Environmental effects on hake catchability in the South African West Coast Survey

Kai Wieland [1], Deon Durholtz [2] and Tracey Fairweather [2]

[1]: Technical University of Denmark, National Institute of Aquatic Resources (DTU Aqua), Section for Monitoring and Data, Hirtshals
[2]: Department of Agriculture, Forestry and Fisheries (DAFF), Cape Town

Background

Variations in the environmental conditions may cause differences in the accuracy of a monitoring survey and changes in true abundance can be confounded with differences in the availability of the target species to the survey trawl. In this case, the use of uncorrected survey indices would introduce inconsistency in the time series of survey indices which may bias stock assessment.
Potential environmental variables affecting abundance estimates for shallow water hake (*Merluccius capensis*) and deep water hake (*Merluccius paradoxus*) in the demersal survey off the South African west coast include oxygen content and temperature of the bottom water as well as chlorophyll concentration in the surface layer and wind speed in addition to time of day.

Data inventory and exploratory analysis

The analysis for South African hake was based on catch rates by species and length group from the west coast summer survey (January/February) in the years 2002 to 2012 conducted with the research vessel FRS *Africana* and in 2013 with the commercial vessel FV *Andromeda*. The survey follows a stratified random design with a target of 100 stations per survey. Survey duration is about three to four weeks. A new trawl gear was introduced in 2004 but the old gear was still periodically used in subsequent years (Tab. 1). 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). Catch rates (CPUE) by length group were expressed in numbers (or weight) per swept area in square nautical miles (n/nmi^2 or kg/nmi^2). The swept area had been calculated from the distance trawled and the recorded or estimated wingspread at a given station.
For some purposes, the CPUE at single stations were divided by the survey mean for the respective year:

$$CPUE^*_{x,y} = CPUE_{x,y} / (\sum CPUE_{x,y} / n_y) \qquad \text{CPUE adjusted for survey mean}$$

where *x* and *y* denote station and year. The adjustment with the survey mean removes confounding effects of changes in true abundance or interannual differences in average catchability related to the two different survey trawls.
Length frequencies were summarized into length groups corresponding commercial sorting grades which were < 21 cm (juveniles, below commercial size), 21 – 42 cm (small), 43 – 57 cm (medium) and > 57 cm (large). Biomass for these length groups were calculated from the length frequencies raised to the stratum areas (Tab. 2) and annual length-weight relationships (Tab. 3).

Hydrographical measurements (temperature, salinity, oxygen and fluorescence) were conducted at most, but not all, of the trawl sites conducted during the surveys with FRS *Africana*. No CTD profiles were taken when a station was sufficiently close to one at which a CTD was already conducted or if time constraints required that the CTD be abandoned. Additional CTD stations conducted at monitoring lines were included in the analysis if they were taken during the same survey (Tab. 1). The information from the CTD stations includes measurements of oxygen content and fluorescence as an index of chlorophyll concentration. Average wind speed and direction during trawl stations has been available for the years 2010 to 2012. Geostatististical analysis of the spatial structure of the environmental variables and subsequent mapping were done with Surfer Version 11.

Distribution of shallow and deep water hake in respect to survey coverage

Highest biomass densities of *M. capensis* were usually recorded in coastal waters north from 32°S (Fig. 1a) whereas the *M. paradoxus* was predominantly found further offshore and widely distributed between 30 and 36°S with some single high catch rates at the outermost limit of the survey area in several years (Fig. 1b). Both hake species showed a pronounce transition to larger depth with increasing size, and medium size (43 – 57 cm) and large (> 57 cm) *M. capensis* overlapped widely with *M. paradoxus* smaller than 21 cm and from 21 to 42 cm (Fig. 2a,b). *M. capensis* smaller than 21 cm and from 21 to 42 cm occurred almost exclusively at depths shallower than 200 m and the medium and larger individuals of this species were predominantly found between 200 and 300 m but almost not deeper than 400 m (Fig. 3a). The biomass distribution of *M. paradoxus* smaller than 21 cm and from 21 to 42 cm with highest proportions in the intermediated strata (Fig. 3b) has always been well within the depth range covered by the survey. In contrast, medium size and large *M. paradoxus* were found in high proportions between 400 and 500 m depth in several years, notably in 2004 (43 – 57 cm) and 2008 (> 57 cm), and the results for 2011 to 2013 with about 25 – 40 % and 20 – 70 % of these two length groups found in waters deeper than 500 m (Fig. 3b) suggest that a substantial part of the population has not been covered in the preceded years in which the survey did not cover this depth range.

