Presence-absence relationship with bottom temperature for deep water hake (*Merluccius paradoxus*) on the west coast of South Africa and its potential for adjusting survey indices

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Abstract

The abundance and distribution of South African demersal resources are routinely monitored using annual swept area surveys. Data collected during the surveys are used to produce time series of abundance indices that are one of the inputs to routine stock assessments of various demersal resources. Surveys conducted prior to 2011 generally encompassed depths shallower than 500 m. Subsequent surveys have been extended to encompass areas deeper than 500 m. This study demonstrates that survey catch rates of deep-water Cape hake (*Merluccius paradoxus*) were high in several years at the offshore limit of the surveyed area, and that presence-absence of deep water hake within the survey domain was related to bottom temperature. The latter observation was used to generate an alternative time series of biomass estimates by estimating correction factors for each year, taking the inter-annual variation of the bottom temperature distribution on the shelf into account. This alternative time series of survey biomass indices may be considered to be representative of the years in which a proportion of the stock was inadequately sampled due to the depth limitation of the survey although some discrepancies between these estimates with observed survey biomass in 2011 and 2012 occurred and no significant correlation with CPUE of the commercial trawler fleet was found.

Introduction

Two species of hake are found in South African waters, the shallow-water Cape hake *Merluccius capensis* and the deep-water hake *M. paradoxus*. Hakes are an important component of the marine ecosystem in the region, and are the basis for the most valuable fishery in South Africa (Payne et al. 1995, Fairweather et al. 2006, Atkinson et al. 2011). The juveniles of both species are pelagic and settle on the bottom at lengths of 10 - 20 cm, with the smallest *M. capensis* being found shallower than 100 m whereas small *M. paradoxus* occur further offshore, at depths of 150 - 200 m. Adult hake move deeper with increasing size, but *M. capensis* is usually not found deeper than 400 m whereas the distribution of *M. paradoxus* extends to about 800 m depth (Botha 1985, Fairweather 2002, Fairweather et al. 2006).

The two species are currently assessed separately using information from the commercial fishery and from routine, fishery-independent swept area surveys that monitor demersal resources in the region (Rademeyer et al. 2008). These surveys have been conducted since 1985 following a pseudo-stratified random design. Prior to 2011, the survey areas typically extended to the 500 m isobath, but have subsequently been extended into deeper water in an attempt to encompass the entire distribution of *M. paradoxus*.

Inter-annual variability in abundance estimates for *M. paradoxus* (Rademeyer et al. 2008) has been larger than would be expected for what is presumed to be a relatively long-lived species. It has been suggested that this inter-annual variability may, to a certain extent, reflect variations in the availability of *M. paradoxus* to the survey gear arising from changes in environmental conditions (Leslie and Lamont 2009).

It has been demonstrated that *M. paradoxus* avoids warm temperatures (Millar 2000). Unfavourable temperature conditions on the shelf may drive a considerable portion of the population to depths larger than 500 m, at or beyond the offshore limit of the survey domain. The present study attempts to quantify this effect by computing estimates of abundance that have been adjusted for the proportion of the stock that may have been outside of the survey area in the years prior to the extension of the surveyed depth range. The approach employed was to identify a threshold of unfavourable temperature using the relationship between the probability of presence of *M. paradoxus* and bottom temperature, and adjust survey biomass estimates according the proportion of the survey area that fell below this threshold. Finally, the new biomass indices were compared with a time series of commercial trawler CPUE.

Material and Methods

The scope of this study has been restricted to trawl catches and CTD data collected during annual summer (January/February) demersal research surveys conducted from 2002 to 2014 along the South African west coast west of 20°E (Fig. 1) by the research vessel FRS Africana in 2002 to 2012 and the commercial trawler FV Andromeda in 2013 and 2014. Data from earlier years were excluded due to missing or insufficient hydrographical information. The survey, usually three to four weeks in duration, follows a pseudo-stratified random design with a target of about 100 stations per survey. The locations of trawl stations are randomly selected within pre-defined depth strata, the number of stations per depth stratum being proportional to the area of the stratum. Fishing is limited to daylight hours (30 minutes after sunrise to 30 minutes before sunset) to avoid possible bias arising from the diurnal migration behaviour of hake. A number of studies have suggested that hake, as with other gadoids, tend to move off the sea floor into the water column at night and return to the sea floor during the day (Pillar and Barange 1997). A modified survey trawl net (“new” gear) was introduced in 2004, but the “old” survey gear was still periodically used in subsequent years (Table 1) to facilitate the calibration of the two different gear types. A major difference of the new survey trawl was the drastic reduction of the sweep length (from 50 to 9 m), which considerably reduced the herding effect. In 2011, the survey area was extended to deeper water and the target increased to 120 stations to maintain the sampling intensity, i.e. the number of stations per stratum (Tab. 1).

The swept area at a given station was calculated as the product of the distance trawled and the recorded (or estimated) wingspread and biomass densities at each station were then expressed in weight per swept area, and total biomass was calculated from the mean densities and the corresponding stratum areas.

