABTS CPUE was patchy and variable and was highest at 275–325 m (Figure 31). CPUE was evidently higher at greater depths from January to March for the SSJF. However, samples size was small and variability high at depths greater than 100 m. In most months, CPUE increased with depth to about 100 m (Figure 32). CPUE in the HistSJ was relatively even across depths in most months, except for March and April when CPUE was consistent to about 90 m then decreasing with depth (Figure 33). Some SJTas fishers operate deeper (>50 m) during December, January and March, but effort was generally restricted to 10–50 m in other months (Figure 34).

CPUE in the CTS appears to have increased in depths 275 m–375 m since the early 2000s relative to shallower depths (Figure 35). Before then, highest CPUE (apart from "deepwater outliers") was from depths 200 m to 250 m. Highest CPUEs in more recent years have been in the depth categories 250 m to 350 m. There appears to be no clear patterns in CPUE with depth over time in the DS. However, in some years CPUE was higher at depths 55–75 m or 135–165 m (Figure 36). Disaggregated to depth and year, sample sizes from the GABTS were too small to reveal patterns in catch by depth over time. However, the depth distribution over which Gould's Squid was reported has narrowed since 2007. This is more likely to be a result of changed fishing practices, reduced number of operators, and a reduction in fishing effort (Figure 37). Before 2002, catches in the SSJF were commonly recorded from depths less than 40 m, albeit by a relatively small number of operators. However, records at those depths have been rare since then (Figure 38). There appears to be no consistent patterns in CPUE with depth over time in the SSJF data. The distribution of CPUEs by the HistSJ varied across depths among years (Figure 39). In the first few years of operation in the HistSJ, CPUEs were generally low across all depths and, as CPUE increased in 1979 and 1980, CPUE decreased with increasing depth. In 1984 and 1985, high CPUEs were recorded across depths of 50–140 m. Before 2007, catches of Gould's Squid were generally recorded from depths 60 m or less. However, the depths fished expanded in later years, with high CPUEs in 60–90 m depth during 2010 and 2013 (Figure 40)

Catches of Gould's Squid by the CTS are getting deeper.

Importance of moon-phase and diel periods

Fishers in the SSJF report catch and effort in a daily logbook with no information on start or end times. Thus, the effect of diel period cannot be assessed for that fishery. Similarly, no start or end fishing times were provided for HistSJ and TasSJ data.

Whereas it appears that mean catch per shot and CPUE were highest during the dawn period in the CTS and then decrease throughout the day and night (Figure 41), the data are positively skewed: more so for the dawn and day period. Examination of logged data reveals the differences aren't large but they are significant ($F (3,248959)=147.7$, $p < 0.0001$). Post hoc analysis reveals that all combinations of diel period were significantly different from each other. Log CPUEs were significantly different between all diel periods for the DS ($F (3,17945)=126$, $p < 0.0001$) and the GABTS ($F (3,27376)=273.5$, $p < 0.0001$). However, for those two sectors, mean CPUEs recorded during dusk and night were clearly higher than those recorded during dawn and daytime (Figure 41).

Overall, moon phase had a small but significant effect on catch rates (CTS: $F(7,248,955)=13.8$, $p < 0.0001$; GABTS: $F(7,27,373)=26.2$, $p < 0.0001$) CPUEs were higher during full and last quarter moon phase (Figure 42). Moon phase had a much greater effect in the squid jig fisheries, being lowest during the full moon and waning gibbous (HistSJ: $F (7,9,558)=13.8$, $p < 0.0001$; SJTas: $F (71,890)=4.1$, $p < 0.001$; SSJ: $F (7,10,947)=35.8$, $p < 0.0001$). Mean CPUE in the HistSJ was about 100 kg/hr during the full moon compared with about 150 kg/hr during the waxing crescent and, for that sector, CPUE was not as affected by the waning gibbous as were the SJTas and SSJF (Figure 42). In the SJHist, mean CPUE during the waning gibbous was about 125 kg/hr and more than 200 kg/hr during the waning crescent. The lowest mean CPUE in the SSJF was during the waning gibbous at about 85 kg/hr compared with 165 kg/hr during the first quarter.

CPUEs in the trawl fisheries were highest during the waning gibbous and full moon, but lowest during those moon phases in the squid jig fisheries. This is likely due to an increase in availability of squid to trawl methods caused by reduced diel vertical migration during those moon phases.

When fishing around the moon with squid jig gear, avoid the waning gibbous like the full moon.

The effect of moon phase on CPUE is different depending on the diel period (Figure 43). Moon phase made very little difference to shots that started during dawn, daytime or dusk in the CTS (less than 5% difference between highest and lowest mean CPUEs). However, mean CPUEs during the new moon in night shots were 17% lower than on the full moon. In the CTS, shots beginning during dawn and the day have the highest CPUE during the last quarter, and lowest during the first quarter. Mean CPUE at dusk decreased from the full moon through the cycle to the first quarter.

In the GABTS, mean CPUE from dawn and day shots were highest in the last quarter, and lowest on the new moon (19% and 28% lower respectively) (Figure 43). Mean CPUE of dusk shots was highest on the full moon and decreased to about 7.4% of full moon CPUE on the new moon. Mean CPUE of night shots shows a similar pattern to that of the CTS: highest on the full moon and about 15% lower at the lowest mean CPUE on the new moon.

Interaction between times of the day and year, month and depth

There was a diurnal effect on seasonal catch rates in the CTS, peaking in May for dawn and day shots, and in February for dusk and night shots (Figure 44). Mean CPUEs were higher in dawn shots for most of the year. Mean CPUEs in day shots were similar to those from dusk and night shots until April when they increased and followed a similar trajectory to dawn shots. The pattern is different in the GABTS where mean CPUEs were highest in the first four months of the year in night shots, at a time when mean CPUE from dusk and particularly day shots were relatively low (Figure 44). Mean CPUE peaked in either April for dusk and night shots, and in May for dawn and day shots. During winter, mean CPUEs declined at a similar rate. Mean CPUEs for the GABTS began increasing earlier in the year than in the CTS, with December night CPUEs reaching close to those recorded in January.

Time of day magnified the effect of depth on mean CPUE in the CTS at intermediate depths, and much less so in the GABTS (Figure 45). In the CTS, mean CPUE was similar at different times of the day in the shallows (less than 175 m). However, from 175–425 m, mean CPUE was much higher in dawn and day time shots. In the GABTS, mean CPUE was higher from 225–325 m in dawn shots and from 275–475 m for day shots.

Results support the hypothesis that differences in trawl catch rates between daylight and night fishing is likely to be a function of surface feeding migration characteristics.

Interaction between moon-phase and month

The effect of moon phase is greatest in the CTS from January to July (Figure 46). Overall, the effect is inconsistent between months and this is likely due to the interaction effects of time of day. Considering night time shots only, mean CPUE was highest on the full moon during all months apart from April, August, and December. There were no consistent trends in CPUE by month and moon phase in the DS (Figure 47).

In the GABTS, mean CPUE on the new moon and last quarter followed similar seasonal trends, increasing to a peak during April, and decreasing to lowest values in September (Figure 48). Mean CPUE for the full moon and first quarter remained steadier from January through to May. Similar trends were observed when just considering night shots. However, mean CPUE on the full moon consistently decreased from January to August of any year.

Moon phase makes the greatest difference to mean CPUE in the SSJF from January to July (Figure 49). Mean CPUE was much lower, but increased, during the full moon and waning gibbous from January to May. Mean CPUE decreased sharply during the first quarter in June, and less so for the other moon phases. In the following month, mean CPUE decreased steeply for all moon phases. Highest CPUEs during February–June were recorded from the waxing crescent, first quarter, and waxing gibbous. The highest CPUE in January was recorded during the last quarter.

Highest mean CPUEs by the HistSJ in January were during the waning crescent and last quarter. However, from February to April, highest CPUEs occurred during the first quarter and waxing crescent (Figure 50)

Because of the lack of data, the effect of month and moon phase on CPUEs in the SJTas fishery is difficult to interpret (Figure 51). However, apart from in January, CPUEs are generally lower on the full moon, higher in December during the new moon and waning crescent, and highest during March on the waning crescent and last quarter.

The SSJF Fishery should target the waxing crescent, first quarter and waxing gibbous to get the highest CPUEs.

Interaction between moon-phase and depth

Moon phase had little effect on the trend in mean CPUE in shallow depths in the CTS (Figure 52). However, from 200 m depth, moon phase appears to have some effect. At 250 m depth highest CPUE was recorded during the waning gibbous, whereas lowest catch rates were recorded during the waxing gibbous. At 300 m depth the CPUE during the waning crescent was much higher than for other moon phases. For night shots only, highest catch rates on the continental shelf were during the waning gibbous and full moon, and on the waxing gibbous at depths 200–250 m. Knuckey *et al.* (2001) found a strong influence of moon phase on catches from depths of 150–350 m, with the highest catches taken during the new moon and last quarter. As for the interaction between diel period and moon phase, their results were not as expected, leading them to suggest that patterns in squid catches are driven by more than just the availability of light. Our results support this in that moon phases corresponding to highest CPUEs included the new moon, waning crescent, the last quarter, and the waning gibbous.

There was less effect of moon phase on CPUE by the DS and no consistent trend was evident from the data (Figure 53). Disaggregation of the GABTS data into moon phase and depth revealed high standard errors (Figure 54). However, mean CPUEs at different moon phases were similar at depths 75–225 m, and relatively high on the full moon from 225–325 m.

Mean CPUEs recorded for the SSJF and SJTas were generally highest around, or just before, the new moon at most depths and lowest around the full moon (Figure 55). CPUEs were low at most depths on the waning gibbous. However, at depths greater than 110 m in the HistSJ and depths of 40 m and greater in the SJTas, CPUEs during the wanning gibbous were relatively high. Where there is a difference (e.g. at 30 m, 80 m and 90 m) highest CPUEs were recorded during the full moon, followed by the last quarter and waning gibbous.

Variability in the catches of squid with geographical position of fishing

About 32% (more than 5,000 t) of the total Gould's Squid catch recorded in CTS logbooks was taken in each of the New South Wales and Western Victoria zones, whereas 23% (about 4,200 t) was caught in Eastern Victoria (Figure 56, and Figure 57). Despite the large catch in Western Victoria, total effort (where Gould's Squid was caught) was lower there than both New South Wales and Eastern Victoria resulting in a much higher CPUE in that zone of about 38 kg/hr (Figure 57). CPUE in New South Wales, Eastern Victoria and Eastern Tasmania ranged from 14–28 kg/hr, whereas Bass Straight had the lowest CPUE at about 7 kg/hr. Mean shot duration ranged 3–4.5 hrs in all zones except for Bass Straight, where it was about 2.3 hrs.

Most effort in the DS is from Eastern Victoria and Bass Strait. That is where most (44% and 47% respectively) of the Gould's Squid was caught (Figure 56). Catches were more evenly spread across the GABTS, with most of the catch coming from the zones Central 2, Central 1, West 1 and West 2 (Figure 56 and Figure 59). In the SSJF, 68% of the catch was from the South-West Victoria zone and 21% from Central Victoria (Figure 56) and, except for South-East King Island where only a small amount of fishing occurred, mean CPUE is highest from the South-West Victoria zone (Figure 60). The HistSJ focused largely on the Central Victoria and South-East King Island zones, and highest CPUEs were recorded from Central Victoria, South-East King Island, South-West Flinders Island, and South-Western Victoria (Figure 61). A total of 43% of the HistSJ catch came from Central Victoria, whereas 22% came from South-East King Island (Figure 56). About 92% of the catch of Gould's Squid by the SJTas was from the east coast (Figure 56).

If there is a need to focus on one region to look at influence of environmental variables, use Western Victoria

There was considerable seasonal variation in catches (Figure 63) and CPUE (Figure 64) of Gould's Squid among zones in the CTS. In the New South Wales and Western Victoria zones most of the catch was taken during May when CPUE was also highest. Catches and CPUE peaked earlier in the year in all other zones. CPUE in the eastern zones begins increasing earlier than in the western zones, showing considerable increases in December from the months with the lowest CPUEs. Seasonal patterns in catch and CPUE by zone for the DS and GABTS are shown in Figure 139 to Figure 142).

Most of the catch by the SSJF in Central Victoria and South-East King Island was taken in February and March, whereas for Western Victoria the greatest catches were taken in April and May in Western Victorian and May in Eastern Victoria (Figure 65). CPUE was also higher earlier in the season in Central Victoria and South-East King Island and, whereas CPUE was low in January in Western Victoria, it was very stable across February to June (Figure 66).

The HistSJ did not fish throughout the year: most of the catch was reported from January to March (Figure 67). Most of the catch from Western Victoria was taken in January when the CPUE was highest (Figure 68). Most of the catch from Central Victoria, South-East King Island, and South-West Flinders Island was taken in February and March. CPUEs were highest in those months for South-West Flinders Island and South-East King Island. The monthly distributions of catch by the HistSJ in the year of the greatest catch (1980) are shown in Figure 69 to Figure 71. The greatest catches during January came from off Anglesea to Apollo Bay, Cape Otway, east of King Island, and north-west of Strahan (Tasmania). Large February catches came from off Apollo Bay and Burnie (Tasmania). In March, the greatest catches came from far western Victoria, east and north-east of King Island, and George Town (Tasmania). Large catches were also taken from east of King Island and off George Town (Tasmania) during April, and south-east of King Island in May.

Annual CTS catches off New South Wales were regularly greater than 200 t until 1994, after which catches decreased to about 100 t before increasing again to greater than 400 t in 2000 (Figure 72). Catches in the New South Wales zone of the CTS have generally decreased and have been about 50 t per year since 2014. CPUE has been variable off New South Wales, with the highest CPUEs coinciding with the highest catches (Figure 73). CPUE increased and remained steady after 2003 at just below 20 kg/hr but increased again in 2012 and 2013. Total catches in Western Victoria were generally low (about 100 t or less) up until 2001 when the annual catch tripled, and remained above 150 t until 2014, when catches decreased below 100 t. CPUE has generally remained between 20–30 kg/hr but reached nearly 60 kg/hr in 2003. Overall, catches in Western Victoria appear cyclic, with peaks in 1995, 2003, 2007 and 2011. The first three of those years coincided with very strong, strong, and weak upwelling events on the Bonney Coast respectively. However, there was no significant upwelling event in 2011, and there were many upwelling events in between when catches were relatively low (Figure 72). Similarly, there appears to be no consistent trend between CPUE and upwelling events (Figure 73). Catches in Western Tasmania appear to follow a similar annual trend. There are also some similarities in CPUE between the Western Tasmania and New South Wales zones of the CTS. Both catch and CPUE of Gould's Squid have increased in Eastern Tasmania since about 2006. Total catch in Eastern Victoria peaked in about 2001 and has slowly decreased to about a third of that level. CPUE has remained steady over that period at about 12 kg/hr but was as high as 23kg/hr in 2013. There has been a general decline in the catch of Gould's squid in the New South Wales and Eastern Victorian zones of the CTS, and an increase in the Eastern Tasmanian zone of the CTS over the same period.

Annual catch and CPUE by zone for DS are shown in Figure 143 and Figure 144. Catch and CPUE in the GABTS also appears to be cyclic at a frequency of about 7 or 8 years and coincides with the annual trend in catches from Western Victoria (Figure 67). This can be seen in most of the zones shown.

The small number of operators and haphazard nature of fishing in the SSJF results in a lack of temporal trends in catch data by zone (Figure 76). SSJF CPUE from South-West Victoria and Central Victoria vary considerably (Figure 77). CPUE was regularly greater than 200 kg/hr in South-West Victoria but was greater than 20 kg/hr only during 2008 in Central Victoria. High CPUEs have sporadically been recorded from other zones. There appears to be no consistent relationship between upwelling events on the Bonney Coast and the catch or CPUE in the SSJF off South West Victoria.

The HistSJ increased their fleet size and range of areas fished during 1997 to 1980 when they fished in nearly every zone in the fishery (Figure 78). Substantial catches were reported from nearly all zones fished in 1980, including about 3,500 t from Central Victoria alone by 66 different vessels. This catch was about 1,500 t more than has ever been caught by the SSJF in all zones in any one year. CPUE in Central Victoria in 1980 was about 160 kg/hr. In 1986 and 1987, when only small numbers of vessels were operating in the fishery, CPUEs were more than 350 kg/hr (Figure 79).

Peaks and troughs in catch and CPUEs from the CTS in Western Victoria and the GAB occur in same years. A possible driving factor is the strength of the Leeuwin Current.

There was no apparent influence of the Bonney upwelling on catch or CPUE in the CTS or SSJF.

Are there similar trends in CPUE and total catch between fisheries and zones?

Standardised CPUE has undergone a steady decline off New South Wales and Eastern Victorian in the CTS and DS sectors, and the DS sector in Bass Strait (Figure 80, Figure 81). This decline has been reversed in both zones of the DS sectors since 2000–2005 and has slowed in the CTS since those years. CPUEs from the CTS off Eastern Victorian and New South Wales show a high positive correlation ($r=0.90$, $p<0.001$), whereas CPUE from the DS off Eastern Victoria is correlated with CPUEs from the CTS off Eastern Victoria ($r=0.69$, $p<0.001$), New South Wales ($r=0.76$, $p<0.001$), and less so off Eastern Tasmania ($r=0.38$, $p<0.05$). There was no such correlation for the SSJF in Bass Strait or Western Victoria, or the CTS in Western Victoria. CPUE of the SSJF off Western Victoria was not strongly correlated with CPUE of the CTS fleet for that zone. Despite these results, cluster analysis revealed similarities in CPUE trends between the CTS and SSJF in Western Victoria which included a larger sub-group with the neighbouring Bass Strait zone for the SSJF and DS (Figure 83). Not surprisingly, the CPUEs from the CTS and DS in New South Wales and Eastern Victoria were also grouped.

Standardised CPUEs declines off New South Wales and Eastern Victoria during the 1990s and early 2000s.

Total catches have increased over time in the CTS and DS sectors in many zones resulting in a strong positive correlation between sectors and zones (Figure 82). Fleets without consistent trends over time show inflection points in the mid 2000s either reversing the direction of the trend from upwards to downwards, or continuing the downward trend after a period of stable catches (e.g. CTS New South Wales). This result coincides with a reduction in the fishing fleet through the 2005 Structural Adjustment Package. Positive correlations in total catches between main areas of each sector include the CTS of Eastern Tasmania and Western Victoria ($r=0.43$, $p<0.05$), CTS of Eastern Tasmania and DS in Bass Strait ($r=0.40$, $p<0.05$), CTS of Eastern Tasmania and DS in Eastern Victoria ($r=0.44$, $p<0.05$),and in Bass Strait and Eastern Victoria, the CTS of Eastern Victoria and Western Victoria ($r=0.50$, $p<0.004$), the CTS of Eastern Victoria and DS off Eastern Victoria ($r=0.43$, $p<0.013$), the CTS of Western Victoria and DS off Eastern Victoria ($r=0.54$, $p<0.002$) and the SSJF of Eastern Victoria and SSJF off Western Victoria ($r=0.47$, $p<0.05$). Catches have consistently declined in the CTS off New South Wales, and there was a negative correlation between the total catches there and those from the CTS in Eastern Tasmania. Because of its generally increasing trend over time, catch by the DS sector off Eastern Victoria has high positive correlations with the other fleets. As with CPUE, the catch of SSJF off Western Victoria was not strongly correlated to the CTS fleet for that zone, possibly because of the sporadic nature of the fishery.

Total catches have generally increased in the main areas of trawl and DS sectors resulting in many strong correlations.

Effects of environmental data on Arrow Squid standardised CPUE

The final model for all zones of the SSJF sector combined included zone, depth, and the interaction of depth and moon phase (Table 8). Year was the greatest source of variation (15.1%). Vessel was omitted from CPUE standardisations in the SSJF sector because it was highly correlated with year ($R^2 = 0.82$ $p<0.0001$) caused by an inconsistency in the way vessels were identified in the data provided. The SSJF data were provided from two different databases, with the older "legacy" data containing boat code numbers, and the more recent data boat names. Zone had little effect on CPUE throughout most of the time series, increasing it in 2004 and decreasing it in 2012 (Figure 84). The inclusion of depth in the model decreased CPUE in most years, whereas the interactions of depth and moon phase increased CPUE in most years.

The final model for the CTS (all zones combined) included year, zone, month, vessel name, depth and the interaction of depth and diel period (Table 9). Boat name (8.5%) and depth yielded the greatest improvement on the model. Both zone and then boat name lowered CPUE overall, but the addition of depth increased CPUE across most of the time series (Figure 85).

Final models for the SSJF sector in Western Victoria and Central Victoria were similar to that for all sectors combined (Table 10). Differences are the addition of month and lack of PC1 to the model from Central Victoria, and the addition of moon phase to that from Western Victoria. Final models for each zone in the CTS sector were also similar to all sectors combined, with month, boat name, and depth in all final models. Diel period was retained in the final model for Eastern Tasmania, whereas the depth and moon phase interaction were also retained in the Eastern Tasmanian model. PC2 was retained in the New South Wales model. Standardisation of CPUE for DS in Bass Strait was overly influenced by data from one vessel (Table 20 and Figure 151), and so that factor was omitted. The final model included month, moon phase, diel period, diel period and moon phase interaction, the diel period and depth interaction, and the depth and moon phase interaction. Data from the DS from Eastern Victoria did not have the same effect of boat names as for Bass Strait, and so that factor was retained. The model for the SJTas sector — which was filtered to include only the East Coast zone — included month, boat name, PC1, depth, moon phase, and the moon phase and depth interaction. The final model for the GAB included month, boat name, PC2, zone, depth diel period and the interaction of depth and moon phase.

Both SST and Chl a were added to the final models reported in Table 10. SST (L3S - 06 day composite - night time) and Chl a (SRS - MODIS - 01 day - Chlorophyll-a concentration) were matched to shot locations based on position and dated. Mean values from a 5 km buffer around those areas were extracted to reduce dropouts.

The addition of SST and Chl a-standardised CPUEs made no appreciable difference to the CPUEs of any zone or sector (Table 14 to Table 22), improving the deviance by at most 0.97% with the addition of SST to the final model for the SSJF in Central Victoria. The addition of Chl a to the final model for the DS in Eastern Victoria improved the deviance by at most 0.9%, and the addition of SST to the final model of the CTS in Eastern Tasmania improved the deviance by 0.7%.

Given the high degree of seasonality in measured environmental variables, it is likely that in models where month was included, the effect of their inclusion was masked by month. For models that didn't include month, the seasonal contrast was greatly reduced by the filtering of months with low CPUEs.

There is no evidence of a direct effect of SST or Chl a data on a shot to shot basis.

Influence of a thermal gradient

The influence of a thermal gradient on CPUE was examined by comparing mean monthly CPUE between shots with a thermal gradient with those shots without (a definition of the thermal gradient used is described in the methods). Where there appeared to be a consistent trend across months and there were sufficient data, the differences between means were compared with 2-way ANOVAs. After examination of a range of transformations, data were logged to conform with the assumption of normality. However, normality of data could sometimes not be achieved. Normality and heteroscedasticity were examined using diagnostic plots and Bartlett's test, or Levene's test where the data were not normally distributed. Deviations from normality and homogeneous variances are indicated in footnotes. Because of the heteroscedasticity, a more conservative p-value of 0.01 was used. Tukey's post hoc test was applied to examine the direction of the difference.

Mean CPUEs from the SSJF were generally higher in shots with no thermal gradient (Figure 86). CPUEs were significantly higher for no thermal gradient off Eastern Tasmania (F (1, 136) = 15.3, p = <0.001) and Western Victoria (F (1, 6478) = 26.0, p = <0.001)[1] but there were no significant differences at the p=0.01 level for Central South Australia (F (1, 333) = 4.7, p = 0.031)[2]. Mean CTS CPUEs were also higher in shots where no thermal front was identified in Bass Strait (F (1, 3825) = 8.4, p = 0.004)**Error! Bookmark not defined.**, New South Wales (F (1, 64872) = 6.0, p = <0.001)**Error! Bookmark not defined.** and higher for a thermal gradient for Eastern Victoria (F (1, 66884) = 9.0, p = 0.003)**Error! Bookmark not defined.** (Figure 87), but surprisingly not for Eastern Tasmania (F (1, 14934) = 3.4, p = 0.066) **Error! Bookmark not defined.**. CPUEs between the presence and absence of a thermal gradient were similar in all months and zones for the GABTS, except in some cases where large error bars indicate low sample sizes (Figure 88). CPUEs were significantly higher for no thermal gradient in the zone West 1 (F (1, 4533) = 8.0, p = 0.005)**Error! Bookmark not defined.** but, whereas data were normally distributed and diagnostic plots showed homogeneity, Bartlett's test revealed variances were heteroscedastic. CPUEs in the presence and absence of a thermal gradient for DS are shown in Figure 89. Shots with no thermal gradient appeared to have a higher CPUE for Eastern Victoria, but this difference was not significant, (F (1, 6943) = <0.3, p = 0.582)**Error! Bookmark not defined., Error! Bookmark not defined.**.

Results suggest that CPUEs are highest in the absence of a thermal gradient.

Influence of a Chl a gradient

Comparisons of CPUE between gradients in Chl a were also examined for zones and months in which there were sufficient data (the effect of month was excluded where both treatments were not present). Any observed differences were analysed with 2-way ANOVAs. As for the SST analyses, after examination of a range of transformations, all data were log transformed. However, violations of assumptions of normality were common and could not be rectified using other transformations. There were no clear and consistent differences in CPUEs between SSJF effort undertaken in the vicinity of a Chl a gradient, and SSJF effort undertaken not in the

[1] Deviated from normality

[2] Deviations from homogeneous variances

vicinity (Figure 90). In the two zones from which the most catch was taken, mean CPUEs appeared identical in each month. CTS zones on the east coast of Australia had higher CPUEs in shots not in the vicinity of a thermal gradient including Eastern Tasmania ($F(1, 10576) = 10.6$, $p = 0.001$)Error! Bookmark not defined., New South Wales ($F(1, 30400) = 236.4$, $p = <0.001$)[2] and Eastern Victoria ($F(1, 34684) = 19.9$, $p = <0.001$)Error! Bookmark not defined.. Low sample sizes resulted in high variability in GABTS CPUEs and there no effect of a Chl a gradient was apparent (Figure 92). Opposite to the CTS CPUEs from Eastern Victoria, DS CPUE was higher in the presence of a Chl a gradient ($F(1, 5035) = 26.6$, $p = <0.001$)Error! Bookmark not defined.,Error! Bookmark not defined., although the data failed to meet the assumptions of normality.

Catch and CPUE by SST

Seasonality in SST was similar among most locations, usually with a maximum SST in February and a minimum in August for Southern New South Wales, Eastern Victoria and Bass Strait, or September for the other locations (Figure 94). The area of the Bonney Upwelling stands apart from the other locations with lower than expected (compared with the nearby Western Victoria SST) SST from January to March coinciding with the summer upwelling. The amplitude is generally 5–6˚C for most areas, but only about 2.5˚C for the Bonney Upwelling area. From May to November, the mean SST was higher at the area of the Bonney Upwelling than nearby Western Victoria, but the SST off Western Victoria was warmer from December to April.

Mean CTS CPUE was generally highest at SSTs of 19–21˚C in Eastern Tasmania, New South Wales and Western Tasmania (Figure 95), whereas off Eastern Victoria highest CPUEs were recorded at 23˚C, and at 16˚C in Bass Strait. CPUEs were relatively stable across the range 15–20˚C of Western Victoria, peaking at 16˚C. The peak CPUE at 16˚C is consistent with comments made by an industry member during the project of Knuckey *et al.,* (2010). Dunning (1998) reported Gould's Squid occurring in water temperatures ranging from 11ºC to greater than 25ºC. However, it appears that this is a general statement regarding the sea surface temperature throughout their range of latitudes across eastern Australia — "*In eastern Australian waters, adult N. gouldi have been caught between 27°13'S and 43°40'S where sea surface temperatures varied from 11° C to over 25° C*". Whereas most of the catch in the CTS has been taken between that range (Figure 96), there were about 370 records across all fisheries with a SST of less than 11˚C, including about 150 records at less than 10˚C. The coldest SST observed was 6.4˚C on 2/6/2013 while fishing in the CTS at a depth of 166 m.

Notably, there are many zones where CPUEs generally increase with SST. The highest CTS CPUEs occur at SSTs higher than those most frequently encountered. This is particularly the case for Eastern Tasmania, Eastern Victoria, and Western Tasmania, and for New South Wales (Figure 95). In Western Victoria, peak CPUEs coincided with most frequent SSTs but CPUEs were still relatively high at unusually high SSTs.

Distributions of significant catches of Gould's Squid across the temperature range was more contracted than for the SST range of high CPUEs (Figure 96). Except for western Victoria and eastern Tasmania, there was a clear pattern indicating a preference towards warmer SSTs than where most fishing effort was undertaken.

For Western Victoria, CPUEs were higher in January at SSTs 17–19˚C (Figure 97). CPUEs were also relatively high at 14–15˚C in January as well as in the following four months. From August to October the SST coinciding with peak catches decreased from 13˚C to 11˚C, generally lower than those SSTs most frequently encountered.

In accordance with the seasonality of the Gould's Squid fisheries, CPUEs increased with SST at the start of the season (Figure 98). Mean SST at shot locations appear to have increased over time, particularly in Western Victoria and Eastern Victoria. Detrended water temperature observations off Portland (SST Lines Western Victoria) appear to show a general increase in SST after about 1998, particularly in peak temperatures (Figure 99). Overall, there was a positive and significant (monotonic) ($S = 706$, $p<<0.001$) trend over time, with a slope of 0.026 (Table 11). No significant change point was detected ($p=0.104$) for the whole times series (Table 11). There was also a significant positive ($S = 708$, $p=<<0.001$) trend over time in Eastern Victoria with a slope of 0.027 (Figure 102, Table 12). As for Western Victoria, no significant change point was detected ($p=0.231$) for the whole times series (Table 12).

The increase in SST over time was more apparent in Western Victoria considering each month separately (Figure 101). Mann-Kendall tests showed significant positive trends for January ($S=94$, $p=0.021$), April ($S=112$, $p=0.006$) and June ($S=88$, $p=0.031$) (Table 11). The largest monotonic slope was from January (0.051). A significant change point was only detected for January ($KT=95$; $p<0.05$) with the change point occurring in 2005. Off Eastern Victoria, positive trends were shown for January ($S=94$, $p=0.021$) and November ($S=110$, $p=0.007$) with a monotonic slope from January of 0.053. The only significant change point observed was from November 2003 ($KT=109$; $p<0.05$).

The pattern of CPUE across SST was different for the SSJF than for the CTS (Figure 102). Of the main SSJF zones, CPUE only showed an increase with SST in the Bass Strait zones (Central Victoria, South-East King Island, and South-West Flinders Island). In Eastern Victoria the maximum CPUE (200 kg/hr) was in shots from 16˚C, decreasing to half that level for SSTs ≥ 18˚C. CPUEs were highest at 17˚C in Western Victoria, 18˚C from Central South Australia, and 21˚C from Central Victoria. In most zones, catch and effort follow the same trends across the range of SSTs (Figure 103). Whereas CPUEs are relatively high across a range of SSTs, most of the catch and effort are recorded from a much narrower range of SSTs (Figure 103). In South West Victoria, nearly all of the catch was taken from fishing in SSTs of 15–17˚C. Off Central Victoria most of the catch was from waters with SSTs of 18–19˚C.

In Western Victoria CPUEs were highest at 18–19˚C in February (Figure 104). CPUEs were relatively steady over the SST range of 16–20˚C in March and 15–18˚C in May.

Figure 105 shows that SSJF CPUEs from Central Victoria were generally high (>200 kg/hr) with SST of about 20˚C in December–February. Except for an increase in SST and CPUE in the early months of the year, no other clear patterns were evident in the time series of monthly CPUE over SST.

CPUE in the DS in Bass Strait was relatively steady at 5–7 kg/shot over the range 15–20˚C (Figure 106), but decreased at lower temperatures to about 2.5 kg/shot at 12˚C. The distribution of catch and effort shows that the catch in waters with SSTs of 18–19˚C was disproportionally higher relative to effort (Figure 106). CPUE off Eastern Victoria increased with SST from 12˚C peaking at 18˚C, and remained relatively high from 18–21˚C. As in Bass Strait, catch was disproportionally high relative to effort at higher temperatures. As for CPUE, catch in Bass Strait and Eastern Victoria was disproportionately higher at warmer SSTs relative to fishing effort (Figure 107). The monthly time series clearly show highest CPUEs occurred at times of highest temperatures (at least since the mid-1990s in Bass Strait and off Eastern Victoria) (Figure 108). However, high summer temperatures don't necessarily result in high CPUEs (for example 2014) (Figure 108).

Apart from SSTs with a low number of records, highest CPUEs in the GABTS were recorded from 18–21˚C and lowest CPUEs at 14–16˚C (Figure 109). The distribution of catch followed effort in the three eastern zones (East, Central1 and Central2). However, as for other sectors, catch in the three western zones (West1, West2 and Far West) was over represented at higher temperatures relative to effort (Figure 110). No consistent trends appear in the time series of monthly CPUE over SST (Figure 111).

CPUEs are higher at higher SSTs, but whether that is because of increased catchability / availability, or just the seasonal effect is unclear. The pattern is somewhat different in Western Victoria.

Catch and CPUE by Chl a

Chl a in Southern New South Wales and off the two Tasmanian locations (Storm Bay and Maria Island) fluctuate at relatively low levels during summer and autumn and increase to a peak during spring (Figure 112). Chl a in the area of the Bonney Upwelling peaked in February at just over 1.1 mg/m^3, but from May to the end of the year was less than 0.5 mg/m^3. Data from Western Victoria showed similar trends from the Bonney Upwelling area, but lagged by one or two months, and mean monthly Chl a fell to below 0.25 mg/m^3 during December and January. Chl a was highest during autumn and winter in Bass Strait and Eastern Victoria.

There is a general trend of decreasing CTS CPUE with increasing Chl a (Figure 113). This can easily be explained for the locations that have highest Chl a levels coinciding with months of low CPUEs (e.g. New South Wales, Tasmania). However, for other locations, high Chl a levels were observed during months of high CPUEs. This was particularly the case for Western and Eastern Victoria. The distribution of catch across Chl a reflects effort and most of the catch comes from shots undertaken in waters with a Chl a of about 0.25 mg/m^3 (Figure 114).

CPUEs off Western Victoria by the SSJF were highest at very low levels of Chl a (0 – 0.125 mg/m^3). However, this may be because in some years peak CPUEs occur in January (Figure 19) and that is the month with the lowest mean Chl a level. (Figure 115). As in the CTS, the distribution of catch across Chl a follows that of effort, and most of the catch comes from shots undertaken in waters with a Chl a level of about 0.25 mg/m^3 (Figure 116).

Although highest CPUEs by DS in Bass Strait were in waters with 0–0.125 mg/m^3 Chl a from a small number of shots, there was a small increase in CPUE from just below 5 kg/ shot at about 1.25 mg/m^3 Chl a to about 7.5 kg/shot at 2.25 mg/m^3 Chl a (Figure 117). The distribution of catch by the DS sector follows effort over the range of Chl a measured in most zones (Figure 118). The range of Chl a levels over which Gould's Squid are caught by the DS is greater than that from other sectors. This is likely due to the DS fishing closer to shore where the effects of run off on nutrient levels and therefore Chl a levels are greater.

CPUEs in the West2 and Central1 zones of the GABTS were highest at 0.75 kg/shot (Figure 119). However, there was very little effort recorded at that Chl a level (Figure 120). Most catch and effort data were recorded from locations with Chl a levels of about 0.25mg/m^3. However, relatively large catches of Gould's Squid have been taken in waters with Chl a levels of 0–0.125 mg/m^3), particularly in the Eastern Zone.

Results suggest that CPUEs are highest in the absence of a Chl a gradient in the CTS in three zones.

Influence of a El Nino and La Nina

No consistent annual trends between standardised CPUE and La Nina and El Nino events were observed whether in the year the data were recorded, or the previous year (Figure 121). Medium to strong La Nina and El Nino events were recorded in the same years as both peak and trough CPUEs spanning periods of increasing and decreasing CPUE. From the start of logbook collection in the CTS in the mid-1980s, there was a consistent decrease in CPUE off eastern Australia which coincided with regular periods of moderate to strong El Nino events. Unfortunately, the time series of CPUE for the SSJF is too short to examine this declining trend.

Annual CPUE against monthly environmental variables

CPUE of the CTS in Western Victoria were weakly correlated with a range of environmental variables, but not particularly strongly with any of them (Figure 122). Chl a and current strength appear to be the two variables that correlate well in terms of strength of correlation, correlation across different measures, and across multiple months. Chla_Lines_WV and to a lesser extent Chla_Lines_BU had a negative correlation with CPUE from July to October with a -1 year lag (as large as R = -0.65), whereas the correlation for ChlaSeaWIFS was strongest in the first half of the year with a -1 year lag. However, there was a relatively strong positive correlation (R=0.50) between Chla_Lines_WV in April and CPUE with no lag. The various measures of current strength also correlate strongly with CPUE both with a -1 year lag and no lag. TotVel_BU was positively correlated with CPUE for most of the -1 year lag, except for June which had a negative correlation (of about -0.4). The correlation between TotVel_BU in April with no lag and standardised CPUE was R = 0.52, and UCUR_WV was also correlated with CPUE in the same month. The strongest correlation between TotVel_WV and CPUE was October with a -1 year lag of R = 0.60. NINO was consistently positively correlated with CPUE (except standardised CPUE) from June with a -1 year lag through to mid-way through the fishing season, whereas SOI was negatively correlated with CPUE from May with a -1 year lag to January, and then in April and May with no lag.

There were strong correlations between ChlaSeaWIFS, ChlaLines_BU and ChlaLines_WV in August or September and CPUE by the SSJF in Western Victoria (Figure 123). The highest correlation (R = 0.59) between TotVel_BU and CPUE was in April with a -1 year lag. UCUR from both the Bonney Upwelling area and off Western Victoria were positively correlated with CPUE over winter and spring for the former, and autumn and winter for the latter, and both also during the fishing season. The correlation between OT_HB and CPUE oscillated between positive and negative on a 1–3 month cycle. The highest correlation was in September with a -1 year lag (R = 0.69). TPI was negatively correlated with CPUE in the year of the fishery in January (R = 0.52) and positively correlated in April (R = 0.60).

EDSeaLevel in February to March with a -1 year lag and no lag showed moderate correlations with CPUE by the CTS in Eastern Victoria (Figure 124). Chla_Lines_EV was moderately and positively correlated with CPUE from May–July with a -1 year lag, negatively from October to November with a -1 year lag, and then positively correlated during January and June in the year of the fishery. Furthermore, the strongest correlation with CPUE by the CTS in Eastern Victoria was with Chla_Lines_EV in December with a lag of -2 years (R = 0.63). The strongest correlation between TotalVel_EV and CPUE was in December with a -1 year lag (R = 0.53). OT_HB was correlated with standardised CPUE in December with a lag of -1 years. SST_Lines_EV was negatively correlated with CPUE from February to July with a -1 year lag, positively correlated in the following 6 months, and then negatively correlated in March, April, and May in the year of the fishery. TPI was most strongly correlated with CPUE during June with no lag (R = 0.48).

Correlation between environmental variables and CPUE by the DS in Eastern Victoria was similar to the CTS CPUE. However, the differences in correlations between the standardised CPUE and log mean and mean CPUEs were greater (Figure 125). EDSeaLevel was correlated with CPUE from March to May with a -1 year lag (as high as R = 0.82) and no lag. Chla_Lines_EV was positively correlated with CPUE over winter with a -1 year lag and negatively correlated over spring with a -1 year lag. However, the highest correlation was in June with no lag (R = 0.69). There were relatively high correlations between TotVel_EV and CPUE in a number of months including March with a -1 year lag (with standardised CPUE only, R = 0.65), September with a -1 year lag (with mean CPUE and log mean CPUE, R = 0.53), and in March with no lag (with standardised CPUE only, R = 0.53). The differences in correlations between the three indices of CPUE were greatest for UCUR_EV, with positive correlations for standardised CPUE and negative for the other two indices. OT_HB was strongly correlated with standardised CPUE in January with no lag (R = 0.77) and with mean CPUE in February with no lag (R = 0.53). As for the CTS in Eastern Victoria, TPI was strongly and positively correlated with mean CPUE in June with no lag (R = 0.79), and moderately negatively correlated with standardised CPUE in the same month (R=0.50).

CPUE from the CTS off Eastern Tasmania was positively correlated with Chla_Lines_TSB in June with no lag (R = 0.55), and less so with Chla_Lines_TMI in May (R = 0.47) with no lag (Figure 126). LogTemp_50 m was strongly correlated with CPUE in June and July with a lag of -1 year (R = 0.68 and 0.61 respectively), and in June with no lag (R = 0.73). CPUE data showed strong positive correlations with both TotVel and UCUR from both the TSB and TMI locations across most months, particularly September with a lag of -1 year (R = 0.58) and February with no lag (R = 0.55) for TotVel_TMI, September (R = 0.69) and December (R = 0.62) with a lag of -1 year for TotVel_TSB, April (R = 0.49) with a lag of -1 year and January (R = 0.48) and April (R = 0.49) with no lag for UCUR_TMI, and January (R = 0.70) and February (R = 0.69) with a lag of -1 year for UCUR_TSB. VCUR at both locations was consistently and negatively correlated with CPUE, particularly in January (R = -0.73) and February (R = -0.73) with a lag of -1 year and May (R = -0.66) and June (R = 0.65) with no lag for VCUR_TMI, and May with a lag of -1 year (R = -0.68), and April – June with no lag (R = -0.69– -0.71). SST_Lines_TMI most strongly correlated with CPUE in November with a -1 year lag (R = 0.55), and less so March to June in the year of the fishery. SST_Lines_TSB correlated higher with CPUE during April (R = 0.60) to June (R = 0.41) with no lag.

As for the DS in Eastern Victoria, there were differences in correlations between the standardised CPUE and log mean and mean CPUEs (Figure 127). There were strong positive correlations between standardised CPUEs and Chla_Lines_TMI in June and July with a -1 year lag (R = 0.61 and 0.57), but strong negative correlations with standardised CPUE in April with a -1 year lag (R = -0.63) and with log mean CPUE in March and April with no lag (R = -0.58 and -0.49). For Chla_Lines_TMS there were also strong positive correlation with standardised CPUE in winter, but stronger still in April and June with no lag (R = 0.63 and 0.74). LogTemp_50m had a strong positive correlation with CPUE in September with a -1 year lag (R = 0.76) and April and June with no lag (R = 0.54 and 0.87), but a strong negative correlation in other months. As for the CTS, CPUE (except standardised CPUE) was positively correlated with TotVel and UCUR from both locations, and negatively correlated with VCUR. The strongest correlation with currents was a positive correlation with TotVel_TSB in December with a -1 year lag (R = 0.75). OT_HB was strongly correlated with standardised CPUE in January with no lag (R = -0.77). SBSeaLevel was strongly correlated with mean and log mean CPUE March and April with a -1 year lag (R = 0.67 and 0.64) and again in March – May with no lag (R = 0.41 and 0.64). There were also strong negative correlations with standardised CPUE in January with a -1 year lag (R = -0.66) and no lag (R = -0.66). There were strong positive correlations between SST_Lines_TMI and CPUE from March to June with no lag (R = 0.49 and 0.53), and April to June for SST_Lines_TSB (R = 0.73 and 0.54). TPI was strongly correlated with CPUE in June with no lag (R = 0.79).

Timing of highest CPUE

Based on the analysis presented in the previous section, environmental variables that correlated strongly with CPUE were chosen to examine the influence on the seasonality of CPUE — specifically the month in which maximum CPUEs were observed in any season. Because lowest CPUEs in all fisheries occur in late winter to early autumn we define the fishing season as running from October to September. For analyses, we recoded months to best fit the seasonality of the fishery, with October = 1 and September = 12. For simplicity we refer to the year of the season in which January falls, and so the lag of -1 year is the previous year.

Previous sections of this report have shown that there has been a general shift in the timing of peak CPUEs to earlier in the season. This is particularly the case for the CTS in Eastern Victoria, Western Tasmania, and Western Victoria (Figure 129) and the SSJF in Central Victoria (Figure 130).

Although there were no strong correlations between the timing of peak CTS CPUEs in Western Victoria and SST or Chl a, there were with the various measures of current strength and Portland sea level (Table 13). Correlations were particularly and consistently strong towards the end of the year with a -1 year lag, and at the start of the year of the fishing season. Correlations were nearly all negative, meaning that the stronger the current (or higher the Portland sea level) the earlier in the year CPUEs peak.

However, SST and Chl a were correlated with the timing of peak SSJF CPUEs in Western Victoria, particularly across a range of months for a -1 year lag (Table 13). Measures of current also correlate with the timing of peak SSJF CPUE in Western Victoria, but this result was inconsistent between months, lags, and measures.

A literature review describing squid jig fishing techniques and practices.

The Technology of Squid Jigging Fisheries

Almost half of the world's squid production is from jig fisheries (Roper and Rathjen, 1991, Arkhipkin *et al.*, 2015). Jigging (an oscillating lure attached to a line) was developed in Japan more than 1000 years ago to catch squid (Murata, 1983). Since then, Japan has continued to develop operating systems for squid jig fisheries with several technical innovations relevant to the Southern Squid Jig Fishery (SSJF). Most of the literature relating to operational matters for squid jig fishing techniques is published in the Japanese language literature. Those relevant studies with English language abstracts are summarised here, together with other research relevant to squid jig fishing techniques.

The Southern Squid Jig Fishery (SSJF)

Commercial fishing in the SSJF is concentrated in waters off Bass Strait near Portland targeting Gould's Squid (Knuckey *et al.*, 2001; Jackson *et al.*, 2005). Vessels operate at night equipped with lights to attract prey (e.g. krill) and squid. Squid are caught with automatic jigging machines operating lines with barbless lures in depths ranging from 60 to 120 m (Knuckey *et al.*, 2001; McKinna *et al.*, 2010). Most commercial vessels operating in the SSJF use up to 10 jigging machines, each with two lines with 20–25 jigs per line (Patterson *et al.*, 2017).

Fishing Technology

Squid jigging relies on two inputs: fishing lights to attract squid and automated squid jigging machines to lure and catch squid (Seafish Industry Association, 1985). Thus, apart from the presence or absence of squid, there are many variables which influence squid fishing success:

- Hauling power and speed;
- Jigging speed and span or length;
- Jigging timing in relation to span or length;
- Depth or distance from bottom;
- Sensitivity when hauling (to take into account vessel surface movement)
- Jig colour
- Light intensity
- Light wavelength.

These variables are evaluated below.

Jigging machines

Automatic squid jigging machines typically use a hexagonal drum which provides the jigging motion of the lure (jig) that attracts the squid (McKinna *et al.,* 2010). Jigging efficiency increases with the number of jigging machines (Araya, 1983). Jigs typically consist of rings of barbless stainless-steel prongs that are attached to a plastic base or stem. This forms a lure and a catching device. Jigging simulates the movement of primary prey species and attracts squid after which they are caught on the barbless hooks.

Squid catching efficiency varies with hauling drum speed with optimal catches within 20–110 rpm) (Mikami *et al.*, 2001). Jigging velocity (the oscillatory movement of the lure) is also influenced by the shape of the hauling drum: hexagonal drums have a higher jigging velocity than nonagonal drums (Mikami *et al.,* 2001). High hauling speeds can cause squid loss through tentacle breakage (squid seize the lure with their tentacles) (Kurosaka *et al.,* 2013). Catch rates are maximised by controlling the upward jig speed at about 2 m/sec for large squid (> 35 cm) and at 1.5 m/sec for smaller squid (Kurosaka *et al.,* 2013). Controlled hauling speeds minimise dropout rates of squid. Vessel movement can also cause loss of squid with significant wave height/wind causing boat rocking (Yamashita *et al.*, 2008). Modern automatic jigging machines can adjust for load (and partially compensate for vessel movement) (Mikami *et al.*, 2001, Kurosaka *et al.,* 2013), and can be programmed to different patterns to optimise searching and targeting at depth. For example, the Belitronic BJ5000[3] has a program that allows setting at a maximum depth then reducing the depth by a specified amount each set until it reaches a minimum depth where it will fish until reset (Figure 133).

Jig type

Colour of the lure or jig can be important. Red coloured jigs reportedly out fish other colours in fishing for *Illex* squid (Aldrich, 1991) and European Squid (*Loligo vulgaris*) on the Middle Eastern coast of Aegean Sea (Ulaş and Aydin, 2011), but green coloured jigs outperformed red lights for European Squid (Altinagac, 2006). Even so, green light and, particularly, red light are mostly absorbed in surface waters (Kirk, 2011) so it is unclear how red or green coloured lures are more attractive to squid than other colours. In any case, the available literature suggests that jig colour is not a major source of variation in squid catch rates. Although Ulaş and Aydin (2011) found that red jigs caught more European Squid, there was no effect of color on mantle length.

Light

Catches of squid are best in calm clear water (Arakawa *et al.,* 1998, Jackson *et al.,* 2005, Choi, 2006). There is a negative correlation of catch rates with Chl a most likely due to reduced transparency of the water column (Postuma and Gasalla, 2010). Particles in the water reduce transparency by scattering light and by selectively absorbing blue light (Kirk, 2011). Thus, conditions of high productivity responsive to prey and squid abundance (e.g. Gonzalez *et al.,* 1997; Cao *et al.,* 2009; Cochrane *et al.,* 2014; Zhang *et al.*, 2015; Ralston *et al.,* 2018) may have a negative effect on squid catch rates. For the SSJF, catches are mostly in depths ranging from 60–120 m (Nowara and Walker, 1998, Knuckey *et al.*, 2001, McKinna *et al.*, 2010). Catch rates for *N. gouldi* are highest around the new moon (Nowara and Walker, 1998, Knuckey *et al.*, 2001) perhaps because of higher light penetration, but also because of increased diel vertical migration. Similarly, calm conditions (and low turbidity) are most conducive to high catch rates probably because of higher light penetration (from the vessel's light array).

[3] http://www.belitronic.se/bj5000/manual/engelsk.pdf

Light quality

Squid are particularly responsive to blue light with retinal adaptation to blue light wavelengths (Jeong *et al.*, 2013). As blue light penetrates deeper than light of other wavelengths, lights which emit blue light may be expected to attract more squid compared with other wavelengths (Inada and Ogura, 1988). However, squid are primarily attracted to prey which are attracted by lights on fishing boats (Matsushita and Yamashita, 2012). Once attracted to prey, squid will assemble in the shadow cast from the fishing vessel and attack prey from within the shadow zone (Seafish Industry Authority, 1985; An and Jeong, 2011). Squid catching efficiency varies with light of different colours (Arimoto, 1991, An *et al.,* 2009, Postuma and Gasalla, 2010): blue light penetrates further to the depths where squid are primarily targeted (60–120 m). However, light intensity rather than quality appears to be a more important source of variation in squid catch rates (Matsushita *et al.*, 2012, Yamashita *et al.*, 2012).

Light quantity

Light source output on squid vessels is a major energy cost (Paulino *et al.*, 2015). LED panels reduce fuel consumption and have good directivity of light emission (Matsushita *et al.*, 2012). However, LED lights can reduce catches (Park *et al.*, 2016) possibly because they are less intense than metal halide lights (Yamashita *et al.*, 2012). As squid are primarily attracted to prey (which are attracted by lights on the fishing vessel), once squid schools are close to the boat, it may not be necessary to have strong lights (Matsushita and Yamashita, 2012). Stage reduced lighting (including LEDs) can lead to greater catches (Matsushita and Yamashita, 2012). Metal halide lamps have a high efficiency and an excellent color rendering [4]

Underwater lamps

The effectiveness of vessel mounted lights reduces at depth, with background light, moon light, and in dirty water. Deployment of an underwater light can reduce the effect of these factors by putting the light source at the depth of the squid, and leading them up the water column to the vessel mounted lights (Figure 134). As the squid get closer to the vessel mounted lights, the underwater light is dimmed so that they become more attracted to them. An example of such a system is the SWSY series which offers three different systems (http://www.takuyo-riken.co.jp/eindex.html). We found no research documenting the effectiveness of underwater lights.

[4] http://www.dkicorp.com/goods_309.html#goodsview

Discussion

The Southern Squid Jig Fishery operates in three distinct water masses: East Australia, Bass Strait, and the GAB[5]. These water masses are subject to factors which influence coastal oceanography (particularly wind, salinity, temperature, ENSO) and therefore squid distribution and abundance. Off eastern Australia, squid populations are influenced mainly by the southerly-flowing east Australian current. Bass Strait is a discrete locally-formed oligotrophic water mass (Fandry, 1981; Gibbs *et al.,* 1986, 1991). Its shallow depth limits mixing and currents are mainly tide and wind driven with occasional intrusion of nutrient rich water from the sub-Antarctic and localised upwelling events off King Island (Fandry, 1981, Middleton and Bye, 2007). The Great Australia Bight/Western Victoria is mainly influenced by the easterly flowing extension of the Leeuwin current with a subsurface (~ 600 m) westerly flowing Flinders current. However, the major influence on the fisheries ecology, particularly off Western Victoria, is upwelling which generally occurs in summer off the Bonney Coast and, to a lesser extent, Kangaroo Island (Middleton and Bye, 2007). Upwelling considerably increases nutrients, phytoplankton and zooplankton in surface waters. SSJF fishers observe high squid abundance associated with high krill abundance. Even so, our analyses show no apparent influence of the Bonney upwelling on catch or CPUE in the SSJF. This may be because of catchability factors or, as discussed below, variables that influence growth and survival are confounded with variables that influence prey availability.

The SSJF, unlike other sectors which operate in the area of the Southern Squid Jig Fishery (Trawl and Danish seine), is spatially focused with most catches off Western Victoria. Only seven boats operate in the fishery (Patterson *et al.*, 2017) and the SSJF is relatively new. Furthermore, effort in the SSJF is spatially and temporally sporadic, resulting in a lack of a consistent time series of catch and effort data. Thus, the data available for evaluation of targeting in the SSJF is limited compared with the other sectors operating in the fishery. However, our analysis of available data and our review of the relevant literature provides insights into sources of variation in catch and catch rates and implications for targeting in the SSJF. As a short-lived species, squid are highly variable in abundance and responsive to environmental factors. Yet these factors interact and other sources of variation e.g. catchability are also important in determining catch rates of squid (including Gould's squid).

Recruitment patterns in squid are influenced by the availability of spawning grounds and food availability (Cabanellas-Reboredo *et al.,* 2012; Alabia *et al.,* 2016a). Altered hydrographic conditions (e.g. temperature, currents) may affect the stock during egg development, hatching, juvenile development, migration, sexual maturity, or spawning; all of which affect recruitment of squid (Chen *et al.*, 2006; Guerra *et al.,* 2010; Cao *et al.*, 2009; Paulino *et al.,* 2016). Relationships between squid populations, food, and mesoscale oceanographic features and the links between these features and larger scale oceanography e.g. ENSO, may assist in forecasting

[5] The International Hydrographic Organization defines the eastern boundary of the GAB as a line from Cape Otway, Victoria to King Island and thence to Cape Grim, the northwest extreme of Tasmania.

recruitment (Gonzalez *et al.,* 1997; Yu *et al.,* 2017). Thus, our observed correlation of squid abundance and SST may be more reflective of nutrient availability and the association of prey species both for paralarval and adult stages. Further to this, water temperature (SST) could potentially effect Gould's Squid in several ways:

- larval survival, feeding, growth (e.g. Chang *et al.*, 2015 for *Loligo pealei*).
- Migration of spawning stock following warm water (e.g. Sato, 1990 for *Heterololigo bleekeri*, Virtue *et al.*, 2011 for Gould's Squid).
- Increased recruitment (e.g. Isoda *et al.*, 2005 for *Todarodes pacificus*).
- Increased growth (e.g. Virtue *et al.*, 2011 for Gould's Squid).

However, given the interaction among factors affecting the early life stages of squid, it is difficult to predict recruitment based on a single factor e.g. SST. Even so, Waluda *et al.,* (2001) showed that 55% of the variability in recruitment of *Illex argentinus* could be explained by variation in SST in spawning grounds during spawning season (see also Cao *et al.,* 2009).

The El Nino Southern Oscillation (ENSO) is the strongest signal in the interannual variation of the ocean-atmosphere system with its cycle of warm (El Nino) and cold (La Nina) climate phases occurring over a 3 to 4-year period. ENSO events have a demonstrable influence on recruitment rates of *Ommastrephes bartramii* (Chen *et al.,* 2007; Cao *et al.,* 2009) and *Loligo opalescens* (Reiss *et al.*, 2004). ENSO events influence Australian coastal oceanography particularly the East Australian current and the Leeuwin current (Middleton and Bye, 2007). For the SSJF, El Nino events considerably attenuate shelf currents during winter. During summer the thermocline is raised by about 150 m (Middleton and Bye, 2007). These hydrological processes may be expected to influence squid abundance. However, ENSO events have little apparent influence on squid catches or catch rates in the SSJF. For example, one of the strongest El Nino events occurred in 1997/98 (Furnas, 2007) yet there was no obvious effect on the SSJF. In other regions, warm conditions and increased upwelling linked to salinity fronts increases squid abundance (Waluda *et al.,* 2004, 2006). Similarly, in cool conditions, reduced upwelling decreases squid abundance (Waluda *et al.,* 2006). Very low catches occur during extreme El Nino conditions possibly because squid are forced offshore away from the fishing fleet (Waluda *et al.,* 2006).

Other hydrological factors can influence squid abundance (including vertical migration patterns). The early life stages of *Ommastrephes bartramii* occur mainly in surface waters (the upper 25 m) (Cao *et al.,* 2009). The highest abundance of paralarvae of loliginid squid occur in nearshore areas associated with retention mechanisms caused by local circulation, seasonal upwelling, the intrusion of nutrient rich waters, and spawning peaks (Rodriguez and Gasalla, 2008; Araujo and Gasalla, 2018). Lower water temperatures decrease the growth rate and extend the duration of early life stages of squid (McInnis and Broenkow, 1978). These findings are consistent with catch data for Gould's squid off Western Victoria: catches are highest in warm water during summer.

The link between currents, upwelling (and associated variation in temperature) is important in influencing squid abundance. The confluence of oceanic currents linked to upwelling events provides for productive aggregations of squid (*Ommastrephes bartramii*) in the northwest Pacific (Cao *et al.,* 2009; Wang *et al.,* 2010; Yu *et al.,* 2016a). Horizontal and vertical temperature (particularly between 0 and 50 m) gradients also influence the spatial dynamics of *Ommastrephes bartramii* (Yu *et al.,* 2016a). Variation in the abundance of *Illex argentinus* has been shown to be associated with thermal gradients associated with different water masses e.g. between major water currents or current and shelf waters. Squid accumulate at these fronts for feeding (Waluda *et al.,* 2004, 2008; Yu *et al.,* 2016b). Such patterns appear generally applicable to squid (Arkhipin *et al.,* 2015) and consistent with the observations of squid fishers in the Southern Squid Jig Fishery (this report). Yet, different oceanographic processes operate north and south of the equator. The presence of meso-scale upwelling (or cells) may be important in accumulating squid and their prey (e.g. Gonzalez *et al.,* 1997; Cao *et al.,* 2011; Cochrane *et al.*, 2014; Zhang *et al.,* 2015; Ralston *et al.,* 2018). Fishers in the SSJF observed that high squid catches were often associated with ocean fronts (e.g. eddies off the continental shelf).

For the SSJF, given the localised area of operation, ENSO and other large-scale oceanographic events may be less important than localised upwellings (e.g. the Bonney upwelling near Portland). Upwellings introduce cold, nutrient-rich waters to surface waters resulting in localised areas of high productivity (characterised by high chlorophyll a, and abundant prey species e.g. krill). Climate change may influence local oceanography (including the frequency and intensity of local upwellings, and the strength of prevailing boundary currents) (McInnes *et al.* 2009). Changes in local hydrology may also be influential in squid population abundance (e.g. by affecting transport mechanisms). As discussed above, mesoscale events (including linkage of upwelling events and local currents) are key drivers of squid abundance patterns. Currents will influence paralarval dispersal and survival. Survival of paralarvae may be reduced if they are transported to areas with unfavourable environmental conditions (Rodhouse *et al.*, 2014). Similarly, high upwelling could reduce abundance of squid through increased offshore transport of squid (e.g. Anderson and Rodhouse, 2001). There is some evidence that migration patterns of Gould's Squid favour movement towards shallow water for females during spawning (e.g. Wilcox *et al.,* 2001). However, the available literature for Gould's Squid suggests that movement/migration patterns are inconsistent and not attributable to any particular life history event (Stark, 2008). Instead, Gould's squid aggregate below 50 m depth probably in response to available prey, but also in response to the occurrence of predators and/or competition with other squid (Stark, 2008).

Although there is not much information available on short-term horizontal movements of Gould's Squid, they are known to undertake vertical migrations during the night to feed (Nowara and Walker, 1998; Jackson and McGrath-Steer, 2003). Nowara and Walker (1998) suggested that differences in catch rates between daylight and night fishing is likely a function of surface feeding migration characteristics, and our data support that hypothesis. A mixed-layer depth created by a strong thermocline may encourage Gould's Squid to migrate vertically to feed. Hatfield and Cadrin (2002) found that diel vertical migrations were influenced by seasonal stratification in the water column — diel effects on CPUE were larger when the water column was thermally stratified compared with a well mixed water column. For the SSJF, de Boyer Monte´gut *et al.*, (2004) showed a cycle of shallow mixed layer depth during summer (20–40 m depth), decreasing from March to minima of 100–125 m (or 150 m in the case of

Tasmania) in June. This is consistent with our observed seasonal variation in catch rates: rates tend to be highest in summer at depths 60-120 m (see also Knuckey *et al.* 2001).

Frontal regions are often associated with nutrient rich waters, resulting in concentrations of plankton and nekton (Olson *et al.*, 1994), predators including finfish (Reddy *et al.*, 1995), and squid (Waluda *et al.*, 2001a). Squid may also follow the feed layer as growth increases with water temperature (particularly in the build up to spawning) or as the mixed layer depth gets closer to the sea floor (see Pethybridge *et al.* (2011) for Gould's Squid). Similarly, seasonal variation in the abundance of teleost prey species of Gould's Squid occurs particularly for those species known for nocturnal vertical migrations (Kaartvedt *et al.*, 1998; Prosch, 1986).

As squid are visual predators they are more likely to inhabit the interface of clear low-productive water and highly productive, low-visibility waters to feed (Waluda *et al.*, 2001a). However, squid may also be associated with warmer waters favourable for post-spawning growth Waluda *et al.* (2001b). Ocean fronts (e.g. opposing currents, eddies, sea features) may act as a barrier to squid egg mass and paralarval transport. Thus, warm water encourages growth and survival of squid. Cold water is often associated with nutrient rich surface water and high prey availability. Such conditions, particularly during summer, reduce water clarity therefore squid tend to aggregate at ocean fronts. This is consistent with fisher observations for the SSJF. Yet, because of this, given the spatial resolution of the data, there is no clear signal for chlorophyll a, SST, and squid CPUE evident in our analyses.

Dominant currents on the eastern southern coast of Australia effect larval retention differently. Condie *et al*. (2011) found that the East Australian Current forms a barrier to onshore transport, and is effective at transporting shelf waters offshore, particularly where the current separates from the coast. However, they also found the Leeuwin Current system across southern Australia "*promotes onshore transport through the combined effects of mean onshore flow and eddy-induced mixing*". Thus, whereas the East Australian Current may help a species maximise dispersion of eggs and larvae, the Leeuwin Current may assist with retention of the same. Wayte (2012) suggested that an increased East Australian current decreased recruitment of Jackass Morwong off eastern Australia through reduced nutrient supply, reduced concentration processes (e.g. ocean fronts, water column stability) and reduced larval retention rates. Our findings support the potential increased retention of Gould's Squid by the Leeuwin Current with a positive correlation between the easterly component of the current off eastern Australia with a lag of -1 year and CPUE. However, a negative correlation between the northerly component of the current off eastern Australia with a lag of -1 year and CPUE would suggest that an increased East Australian Current would also increase availability or catchability of squid.

Our results show that standardised CPUE for squid has declined off eastern Australia. The short lifespan of Gould's Squid means that prolonged unfavourable environmental conditions have the potential to reduce abundance for multiple generations (Noriega *et al.*, 2015). The addition of SST and Chl a made very little difference to standardised CPUE in the SSJF. It is likely that the interaction of these factors with others (e.g. catchability) masks spatial and temporal trends as discussed above. For example, growth and survival of squid is increases with SST but lower SST in summer is associated with high productivity (i.e. chlorophyll a, reflecting seasonal upwelling off Western Victoria). High chlorophyll a and associated secondary productivity increases water turbidity (Postuma and Gasalla, 2010) and therefore catches (through reduced light transmittance for SSJF vessels). Particles in the water reduce transparency by scattering light and by selectively absorbing blue light (Kirk, 2011). Thus, conditions of high productivity responsive to prey and squid abundance (e.g. Gonzalez *et al.,* 1997, Cao *et al.,* 2009, Cochrane *et al.,* 2014, Zhang *et al.,* 2015, Ralston *et al.*, 2018) may have a negative effect on squid catch rates in the SSJF. Fishers in the SSJF note that catches of Gould's Squid are highest in clear, calm water (see also Jackson *et al.*, 2005) as they are for other species of squid (Arakawa *et al.*, 1998, Choi, 2006).

Compared with other sectors in the fishery, the interaction of light and fishing activity is important. As the SSJF operates at night with powerful lights to attract squid, lighting is an important determinant of catches (McKinna *et al.,* 2010). Fishers in the SSJF generally operate in new moon periods from January to June (Jackson *et al.,* 2003). The main cause of reduced CPUEs in the SSJF during the full moon is generally attributed to the reduced effectiveness of the lights to attract squid because of the lack of contrast of the lights against a bright sky (Nowara and Walker, 1998, Knuckey *et al.,* 2001). Catch rates in the SSJF are highest around the new moon perhaps because of higher light penetration (from the squid vessel light arrays) (see also Jackson *et al.,* 2005). However, our results for demersal trawlers showed higher CPUEs for squid during the full moon suggest that Gould's Squid may not undergo night time vertical migrations readily, preferring to remain near the sea floor. A likely hypothesis for this is predator avoidance, whereby they are silhouetted against the bright sky, and more susceptible to predation from below.

Research undertaken on light quantity and quality in squid jig fisheries suggests that catches of squid can be improved through adoption of specific lighting regimes (Arimoto, 1991; An *et al.,* 2009; Postuma and Gasalla, 2010). The use of directional lighting, including wavelengths that can penetrate to depths where squid accumulate, may increase catches of Gould's squid. More importantly, lights attract those prey which in turn attract squid (Matsushita and Yamashita 2012). A focus on attraction of particular prey species (with optimal light quantity/quality) may be fruitful for the SSJF. Once attracted (to prey) squid actively avoid bright light (sheltering in the shadow of the fishing vessel hull) (Seafish Industry Authority, 1984; An and Jeong, 2011). Taking squid behaviour into account (with targeted fishing technology) may improve catchability of Gould's squid in the SSJF.

Technology applicable to automatic squid jigging machines can optimise catch rates by minimising loss of squid (once caught on jigs) (Mikami *et al.,* 2001, Kurosaka *et al.,* 2013). Thus, jigging velocity (influenced by drum shape) and hauling speed (which influences squid drop out) can be controlled for size and abundance of squid. There is evidence that catching efficiency increases with the number of jigging machines (Araya, 1983) but this number is limited by input management arrangements in the SSJF — specifically, the number of SFRs applicable to a jigging machine in any year (AFMA, 2007). High current strength may reduce the effectiveness of jigs (Yamashita *et al.,* 2008, McKinna *et al.,* 2010).

Conclusions

We have evaluated sources of variation in squid catches in the Southern Squid Fishery: including the trawl, Danish seine, and the (more recent) SSJF. No clear or obviously important source of variation emerges that we can recommend to improve targeting in the Southern Squid Jig Fishery. This is most likely due to confounding variables affecting squid distribution and abundance. There is evidence that squid accumulate at the boundaries of ocean fronts: Fronts include boundaries of highly productive cold water derived from upwellings (e.g. off the Bonney coast) and warm clear water. As visual predators, squid require clear water to attach prey which accumulate in more turbid waters. Taking a more focused spatial approach, variation in coastal oceanographic productivity associated with the Bonney upwelling and the abundance of prey species (particularly krill) is an important driver of squid population abundance. Thus, seasonal catches are optimal during summer when oceanic processes favour squid accumulation off Western Victoria. Similarly, changes in the frequency and intensity of upwelling due to, for example, ENSO events and climate change will influence squid abundance. More specifically, advances in technology associated with jigging and squid/prey attraction appear promising. Targeting squid around the new moon, in clear water, with lights (including blue wavelengths) and automated jigging machines (to account for sea state and squid depth) reflect our findings both for the Southern Squid fishery and for squid jig fisheries more generally. Adoption, development, and improvement of such technology may provide for improved catch rates in the SSJF.

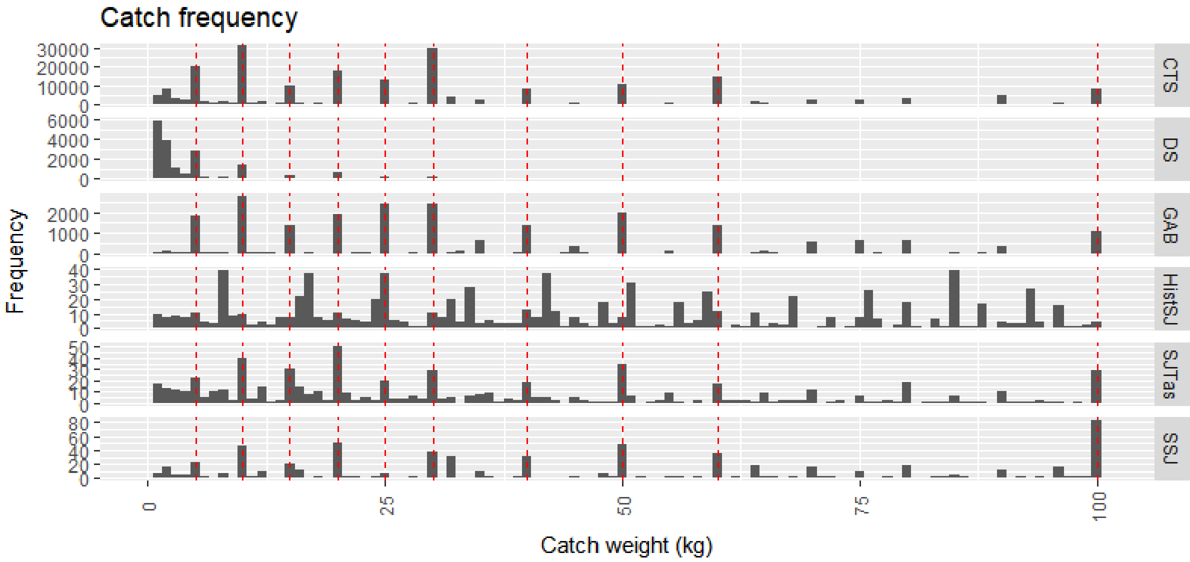


Figure 6. Catch frequency of Gould's Squid in the CTS, DS, GABTS HistSJ, SJTas and SSJF. Vertical red lines are at 5, 10, 15, 20, 25, 30, 40, 50, 60 and 100 kg. Note figures are restricted to catches of 100 kg or less.

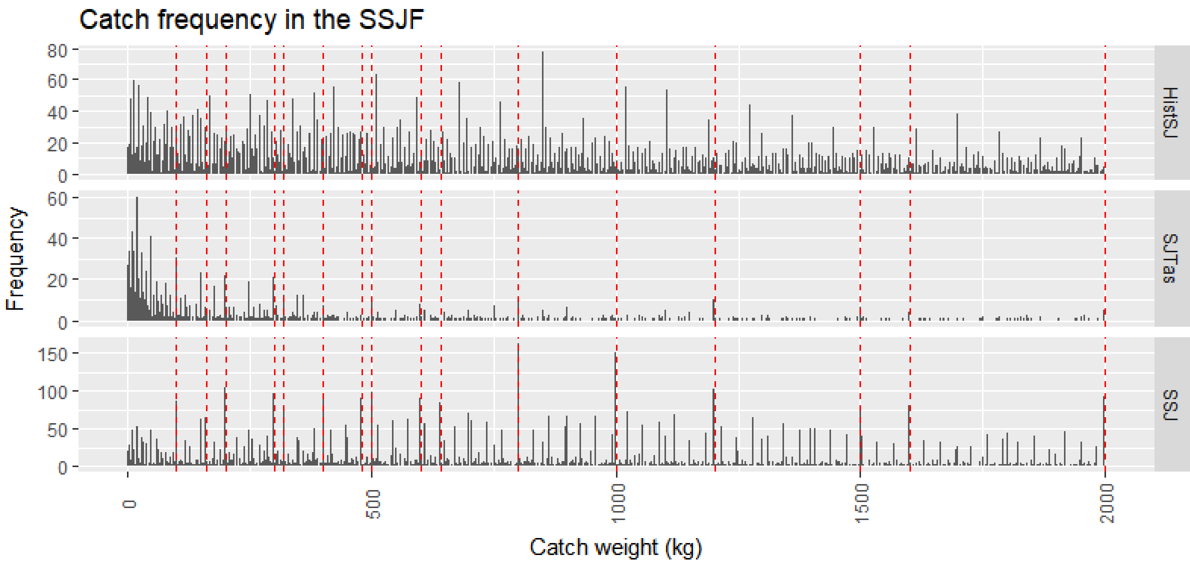


Figure 7. Catch frequency of Gould's Squid in HistSJ, SJTas and SSJF. Vertical red lines are at 100, 160, 200, 300, 320,400,480, 500, 600, 640, 800, 1000, 1200, 1500, 1600, 2000 kg. Note figures are restricted to catches less than 2000 kg and catch weights are binned into groups of 2 to aid visualisation.

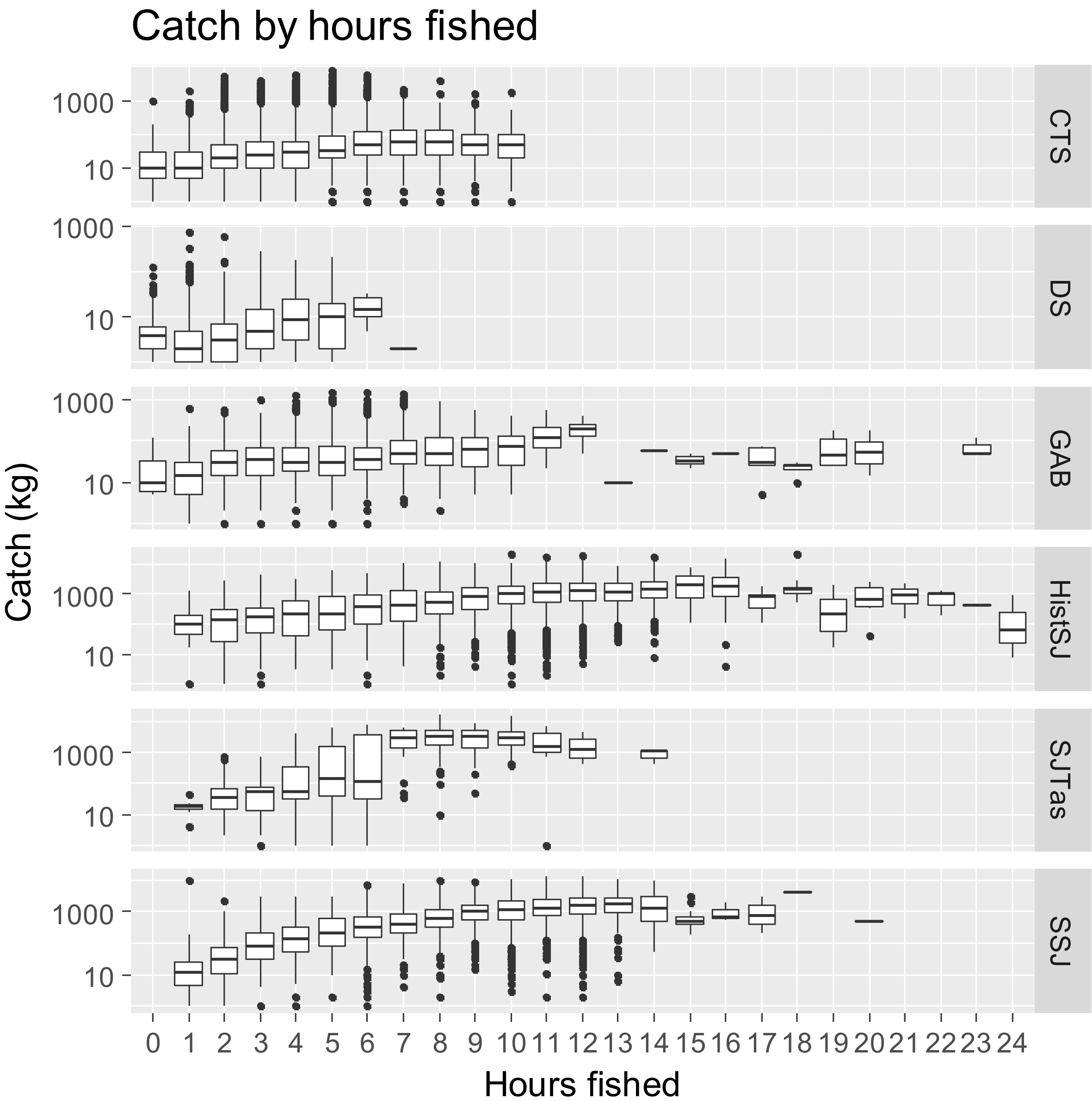


Figure 8. Catch per fishing unit (kg) against duration of fishing effort (hours fished) for the CTS, GABTS, HistSJ, SJTas and SSJF. Note that the log scale of the y-axis.

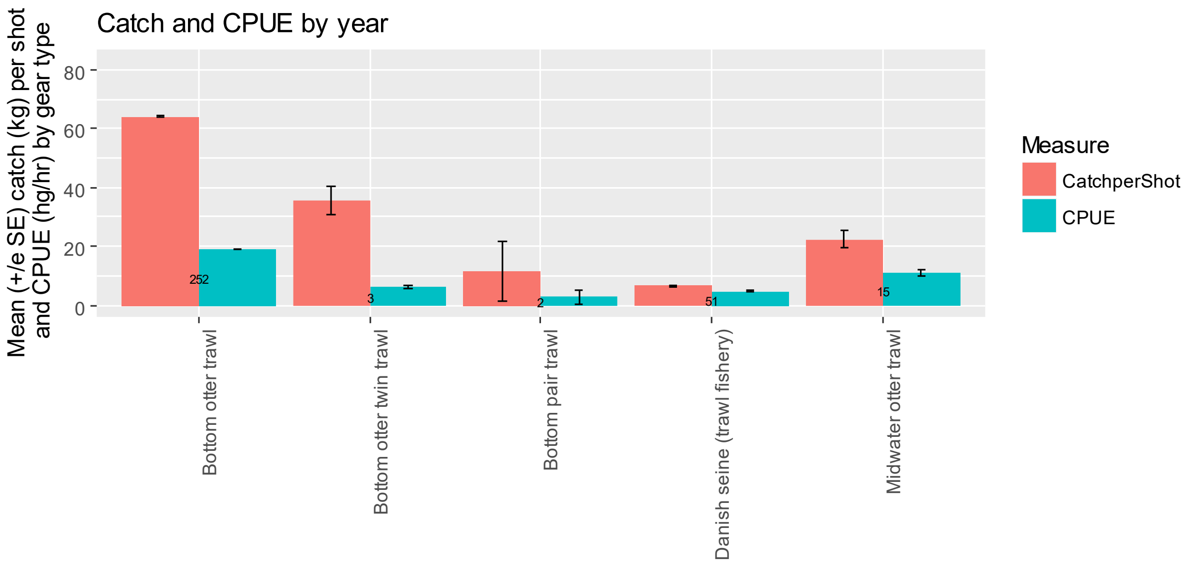


Figure 9. Mean catch per shot and CPUE by gear type in the CTS.

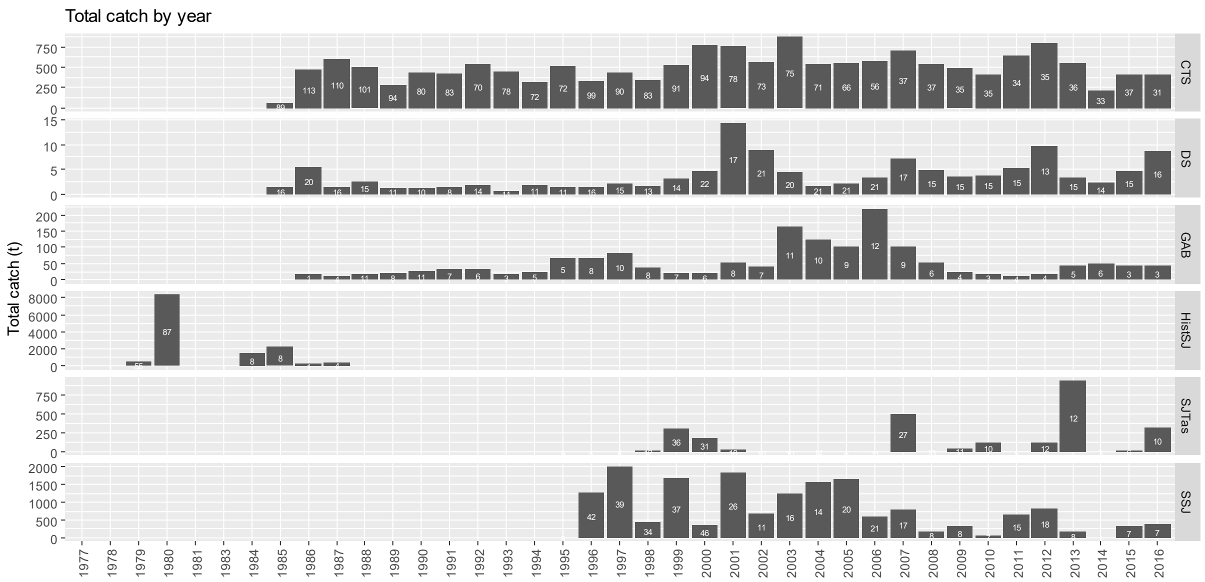


Figure 10. Total annual catch (t) of Gould's Squid in the CTS, DS, GABTS, HistS, SJTas and SSJF.

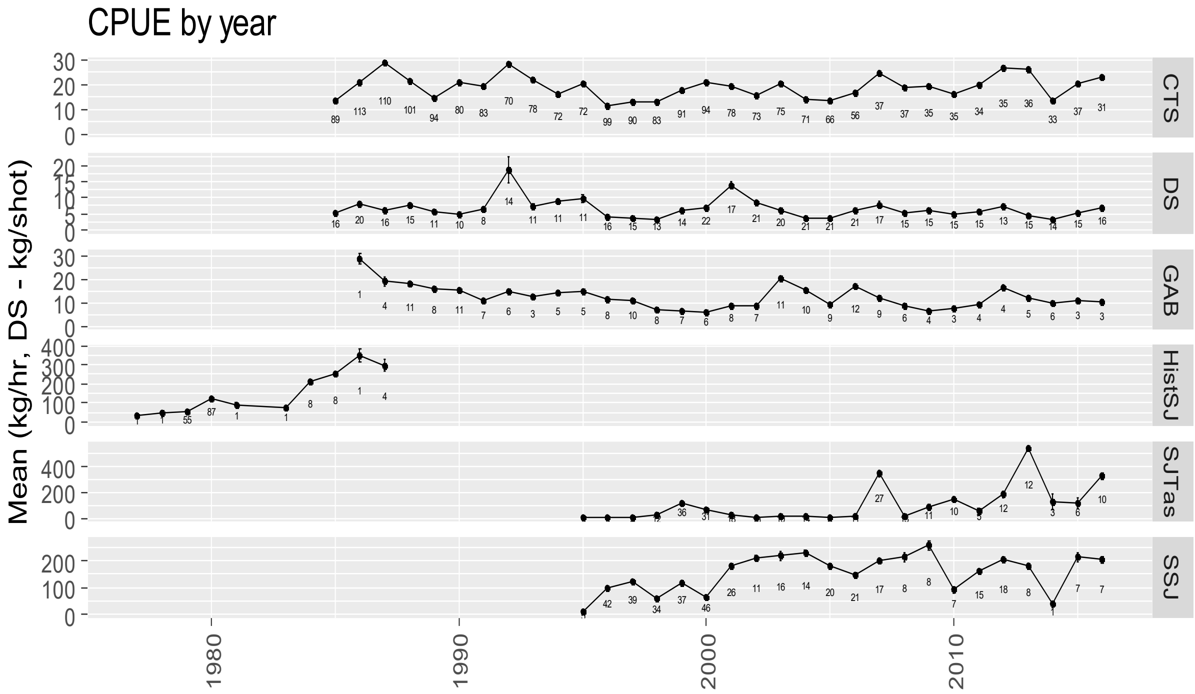


Figure 11. Mean CPUE (kg / hr) of Gould's Squid in the CTS, GABTS, HistS, SJTas and SSJF.

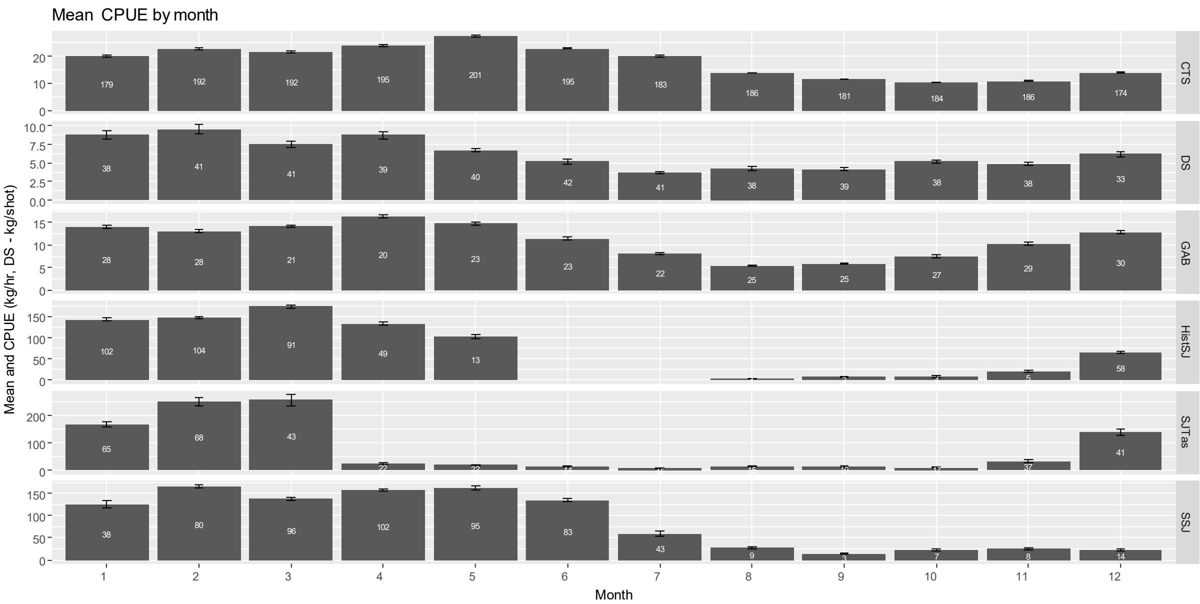


Figure 12. Mean monthly CPUE (kg / hr, kg/shot for DS) of Gould's Squid in the CTS (bottom trawl), DS, GABTS, HistSJ, SJTas and SSJF.