Time of day

The survey sampled the different depth strata independent of time of day (Fig. 4). The frequency of stations in relation to 4 hour time of day bins indicates that the proportion of stations conducted in the early morning when not all hake might have returned to the bottom from diurnal feeding migration is similar across the depth strata. Furthermore, no inter-annual difference in the allocation of stations in respect of time of day is obvious with the exception for the shallower strata (< 301 m) in 2012 in which a slightly higher proportion of tows were made in the early morning than in the other years (Fig. 4). Zero catches were found at all times of day for the four length groups of both hake species and the positive catches showed no pattern as well (Fig. 5). There is no indication of a systematic bias of the catch rates in relation to time of day and hence a correction of the survey indices in this respect appears to be unnecessary.

Effect of environmental conditions on the observed survey CPUE of the two hake species

Wind speed

Five locations in small region of the southern survey area (34°30’ – 34°55’ S, 18°15’ – 18°40’ E) were sampled twice during the survey in 2003. The time interval between the repeated sampling was 20 days and the wind was strong during first sampling and moderate during the second one, and, on average, CPUE of both hake species was considerably higher at moderate than during strong wind in all cases in which the station depth corresponded to the preferred range of each species (Fig. 6).

South-easterly winds were considerably stronger in 2011 than in 2010 and 2012 with wind speeds exceeding 25 knots at various stations south of 33 °S (Fig. 7). Catch rates of both hake species were generally low when wind speed exceeded 25 knots (Fig. 8). Absolute upper threshold limits for wind speed at which the catch rates of hake becomes negatively biased are difficult to define because the effect of wind stress on catch rates depends on water depth and geographical position. However, it appears advisable to limit trawling in future surveys to wind speeds below 25 knots (≈ 13 m/s) at least in the southern part of the survey area in which a jet stream on the shelf edge (Bang & Andrews 1974) is established within 8 hours after the onset of strong south-easterly winds (Maree 1999). Consequently, catch data from previous surveys collected at these conditions should be discarded from the calculation of the survey indices (Tab. 4). Further work on this topic is needed when the wind data from more years have been compiled, however it will not be possible to separate between the effect of wind speed on trawl performance and the effect of the jet stream on the vertical distribution of hake based on the routinely collected information from the monitoring surveys alone.

Green water

High chlorophyll concentrations in the surface layer (‘green water’) reduce the light level in the bottom water. This may cause hake to leave the bottom, which would decrease the availability of hake to the survey gear. However, neither light measurements nor echograms at contrasting chlorophyll conditions are available and hence documentation for the existence of such a process is missing.
High surface layer chlorophyll concentrations were observed in the area between 33 and 34 °S in 2010 and 2011 and to some lesser extent in 2008 (Fig. 9). High catch rates of shallow and deep water hake were recorded to an upper limit of surface layer chlorophyll concentrations of about 300 and 200 mg/m^3, respectively (Fig. 10). However, low catch rates or zero catches were observed at all levels of surface layer chlorophyll indicating little evidence that the catches had been affected by the presence of ‘green water’.
Hake may easily avoid local high chlorophyll concentrations by horizontal migration and it seems unlikely that the presence of ‘green’ water during a quite limited part of the survey have seriously affected the annual mean catch rates of any of the length groups of the two hake species.

Oxygen content of the bottom layer and bottom temperature

Oxygen levels of the bottom layer (defined as 10 m off the ocean floor) were lowest (3 ml/l) in water shallower than 250 m whereas bottom temperature decreased almost continuously with depth over the entire range (Fig. 11).

Relative high catch rates of juvenile and small *M. capensis* were found at bottom oxygen levels as low as 1 ml/l while medium and large individuals were caught predominantly at oxygen levels above 2 ml/l (Fig. 12). In contrast, *M. paradoxus* was infrequently caught (relative to *M. capensis*) at oxygen levels below 2 ml/l and in particular medium and large individuals of deep water hake were only found at oxygen levels above 2.5 ml/l (Fig. 12). The proportion of tows per size category with zero catches indicates a pronounced progression from low to higher oxygen levels with increasing size for both hake species (Fig. 13). The minimum proportion of tows with zero catches increased from low (< 2 ml/l) to intermediate (3 – 4 ml/l) levels of bottom oxygen content for *M. capensis* whereas the lowest proportion of zero catches progressed from intermediate (3 – 4 ml/l) to high (4 –5 ml/l) levels of bottom oxygen for deep water hake. Significant differences (paired t-tests with $P < 0.05$) in the proportion of zero tows in relation to bottom oxygen content between the old and the old survey gear were found for large (> 57 cm) *M. capensis* as well as for small (21 -42 cm), medium (43 – 57 cm) and large (> 57 cm) *M. paradoxus*. For these length groups, a higher portion of zero tows were recorded which may indicate the effect of a reduced herding of the new survey trawl in relation to oxygen content of the bottom water.

Juvenile (<21 cm) *M. capensis* were found in a relatively narrow bottom temperature range of 7.5 to 10.5 °C while larger individuals were caught across a wider temperature range (Fig. 14). All length groups of *M. paradoxus* showed a highly variable distribution of catch rates in relation to bottom temperature, but they were usually absent at values above 10 °C (Fig. 14), and the proportion of tows with zero catches indicates a pronounced progression towards lower temperature levels with increasing size (Fig. 15).