The biomass densities were re-coded in 0 (absence) and 1 (presence), and the probability of a non-zero tow was modelled as a Bernoulli random variability with the probability p given by:

$$ln\left(p/(1-p)\right) = a + bx$$

or, equivalently

$$p = \frac{1}{1+e^{-(a+bx)}}$$

where x is bottom temperature. The parameters a and b and their standard errors were estimated by logistic regression using a generalized linear model of the binominal family. The resulting fit were compared graphically with the observed probabilities of presence averaged for 1°C bins of bottom temperature for which the standard error (se) of a binomial proportion was computed as:

$$se = \sqrt{p(1-p)/n}$$

where n is the number of observations in the corresponding temperature bin. These calculations were done in R version 3.1.1 (R core team 2014) based on Crawley (2007) and the figures were redrawn using SigmaPlot® version 12.5 (www.sigmaplot.com).

Spatial interpolation of temperature in the near-bottom layer (10 m above bottom depth) was done by simple kriging using omnidirectional variograms (Chilès and Delfiner 1999, Rivoirard et al. 2000) with a maximum distance of 200 km and a lag width of 10 km. The kriged maps of bottom temperature produced with Surfer® version 11.6 (www.Golden Software.com) were then used to calculate the spatial extent of the area where bottom temperatures were above the estimated threshold at 50 % probability of presence of *M. paradoxus*. The annual factors for biomass adjustment f were then expressed as the ratios of these areas to the entire survey area ≤ 500 m depth. Finally, a length independent conversion from old to new gear (Smith et al. 2013) was applied and the new biomass indices were computed as:

$$B_{estimated} = B_{0-500\,m,old\,trawl} * 0.883 * f$$

or

$$B_{estimated} = B_{0\,-\,500\,m,new\,trawl} * f$$

with

$$f = 1 + \frac{Area_{Bottom\,temperature > x}}{Area_{0-500\,m}}$$

where x is the bottom temperature at 50 % probability of presence for *M. paradoxus*.

Standardized CPUE indices for commercial trawler operating offshore at the South African west and south coast are routinely used in the stock assessments of hake. These indices are based on species-specific and coast-specific GLMs and comprise all months and depths (Glazer 2014). For the purpose of the present study, new indices were calculated for *M. paradoxus* at the west coast constraining the GLM to the season in which the scientific survey is usually carried out (January to March) and to two depth intervals (201 – 500 m and > 500 m) which are most relevant for the west coast.

Results

The spatial distribution of survey densities illustrates that *M. paradoxus* avoids the coastal waters with depths shallower than 100 m and that areas of high concentration can be found along a wide ranges of latitudes but with some differences between the years (Fig. 2). The highest proportion of biomass was usually recorded between 200 and 400 m depth but in some years, notably 2004 and 2008, *M. paradoxus* was most prominent in the 401 to 500 m depth stratum, and since the survey had been extended to depths below 500 m in 2011 a considerable amount of deep water hake was recorded there as well (Fig. 3).

Almost all tows were positive at bottom temperatures below 8 °C but at higher temperatures the CPUE declined and the number of stations at which no *M. paradoxus* was caught increased (Fig. 4). Bottom temperature had a highly significant effect on the presence of *M. paradoxus* (Tab. 2) and the level of temperature beyond which 50 % of the stations would yield zero-catches was estimated to be 9.46 °C with a standard error of 0.04 °C.

The bottom temperatures showed a strong spatial correlation for distances of 150 to 200 km and variograms could be fitted without major problems for almost all years but with varying values for a nugget and the sill and range for the spherical component (Fig. 5). Bottom temperatures where highest close to the coast with additional isolated areas with values above 9 °C further offshore in 2002, 2005, 2005, 2006 and 2011 (Fig. 6). And For those years, the extension of the area unsuitable for *M. paradoxus* was largest and hence the index correction factors were the highest in the time series (Tab. 3).

Survey biomass estimated for 0 to 1000 m showed in principal the same trend than the observed survey biomass for 0 to 500 m but with highest deviations in the warm years (Fig. 7). The estimated biomass corresponded very well with the observed value in 2014 but not for 2011 and 2012 where the trend was opposite (Tab. 4). The commercial CPUE series for 201 to 500 m and for > 500 m showed almost a similar tendency for the entire time series but both series exhibited contrasting signals to the survey biomass series for the years 2010 to 2012 and to the overall commercial CPUE series comprising both depth ranges and all months (Fig. 7).

The estimated survey biomass for 0 to 1000 m was positively correlated (Spearman Rank Correlation, $r_s = 0.594$, $p = 0.039$) with the biomass difference between 0 to 1000 m (estimated) and 0 to 500 m (observed) suggesting that in the warm years in which a relative high amount of *M. paradoxus* were found at the traditional offshore survey limit at 500 m also a considerable biomass in the deeper could have been expected. However, neither the the observed survey biomass for 0 to 500 m nor the difference between the estimated survey biomass for 0 to 1000 m and the observed survey biomass for 0 to 500 m were significantly correlated with the commercial CPUE for 201 to 500 m ($r_s = 0.350$, $p = 0.253$) or the commercial CPUE for > 500 m ($r_s = 0.100$, $p = 0.755$) in January to March. On the other hand, the estimated survey biomass for 0 to 1000 m was significantly correlated with the overall commercial CPUE comprising both depth ranges and all months (Pearson Product Moment Correlation, $r_P = 0.711$, $p = 0.014$) whereas the observed survey biomass for 0 to 500 m was not ($r_P = 0.568$, $P = 0.054$) (Fig. 8).