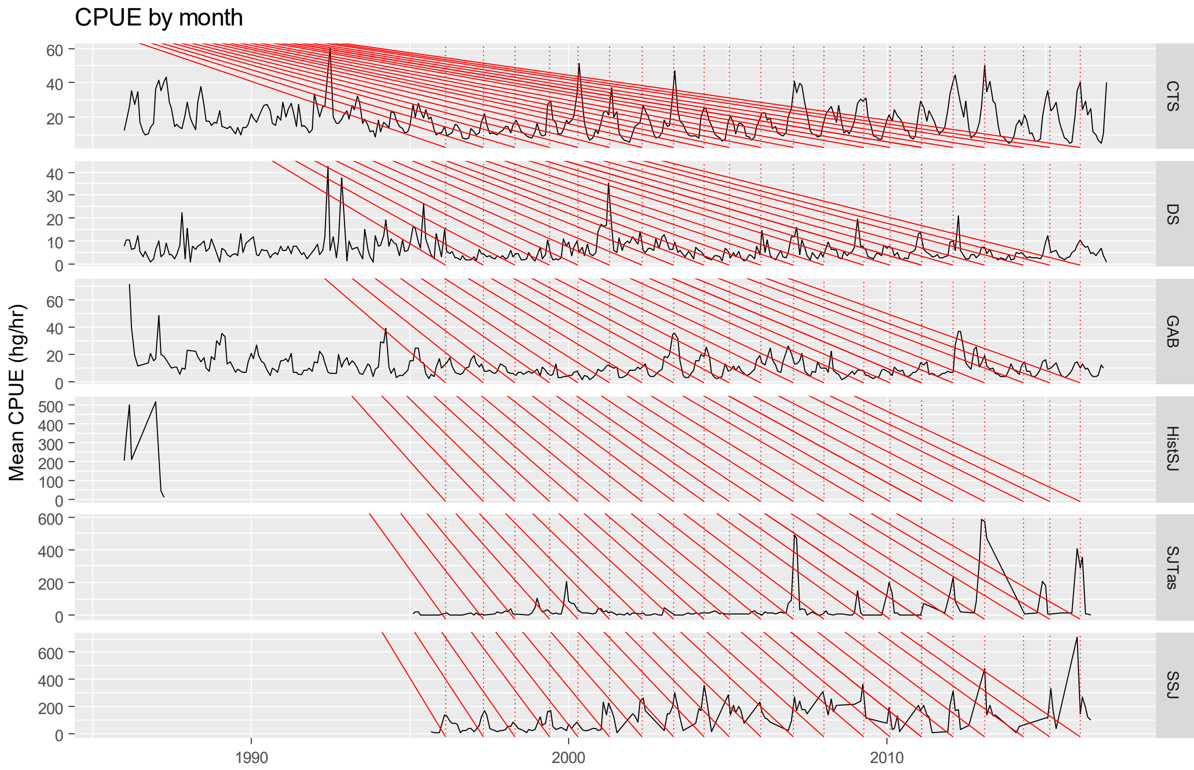


Figure 13. Mean monthly CPUE (kg/hr, kg/shot for DS) of Gould's Squid in the CTS (trawl), and DS GABTS and SSJF. Vertical red lines show months where peak catches in any year line up with multiple fisheries.

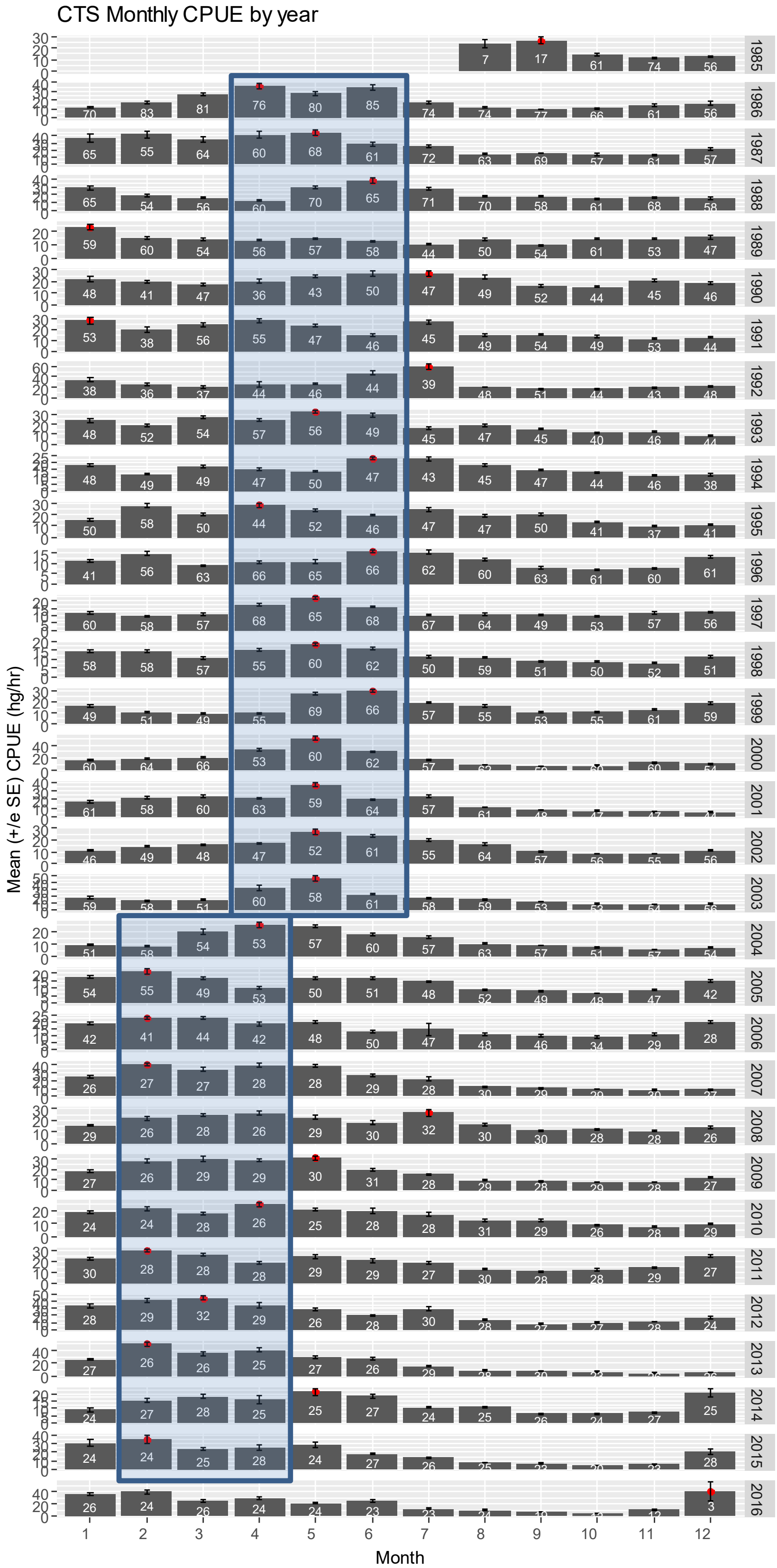


Figure 14. Mean monthly CPUE (kg/hr) of Gould's Squid in the CTS by year. Red dots denote months with the highest mean monthly CPUE in each year.

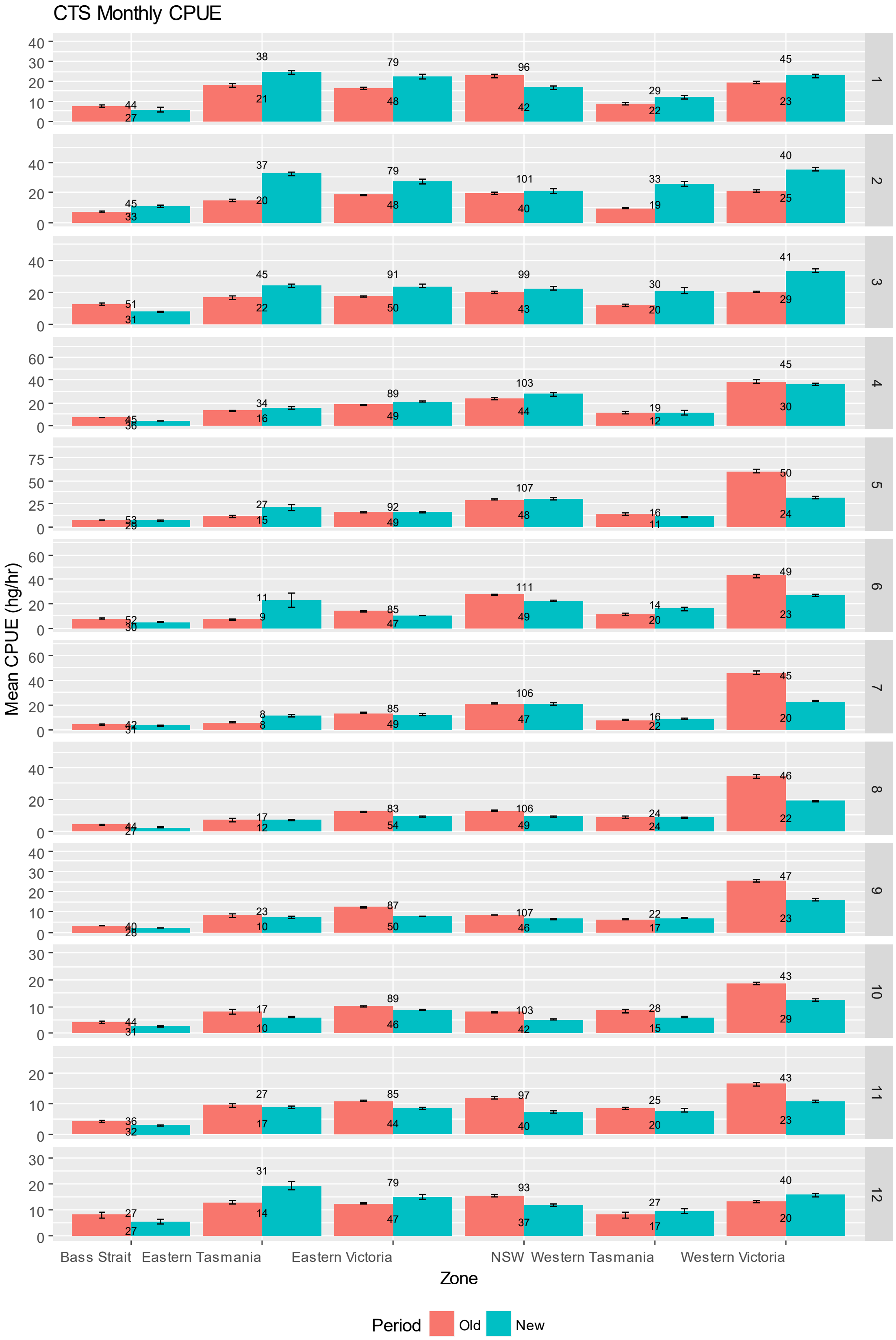


Figure 15. Mean monthly CPUE of Gould's Squid by zone in the CTS for the period old (before 2004) and new (since 2004).

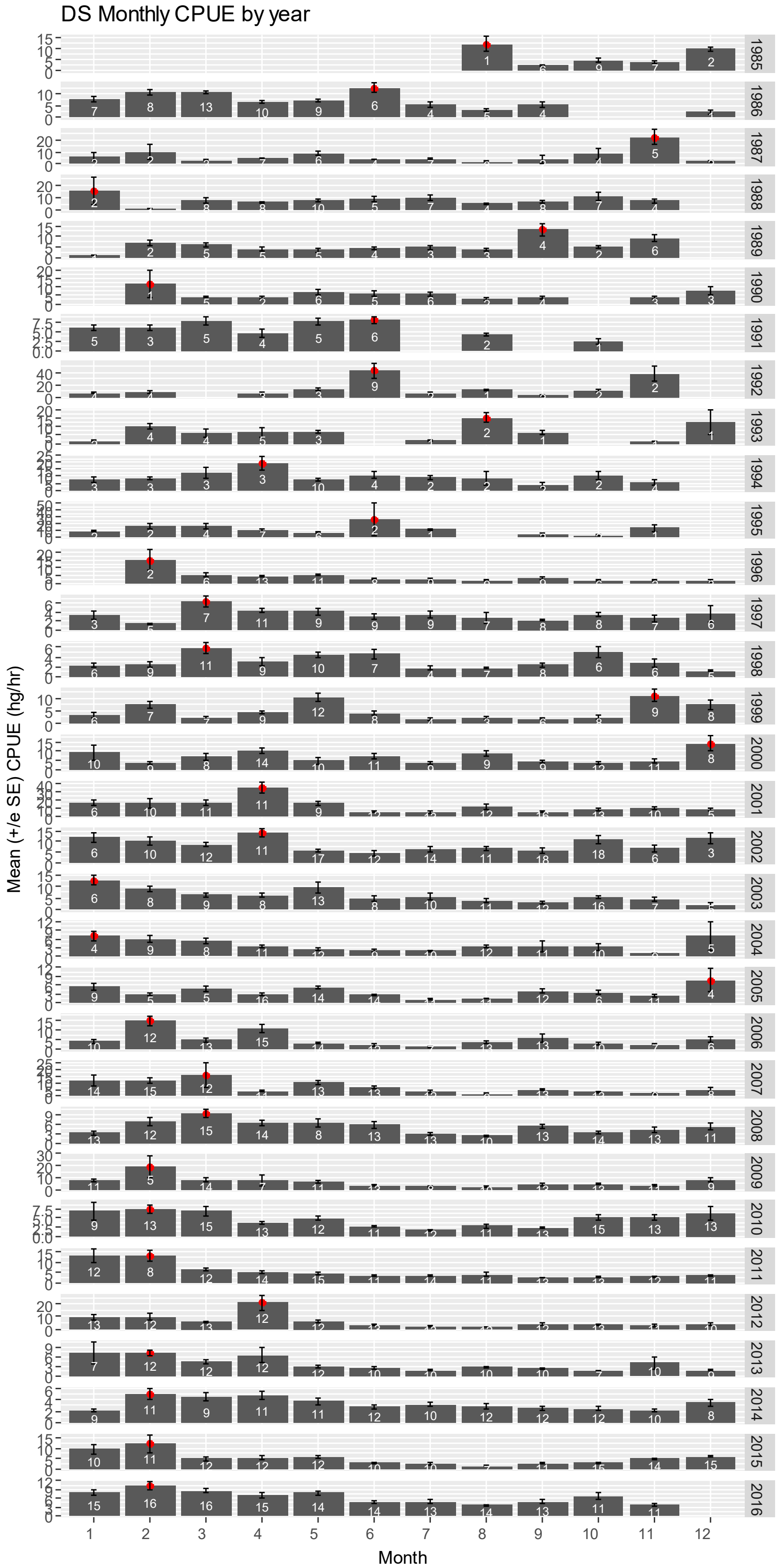


Figure 16. Mean monthly CPUE (catch per shot) of Gould's Squid in the DS by year. Red dots denote months with the highest mean monthly CPUE in each year.

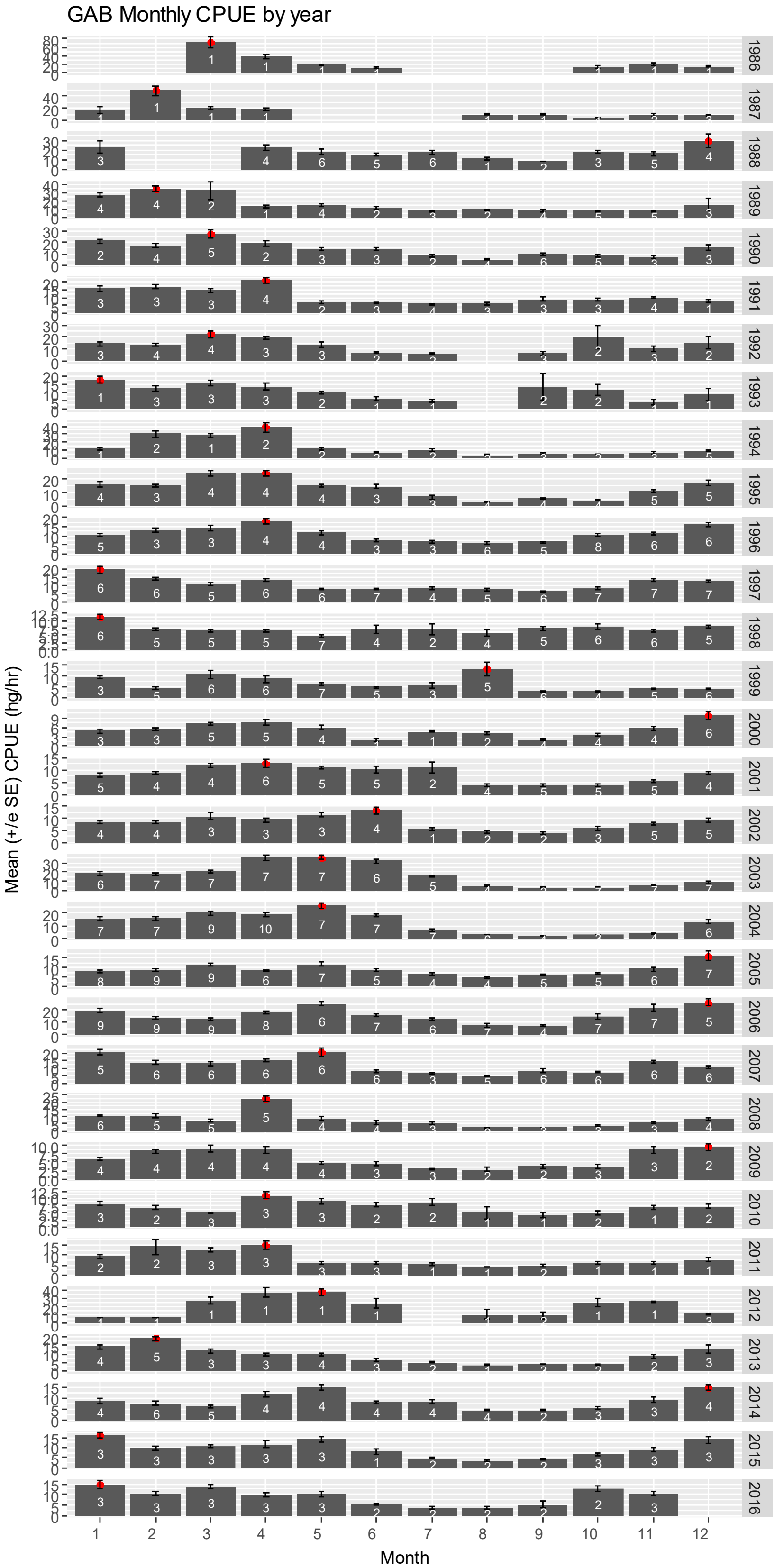


Figure 17. Mean monthly CPUE (kg/hr) of Gould's Squid in the GABTS by year. Red dots denote months with the highest mean monthly CPUE in each year.

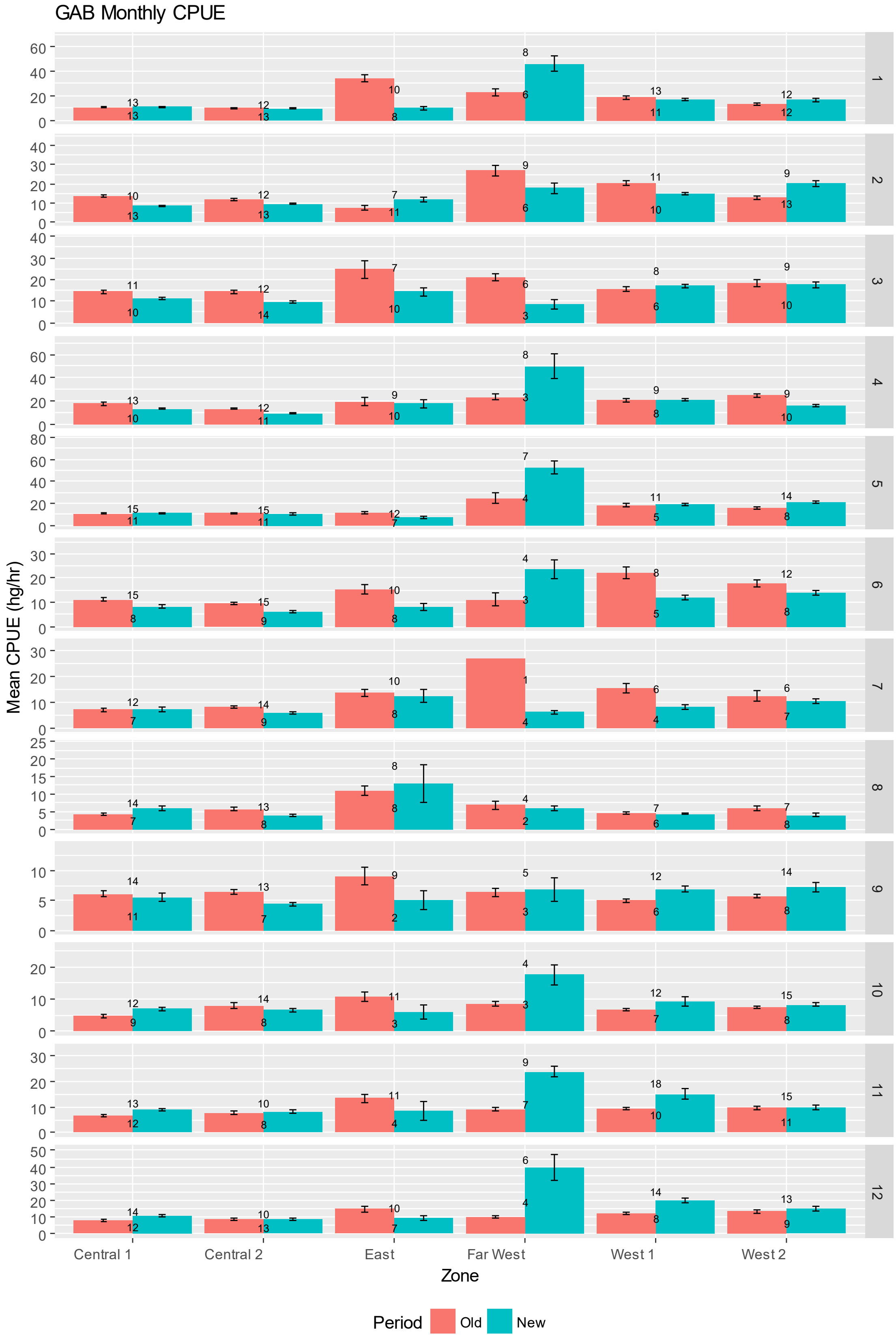


Figure 18. Mean monthly CPUE of Gould's Squid by zone in the GABTS for the period old (before 2004) and new (since 2004).

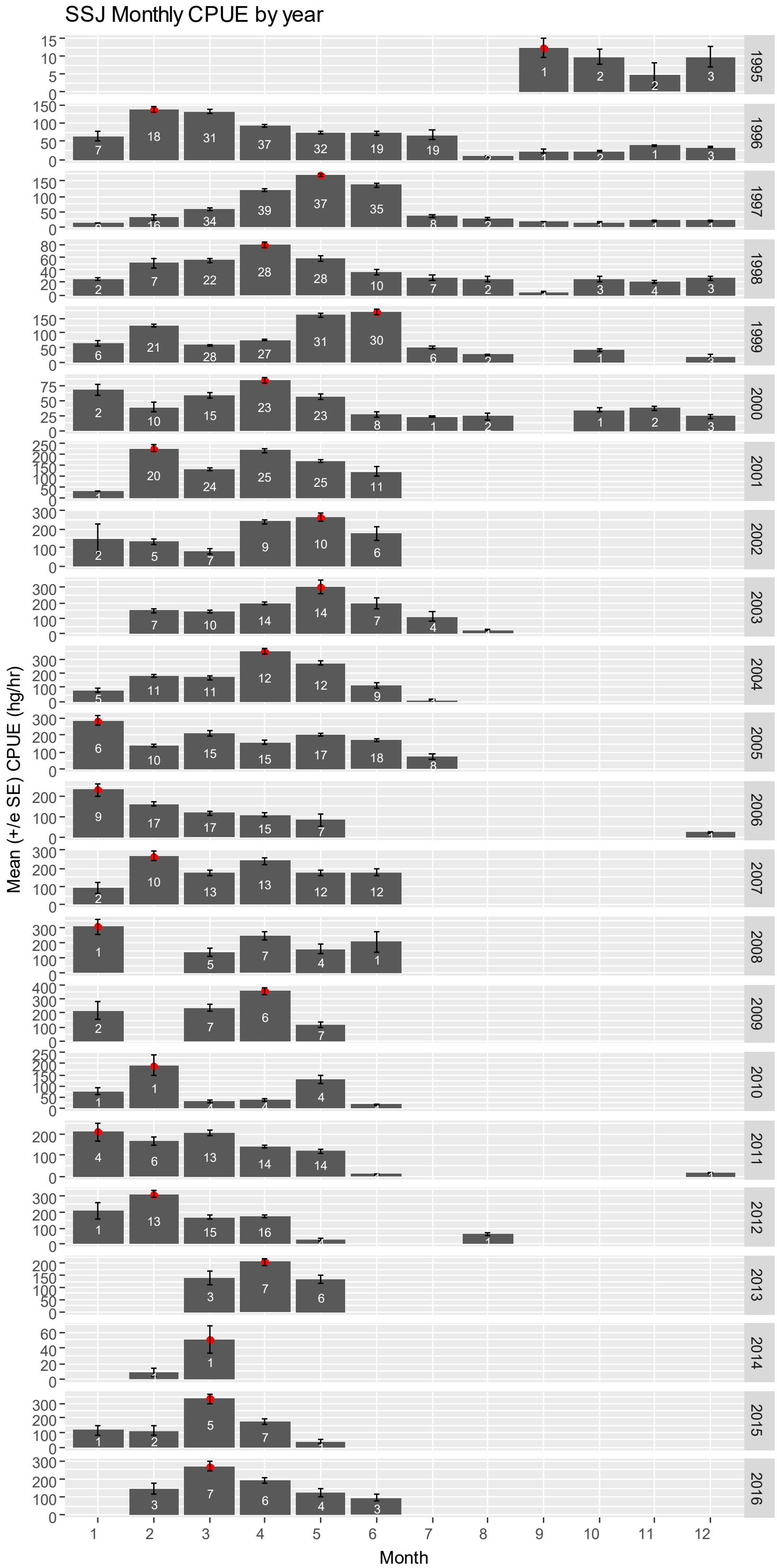


Figure 19. Mean monthly CPUE (kg/hr) of Gould's Squid in the SSJF by year. Red dots denote months with the highest mean monthly CPUE in each year.

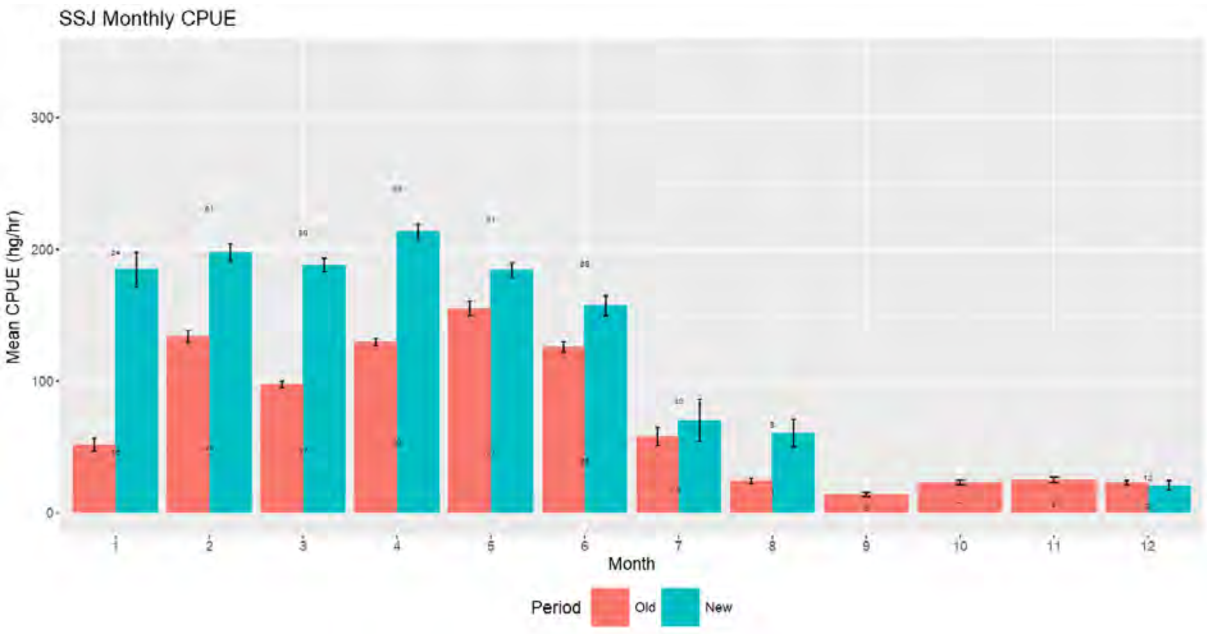


Figure 20. Mean monthly CPUE of Gould's Squid in the SSJF for the period old (before 2004) and new (since 2004). Note that data are not split into zones because of the sparsity of data.

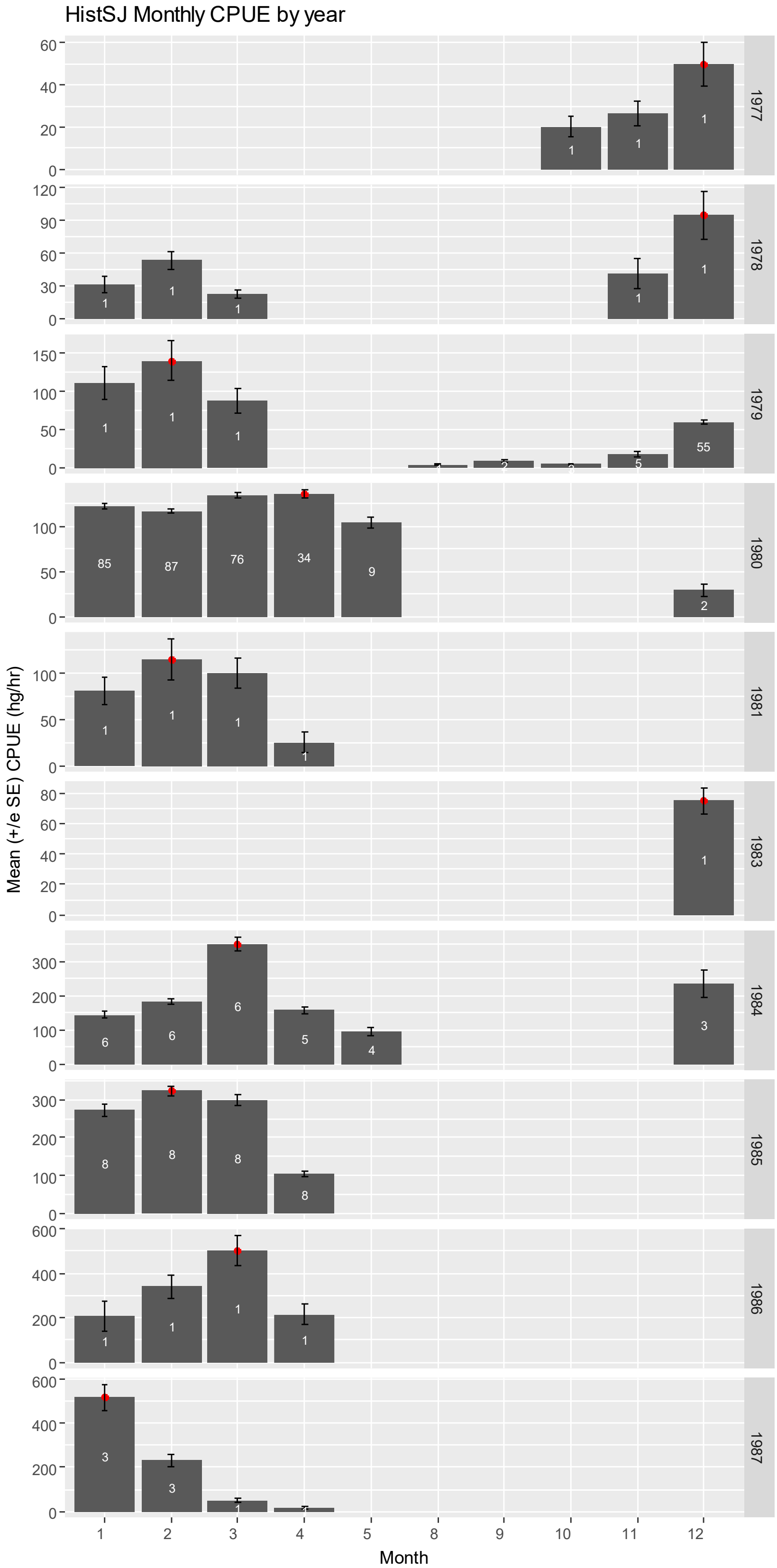


Figure 21. Mean monthly CPUE (kg/hr) of Gould's Squid in the HistSJ by year. Red dots denote months with the highest mean monthly CPUE in each year.

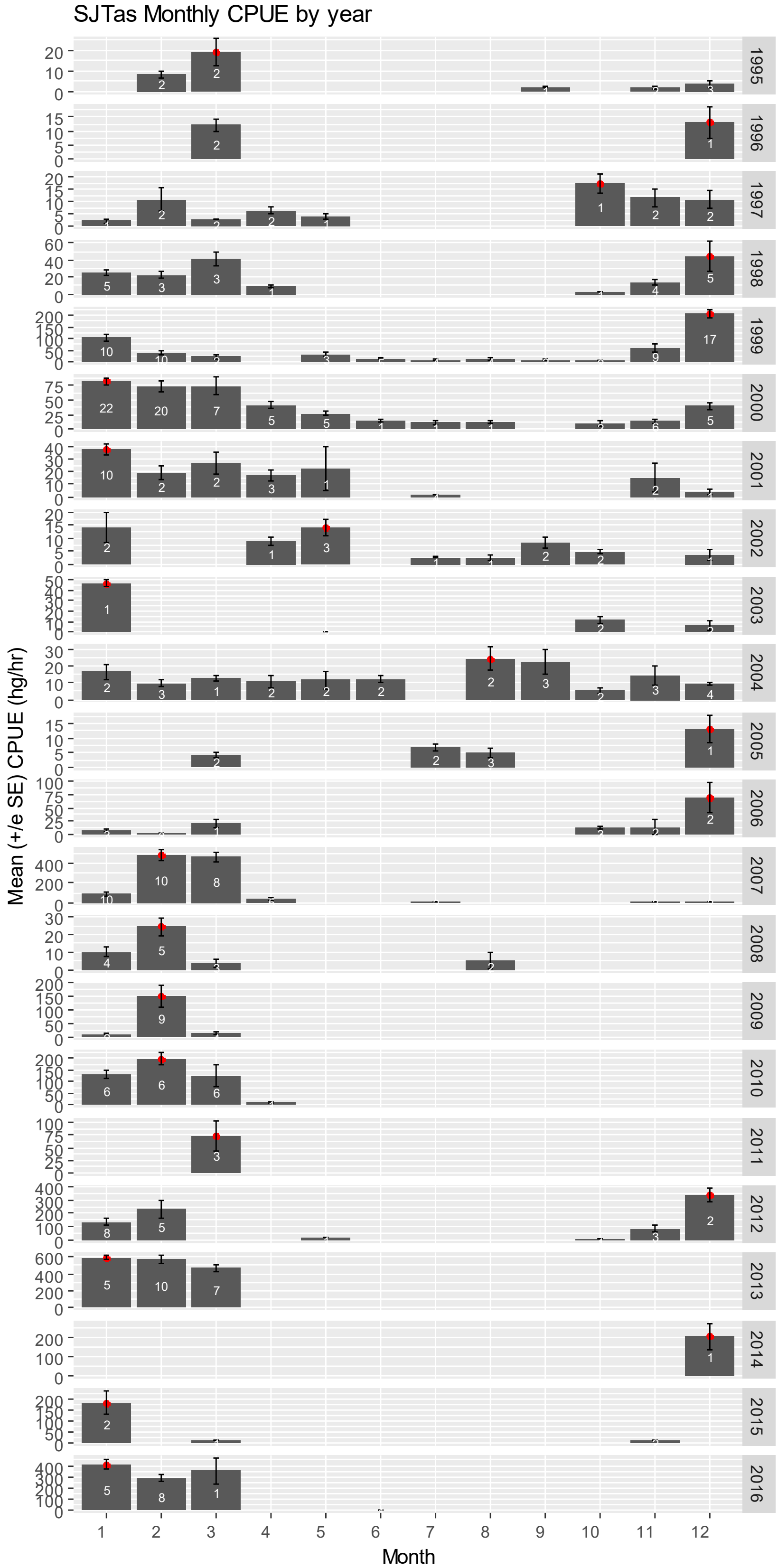


Figure 22. Mean monthly CPUE (kg/hr) of Gould's Squid in the SJTas by year. Red dots denote months with the highest mean monthly CPUE in each year.

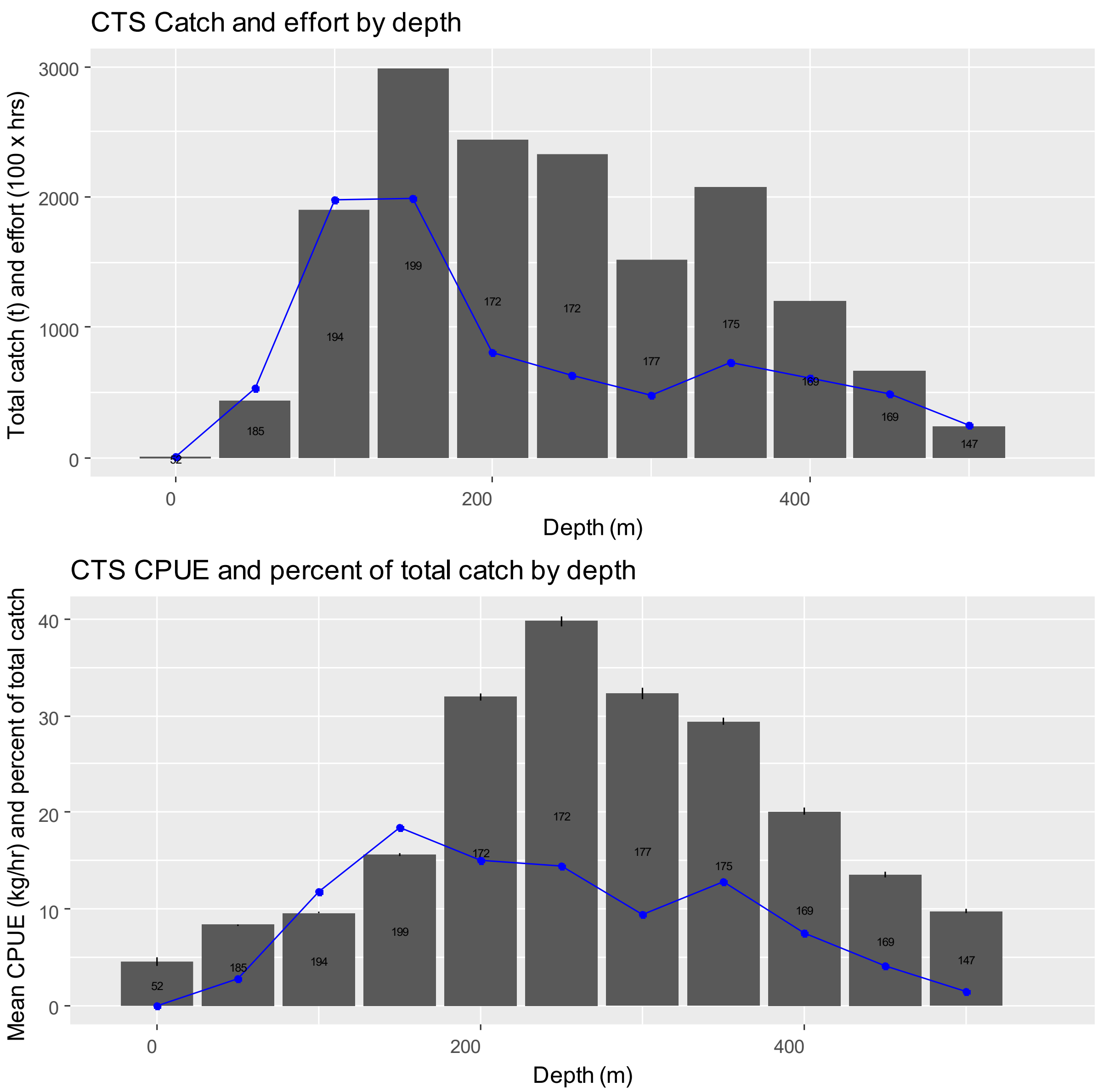


Figure 23. Top panel: Total catch (bars) and effort (line) in the CTS by depth. Lower panel: Mean CPUE (bars) and percent of total catch (line) in the CTS by depth. Note that depth are the mid-point for each bin (i.e. depths binned to 50 range >25 to <75).

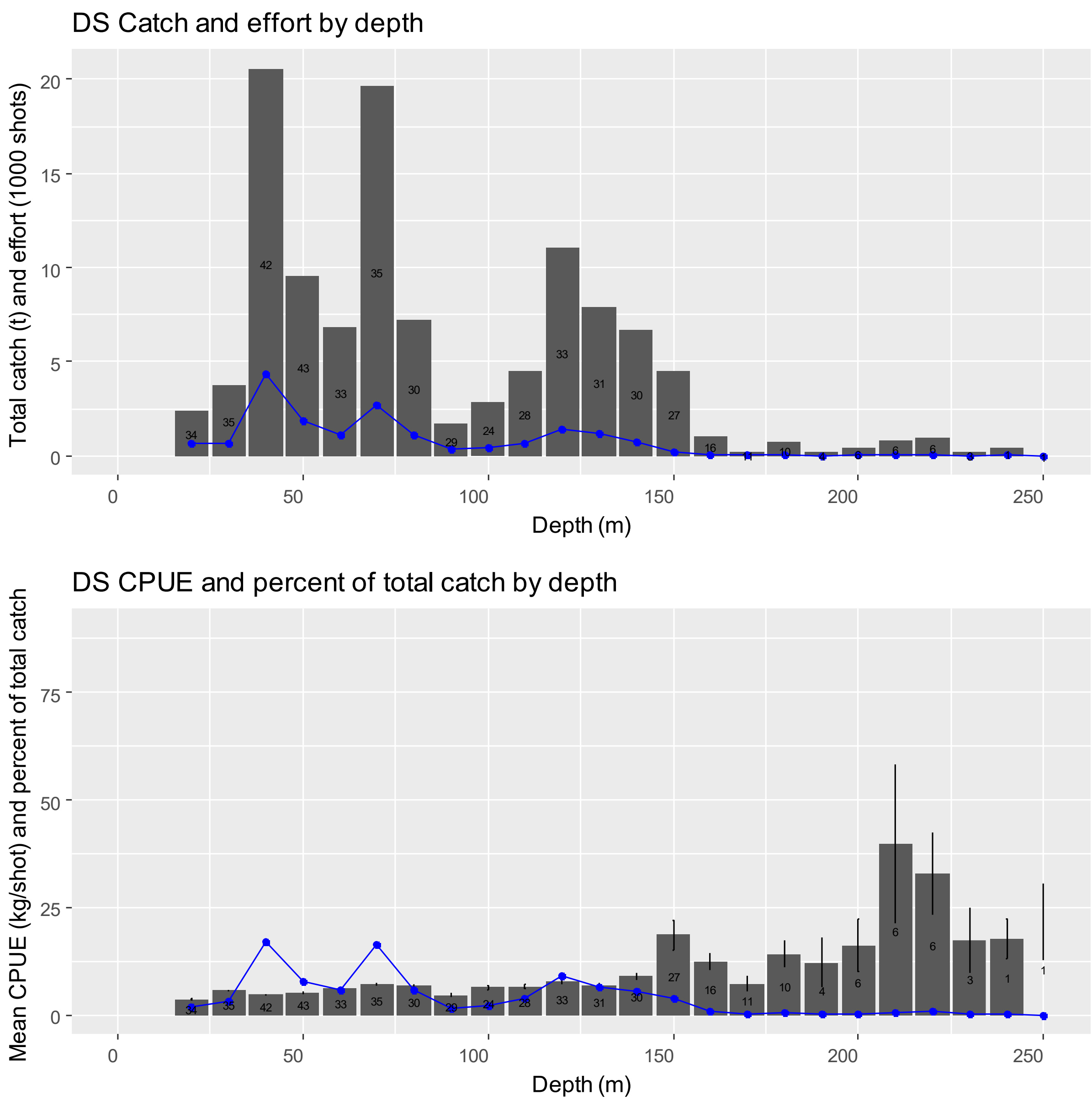


Figure 24. Top panel: Total catch (bars) and effort (line) in the DS by depth. Lower panel: Mean CPUE (bars) and percent of total catch (line) in the CTS by depth. Note that depths are the mid-point for each bin (i.e. depths binned to 50 range >45 to <55).

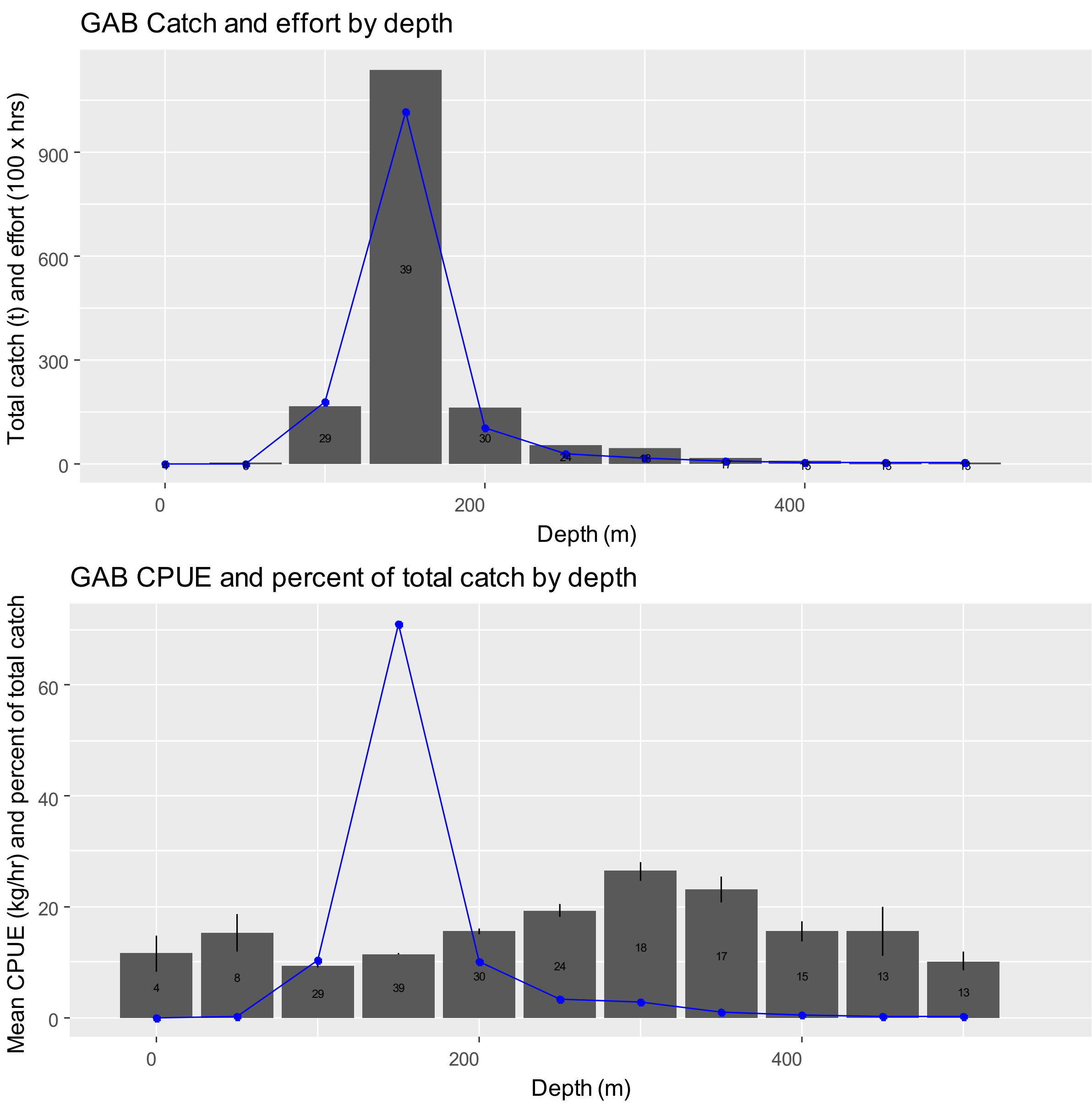


Figure 25. Top panel: Total catch (bars) and effort (line) in the GABTS by depth. Lower panel: Mean CPUE (bars) and percent of total catch (line) in the GABTS by depth.

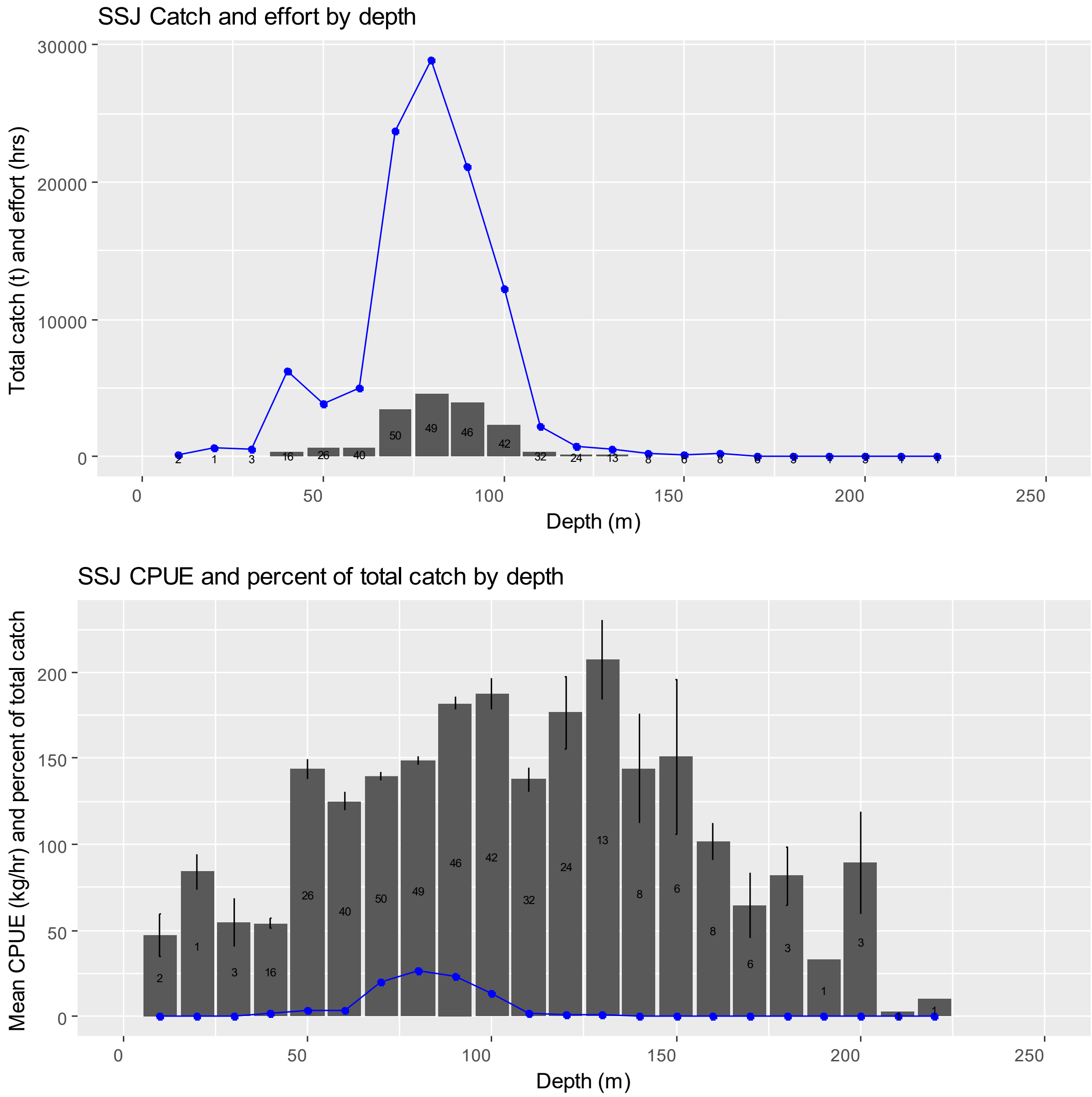


Figure 26. Top panel: Total catch (bars) and effort (line) in the SSJF by depth. Lower panel: Mean CPUE (bars) and percent of total catch (line) in the SSJF by depth.

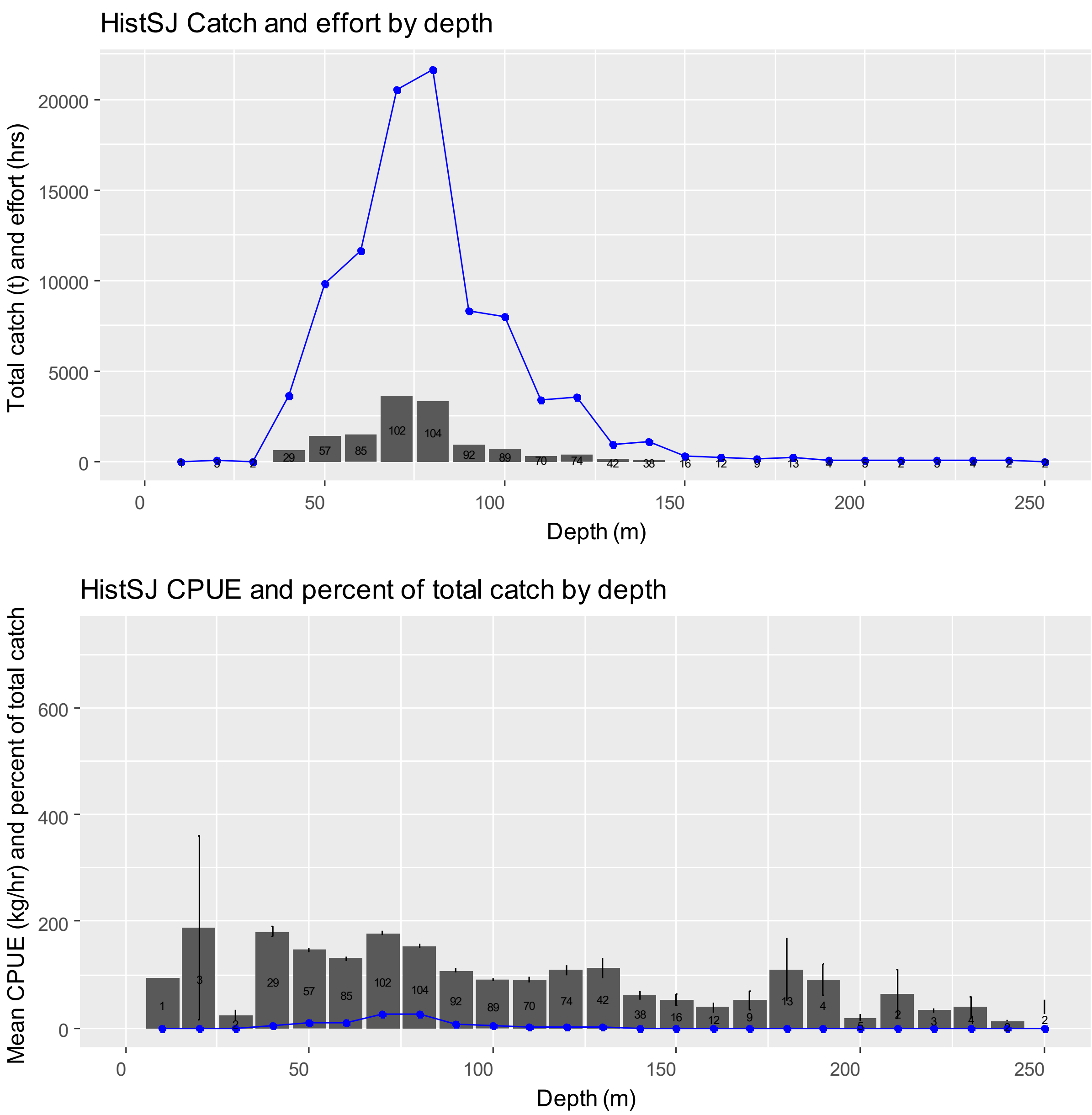
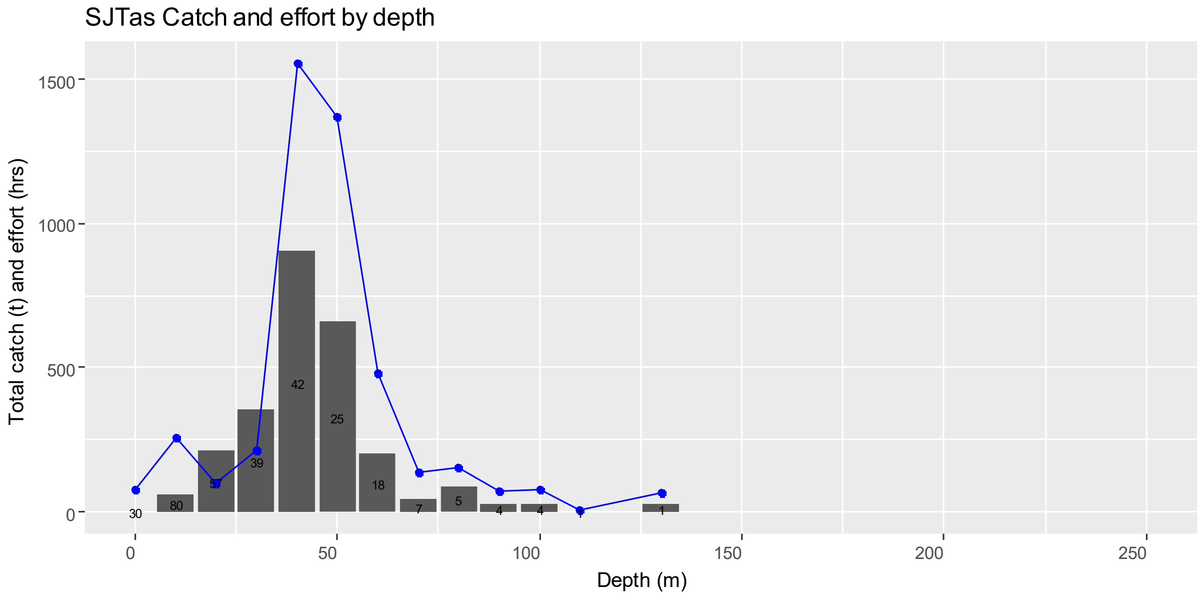


Figure 27. Top panel: Total catch (bars) and effort (line) in the HistSJ by depth. Lower panel: Mean CPUE (bars) and percent of total catch (line) in the HistSJ by depth.



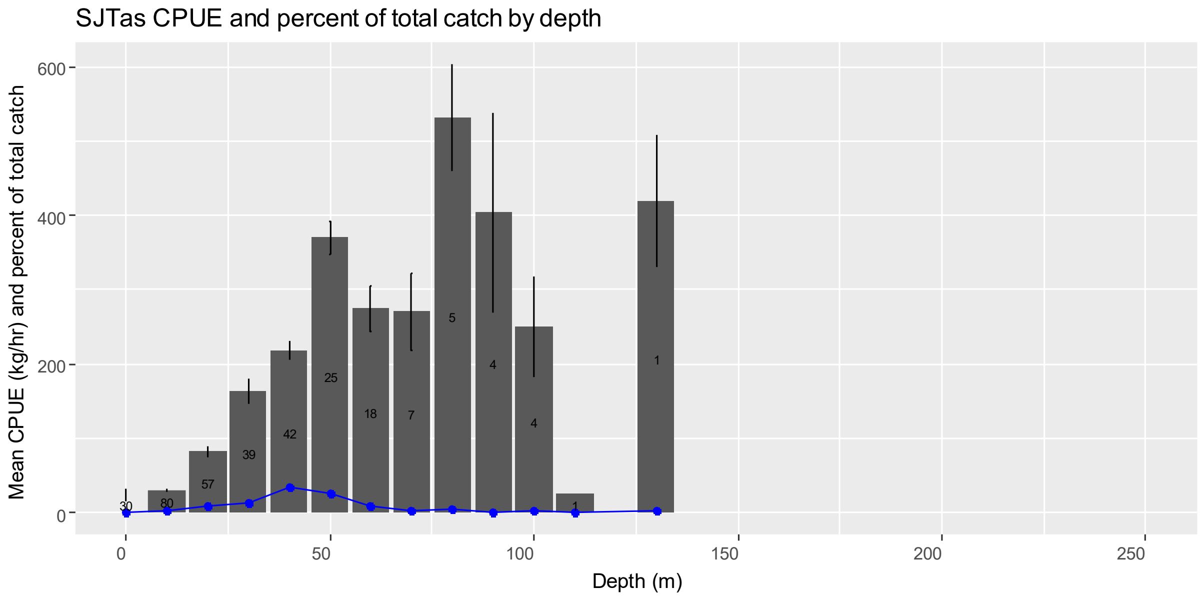


Figure 28. Top panel: Total catch (bars) and effort (line) in the TasSJ by depth. Lower panel: Mean CPUE (bars) and percent of total catch (line) in the TasSJ by depth.

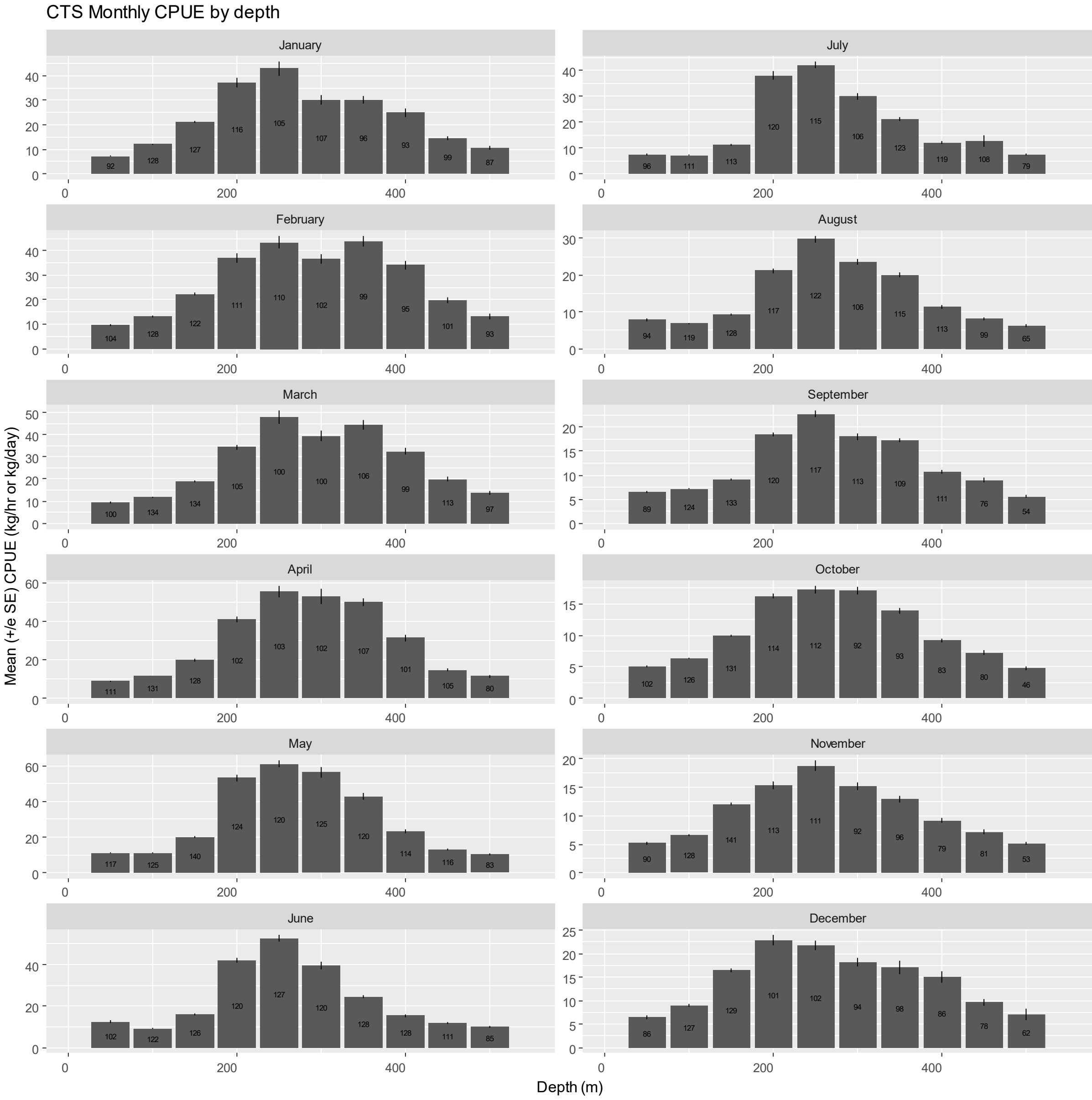


Figure 29. Mean CPUE by month and depth in the CTS.

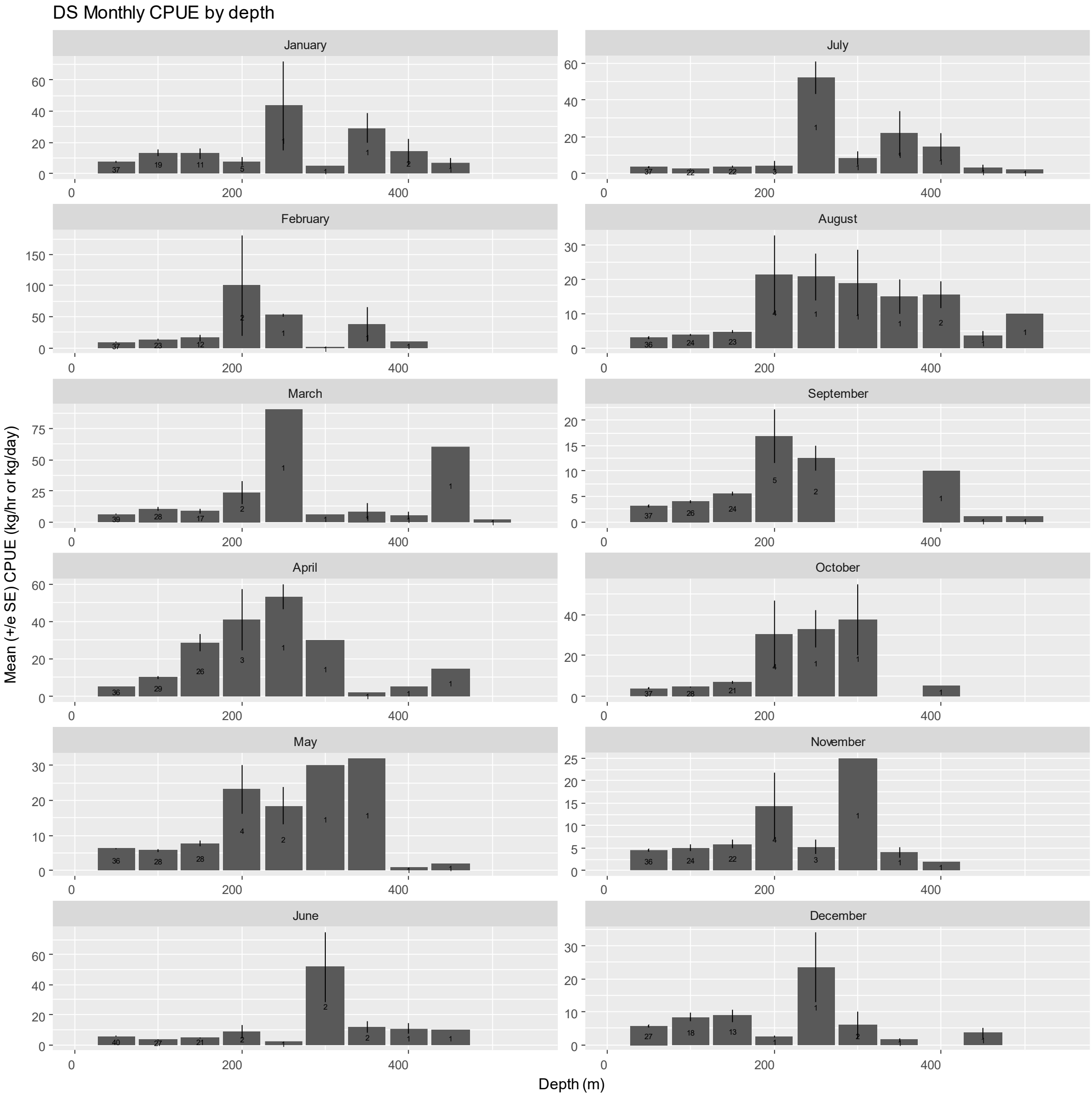


Figure 30. Mean CPUE by month and depth in the DS.

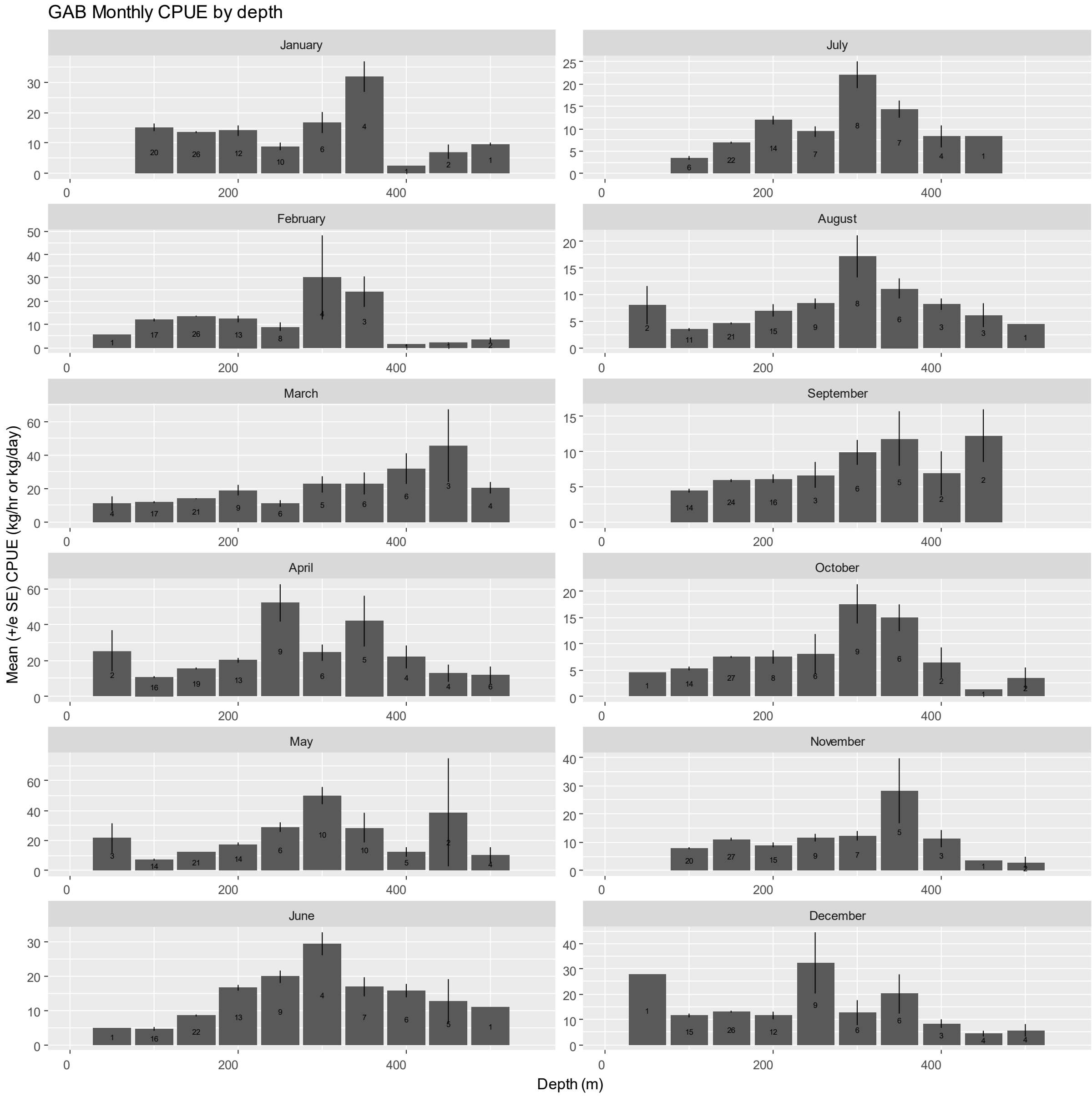


Figure 31. Mean CPUE by month and depth in the GABTS.

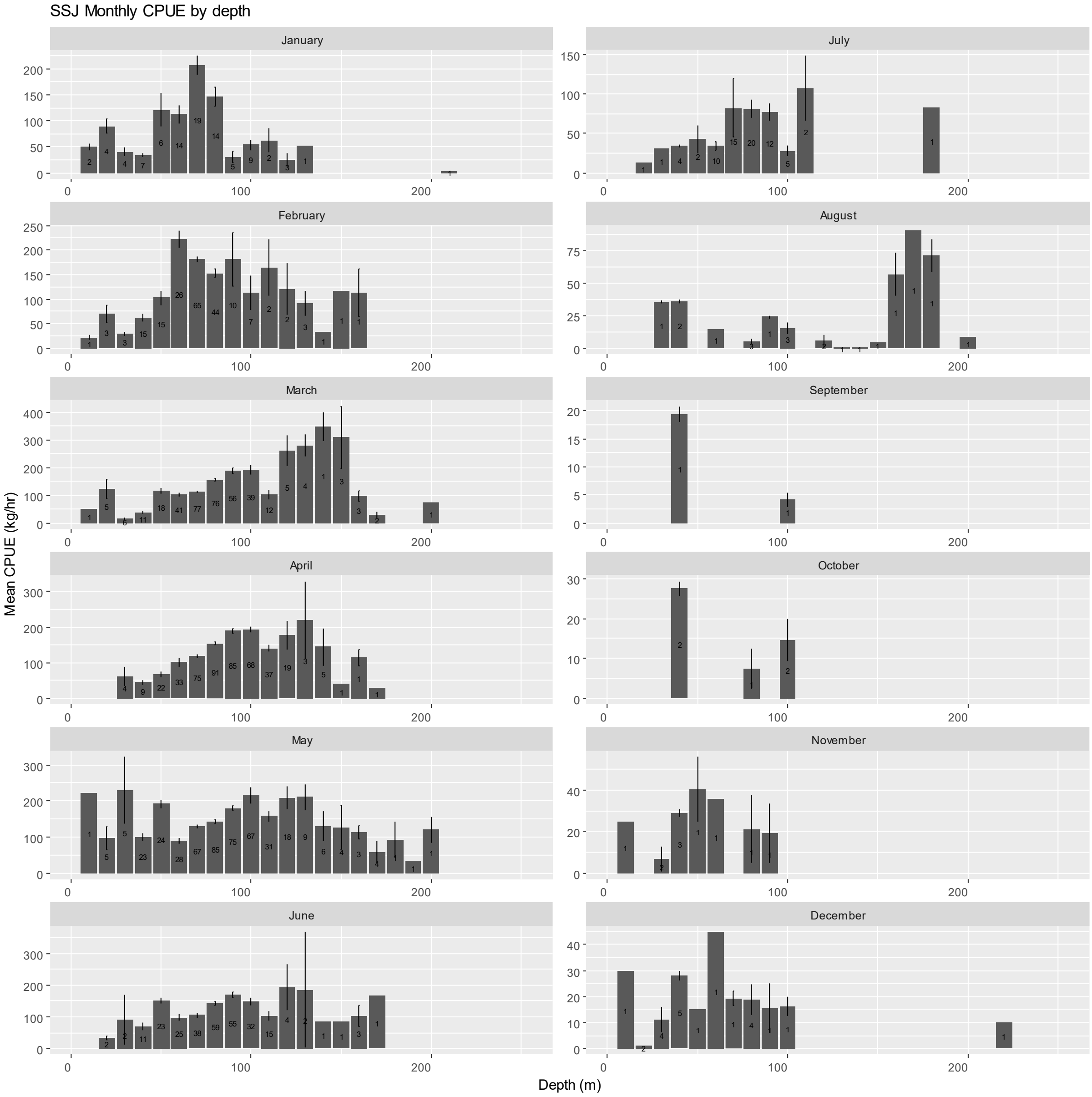


Figure 32. Mean CPUE by month and depth in the SSJF.

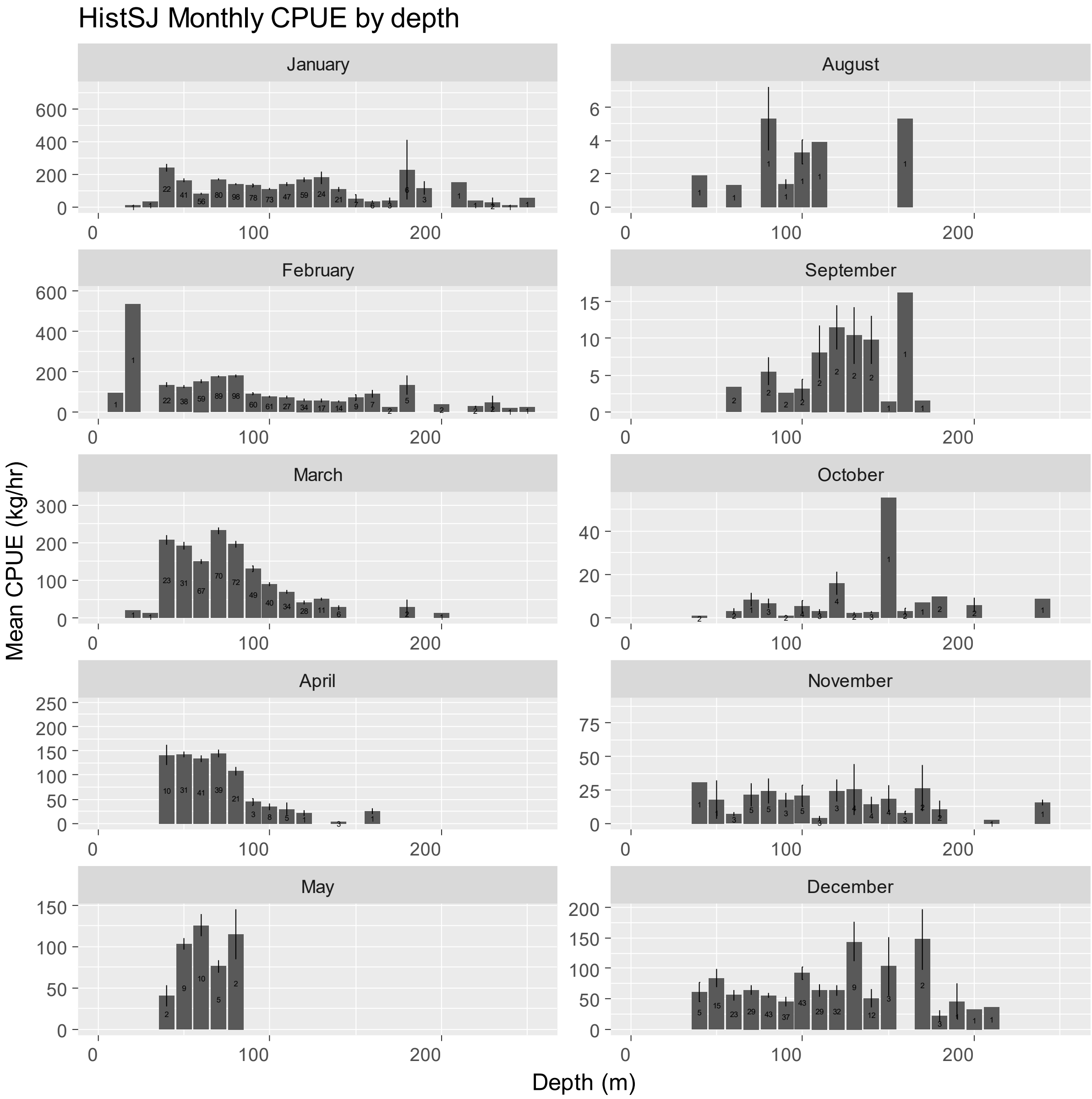


Figure 33. Mean CPUE by month and depth in the HistSJ.

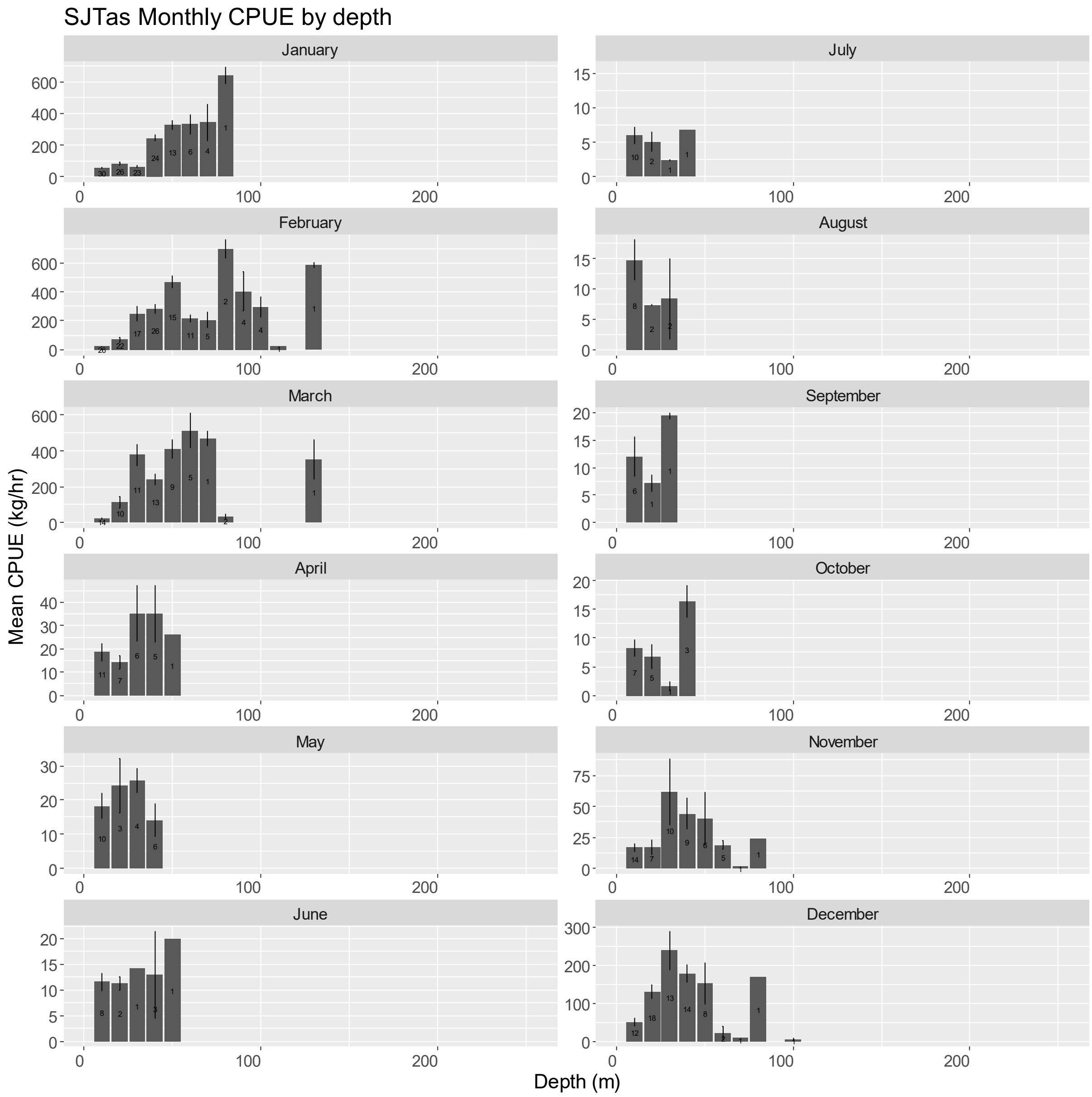


Figure 34. Mean CPUE by month and depth in the SJTas.