Oxygen depletion is usually restricted to the coastal areas (Jarre et al. in press) and can be avoided by hake by vertical or horizontal migration. In contrast, warm temperatures may extend to the offshore shelf break and temperature usually increases from the sea floor to the surface (Shannon 1985), and thus temperatures above the preferred range can only be avoided by horizontal migration towards deeper water. This suggests that medium and large *M. paradoxus* might have migrated to water beyond the offshore limit of the survey at 500 m (until 2011) in warmer years (Leslie & Lamont 2009).

Correction of survey indices for deep water hake

To account for the proportion of the population of *M.* paradoxus which might have been missed in the surveys shallower than 500 m depth, annual adjustment factors for the survey indices were calculated from the length group-specific presence-absence relationships in relation to bottom temperature (*BT*) and the fraction of the survey area covered by bottom temperatures above this threshold:

$$f_{LG,y} = 1 + Area_{BT > b_{LG},y} / Area_{total < 500m}$$

where *y* denotes year and b is the bottom temperature at which 50 % of the catches were zero for a given length group (*LG*) determined by logistic regressions on the data pooled for all years (2002 to 2012, Fig. 15):

$$P = 1 / (1 + \exp(-(BT - x) / a))$$

where *P* is the proportion of zero-catches of a given size category in 1 °C bins of bottom temperature (*BT*), and *a* and *b* are the regression coefficients with *b* denoting the level of bottom temperature at which 50 % of the stations yielded a zero catch of the size category in question.

As expected from the decrease of the threshold values for the critical bottom temperature from 9.6°C for small *M. paradoxus* to 8.3°C for medium and 7.8 °C for large individuals and the prevailing conditions on the shelf (Fig. 16), the resulting correction factors (Tab. 5) were highest for the large *M. paradoxus* in years in which cold water (< 6 °C) was absent, i.e. 2003 and 2009, or warm water (> 8°C) covered most of the survey area, i.e. 2006, 2010 and 2011.

Comparison of survey indices with commercial CPUE

To ensure that the data were comparable over surveys conducted with the two different gear conformations, length frequencies (raised to the level of the depth strata) from the surveys conducted with the "old" gear were converted to the "new" gear standard using length-specific catchability ratios (Cotter 2012):

$R_l = \exp(0.30 - 8.09/l)$ for *M. capensis*, and

$R_l = \exp(-2.77/l)$ for *M. paradoxus*

where *R* is the catchability ratio "old"/"new" and *l* is the total length (cm).

Standardized CPUE indices for offshore trawlers on the South African west coast (Glazer 2013) were compared with the annual survey biomass indices computed as:

$$B_{Survey} = \sum_{Stratum} (N'_l * W_l)$$

where *N'* is the numbers at length raised to the stratum areas and converted to the new gear standard, and *W* is the individual weight-at-length from the length-weight relationship in a given year. The offshore west coast trawl fleet operates mainly at depths greater than 200 m and do not take juvenile (<21 cm) hake (Glazer 2013). Hence, survey indices which exclude this depth range and size group of hake were calculated as well, and in the case of *M. paradoxus* the adjustment factors accounting for the assumed proportion of the population outside the survey domain (> 500 m) were additionally applied.

For *M. capensis*, survey biomass for 0 – 500 m and standardized offshore CPUE showed some similarity regarding the major trends (Fig. 18). However, overall correlation is poor and does not improve when juveniles (< 21 cm) and depth strata shallower than 200 m are removed from the survey index (Fig. 18). The reason for the latter is not quite clear but as a large proportion of the west coast *M. capensis* population is found in waters shallower than those fished by the offshore fleet it may be concluded that the survey provides more representative estimates of *M. capensis* stock status than the commercial CPUE series.

Survey biomass and commercial CPUE for *M. paradoxus* corresponded closely but with some discrepancies in a few years (Fig. 19 upper panel). Three years, i.e. 2008, 2009 and 2011, did deviate from the other years even when juveniles (< 21 cm) and depth strata shallower than 200 m were excluded from the survey index (Fig. 19 lower left panel). The correlation between the survey and the commercial CPUE series improved when the survey estimates for the depth range > 201 m also took the effect of bottom temperature into account, except for two years (2008 and 2009; Fig. 19 lower right panel). This may indicate that the commercial CPUE series is a better indicator for *M.paradxous* stock size than the survey index, at least until the problem of missing information for the depths greater than 500 m from the survey is solved.