Discussion

Bottom trawl surveys conducted for resource monitoring typically maintain the same method and gear over time to ensure that catchability does not vary. Selection of fishing positions is usually random, so the survey abundance estimates should not be affected by changes in the distribution of the fish provided that the surveyed area covers the entire range of the target population, or at least a constant proportion of it. In the present case, however, the assumption that the distributional range of deep water hake was adequately surveyed in each year is questionable.

Knowledge of environmental effects on survey catchability of deep water hake in the southern Benguela region is quite sparse and generally limited to short term studies in a restricted area, or focused on diurnal variation in catch rates (Maree 1999, Huse et al. 1998, Gordoa and Macpherson 1991). However, associations between survey abundance and near bottom temperatures have been found for Atlantic cod on the Scotian shelf, and year effects disappeared when the inter-annual variability of the cod distribution in relation to the area affected by the cold intermediate layer were included in the calculation of the abundance indices (Smith and Page 1996).

Temperature off the South African west coast increases from the sea floor to the surface (Shannon 1985), and thus unfavourable conditions (i.e. warmer water) can only be avoided by horizontal migration, not by vertical migration. Hence, adverse temperatures should not cause a vertical movement of deep water hake above the headline height of the bottom trawl at a given location but would rather cause a bias in the overall survey abundance and biomass indices if the population moves beyond the limit of the survey domain.

In general, poor correlation between the survey biomass and the commercial trawler CPUE was found. However, the commercial CPUE might have been affected by other environmental and technical factors than the survey as described for hake fisheries in other regions (Mahévas et al 2011) and may thus not be adequate to prove the consistency of the survey time series.

The method suggested here to retrospectively adjust survey estimates needs revision e.g. by including other environmental variables such as bottom oxygen and its potential should be validated when more data encompassing the entire range of deep water hake distribution with depth have become available.

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Tab. 1: Number of valid trawl stations by depth stratum and number of CTD casts, South African west coast survey, 2002 -2014 (Gear type old: German 180 foot 2 panel bottom trawl with rope and chain footrope and 50 m sweeps, vertical opening appr. 2 m; new: German 180 foot 4 panel bottom trawl with modified rockhopper footrope and 9 m sweeps, vertical opening appr. 4 m; codend meshsize: 35 mm in both cases, *: no CTD used, **: CTD instrument package mounted on trawl headline, see Wieland et al. (2014) for specifications).

		Trawl stations by depth range							CTD casts		
Year	Gear type	< 100m	101-200m	201-300m	301-400m	401-500m	501-1000m	total	at trawl positions	on transects	total
2002	old	6	48	29	9	16	0	108	95	18	113
2003	old	7	42	29	13	10	0	101	90	13	103
2004	new	7	47	29	11	10	1	105	101	35	136
2005	new	7	46	34	11	14	1	113	96	33	129
2006	old	6	44	27	9	10	1	98	75	14	99
2007	new	8	45	27	10	10	1	101	97	16	113
2008	new	8	43	29	7	17	1	105	94	2	96
2009	new	7	46	29	12	14	0	108	96	14	110
2010	old	6	43	25	11	12	1	98	91	6	97
2011	new	8	38	26	14	12	23	121	112	14	126
2012	new	6	42	27	13	10	21	119	115	0	115
2013*	new	6	41	29	16	11	19	122	-	-	-
2014**	new	3	46	27	12	16	21	125	120	-	120

Tab. 2: Result of logistic regression (binomial GLM) of presence / absence of for deep water hake in relation to bottom temperature (Null deviance: 1284.27 on 1167 degrees of freedom, residual variance: 845.45 on 1166 degrees of freedom, bottom temperature (°C) at 50 % probability of presence: 9.46 with a standard error of 0.04).

Model term	Estimate	Standard error	P
Intercept	22.2371	1.5766	< 0.001
Bottom temperature	-2.3508	0.1711	< 0.001

Tab. 3: Area with bottom temperature above threshold of 50 % probability of presence in 0 to 500 m depth and corresponding index adjustment factors for deep water hake, 2002 – 2012 and 2014 (no temperature measurements available for 2013).

Year	Area (km²) with bottom temperature > 9.46 °C	Index adjustment factor
2002	21563	1.19
2003	5046	1.04
2004	12248	1.11
2005	20639	1.18
2006	17279	1.15
2007	15659	1.14
2008	15853	1.14
2009	21054	1.19
2010	16845	1.15
2011	41986	1.37
2012	1508	1.01
2013	-	-
2014	21969	1.20

Tab. 4: Observed, converted and estimated biomass indices for deep water hake (*M. paradoxus*), South African west coast survey, 2002 – 2014 (conversion factor old to new trawl: 0.883, Smith et al. 2013).