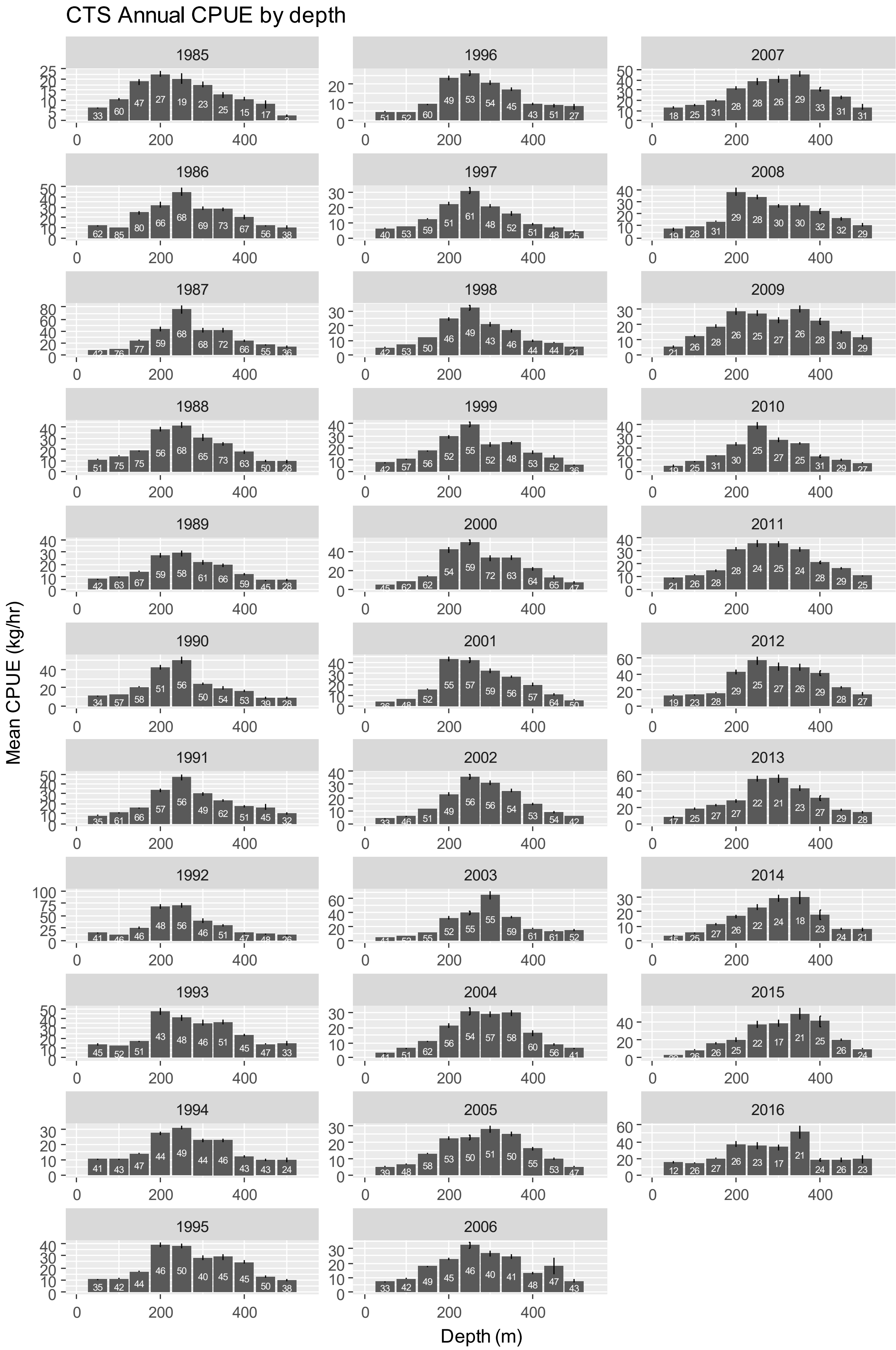


Figure 35. Mean CPUE by year and depth in the CTS.

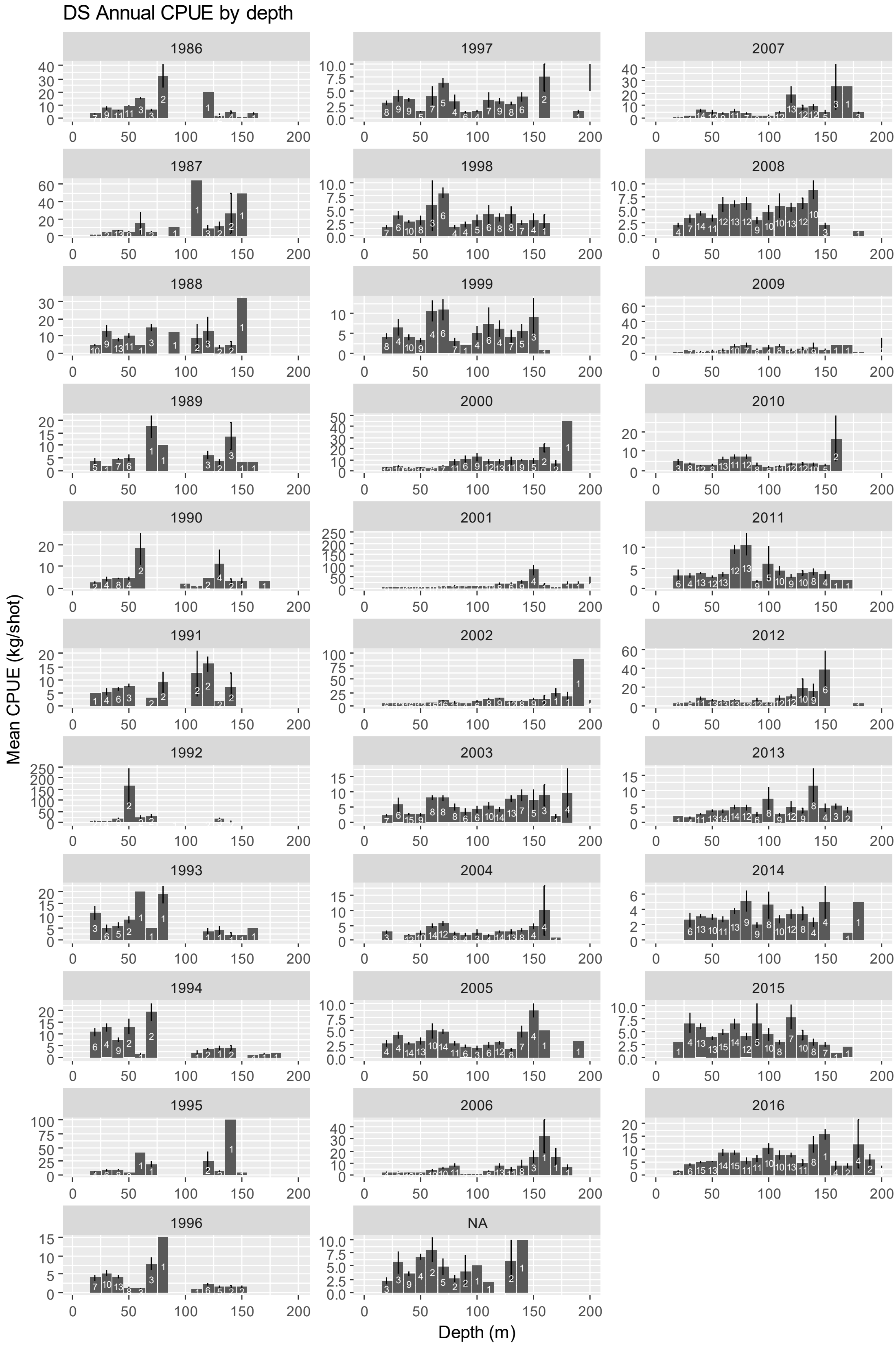


Figure 36. Mean CPUE by year and depth in the DS.

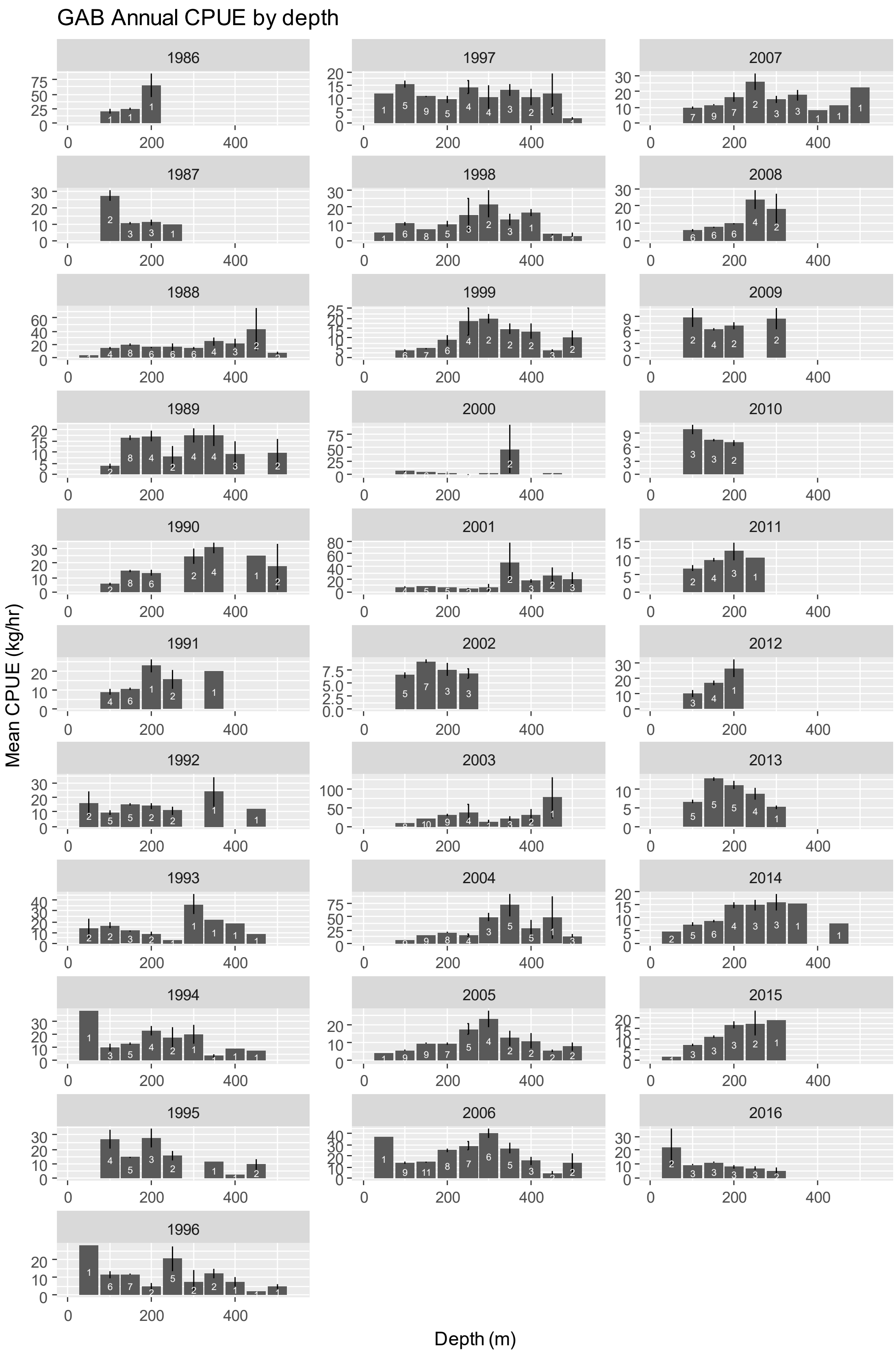


Figure 37. Mean CPUE by year and depth in the GABTS.

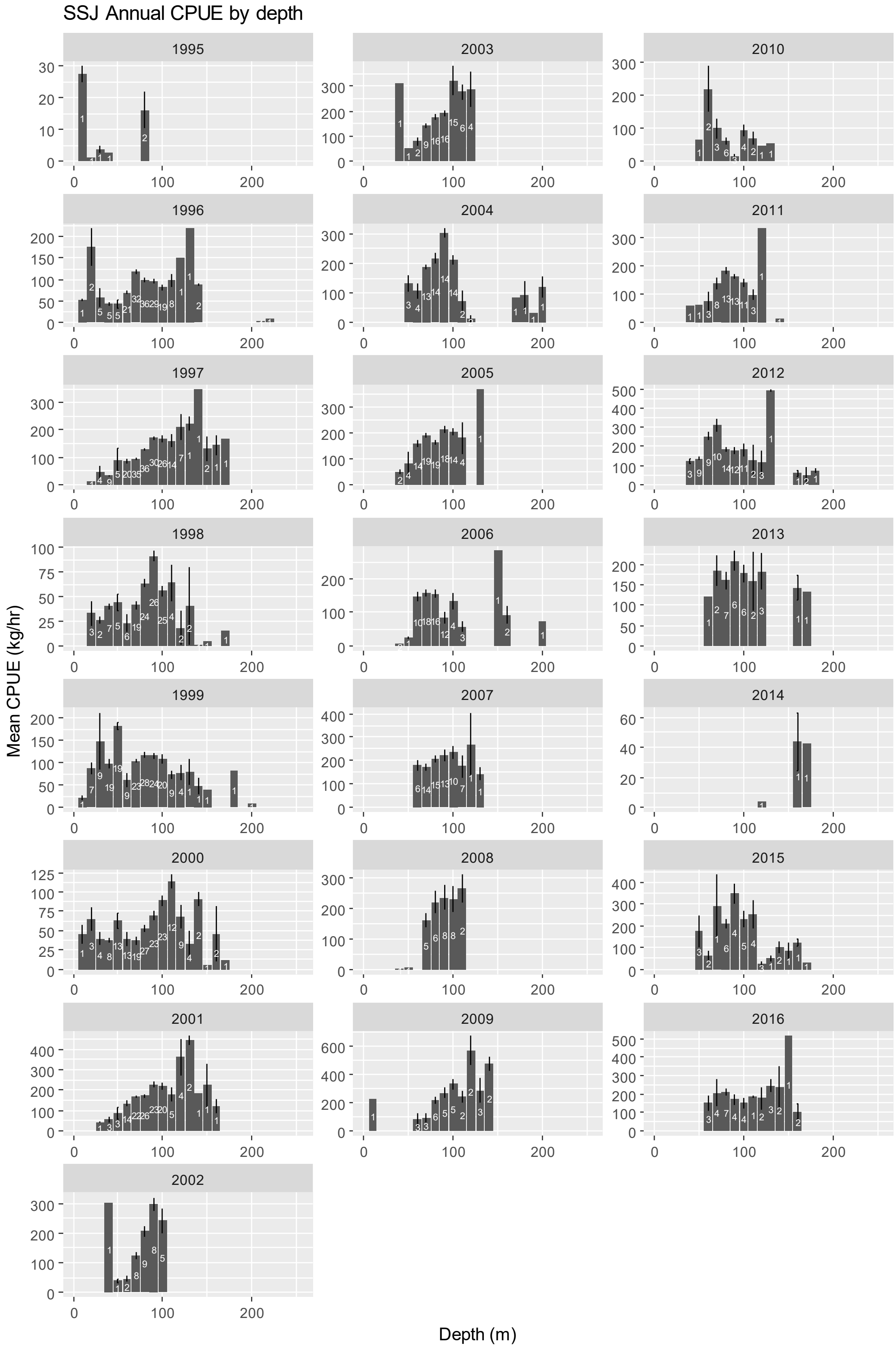


Figure 38. Mean CPUE by year and depth in the SSJF.

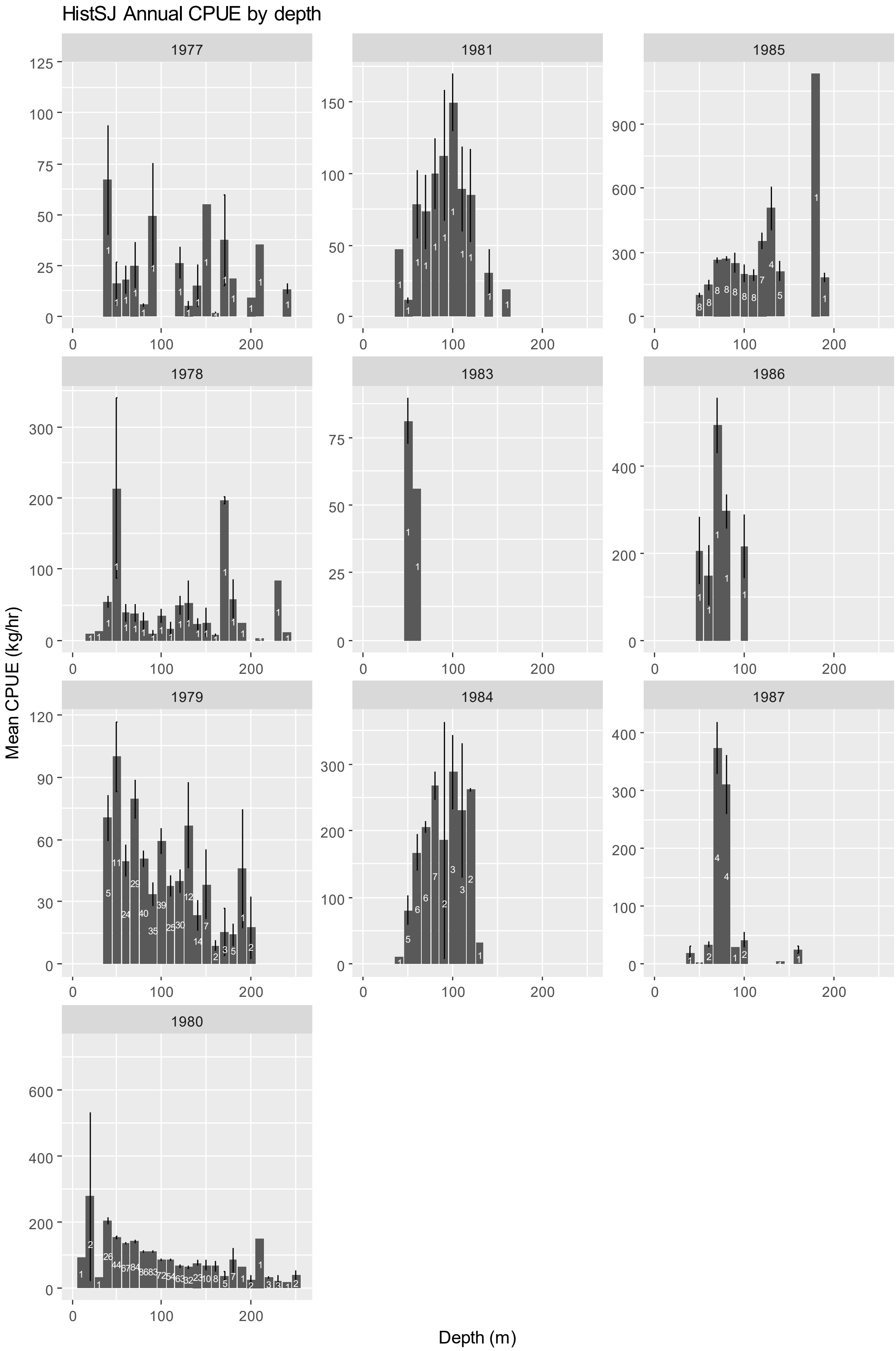


Figure 39. Mean CPUE by year and depth in the HistSJ.

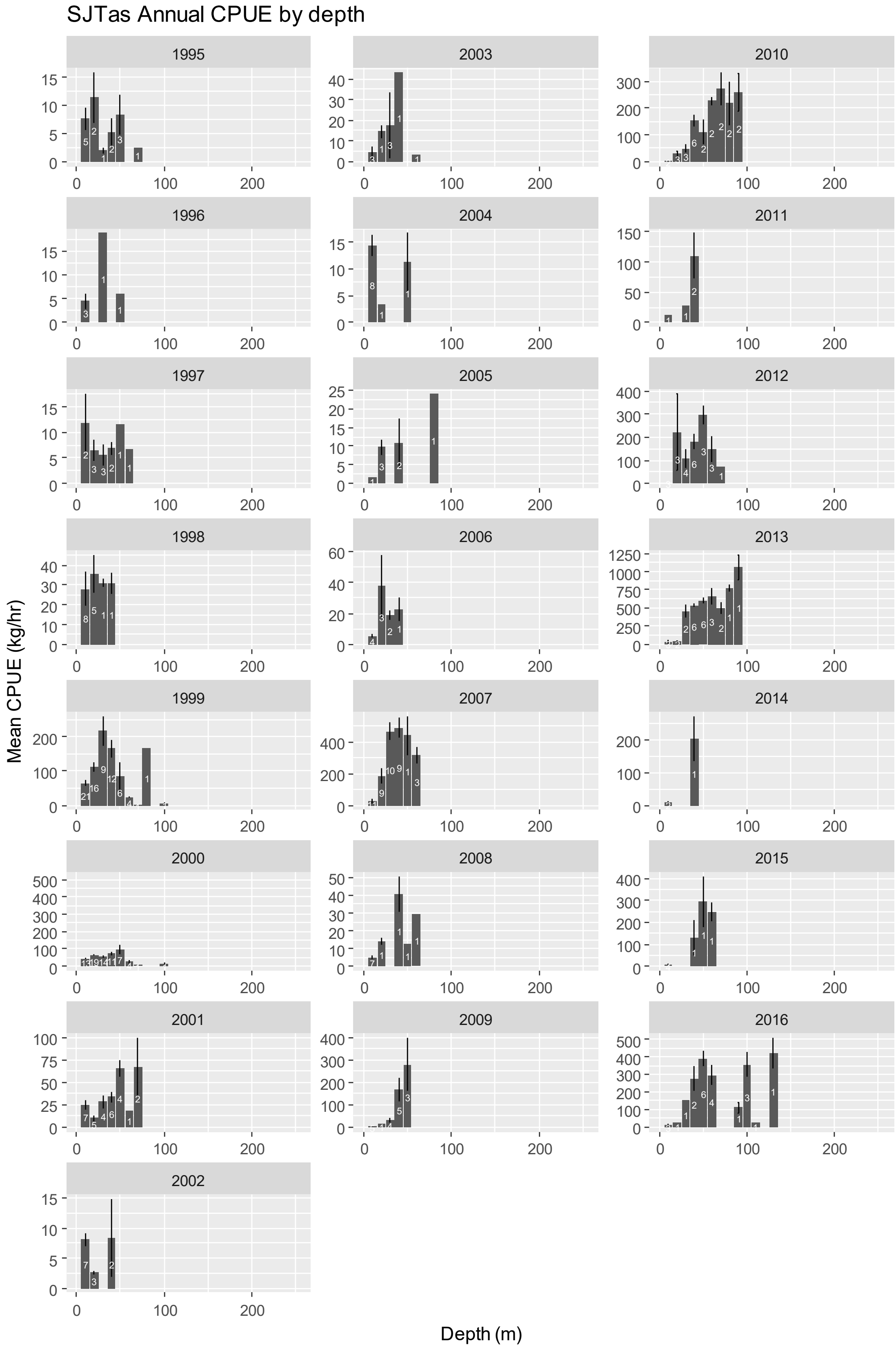
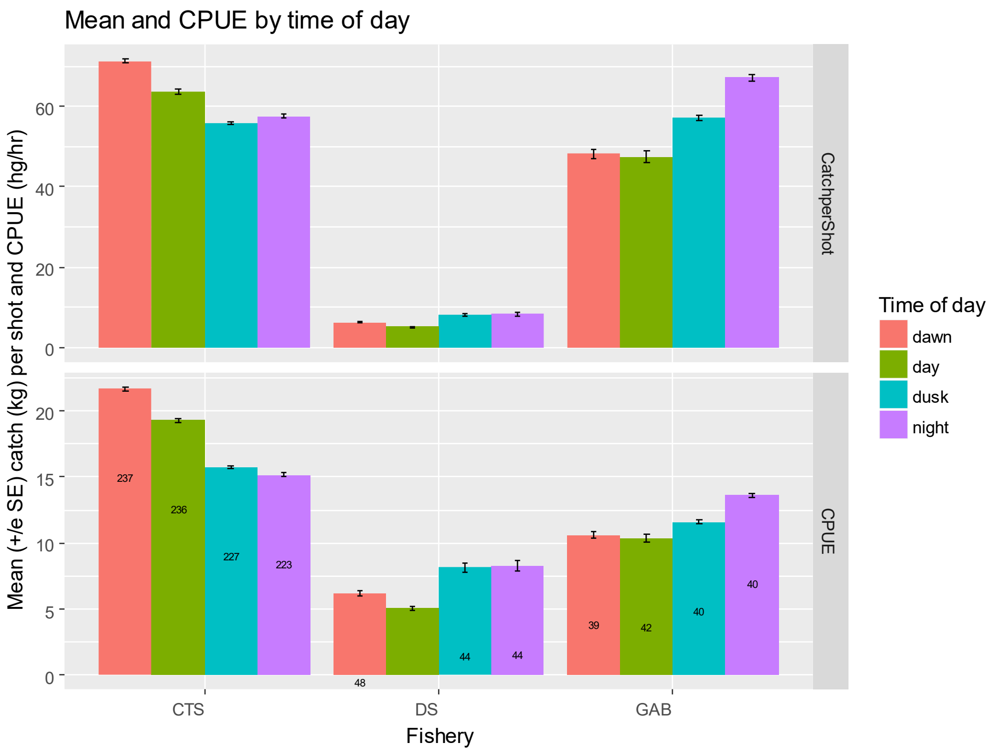


Figure 40. Mean CPUE by year and depth in the TasSJ.



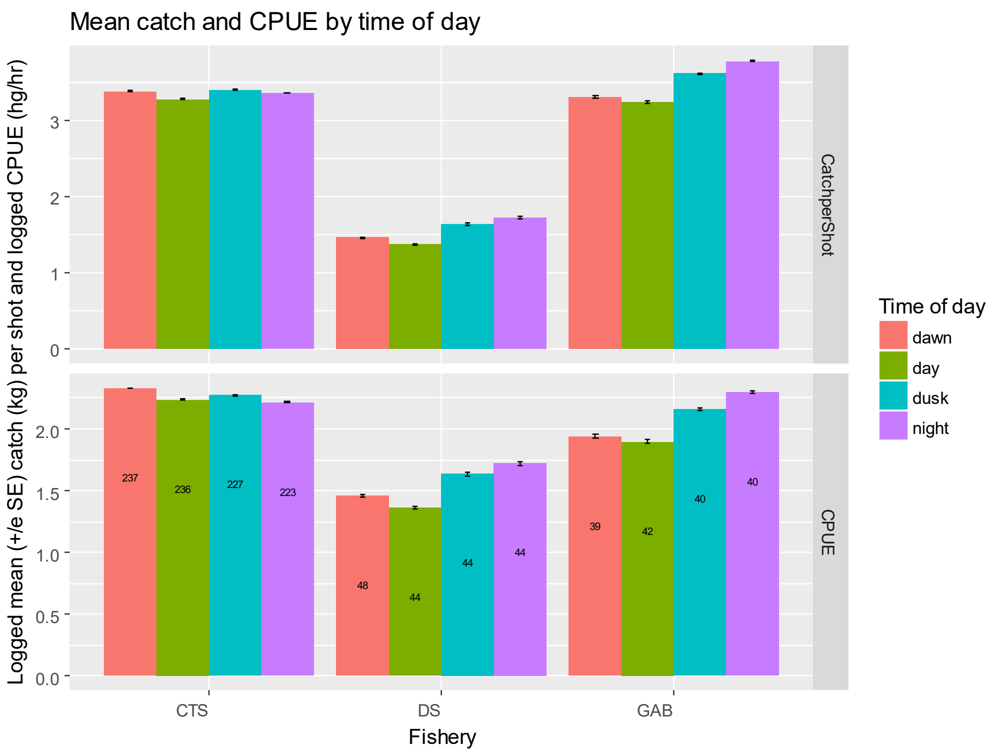
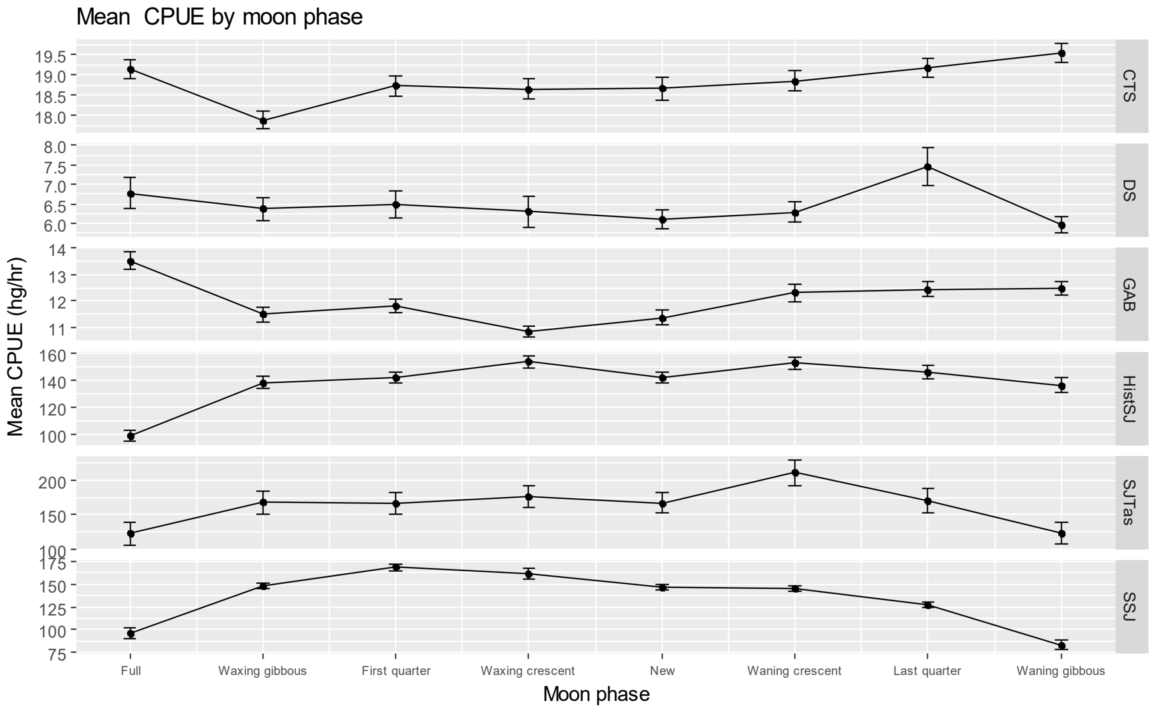


Figure 41. Upper panel: Mean catch per shot and CPUE by time of day in the CTS, DS and GABTS. Lower panel: Mean logged catch per shot and logged CPUE by time of day in the CTS, DS and GABTS. Diel periods are: dawn=03:00–09:00; day = 09:00–15:00; dusk 15:00–21:00; and night 21:00–03:00.



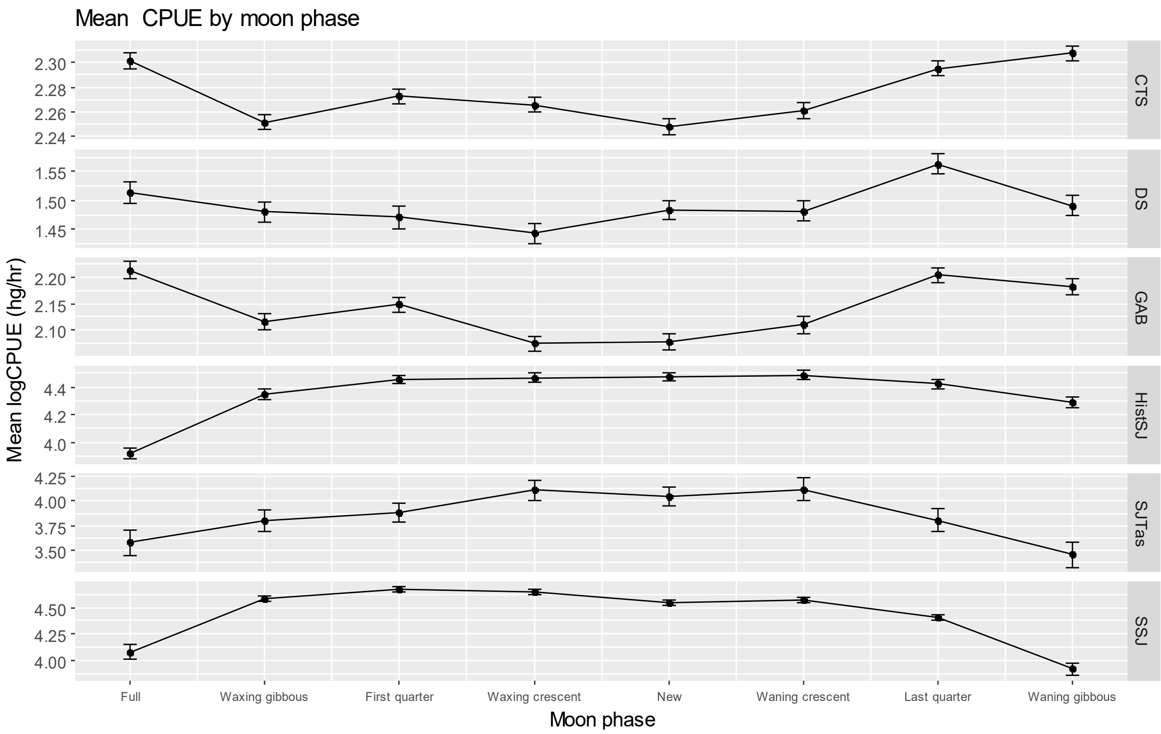


Figure 42. Mean logCPUE by moon phase in each fishery.

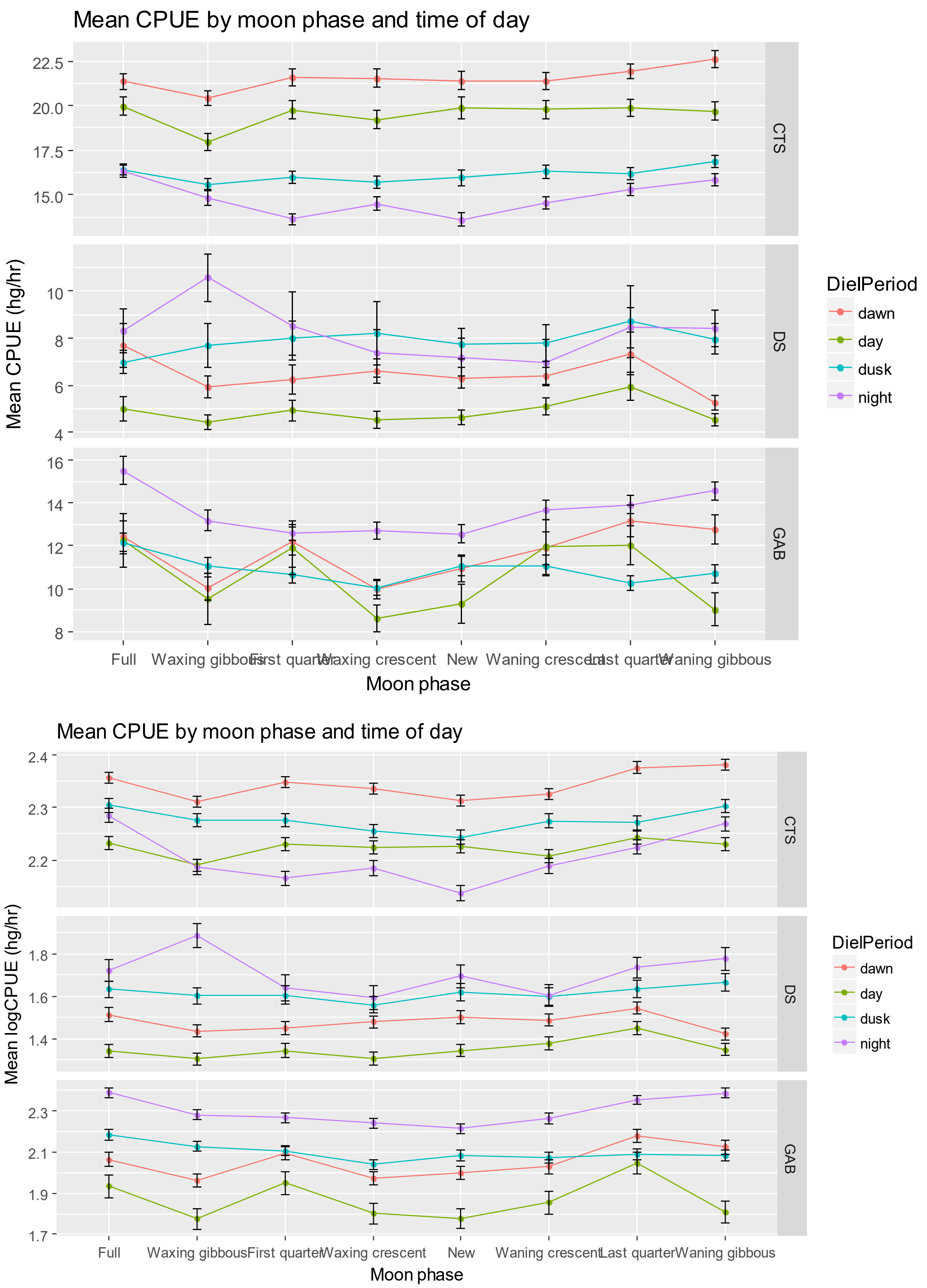


Figure 43. Mean CPUE by time of day and moon phase in the CTS, DS and GABTS; and mean logCPUE by time of day and moon phase in the CTS, DS and GABTS.

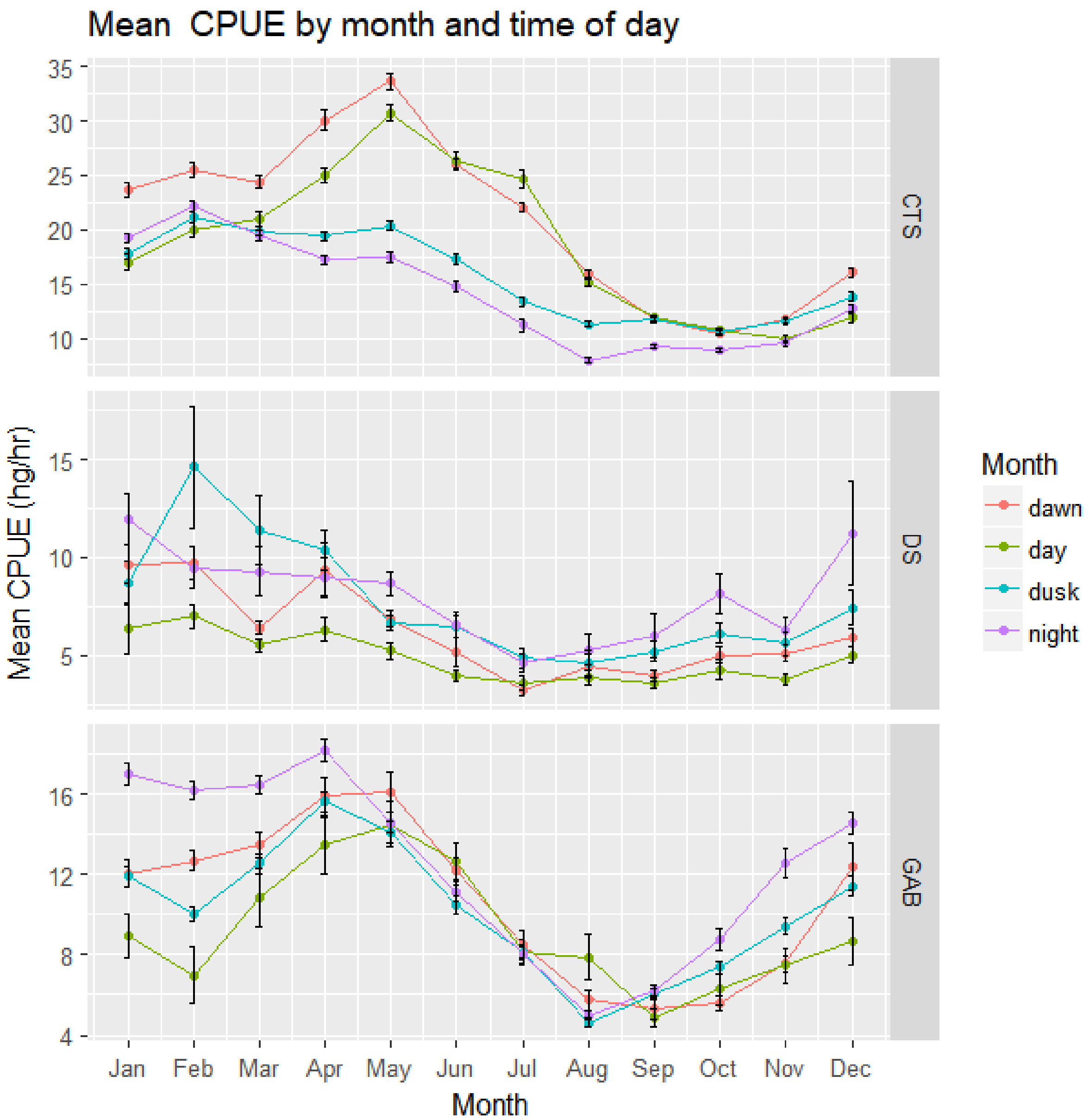


Figure 44. Mean monthly CPUE by time of day in the trawl fisheries (note that CPUE for DS is kg per shot.

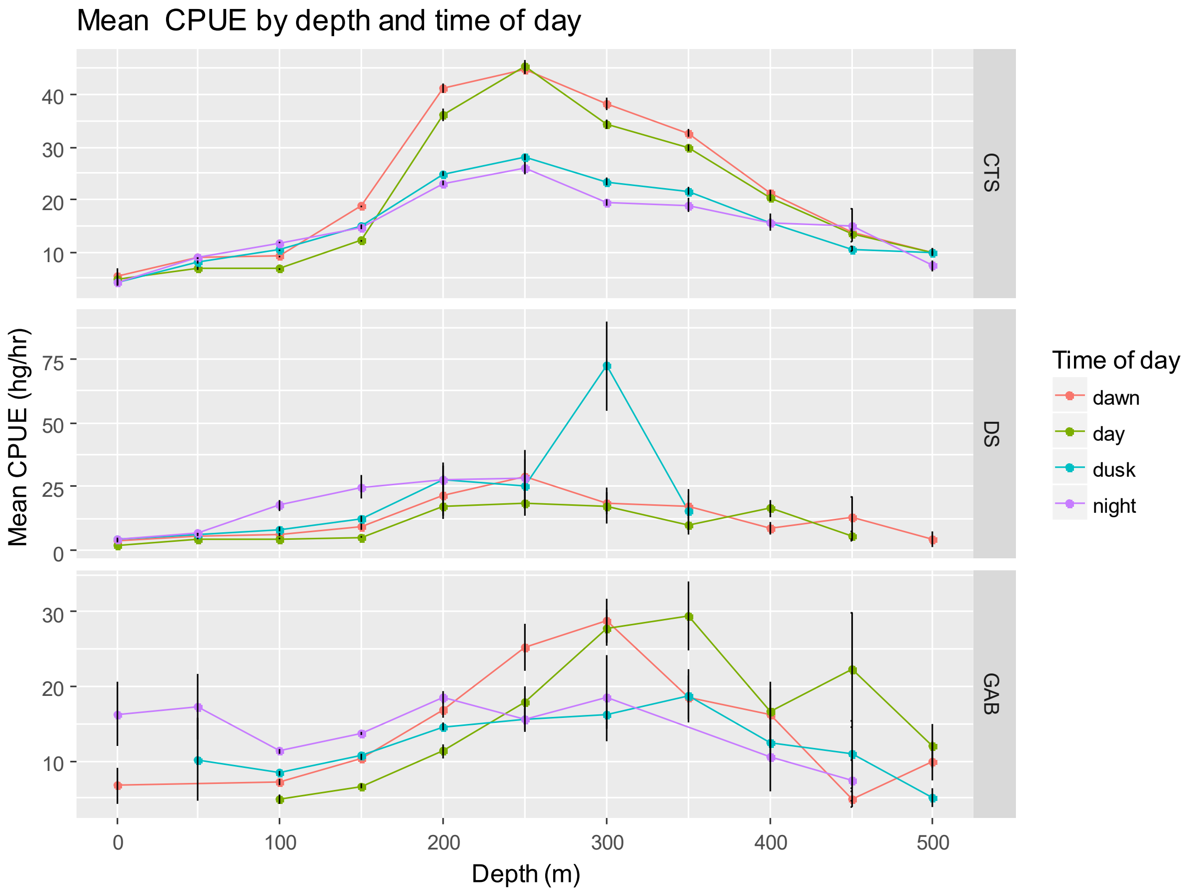


Figure 45. Mean CPUE by time of day and depth in the CTS, DS and GABTS.

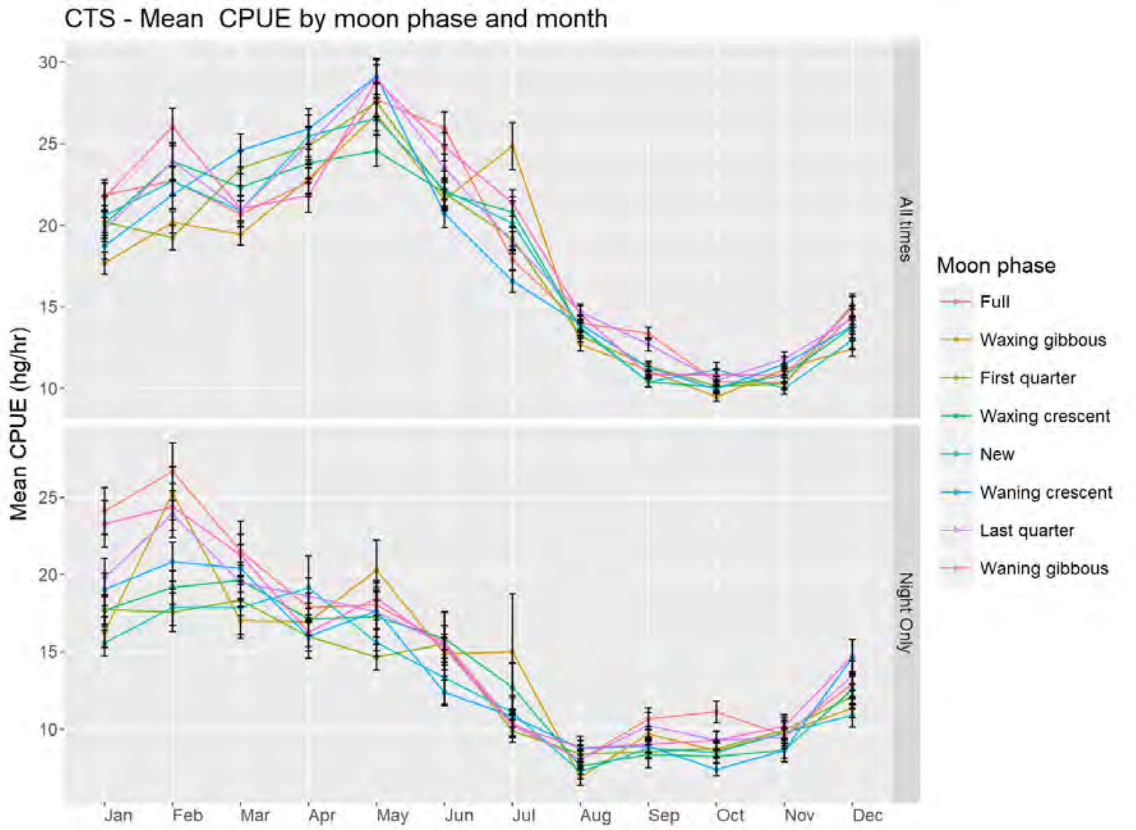


Figure 46. Mean monthly CPUE by moon phase in the CTS.

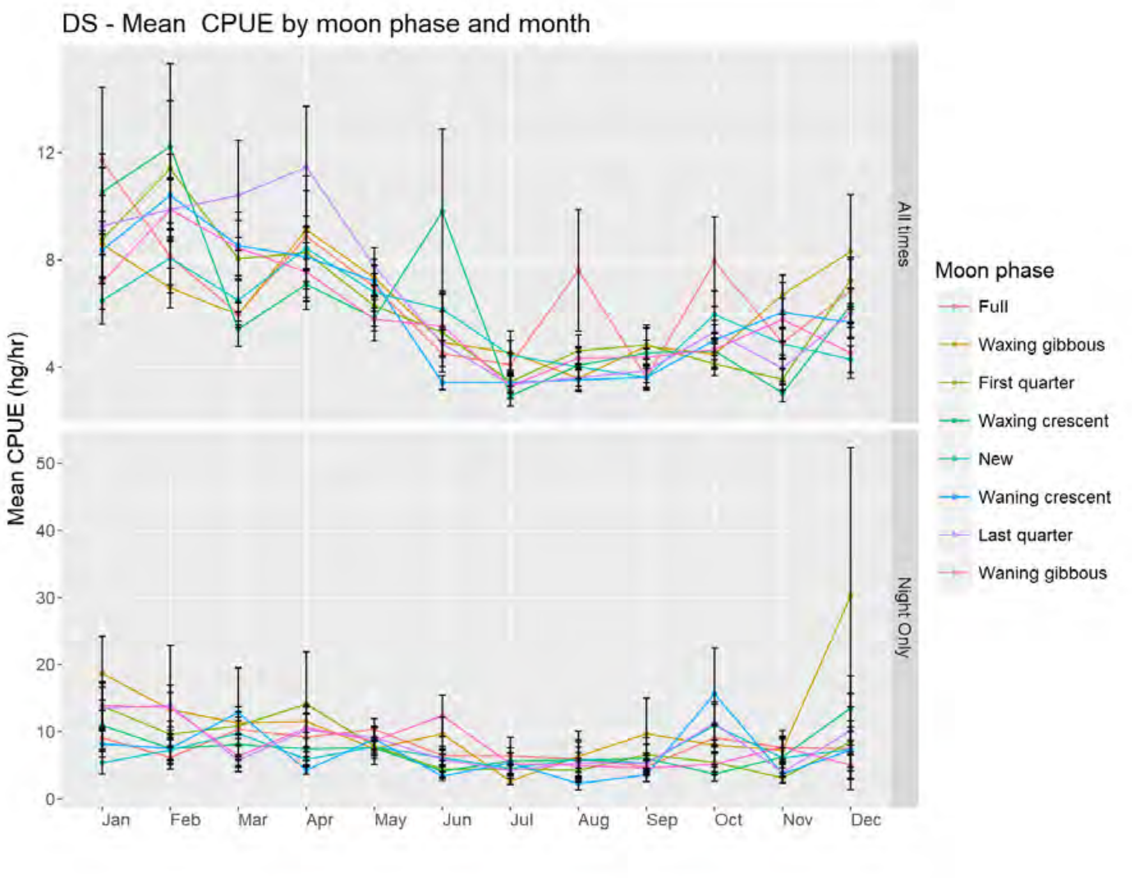


Figure 47. Mean monthly CPUE by moon phase in the DS.

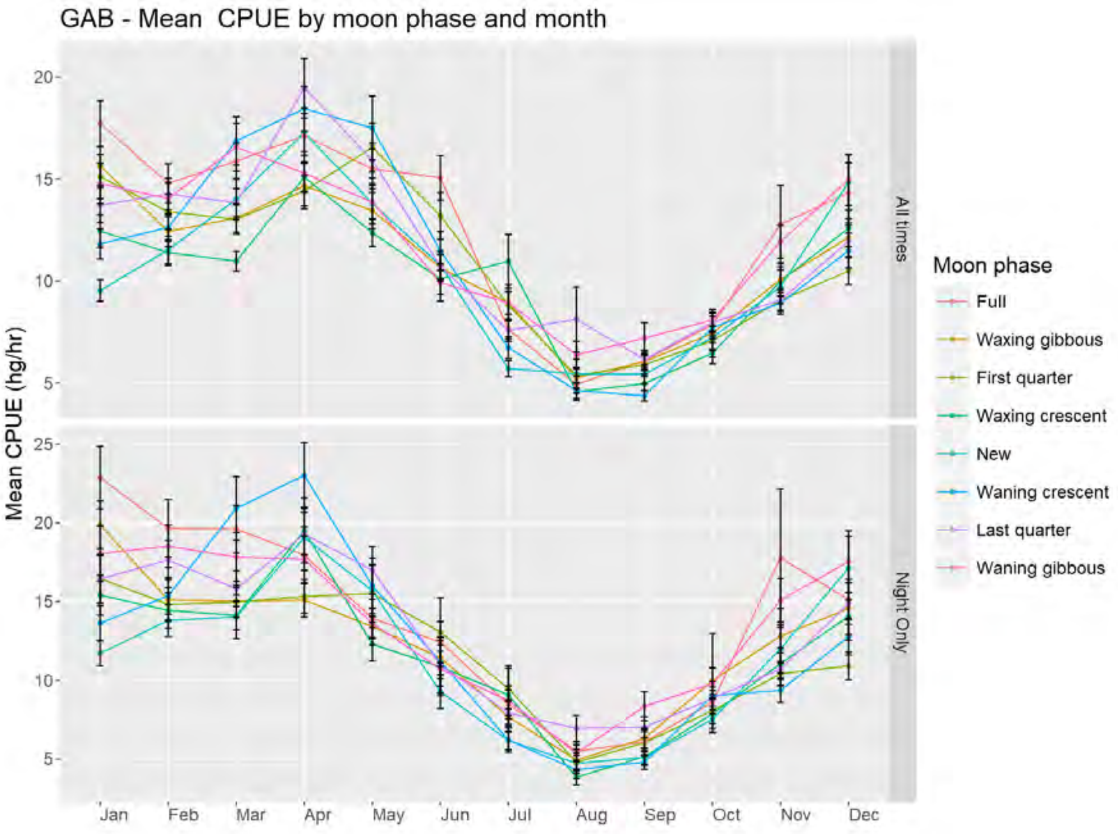


Figure 48. Mean monthly CPUE by moon phase in the GABTS.

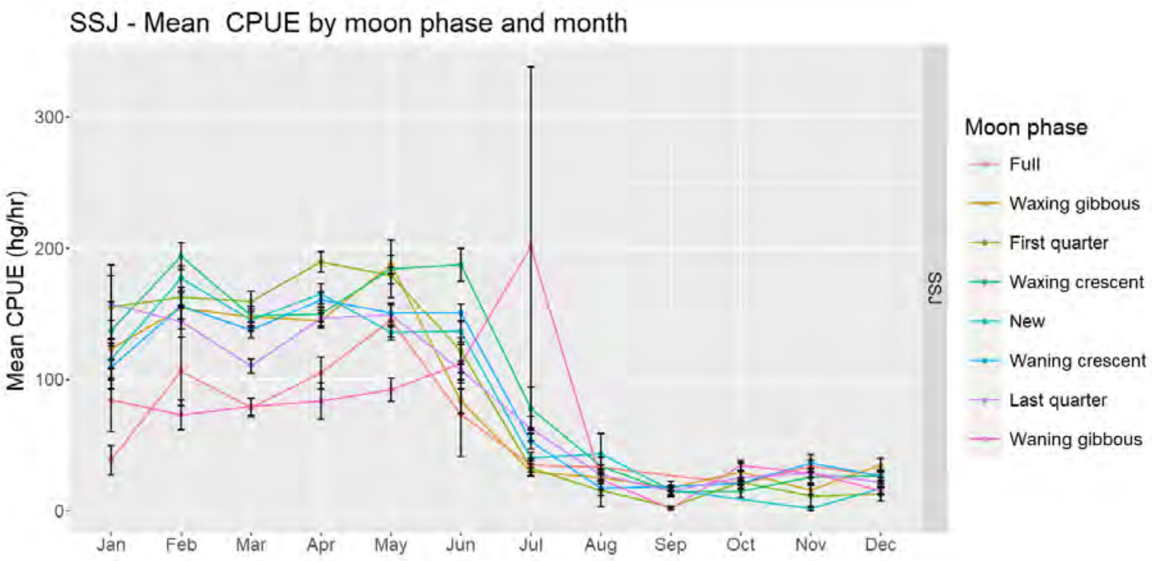


Figure 49. Mean monthly CPUE by moon phase in the SSJF.

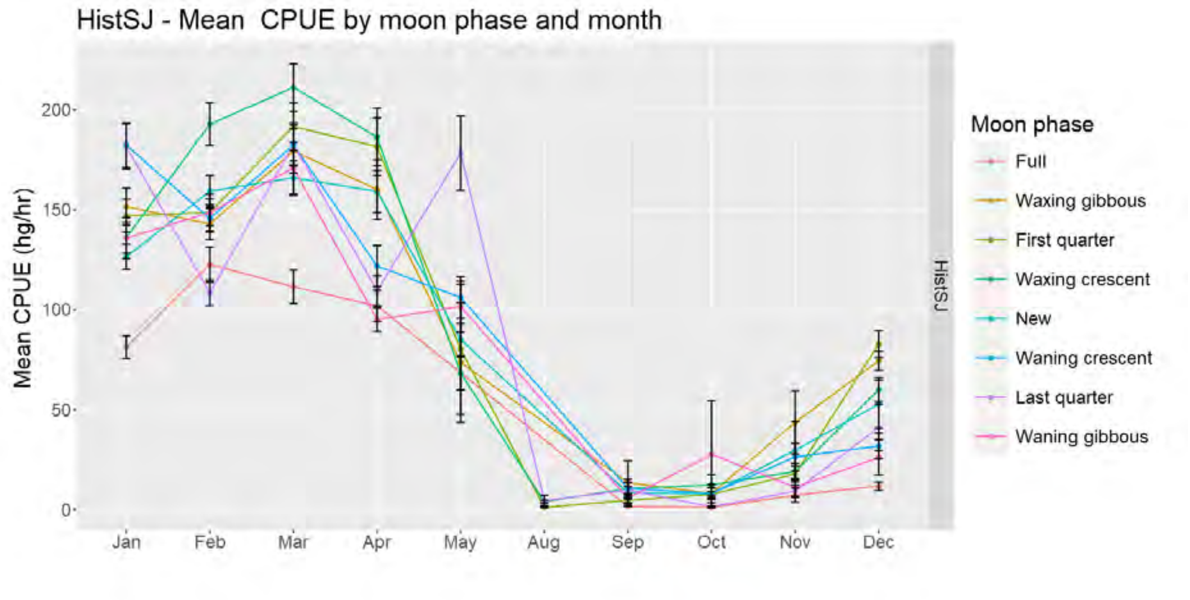


Figure 50. Mean monthly CPUE by moon phase in the HistSJ. Note there were no data points for June of July.

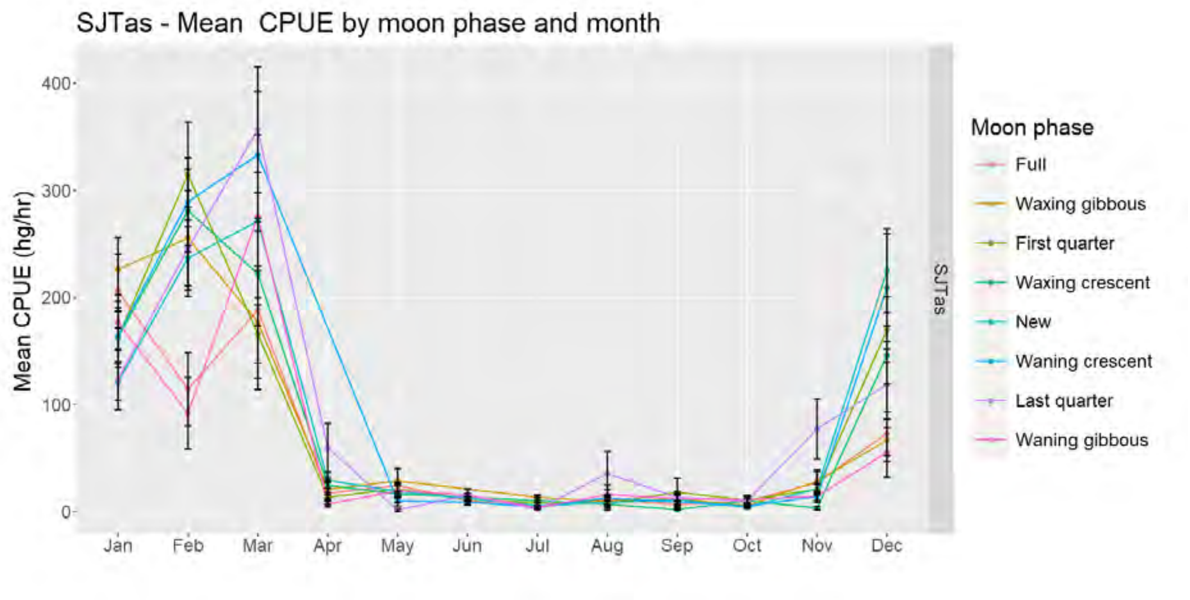


Figure 51. Mean monthly CPUE by moon phase in the SJTas.

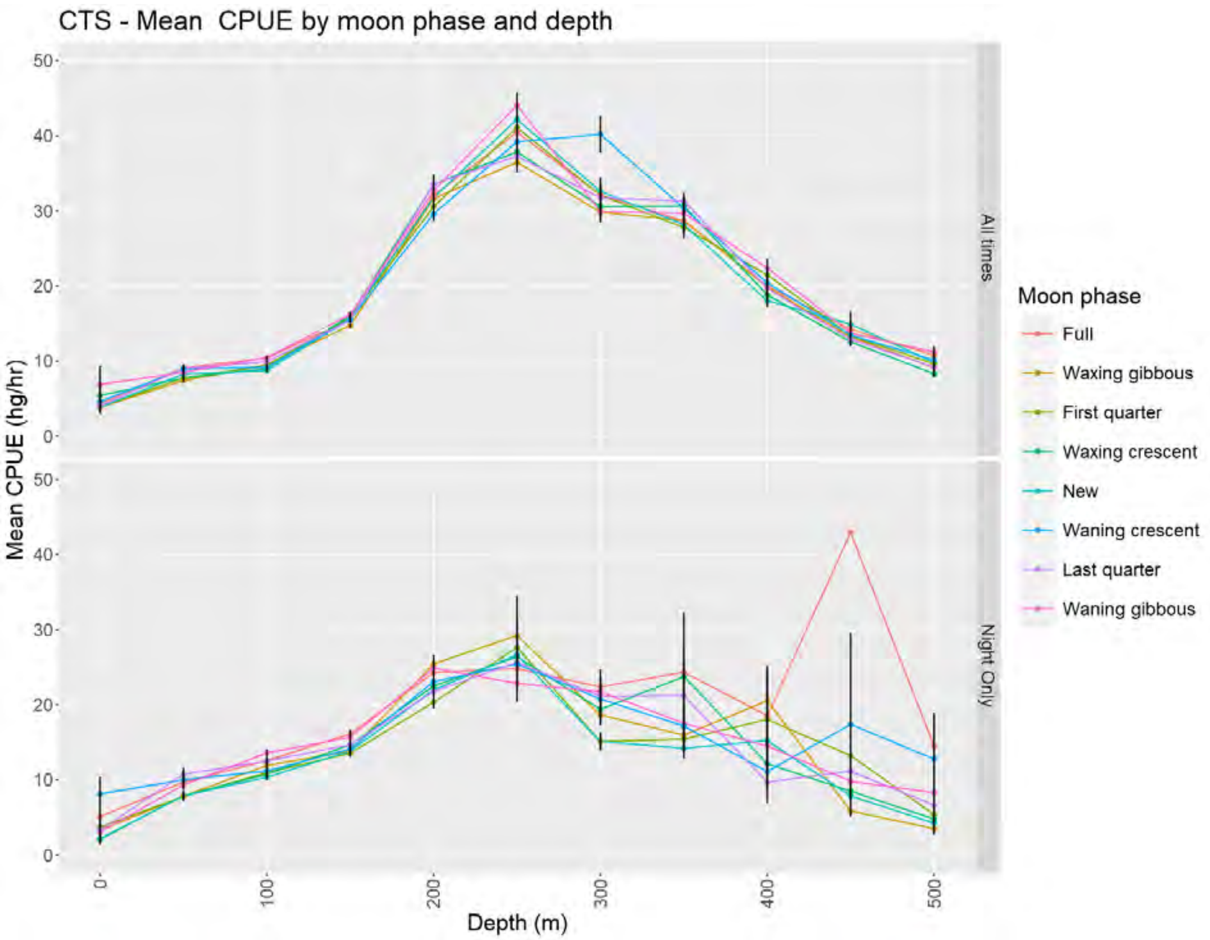


Figure 52. Mean CPUE by depth and moon phase in the CTS at all times of day and at night only.

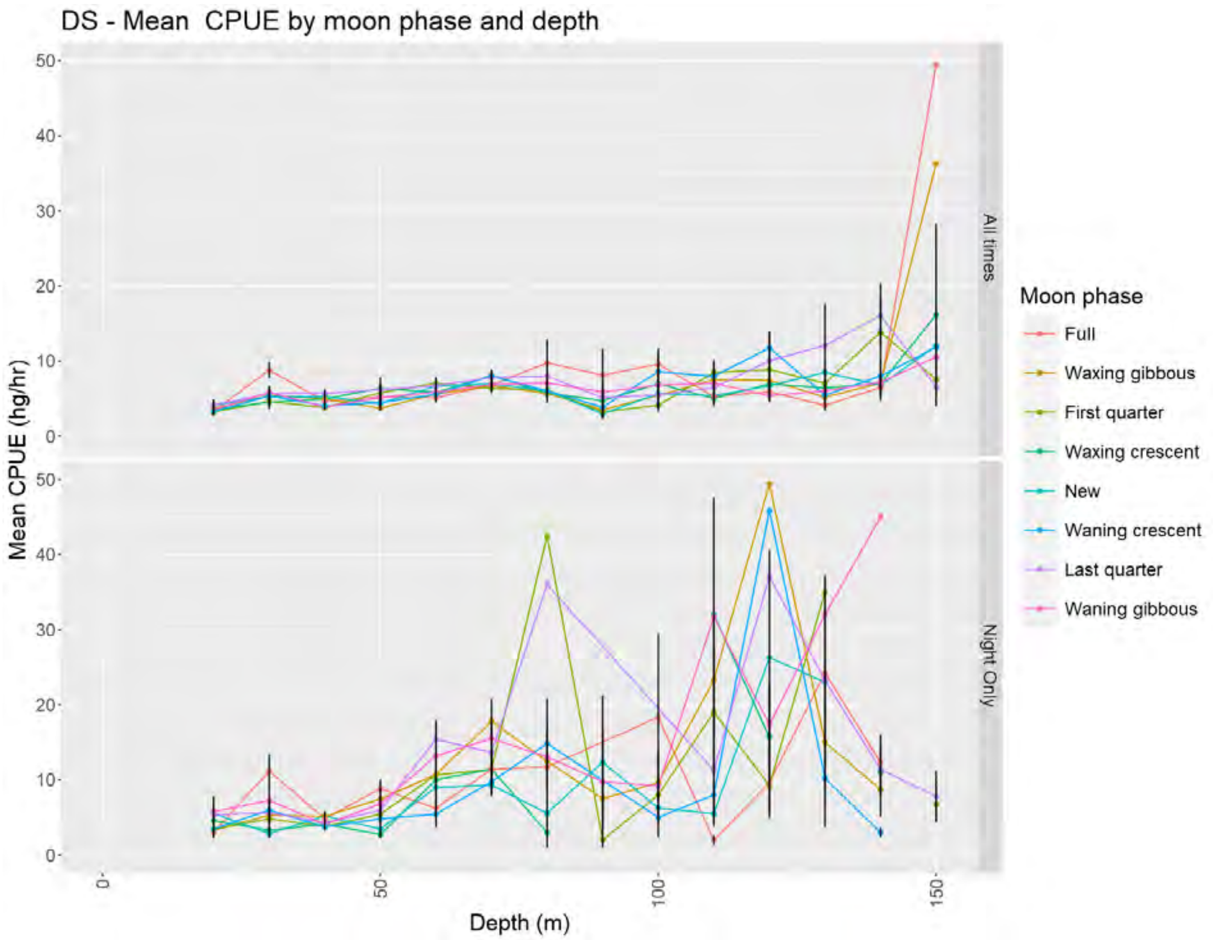


Figure 53. Mean CPUE by depth and moon phase in the DS at all times of day and at night only.

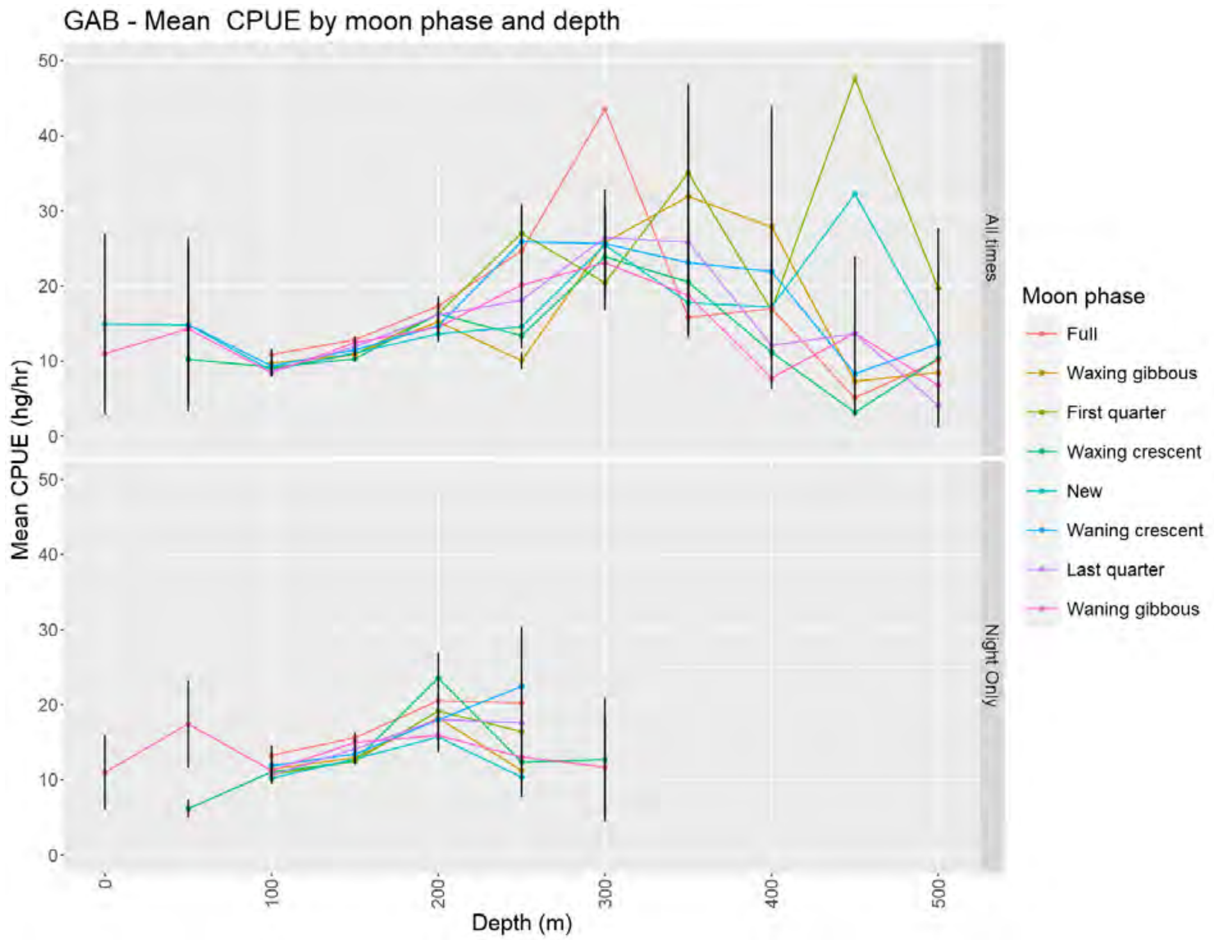


Figure 54. Mean CPUE by depth and moon phase in the GABTS at all times of day and at night only.

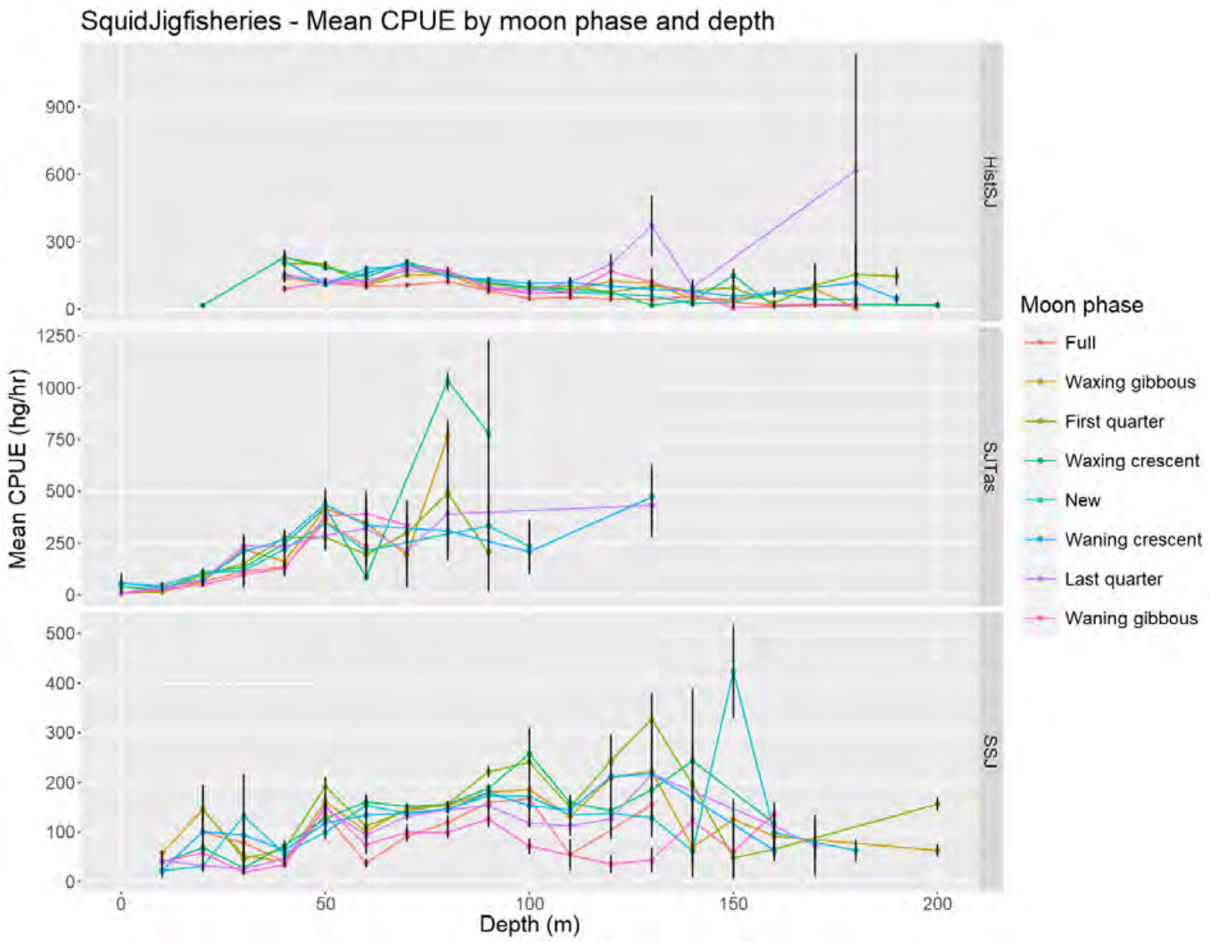


Figure 55. Mean CPUE by depth and moon phase in the SSJF. Note that a limit of 200 m was imposed on the x-axis.

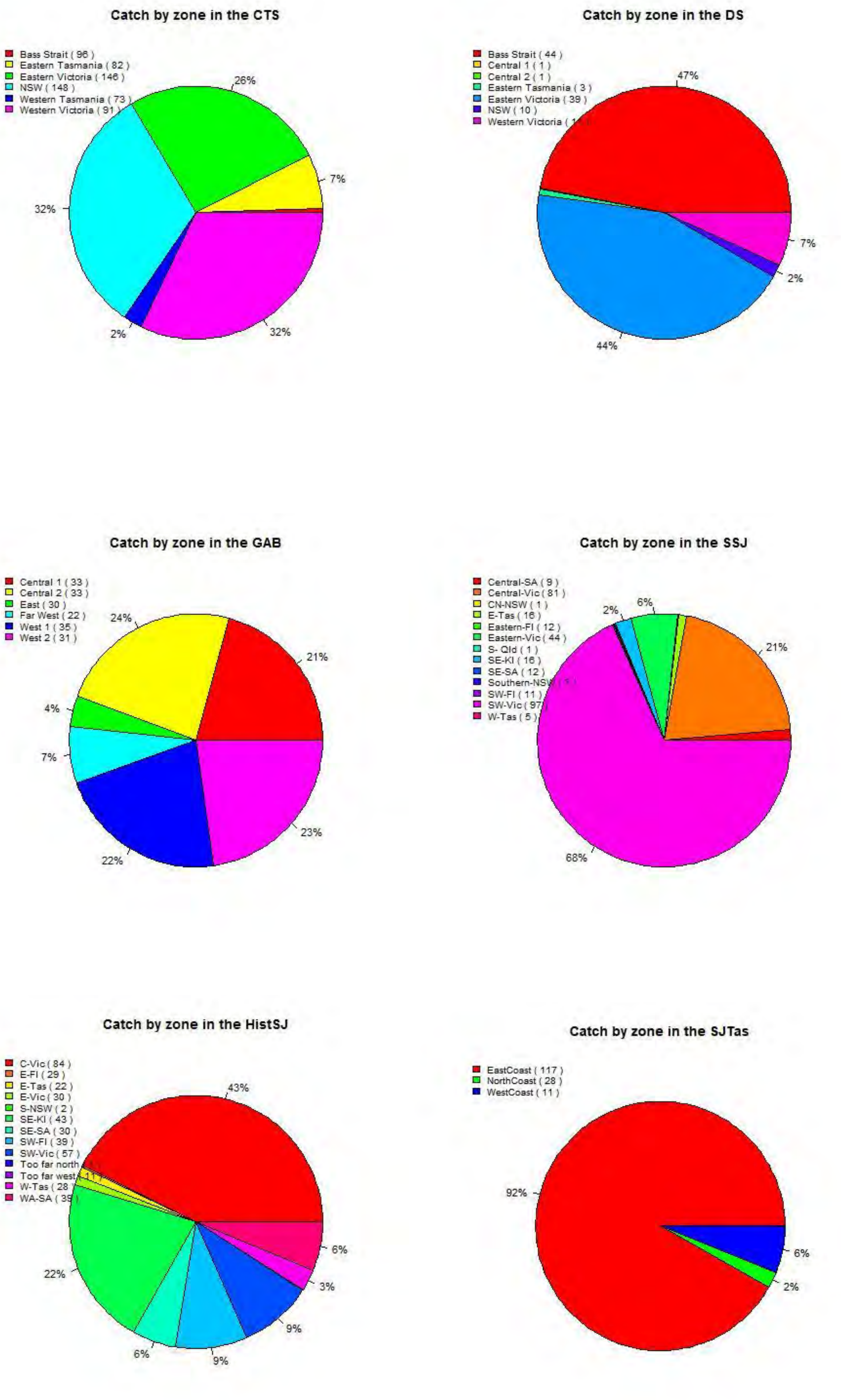
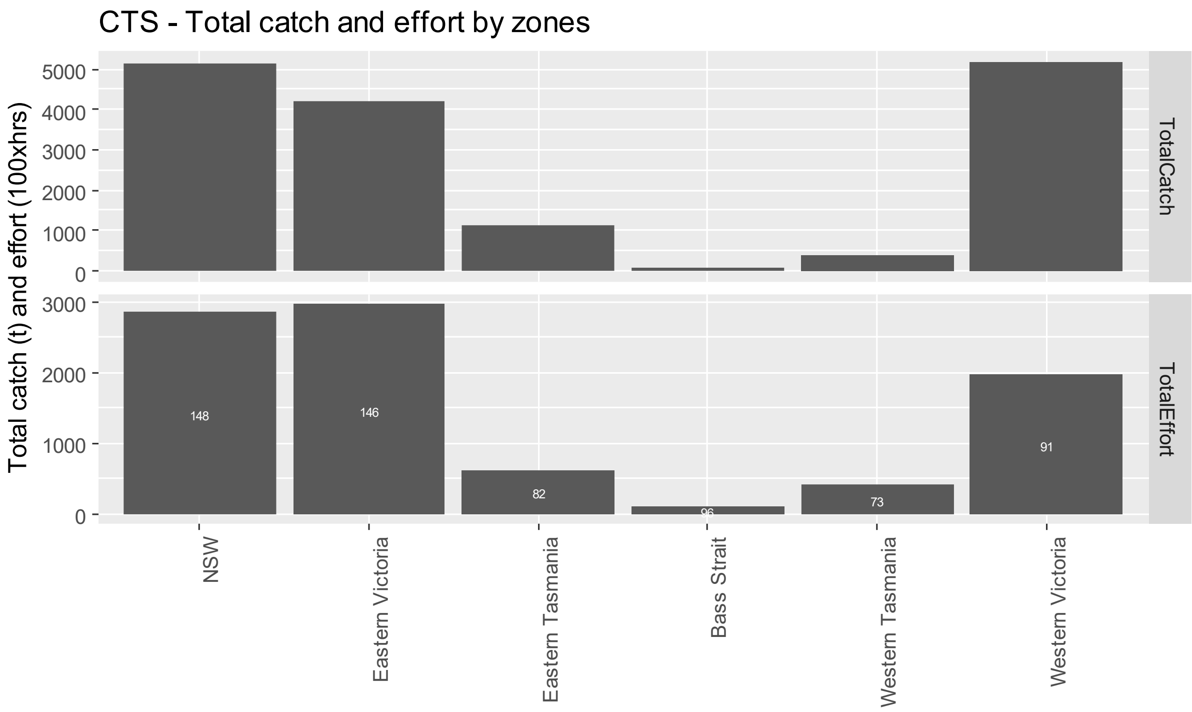


Figure 56. Distribution of catch of Gould's Squid by zone in the CTS, DS, GABTS, SSJF, HistSJ Fishery and SJTas.



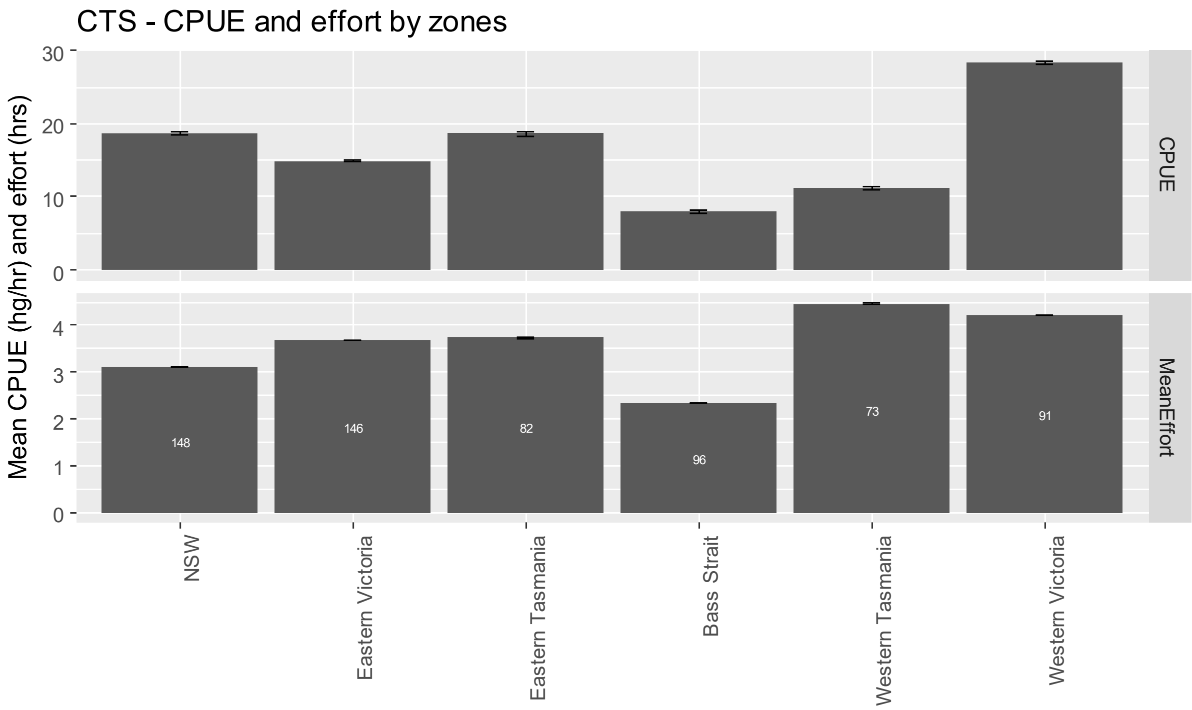


Figure 57. Top panel: total catch and effort in each zone by the CTS; and bottom panel: mean CPUE and effort by zone in the CTS.

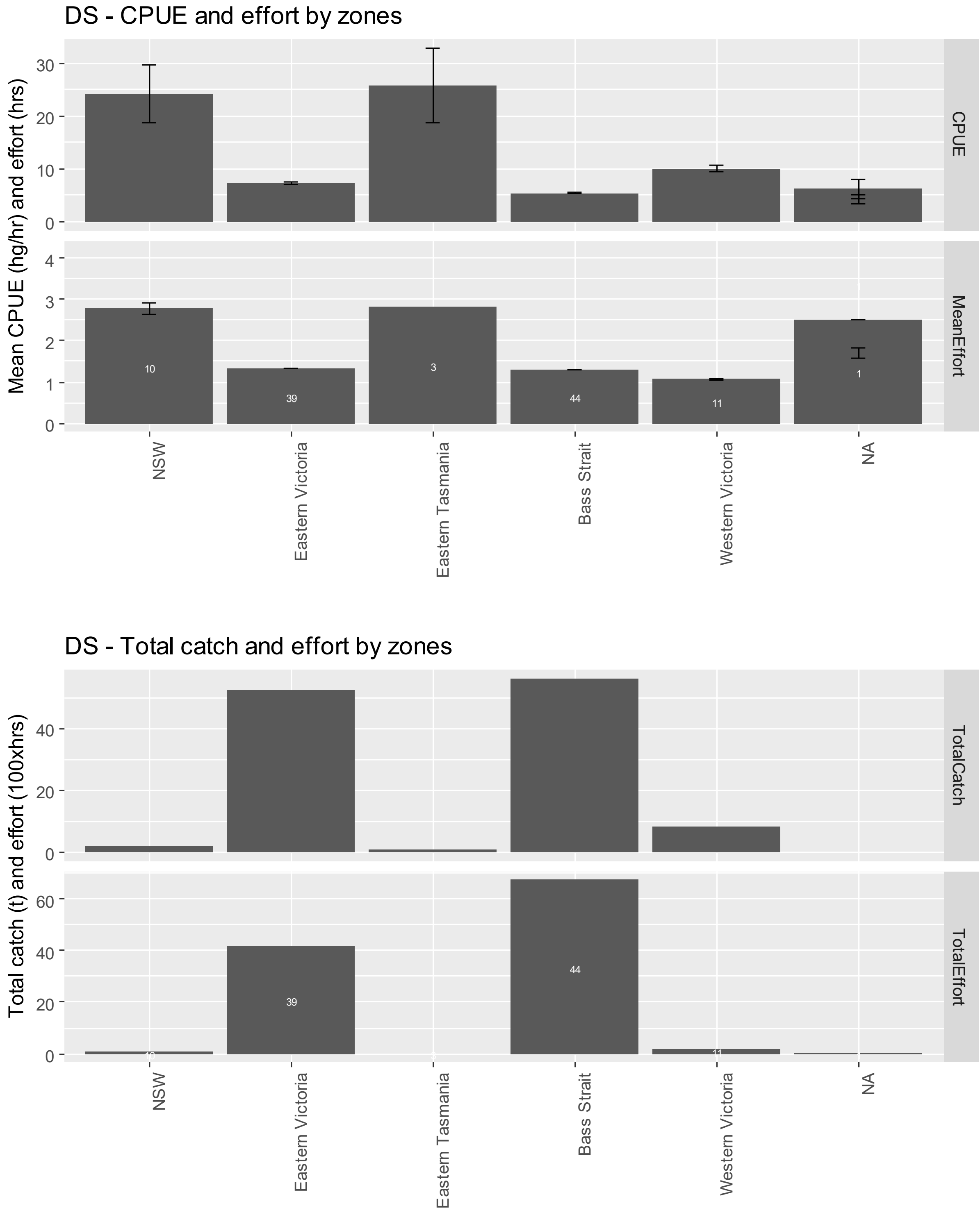
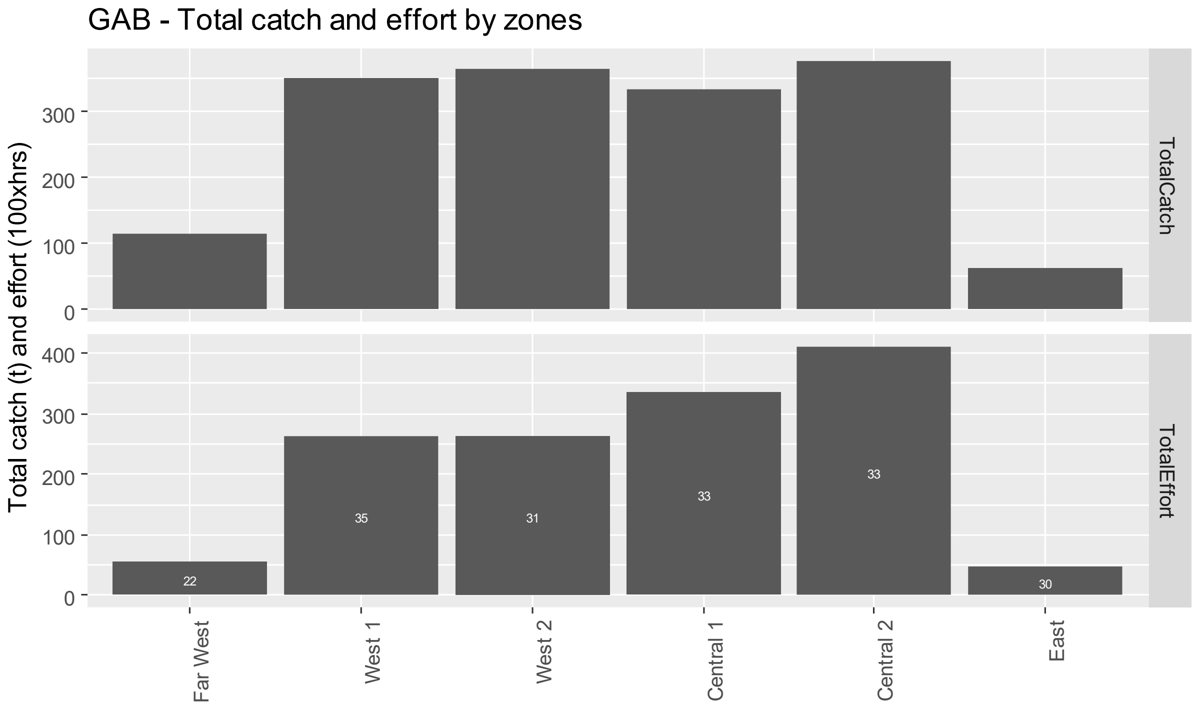


Figure 58. Top panel: total catch and effort in each zone by the DS; and bottom panel: mean CPUE and effort by zone in the DS.