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Tab. 1: Number of valid trawl and CTD stations from the SA west coast summer survey, 2002-2013 (Gear type old: German 180 foot 2 panel bottom trawl with rope and chain footrope and 50 or 100 m sweeps, vertical opening appr. 2 m; new: German 180 foot 4 panel bottom trawl with modified rockhopper footrope and 8 m sweeps, vertical opening appr. 4 m (Leslie 2013); *: FV *Andromeda*, all other years: FRS *Africana*).

		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
2002	old	6	48	29	9	16	0	108	95	18
2003	old	7	42	29	13	10	0	101	90	13
2004	new	7	47	29	11	10	1	105	101	35
2005	new	7	46	34	11	14	1	113	96	33
2006	old	6	44	27	9	10	1	98	75	14
2007	new	8	45	27	10	10	1	101	97	16
2008	new	8	43	29	7	17	1	105	94	2
2009	new	7	46	29	12	14	0	108	96	14
2010	old	6	43	25	11	12	1	98	91	6
2011	new	8	38	26	14	12	23	121	103	24
2012	new	6	42	27	13	10	21	119	115	0
2013*	new	6	41	29	16	11	19	122	-	-

Tab. 2: Stratum areas (in square nautical miles) in the SA west coast survey.

Depth	Area (nmi^2)
000-100 m	2 227.73
101-200 m	14 347.65
201-300 m	8 657.64
301-400 m	4 265.70
401-500 m	3 233.38
501-1000 m	8 552.54
Total:	32 732.10

Tab. 3: Coefficients of length-weight relationships ($W = a * L^b$) for deep water hake (*M. paradoxus*) from the South African west coast survey, 2002 – 2013 (W: weight in g, L: length in cm).

	M.capensis		*M. paradoxus*	
Year	a	b	a	b
2002	0.0049	3.1350	0.0044	3.1401
2003	0.0048	3.1319	0.0065	3.0349
2004	0.0059	3.0751	0.0065	3.0287
2005	0.0053	3.1028	0.0063	3.0331
2006	0.0048	3.1243	0.0060	3.0468
2007	0.0048	3.1243	0.0073	3.0054
2008	0.0057	3.0799	0.0069	3.0165
2009	0.0055	3.0913	0.0069	3.0165
2010	0.0054	3.1014	0.0066	3.0265
2011	0.0056	3.0768	0.0061	3.0343
2012	0.0060	3.0663	0.0066	3.0195
2013	0.0075	3.0086	0.0069	3.0103

Tab. 4: Stations which should be excluded from index calculation (in brackets: depth).

	Wind effect					
Year	M. capensis			M. paradoxus		
2002	A21287 (240 m)	A21288 (164 m)	A21289 (173 m)	A21285 (486 m)	A21286 (364 m)	A21287 (240 m)
2003						
2004						
2005						
2006						
2007						
2008						
2009						
2010	keep all			keep all		
2011	A31385 (144 m)	A31387 (172 m)	A31393 (223 m)	A31383(560 m)	A31387 (172 m)	A31393 (223 m)
2012	keep all			keep all		
2013						

Tab. 5: Area with bottom temperature above specific thresholds in 0 to 500 m depth and corresponding index correct factors for small (21 – 42 cm), medium (43 – 57 cm) and large (> 57 cm) deep water hake, 2002 – 2012 (M.p.: *Merluccius paradoxus*).

Year	Area (km²) with > 9.59 °C	Index correction factor for M.p. 21 - 42 cm	Area (km²) with > 8.28 °C	Index correction factor for M.p. 43 -57 cm	Area (km²) with > 7.80 °C	Index correction factor for M.p. > 57 cm
2002	15577	1.14	75642	1.69	87798	1.80
2003	1511	1.01	81983	1.74	100995	1.92
2004	9568	1.09	73522	1.67	90928	1.83
2005	12709	1.12	80785	1.73	90292	1.82
2006	12891	1.12	81860	1.74	92523	1.84
2007	10290	1.09	79802	1.72	89128	1.81
2008	8846	1.08	74268	1.67	85533	1.78
2009	16037	1.15	75333	1.68	91814	1.83
2010	11179	1.10	84281	1.77	95061	1.86
2011	35527	1.32	85788	1.78	92543	1.84
2012	0	1.00	40538	1.37	83484	1.76