		Survey biomass ('000 t)			
		0 - 500 m depth		0 - 1000 m depth	
Year	Gear	observed	converted	observed	estimated
2002	old	267.487	236.191	-	281.556
2003	old	411.177	363.069	-	379.387
2004	new	259.527	-	-	287.840
2005	new	288.529	-	-	341.571
2006	old	315.310	278.419	-	321.270
2007	new	397.049	-	-	452.429
2008	new	246.542	-	-	281.356
2009	new	330.235	-	-	392.164
2010	old	589.533	520.557	-	598.661
2011	new	347.082	-	398.828	476.884
2012	new	377.515	-	490.043	382.587
2013	new	233.795	-	274.717	-
2014	new	261.209	-	307.102	312.324

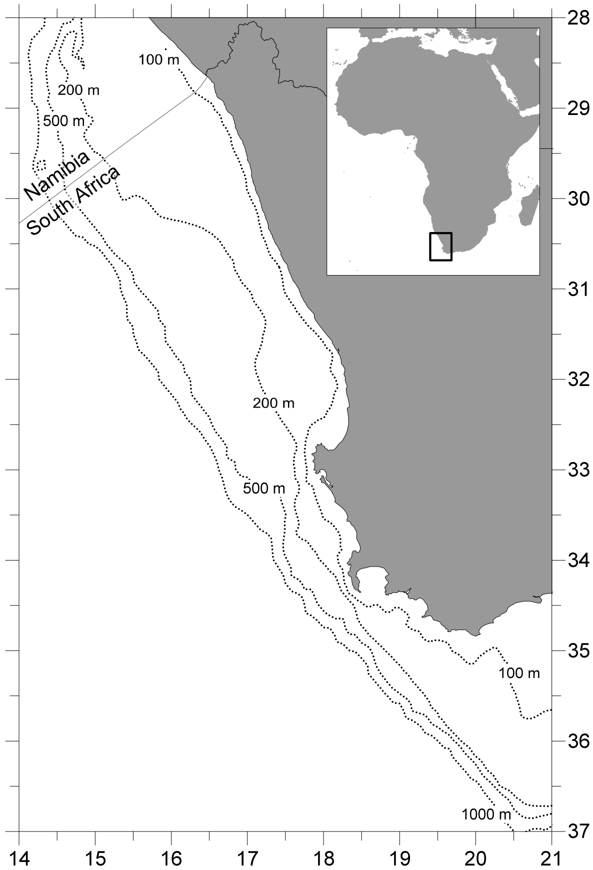

Fig. 1: Study area and depth contours (100, 200, 500 and 1000 m).

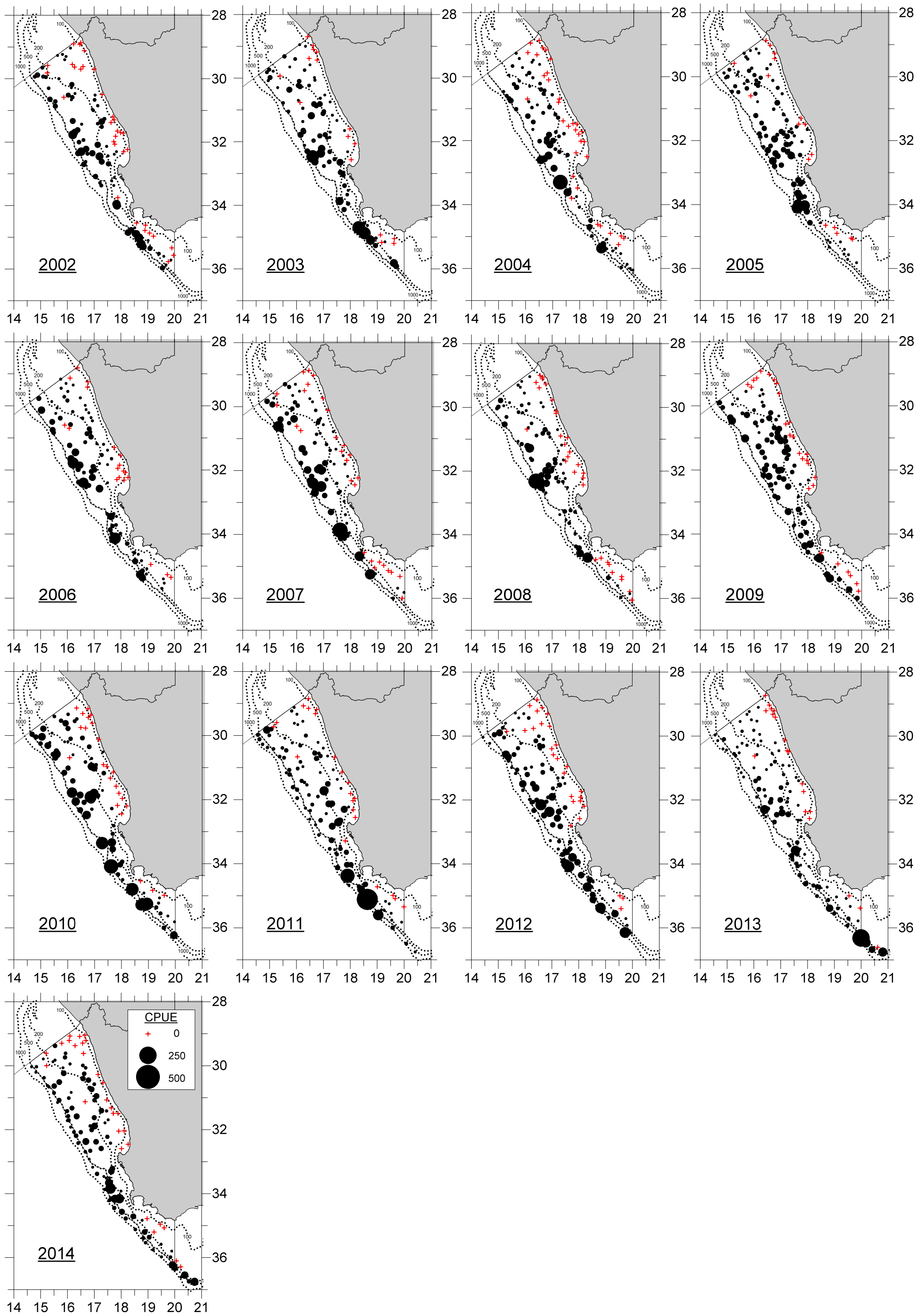

Fig. 2: Geographical distribution of survey CPUE (t/nmi²) of deep water hake 2002 – 2014.