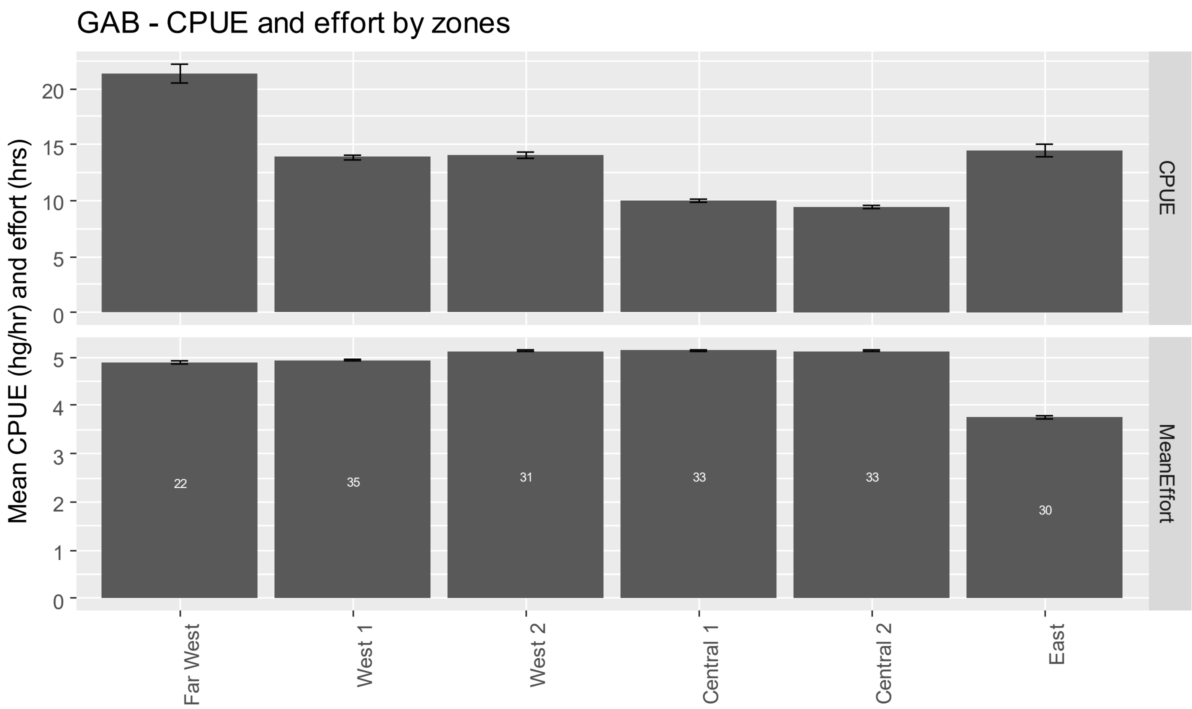
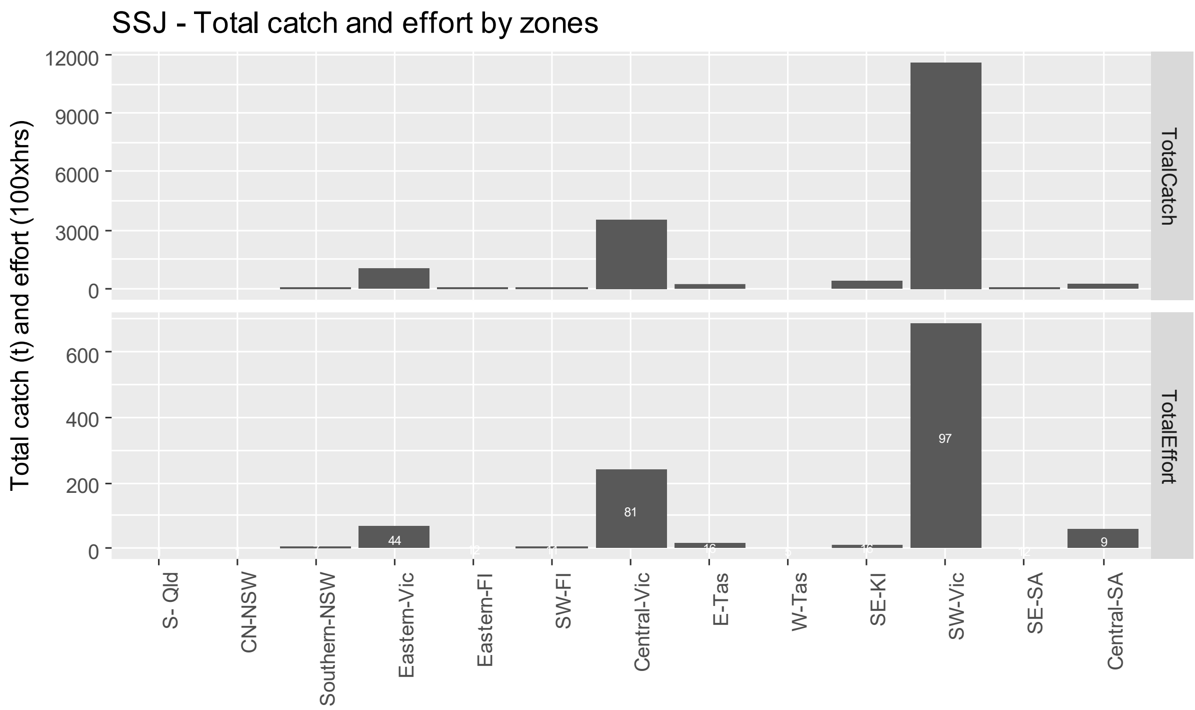


Figure 59. Top panel: total catch and effort in each zone by the GABTS; and bottom panel: mean CPUE and effort by zone in the GABTS.



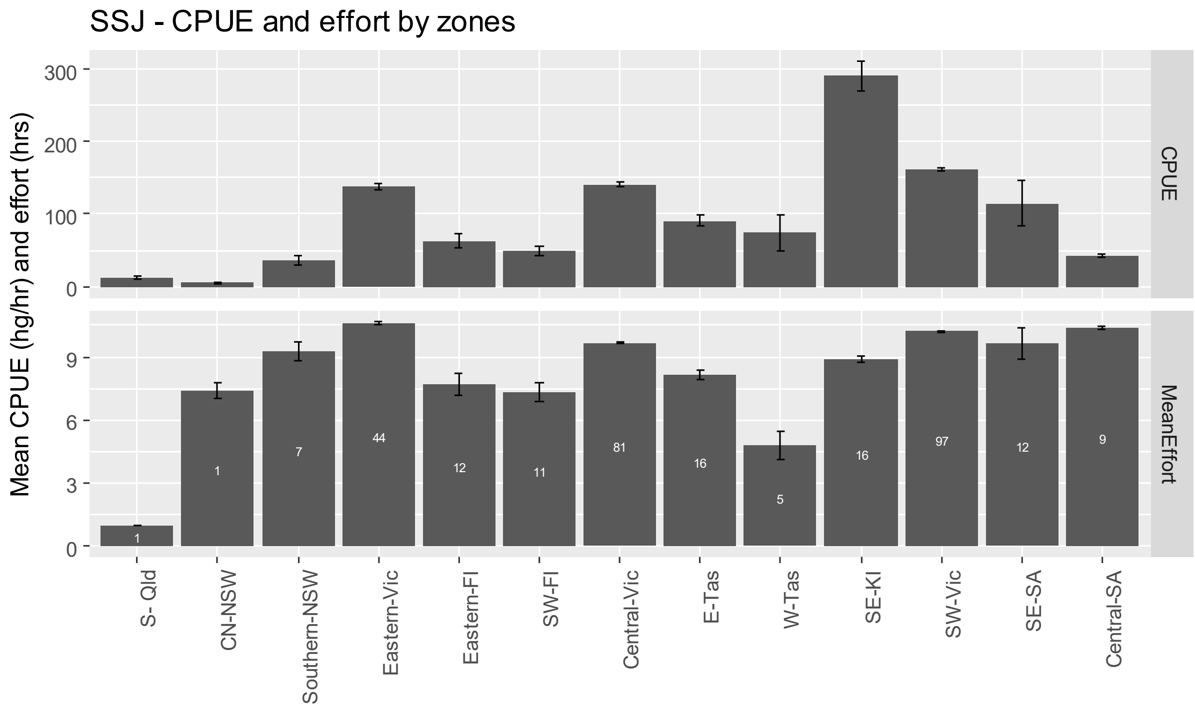
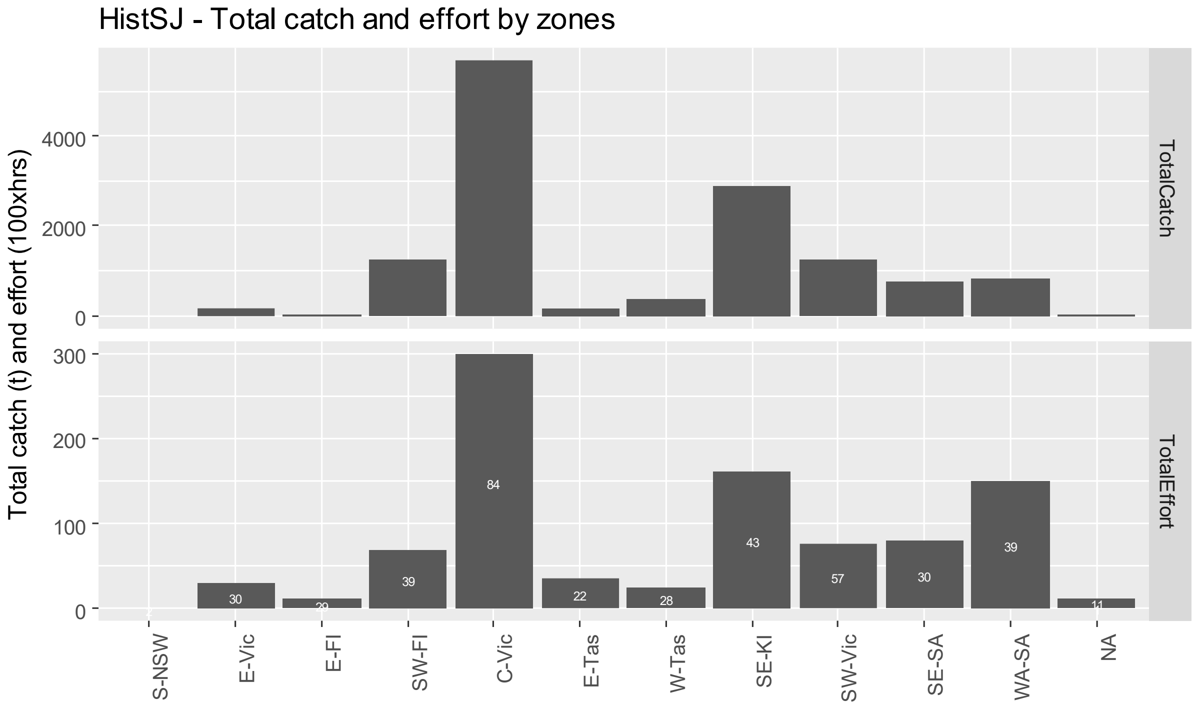


Figure 60. Top panel: total catch and effort in each zone by the SSJF; and bottom panel: mean CPUE and mean effort by zone in the SSJF.



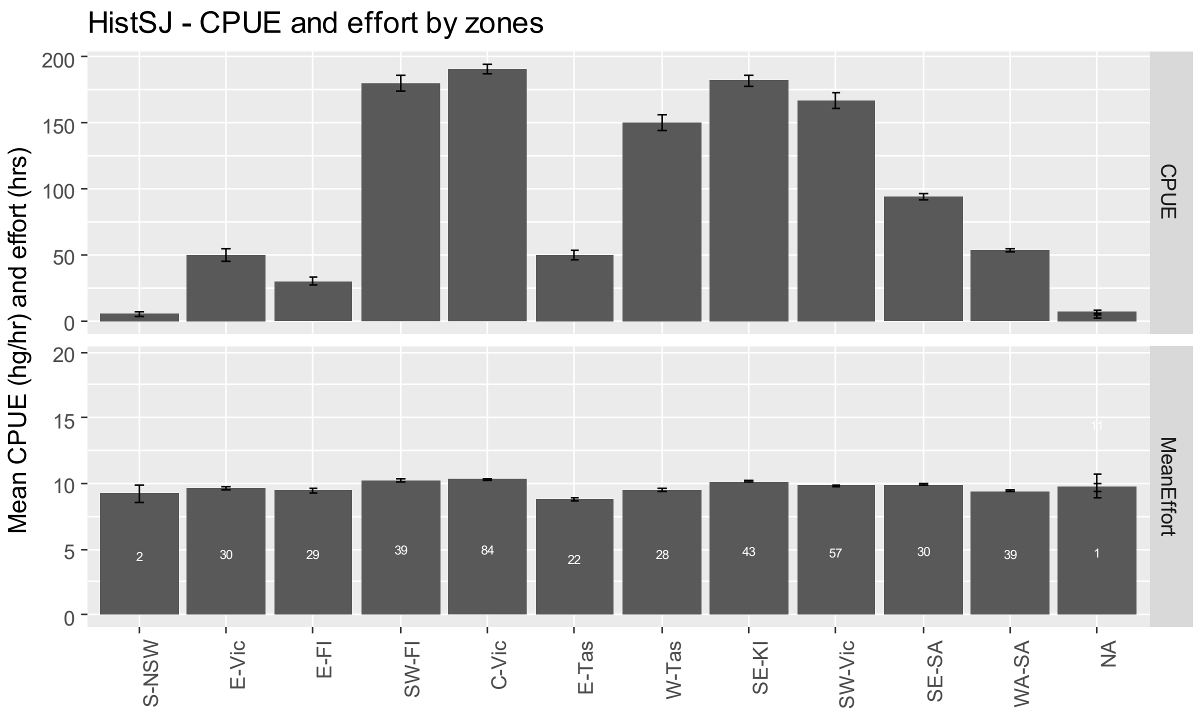


Figure 61. Top panel: total catch and effort in each zone by the HistSJ Fishery; and bottom panel: mean CPUE and mean effort by zone in the HistSJ Fishery.

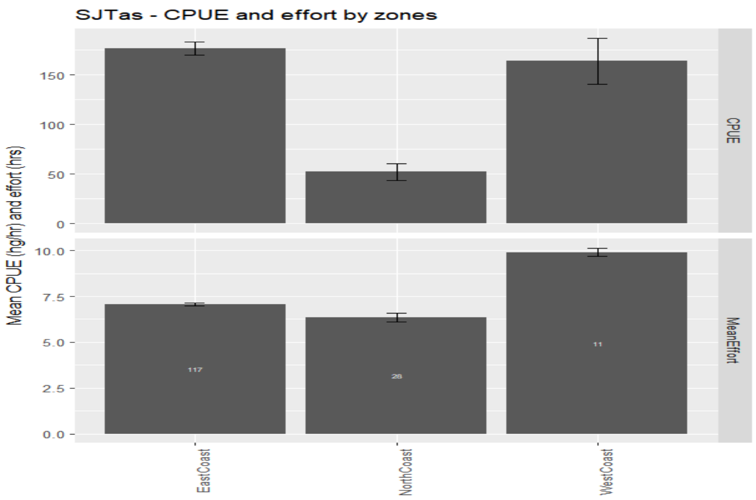


Figure 62. Mean CPUE and mean effort by zone in the SJTas Fishery.

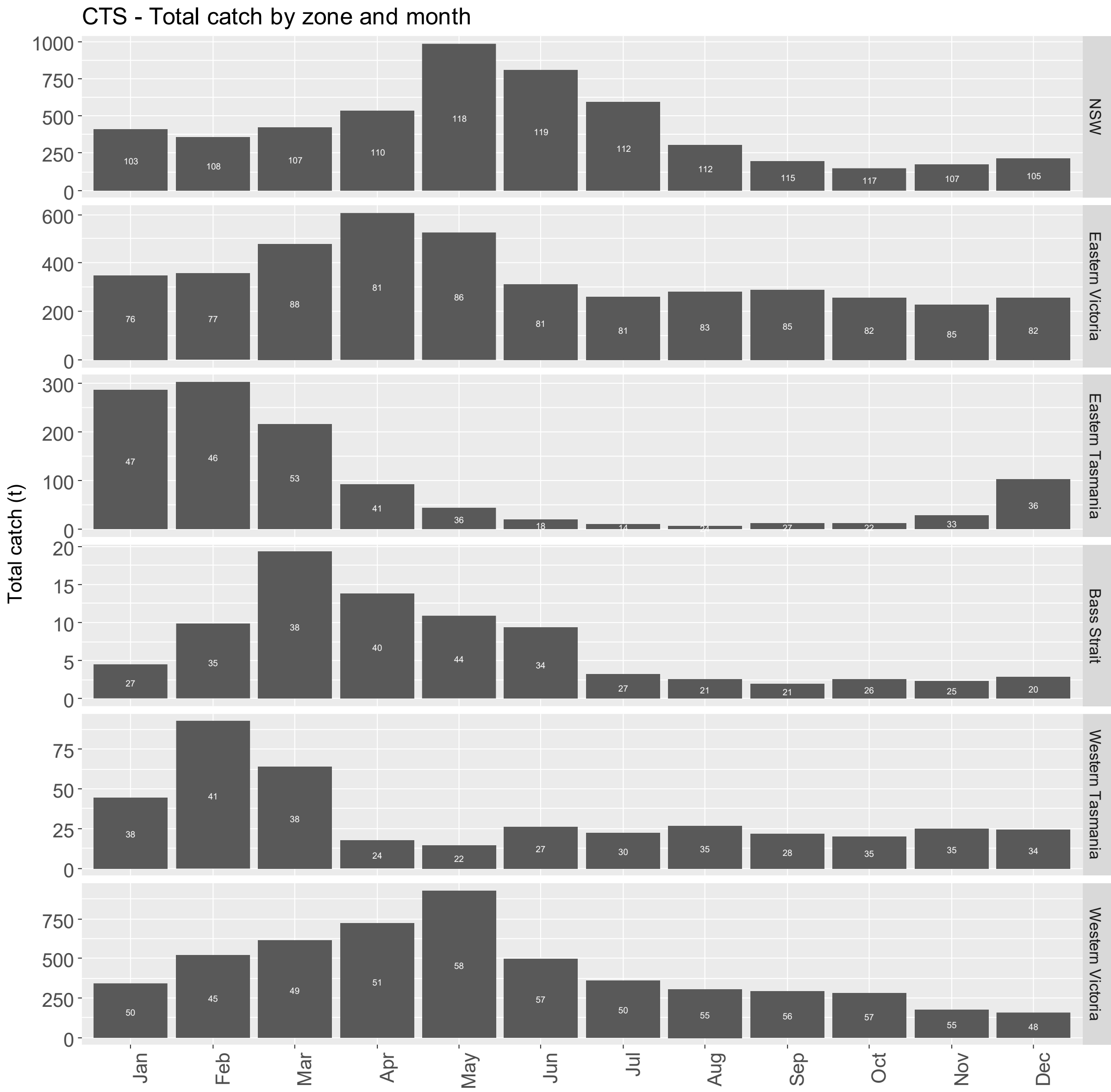


Figure 63. Total catch of Gould's Squid by zone and month in the CTS.

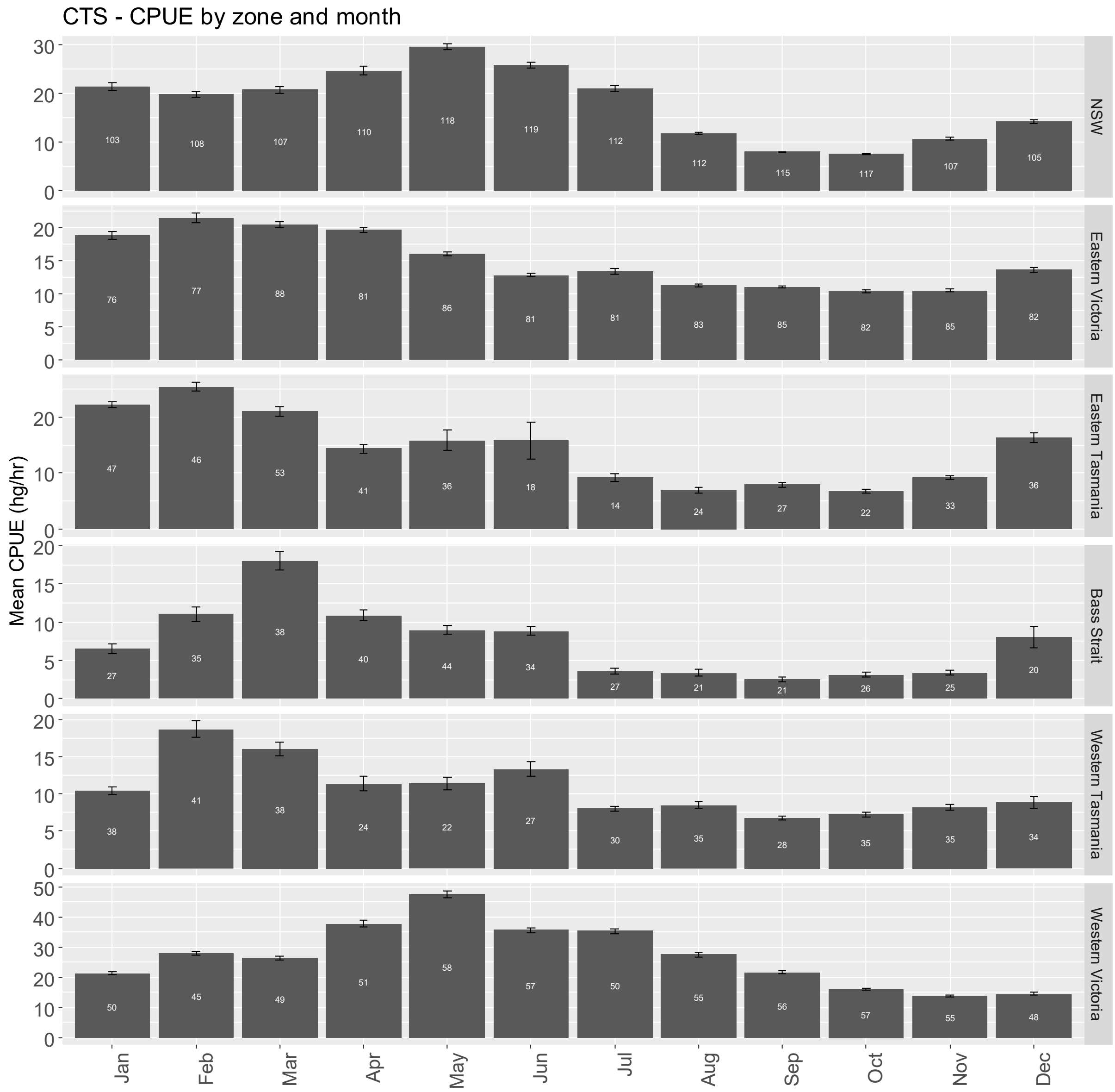


Figure 64. Mean monthly CPUE of Gould's Squid by zone and month in the CTS.

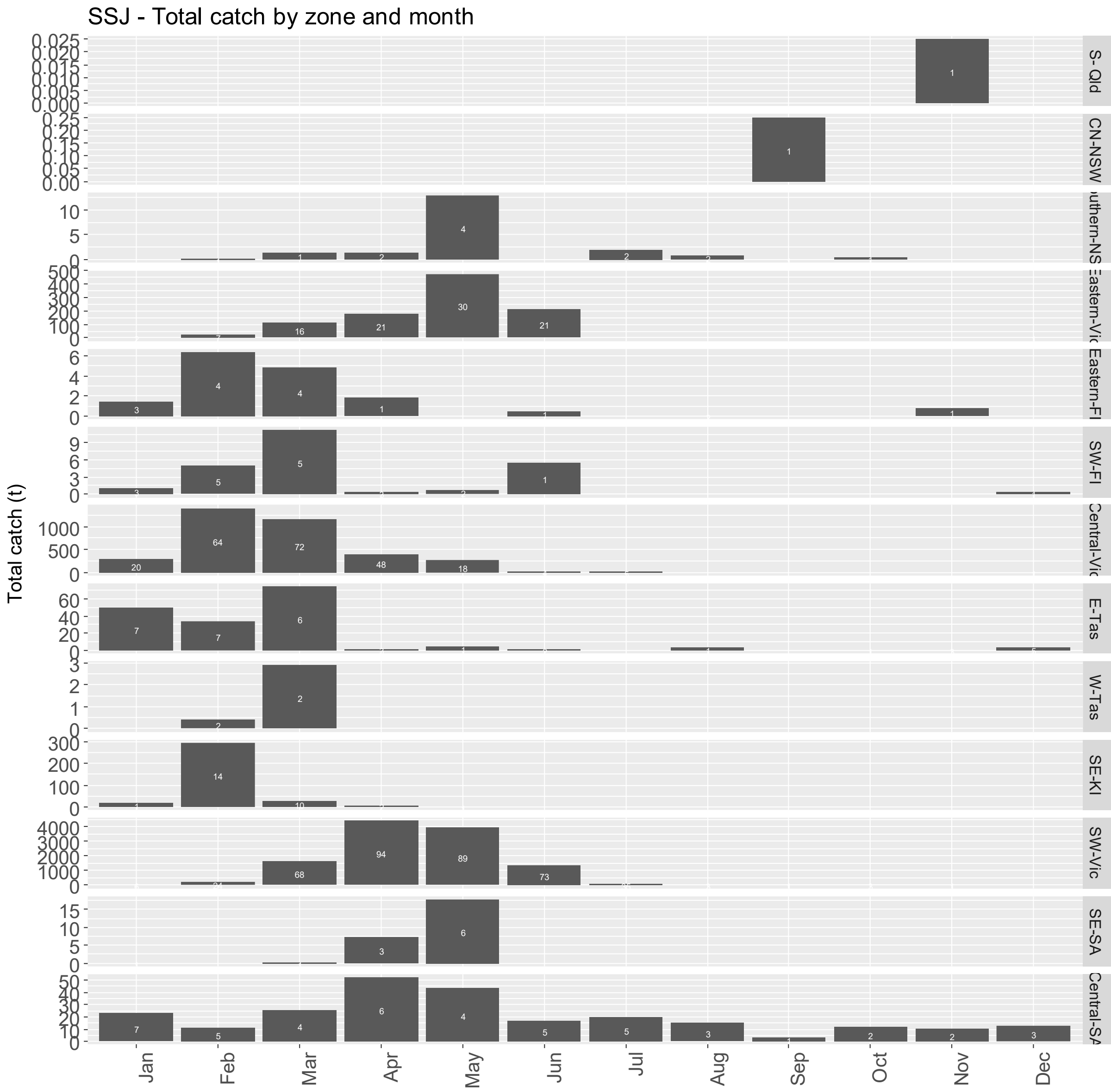


Figure 65. Total catch of Gould's Squid by zone and month in the SSJF.

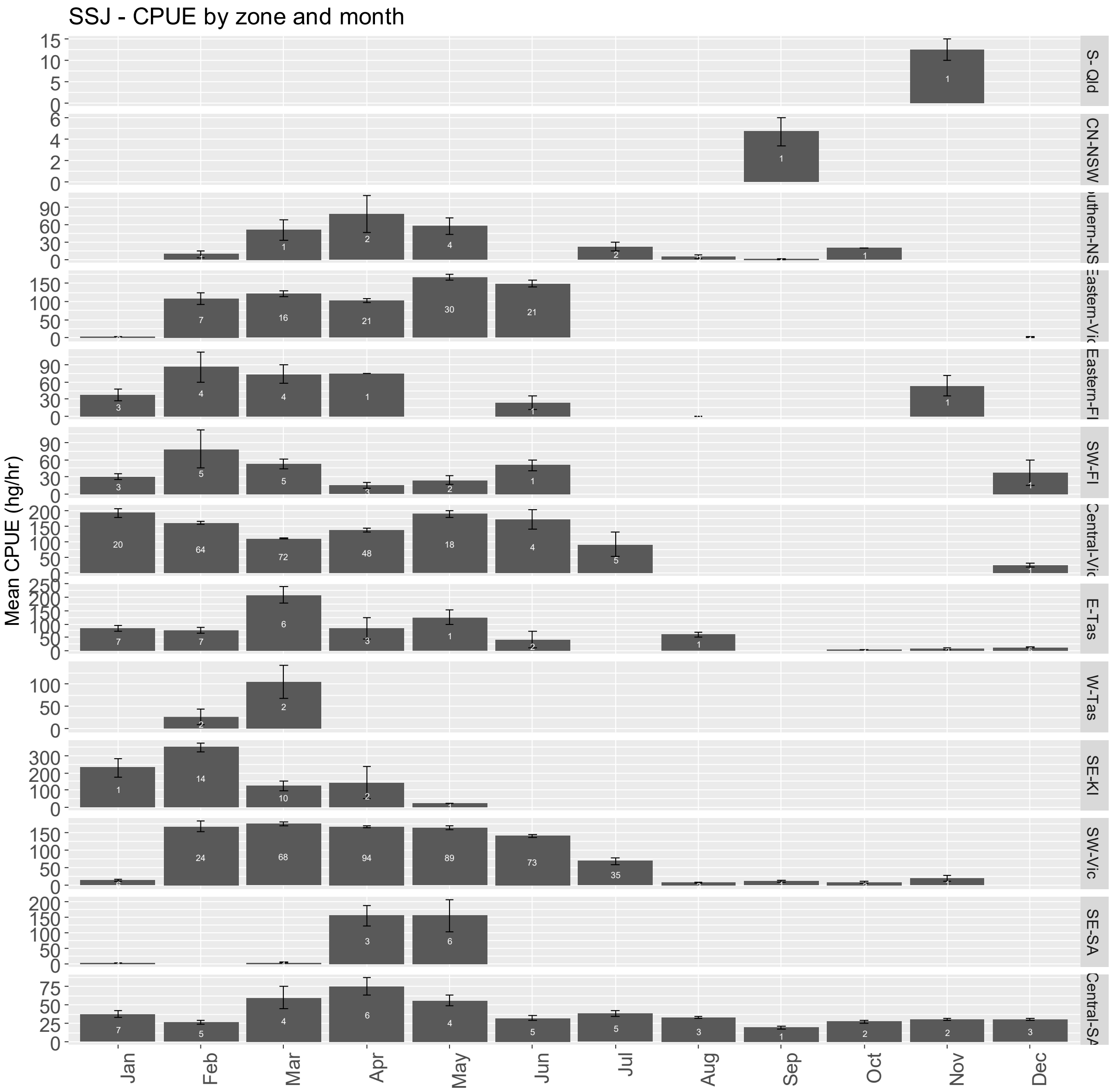


Figure 66. Mean monthly CPUE of Gould's Squid by zone and month in the SSJF.

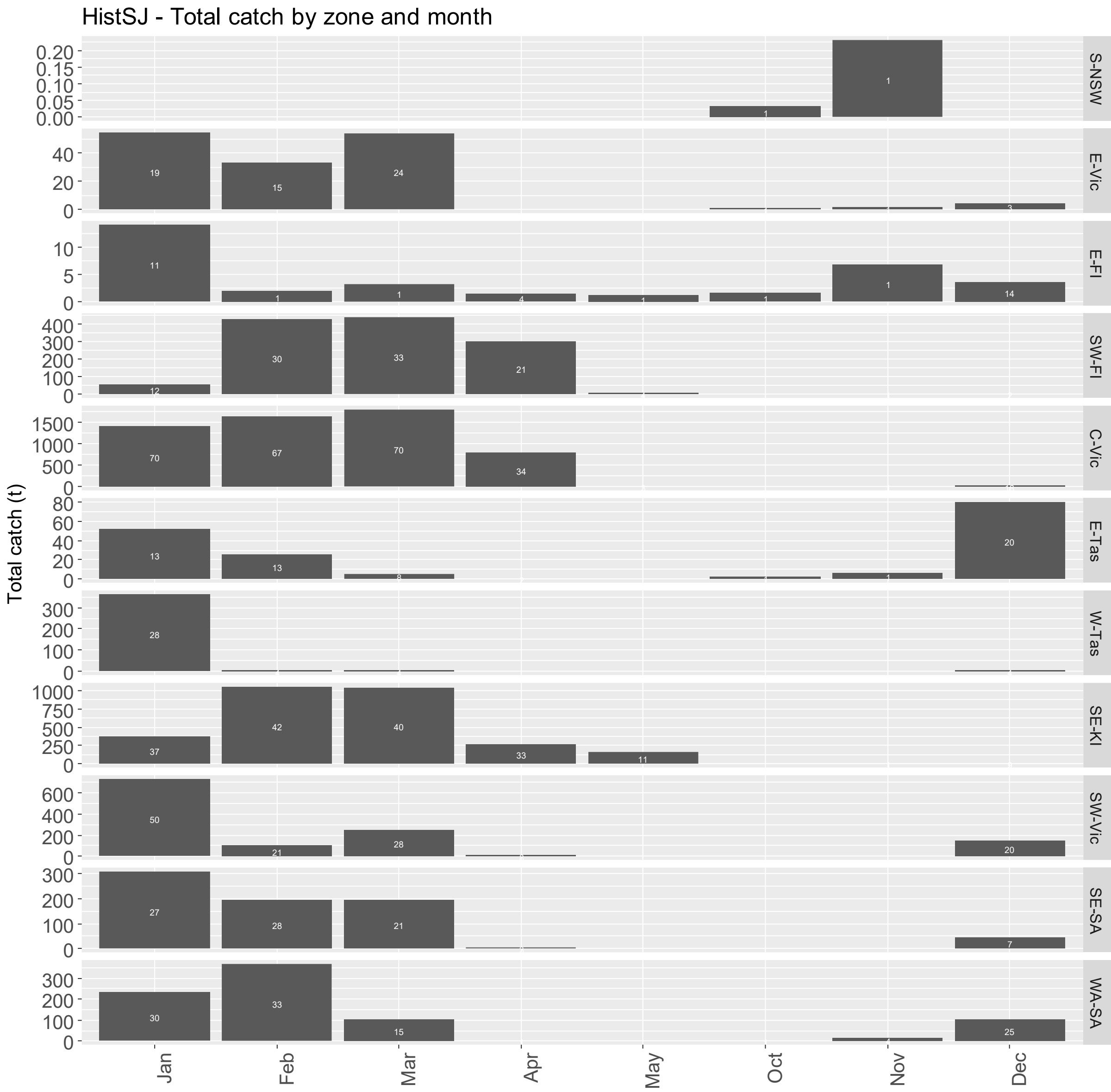


Figure 67. Total catch of Gould's Squid by zone and month in the HistSJ.

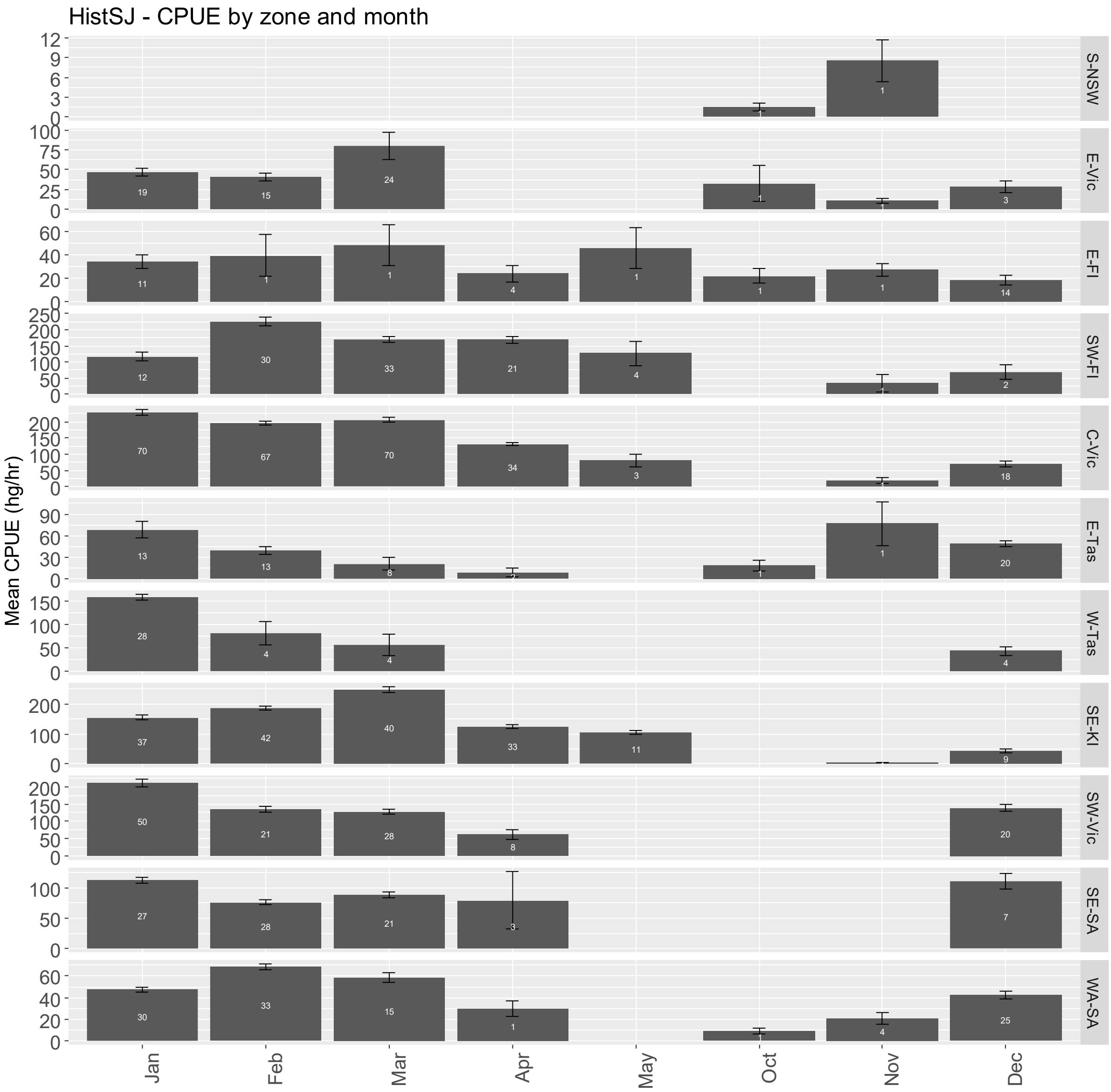
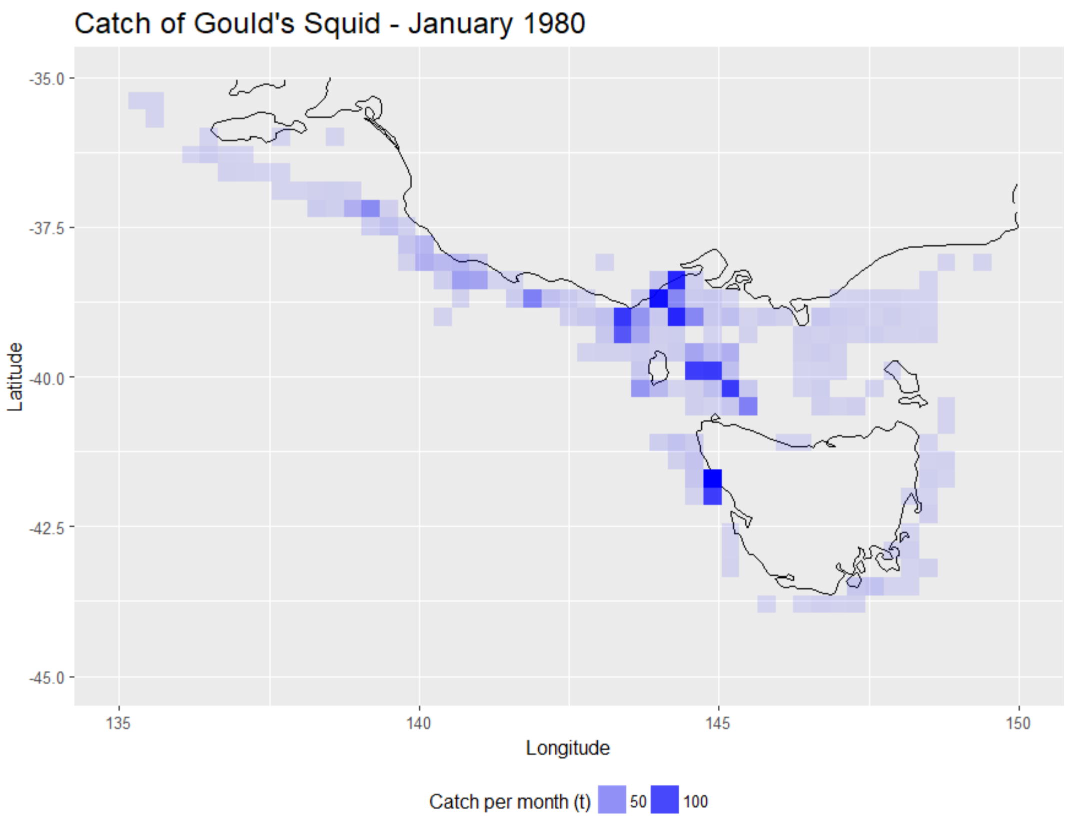


Figure 68. Mean monthly CPUE of Gould's Squid by zone and month in the HistSJ.



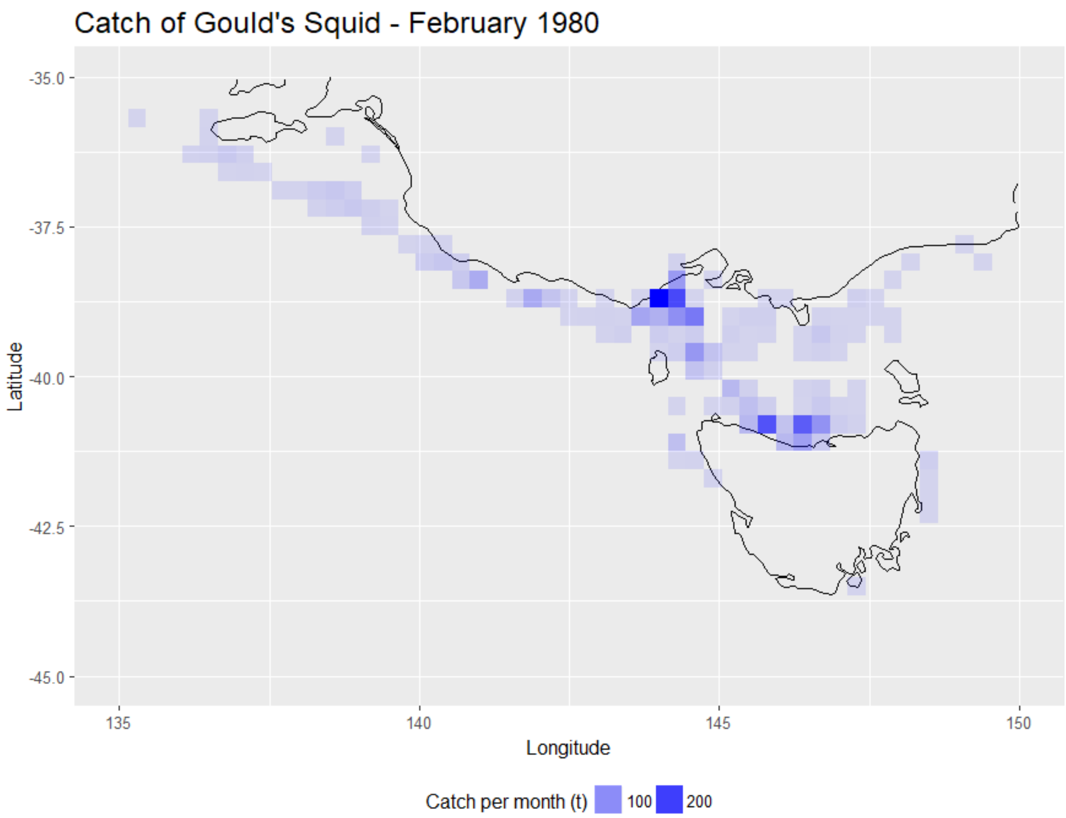
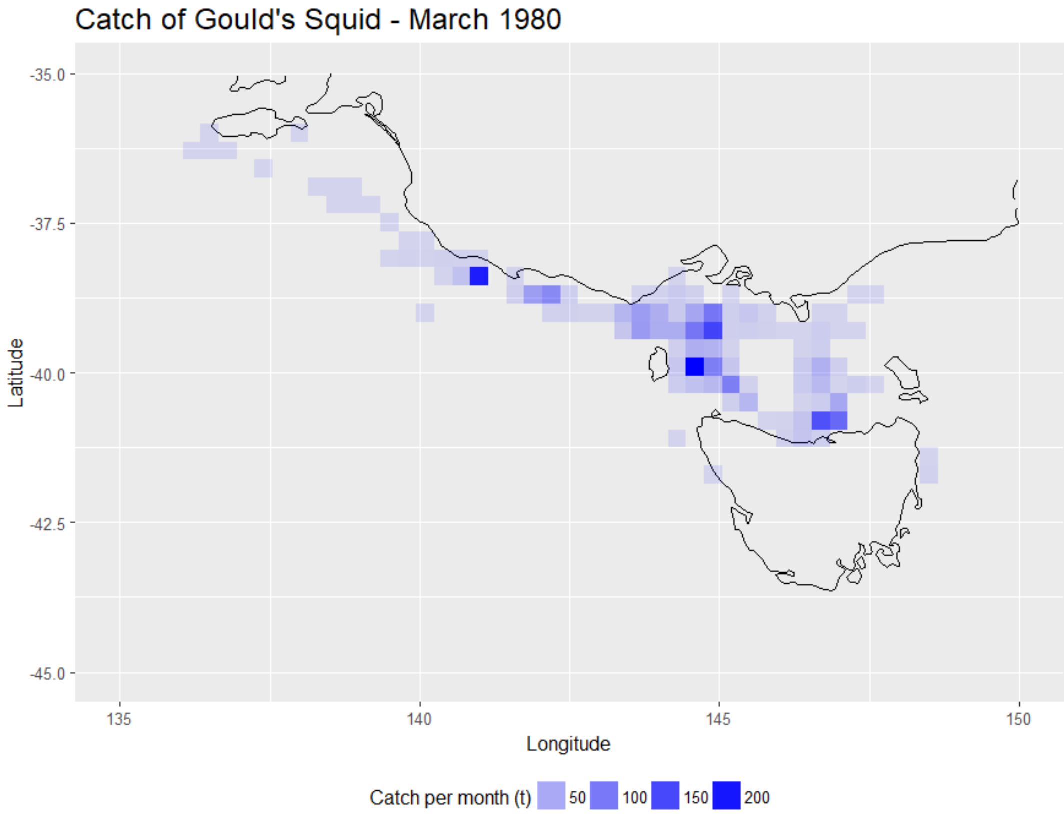


Figure 69. Total catch by 0.3 x 0.3 degree cells by the HistSJ Fishery in January and February 1980.



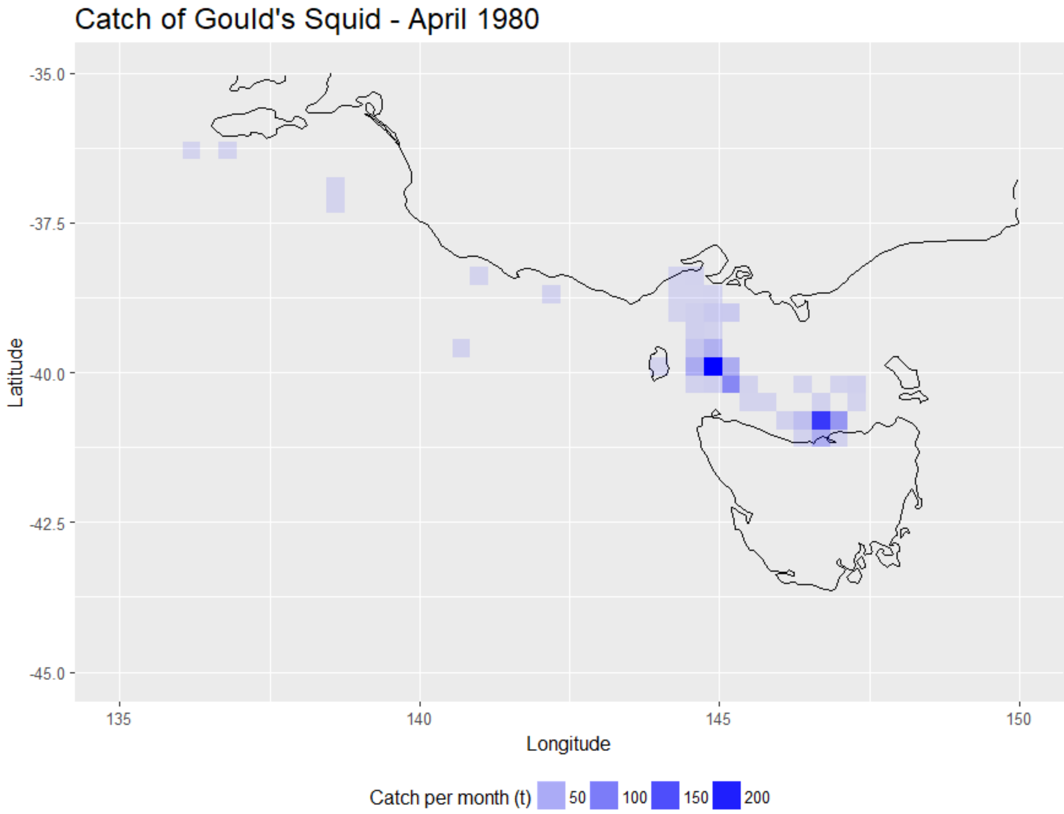


Figure 70. Total catch by 0.3 x 0.3 degree cells by the HistSJ Fishery in March and April 1980.

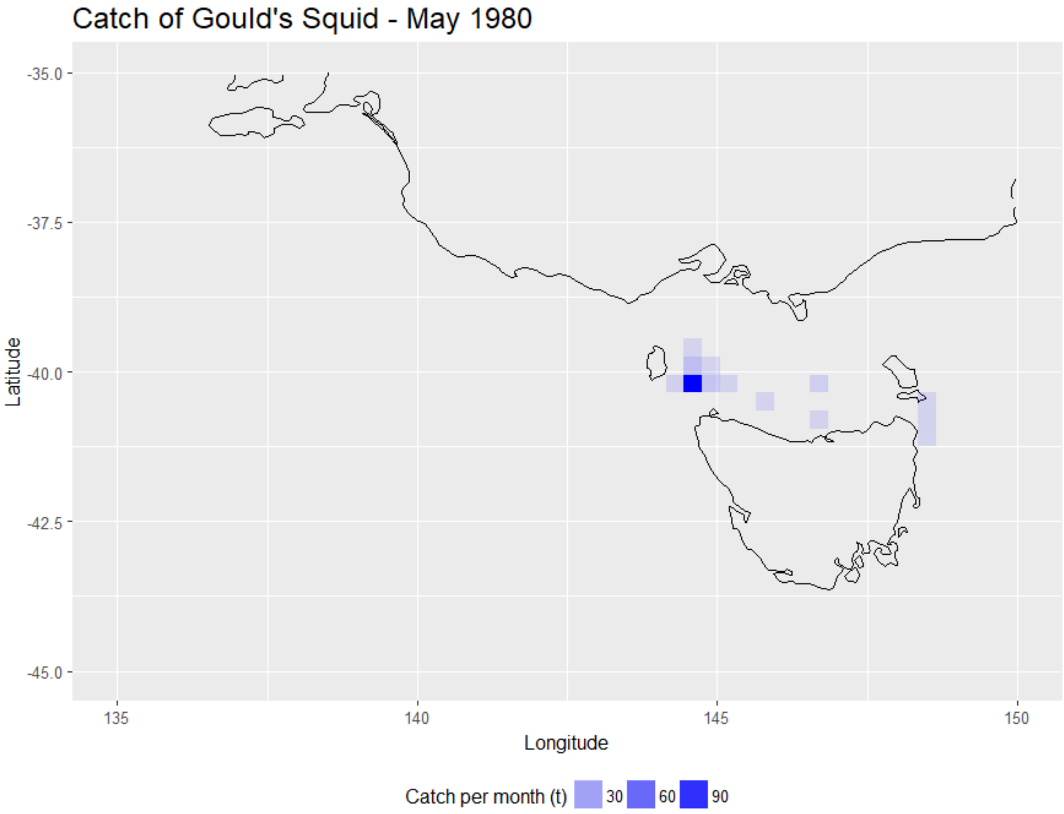


Figure 71. Total catch by 0.3 x 0.3 degree cells by the HistSJ Fishery in May 1980.

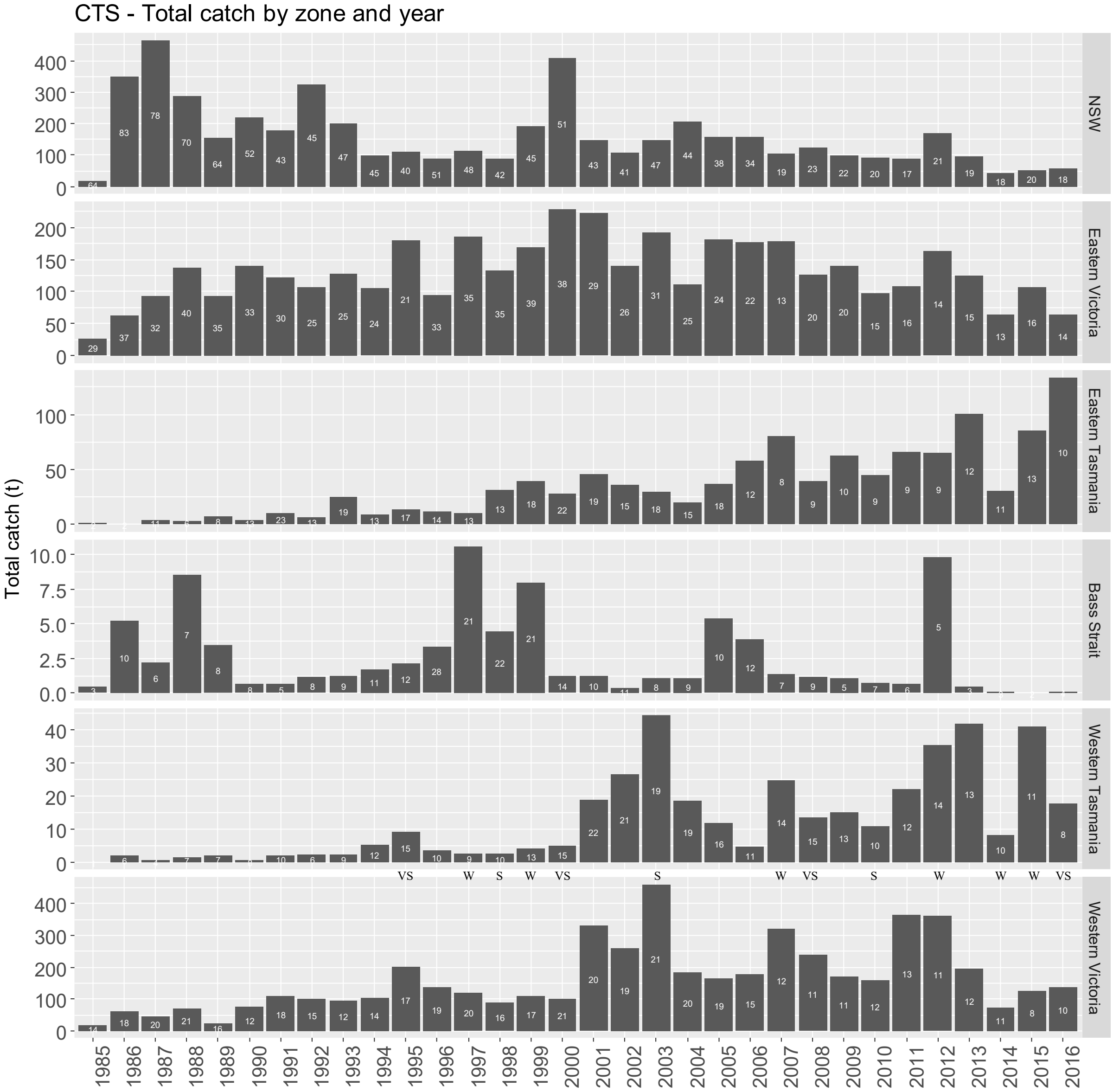


Figure 72. Total catch of Gould's Squid by zone and year in the CTS. Data from Western Victoria have been annotated with the relative strength of upwelling on the Bonney Coast: W = weak SST anomaly of -0.5 – -1.5 in the first three months of the year; S = strong SST anomaly of < -1.5 in the first three months of the year over a limited area; and VS = very strong SST anomaly of < -1.5 in the first three months of the year over a wide area.

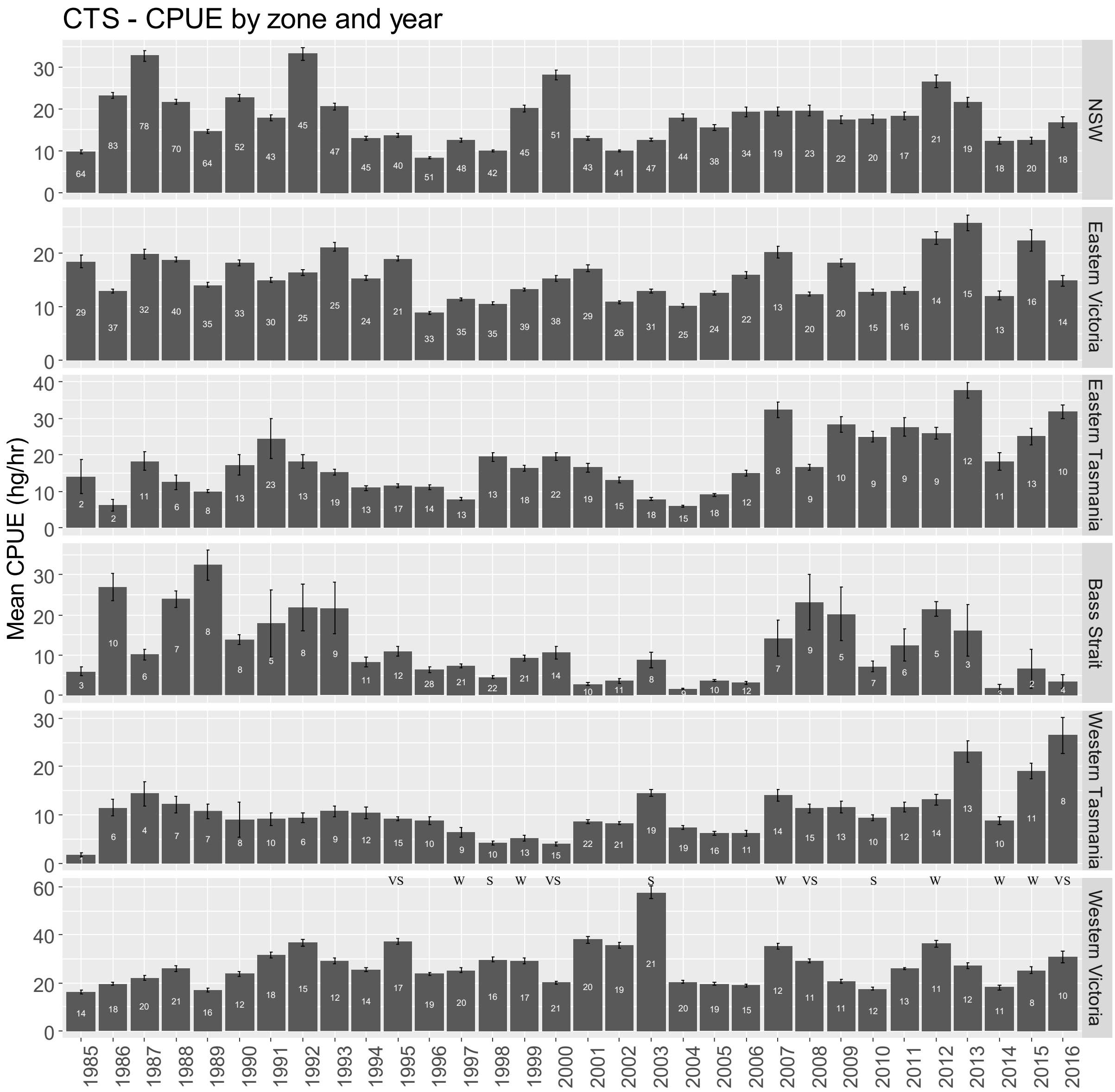


Figure 73. Mean annual CPUE of Gould's Squid by zone in the CTS. Data from Western Victoria have been annotated with the relative strength of upwelling on the Bonney Coast: W = weak SST anomaly of -0.5 – -1.5 in the first three months of the year; S = strong SST anomaly of < -1.5 in the first three months of the year over a limited area; and VS = very strong SST anomaly of < -1.5 in the first three months of the year over a wide area.

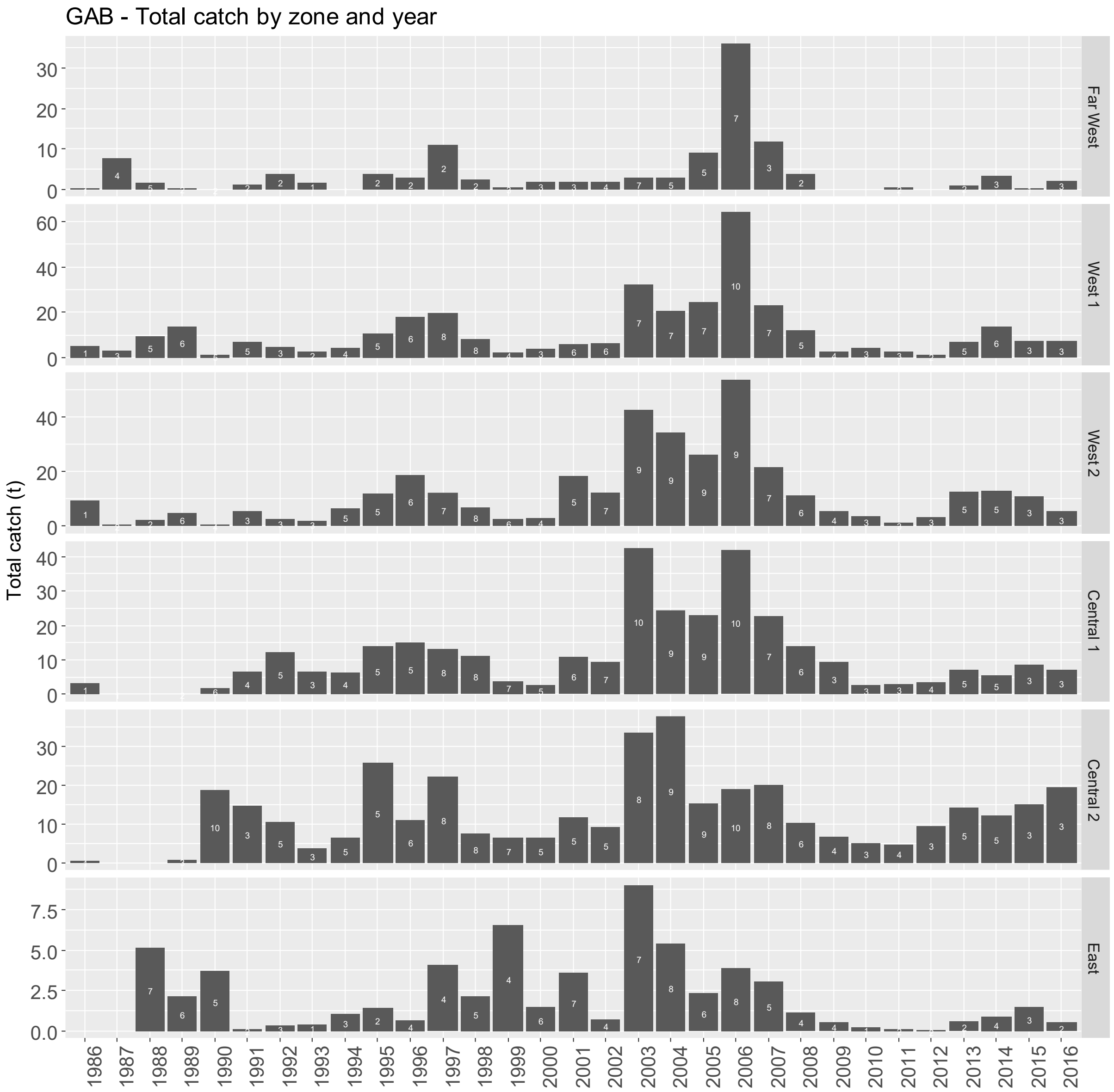


Figure 74. Total catch of Gould's Squid by zone and year in the GABTS.

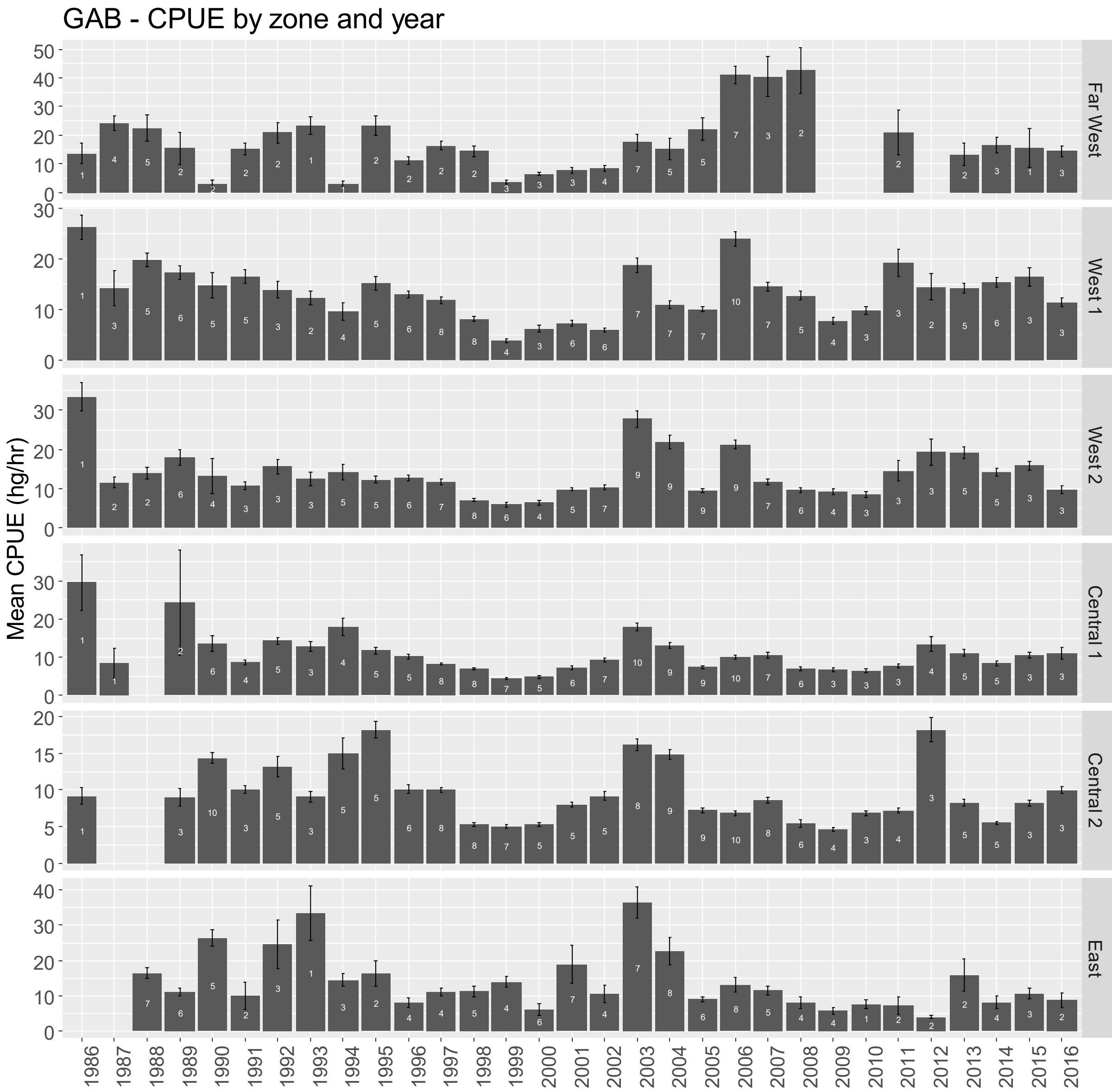


Figure 75. Mean annual CPUE of Gould's Squid by zone in the GABTS.

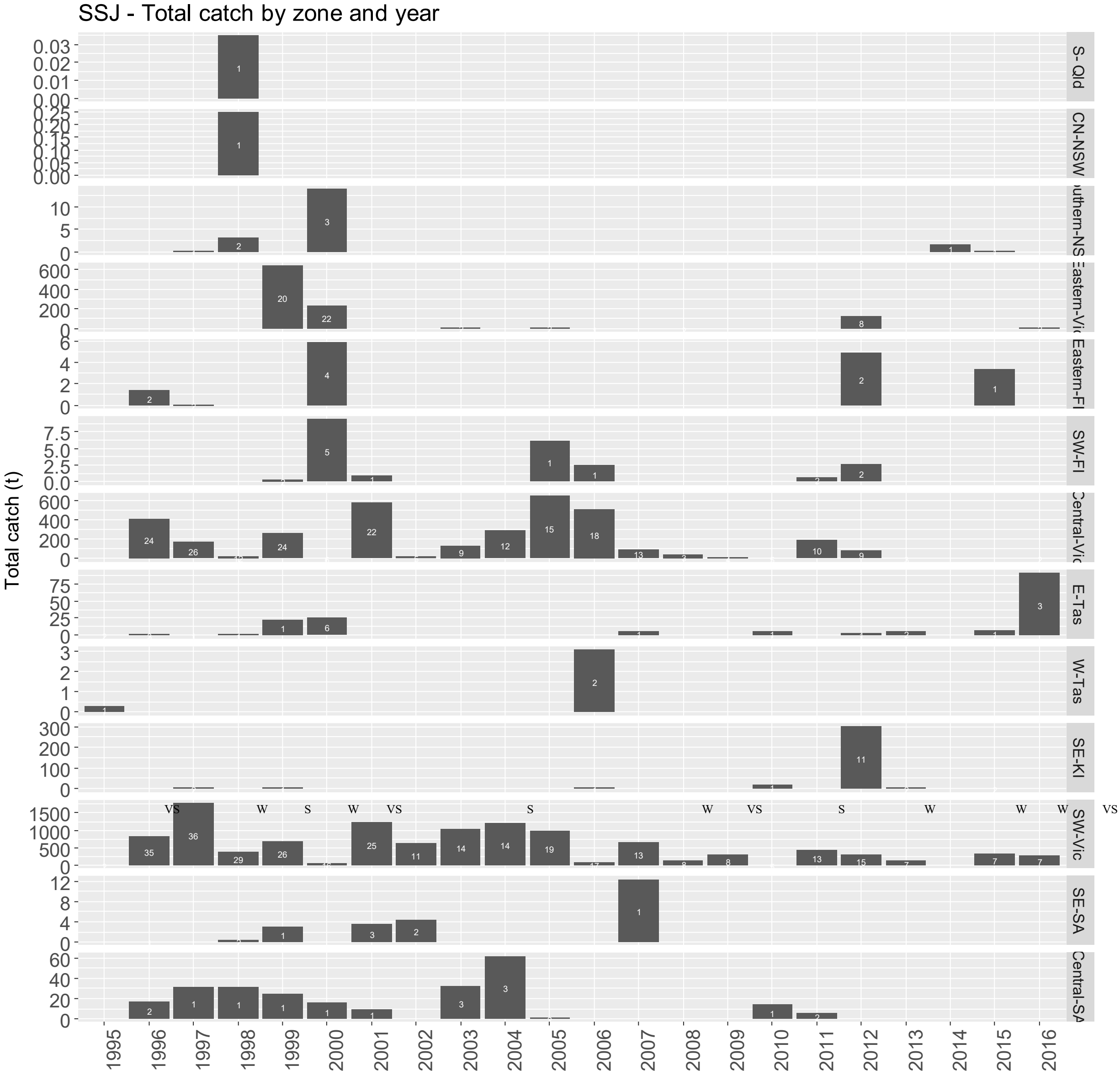


Figure 76. Total catch of Gould's Squid by zone and year in the SSJF. Data from Western Victoria have been annotated with the relative strength of upwelling on the Bonney Coast: W = weak SST anomaly of -0.5 – -1.5 in the first three months of the year; S = strong SST anomaly of < -1.5 in the first three months of the year over a limited area; and VS = very strong SST anomaly of < -1.5 in the first three months of the year over a wide area.

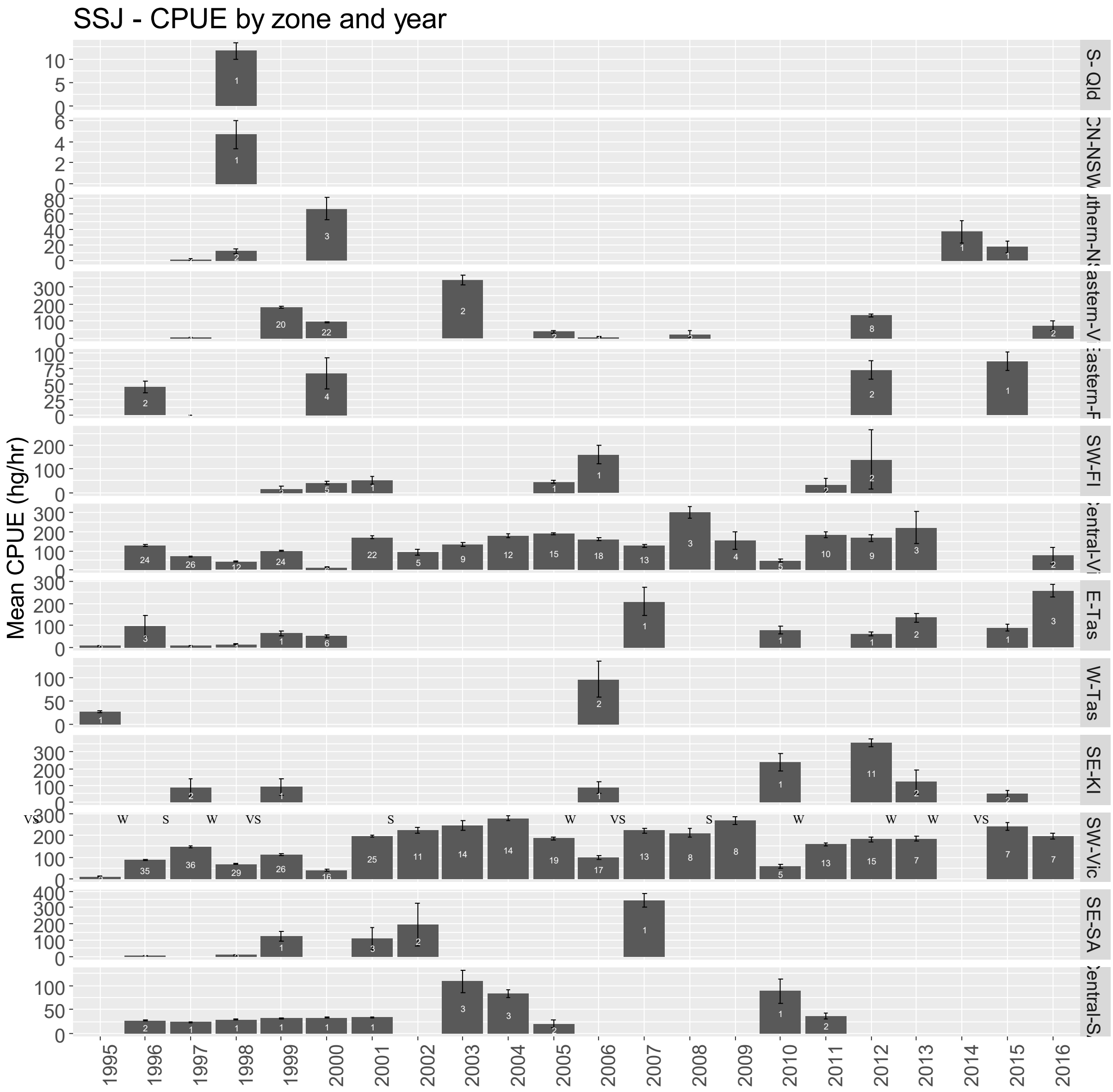


Figure 77. Mean annual CPUE of Gould's Squid by zone in the SSJF. Data from Western Victoria have been annotated with the relative strength of upwelling on the Bonney Coast: W = weak SST anomaly of -0.5 – -1.5 in the first three months of the year; S = strong SST anomaly of < -1.5 in the first three months of the year over a limited area; and VS = very strong SST anomaly of < -1.5 in the first three months of the year over a wide area.

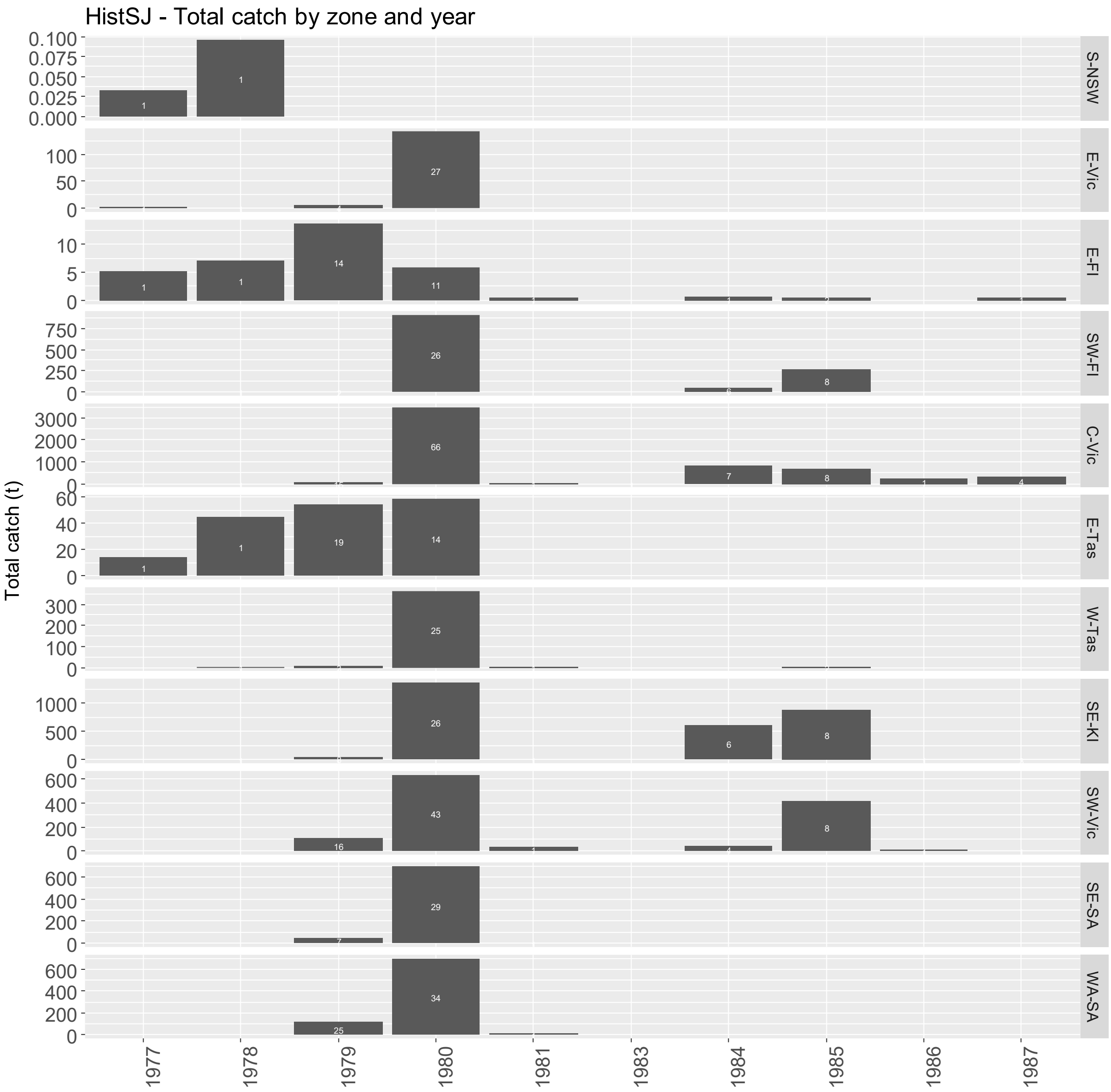


Figure 78. Total catch of Gould's Squid by zone and year in the HistSJ Fishery.

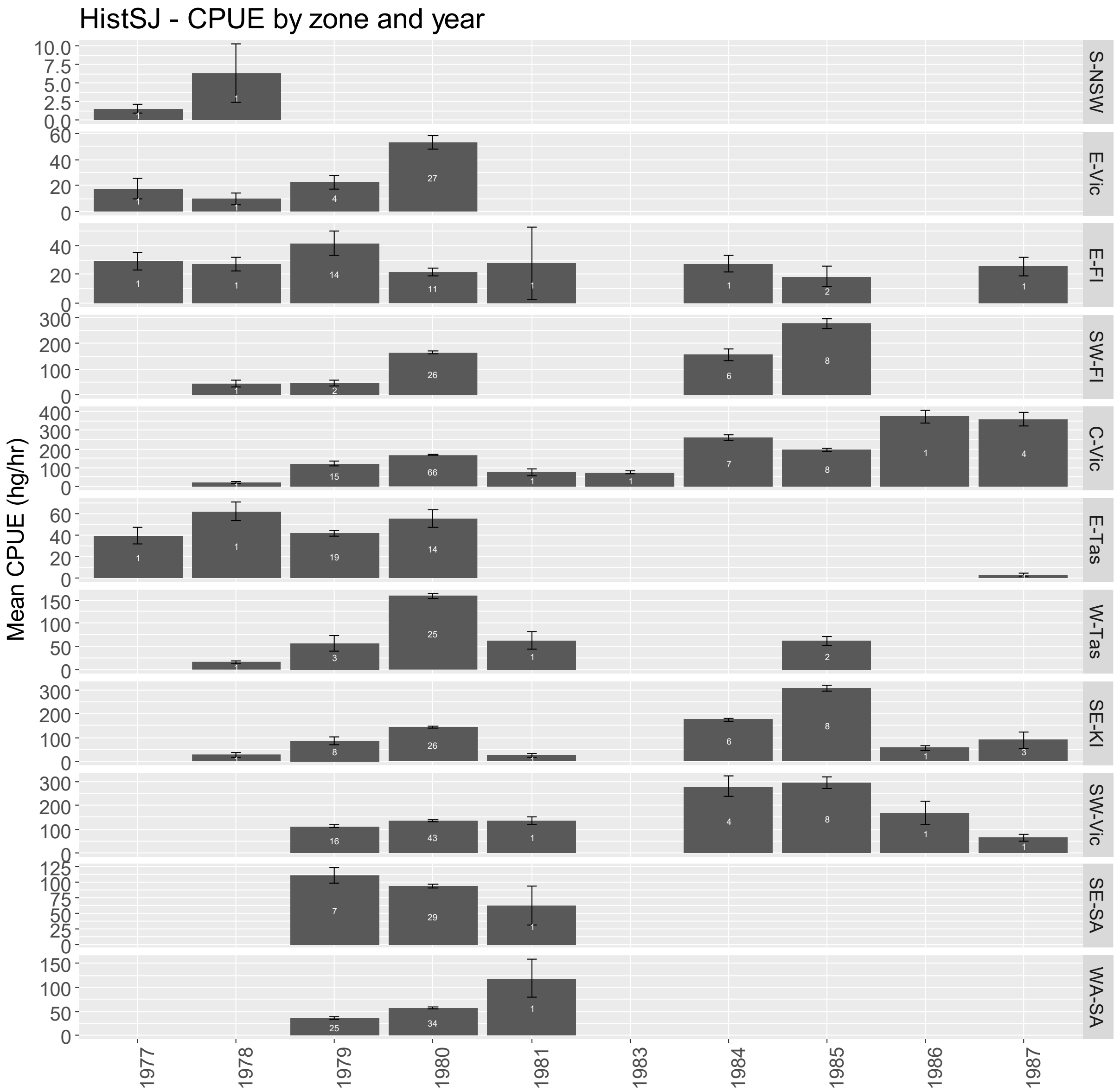


Figure 79. Mean annual CPUE of Gould's Squid by zone in the HistSJ Fishery.