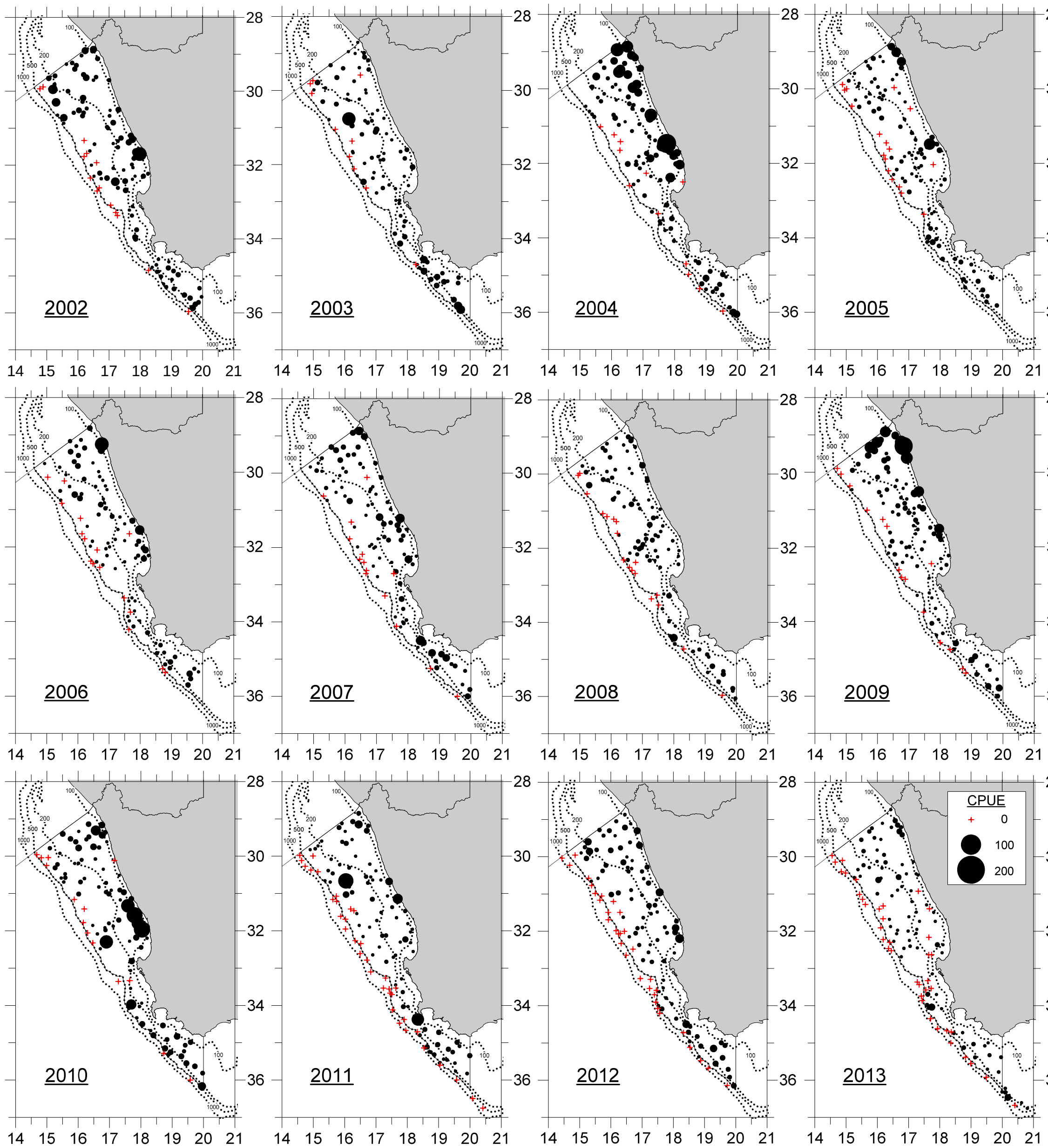

Fig. 1a: Geographical distribution of survey CPUE (t/nmi²) of shallow water hake 2002 – 2013.