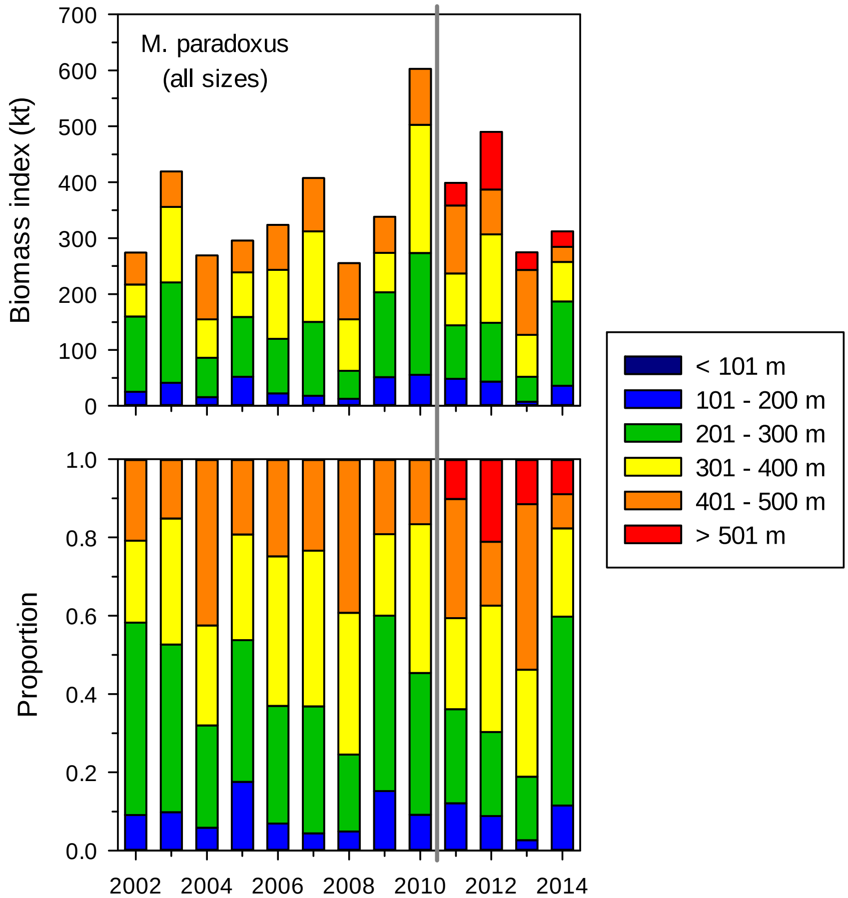

Fig. 3: Deep water hake survey biomass by depth stratum 2002 – 2014 (Depth range > 500 m covered systematically first since 2011).