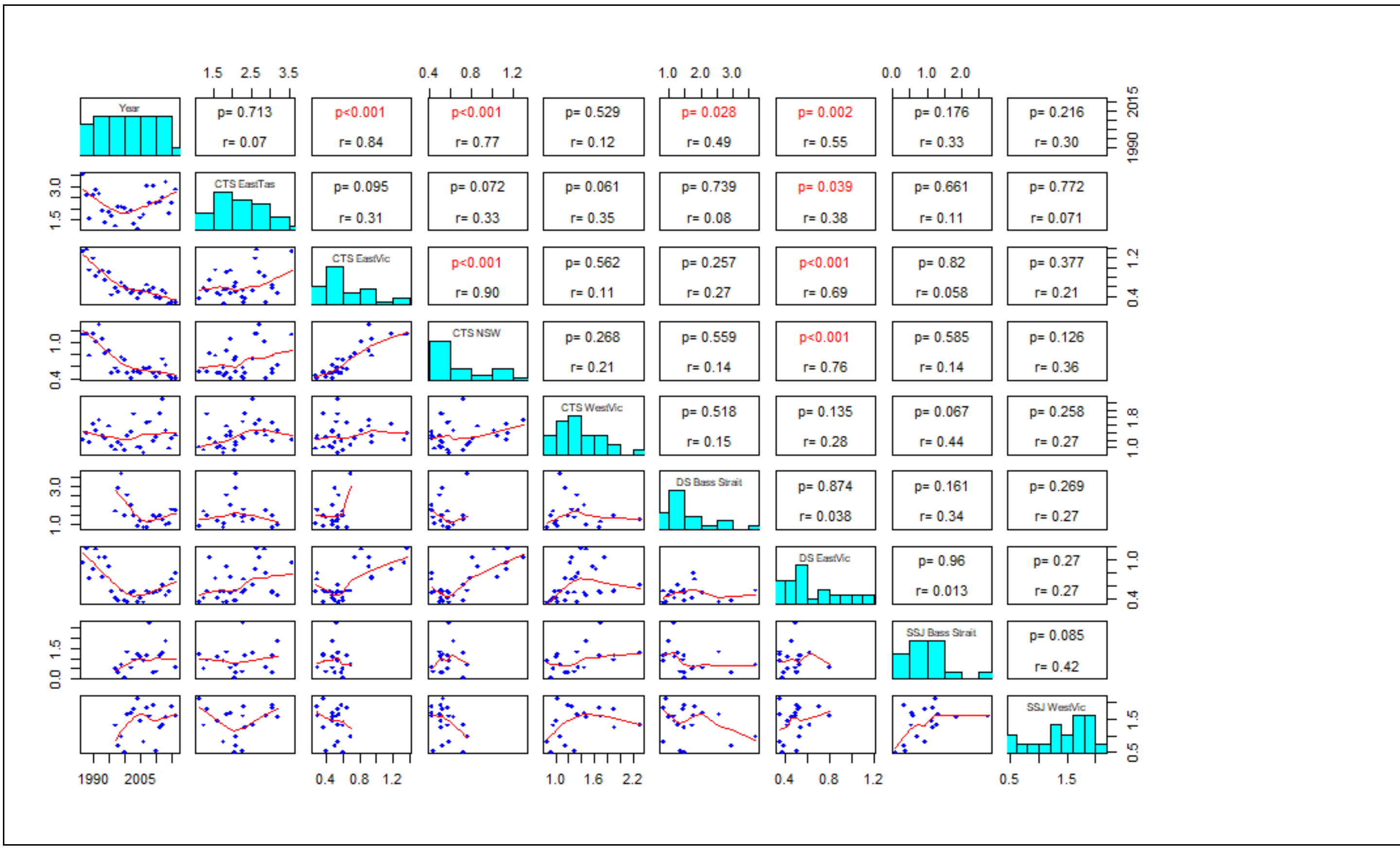


Figure 80. Correlation matrices: standardised CPUE for main areas of fisheries from 1987–2016 (1997–2016 for DS Bass Strait and the SSJF data) showing R^2 value, p value, smoothed trend and histogram of observations.

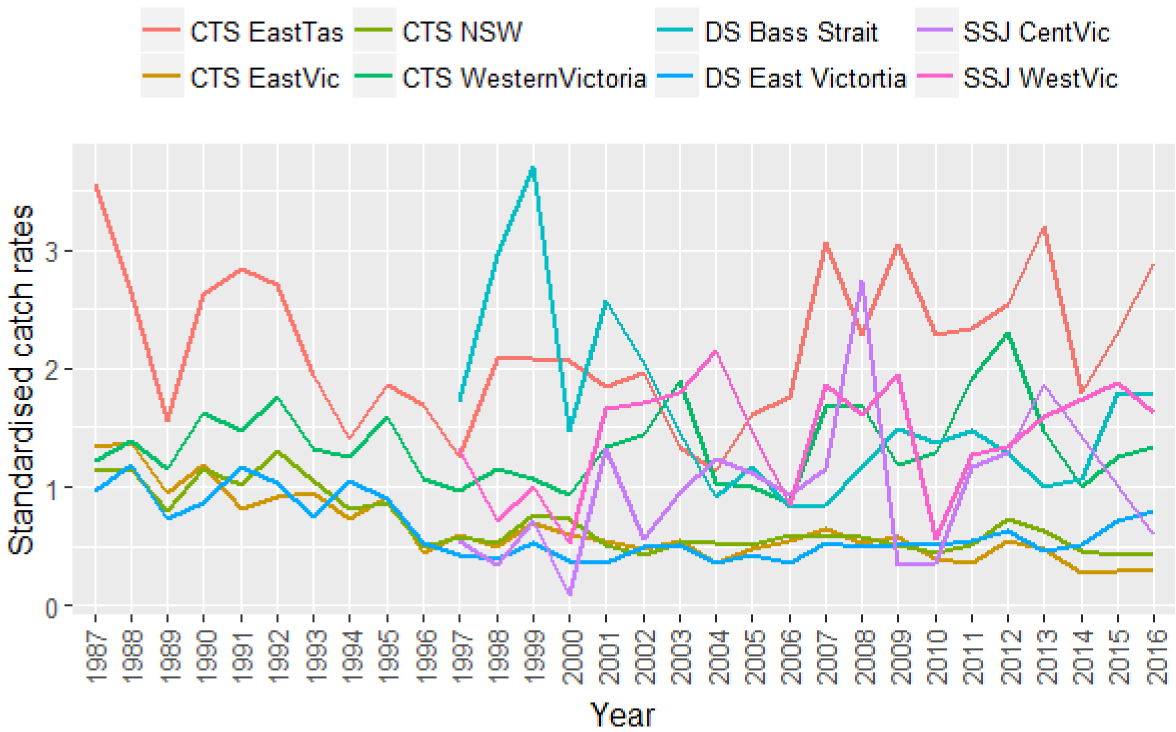


Figure 81. Standardised catch rates for main areas of fisheries from 1987–2016 (1997–2016 for DS Bass Strait and the SSJF data).

Figure 82. Correlation matrices for top panel: Catch (t) from the fishery/ region of interest from 1987–2016 (1997–2016 for DS Bass Strait and the SSJ data) showing R^2 value, p value, smoothed trend and histogram of observations.

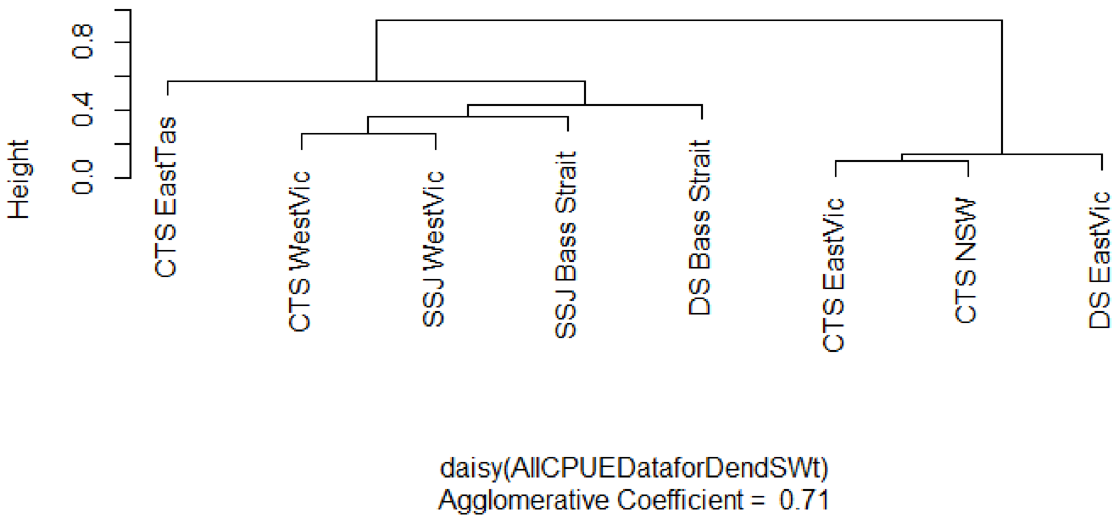


Figure 83. Cluster analysis showing similarities in trends of CPUE between sectors and zones (Agglomerative Coefficient = 0.71).

Table 8. Models examined in CPUE standardisation of the SSJF (all zones combined). Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% Improvement
Null deviance				9946	
fit1	log(CPUE)~year	25767	21	8447	15.1%
fit2	log(CPUE)~year + monthf	25695	25	8375	0.6%
fit3	log(CPUE)~year + zone	25342	31	8057	4.6%
fit4	log(CPUE)~year + zone + PC1	25291	32	8012	0.6%
fit5	(log(CPUE)~year + zone + PC2	25336	32	8051	<0.1%
fit6	log(CPUE)~year + zone + depth	25115	50	7834	2.8%
fit7	log(CPUE)~year + zone + depth + EightPhaseMoon	25071	55	7789	0.6%
fit8	log(CPUE)~year + zone + PC1 + depth + depth*moonphase	25058	131	7655	2.3%

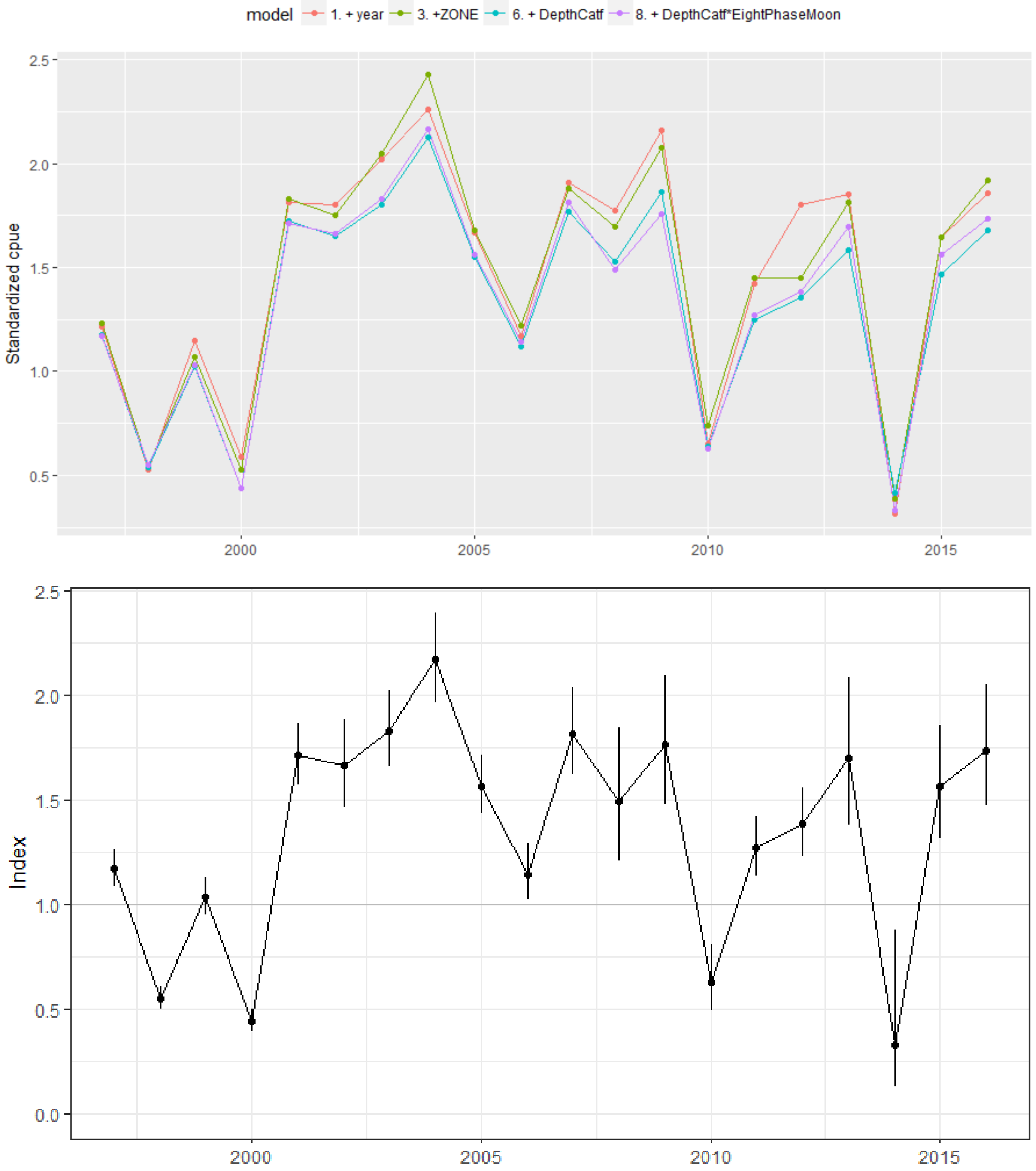
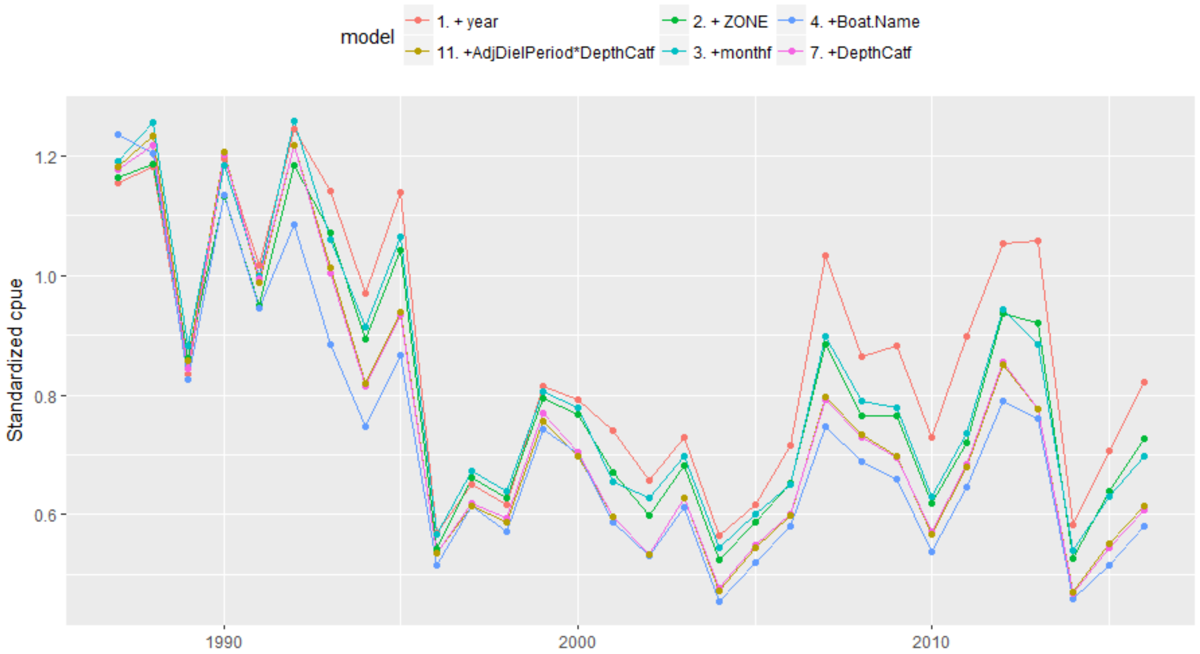


Figure 84. SSJ All data combined. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 9. Models examined in CPUE standardisation of the CTS (all zones combined). Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% Improvement
Null deviance				411570	
fit1	log(CPUE) ~ year	798012	31	397796	3.3%
fit2	log(CPUE) ~ year + zone	779990	36	368786	7.3%
fit3	log(CPUE) ~ year + zone + monthf	771680	47	356104	3.4%
fit4	log(CPUE) ~ year + zone + monthf + Boat.Name	750902	291	325680	8.5%
Fit5	log(CPUE) ~ year + zone + monthf + Boat.Name + PC1	750754	292	325475	0.1%
Fit6	log(CPUE) ~ year + zone + monthf + Boat.Name + PC1	749899	292	324308	0.4%
Fit7	log(CPUE) ~ year + zone + monthf + Boat.Name + depth	724158	315	291022	10.6%
Fit8	log(CPUE) ~ year + zone + monthf + Boat.Name + depth + moonphase	724029	322	290847	0.1%
Fit9	log(CPUE) ~ year + zone + monthf + Boat.Name + depth + AdjDielPeriod	723466	318	290170	0.3%
fit10	log(CPUE) ~ year + zone + monthf + Boat.Name + depth + moonphase * AdjDielPeriod	723297	346	289896	0.4%
fit11	**log(CPUE) ~ year + zone + monthf + Boat.Name + depth + AdjDielPeriod * depth**	720411	390	286298	**1.6%**
fit12	log(CPUE) ~ year + zone + monthf + Boat.Name + depth + AdjDielPeriod * depth + depth * moonphase	720358	565	285814	0.2%



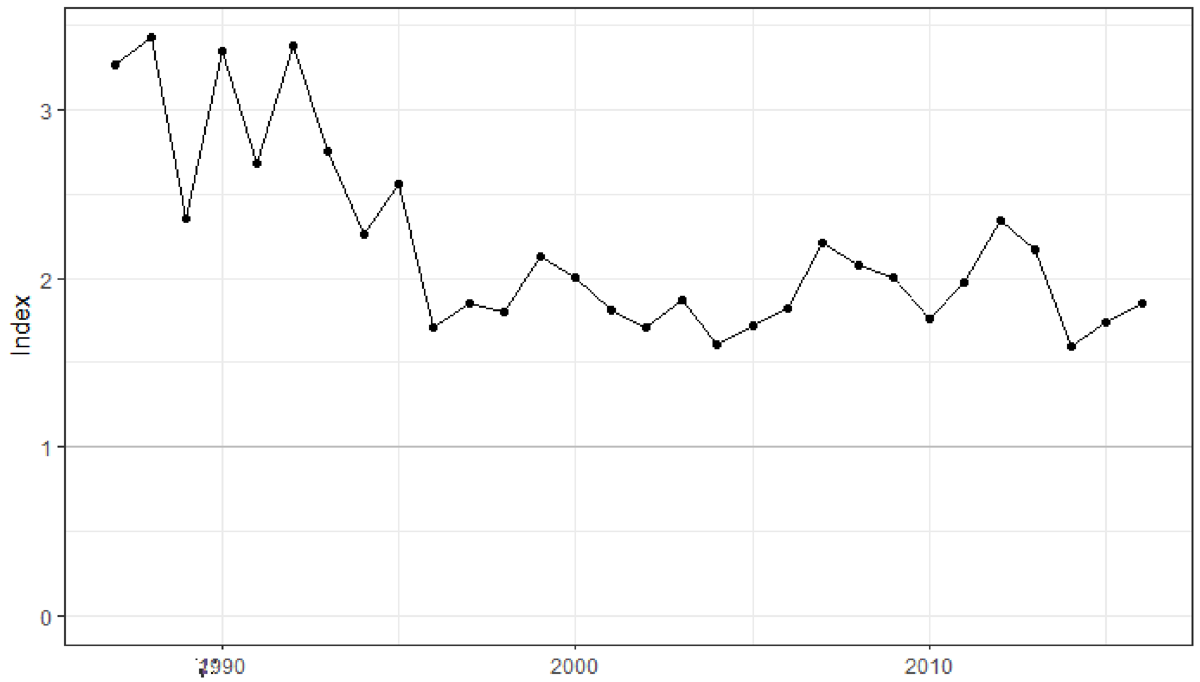


Figure 85. CTS All data combined. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 10. Final models for CPUE standardisation of the for main zones in the SSJ, CTS and DS sectors. Full results can be found in the referenced tables.

Fishery	Zone	Final model	Full results table	Full results figure
SSF	Western Victoria	log(CPUE)~year+ PC1+depth+moonphase+ depth*moonphase	Table 14	Figure 145
	Central Victoria	log(CPUE)~ year + monthf + depth + depth*moonphase	Table 15	Figure 146
CTS	Western Victoria	log(CPUE)~year+monthf+Boat.Name+depth	Table 16	Figure 147
	Eastern Victoria	log(CPUE)~year+monthf+Boat.Name+depth	Table 17	Figure 148
	Eastern Tasmania	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod+AdjDielPeriod*depth+depth*moonphase	Table 18	Figure 149
	New South Wales	log(CPUE)~year+monthf+Boat.Name+ PC2+ depth +AdjDielPeriod*depth	Table 19	Figure 150
DS	Bass Strait	log(CPUE)~year+monthf+ AdjDielPeriod+ moonphase*AdjDielPeriod +depth*AdjDielPeriod + moonphase *depth	Table 20	Figure 151
	Eastern Victoria	log(CPUE)~year+monthf+Boat.Name+AdjDielPeriod+depth*AdjDielPeriod + moonphase *depth	Table 21	Figure 152
SJTas	East Coast	log(CPUE)~year+monthf+Boat.Name+ PC1+depth+moonphase + depth*moonphase	Table 22	Figure 153
GAB	Central 1, Central 2, West 1, West 2	log(CPUE)~year+monthf+Boat.Name+PC2+zone+depth+AdjDielPeriod+depth*moonphase	Table 23	Figure 154

Figure 86. Mean CPUE (kg/hr) for SSJF effort in the vicinity of a SST frontal gradient by month and zone.

Figure 87. Mean CPUE (kg/hr) for CTS effort in the vicinity of a SST frontal gradient by month and zone.

Figure 88. Mean CPUE (kg/hr) for GABTS effort in the vicinity of a SST frontal gradient by month and zone.

Figure 89. Mean CPUE (kg/shot) for DS effort in the vicinity of a SST frontal gradient by month and zone.

Figure 90. Mean CPUE (kg/shot) for SSJF effort in the vicinity of a Chl a gradient of 0.5 mg/m^3 by month and zone.

Figure 91. Mean CPUE (kg/shot) for CTS effort in the vicinity of a Chl a gradient of 0.5 mg/m^3 by month and zone.

Figure 92. Mean CPUE (kg/shot) for GABTS effort in the vicinity of a Chl a gradient of 0.5 mg/m^3 by month and zone.

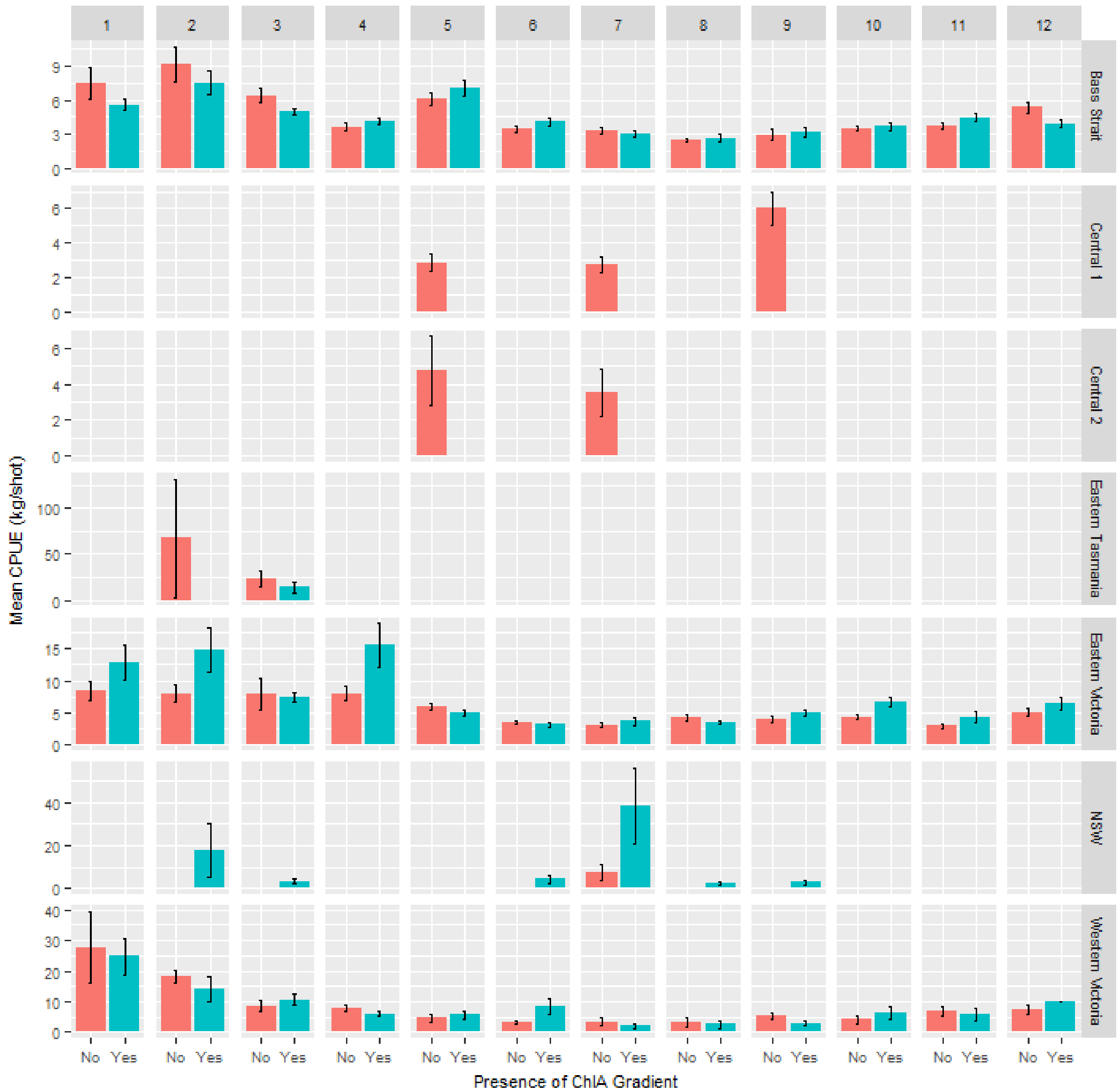


Figure 93. Mean CPUE (kg/shot) for DS effort in the vicinity of a Chl a gradient of 0.5 mg/m³ by month and zone.

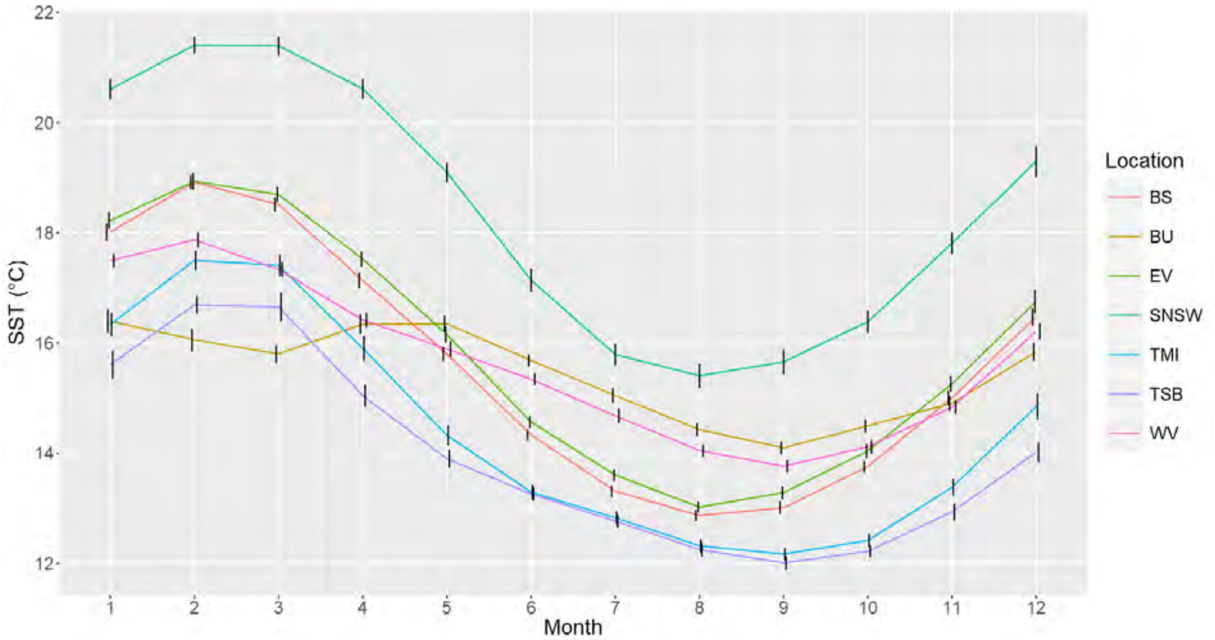


Figure 94. Mean monthly SST (˚C) along lines from different locations around south-east Australia. Location lines can be seen in Figure 3.

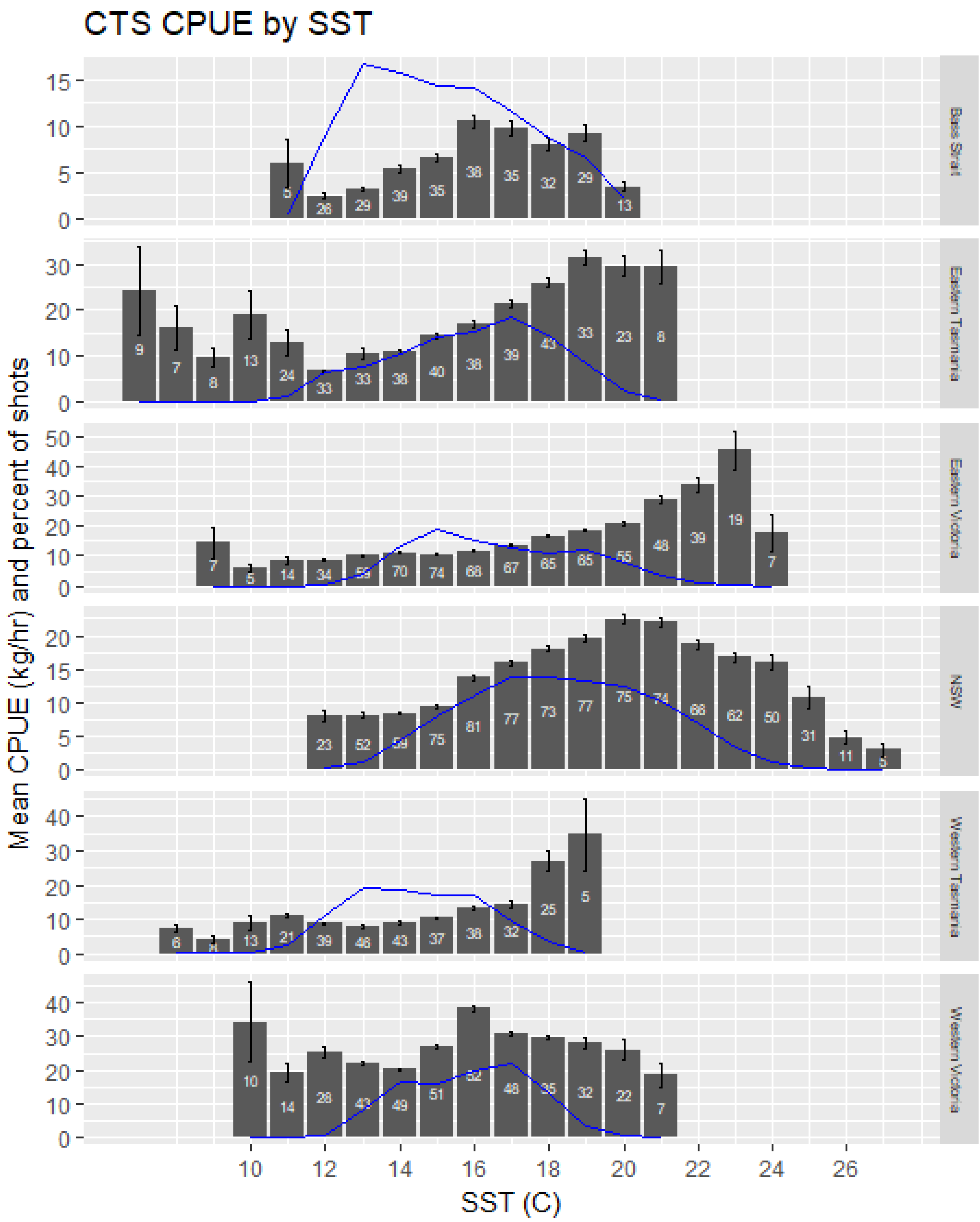


Figure 95. Mean CPUE (kg/hr) by SST (bars) and percent frequency of SST (lines) records for the CTS by zone. Note, records with less than 5 vessels have been removed.

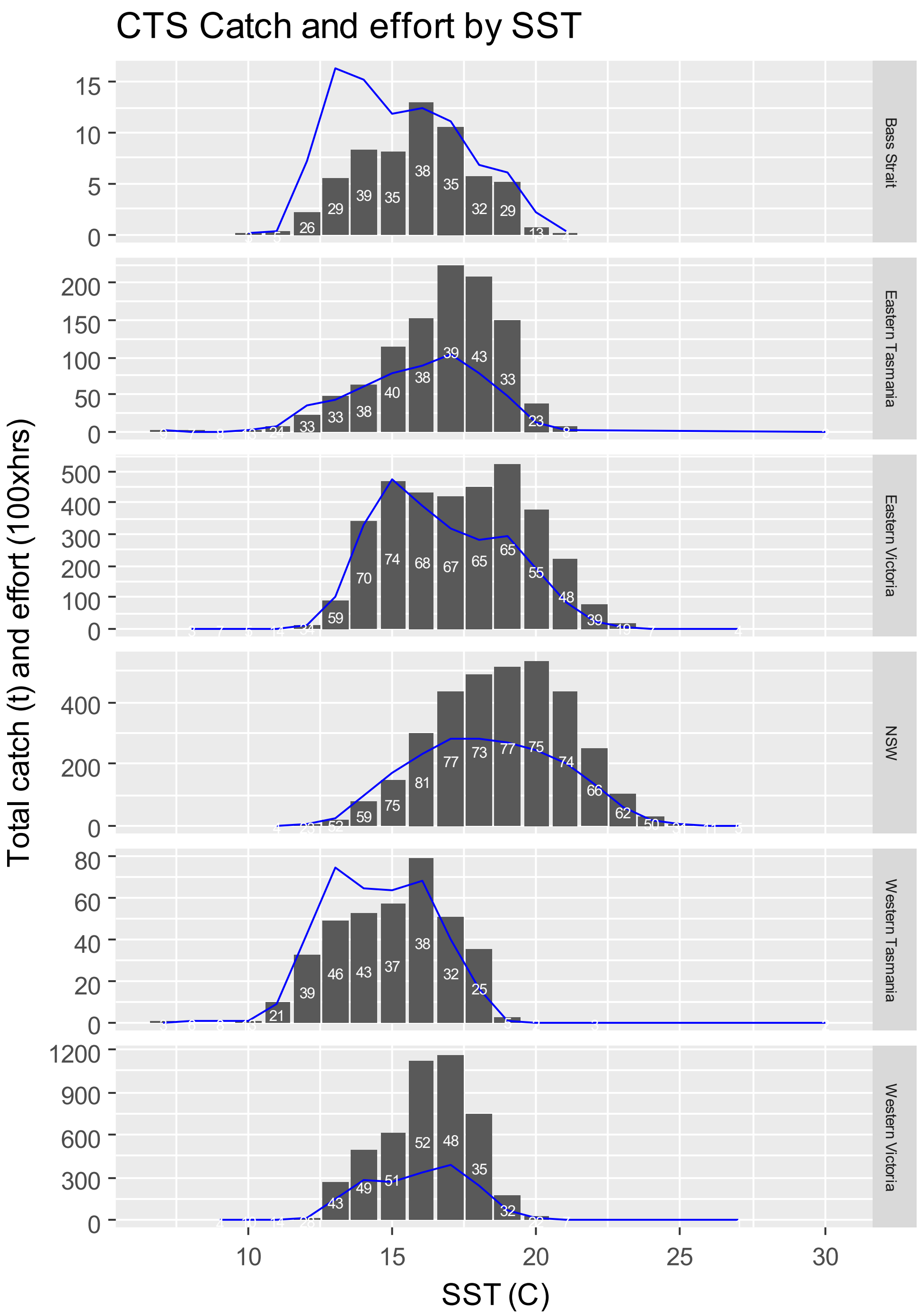


Figure 96. Total catch (t) and effort (100xhrs) by SST (˚C) for the CTS by zone.

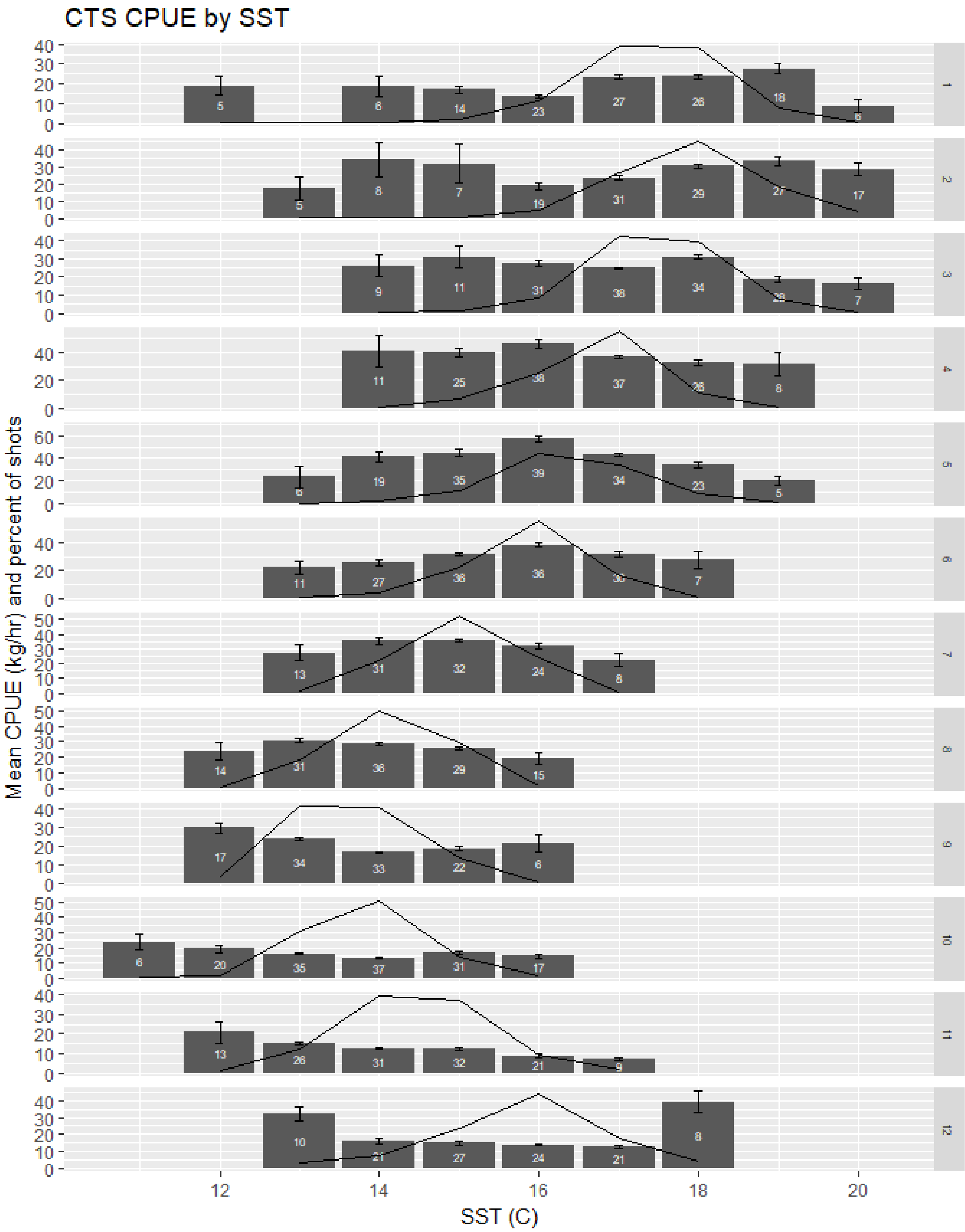


Figure 97. Mean CPUE (kg/shot) by SST and percent frequency of SST (lines) for the CTS by month in Western Victoria.

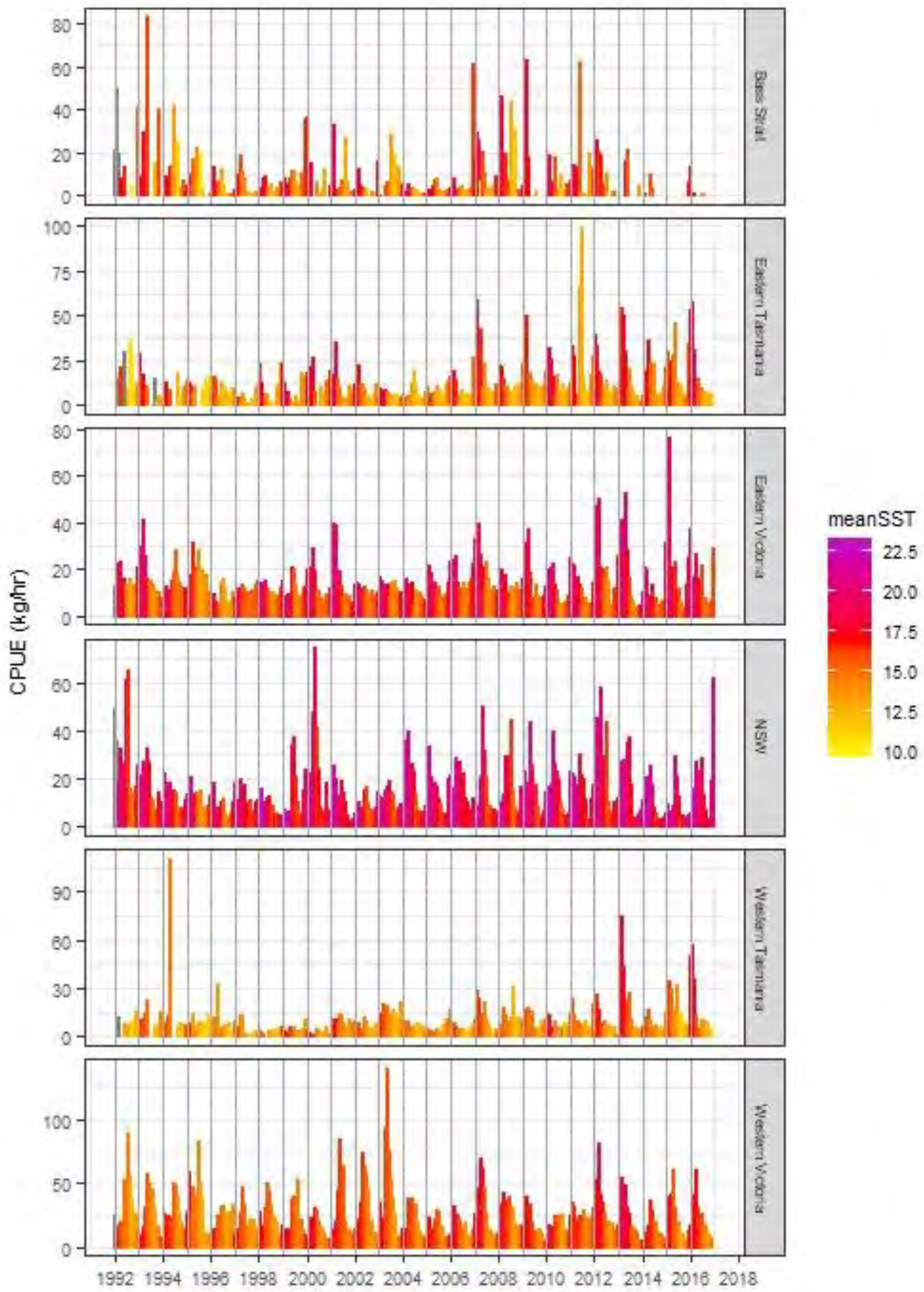


Figure 98. Time series of mean monthly CPUE (kg/shot) for the CTS by zone coloured by mean SST. Vertical grid lines intercept the x-axis in January each year.

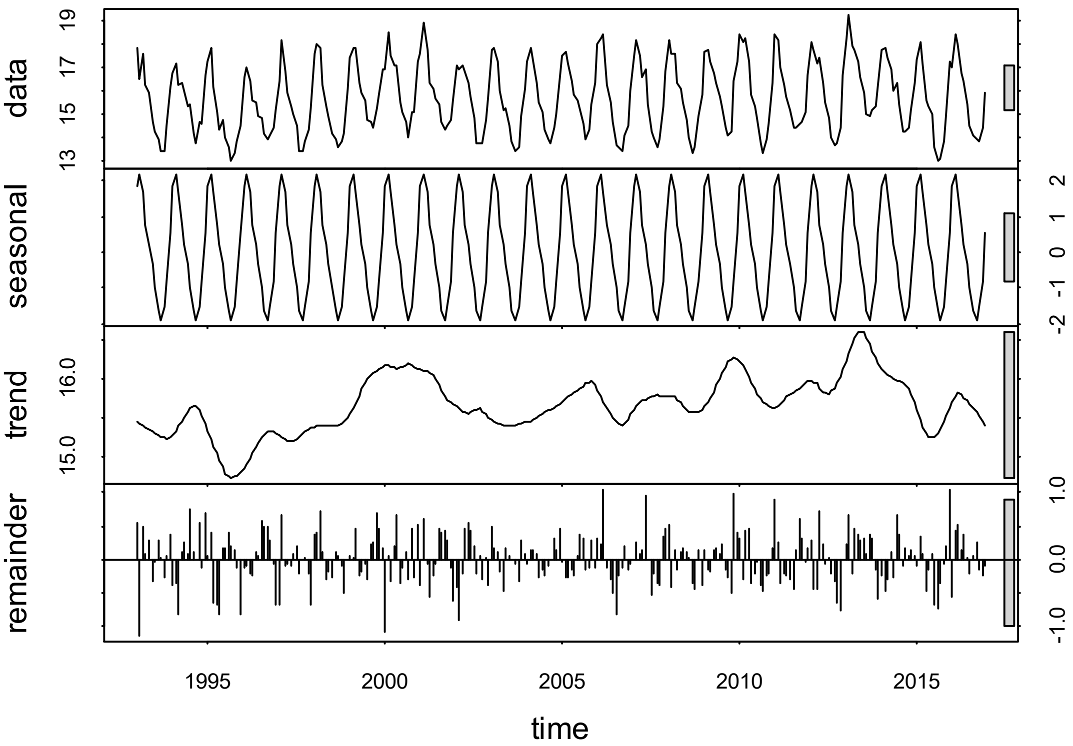


Figure 99. STL Decomposition of SST off Western Victoria from 1993-2016 showing the original data, the seasonal component, trend component and the remainder.

Table 11. Results of Mann-Kendall test, Sen's Slope and Pettitt's change point detection for monthly SST off Western Victoria from 1993-2016 calculated on each month separately, and for the whole times series.

Month	Mann-Kendall test		Sen's Slop	Pettitt's change-point detection		
	Statistic S	p		t	KT	p
January	94	0.021	0.051	2005	95	0.047
February	68	0.097	0.033	1996	62	0.403
March	60	0.143	0.034	1997	73	0.217
April	112	0.006	0.043	1999	85	0.099
May	64	0.118	0.027	1998	64	0.363
June	88	0.031	0.032	1998	90	0.068
July	24	0.568	0.010	2007	33	1.27
August	22	0.602	0.009	1998	42	0.959
September	30	0.472	0.014	1998	46	0.828
October	16	0.710	0.005	1998	48	0.766
November	68	0.097	0.027	1998	94	0.050
December	60	0.143	0.041	1998	60	0.446
Whole time series	706	<<0.001	0.026	Nov, 1998	3437	0.104

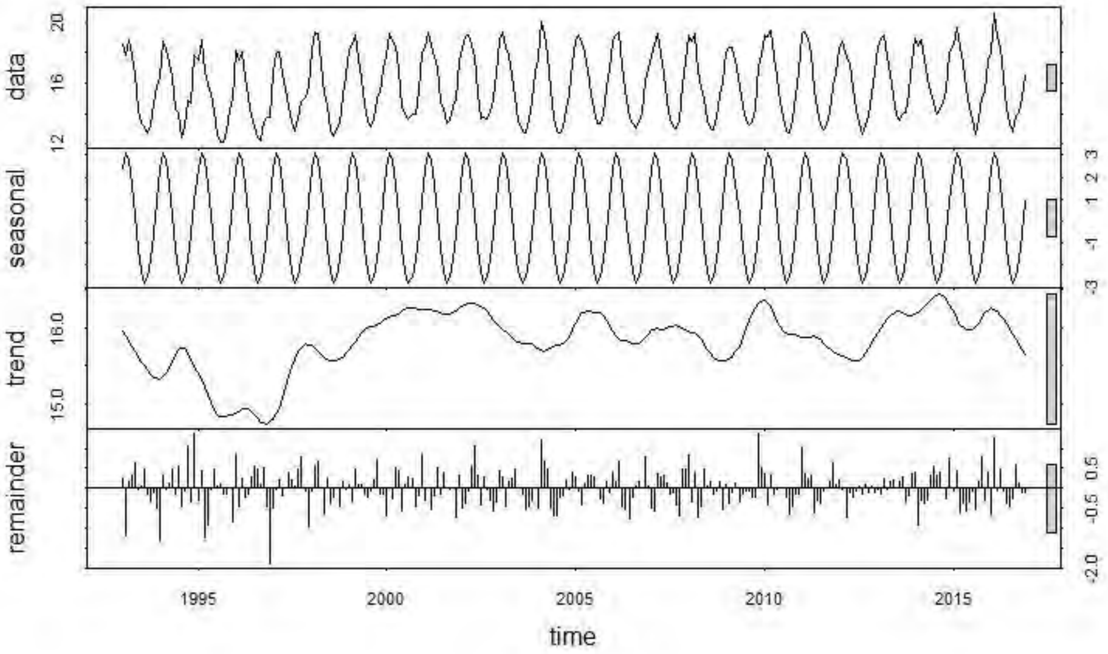


Figure 100. STL Decomposition of SST off Eastern Victoria from 1993-2016 showing the original data, the seasonal component, trend component and the remainder.

Table 12. Results of Mann-Kendall test, Sen's Slope and Pettitt's change point detection for monthly SST off Eastern Victoria from 1993-2016 calculated on each month separately, and for the whole times series.

Month	Mann-Kendall test		Sen's Slop	Pettitt's change-point detection		
	Statistic S	p		t	KT	p
January	94	0.021	0.053	2000	84	0.106
February	52	0.206	0.032	1997	71	0.245
March	40	0.333	0.018	1997	73	0.217
April	46	0.264	0.023	1999	73	0.217
May	16	0.710	0.007	1998	62	0.403
June	50	0.224	0.022	1996	60	0.446
July	50	0.224	0.017	1999	56	0.469
August	44	0.286	0.018	1998	80	0.139
September	80	0.050	0.033	2012	72	0.231
October	28	0.157	0.0122	2012	48	0.766
November	110	0.007	0.036	2003	109	0.014
December	68	0.097	0.049	1998	74	0.204
Whole time series	708	<<0.001	0.027	Nov, 1998	2937	0.231

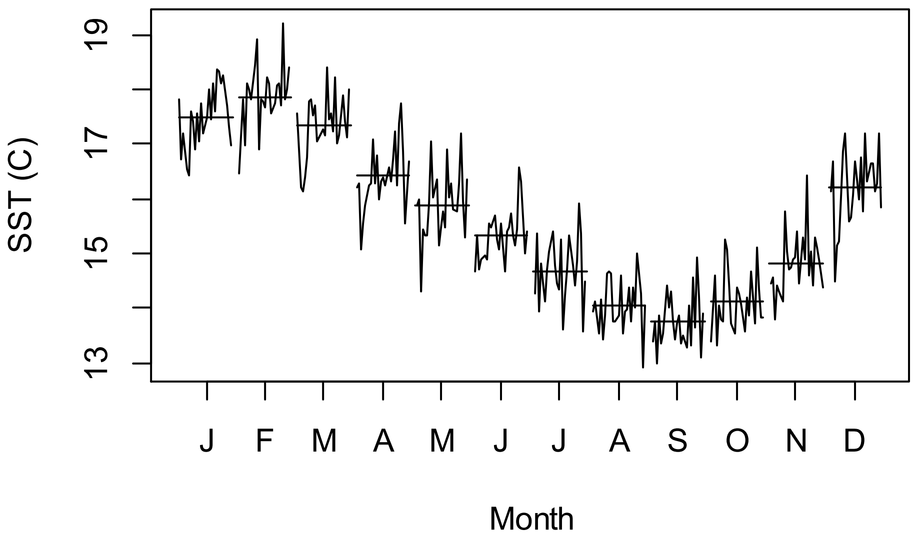


Figure 101. Monthly plot of STL Decomposition of SST off Western Victoria from 1993-2016.

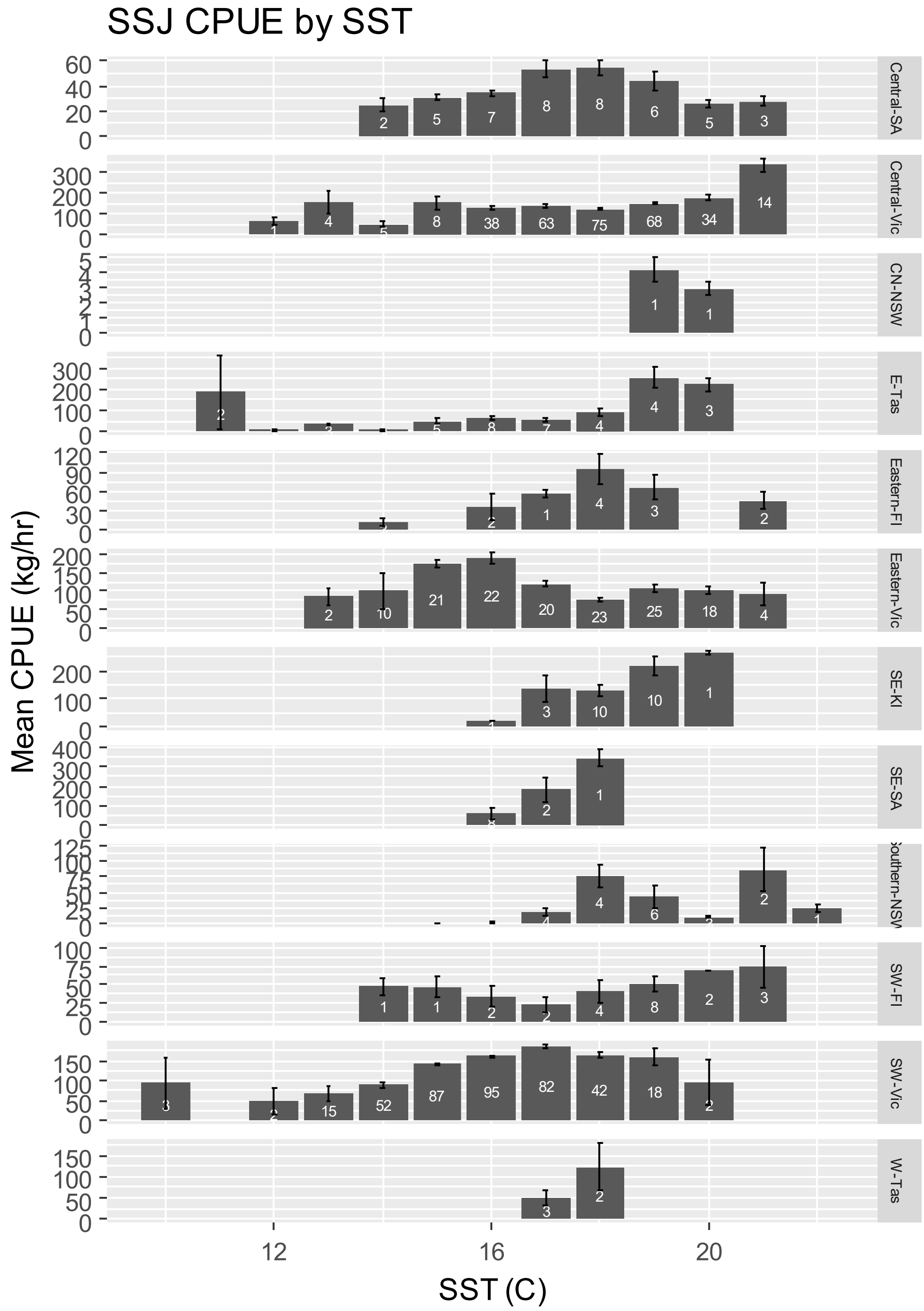


Figure 102. Mean CPUE by SST (kg/shot) for the SSJF by zone.

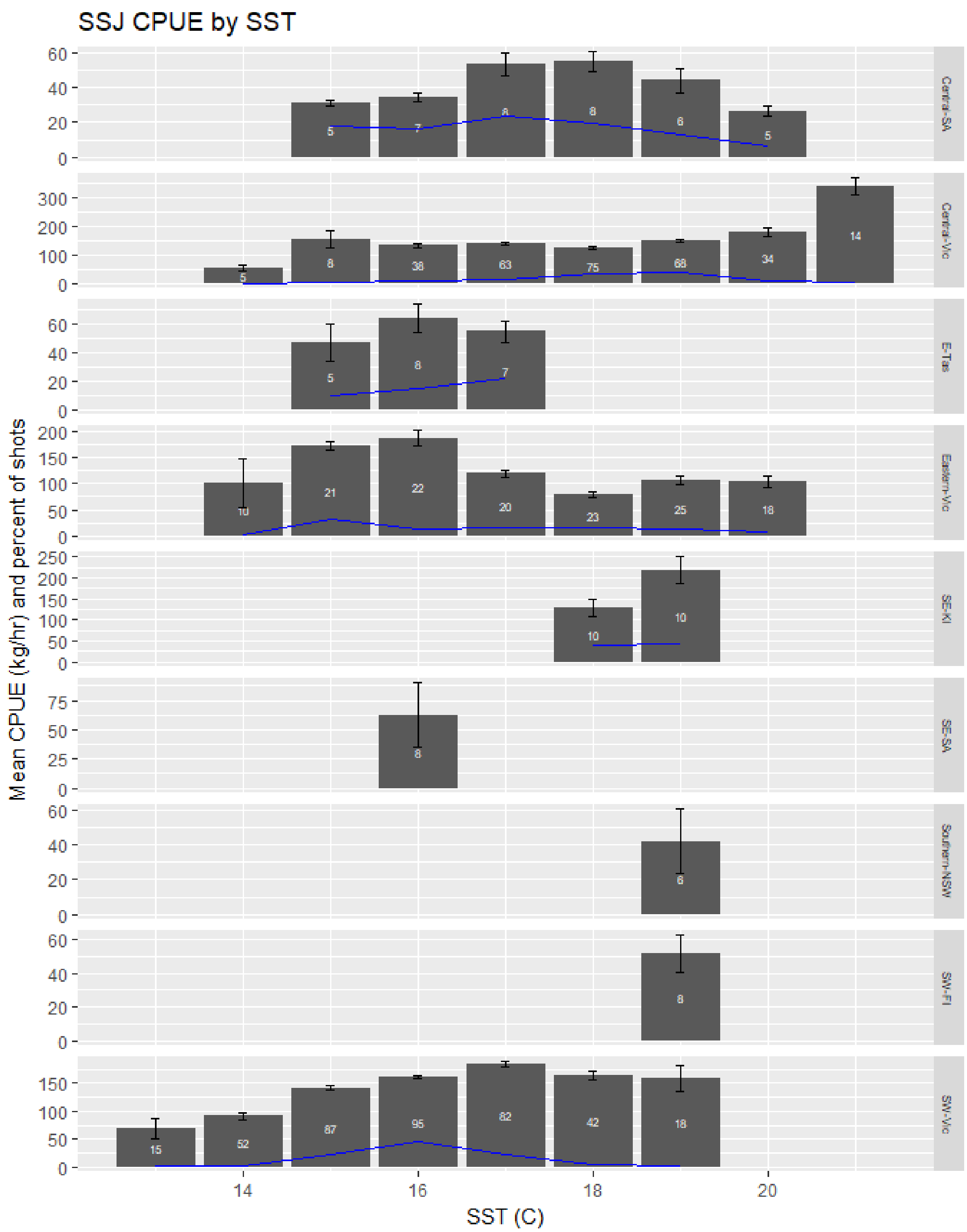


Figure 103. Total catch (t) and effort (10xhrs) by SST (˚C) for the SSJF by zone.

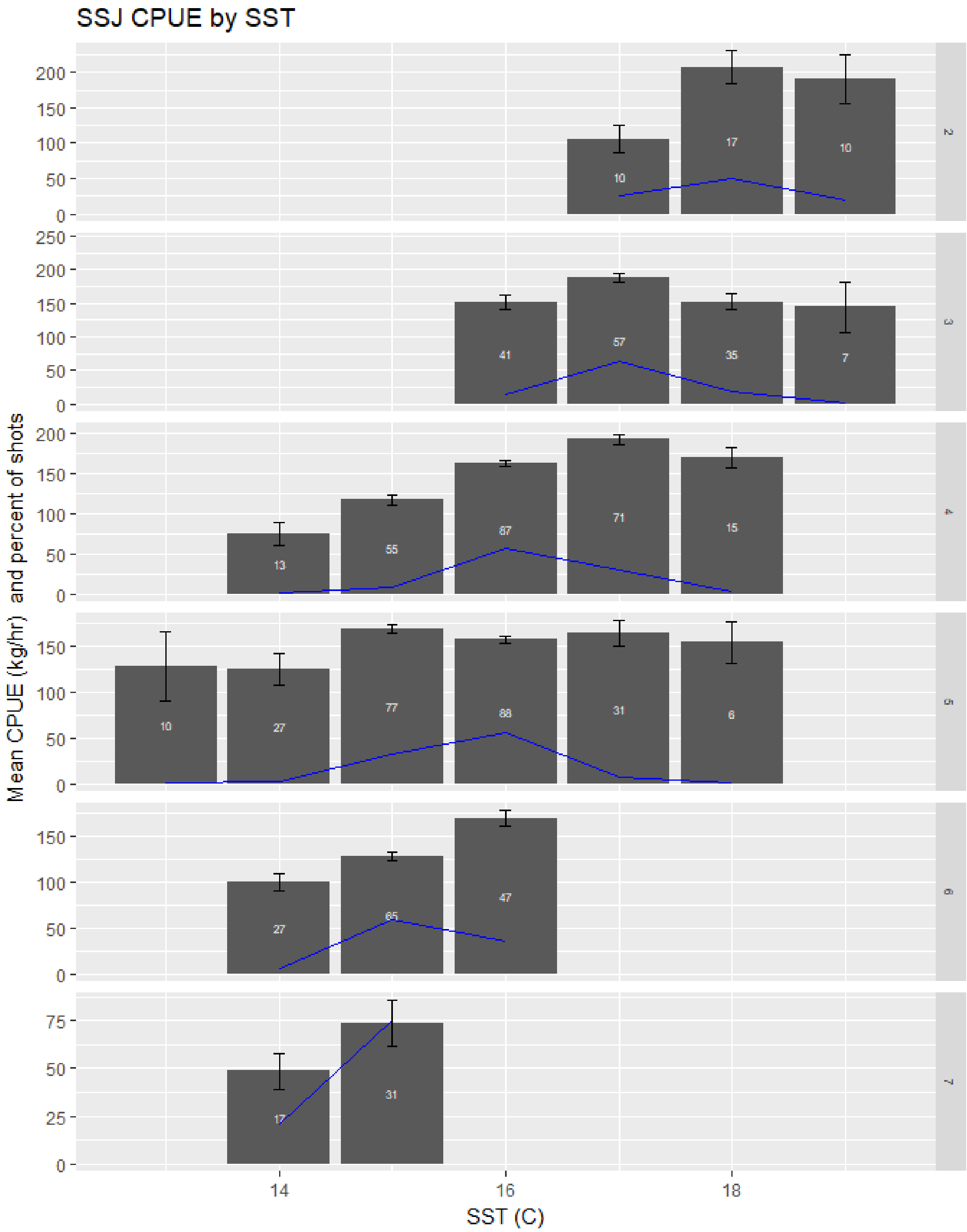


Figure 104. Mean CPUE by SST (kg/shot) and percent frequency of SST records for the SSJF by month in Western Victoria. Note that records comprising less than five vessels have been removed.

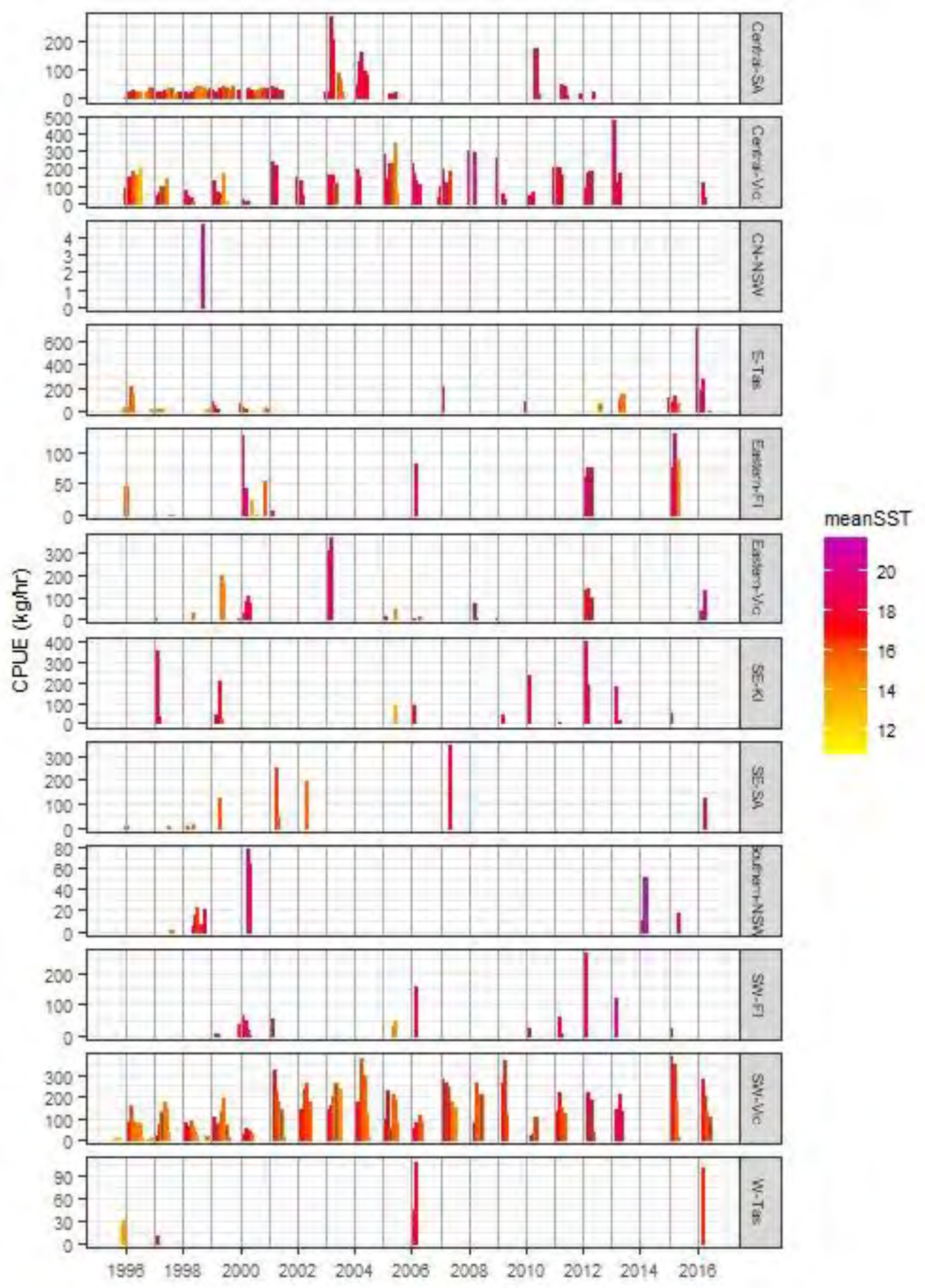


Figure 105. Time series of mean monthly CPUE (kg/shot) for the SSJ by zone coloured by mean SST. Vertical grid lines intercept the x-axis in January each year.

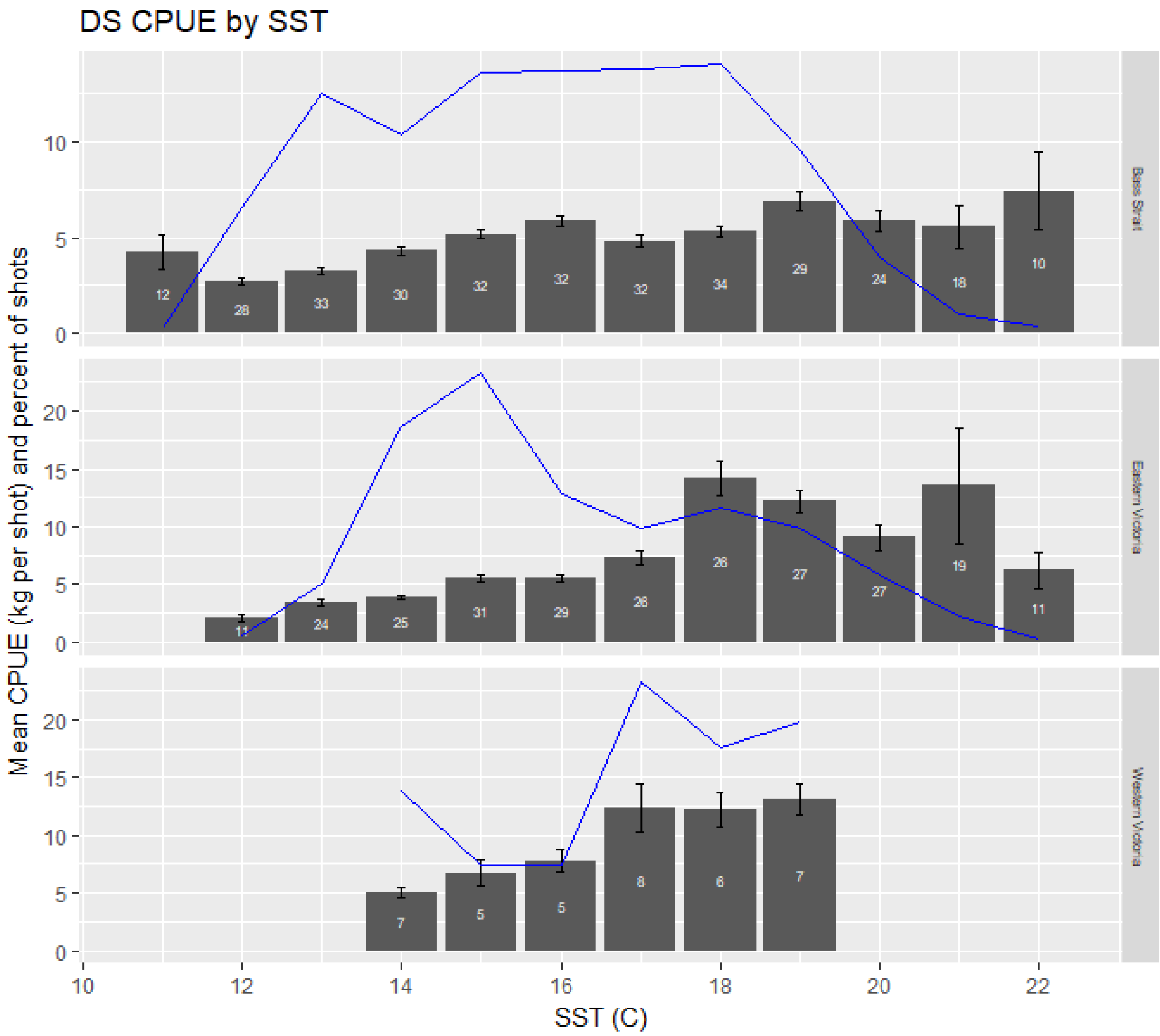


Figure 106. Mean CPUE by SST (kg/shot) and percent frequency of SST records for the DS by zone. Note that records comprising less than five vessels have been removed.

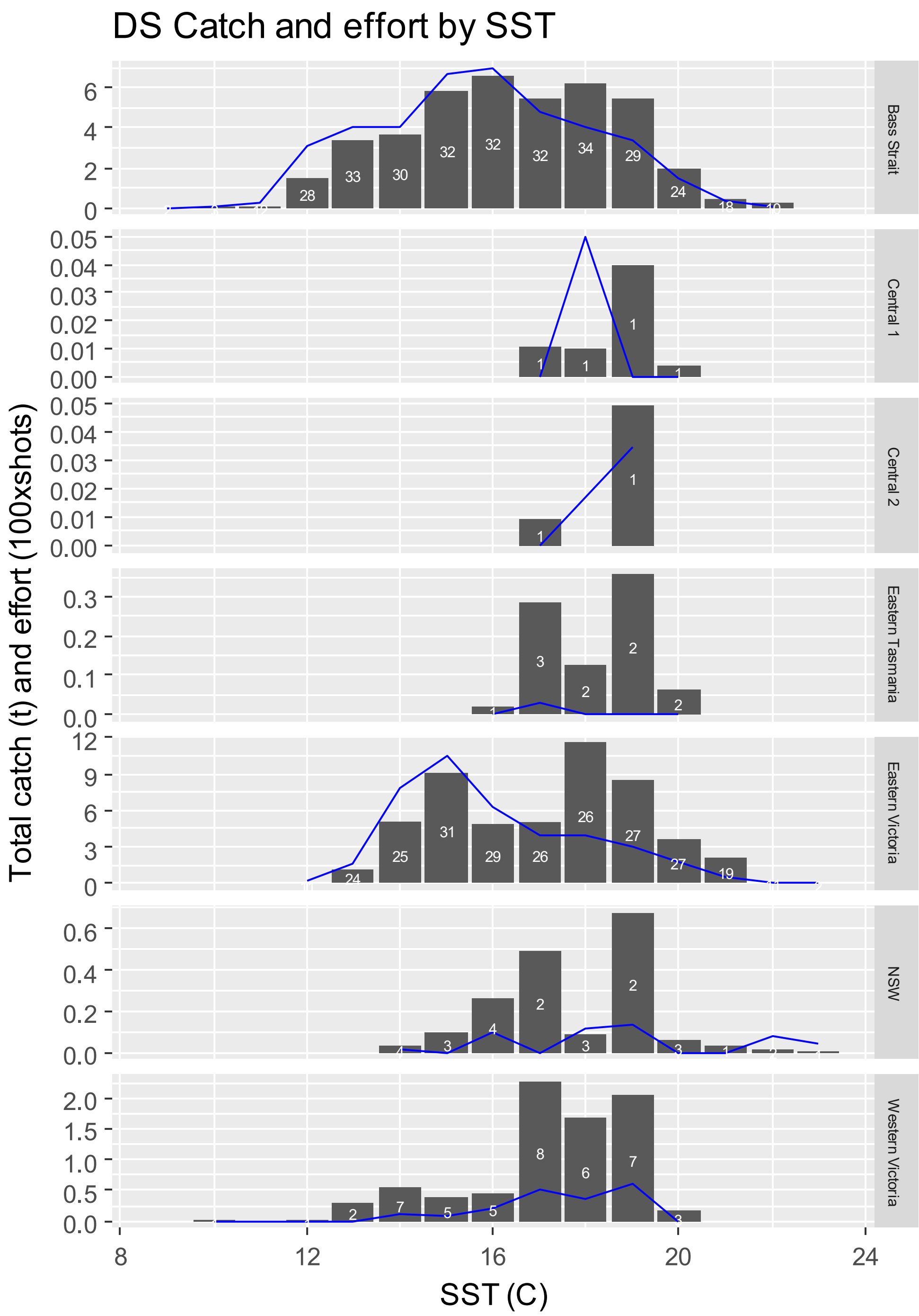


Figure 107. Total catch (t) and effort (100xhrs) by SST (˚C) for the DS by zone.

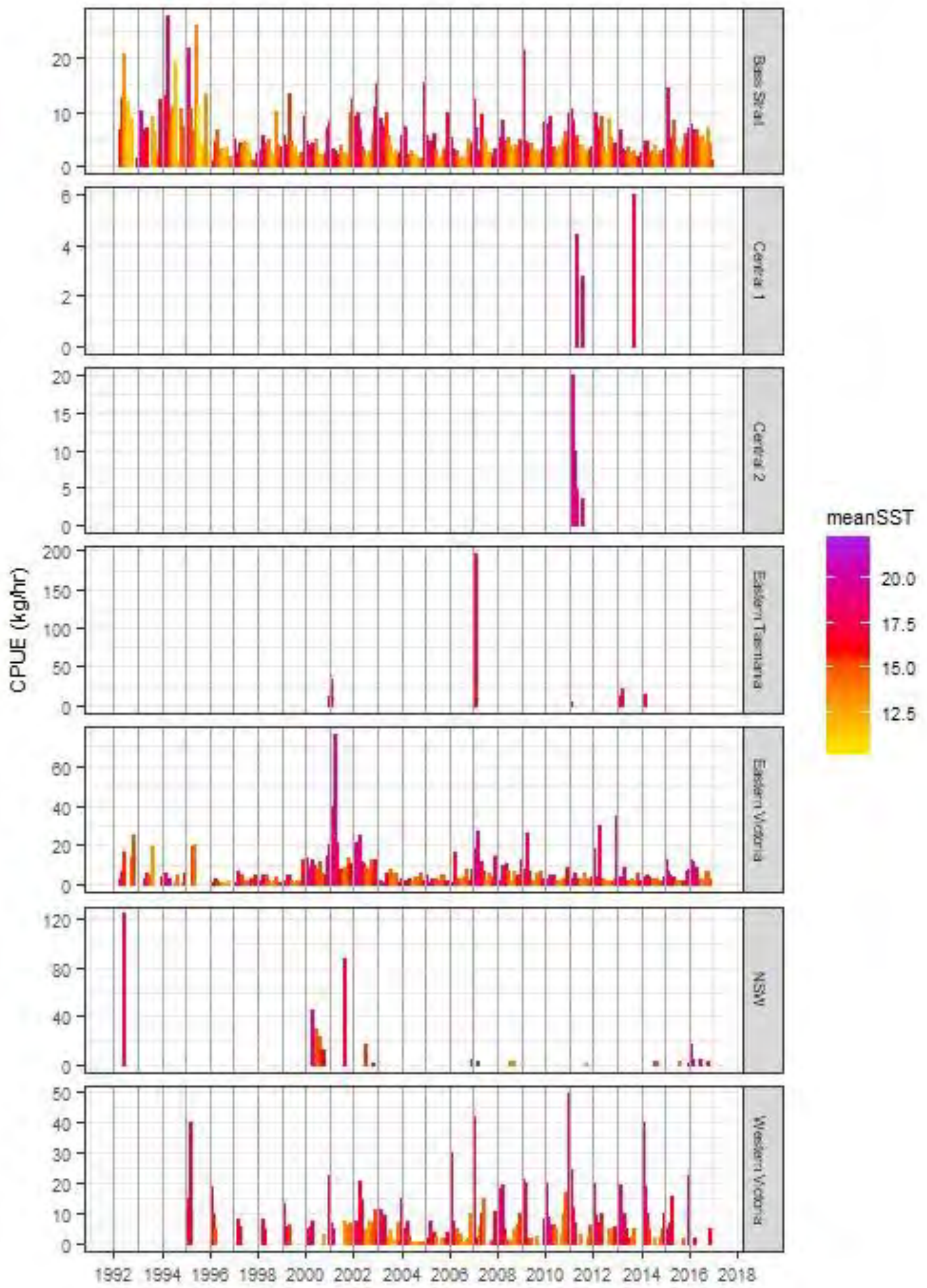


Figure 108. Time series of mean monthly CPUE (kg/shot) for the DS by zone coloured by mean SST. Vertical grid lines intercept the x-axis in January each year.

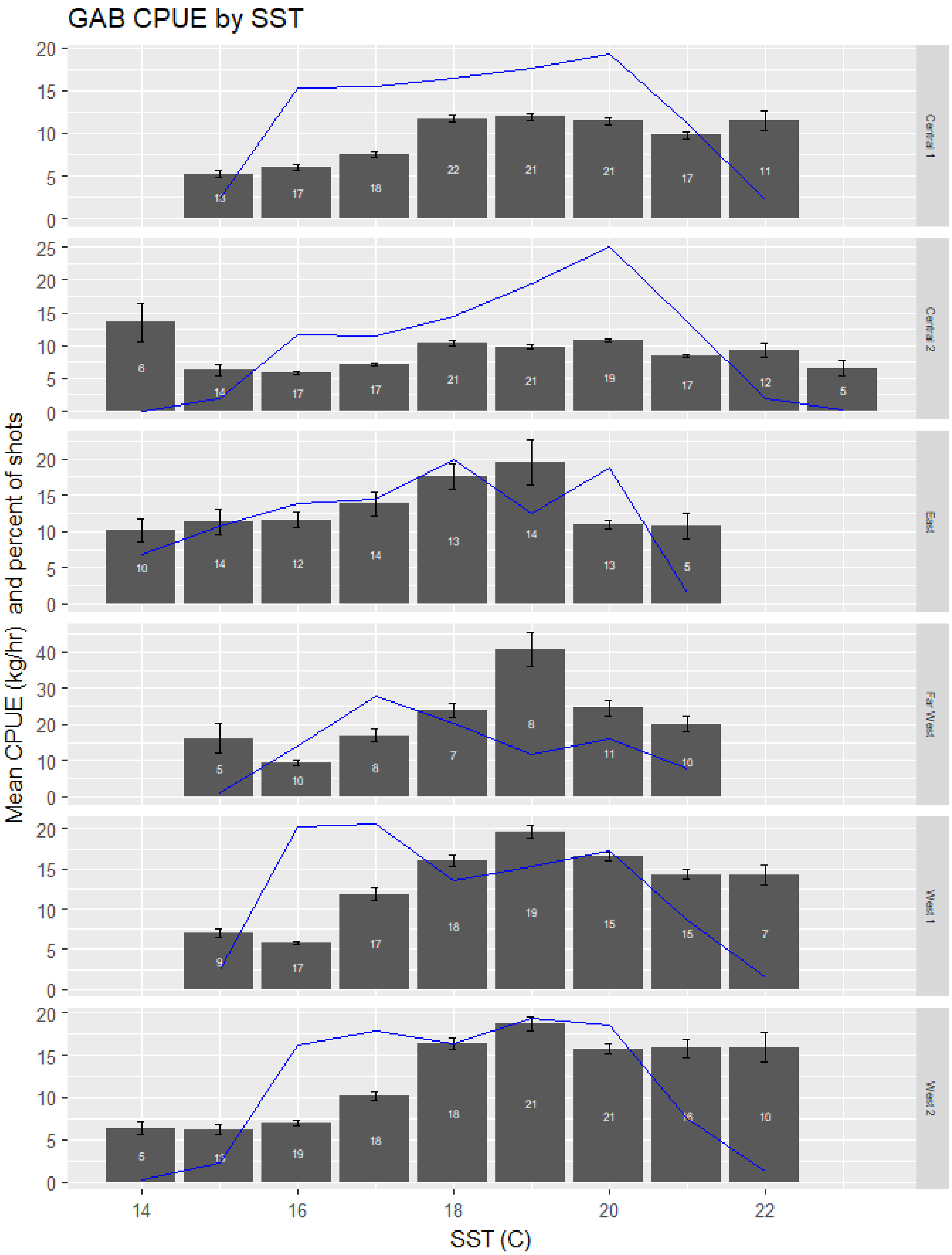


Figure 109. Mean CPUE by SST (kg/shot) and percent frequency of SST records for the GABTS by zone. Note that records comprising less than five vessels have been removed.