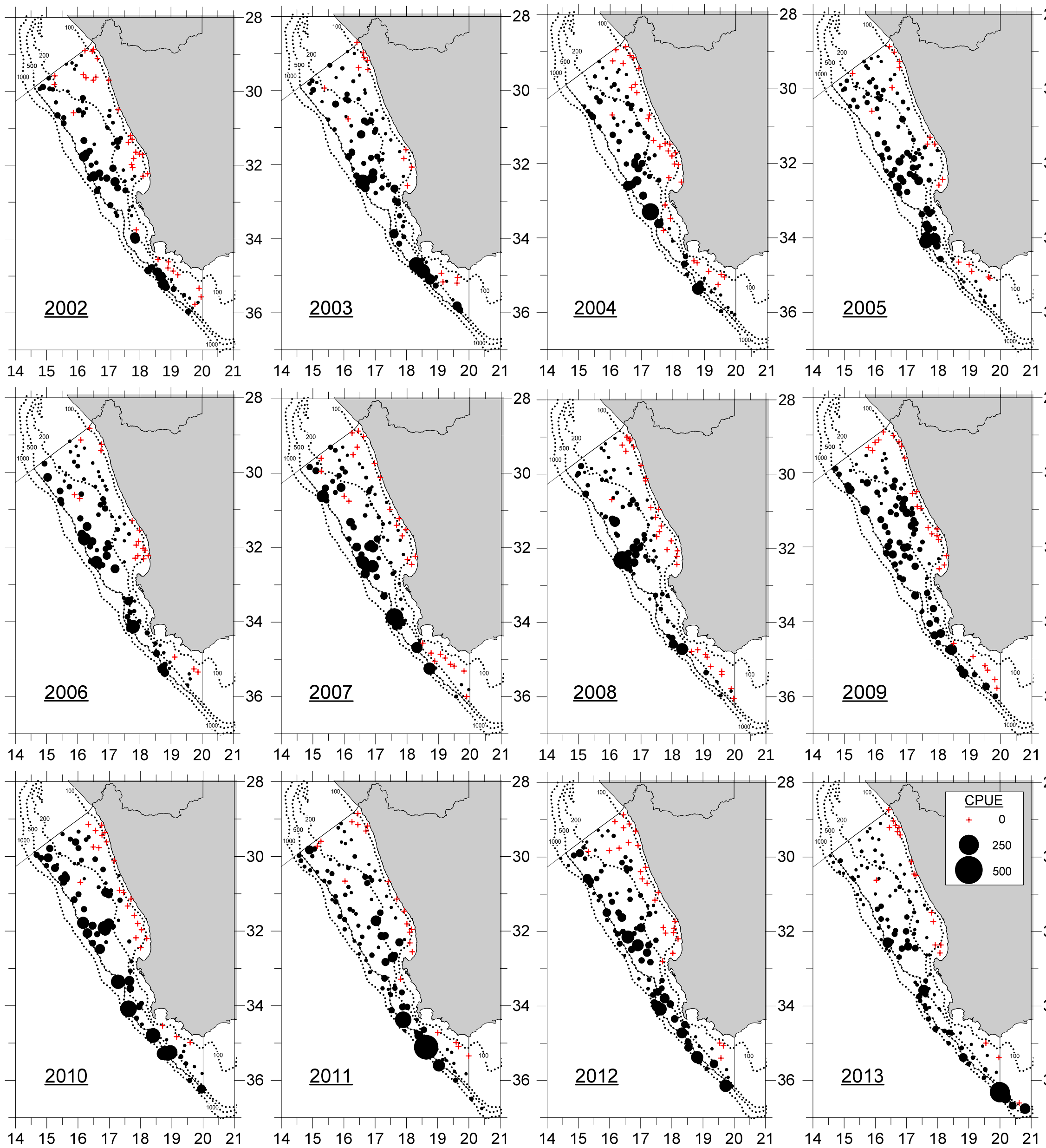

Fig. 1b: Geographical distribution of survey CPUE (t/nmi²) of deep water hake 2002 – 2013.