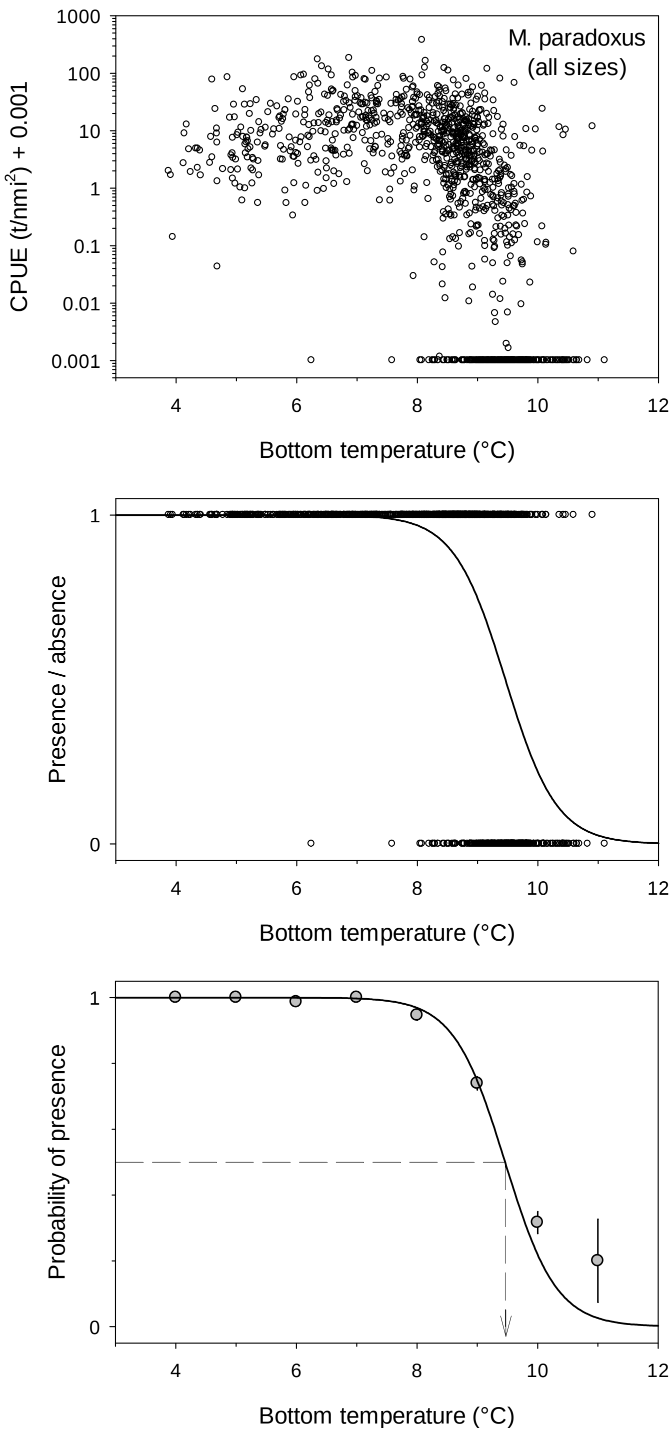

Fig. 4: Catch rate (in tons per square nautical mile), presence/absence and probability of presence (mean and standard error) of deep water hake in relation to temperature (°C) in the bottom water (10 m layer above bottom depth), 2002 – 2012 and 2014 (solid lines: two parameter logistic regression, dashed line: temperature at 50 % probability of presence).

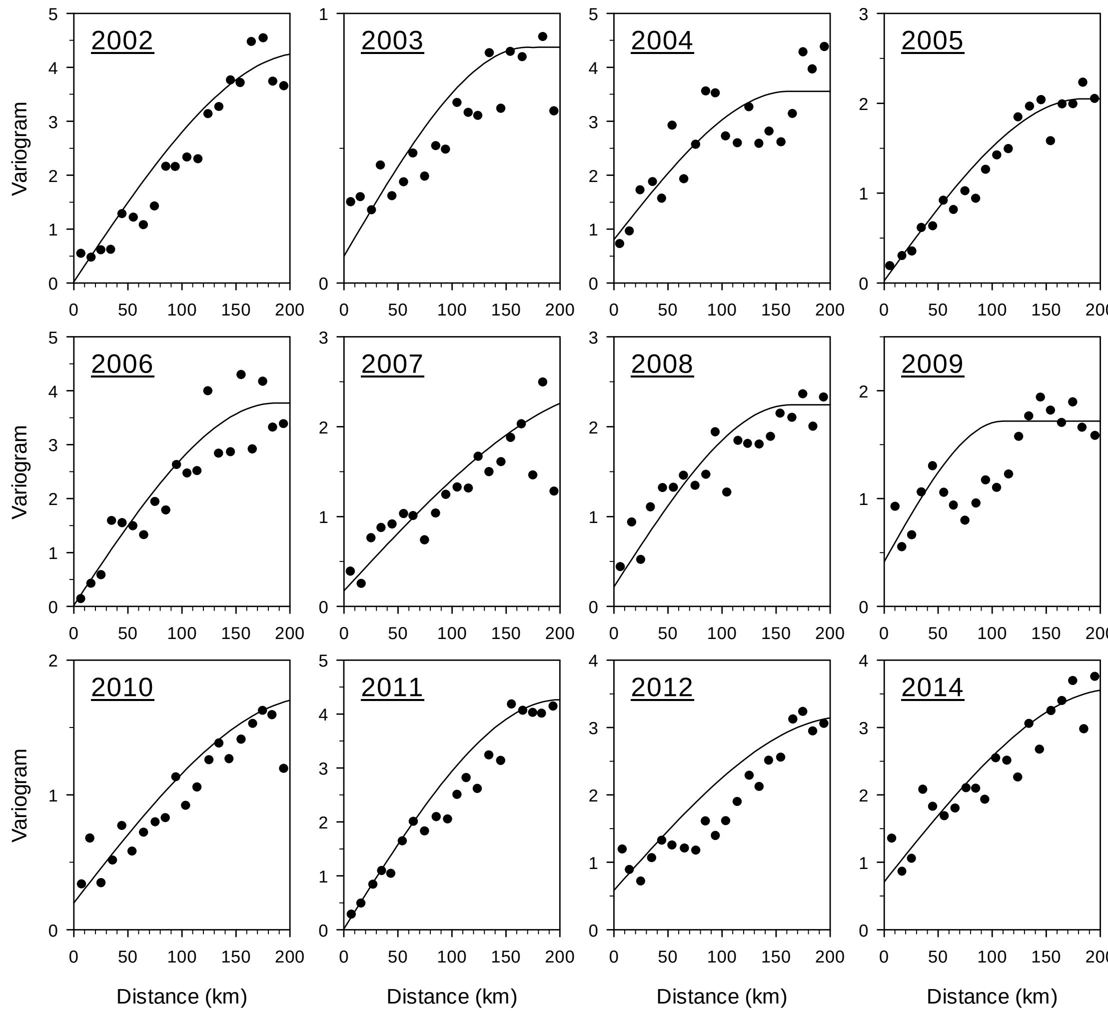

Fig. 5: Observed spatial structure of temperature (°C) in the bottom water (10 m layer above bottom depth) and fitted variogram models (nugget and spherical component, number of lags: 20, lag width: 10 km), 2002 – 2012 and 2014 (no data for 2013).