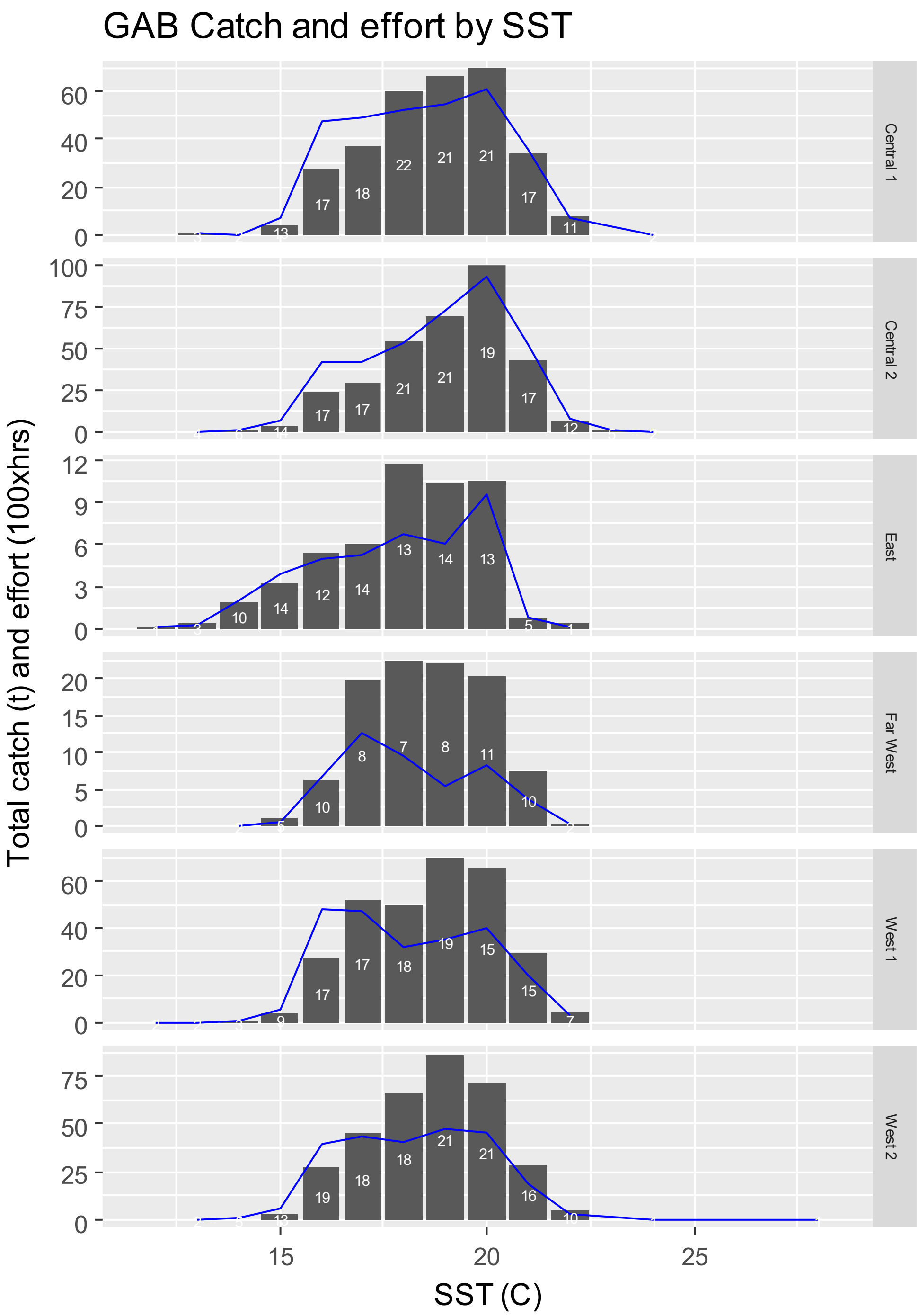


Figure 110. Total catch (t) and effort (100xhrs) by SST (˚C) for the GABTS by zone.

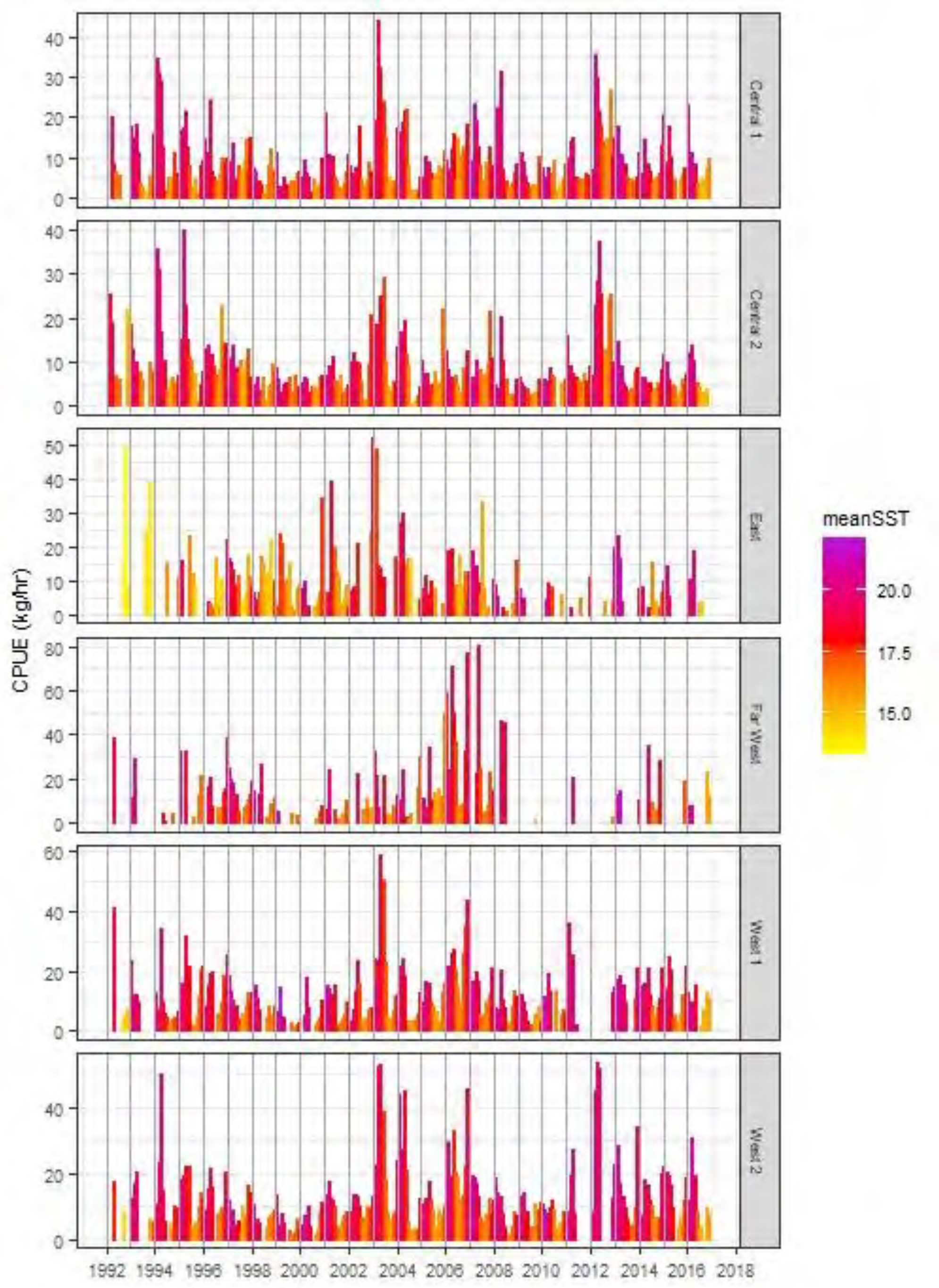


Figure 111. Time series of mean monthly CPUE (kg/shot) for the GAB by zone coloured by mean SST. Vertical grid lines intercept the x-axis in January each year.

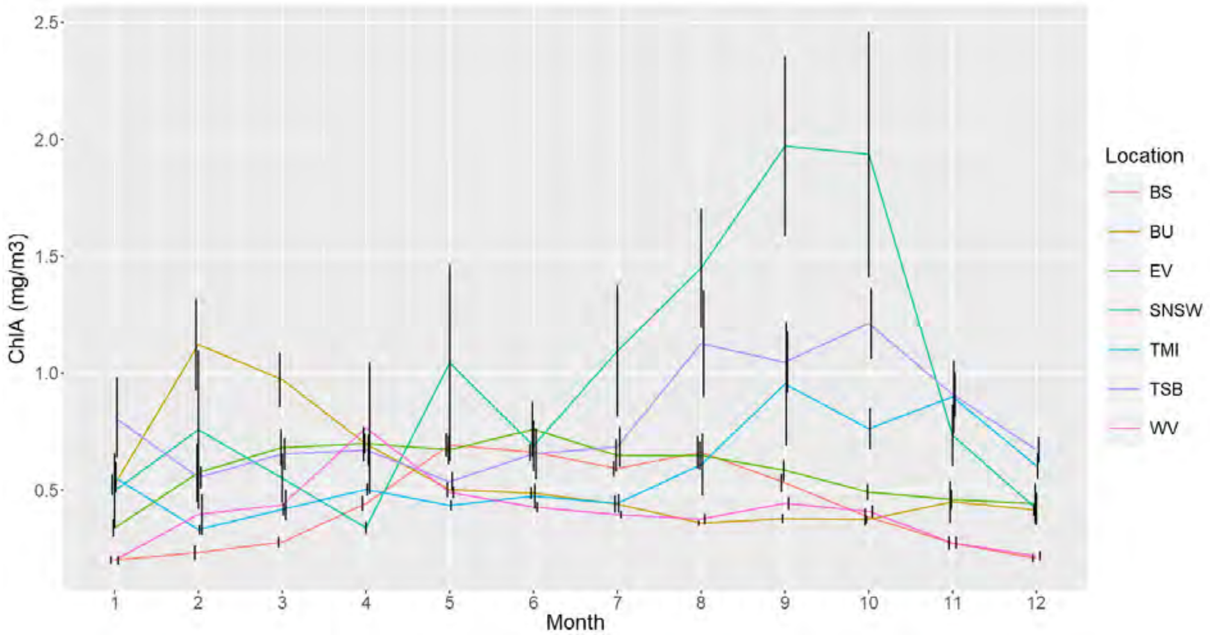


Figure 112. Mean monthly Chl a (mg/m^3) along lines from different locations around south-east Australia. Location lines can be seen in Figure 3.

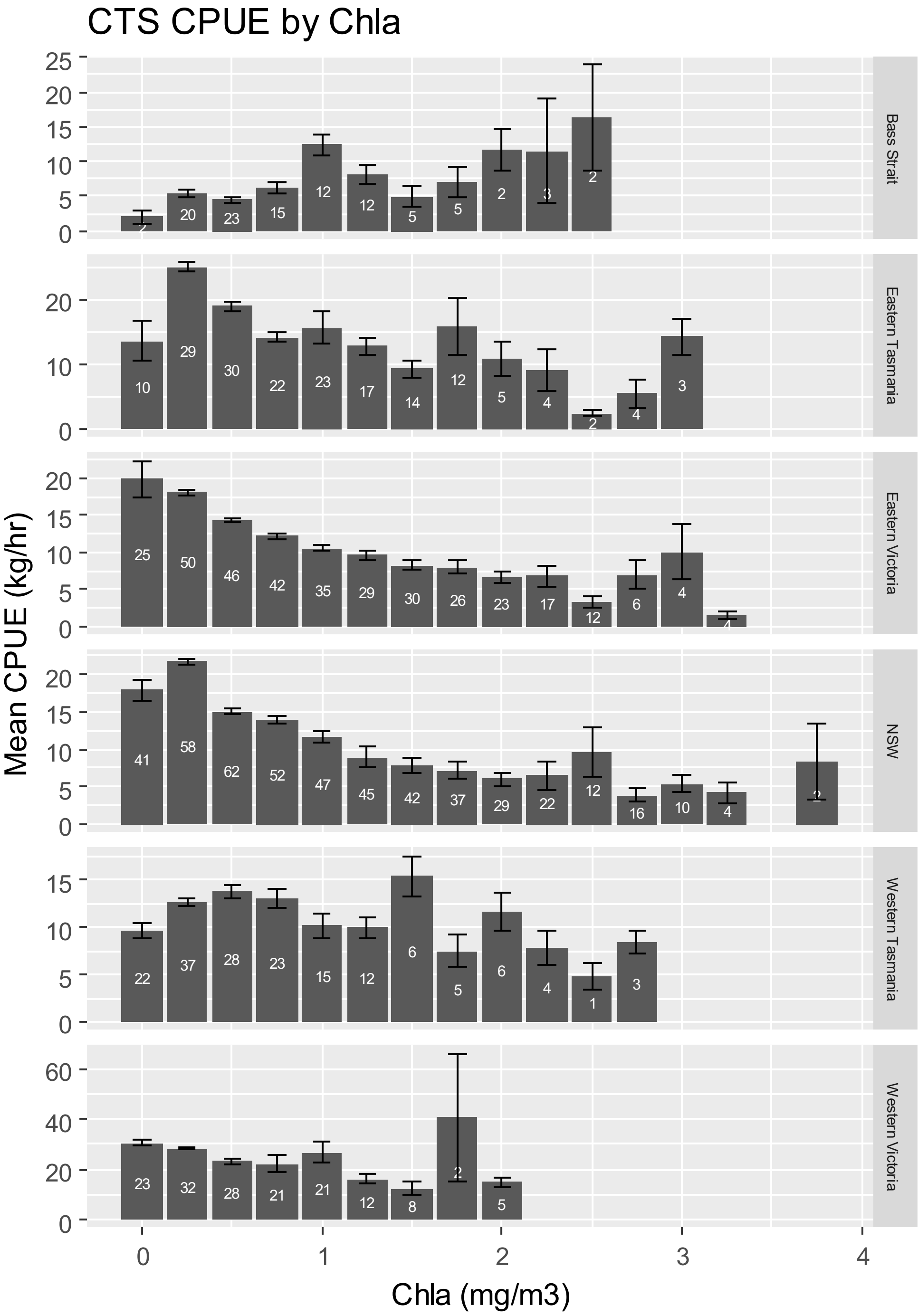


Figure 113. Mean CPUE by Chl a (mg/m^3) for the CTS by zone. Note that Chl a was rounded to the nearest 0.25 increment including zero, so for example a value of zero could include values ranging 0–0.125 mg/m^3.

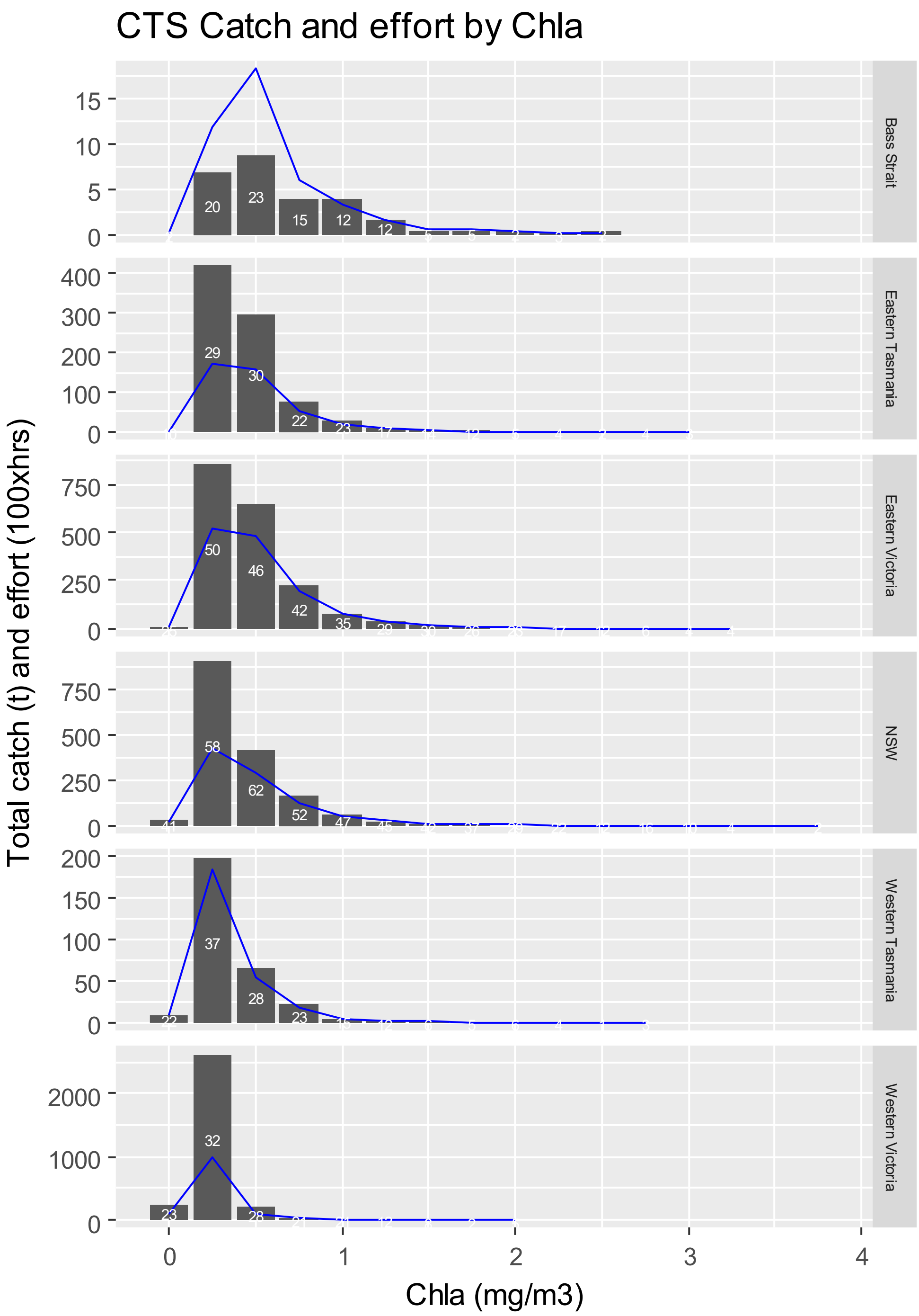


Figure 114. Total catch (t) and effort (100xhrs) by Chl a (mg/m^3) for the CTS by zone.

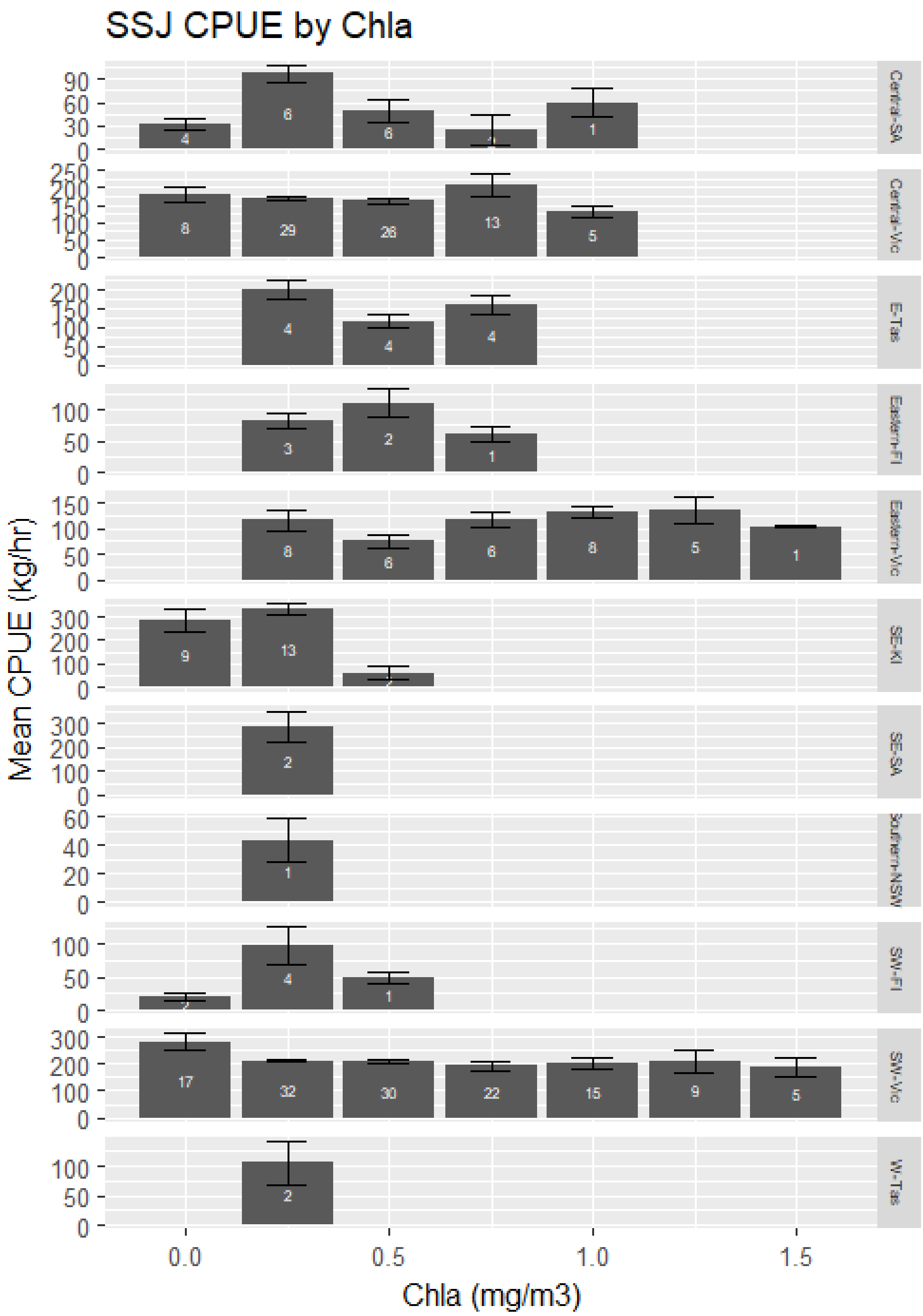


Figure 115. Mean CPUE by Chl a (mg/m^3) for the SSJF by zone.

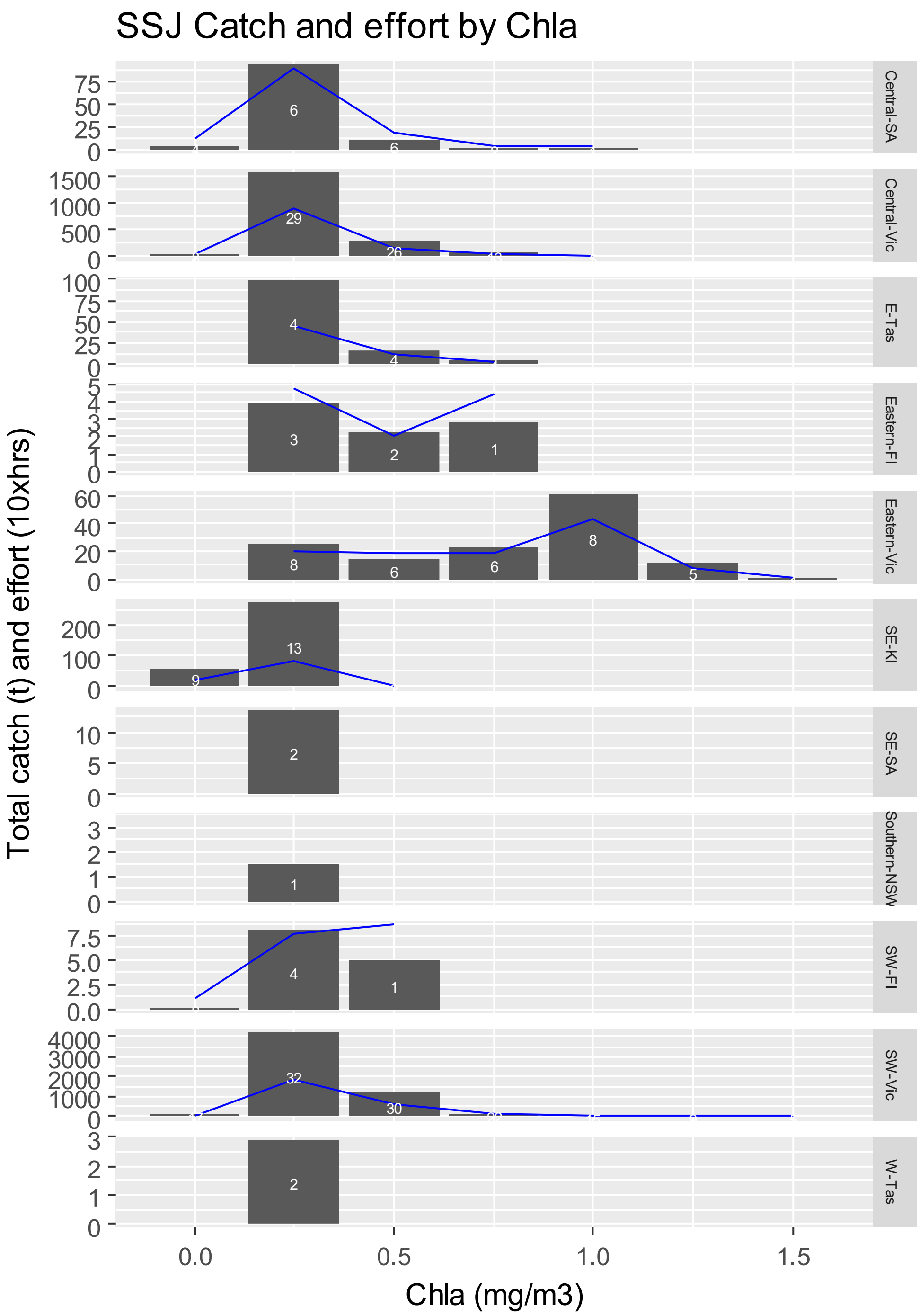


Figure 116. Total catch (t) and effort (100xhrs) by Chl a (mg/m^3) for the SSJF by zone.

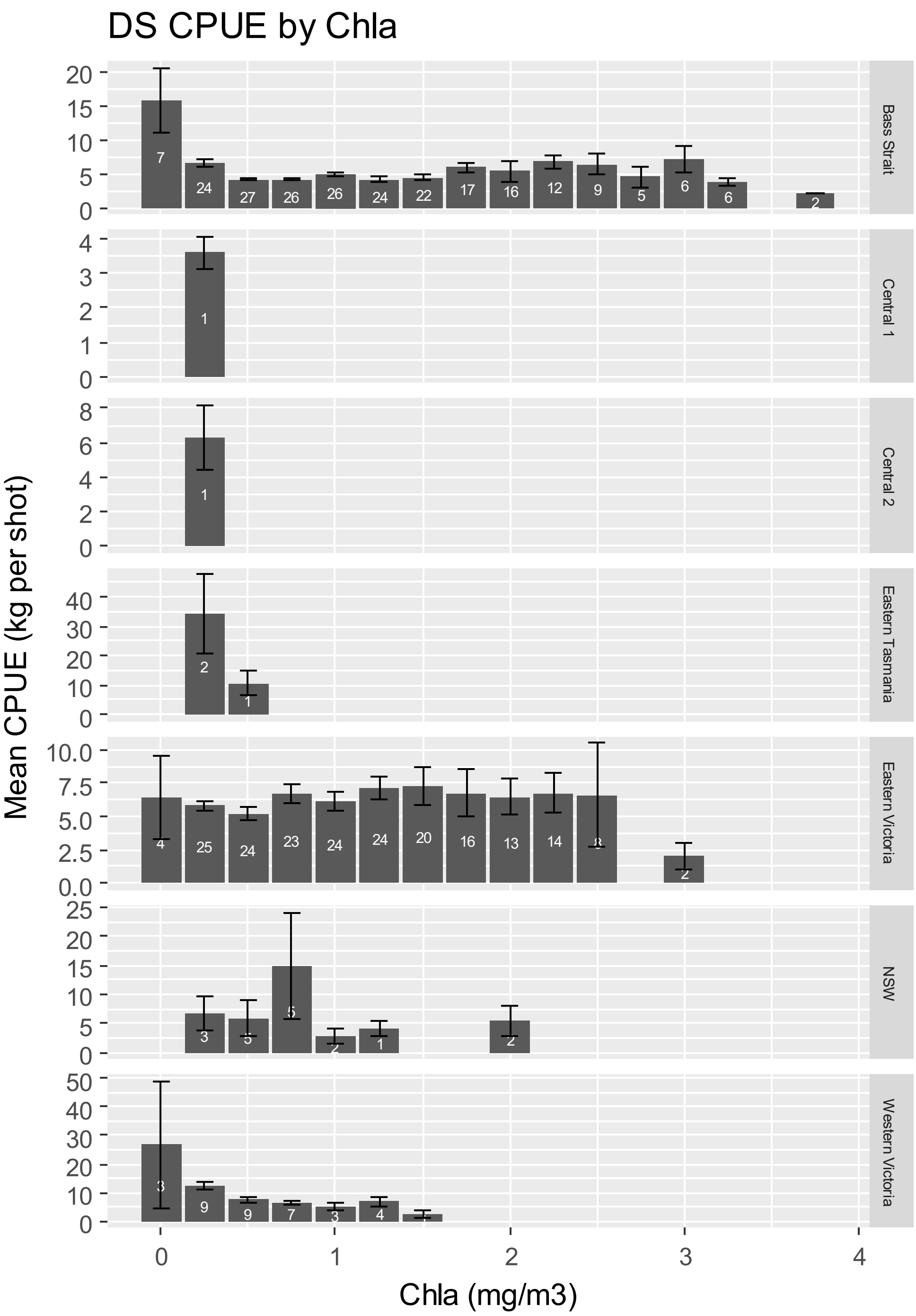


Figure 117. Mean CPUE by Chl a (mg/m^3) for the DS by zone.

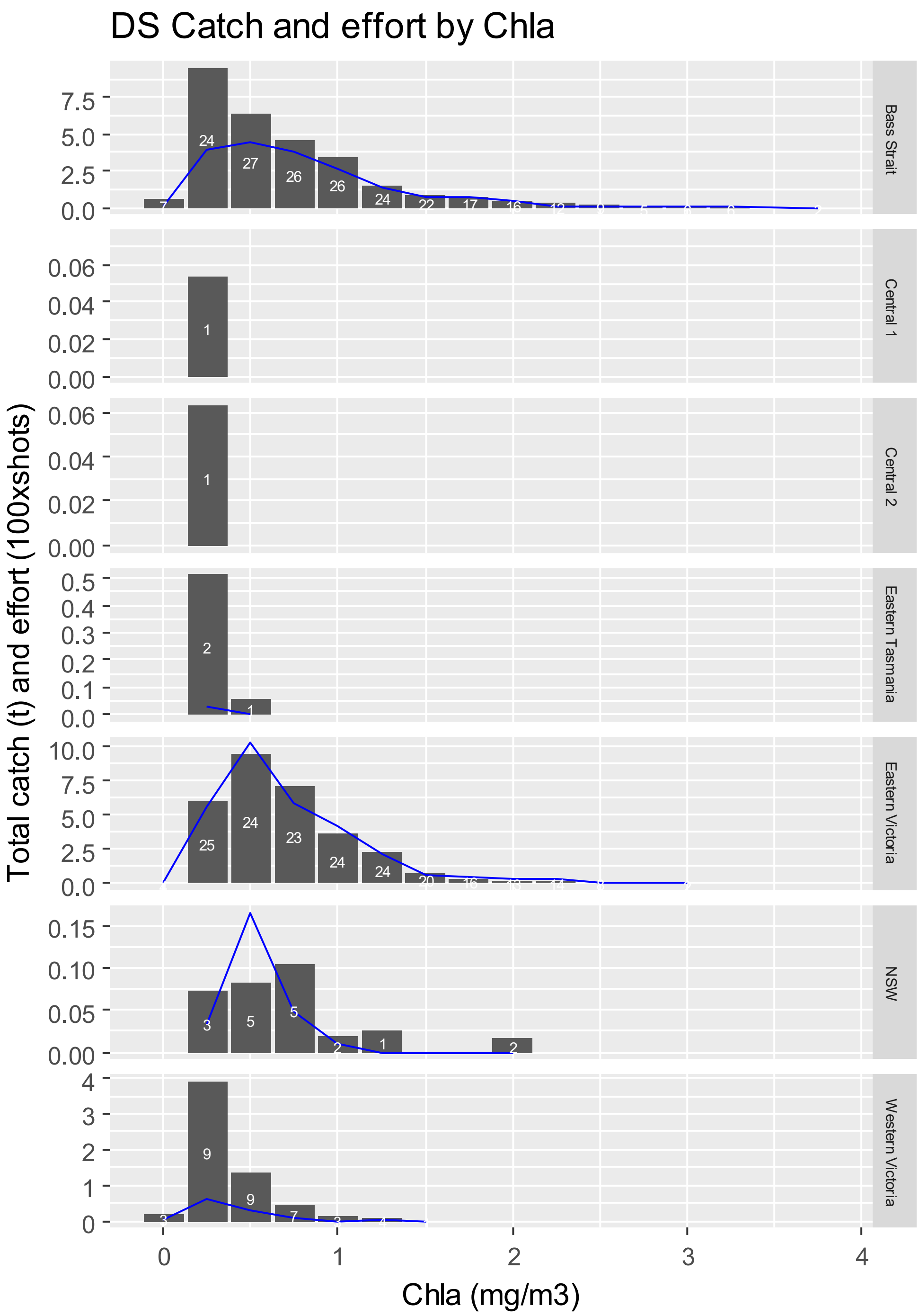


Figure 118. Total catch (t) and effort (100xhrs) by Chl a (mg/m^3) for the DS by zone.

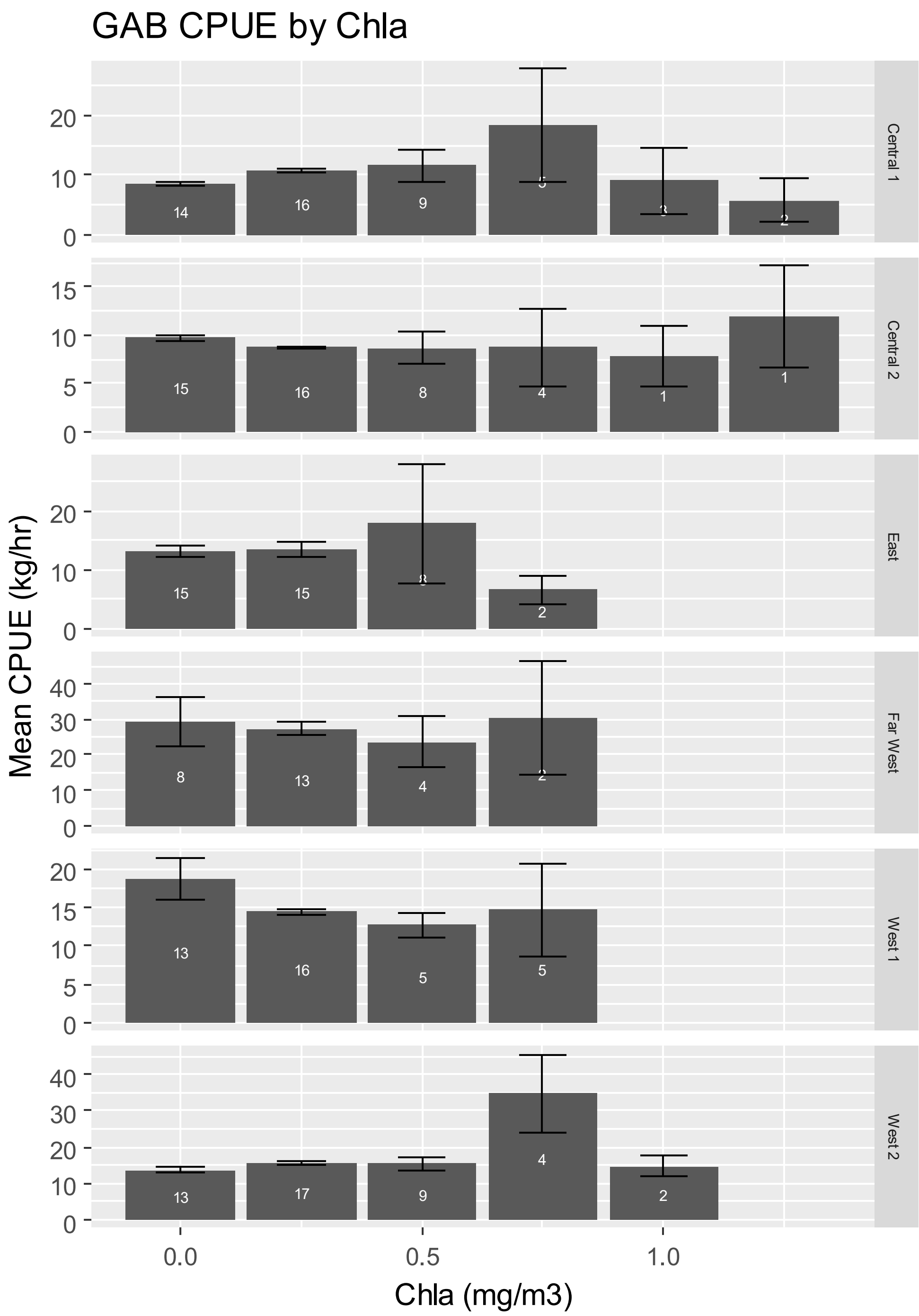


Figure 119. Mean CPUE by Chl a (mg/m^3) for the GAB by zone.

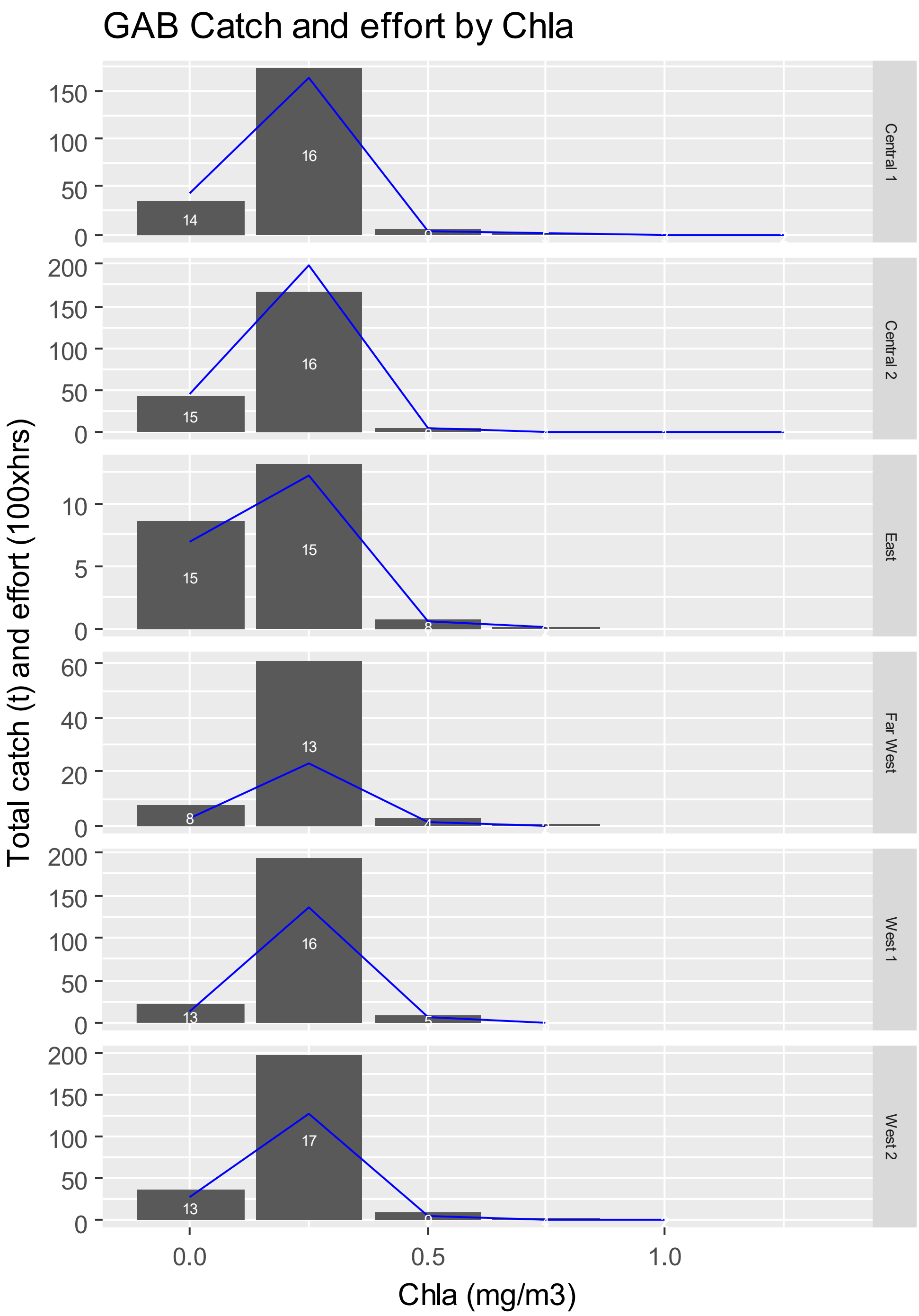


Figure 120. Total catch (t) and effort (100xhrs) by Chl a (mg/m^3) for the GABTS by zone.

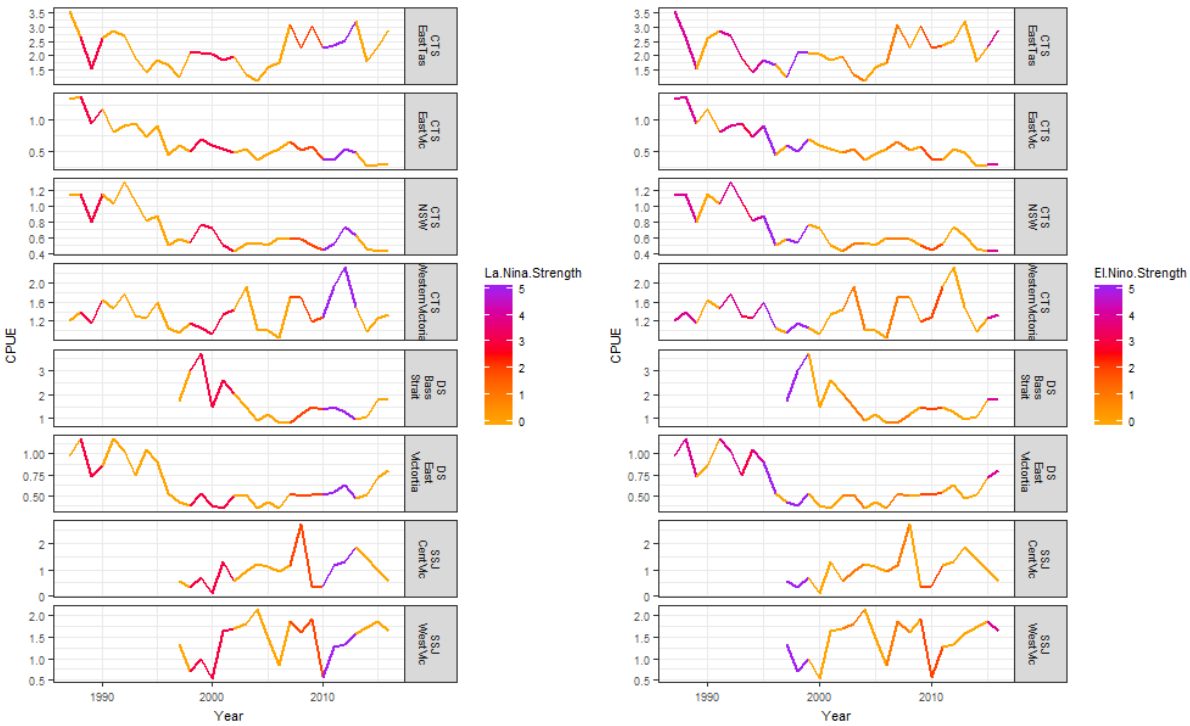


Figure 121. Annual standardised CPUE of the CTS, DS and SSJF fisheries in the main zones where Gould's Squid are caught in greatest quantities against relative La Nina and El Nino strength.

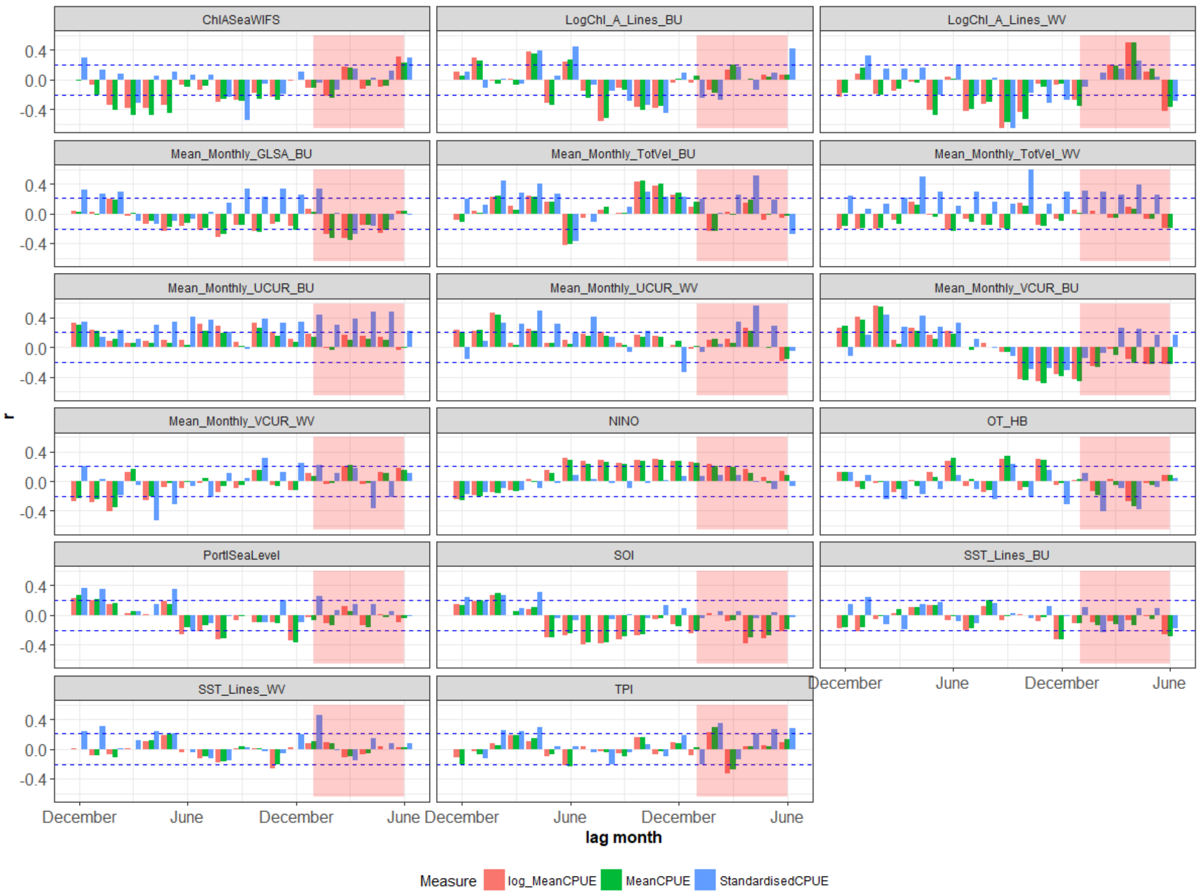


Figure 122. Correlation (r-value) between the environmental variables and three measures of squid CPUE for the CTS in Western Victoria for the year before fishing and first six months of the year of the fishery. Dashed horizontal lines represent 95% confidence intervals, dashed vertical lines indicate end of fishery period.

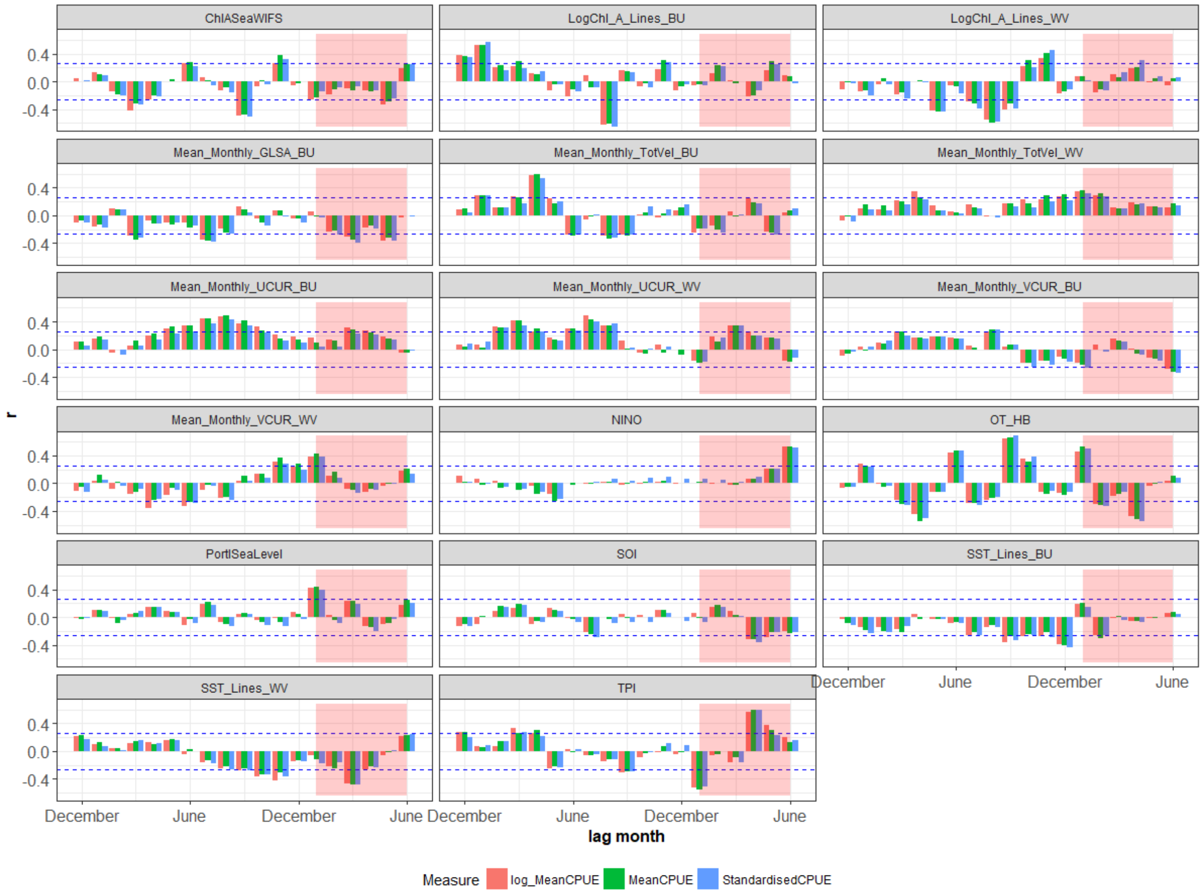


Figure 123. Correlation (r-value) between the environmental variables and three measures of squid CPUE for the SSJF in Western Victoria for the year prior to fishing and first six months of the year of the fishery. Dashed horizontal lines represent 95% confidence intervals, dashed vertical lines indicate end of fishery period.

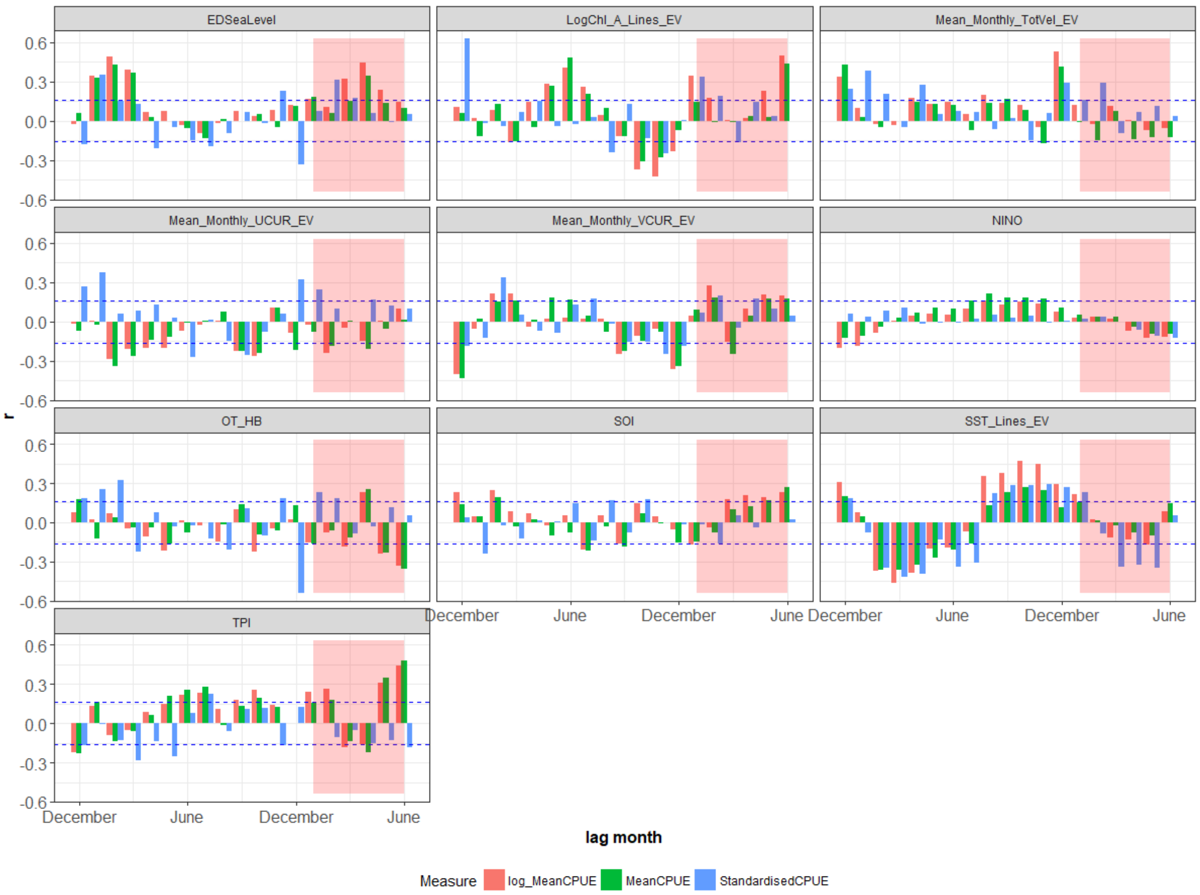


Figure 124. Correlation (r-value) between the environmental variables and three measures of squid CPUE for the CTS in Eastern Victoria for the year before fishing and first six months of the year of the fishery. Dashed horizontal lines represent 95% confidence intervals, dashed vertical lines indicate end of fishery period.

Figure 125. Correlation (r-value) between the environmental variables and three measures of squid CPUE for the DS in Eastern Victoria for the year before fishing and first six months of the year of the fishery. Dashed horizontal lines represent 95% confidence intervals, dashed vertical lines indicate end of fishery period.

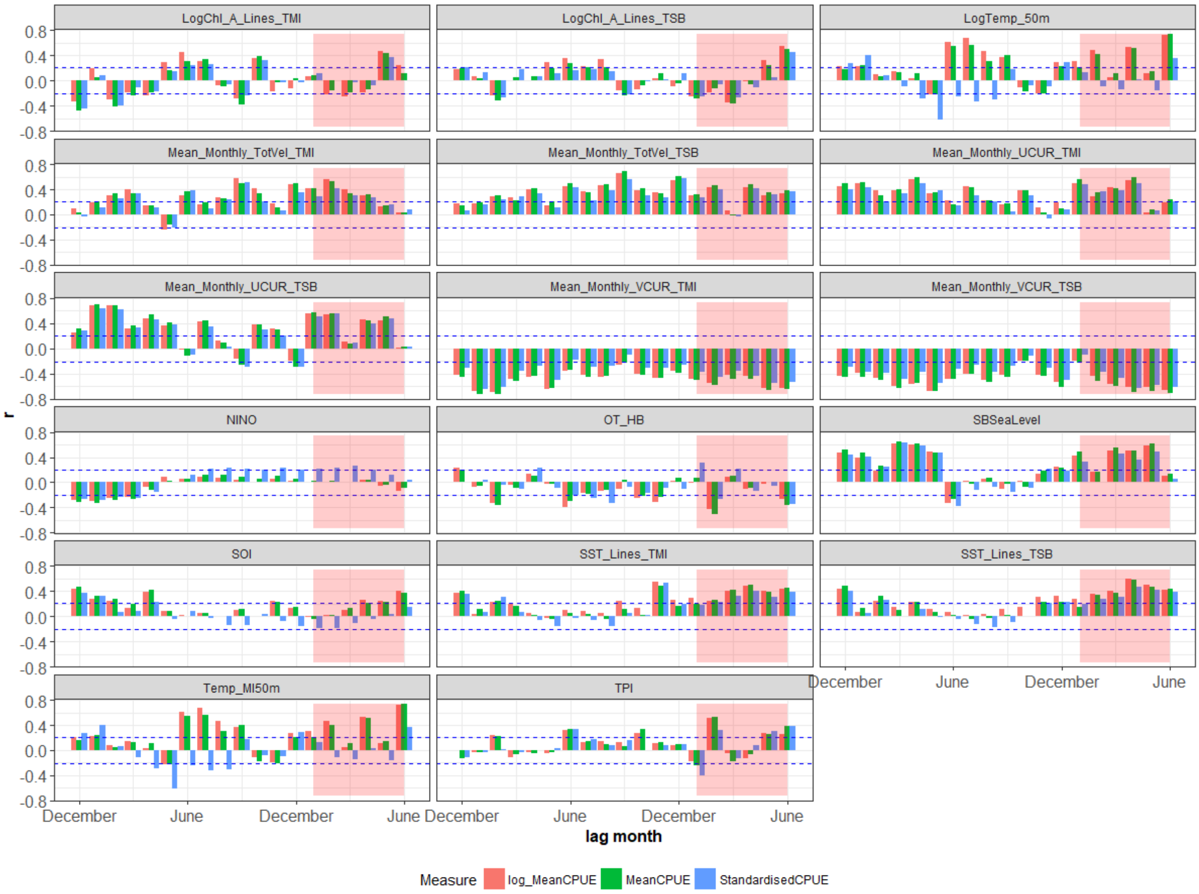


Figure 126. Correlation (r-value) between the environmental variables and three measures of squid CPUE for the CTS in Eastern Tasmania for the year before fishing and first six months of the year of the fishery. Dashed horizontal lines represent 95% confidence intervals, dashed vertical lines indicate end of fishery period.

Figure 127. Correlation (r-value) between the environmental variables and three measures of squid CPUE for the SJTas in Eastern Tasmania for the year before fishing and first six months of the year of the fishery. Dashed horizontal lines represent 95% confidence intervals, dashed vertical lines indicate end of fishery period.

Figure 128. Correlation (r-value) between the environmental variables and three measures of squid CPUE for the DS in Bass Strait for the year before fishing and first six months of the year of the fishery. Dashed horizontal lines represent 95% confidence intervals, dashed vertical lines indicate end of fishery period.

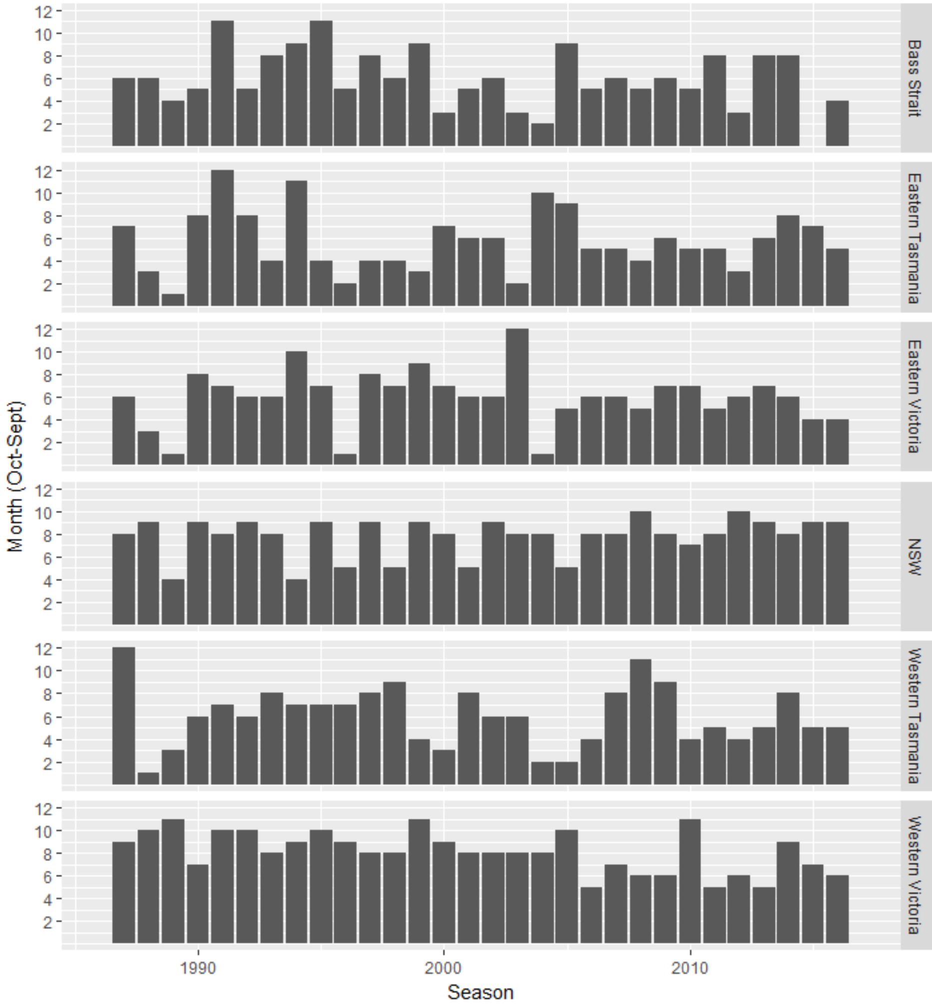


Figure 129. Recoded month with the greatest monthly CPUE in each season by the CTS in each zone. Month 1 = October, Month 12 = September.

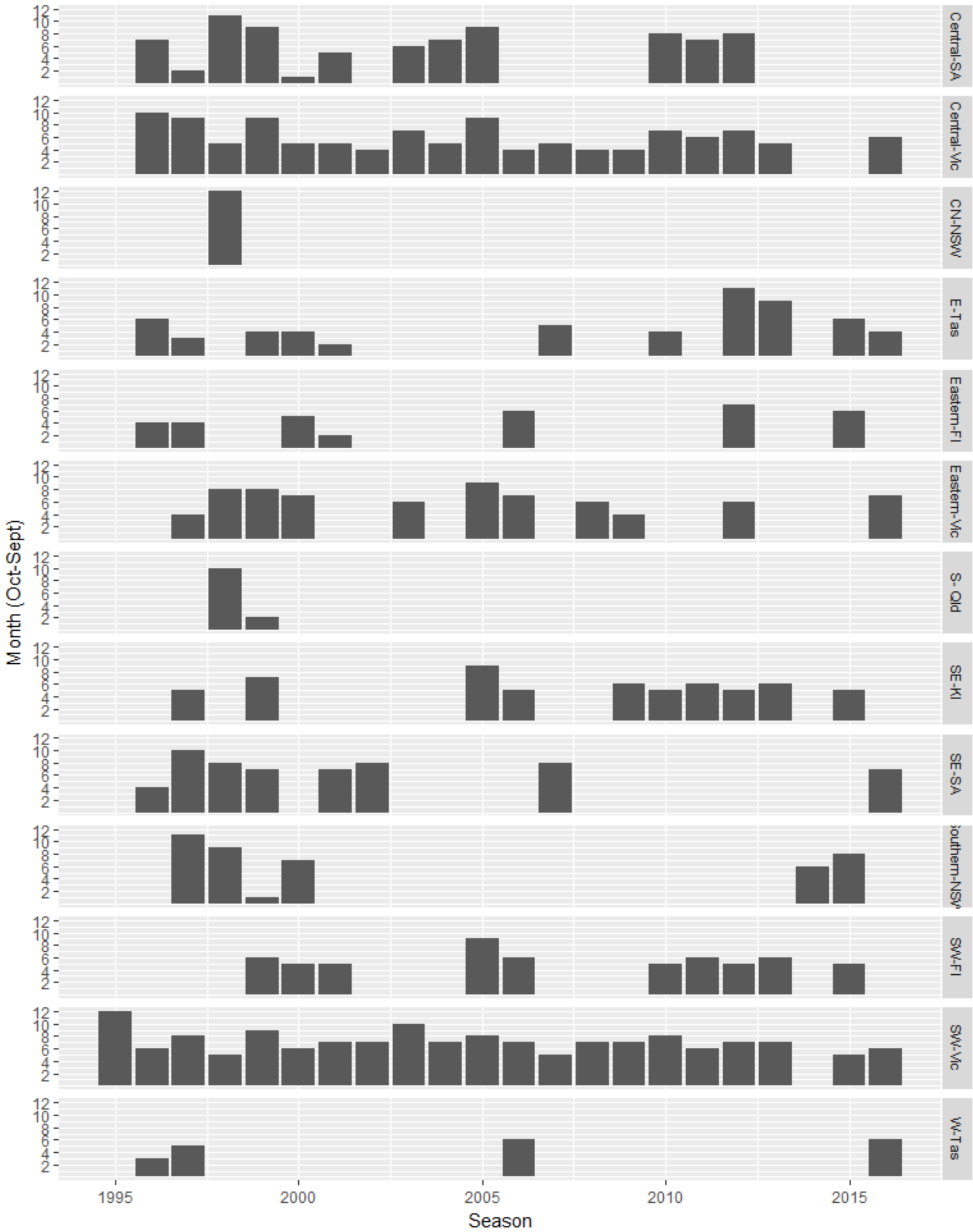


Figure 130. Recoded month with the greatest monthly CPUE in each season by the SSJF in each zone. Month 1 = October, Month 12 = September.

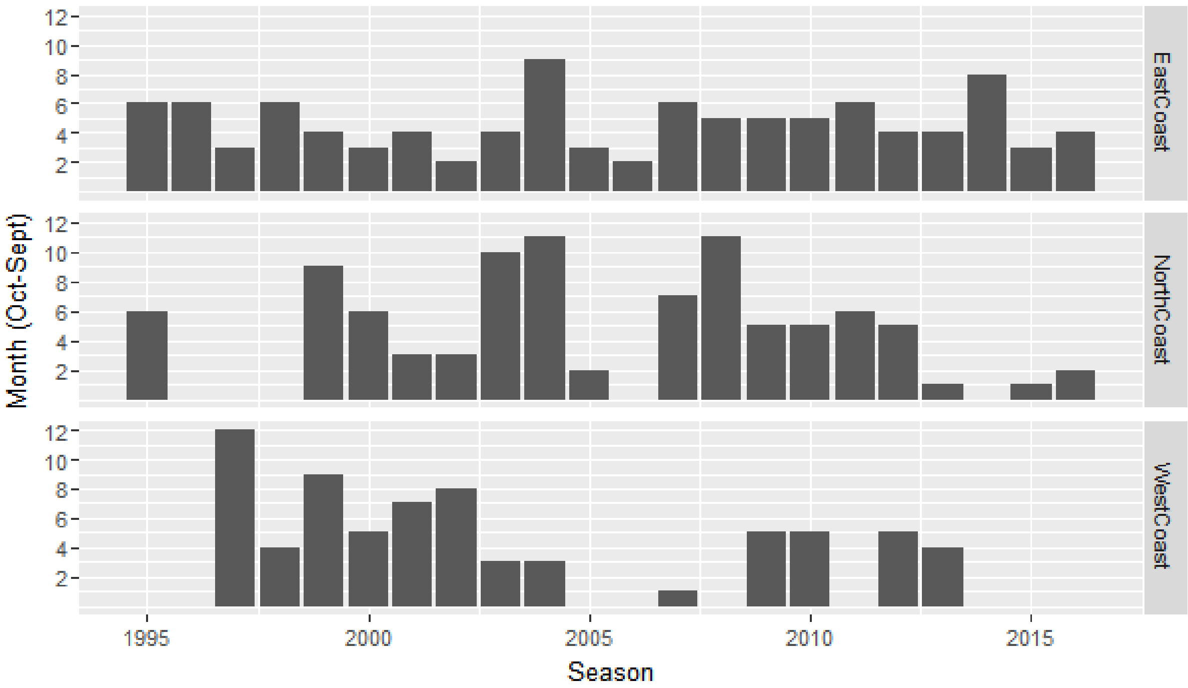


Figure 131. Recoded month with the greatest monthly CPUE in each season by the SJTas in each zone. Month 1 = October, Month 12 = September.

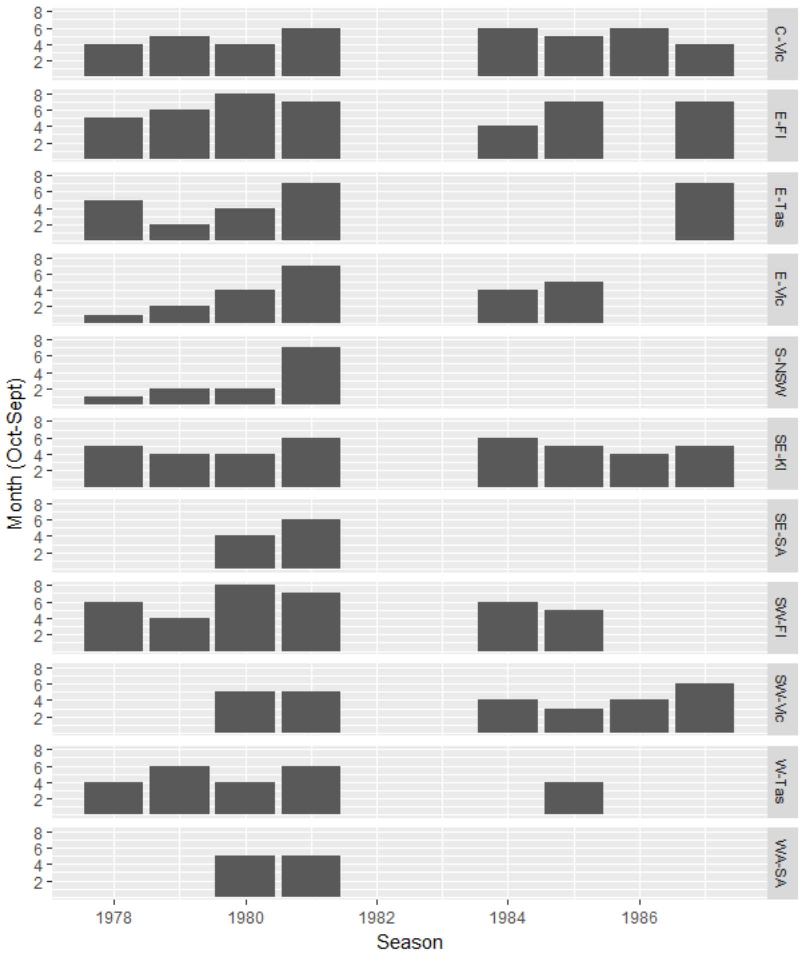


Figure 132. Recoded month with the greatest monthly CPUE in each season by the HistSJ in each zone. Month 1 = October, Month 12 = September.

Table 13. Correlation coefficients of environmental variables with month of greatest CPUE or catch by the CTS, SSJF and SJTAS in Western Victoria and Eastern Tasmania. correlation coefficients, r, listed. 0 '*' 0.001 '**' 0.01 '*' 0.05.**

Indicator	Zone	Environmental variable	Lag	Month/s	R (signif.)
CTS CPUE	WV	GLSA	0	Feb	-0.41*
		GLSA	-1	Oct-Dec	-0.51*
		PSL	0	Jan-Mar	-0.60**
		PSL	-1	Dec	-0.59**
		UCUR_BU	0	Mar	-0.46*
		UCUR_BU	-1	Apr -Dec	-0.46*
		UCUR_WV	0	Mar	-0.46*
		UCUR_WV	-1	Apr	-0.53**
		VCUR_BU	0	Apr	-0.56**
		VCUR_BU	-1	Jun	-0.49*
		VCUR_WV	0	Jan	-0.46*
		VCUR_WV	-1	Apr	0.64**
		TOT_VEL_BU	0	Jan-Mar	-0.50*
		TOT_VEL_BU	-1	Apr	-0.52*
		TOT_VEL_WV	0	Jan	-0.53**
		TOT_VEL_WV	-1	Apr-Dec	-0.49*
SSJ CPUE		SST_Lines_WV	0	May	-0.49*
		SST_Lines_WV	-1	Jan-May	-0.50*
		ChlA_Lines_BU	-1	Jan-Dec	-0.61*
		GLSA	0	Feb	-0.47*
		UCUR_WV	0	Jan	0.47*
		UCUR_WV	-1	June	-0.47*
		VCUR_BU	0	Apr	-0.51*
		TOT_VEL_BU	0	Jul	0.58**
		TOT_VEL_WV	0	Apr	-0.46*
CTS CPUE	ET	ChlA_Lines_TMI	-1	May	-0.70**
		UCUR_TSB	0	Jan	-0.56**
		UCUR_TSB	0	May	-0.61**
SJTas CPUE		SST_Lines_TMI	-1	Oct	-0.51*
SJTas Catch		Storm Bay Sea level	-1	Aug	0.56**
		ChlA_Lines_TMI	-1	Jul-Nov	-0.65*

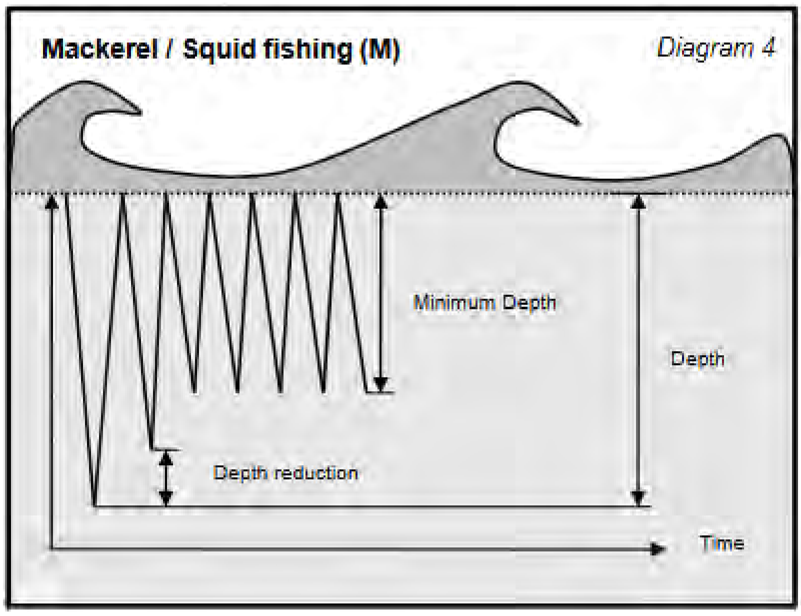
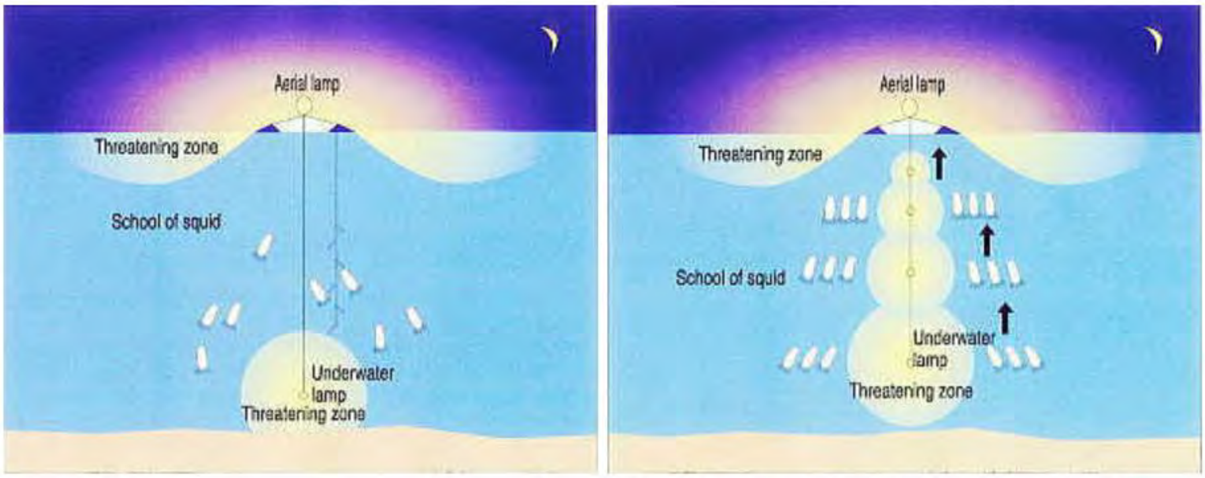


Figure 133. Diagrammatic representation of the squid program in the Belitronic BJ5000. Reproduced from [Error! Bookmark not defined.].



1.Illumination at the rated voltage in the deep sea at night.

2.Gradually decreasing the illumination while luring the squid to the aerial lamp.(1986-year realization)

Figure 134. Diagrammatic representation of use of the underwater lighting system to raise squid off the sea floor. Reproduced from [6].

[6] http://www.takuyo-riken.co.jp/eindex.html

Acknowledgments

We wish to thank

John Garvey

Maria Island water temperature, all SST and ChlA data was sourced from the Integrated Marine Observing System (IMOS) - IMOS is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy (NCRIS) and the Super Science Initiative (SSI)\"

Edward King (CSIRO) and Nick Hardman-Mountford (CSIRO) provided advice on using OC3 data.

Xavier Hoener (UTAS) provided advice on processing IMOS data products, and R code for that processing was obtained from the IMOS user code library, written by Xavier (https://github.com/aodn/imos-user-code-library).

Greg Jenkins and John Morrongiello (Melbourne University) for providing ZWW data

Paul Hamer for providing the Otway-Hobart index

References

AFMA. (2007). Southern Squid Arrow Squid Fishery Harvest Strategy. Australian Fisheries Management Authority, Canberra. http://www.afma.gov.au/wp-content/uploads/2014/11/Arrow-Squid-FisheryHS.pdf. (Accessed 5/29/2018).

AFMA. (2007). Southern Squid Jig Fishery Management Arrangements Booklet Season 2017. Australian Fisheries Management Authority, Canberra. www.afma.gov.au/wp-content/uploads/2016/12/SSJF-Management-Arrangements-Booklet-2017-FINAL.pdf

Aldrich, F. A. (1991). The history and evolution of the Newfoundland squid jigger and jigging. Journal of Cephalopod Biology 2, 23-29.

Altinagac, U. (2006). Effect of Jigs color to catching efficiency in the Squid Fishery in Turkey. Pakistan Journal of Biological Sciences, 9: 2916-2918.

An, Y. I., and Jeong, H. G. (2011). Catching efficiency of LED fishing lamp and behavioural reaction of common squid Todarodes pacificus to the shadow section of color LED light. Journal of the Korean Society of Fisheries Technology 47, 183-193.

An, Y. I., Jeong, H. G., Jung, B. M. (2009). Behavioural reaction of common squid *Todarodes pacificus* to different colours of LED light. Journal of the Korean Society of Fisheries Technology 45, 135-143.

Anderson, C.I.H., Rodhouse, P.G., 2001. Life cycles, oceanography and variability: ommastrephid squid in variable oceanographic environments. Fish. Res. 54, 133–143

Arakawa, H. Choi, S. J., Arimoto, T., Nakamura, Y. (1998). Relationship between underwater irradiance and distribution of Japanese common squid under fishing lights of a squid jigging boat. Fisheries Science 64, 553-557.

Araya, H. (1983). Fishery, biology and stock assessment of *Ommastrephes bartrammii* in the North Pacific Ocean. Memoirs of the National Museum of Victoria Melbourne 44, 269-283.

Arimoto, T. (1991). Fish behaviour control by the use of light. Fisheries Engineering 28, 71-76.

Arkhipkin, A. I., D. A. J. Middleton, A. M. Sirota, and R. Grzebielec. (2004). The effect of Falkland Current inflows on offshore ontogenetic migrations of the squid Loligo gahi on the southern shelf of the Falkland Islands. Estuarine Coastal Shelf Sci., 60: 11–22.

Arkhipkin, A.I, Rodhouse, P. G.K., Pierce, G. J., Sauer, W., Sakai, M., Allcock, L., Arguelles, J., Bower, J. R., Castillo, G., Ceriola, L., Chen, C, Chen, X., Diaz-Santana, M., Downey, N., González, A.F., Granados Amores, J., Green, C. P., Guerra, A, Hendrickson, L. C., Ibáñez, C. Ito, K., Jereb, P., Kato, Y., Katugin, O. N., Kawano, M., Kidokoro, M., Kulik, V. V., Laptikhovsky, V.V., Lipinski, M. R., Liu, B., Mariátegui, L., Marin, W., Medina, M., Miki, K., Miyahara, K., Moltschaniwskyj, N., Moustahfid, H., Nabhitabhata, J., Nanjo, N., Nigmatullin, C. M., Ohtani, T., Pecl, G. , Perez, A. A., Piatkowski, U., Saikliang, P., Salinas-Zavala, C. A., Steer, M., Tian, Y., Ueta, Y., Vijai, D., Wakabayashi, T., Yamaguchi, T., Yamashiro, C., Yamashita, N. and Zeidberg, L. D. (2015). World Squid Fisheries, Reviews in Fisheries Science & Aquaculture, 23, 92-252.

Bakun, A., and Csirke, J. 1998. Environmental processes potentially involved in recruitment variability of Illex squids. In Squid Recruitment Dynamics, pp. 105 – 124. Ed. by P. G. Rodhouse, E. G. Dawe, and R. K. O'Dor. Food and Agriculture Organization of the United Nations Fisheries Technical Paper. No. 376. FAO, Rome. xii + 273 pp.

Blondeau-Patissier, D., Gower, J.F.R., Dekker, A.G., Phinn, S.R., and Brando, V.E. (2017). A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans, Progress in Oceanography, Volume 123, 2014, Pages 123-144, http://dx.doi.org/10.1016/j.pocean.2013.12.008.

Brandt, S. B. (1983a). Temporal and spatial patterns of lanternfish (family Myctophidae) communities associated with a warm-core eddy. Mar. Biol. 74: 231–244

Brandt, S.B. (1983b). Pelagic squid associations with a warm-core eddy of the East Australian Current. Aust. J. Mar. Freshwater Res. 34: 573-585.

Brando, V., Dekker, A., Marks, A., Qin, Y., Oubelkheir, K. (2006). Chlorophyll and suspended sediment assessment in a macrotidal tropical estuary adjacent to the Great Barrier Reef: Spatial and temporal assessment using remote sensing. Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (Coastal CRC), Indooroopilly Qld.

Brodziak, J. & Hendrickson, L. (1999). An analysis of environmental effects on survey catches of squids *Loligo pealei* and *Illex illecebrosus* in the northwest Atlantic. Fishery Bulletin 97, 9-24.

Cabanellas-Reboredo, M., Alo´s, J., Palmer, M., and Morales-Nin, B. 2012. Environmental effects on recreational squid jigging fishery catches. – ICES Journal of Marine Science, 69: 1823–1830.

Cao, J., Chen, X., and Chen., Y. (2009). Influence of surface oceanographic variability on abundance of the western winter-spring cohort of neon flying squid *Ommastrephes bartramii* in the NW Pacific Ocean. Marine Ecology Progress Series 381, 119-127.

Challier, L., Royer, J., Pierce, G. J., Bailey, N., Roel, B. and Robin, J. P. (2005). Environmental and stock effects on recruitment variability in the English Channel squid *Loligo forbesi*. Aquatic Living Resources 18, 353-360.

Chang,K-Y., Chen, C-S., Wang, H-Y., Kuo, C-L. and Chiu, T-S. (2015). The Antarctic Oscillation index as an environmental parameter for predicting catches of the Argentine shortfin squid (*Illex argentinus*) (Cephalopoda: Ommastrephidae) in southwest Atlantic waters. Fish. Bull. 113:202–212 (2015). doi: 10.7755/FB.113.2.8

Chen, C.S., Pierce, G. J., Wang, J., Robin, J.P., Poulard, J. C., Pereira, J., Zuur, A. F., Boyle, P. R., Bailey, N. Beare, D. J., Jereb, P., Ragonese, S., Mannini, A., and Orsi-Relini, L. (2006). The apparent disappearance of *Loligo forbesi* from the south of its range in the 1990s: Trends in *Loligo* spp. abundance in the northeast Atlantic and possible environmental influences. Fisheries Research 78, 44-54.

Choi, S. J. (2006). Radiation and underwater transmission characteristics of a high luminance light-emitting diode as the light source for fishing lamps. Journal of the Korean Society of Fisheries Technology 39, 480-486.

Cochrane, K. L., Oliver, B., and Sauer, W. (2014). An assessment of the current status of the chokka squid fishery in South Africa and an evaluation of alternative allocation strategies. Marine Policy 43, 149-163.

Coelho, M.L., Stobberup, K.A., O'Dor, R., and Dawe, E.G. (1994). Life history strategies of the squid, *Inlex illecebrosus*, in the Northwest Atlantic Aquat. Living Resour. 7: 233-246.

Condie, S.A., Mansbridge, J.V., Cahill, M.L., 2011. Contrasting local retention and cross-shore transports of the East Australian Current and the Leeuwin Current and their relative influences on the life histories of small pelagic fishes. Deep-Sea Res. 58, 606–615.

de Boyer Monte´gut, C., G. Madec, A. S. Fischer, A. Lazar, and D. Iudicone (2004), Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, J. Geophys. Res., 109, C12003, doi:10.1029/2004JC002378.

Dormann, C. F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J. R. G., Gruber, B., Lafourcade, B., Leitão, P. J., Münkemüller, T., McClean, C., Osborne, P. E., Reineking, B., Schröder, B., Skidmore, A. K., Zurell, D. and Lautenbach, S. (2013), Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography, 36: 27–46. doi:10.1111/j.1600-0587.2012.07348.x

Downey, N. J., Roberts, M. J., and Baird, D. (2010). An investigation of the spawning behaviour of the chokka squid *Loligo reynaudii* and the potential effects of temperature using acoustic telemetry. ICES Journal of Marine Science, 67: 231–243.

Dunning, M. and S.B. Brandt. (1985). The distribution and life history of commercially important deep-water squid from Australia. Aust. J. Mar. Freshw. Res. 36:343-359.Earth Science WA. (2018). The Leeuwin Current and ENSO. http://www.earthsciencewa.com.au/mod/resource/view.php?id=1060. (Accessed 19/4/2018)

Fandry, C.B., (1981). Development of numerical model of tides and wind-driven circulation in Bass Strait. Australian Journal of Marine and Freshwater Research 32, 9-29.

Furnas, M. (2007). Intra-seasonal and inter-annual variations in phytoplankton biomass, primary production and bacterial production at Northwest Cape, Western Australia: links to the 1997-1998 El Nino event. Continental Shelf Research 27, 958-980.

Gibbs, C.F., Tomczak, M, and Longmore, A.R. (1986). The nutrient regime of Bass Strait. Australian Journal of Marine and Freshwater Research 37, 451-466.

Gibbs, C.F., Arnott, G.H., Longmore, A.R., and Marchant, J.W. (1991). Nutrient and plankton distribution near a shelf break front in the region of the Bass Strait cascade. Australian Journal of Marine and Freshwater Research 42, 201-217.

Gonzalez, A. F., Trathan, P. N., Yau, C., and Rodhouse, P. G. (1997). Interactions between oceanography, ecology and fishery biology of the ommastrephid squid *Martialia hyadesi* in the South Atlantic. Marine Ecology Progress Series 152, 205-215.

Green, C.P. (2011). Influence of environmental factors on population structure of Arrow Squid *Nototodarus gouldi*: implications for stock assessment. Doctor of Philosophy, University Of Tasmania, October 2011.

Griffiths, F.B. and S.B. Brandt. (1983a). The distribution of mesopelagic decapod crustacea in and around a warm-core eddy in the Tasman Sea. Mar. Ecol. Prog. Ser. 12(2): 175-184.

Griffiths, F.B. and S.B. Brandt. (1983b). Mesopelagic crustacea in and around a warm-core eddy in Tasman Sea. Aust. J. Mar. Freshw. Res. 34:609-623.

Guerra, A., Allcock, L. and Pereira, J. (2010). Cephalopod life history, ecology and fisheries: An introduction. Fisheries Research 106, 117-124.