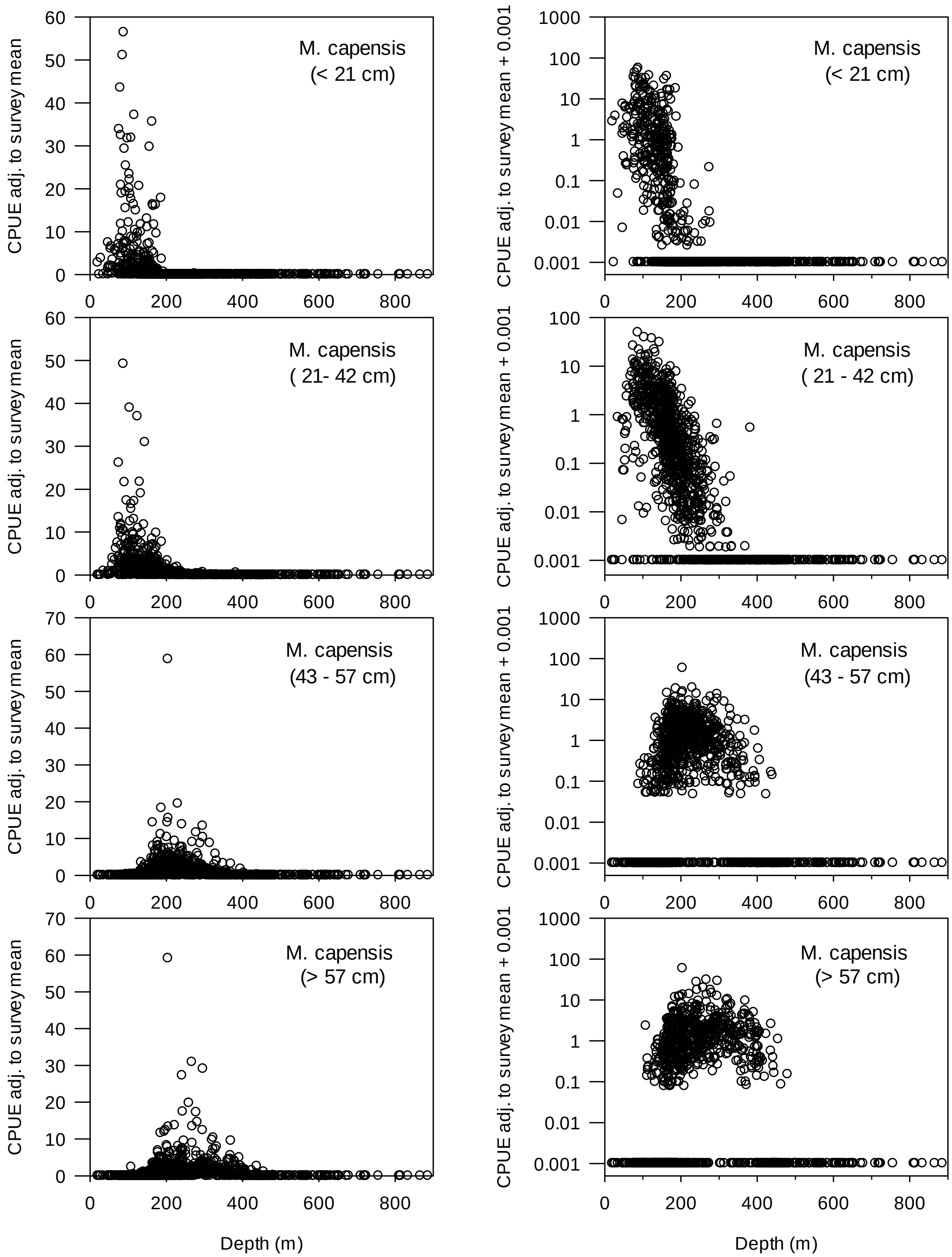

Fig. 2a: Observed survey CPUE of shallow water hake by length group in relation to depth, 2002 to 2013.