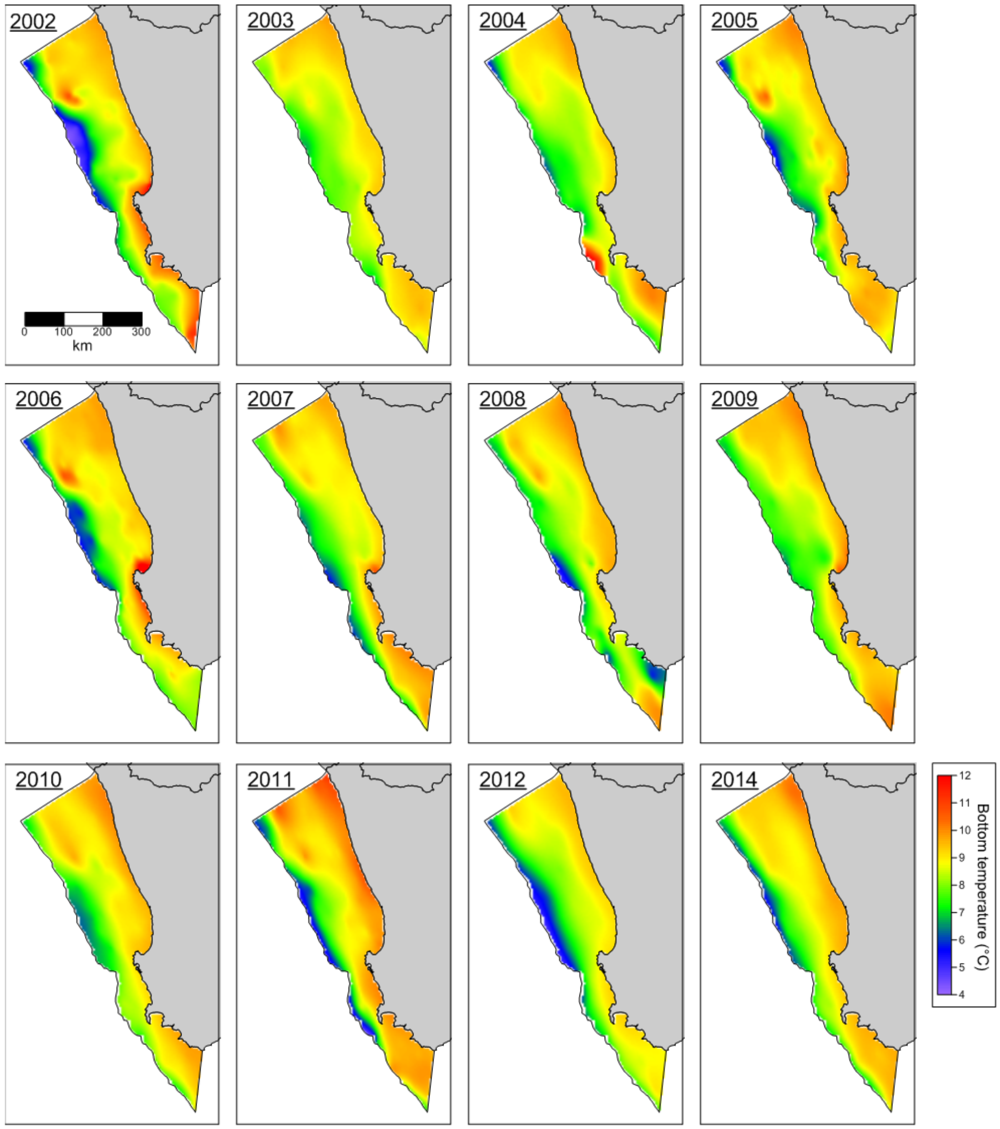

Fig. 6: Geographical distribution of temperature (°C) in the bottom water, 2002 – 2012 and 2014 (UTM projection, no data for 2013).