Hamer, P., Jenkins G., Kemp, J. (2010) Linking key environmental and life history indicators for monitoring and assessment of bay and inlet fisheries in Victoria. Fisheries Victoria Research Report Series No. 44.

Harrison, A. J. (1983). Assessment of a squid fishery off Tasmania. Mem. Nut. Mus. Vic. 44. (Unpublished)

Hirtle, R. W. M. & O'Dor, R. K. (1981). A comparison of feeding and growth in natural and captive squid (*Illex illecebrosus*). Journal of Shellfish Research 1, 116.

Hurst R.J., Ballara, S.L., MacGibbon, D., Triantafillos, L. (2012). Fishery characterisation and standardised CPUE analyses for arrow squid (*Nototodarus gouldi* and *N. sloanii*), 1989–90 to 2007–08, and potential management approaches for southern fisheries. New Zealand Fisheries Assessment Report 2012/47. 303 p.

Inada, H. and Ogura, M. (1988). Historical changes in fishing light and its operation in squid jigging fisheries. Report Tokyo University of Fisheries 24, 189-207.

Isoda, Y., Bower, J.R. and Hasegawa, S. (2005). Assessing environmental effects on recruitment of Japanese common squid (*Todarodes pacificus*) in the Japan Sea using a biomass dynamics model. Bulletin of Fisheries Sciences, Hokkaido University. 56, 19–31.

Jackson GD, McGrath Steer BL, Wotherspoon S, Hobday AJ (2003) Variation in age, growth and maturity in the Australian arrow squid *Nototodarus gouldi* over time and space – what is the pattern? Mar Ecol Prog Ser 264: 57-71

Jackson, G. D. & Moltschaniwskyj, N. A. (2001a). The influence of ration level on growth and statolith increment width of the tropical squid *Sepioteuthis lessoniana* (Cephalopoda: Loliginidae): an experimental approach. Marine Biology 138, 819-825.

Jackson, G.D., Wotherspoon, S., and McGrath-Steer, B. L. (2005). Temporal population dynamics in arrow squid *Nototodarus gouldi* in Australian waters. Marine Biology 146, 975-983.

Jackson, GD and McGrath-Steer, BL 2003, Arrow squid in southern Australian waters—supplying management needs through biological investigations, final report to the Fisheries Research and Development Corporation, project 1999/112, Institute of Antarctic and Southern Ocean Studies, University of Tasmania, Hobart.

Jeong, H., Yoo, S., Lee, J., and An, Y. (2013). The retinular responses of common squid *Todarodes pacificus* for energy efficient fishing lamp using LED. Renewable Energy 54, 101-104.

Kaartvedt, S., Knutsen, T. and Holst, J. (1998). Schooling of the vertically migrating mesopelagic fish *Maurolicus muelleri* in light summer nights. Marine Ecology-progress Series - MAR ECOL-PROGR SER. 170. 287-290. 10.3354/meps170287.

Kato, M. & Mitani, I. (2001). Comparison of catch, CPUE, and sea surface temperature in the fishing ground between good and poor fishing years for the squid jigging fishery target New Zealand southern arrow squid *Nototodarus sloanii* in New Zealand waters. Bull. Kanagawa Prefect. Fish. Res. Inst, 35-46.

Kirk, J.T.O. (2011). Light and photosynthesis in aquatic ecosystems. 3rd Edition. Cambridge University Press.

Knuckey, I., Day, J., Zhu, M., Koopman, M., Klaer, N., Ridgway, K. And Tuck, G. (2010). The influence of environmental factors on recruitment and availability of fish stocks in south-east Australia. Final Report to Fisheries Research and Development Corporation - Project 2005/006. Fishwell Consulting and CSIRO, 300pp.

Knuckey, I., Sahlqvist, P. and Hindell, J. 2001. Analysis of catch and effort data for arrow squid (*Nototodarus gouldi*, McCoy) in the Southern Squid Jig Fishery and South East Trawl Fishery. Final Report to the Australian Fisheries Management Authority. Marine and Freshwater Resources Institute, Queenscliff.

Kurosaka, K., Ochi, Y., Inada, H., Arimoto, T., and Sakai, H. (2013). Strategy for controlling the hauling speed of the jigging machine for reducing the catch loss of neon flying squid *Ommastrephes bartramii*. Nippon Suisan Gakkaishi 79. 327-336.

Lazaridis, E. (2014). lunar: Lunar Phase & Distance, Seasons and Other Environmental Factors (Version 0.1-04). Available from http://statistics.lazaridis.eu

Maechler, M., Rousseeuw, P., Struyf, A., Hubert, M., and Hornik, K., Studer, M., Roudier, P. and Gonzalez, J. (2017). Finding Groups in Data": Cluster Analysis Extended. R package version 2.0.6.

Martins, R. S., J. A. A. Perez, and C. A. F. Schetini. (2004). The squid Loligo plei around Santa Catarina Island, Southern Brazil: Ecology and Interactions with Coastal Oceanographic environment. J. Coast. Res. 38: 1285–1290.

Matsushita, Y. and Yamashita, Y. (2012). Effect of a stepwise lighting method termed "stage reduced lighting" using LED and metal halide fishing lamps in the Japanese common squid jigging fishery. Fisheries Science 78, 977-983.

Matsushita, Y., Azuno, T., and Yamashita, Y. (2012). Fuel reduction in coastal squid jigging boats equipped with various combinations of conventional metal halide lamps and low-energy LED panels. Fisheries Research 125-126, 14-19.

McGrath Steer, B. L. and Jackson, G. D. (2004). Temporal shifts in the allocation of energy in the arrow squid, *Nototodarus gouldi*: Sex-specific responses. Marine Biology 144, 1141-1149.

McGrath Steer, B. L. and Jackson, G. D., Pecl, G.T. (2004).

McInnes, K.L., Macadam, I., Hubberty, G.D., and O'Grady, J.G. (2009). A modelling approach for estimating the frequency of sea level extremes and the impact of climate change in southeast Australia. Natural Hazards 51, 115-137.

McKinna *et al.* (2010). Improving the efficiency of Southern Squid Jig Fisheries. Fisheries Research and Development Corporation. Final Report Project No. 2009/221.

Mikami, T., Yamashita, N., and Sugaki, S. (2001). Control of jig velocity by control of hauling drum parameters for automatic squid jigging machine. Nippon Suisan Gakkaishi 67, 481-488.

Medellin-Ortiz, Cadena-Cardenas, L., and Santana-Morales, O. (2016). Environmental effects on the jumbo squid fishery along Baja California's west coast. Fisheries Science 82, 851-861.

Morales-Borjorquez, E., Cisneros-Mata, M. A., Nevarez-Martinez, M. O. and Hernandez-Herrera, A. (2001). Review of stock assessment and fishery biology of *Dosidicus gigas* in the Gulf of California, Mexico. Fisheries Research 54, 83-94.

Moreno, A., Azevedo, M., Pereira, J. and Price, G. (2007). Growth strategies in the squid *Loligo vulgaris* from Portuguese waters. Marine Biology Research. 3: 49–59.

Murata, M. (1983). Quantitative assessment of oceanic squid by means of jigging surveys. Biological Oceanography 2, 433-456.

Murata, M. (1989). Population assessments, management and fishery for the Japanese common squid, *Todarodes pacifies*. Marine Invertebrate Fisheries: Their Assessment and Management (ed J.F. Caddy), pp. 613–36. J. Wiley and Sons, New York.

Noriega, R, Lyle, J, Hall, K, Emery, T. 2015, Gould's Squid Nototodarus gouldi, in Carolyn Stewardson, James Andrews, Crispian Ashby, Malcolm Haddon , Klaas Hartmann, Patrick Hone, Peter Horvat, Stephen Mayfield, Anthony Roelofs, Keith Sainsbury, Thor Saunders, John Stewart, Ilona Stobutzki and Brent Wise (eds) 2016, Status of Australian fish stocks reports 2016, Fisheries Research and Development Corporation, Canberra.

Noriega, R., Bell, J. And Lyle, J. 2014. Gould's Squid Nototodarus gouldi, in M Flood, I Stobutzki, J Andrews, C Ashby, G Begg, R Fletcher, C Gardner, L Georgeson, S Hansen, K Hartmann, P Hone, P Horvat, L Maloney, B McDonald, A Moore, A Roelofs, K Sainsbury, T Saunders, T Smith, C Stewardson, J Stewart & B Wise (eds) 2014, Status of key Australian fish stocks reports 2014, Fisheries Research and Development Corporation, Canberra.

Nowara, G. B. & Walker, T. I. (1998). Effects of time of solar day, jigging method and jigging depth on catch rates and size of Gould's squid, *Nototodarus gouldi* (McCoy), in southeastern Australian waters. Fisheries Research 34, 279-288.

O'Reilly, J. E., *et al.* (2000), Ocean color chlorophylla algorithms for SeaWiFS, OC2 and OC4: Version 4, in SeaWiFS Postlaunch Calibration and Validation Analyses, Part 3,SeaWiFS Postlaunch Tech. Rep. Ser. , vol. 11, edited by S. B. Hooker, E. R. Firestone, and R. Firestone, NASA Tech. Memo. 206892 , pp. 9–27, NASA, Washington, D. C.

O'Sullivan, D. and Cullen, J.M. (1983). Food of the Squid *Nototodarus gouldi* in Bass Strait. Aust. J. Mar. Freshw. Res. 34: 261–85.

Olson, D.B., Mariano, A.J., Ashjian, C.J., Peng, G., Nero, R.W. and PodestaÂ, G.P. (1994) Life on the edge: marine life and fronts. Oceanography 7:52±60.

Park, J. A., Gardner, C., Jang, Y., Chang, M., and Seo, Y. (2015). The economic feasibility of light-emitting diode (LED) lights for the Korean offshore squid-jigging fishery. Ocean and Coastal Management 116, 311-317.

Patterson, H, Noriega R, Georgeson, L, Larcombe, J and Curtotti, R. (2017). Fishery status reports 2017. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. CC BY 4.0.

Paulino, C., Segura, M. and Chacon, G. (2016). Spatial variability of jumbo flying squid (*Dosidicus gigas*) fishery related to remotely sensed SST and chlorophyll-a concentration (2004-2012). Fisheries Research 173, 122-127.

Pebesma, E.J., R.S. Bivand, 2005. Classes and methods for spatial data in R. R News 5 (2), https://cran.r-project.org/doc/Rnews/.

Pethybridge H.P., Virtue P, Casper R., Yoshida T., Green C.P., Jackson G. and Nichols P.D. (2011). Seasonal variations in diet of Arrow Squid *Nototodarus gouldi*: stomach content and signature fatty acid analysis. In: Green, C.P. (2011). Influence of environmental factors on population structure of Arrow Squid *Nototodarus gouldi*: implications for stock assessment. Doctor Of Philosophy, University Of Tasmania, October 2011.

Pierce G.J. and P.R. Boyle. 2003. Empirical modelling of interannual trends in abundance of squid (*Loligo forbesi*) in Scottish waters. Fisheries Research 59: 305-326.

Pierce, G.J. (1995). Stock assessment with a thermometer: correlations between sea surface temperature and landings of squid (*Loligo forbesi*) in Scotland. ICES, CM 1995/K:21.

Pierce, G.J., Begoña Santos, M., MacLeod, C.D., Wang, J., Valavanis, V. and Zuur, A. 2006. Modelling environmental influences on squid life history, distribution and abundance. The role of squid in open ocean ecosystems, 16-17 November 2006, Hawaii, USA.

Pohlert, T. (2018). trend: Non-Parametric Trend Tests and Change-Point Detection. R package version 1.1.0. https://CRAN.R-project.org/package=trend

Portela, J., Sacau-Cuadrado, M.M., Wang, J., Pierce, G.J., Santos, M.B. and Cardoso, X.A. (2005). Analysis of the variability in the abundance of shortfin squid *Illex argentinus* in the southwest Atlantic fisheries during the period 1999-2004. ICES CM 2005/O:16.

Postuma, F. A., and Gasalla, M. A. (2010). On the relationship between squid and the environment: artisanal jigging for *Loligo plei* at Sao Sebastiao Island (24o S), southeastern Brazil. ICES Journal of Marine Science 67, 1353-1362.

Prosch, R.M. (1986). The biology, distribution and ecology of *Lampanyctodes hectoris* and *Maurolicus muelleri* along the South African coast. Master Thesis, University of Cape Town.

Puneeta, P., Vijai, D., Yoo, H.-K., Matsui, H. and Sakurai, Y. (2015). Observations on the spawning behavior, egg masses and paralarval development of the ommastrephid squid *Todarodes pacificus* in a laboratory mesocosm. J. Exp. Biol. 218, 3825-3835. doi:10.1242/jeb.127670 Permanent Service for Mean Sea Level (PSMSL), 2017, "Tide Gauge Data", Retrieved 25 Sep 2017 from http://www.psmsl.org/data/obtaining/.

R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Ralston, S., Dorval, E., Ryley, L., Sakuma, K.M., and Field, J. C. (2018). Predicting market squid (*Doryteuthis opalescens*) landings from pre-recruit abundance. Fisheries Research 199, 12-18.

Reddy, R., Lyne, V., Gray, R., Easton, A. and Clarke, S. (1995). An application of satellite-derived sea-surface temperatures to southern bluefin tuna and albacore off Tasmania, Australia. Sci. Mar. 59:445±454.

Roberts, M.J. and Sauer, W.H.H. 1994. Environment: the key to understanding the South African chokka squid (*Loligo vulgaris reynaudio* life cycle and fishery? Antarctic Science 6 (2): 249-258.

Robin, J.P. and Denis, V. 1999. Squid stock fluctuations and water temperature: temporal analysis of English Channel Loliginidae. Journal of Applied Ecology, 36: 101-110.

Rodhouse P. G. K., Pierce G. J., Nichols O. C., Sauer W. H. H., Arkhipkin A. I., Laptikhovsky V. V., Lipiński M. R., Ramos J. E., Gras M., Kidokoro H., Sadayasu K., Pereira J., Lefkaditou E., Pita C., Gasalla M., Haimovici M., Sakai M., Downey N. (2014). Environmental effects on cephalopod population dynamics: Implications for management of fisheries. Adv. Mar. Biol. 67, 99–233.

Roper, C. F. E., and Rathjen, W. F. (1991). World-wide squid fisheries: a summary of landings and capture techniques. Journal of Cephalopod Biology 2, 51-62.

Sakurai, Y., Kiyofuji, H., Saitoh, S., Goto, T., and Hiyama, Y. (2000). Changes in inferred spawning areas of *Todarodes pacificus* (Cephalopoda: Ommastrephidae) due to changing environmental conditions. ICES Journal of Marine Science, 57: 24-30.

Sato, M. (1990). The movement and migration of *Loligo bleekeri* in the northern Japan Sea. In: Report of the 1990 Meeting on Squid Resources and Oceanographic Conditions, pp.49–57 (Tohoku National Fisheries Research Institute (TNFRI), Eds.). Hachinohe, Japan, TNFRI [in Japanese].

Seafish Industry Authority (1985). Squid jigging from small boats. Internal Report No. 1176, Seafish Industry Authority, Industrial Development Unit, St. Andrews Dock, Hull HU3 4QE.

Simon J. Holgate, Andrew Matthews, Philip L. Woodworth, Lesley J. Rickards, Mark E. Tamisiea, Elizabeth Bradshaw, Peter R. Foden, Kathleen M. Gordon, Svetlana Jevrejeva, and Jeff Pugh (2013) New Data Systems and Products at the Permanent Service for Mean Sea Level. Journal of Coastal Research: Volume 29, Issue 3: pp. 493 – 504. doi:10.2112/JCOASTRES-D-12-00175.1.

Sims, D.W., Genner, M.J., Southward, A.J. and Hawkins, S.J. 2001. Timing of squid migration reflects North Atlantic Climate variability. Proc.R.Soc.Lond. 268: 2607-2611.

Sokolov, S., and S. R. Rintoul, (2003). Subsurface structure of interannual temperature anomalies in the Australian sector of the Southern Ocean, J. Geophys. Res., 108(C9), 3285, doi:10.1029/2002JC001494, 2003.

Steve O'Shea , Kathrin S. Bolstad & Peter A. Ritchie (2004) First records of egg masses of *Nototodarus gouldi* McCoy, 1888 (Mollusca: Cephalopoda: Ommastrephidae), with comments on egg -mass susceptibility to damage by fisheries trawl, New Zealand Journal of Zoology, 31:2, 161-166, DOI: 10.1080/03014223.2004.9518369

Takahashi, M., and H. Furuta. Relationship between fishing grounds and oceanographic structure of *Loligo edulis* and *Loligo edulis budo* in angling fishery of Chikuzenkai, north coastal waters off Fukuoka. Bull. Fukuoka Fish. Exp. Stn., 14: 13–21 (1988) [in Japanese].

Ulaş, A. and Aydin, I. (2011). The effects of jig color and lunar bright on coastal squid jigging. African Journal of Biotechnology 10:1721-1726.

Virtue, P., Green, C., Pethybridge, H., Moltschaniwskyj, N., Wotherspoon, S. and Jackson, G. (2011). Arrow squid: stock variability, fishing techniques, trophic linkages - facing the challenges. FRDC Final Report 2006/12, 207pp.

Waluda C.M., Trathan P.N. and Rodhouse P.G. 1999. Influence of oceanographic variability on recruitment in the *Illex argentinus* (Cephalopoda:Ommastrephidae) fishery in the South Atlantic. Marine Ecology Progress Series , 183, 159-167.

Waluda, C.M. and Rodhouse, P.G. (2006). Remotely sensed mesoscale oceanography of the Central Eastern Pacific and recruitment variability in *Dosidicus gigas*. Marine Ecology Progress Series, 310, 25-32.

Waluda, C.M., Rodhouse, P.G., Podesta, G.P., Trathan, P.N., and Pierce, G.J. (2001b). Surface oceanography of the inferred hatching grounds of *Illex argentinus* (Cephalopoda: Ommastrephidae) and influences on recruitment variability. Marine Biology 139, 671-679.

Waluda, C.M., Rodhouse, P.G., Trathan, P.N., and Pierce, G.J. (2001a). Remotely sensed mesoscale oceanography and the distribution of *Illex argentines* in the South Atlantic. Fish. Oceanogr. 10:2, 207–216.

Wang, W., Zhou, C., Shao, Q., and Mulla, D. J. (2010). Remote sensing of sea-surface temperature and chlorophyll-a: implications for squid fisheries in the north-west Pacific Ocean. International Journal of Remote Sensing 31, 4515-4530.

Wayte, S.E. (2012). Management implications of including a climate-induced recruitment shift in the stock assessment for jackass morwong (*Nemadactylus macropterus*) in south-eastern Australia. Fish. Res. http://dx.doi.org/10.1016/j.fishres.2012.07.009

Wilcox, S., Lyle, J., and Steer, M. (2001). Tasmanian arrow squid fishery – status report 2001. Tasmanian Aquaculture and Fisheries Institute, Hobart.

Xu, J., Chen, X., Chen, Y., Ding, Q., and Tian, S. (2016). The effect of sea surface temperature increase on the potential habitat of *Ommastrephes bartramii* in the Northwest Pacific Ocean. Acta *Oceanologica Sinica* 35, 109-116.

Yamashita, H., Kurosaka, K., Ochi, Y., and Ogawa, M. (2008). The effect of ship rocking on the dropout of neon flying squid *Ommastrephes bartramii* in jigging fishery. Nippon Suisan Gakkaishi 74, 697-699.

Yamashita, Y., Matsushita, Y., and Azuno, T. (2012). Catch performance of coastal squid jigging boats using LED panels in combination with metal halide lamps. Fisheries Research 113, 182-189.

Young, J. W., Blaber, S. J. M., Rose, R. (1987). Reproductive biology of three species of midwater fishes associated with the continental slope of eastern Tasmania, Australia. Mar. Biol. 95: 323–332

Yu W, Chen X, Yi Q, Chen Y, Zhang Y (2015) Variability of Suitable Habitat of Western Winter-Spring Cohort for Neon Flying Squid in the Northwest Pacific under Anomalous Environments. PLoS ONE 10(4): e0122997. doi:10.1371/journal. pone.0122997

Yu, W., Chen, X., Yi, Q., and Chen, Y. (2016a). Spatio-temporal distributions and habitat hotspots of the winter-spring cohort of neon flying squid *Ommastrephes bartramii* in relation to oceanographic conditions in the Northwest Pacific Ocean. *Fisheries Research* 175, 103-115.

Yu, W., Chen, X., Yi, Q., and Chen, Y. (2016b). Modelling the effects of climate variability on habitat suitability of jumbo flying squid, *Dosidicus gigas*, in the Southeast Pacific Ocean off Peru. ICES Journal of Marine Science 73, 239-249.

Yu, W., Yi, Q, Chen, X., and Chen, Y. (2017). Climate-driven latitudinal shift in fishing ground of jumbo flying squid (*Dosidicus gigas*) in the Southeast Pacific Ocean off Peru. *International Journal of Remote Sensing* 38, 3531-3550.

Zeidberg L. D., W. M. Hamner, N. P. Nezlin, and A. Henry. The fishery of the California market squid, *Loligo opalescens* (Cephalopoda, Myopsida), from 1981–2003. Fish. Bull., 104: 46–59 (2006).

Zhang, J., Chen, Z., Chen, G., Zhang, P., Qui, Y. (2015). Hydroacoustic studies on the commercially important squid *Sthenoteuthis oualaniensis* in the South China sea. Fisheries Research 169, 45-51.

Zuur A.F. and G.J. Pierce. 2004. Common trends in Northeast Atlantic squid time series. Netherlands Journal of Sea Research 52: 57-72.

Appendix 1. Agenda for the first industry workshop.

Improved location and targeting of economically viable aggregations of squid by the jig fleet

27 January 2017, 9:30am to 4:30 pm
Holiday Inn – Melbourne Airport (03) 9933 5111
10-14 Centre Rd, Melbourne VIC 3045

Time	Item	Presenter
9:30 am	**Welcome and background** • Introductions and house keeping • Overview • What we want to achieve today	Ian Knuckey
10:00 am	**Fisheries data** • Data availability – Type of data – Spatial temporal resolution – Limitations	Matt Koopman
10:30 am	**Oceanographic data** • Data availability – Type of data – Spatial temporal resolution – Limitations	Madeleine Cahill
11:00	**Morning Tea**	
11:30	• Individual input by industry on what factors they think most influence good fishing, catch rates, abundance, availability	All Industry members
1:00 pm	**Lunch**	
1:30 pm	**Initial analyses** • Brief description of results • Discussion	Matt Koopman
2:30 pm	**Future analyses** • What can we do to best analyse the data? • Discussion	Group Ian Knuckey Matt Koopman Madeleine Cahill Industry
4:30pm		Meeting Close

Appendix 2. Agenda for the second industry workshop.

Improved location and targeting of economically viable aggregations of squid by the jig fleet

Friday 3rd November 2017, 9:30am to 4:30 pm
Holiday Inn – Melbourne Airport (03) 9933 5111
10-14 Centre Rd, Melbourne VIC 3045

Time	Item	Presenter
9:30 am	**Welcome and background** • Introductions and house keeping • Overview • What we want to achieve today	Ian Knuckey
10:00 am	**Fisheries and Oceanographic data** • Data availability – Type of data – Spatial temporal resolution – Limitations	Matt Koopman Madeleine Cahill
10:30 am	**How did we analyse the data?** • Combining Fisheries & Oceanographic data • Types of data analyses – Trends and Correlations – Underlying mechanisms – Limitations	Matt Koopman Madeleine Cahill
11:00	**Morning Tea**	
11:30	**Presentation of results** • What worked and what didn't • What are the most promising results?	Matt Koopman
1:00 pm	**Lunch**	
1:30 pm	**Interpretation and feedback on results** • Does it make sense? • Can we improve the analyses? • Discussion	Industry Managers Researchers
2:30 pm	**What next?** • Implications for commercial fishing? • Implications for fishery management?	Group
4:30pm		Meeting Close

Interaction between moon-phase and year

There are few clear patterns in diurnal influence on mean CPUE over time in the CTS (Figure 135). All moon phases appear as both the highest and lowest mean CPUE throughout the time series. Mean CPUE during the first quarter and new moon appear as the lowest in more years than other moon phases, while it is highest most often on the full moon and last quarter. Looking only at night shots, the dominance of mean CPUE during the full moon is magnified in many years (e.g. 1999, 2010, 2013 and 2016).

While the highest Annual CPUE for the DS fishery was during the first quarter (1992), this was largely a result of several very large catches (Figure 136)

In the GABTS, mean CPUE is lowest on the new moon in most years, and highest on the full moon and last quarter in most years. (Figure 137). Considering only night shots has a mixed effect, magnifying the differences between moon phases in some years (e.g. 2006), and reducing the difference in others (e.g. 1999).

The difference in mean CPUE between moon phases appears to have increased in the SSJF from 1995 to 2004 (Figure 55), however variability also increased over that time due to reduced effort (Figure 19).

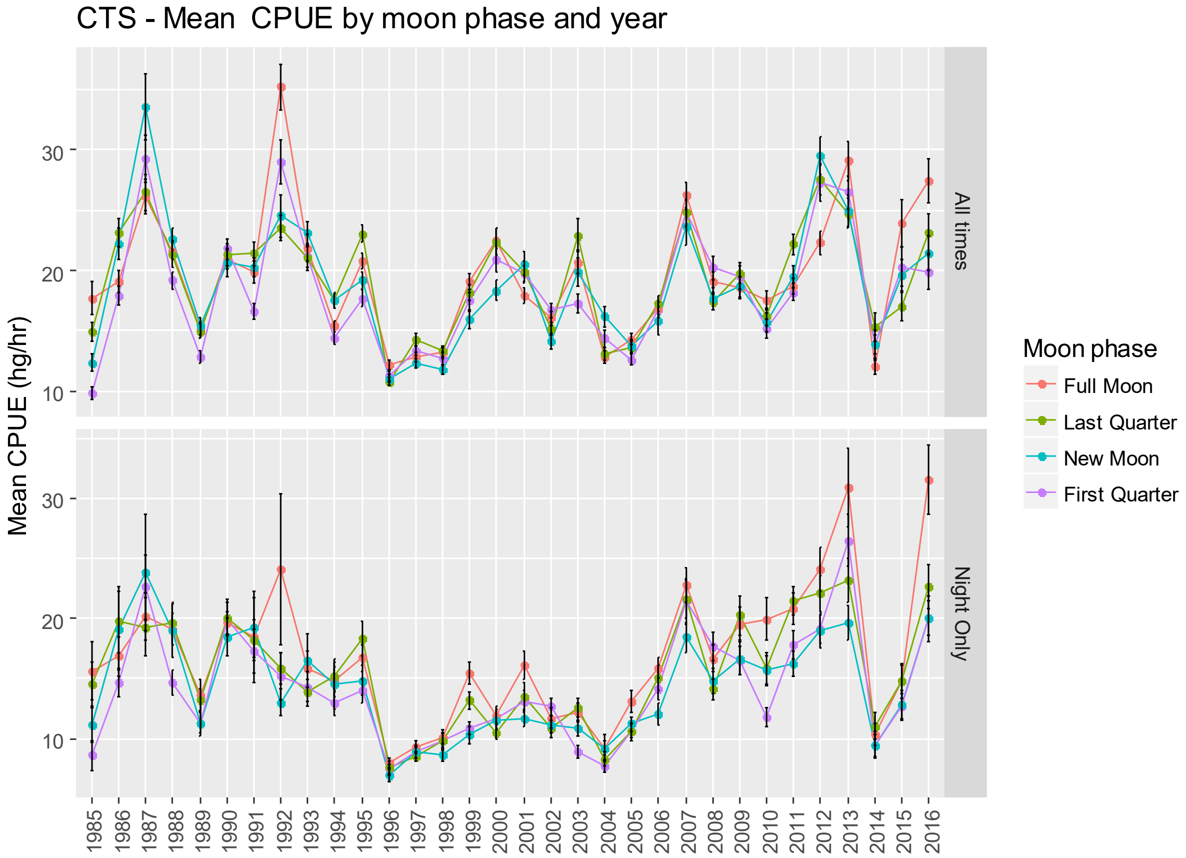


Figure 135. Mean annual CPUE by moon phase in the CTS.

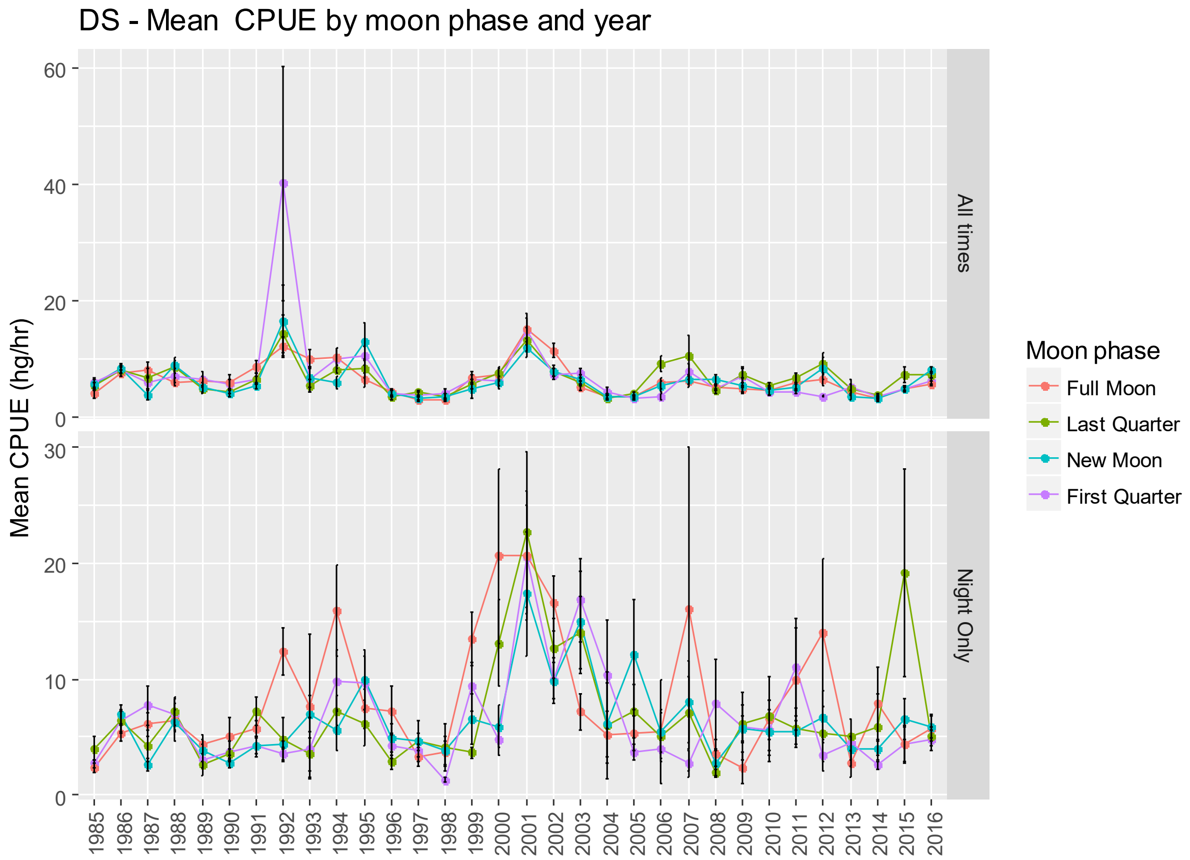


Figure 136. Mean annual CPUE by moon phase in the DS.

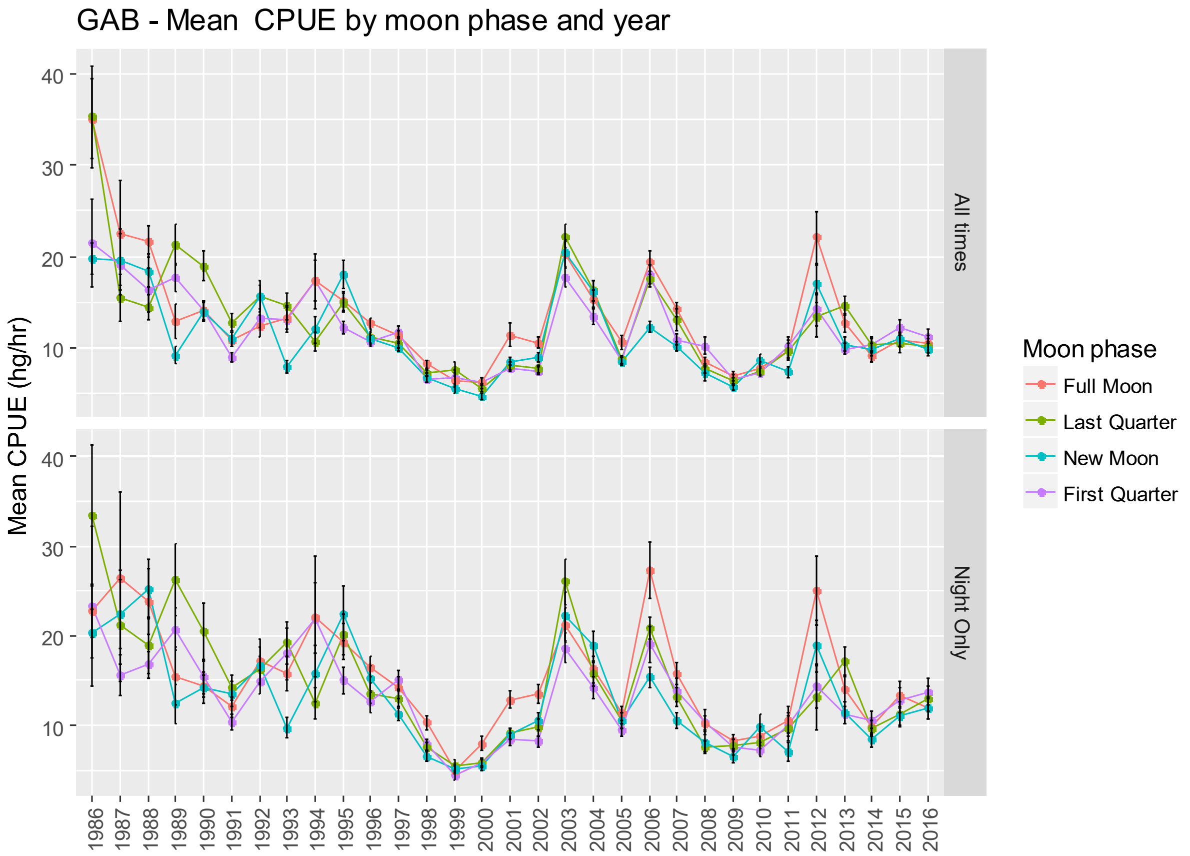


Figure 137. Mean annual CPUE by moon phase in the GABTS.

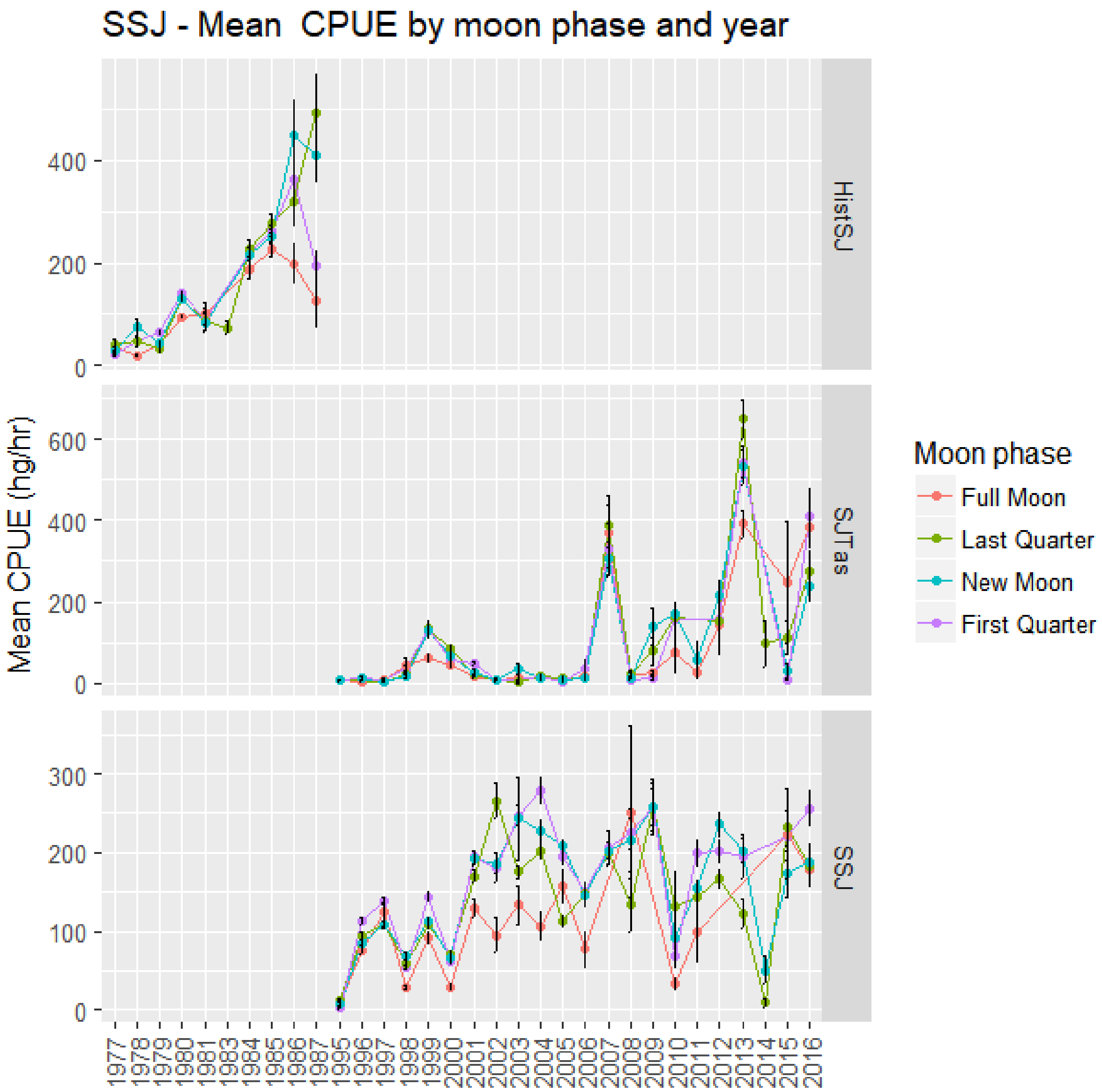


Figure 138. Mean annual CPUE by moon phase in the squid jig fisheries.

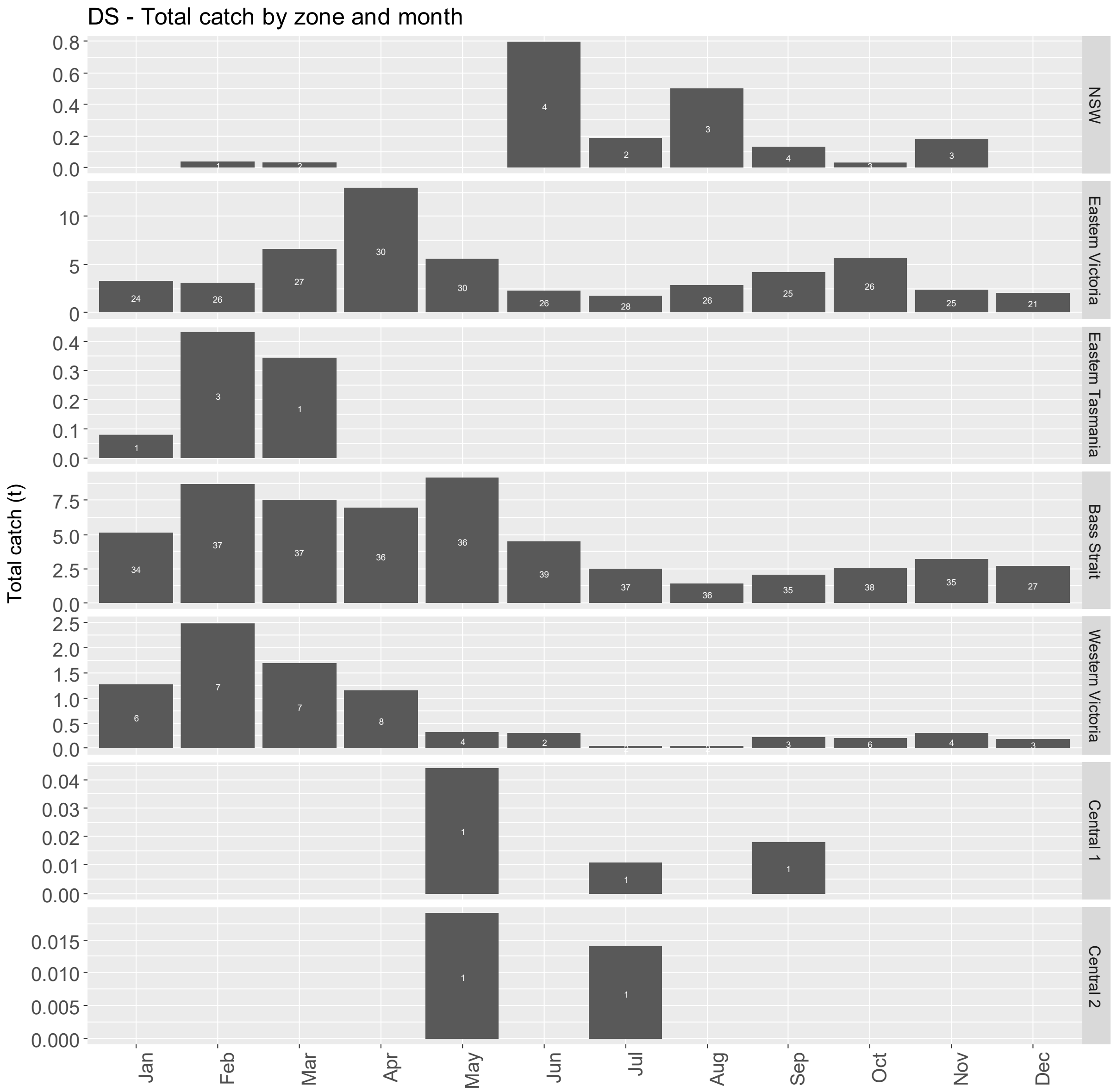


Figure 139. Total catch of Gould's Squid by zone and month in the DS.

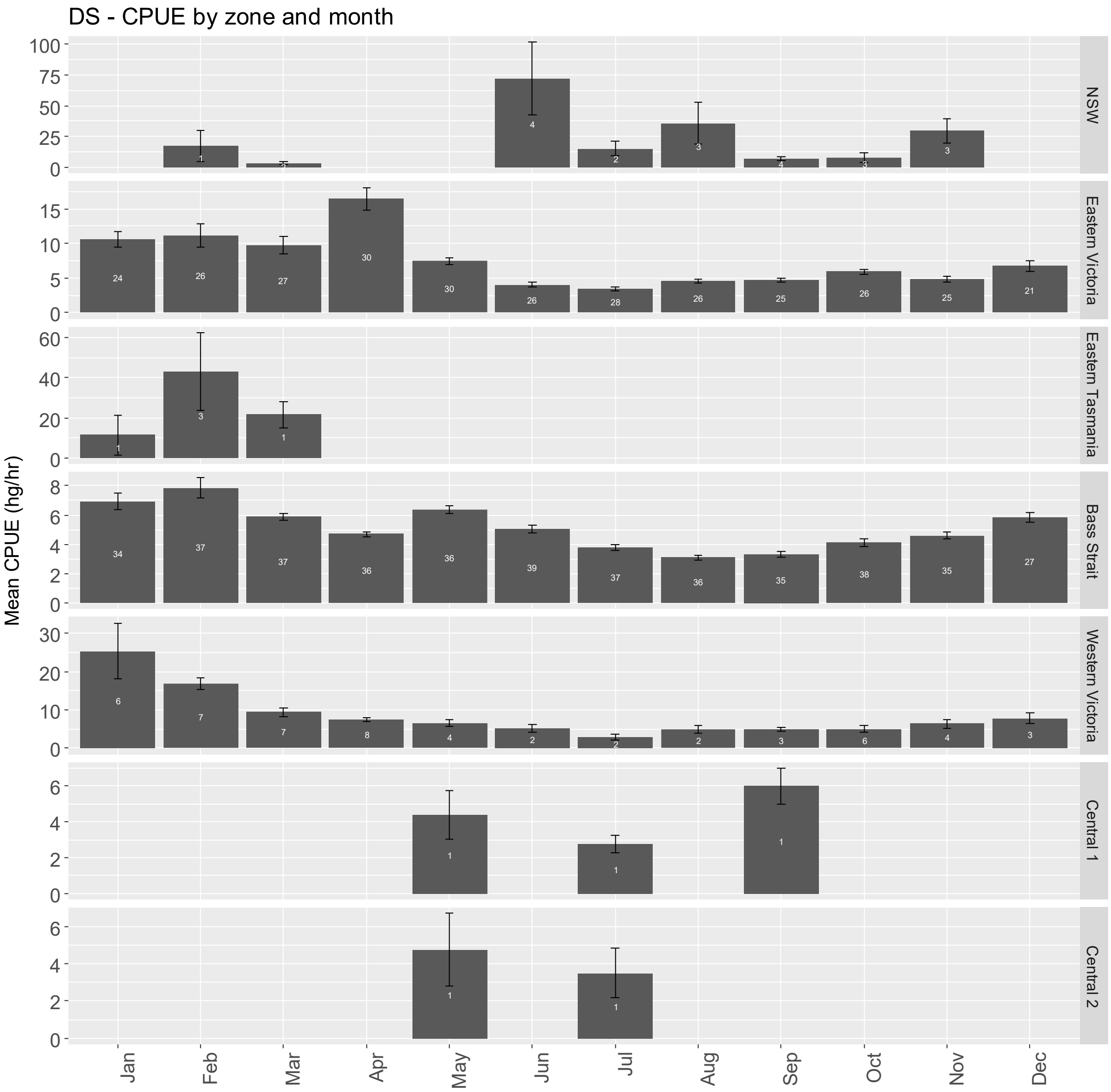


Figure 140. Mean monthly CPUE of Gould's Squid by zone and month in the DS.

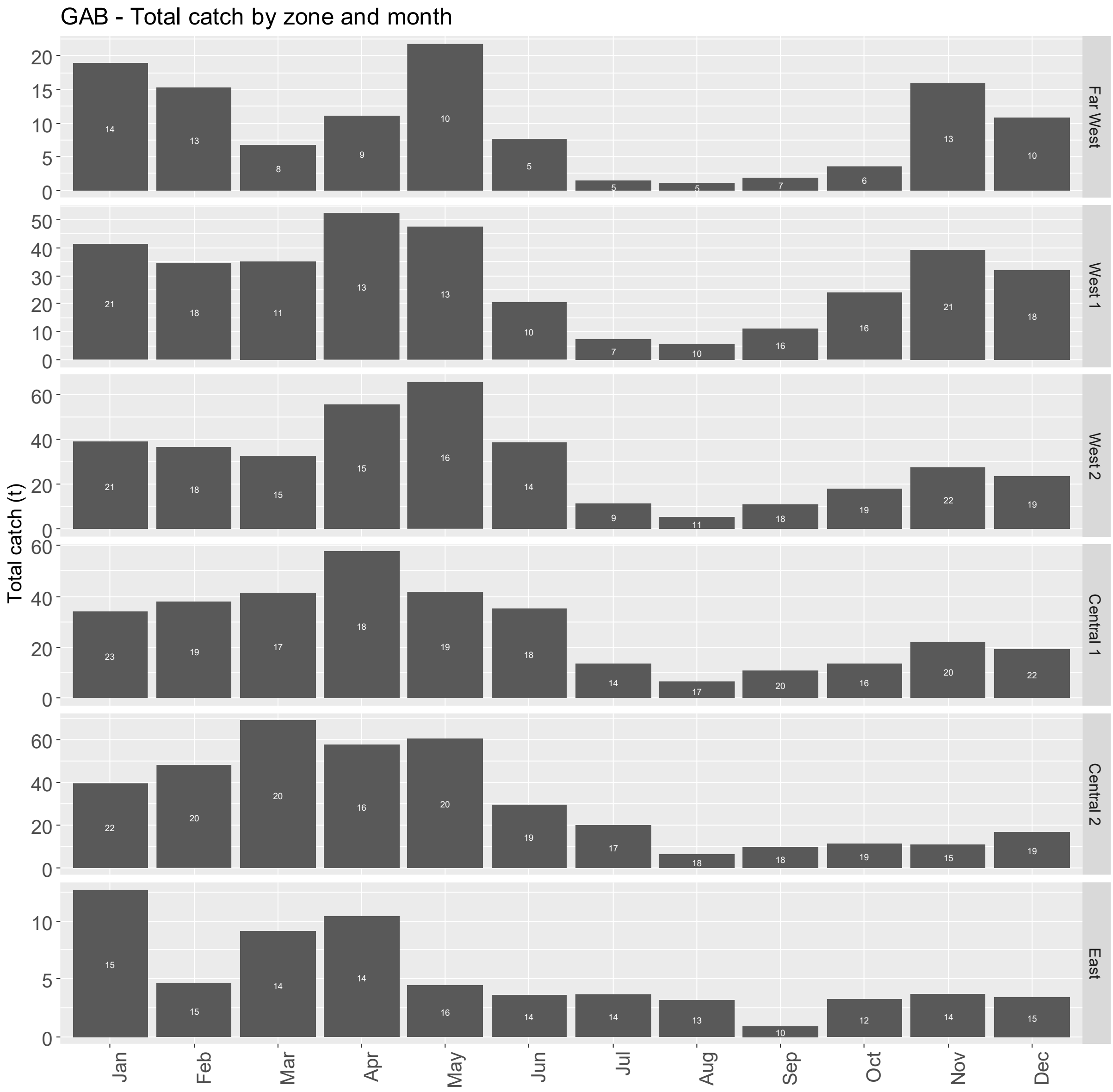


Figure 141. Total catch of Gould's Squid by zone and month in the GABTS.

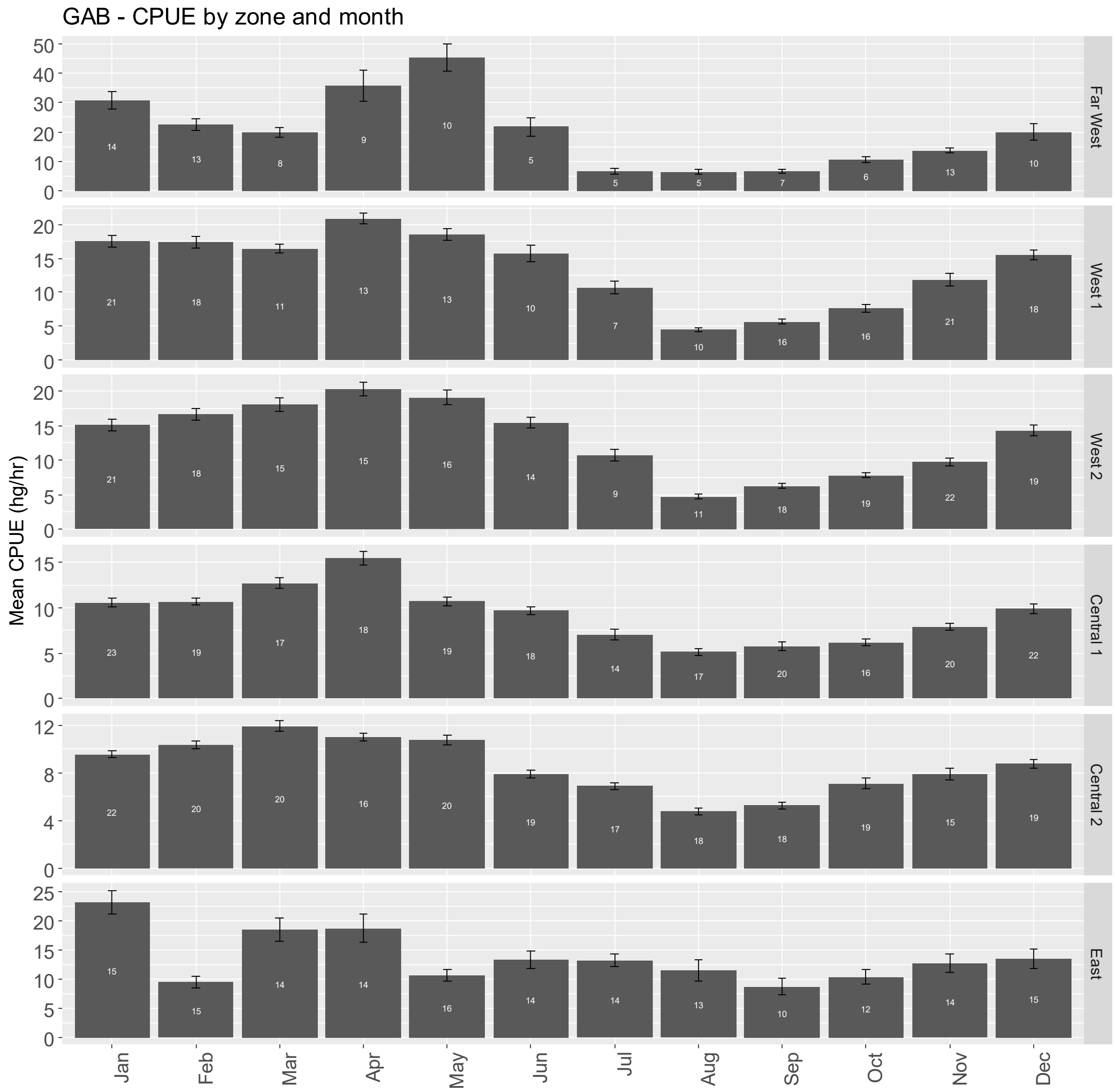


Figure 142. Mean monthly CPUE of Gould's Squid by zone and month in the GABTS.

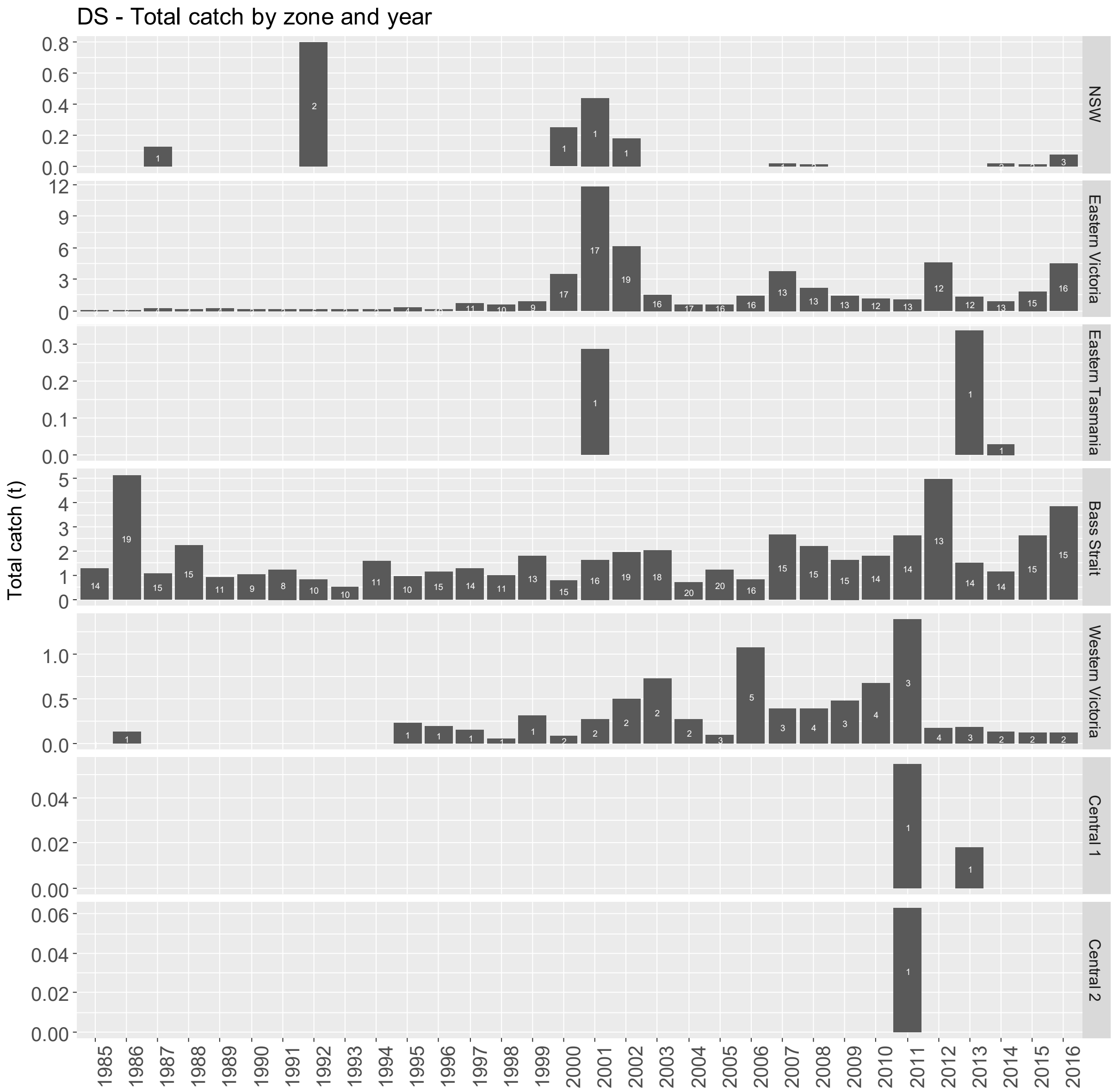


Figure 143. Total catch of Gould's Squid by zone and year in the DS.

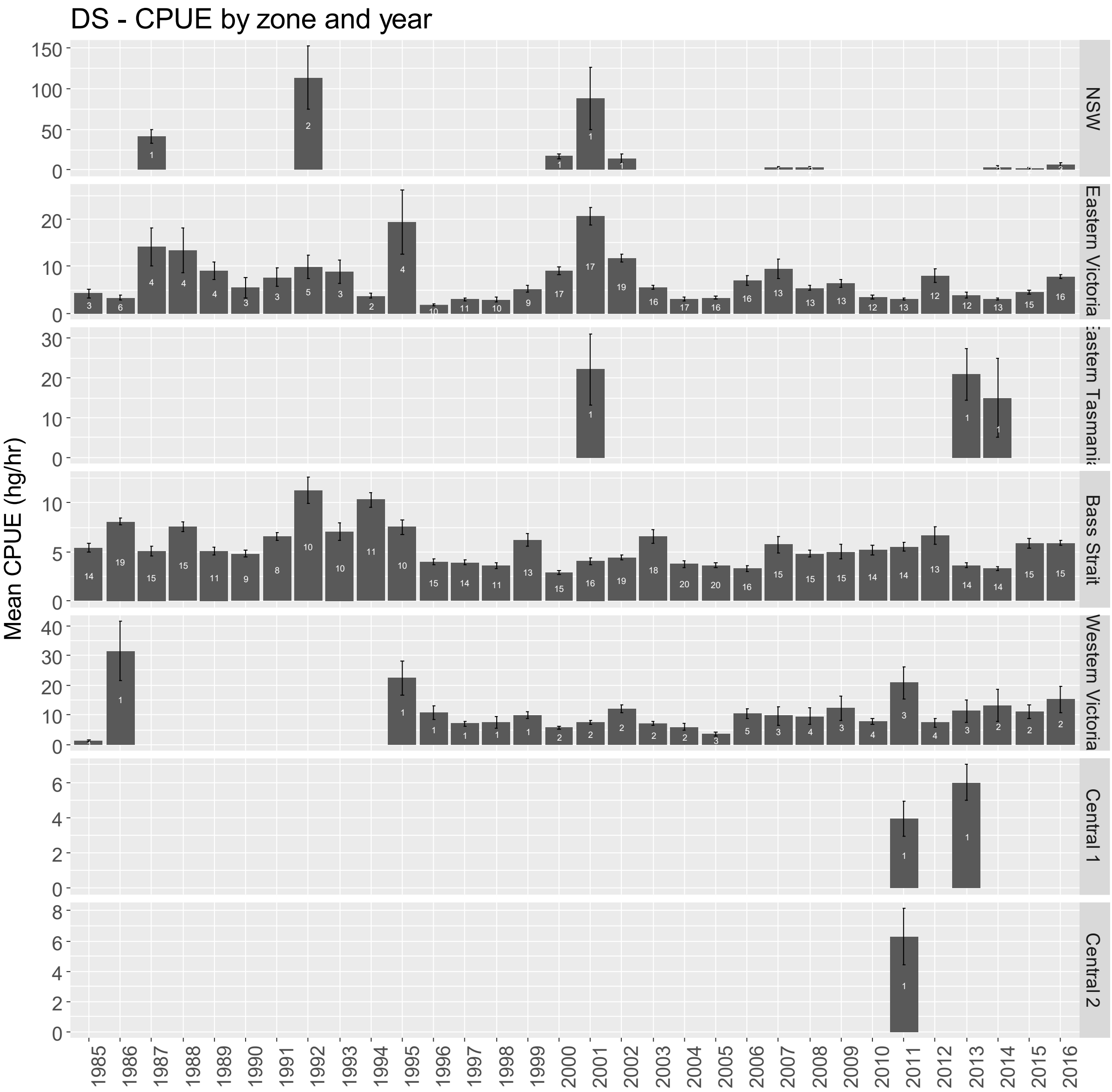


Figure 144. Mean annual CPUE of Gould's Squid by zone in the DS.

Table 14. Models examined in CPUE standardisation of the SSF In Western Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% Improvement
Null deviance				6610	
fit1	log(CPUE)~ year	16588	20	5288	20.0%
fit2	log(CPUE)~year + month	16575	24	5270	0.3%
fit3	(log(CPUE)~year + PC1	16449	21	5168	2.3%
fit4	log(CPUE)~year + P C1 + PC2	16449	22	5167	<0.1%
fit5	log(CPUE)~year + PC1+ depth	16348	37	5058	2.1%
fit6	log(CPUE)~year + PC1+ depth +moonphase	16304	42	5014	0.9%
fit7	log(CPUE)~year+ PC1+depth+moonphase+depth +depth*moonphase	16327	104	4932	2.5%
SST	log(CPUE)~year+ PC1+depth+moonphase+ depth +depth*moonphase + SST				
CHla	l log(CPUE)~year+ PC1+depth+moonphase+ depth +depth*moonphase + ChlA				

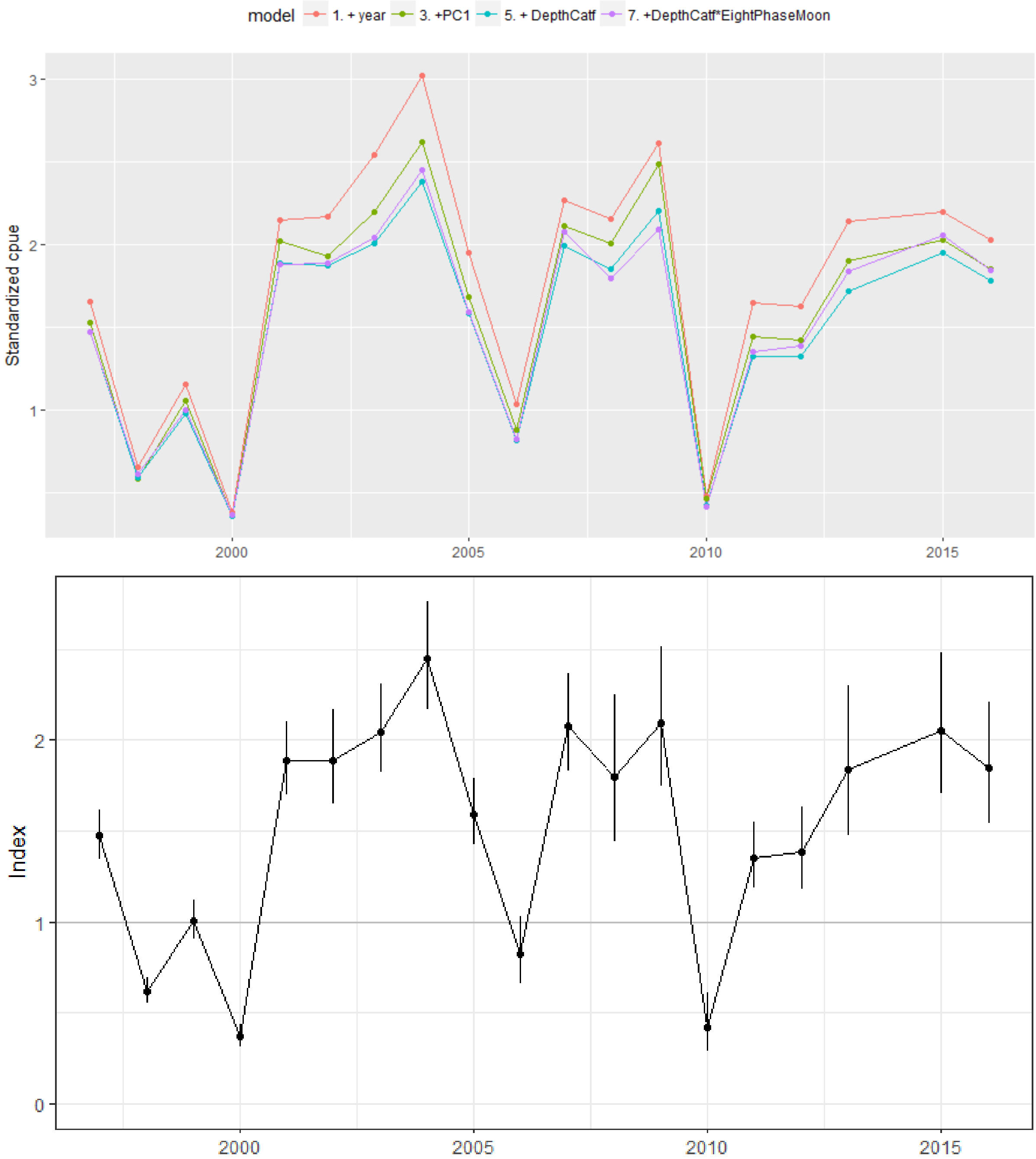
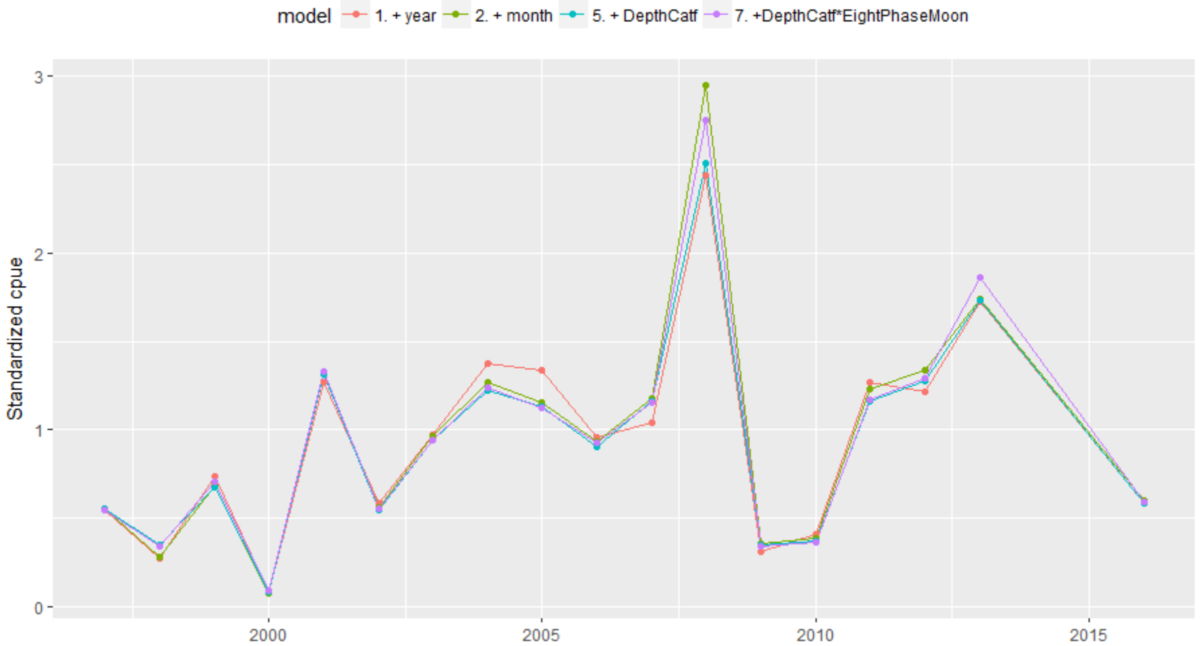


Figure 145. SSJ from Western Victoria. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 15. Models examined in CPUE standardisation of the SSF in Central Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model. Note that merging SST and ChlA with CPUE data resulted in some dropouts due to missing data. As a result, percent improvement in deviance is compared to results of the full model applied to the reduced dataset.

	Model	AIC	DF	Deviance	% Improvement
Null deviance				1760	
fit1	log(CPUE)~ year	5183	19	1375	21.9%
fit2	log(CPUE)~year + monthf	5084	23	1308	4.9%
fit3	(log(CPUE)~year+ monthf + PC1	5086	24	1308	<0.1%
fit4	log(CPUE)~year + monthf + PC2	5082	24	1306	0.2%
fit5	log(CPUE)~year + monthf + depth	5037	33	1268	3.1%
fit6	log(CPUE)~ year + monthf + depth +moonphase	5042	38	1265	0.2%
fit7	**log(CPUE)~ year + monthf + depth + depth*moonphase**	5029	65	1226	**3.3%**
SST	log(CPUE)~ year + monthf + depth + depth*moonphase + SST	5537	64	1434	0.97%
CHla	log(CPUE)~ year + monthf + depth + depth*moonphase + ChlA	2752	44	731	<0.1



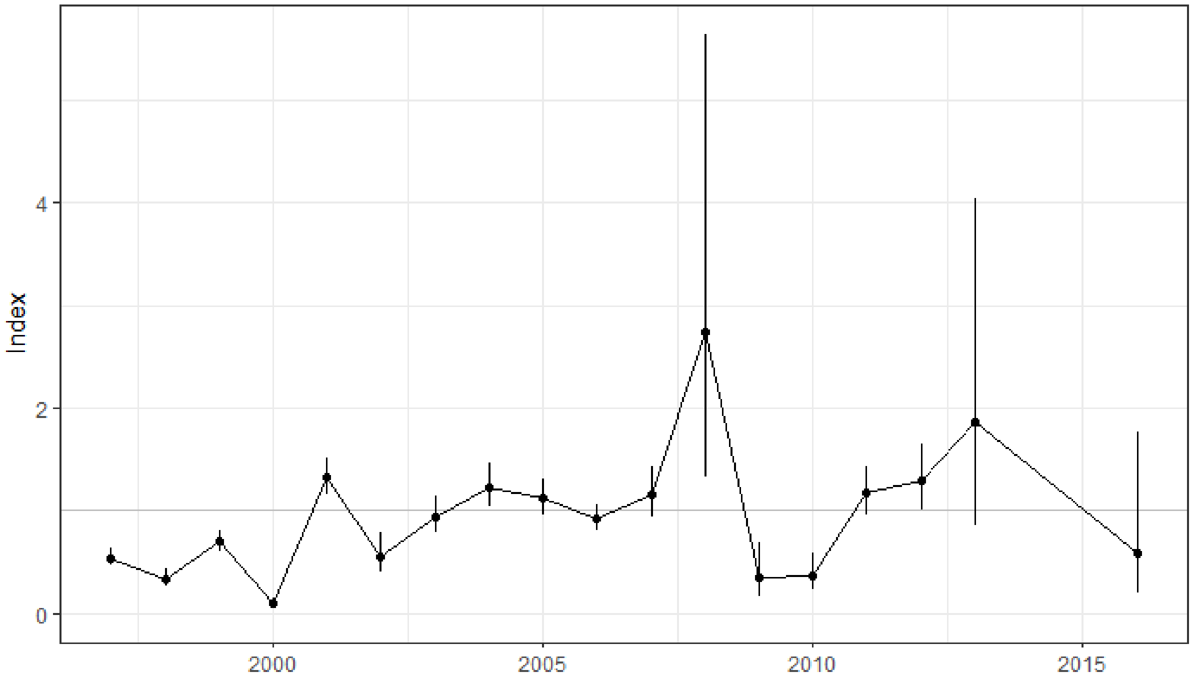
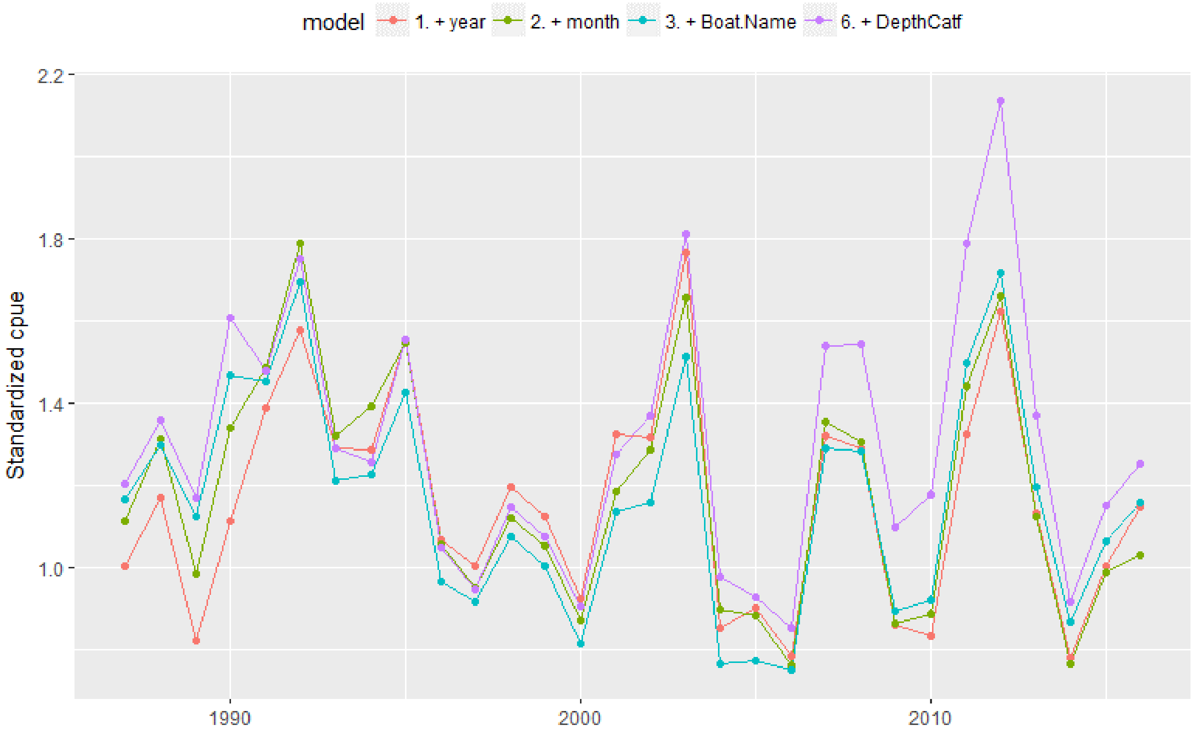


Figure 146. SSJ from Central Victoria. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 16. Models examined in CPUE standardisation of the CTS in Western Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model. Note that merging SST and ChlA with CPUE data resulted in some dropouts due to missing data. As a results, percent improvement in deviance is compared to results of the full model applied to the reduced dataset.

	Model	AIC	DF	Deviance	% Improvement
Null deviance				50241	
fit1	log(CPUE)~year	129050	31	48810	4.4%
fit2	log(CPUE)~year+monthf	125173	42	44650	8.5%
fit3	log(CPUE)~year+monthf+Boat.Name	121778	129	41154	7.8%
fit4	log(CPUE)~year+monthf+Boat.Name+PC1	121645	130	41027	0.3%
Fit5	log(CPUE)~year+monthf+Boat.Name+PC2	121730	130	41107	0.1%
Fit6	log(CPUE)~year+monthf+Boat.Name+depth	117146	153	36980	10.1%
Fit7	log(CPUE)~year+monthf+Boat.Name+depth+moonphase	117063	160	36899	0.2%
Fit8	**log(CPUE)~year+monthf+Boat.Name+depth**	116119	156	36118	2.3%
Fit9	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod+moonphase*AdjDielPeriod	116039	184	36006	0.3%
Fit10	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod +AdjDielPeriod*depth	115921	228	35837	0.1%
Fit11	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod +depth*moonphase	116050	328	35779	-1.7
SST	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod +depth*moonphase + SST	100099	128	31329	<0.1
CHla	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod +depth*moonphase + ChlA	59902	86	18931	<0.1



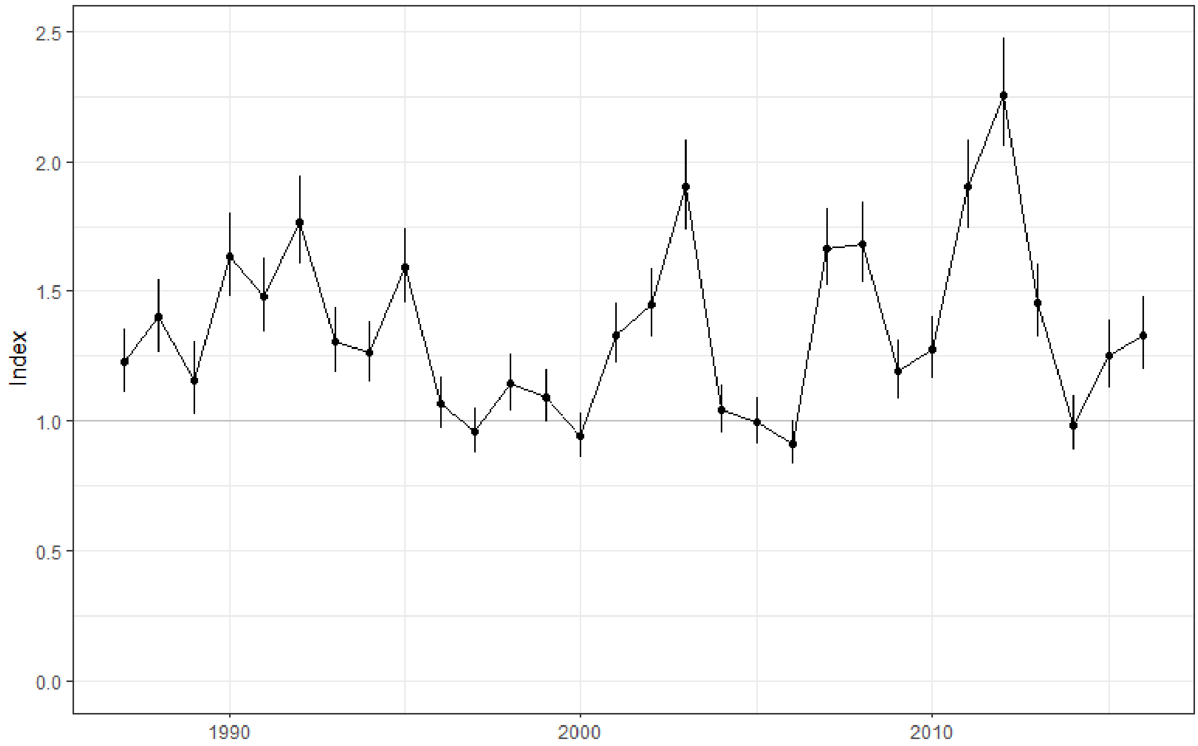


Figure 147. CTS Western Victoria. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 17. Models examined in CPUE standardisation of the CTS in Eastern Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model. Note that merging SST and ChlA with CPUE data resulted in some dropouts due to missing data. As a results, percent improvement in deviance is compared to results of the full model applied to the reduced dataset.

	Model	AIC	DF	Deviance	% Improvement
Null deviance				134580	
fit1	log(CPUE)~year	241719	31	117337	5.6%
fit2	log(CPUE)~year+monthf	240019	42	114598	2.3%
fit3	log(CPUE)~year+monthf+Boat.Name	232285	176	102690	10.4%
fit4	log(CPUE)~year+monthf+Boat.Name+PC1	232283	177	102685	<0.1%
fit5	log(CPUE)~year+monthf+Boat.Name+PC2	231932	177	102192	0.5%
Fit6	**log(CPUE)~year+monthf+Boat.Name+depth**	223684	200	91207	11.2%
Fit7	log(CPUE)~year+monthf+Boat.Name+depth+moonphase	223670	201	91187	<0.1%
Fit8	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod	223592	203	91084	0.1%
Fit9	log(CPUE+1)~year+monthf+Boat.Name+depth+moonphase*AdjDielPeriod	223577	231	90996	0.2%

fit10	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod*depth	223153	275	90359	0.9%
fit11	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod*depth+depth*moonphase	223745	373	90851	0.4%
SST	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod*depth + SST	189114	163	79475	<0.1
CHla	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod*depth + ChlA	99410	107	44575	<0.1

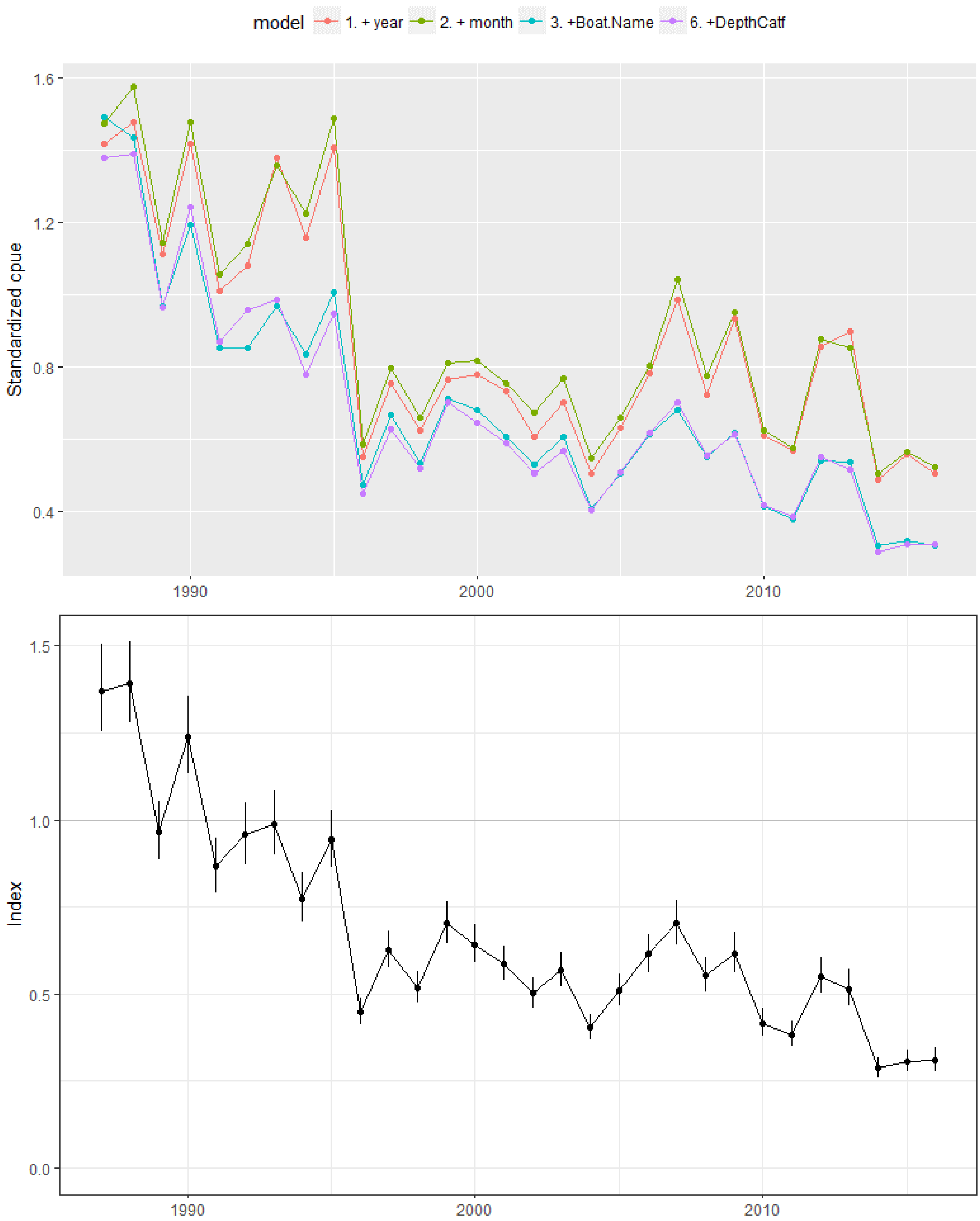
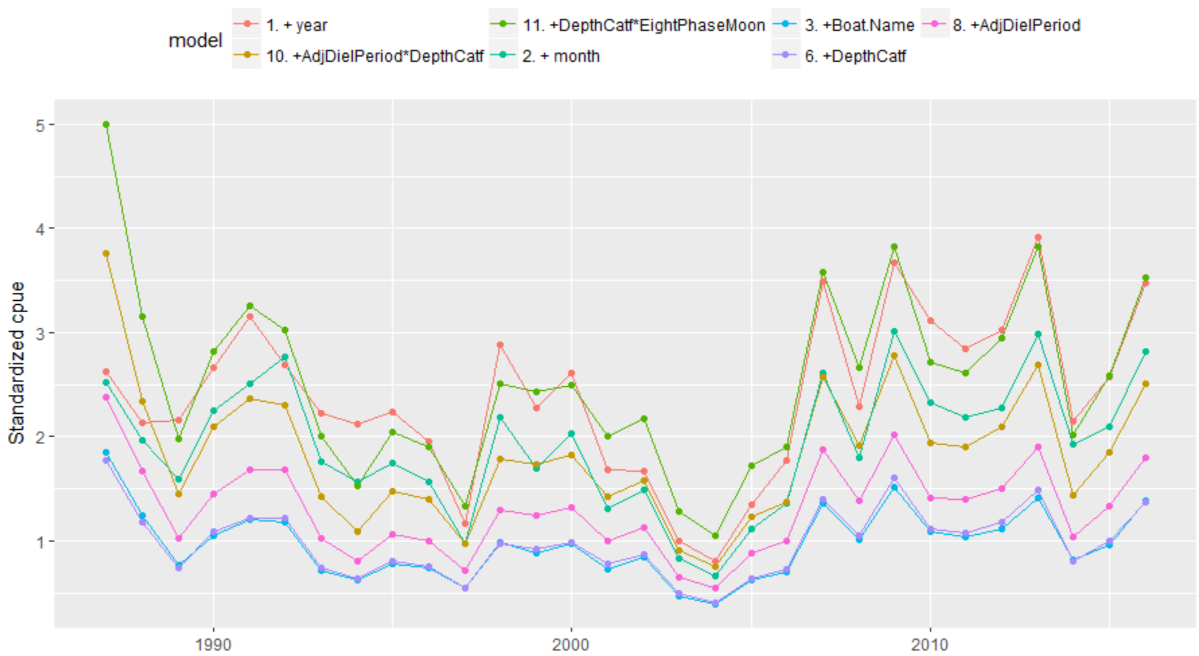


Figure 148. CTS Eastern Victoria. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 18. Models examined in CPUE standardisation of the CTS in Eastern Tasmania. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to

the previous model. Note that merging SST and ChlA with CPUE data resulted in some dropouts due to missing data. As a results, percent improvement in deviance is compared to results of the full model applied to the reduced dataset.

	Model	AIC	DF	Deviance	% Improvement
Null deviance				28865	
fit1	log(CPUE)~year	53222	31	25743	10.8%
fit2	log(CPUE)~year+monthf	52738	42	24945	3.1%
fit3	log(CPUE)~year+monthf+Boat.Name	51234	121	22492	9.8%
fit4	log(CPUE)~year+monthf+Boat.Name+PC1	51096	122	22297	0.9%
fit5	log(CPUE)~year+monthf+Boat.Name+ PC2	51225	122	22476	0.1%
fit6	log(CPUE)~year+monthf+Boat.Name+ depth	50910	144	21980	2.3%
fit7	log(CPUE)~year+monthf+Boat.Name+depth+moonphase	50850	151	21879	0.5%
fit8	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod	49751	147	20442	7.0%
fit9	log(CPUE+1)~year+monthf+Boat.Name+depth+AdjDielPeriod+moonphase*AdjDielPeriod	49692	175	20296	0.7%
fit10	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod+AdjDielPeriod*depth	49503	215	19958	2.3%
fit11	**log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod+AdjDielPeriod*depth+depth*moonphase**	49538	383	19589	1.9%
SST	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod+AdjDielPeriod*depth+depth*moonphase + SST	45347	357	17963	0.7%
CHla	log(CPUE)~year+monthf+Boat.Name+depth+AdjDielPeriod+AdjDielPeriod*depth+depth*moonphase + ChlA	32442	313	13135	0.1%



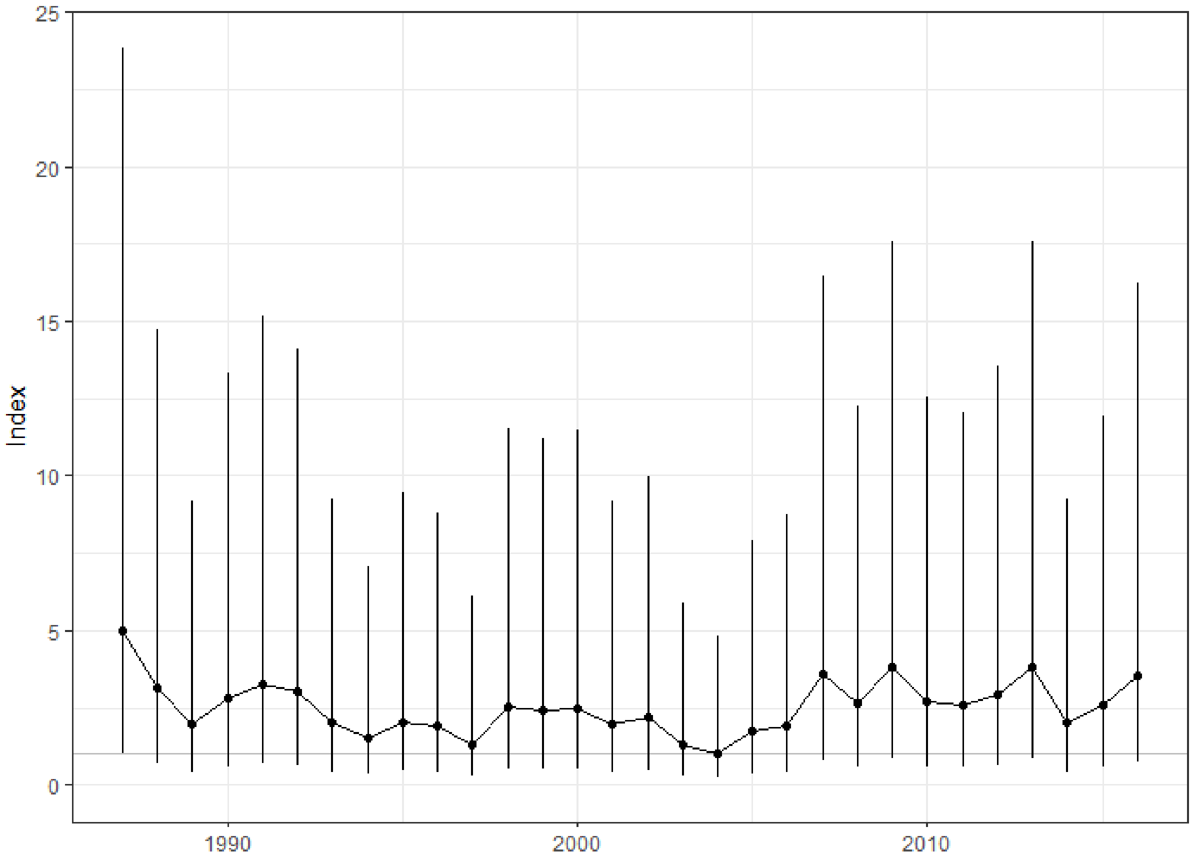


Figure 149. CTS Eastern Tasman. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 19. Models examined in CPUE standardisation of the CTS in New South Wales. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model. Note that merging SST and ChlA with CPUE data resulted in some dropouts due to missing data. As a results, percent improvement in deviance is compared to results of the full model applied to the reduced dataset.

	Model	AIC	DF	Deviance	% improvement
Null deviance				147877	
fit1	log(CPUE)~year	293559	31	140626	4.9%
fit2	log(CPUE)~year+monthf	288542	42	132894	5.5%
fit3	log(CPUE)~year+monthf+Boat.Name	280392	187	120882	9.0%
fit4	log(CPUE)~year+monthf+Boat.Name+PC1	280393	188	120881	<0.1%
fit5	log(CPUE)~year+monthf+Boat.Name+ PC2	276702	188	115975	4.1%
fit6	log(CPUE)~year+monthf+Boat.Name+ PC2+ depth	265118	212	101780	12.8%
fit7	log(CPUE)~year+monthf+Boat.Name+ PC2+ depth +moonphase	265110	213	101768	<0.1%
fit8	log(CPUE)~year+monthf+Boat.Name+PC2+depth+AdjDielPeriod	264671	215	101264	0.5%
fit9	log(CPUE+1)~year+monthf+Boat.Name+ PC2+ depth +moonphase*AdjDielPeriod	264678	243	101208	0.6%
fit10	log(CPUE)~year+monthf+Boat.Name+ PC2+ depth +AdjDielPeriod*depth	264031	287	100376	1.4%
fit11	log(CPUE)~year+monthf+Boat.Name++ PC2+ depth +AdjDielPeriod*depth +depth*moonphase	264092	462	100051	0.3%
SST	log(CPUE)~year+monthf+Boat.Name+ PC2+ depth +AdjDielPeriod*depth + SST	188832	227	72476	<0.1%
CHla	log(CPUE)~year+monthf+Boat.Name+ PC2+ depth +AdjDielPeriod*depth + ChlA	90446	188	36309	<0.1%

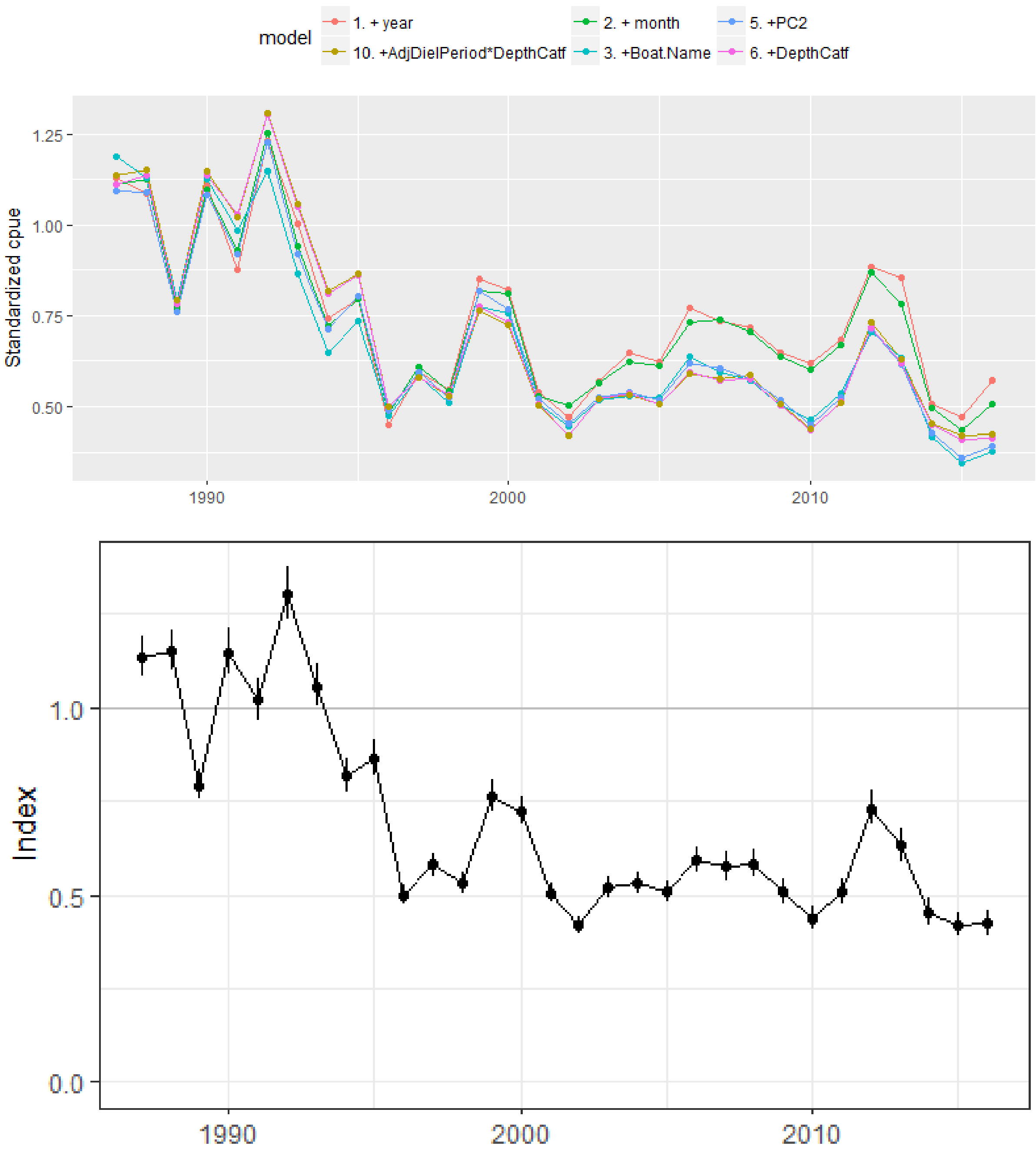


Figure 150. CTS NSW. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 20. Models examined in CPUE standardisation of the DS in Bass Strait. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model. Note that boat name was removed from the model because of the large influence of the catch by one vessel.

	Model	AIC	DF	Deviance	% improvement
Null deviance				7267	
fit1	log(CPUE)~year	5071	21	1603	10.6%
fit2	log(CPUE)~year+monthf	4900	32	1446	9.8%
fit3	log(CPUE)~year+monthf+Boat.Name	4773	40	1340	7.4%
fit4	log(CPUE)~year+monthf++PC1	4895	33	1441	0.4%
fit5	log(CPUE)~year+monthf+ PC2	4902	33	1446	<0.1%
fit6	log(CPUE)~year+monthf+ depth	4903	42	1433	0.9%
fit7	log(CPUE)~year+monthf+ moonphase	4898	39	1434	0.8%

fit8	log(CPUE)~year+monthf+ AdjDielPeriod	4812	35	1397	3.4%
fit9	log(CPUE)~year+monthf+ AdjDielPeriod+ moonphase*AdjDielPeriod	4842	63	1377	1.4%
fit10	log(CPUE)~year+monthf+ AdjDielPeriod+ moonphase*AdjDielPeriod +depth*AdjDielPeriod	4866	89	1357	1.5%
fit11	log(CPUE)~year+monthf+ AdjDielPeriod+ moonphase*AdjDielPeriod +depth*AdjDielPeriod + moonphase *depth	4881	118	1326	3.7%
SST	log(CPUE)~year+monthf+ AdjDielPeriod+ moonphase*AdjDielPeriod +depth*AdjDielPeriod + moonphase *depth + SST	4778	118	1296	<0.1%
CHla	loog(CPUE)~year+monthf+ AdjDielPeriod+ moonphase*AdjDielPeriod +depth*AdjDielPeriod + moonphase *depth + ChlA	4089	111	1127	<0.1%

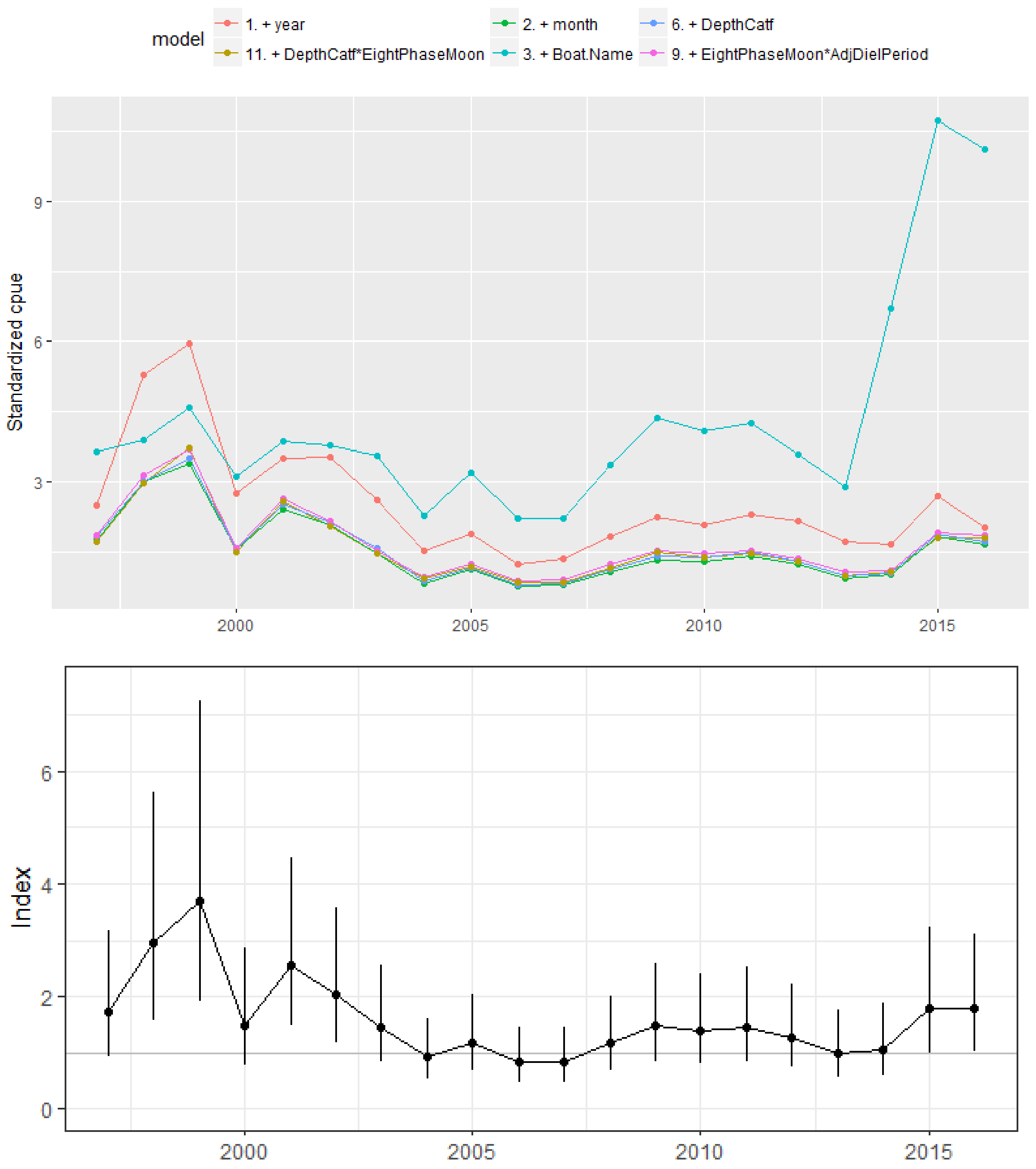
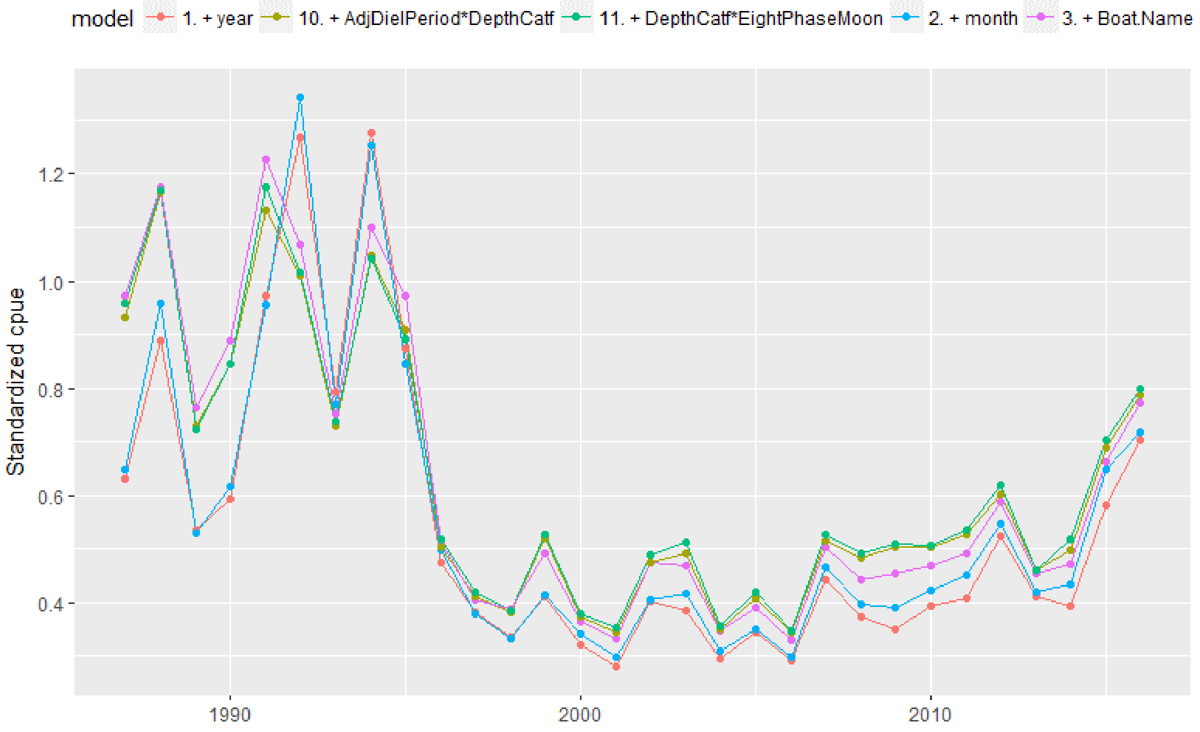


Figure 151. DS Bass Strait. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model. Note that boat name was removed from the model because of the large influence of the catch by one vessel.

Table 21. Models examined in CPUE standardisation of the DS in Eastern Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance				7267	
fit1	log(CPUE)~year	20191	31	6085	16.3%
fit2	log(CPUE)~year+monthf	20007	42	5926	2.6%
fit3	log(CPUE)~year+monthf+Boat.Name	19149	83	5249	11.4%
fit4	log(CPUE)~year+monthf+Boat.Name+PC2	19143	84	5244	0.1%
fit5	log(CPUE)~year+monthf+Boat.Name+PC2	19148	84	5247	<0.1%
fit6	log(CPUE)~year+monthf+Boat.Name+depth	19134	104	5211	0.7%
fit7	log(CPUE)~year+monthf+Boat.Name+moonphase	19140	90	5233	0.3%
fit8	log(CPUE)~year+monthf+Boat.Name+AdjDielPeriod	18416	86	5029	4.2%
fit9	log(CPUE)~year+monthf+Boat.Name+AdjDielPeriod+ moonphase*AdjDielPeriod	18423	114	4996	0.7%
fit10	log(CPUE)~year+monthf+Boat.Name+AdjDielPeriod +depth*AdjDielPeriod	18439	139	4974	1.1%
fit11	**log(CPUE)~year+monthf+Boat.Name+AdjDielPeriod+depth*AdjDielPeriod + moonphase *depth**	**18440**	**206**	**4886**	**1.8%**
SST	log(CPUE)~year+monthf+Boat.Name+AdjDielPeriod+depth*AdjDielPeriod + moonphase *depth + SST	14575	116	4001	0.2%
CHla	log(CPUE)~year+monthf+Boat.Name+AdjDielPeriod+depth*AdjDielPeriod + moonphase *depth + ChlA	9450	103	2611	0.9%



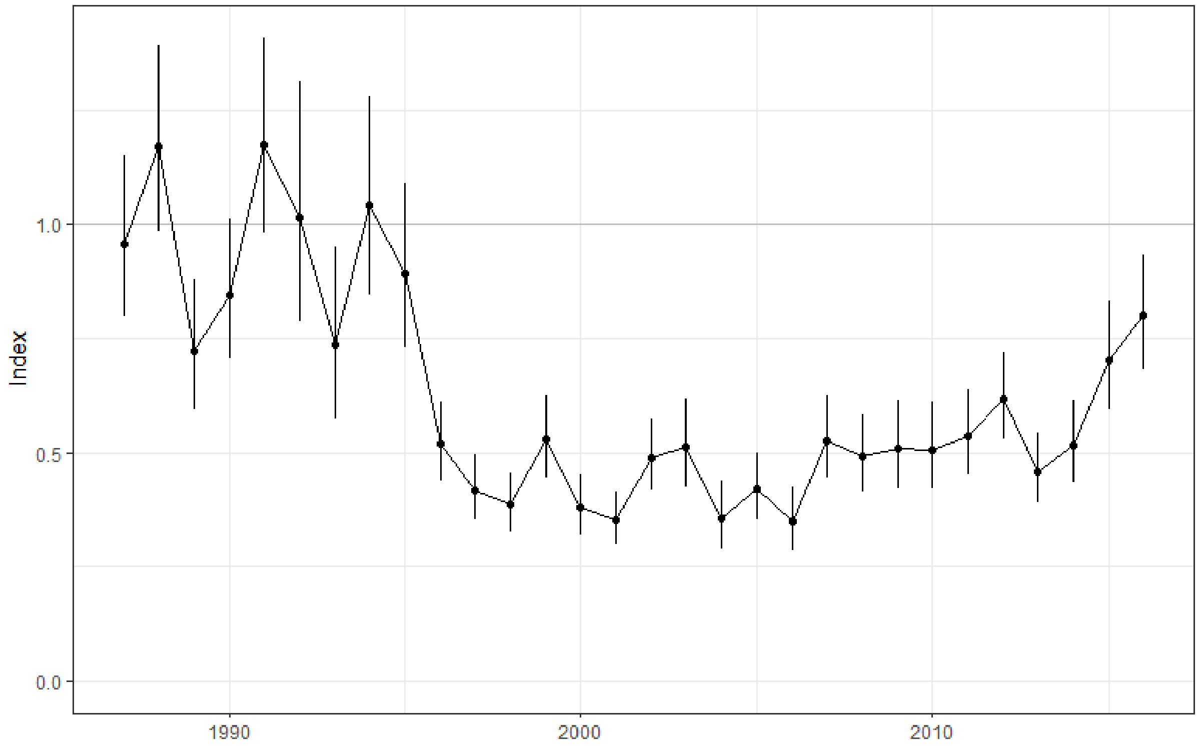


Figure 152. DS Eastern Victoria. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 22. Models examined in CPUE standardisation of the SJTas in East Coast. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance				4492	
		20191	31	6085	
fit1	log(CPUE)~year	20007	42	5926	46.7%
fit2	log(CPUE)~year+monthf	19149	83	5249	3.0%
fit3	log(CPUE)~year+monthf+Boat.Name	19143	84	5244	51.7%
fit4	log(CPUE)~year+monthf+PC1	19148	84	5247	1.9%
fit5	log(CPUE)~year+monthf+Boat.Name+PC1+PC2	19134	104	5211	0.1%
fit6	log(CPUE)~year+monthf+Boat.Name+PC1+ depth	19140	90	5233	11.6%
Fit7	log(CPUE)~year+monthf+Boat.Name+PC1+ depth+moonphase	18416	86	5029	1.8%
Fit8	log(CPUE)~year+monthf+Boat.Name+ PC1+depth+moonphase + depth*moonphase	18423	114	4996	6.8%
SST	log(CPUE)~year+monthf+Boat.Name+ PC1+depth+moonphase + depth*moonphase + SST	889	79	195	0.3%
ChlA	log(CPUE)~year+monthf+Boat.Name+ PC1+depth+moonphase + depth*moonphase + ChlA	1118	87	246	0.2%

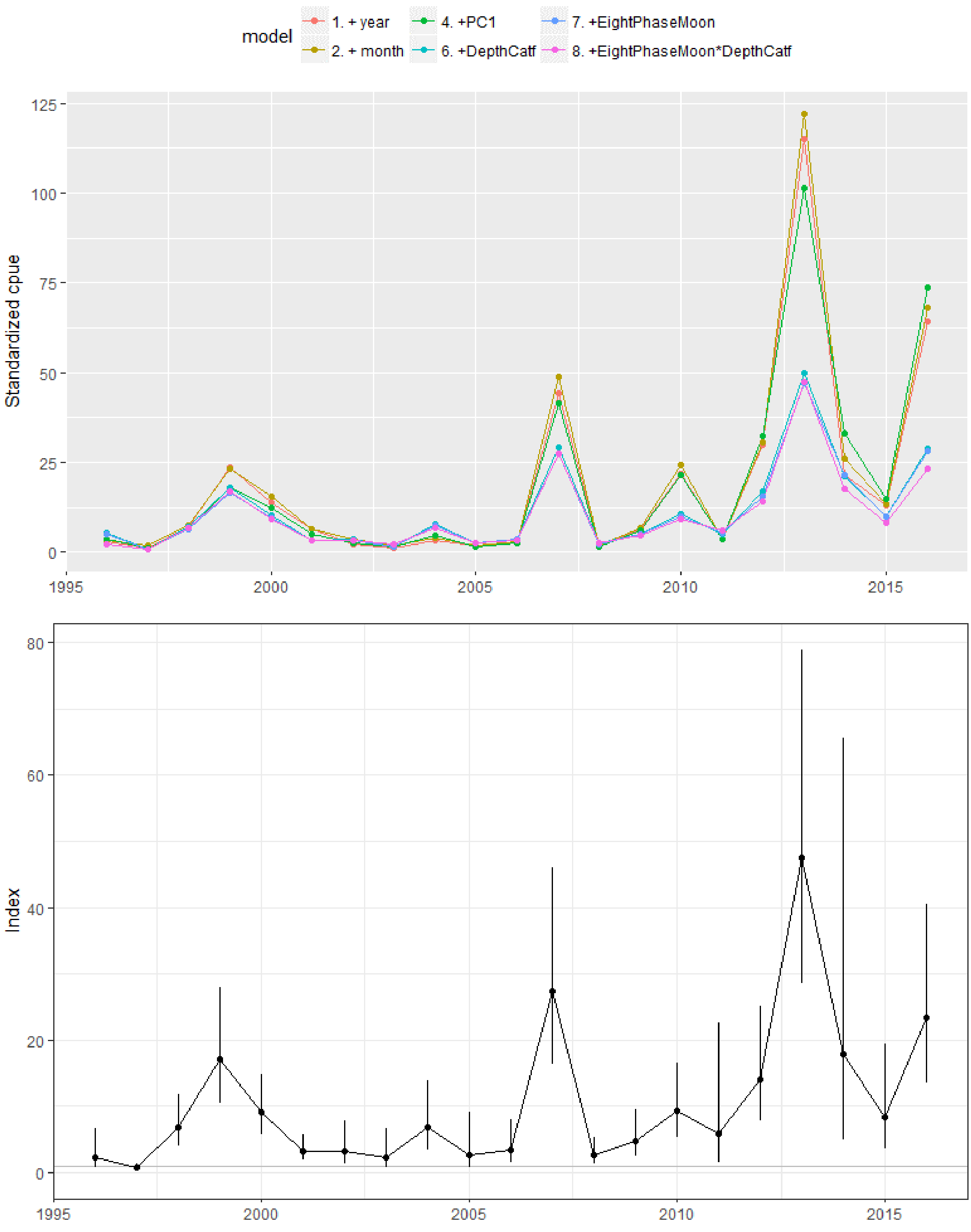
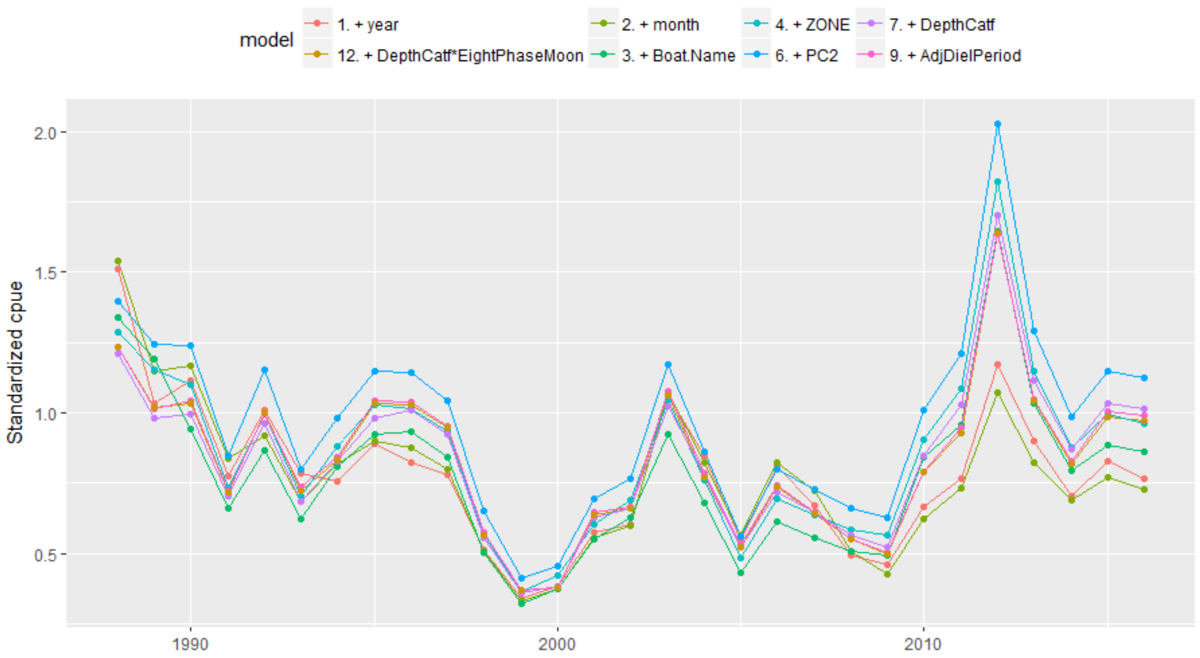


Figure 153. SJTas East Coast. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 23. Models examined in CPUE standardisation of the GAB (Central 1, Central 2, West 1, West 2).. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance				27107	
fit1	log(CPUE)~year	70374	30	25136	7.3%
fit2	log(CPUE)~year+monthf	68087	41	22882	9.0%
fit3	log(CPUE)~year+monthf+Boat.Name	64864	80	20007	12.6%^
fit4	log(CPUE)~year+monthf+Boat.Name+zone	64540	83	19740	1.3%
fit5	log(CPUE)~year+monthf+Boat.Name+zone+PC1	64428	84	19649	0.5%
fit6	log(CPUE)~year+monthf+Boat.Name+zone+PC2	64254	84	19511	1.2%
Fit7	log(CPUE)~year+monthf+Boat.Name+zone+PC2+depth	63741	109	19069	2.3%
Fit8	log(CPUE)~year+monthf+Boat.Name+zone+PC2+depth+moonphase	63637	116	18977	0.5%
Fit9	log(CPUE)~year+monthf+Boat.Name+PC2+zone+depth+AdjDielPeriod	61834	112	17642	7.5%
fit10	log(CPUE)~year+monthf+Boat.Name+PC2+zone+depth+AdjDielPeriod+moonphase*AdjDielPeriod	61705	140	17509	0.8%
fit11	log(CPUE)~year+monthf+Boat.Name+PC2+zone+depth+AdjDielPeriod+AdjDielPeriod*depth	61803	166	17542	0.6%
fit12	**log(CPUE)~year+monthf+Boat.Name+PC2+zone+depth+AdjDielPeriod+depth*moonphase**	61796	233	17441	**1.1%**
SST	log(CPUE)~year+monthf+Boat.Name+PC2+zone+depth+AdjDielPeriod+depth*moonphase + SST	56197	212	16021	0.1%
ChlA	log(CPUE)~year+monthf+Boat.Name+PC2+zone+depth+AdjDielPeriod+depth*moonphase + ChlA	36182	176	10080	<0.1%



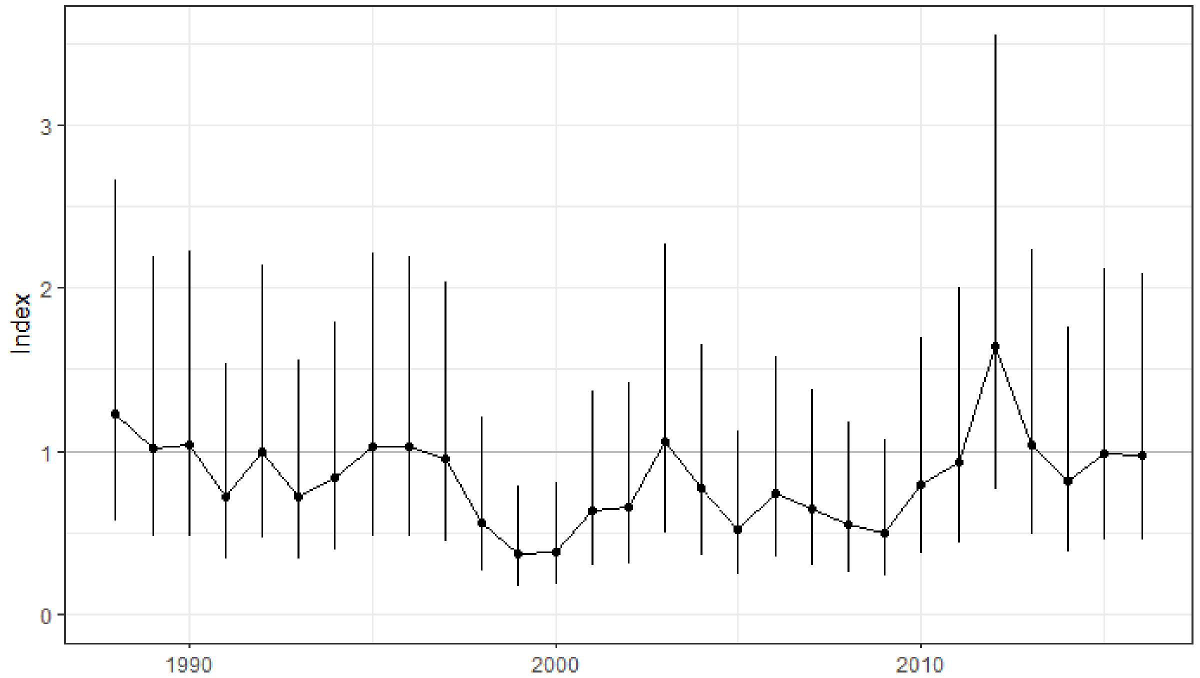
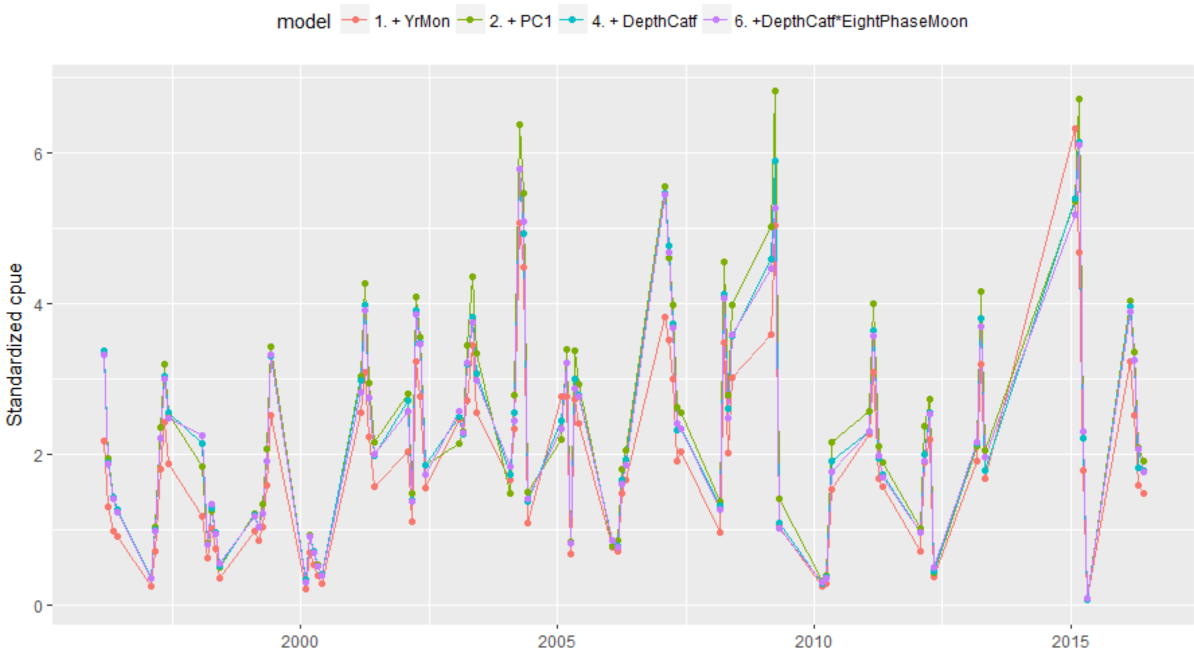


Figure 154. GAB (Central 1, Central 2, West 1, West 2). Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 24. Models examined in CPUE standardisation of the SSJ in Western Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance				6610	
1	log(CPUE)~YrMon	15834	87	4578	30.1%
2	log(CPUE)~ YrMon + PC1	15638	88	4433	3.2%
3	log(CPUE)~YrMon+ PC1 + PC2	15638	89	4432	<0.1%
4	log(CPUE)~YrMon+ PC2 + depth	15523	104	4329	2.3%
5	log(CPUE)~ YrMon+ PC2 + depth + moonphase	15495	109	4303	0.6%
6	log(CPUE)~YrMon+zone+ depth+ depth*moonphase	15520	171	4234	2.2%



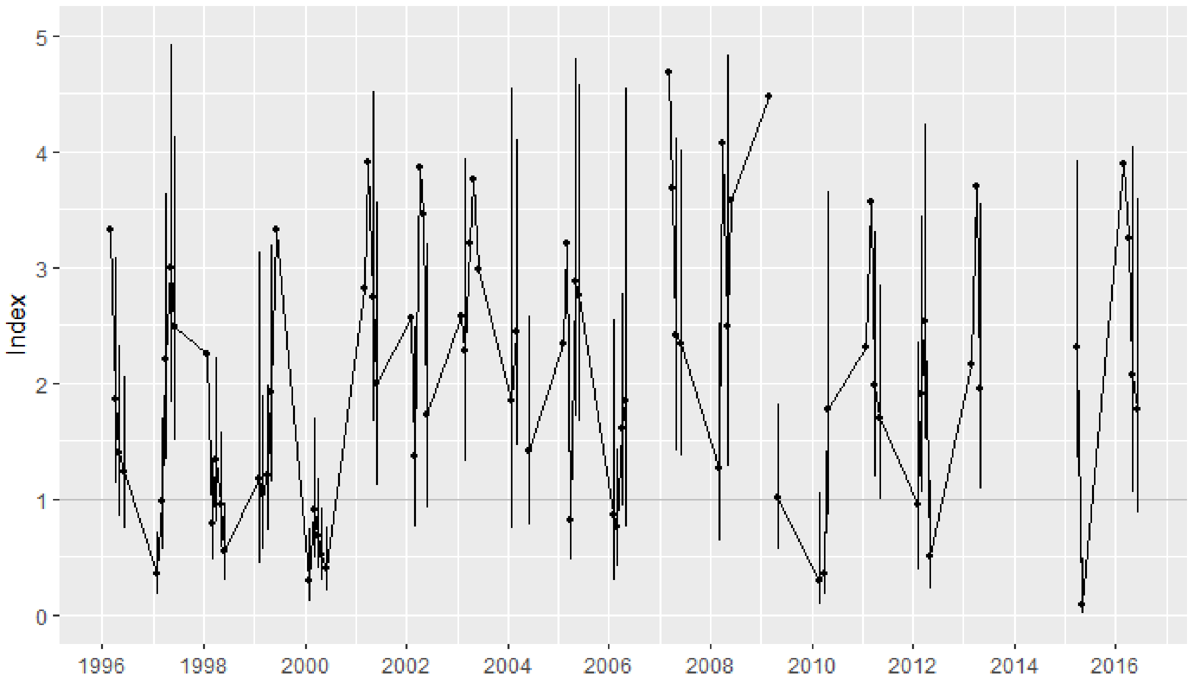


Figure 155. Western Victoria. Top panel - change in standardised CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

Table 25. Models examined in CPUE standardisation of the SSJ in Central Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			1760		
1	log(CPUE)~YrMon	4882	59	1152	34.6%
2	log(CPUE)~ YrMon + PC1	4883	60	1151	<0.1%
3	log(CPUE)~YrMon+ PC2	4883	60	1151	<0.1%
4	log(CPUE)~YrMon+ depth	4844	69	1121	2.6%
5	log(CPUE)~ YrMon+ depth + moonphase	4851	74	1120	0.1%
6	log(CPUE)~YrMon+ depth+ depth*moonphase	4847	101	1090	2.8%^

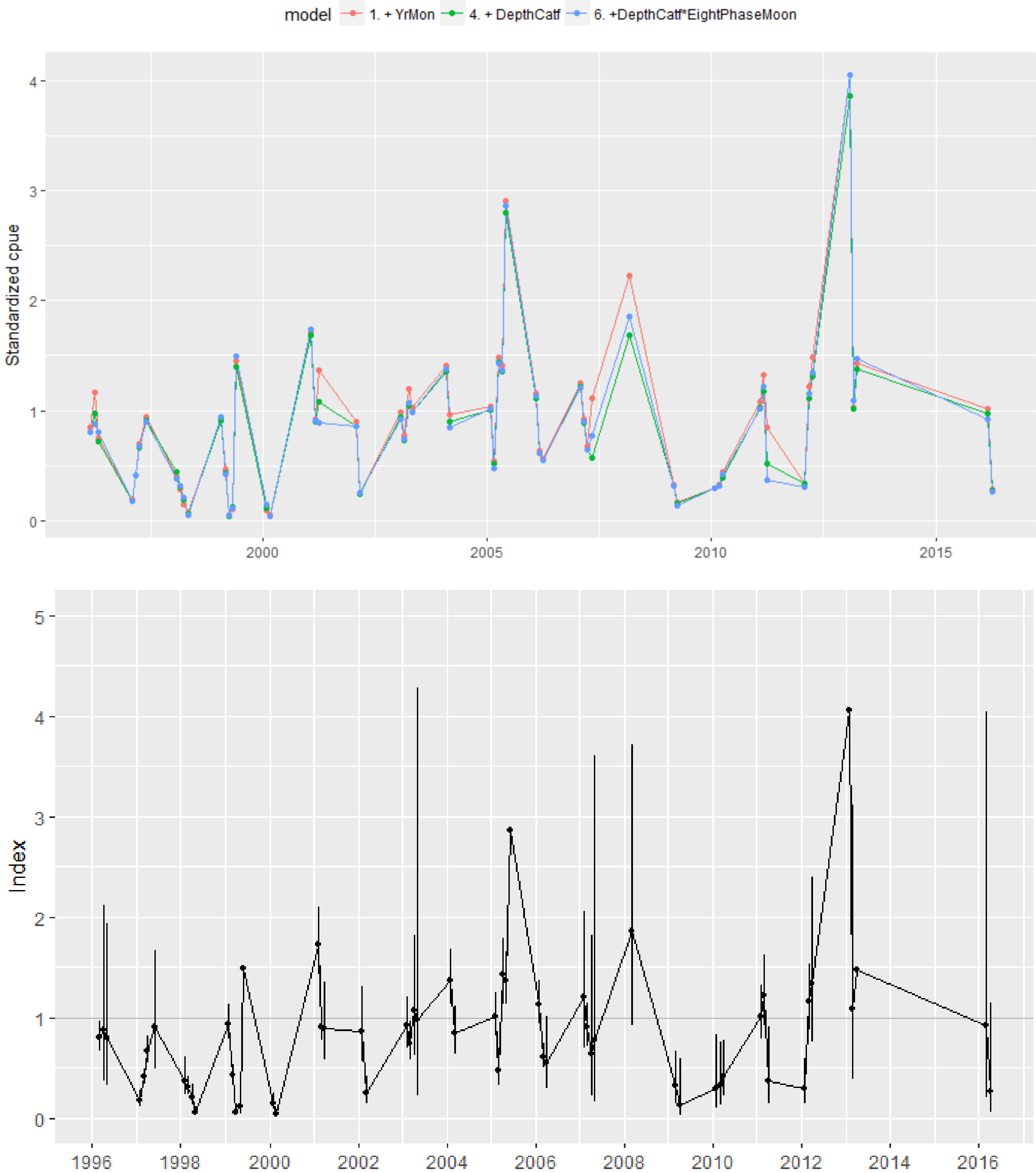
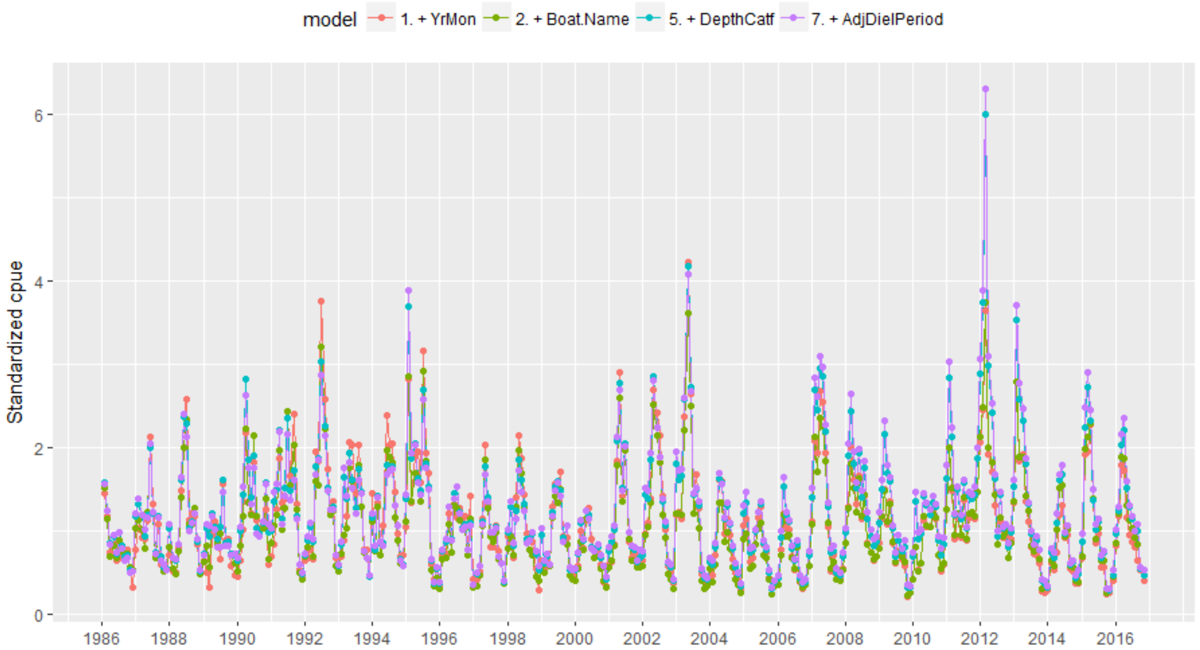


Figure 156. SSJ Central Victoria. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised monthly CPUE using the final model.

Table 26. Models examined in CPUE standardisation of the CTS off Western Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			50241		
1	log(CPUE)~YrMon	118465	371	38200	24.0%
2	log(CPUE)~YrMon+Boat.Name	115087	454	35209	7.8%
3	log(CPUE)~YrMon+Boat.Name+PC1	114983	455	35123	0.2%
4	log(CPUE)~YrMon+Boat.Name+PC2	115034	455	35164	0.1%
5	log(CPUE)~YrMon+Boat.Name+depth	110251	478	31466	10.6%
6	log(CPUE)~YrMon+Boat.Name+depth+moonphase	110178	485	31403	0.2%
7	log(CPUE)~YrMon+Boat.Name+depth+AdjDielPeriod	109207	481	30714	2.4%
8	log(CPUE)~YrMon+Boat.Name+depth+AdjDielPeriod+moonphase*AdjDielPeriod	109130	509	30620	0.3%
9	log(CPUE)~YrMon+Boat.Name+depth+AdjDielPeriod+AdjDielPeriod*depth	109084	553	30526	0.6%
10	log(CPUE)~YrMon+Boat.Name+depth+AdjDielPeriod+depth*moonphase	109196	651	30468	0.8%



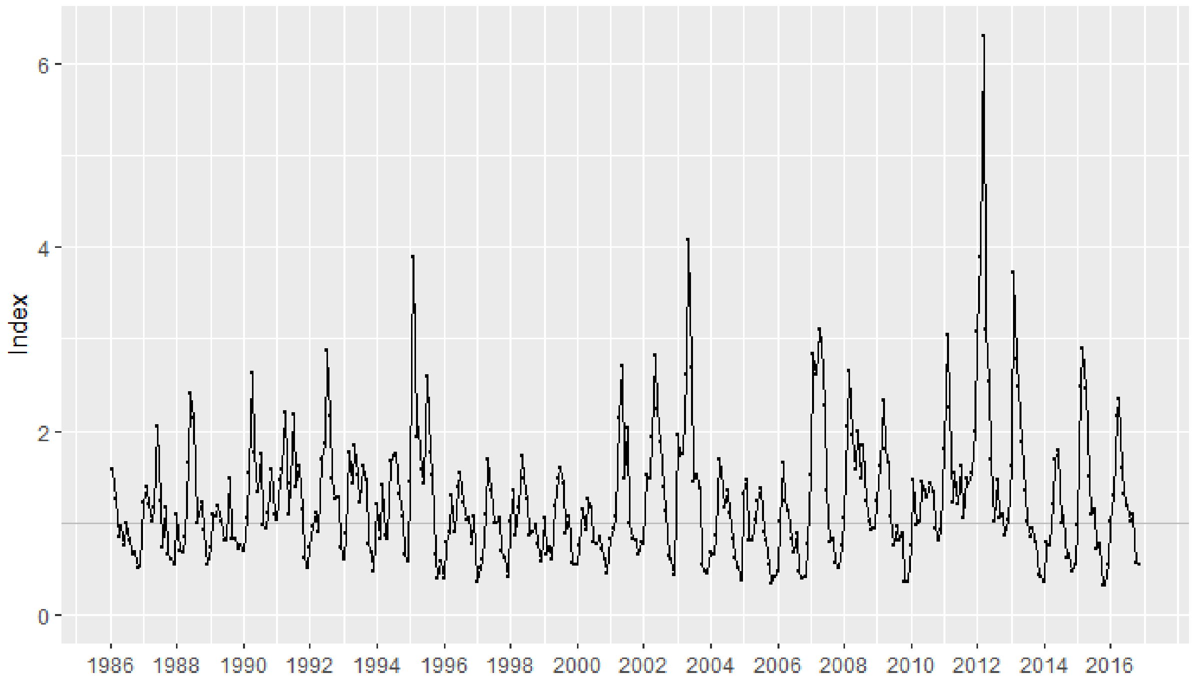


Figure 157. CTS Western Victoria. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised monthly CPUE using the final model.

Table 27. Models examined in CPUE standardisation of the CTS off Eastern Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			134580		
1	log(CPUE)~YrMon	249350	372	114891	14.6%
2	log(CPUE)~YrMon+Boat.Name	239377	521	100487	12.5%
3	log(CPUE)~YrMon+Boat.Name+PC1	239374	522	100480	<0.1%
4	log(CPUE)~YrMon+Boat.Name+PC2	239013	522	100008	0.5%
5	log(CPUE)~YrMon+Boat.Name+depth	229985	545	88846	11.6%
6	log(CPUE)~YrMon+Boat.Name+depth+moonphase	229954	552	88795	0.1%
7	log(CPUE)~YrMon+Boat.Name+depth+AdjDielPeriod	229827	548	88657	0.2%
8	log(CPUE)~YrMon+Boat.Name+depth+moonphase*AdjDielPeriod	229796	576	88556	0.3%
9	log(CPUE)~YrMon+Boat.Name+depth+ AdjDielPeriod*depth	229084	620	87637	1.4%
10	log(CPUE)~YrMon+Boat.Name+depth+ AdjDielPeriod*depth +depth*moonphase	229127	795	87287	0.4%

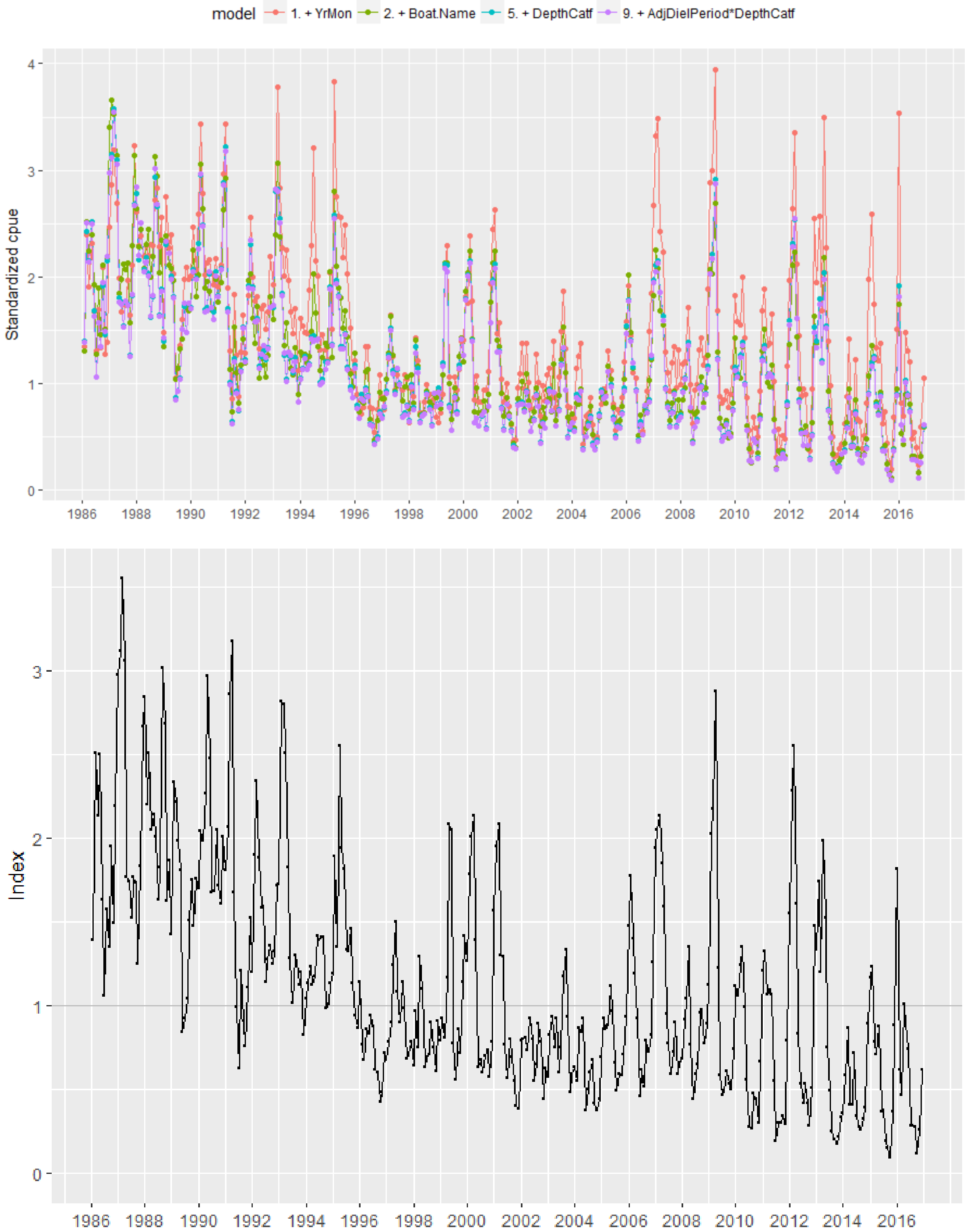
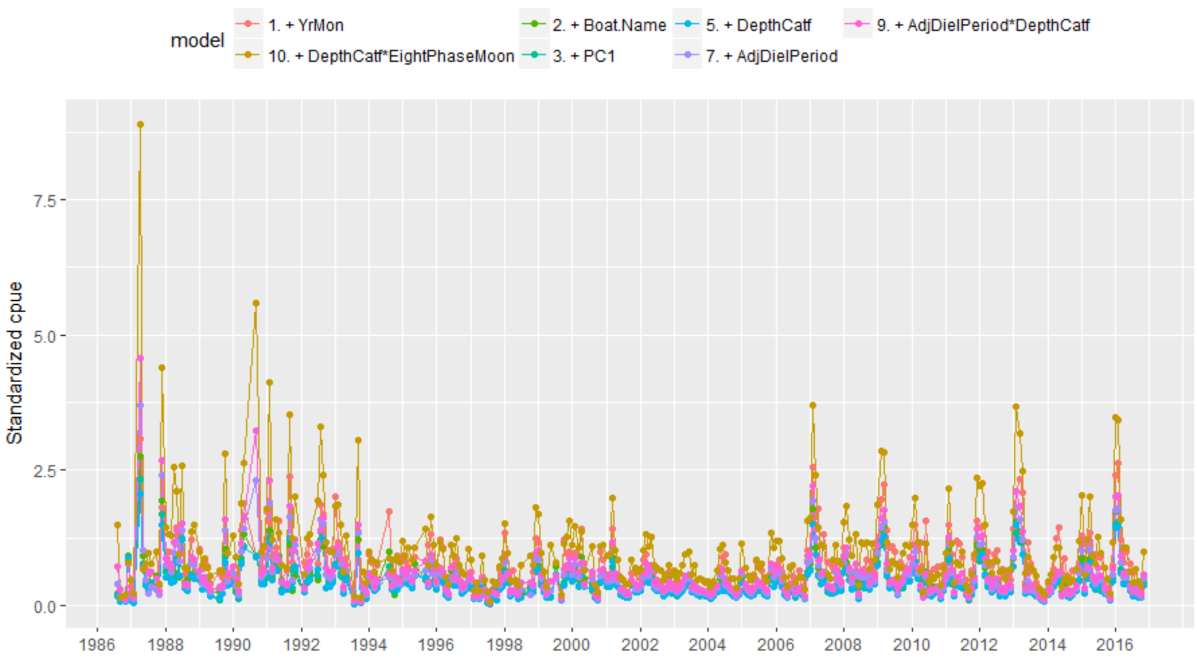


Figure 158. CTS Eastern Victoria. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised CPUE using the final model.

CTS – east Tas

Table 28. Models examined in CPUE standardisation of the CTS off Eastern Tasmania. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			28865		
fit1	log(CPUE)~YrMon	51495	335	22259	22.9%
fit2	log(CPUE)~YrMon+Boat.Name	50038	412	20135	9.5%
fit3	log(CPUE)~YrMon+Boat.Name+PC1	49849	413	19897	1.2%
fit4	log(CPUE)~YrMon+Boat.Name+PC1+PC2	49818	414	19856	0.2%
fit5	log(CPUE)~YrMon+Boat.Name+PC1+depth	49394	436	19286	3.1%
fit6	log(CPUE)~YrMon+Boat.Name +PC1+depth +moonphase	49349	443	19215	0.4%
fit7	log(CPUE)~YrMon+Boat.Name+PC1+depth +AdjDielPeriod	48022	439	17701	8.2%
fit8	log(CPUE)~YrMon+Boat.Name+PC1+depth +AdjDielPeriod +moonphase*AdjDielPeriod	47978	467	17591	0.6%
fit9	log(CPUE)~YrMon+Boat.Name+PC1+depth +AdjDielPeriod + AdjDielPeriod*depth	47756	507	17262	2.5%
fit10	log(CPUE)~YrMon+Boat.Name+PC1+depth +AdjDielPeriod + AdjDielPeriod*depth +depth*moonphase	47798	675	16950	1.8%



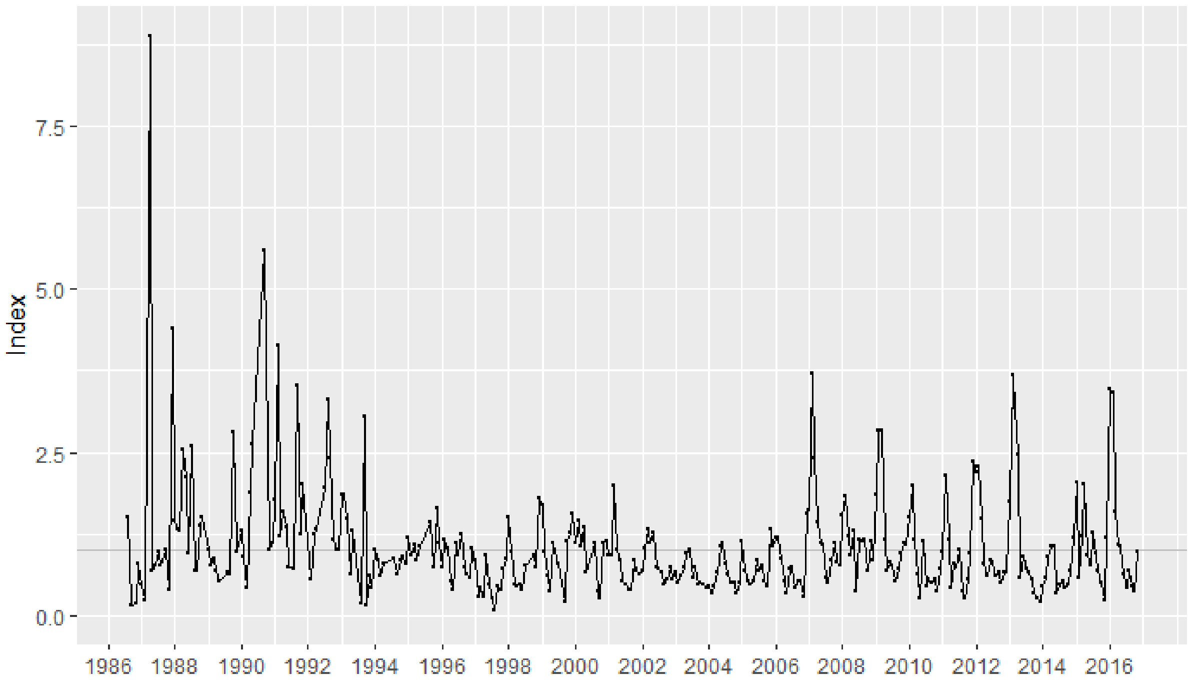


Figure 159. CTS Eastern Tasmania. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised monthly CPUE using the final model.

CTS – NSW

Table 29. Models examined in CPUE standardisation of the CTS off NSW. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			147877		
fit1	log(CPUE)~YrMon	284807	372	126497	14.5%
fit2	log(CPUE)~YrMon+Boat.Name	276664	517	115072	9.0%
fit3	log(CPUE)~YrMon+Boat.Name+PC1	276658	518	115062	<0.1%
fit4	log(CPUE)~YrMon+Boat.Name+ PC2	273278	518	110778	3.7%
fit5	log(CPUE)~YrMon+Boat.Name+PC2+depth	261438	542	96941	12.5%
fit6	log(CPUE)~ YrMon+Boat.Name+PC2+depth +moonphase	261425	549	96911	0.03%
fit7	log(CPUE)~ YrMon+Boat.Name+PC2+depth +AdjDielPeriod	260965	545	96421	0.5%
fit8	log(CPUE)~ YrMon+Boat.Name+PC2+depth +moonphase*AdjDielPeriod	260968	573	96363	0.6%
fit9	log(CPUE)~ YrMon+Boat.Name+PC2+depth +AdjDielPeriod*depth	260299	617	95548	1.4%
fit10	log(CPUE)~ YrMon+Boat.Name+PC2+depth +AdjDielPeriod*depth +depth*moonphase	260358	792	95236	0.3%

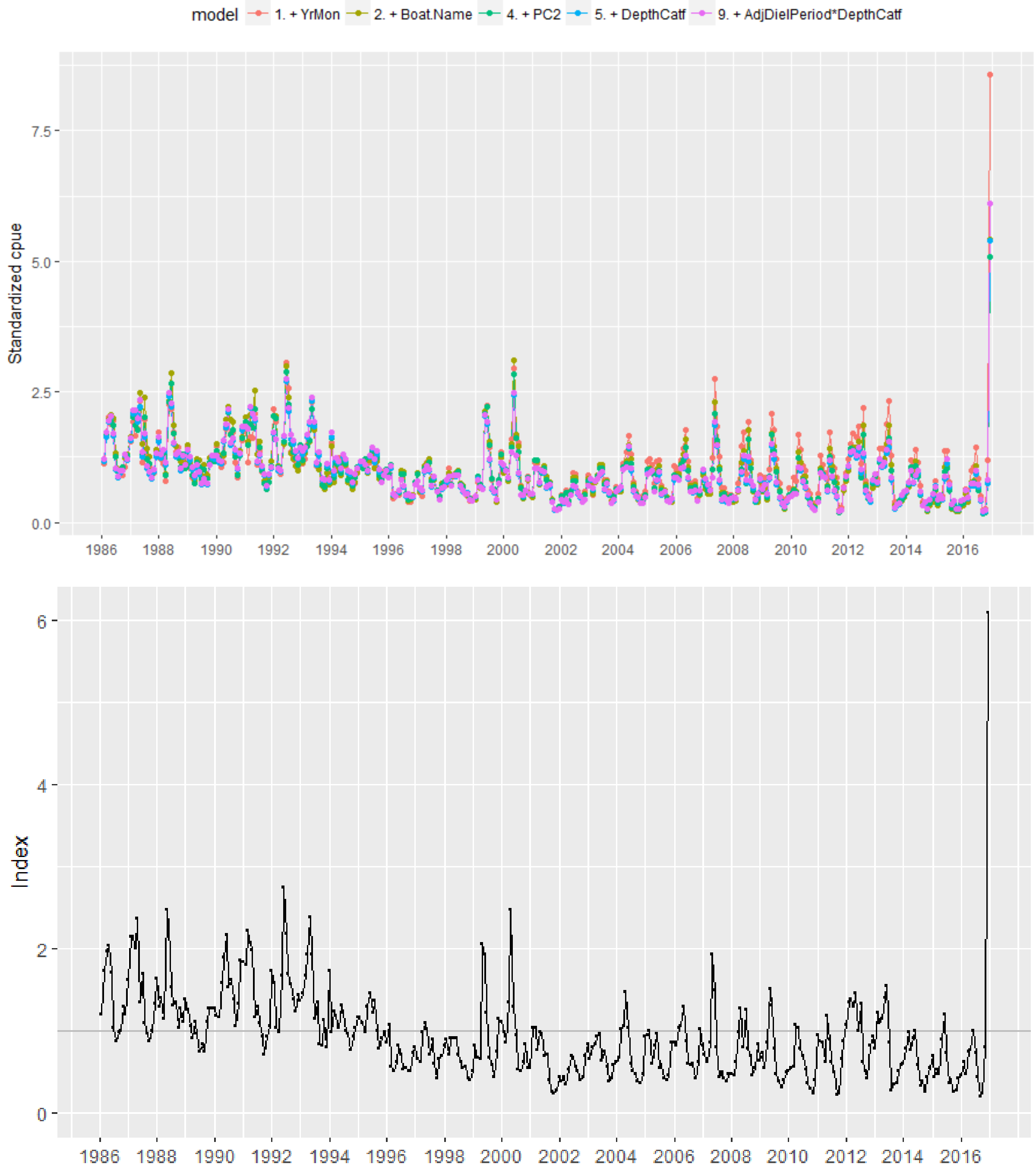
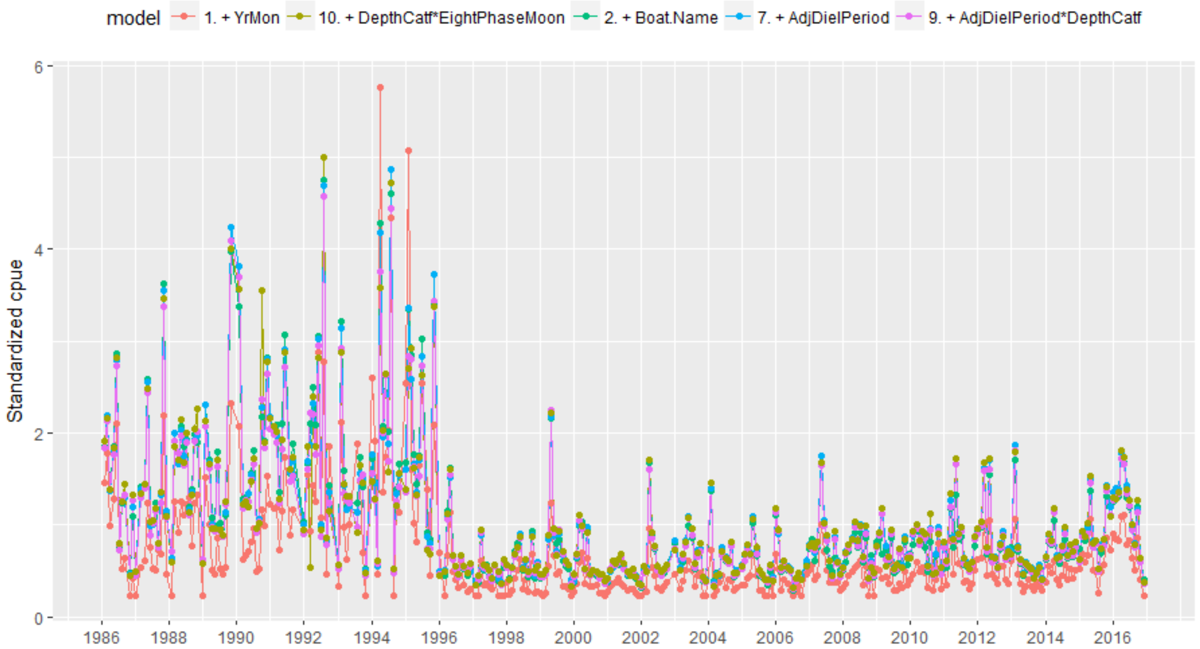


Figure 160. CTS NSW. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised monthly CPUE using the final model.

Table 30. Models examined in CPUE standardisation of the DS Eastern Victoria. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			7267		
fit1	log(CPUE)~YrMon	19654	345	5236	27.9%

fit2	log(CPUE)~YrMon+Boat.Name	18823	386	4655	11.1%
fit3	log(CPUE)~YrMon+Boat.Name+PC1	18811	387	4646	0.2%
fit4	log(CPUE)~YrMon+Boat.Name+ PC2	18812	387	4647	0.2%
fit5	log(CPUE)~YrMon+Boat.Name+ depth	18794	407	4612	0.9%
fit6	log(CPUE)~ YrMon+Boat.Name++moonphase	18814	393	4641	0.3
fit7	log(CPUE)~ YrMon+Boat.Name+AdjDielPeriod	18117	389	4455	4.3%
fit8	log(CPUE)~ YrMon+Boat.Name+AdjDielPeriod +moonphase*AdjDielPeriod	18126	417	4427	0.6%
fit9	log(CPUE)~ YrMon+Boat.Name + AdjDielPeriod +AdjDielPeriod*depth	18120	442	4394	1.4%
fit10	log(CPUE)~ YrMon+Boat.Name+ AdjDielPeriod +AdjDielPeriod*depth +depth*moonphase	18134	509	4324	1.6%



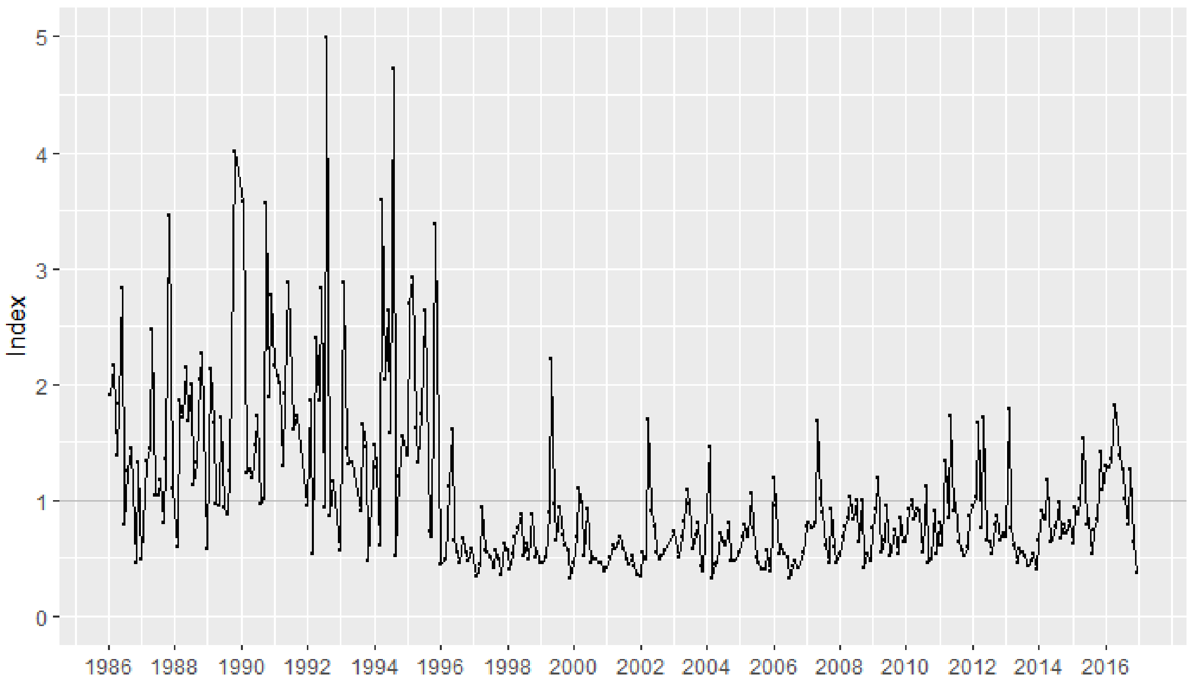
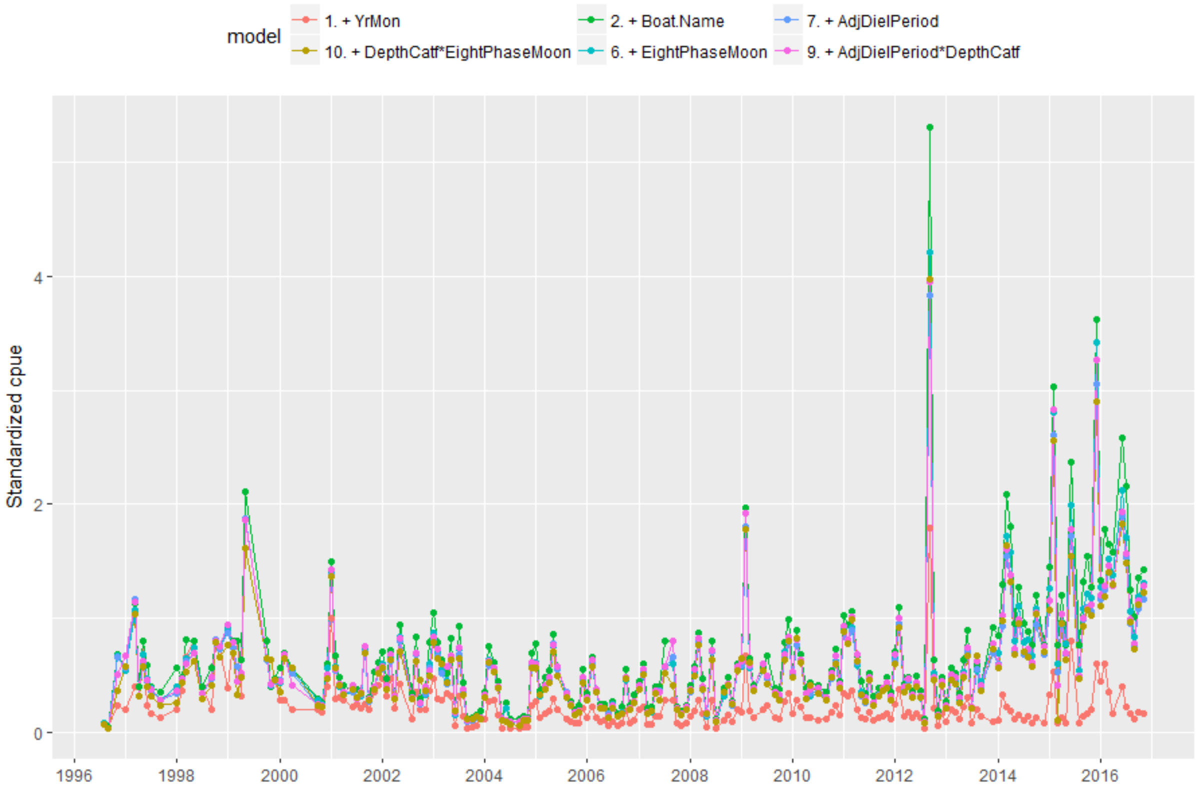


Figure 161. DS Eastern Victoria. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised monthly CPUE using the final model.

Table 31. Models examined in CPUE standardisation of the DS Bass Strait. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			1793		
fit1	log(CPUE)~YrMon				35.6%
fit2	log(CPUE)~YrMon+Boat.Name				6.0%
fit3	log(CPUE)~YrMon+Boat.Name+PC1				0.4%
fit4	log(CPUE)~YrMon+Boat.Name+ PC2				<0.1%
fit5	log(CPUE)~YrMon+Boat.Name+ depth				1.0%
fit6	log(CPUE)~ YrMon+Boat.Name+moonphase				1.8%
fit7	log(CPUE)~ YrMon+Boat.Name+moonphase +AdjDielPeriod				1.8%
fit8	log(CPUE)~ YrMon+Boat.Name+AdjDielPeriod +moonphase*AdjDielPeriod				0.8%
fit9	log(CPUE)~ YrMon+Boat.Name +moonphase +AdjDielPeriod +AdjDielPeriod*depth				1.7%
fit10	log(CPUE)~ YrMon+Boat.Name +moonphase +AdjDielPeriod +AdjDielPeriod*depth +depth*moonphase				2.4%



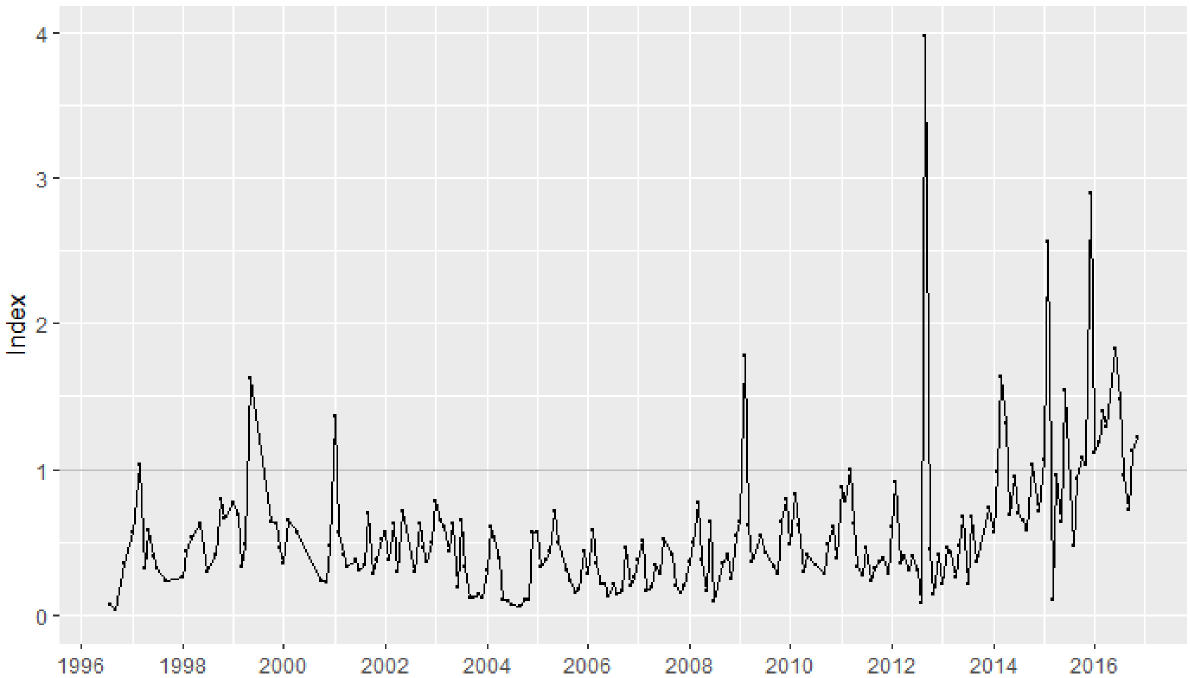


Figure 162. DS Bass Strait. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised monthly CPUE using the final model.

Table 32. Models examined in CPUE standardisation of the SJTAS off the East Coast. Greyed out lines are models that were rejected because of a lack of improvement to the fit compared to the previous model.

	Model	AIC	DF	Deviance	% improvement
Null deviance			4491		
fit1	log(CPUE)~ YrMon	4469	88	1736	61.3%
fit2	log(CPUE)~ YrMon + Boat.Name	3843	180	977	43.7%
fit3	log(CPUE)~ YrMon + Boat.Name+PC1	3845	181	977	<1%
fit4	log(CPUE)~ YrMon +Boat.Name+ PC2	3844	181	976	<0.1
fit5	log(CPUE)~ YrMon + Boat.Name + depth	3833	192	954	2.4%
fit6	log(CPUE)~ YrMon+Boat.Name+ depth +moonphase	3834	199	945	0.9%
Fit7	log(CPUE)~ YrMon + Boat.Name++depth +moonphase + depth*moonphase	3823	260	860	9.9%

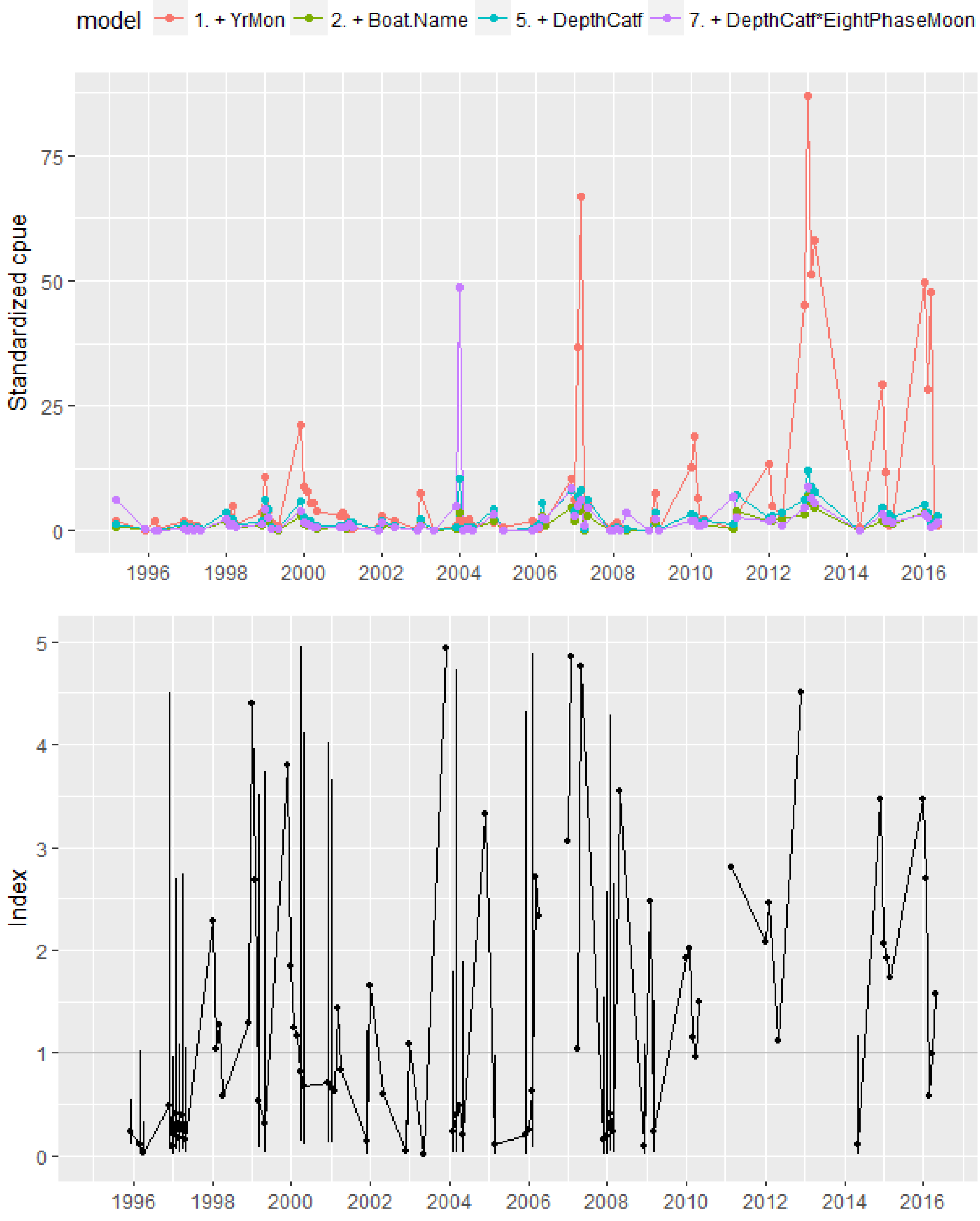


Figure 163. SJTAS East Coast. Top panel - change in standardised monthly CPUE with addition of variables to the model; and bottom panel - standardised monthly CPUE using the final model.