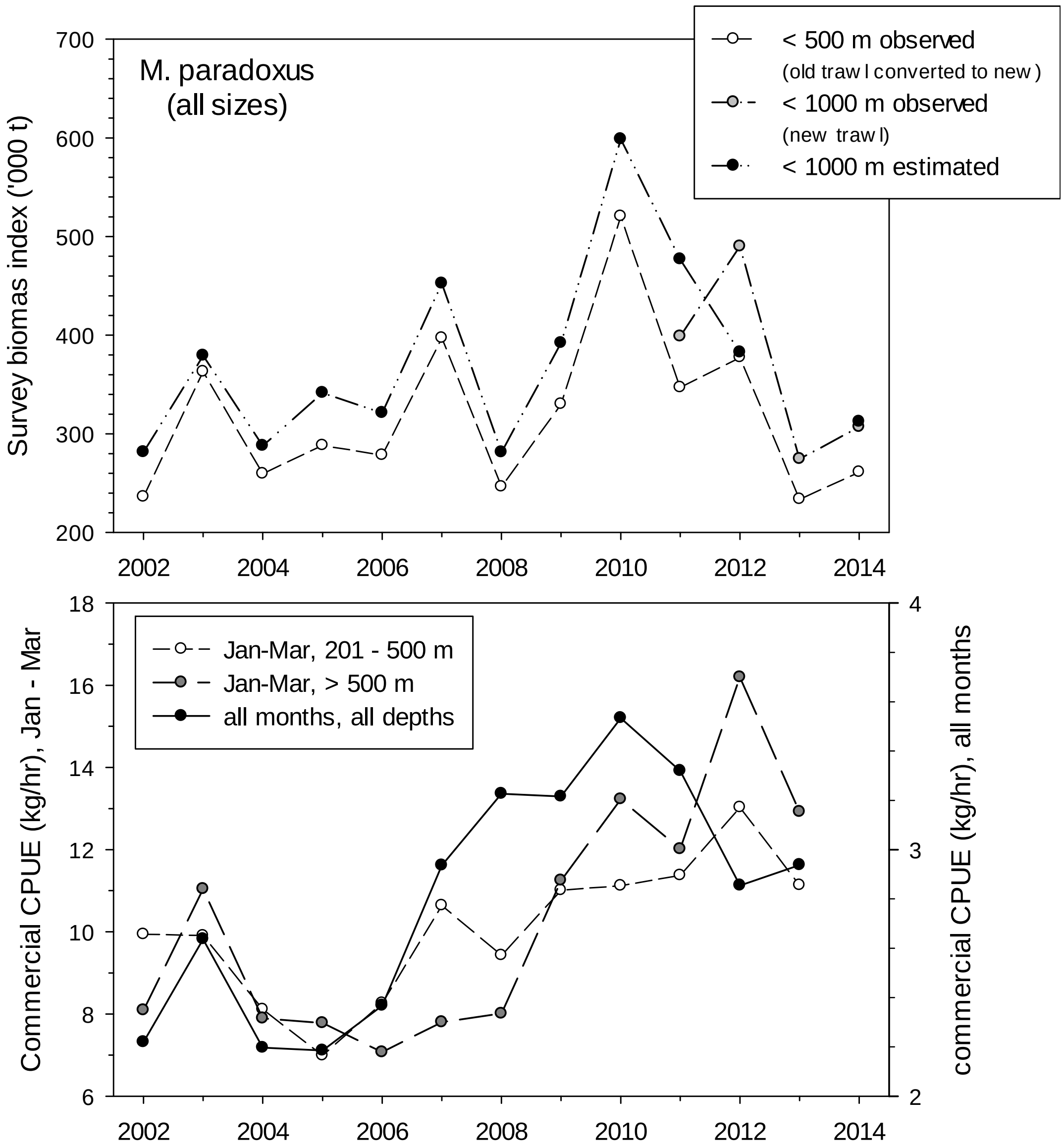

Fig. 7: Survey biomass indices and a commercial trawler CPUE series for deep water hake at the South African west coast 2002 – 2014 (survey < 1000 m estimated: not available for 2013 (see tab. 4), commercial CPUE: data for 2014 not yet available).

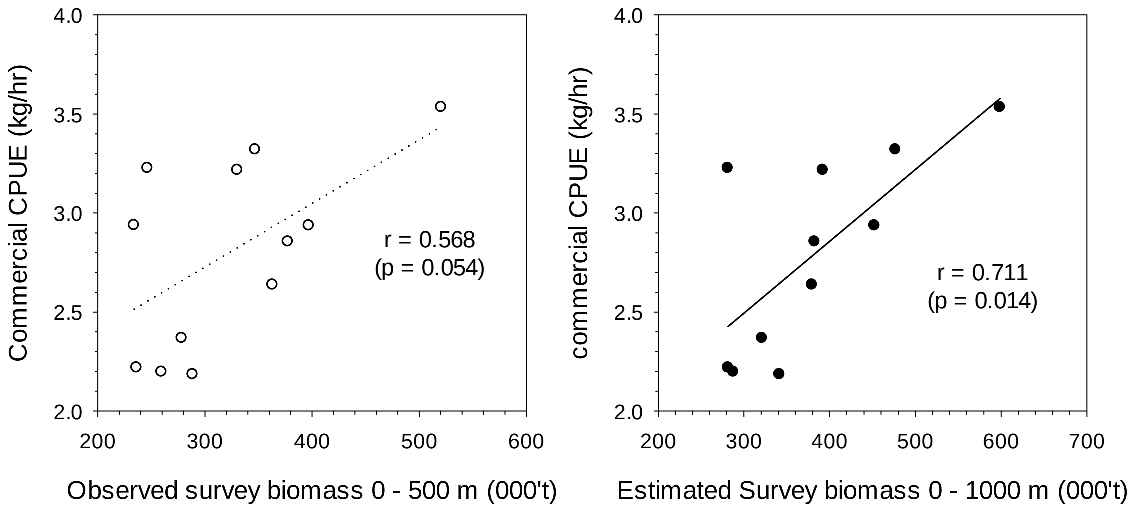

Fig. 8: Comparison of survey biomass indices and a commercial trawler CPUE series for deep water hake at the South African west coast 2002 – 2014 (survey < 1000 m estimated: not available for 2013 (see tab. 4), commercial CPUE: data for 2014 not yet available).