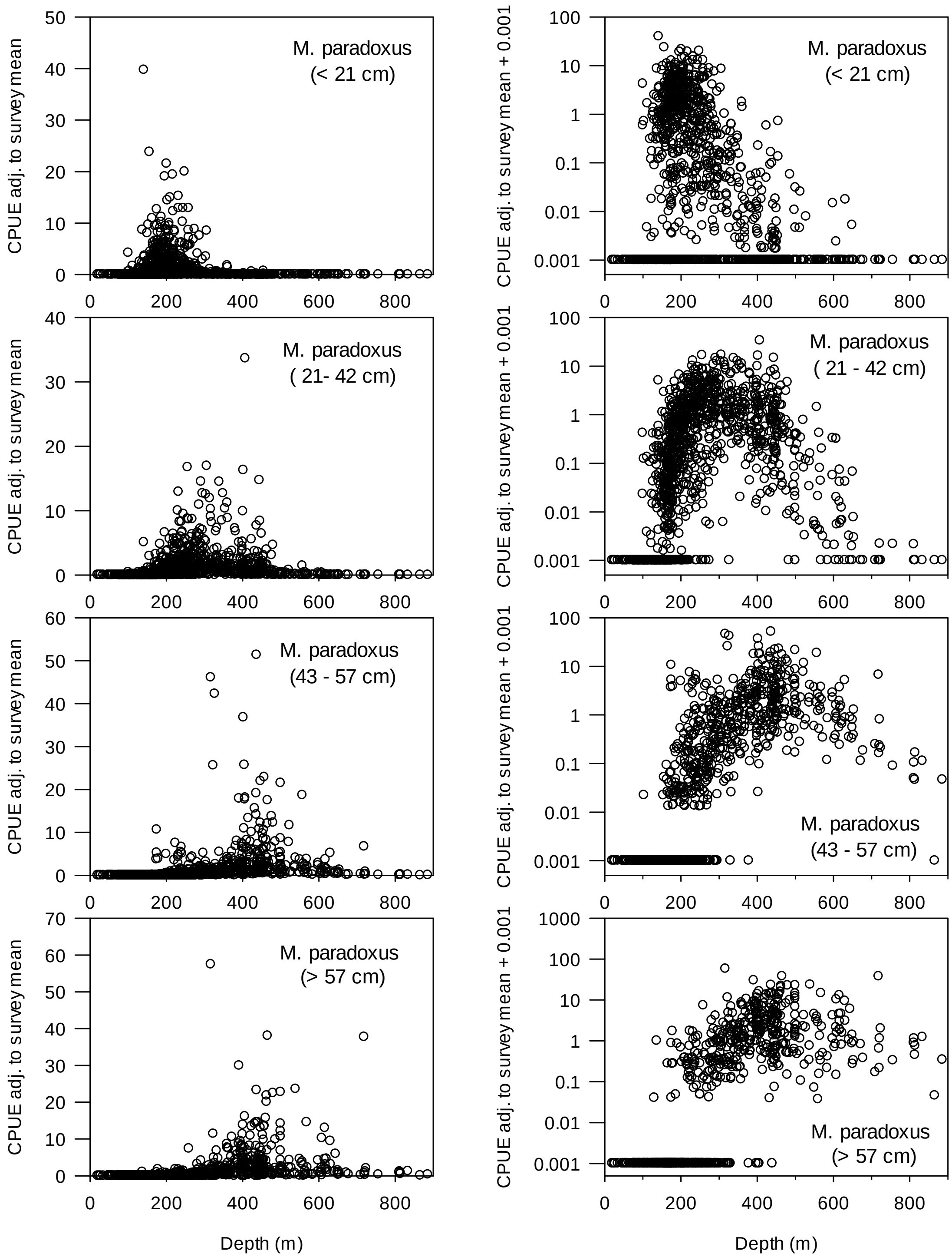

Fig. 2b: Observed survey CPUE of deep water hake by length group in relation to depth, 2002 to 2013.

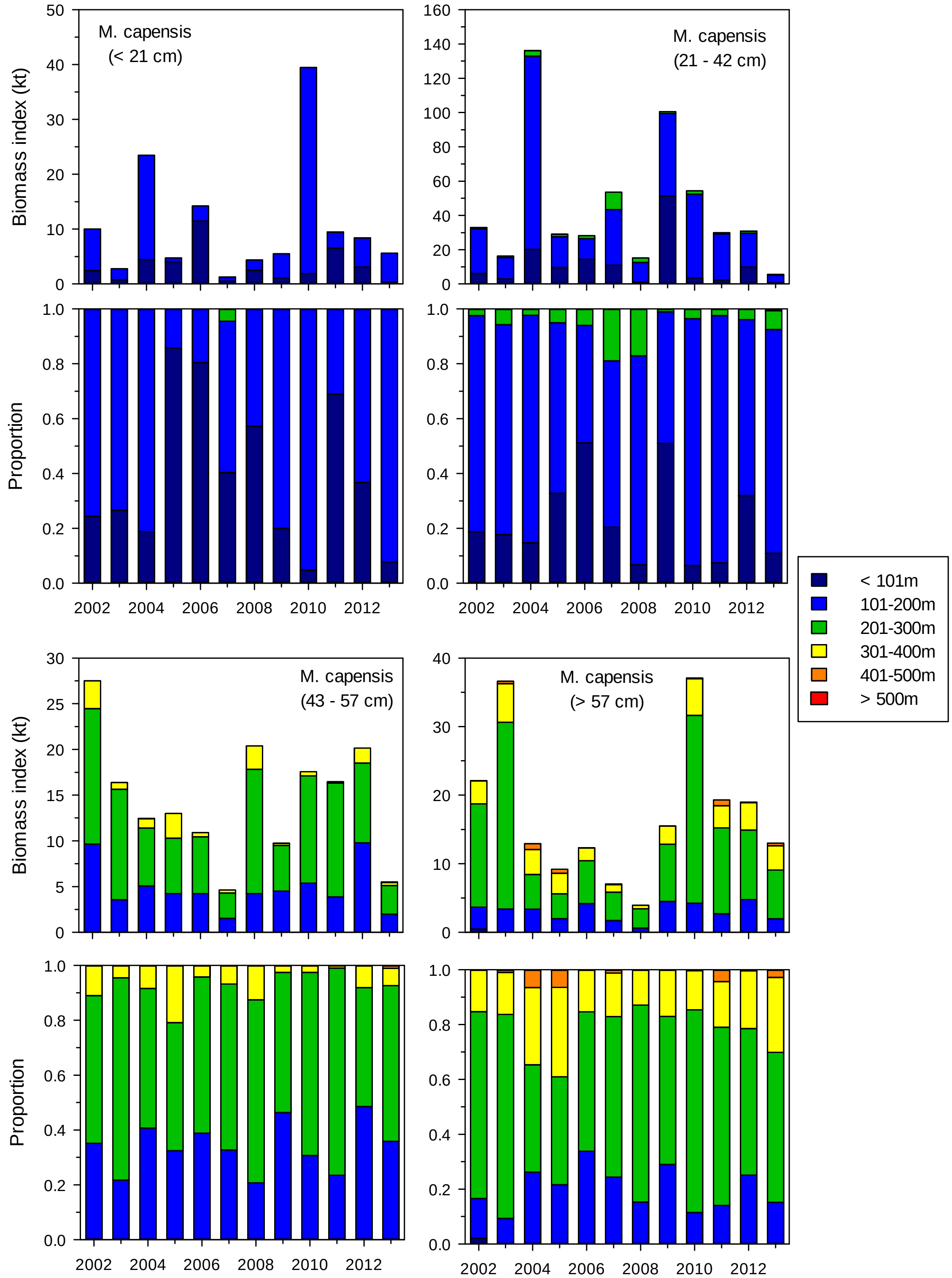

Fig. 3a: Survey biomass of shallow water hake by length group and depth stratum (Depth range > 500 m first covered since 2011).

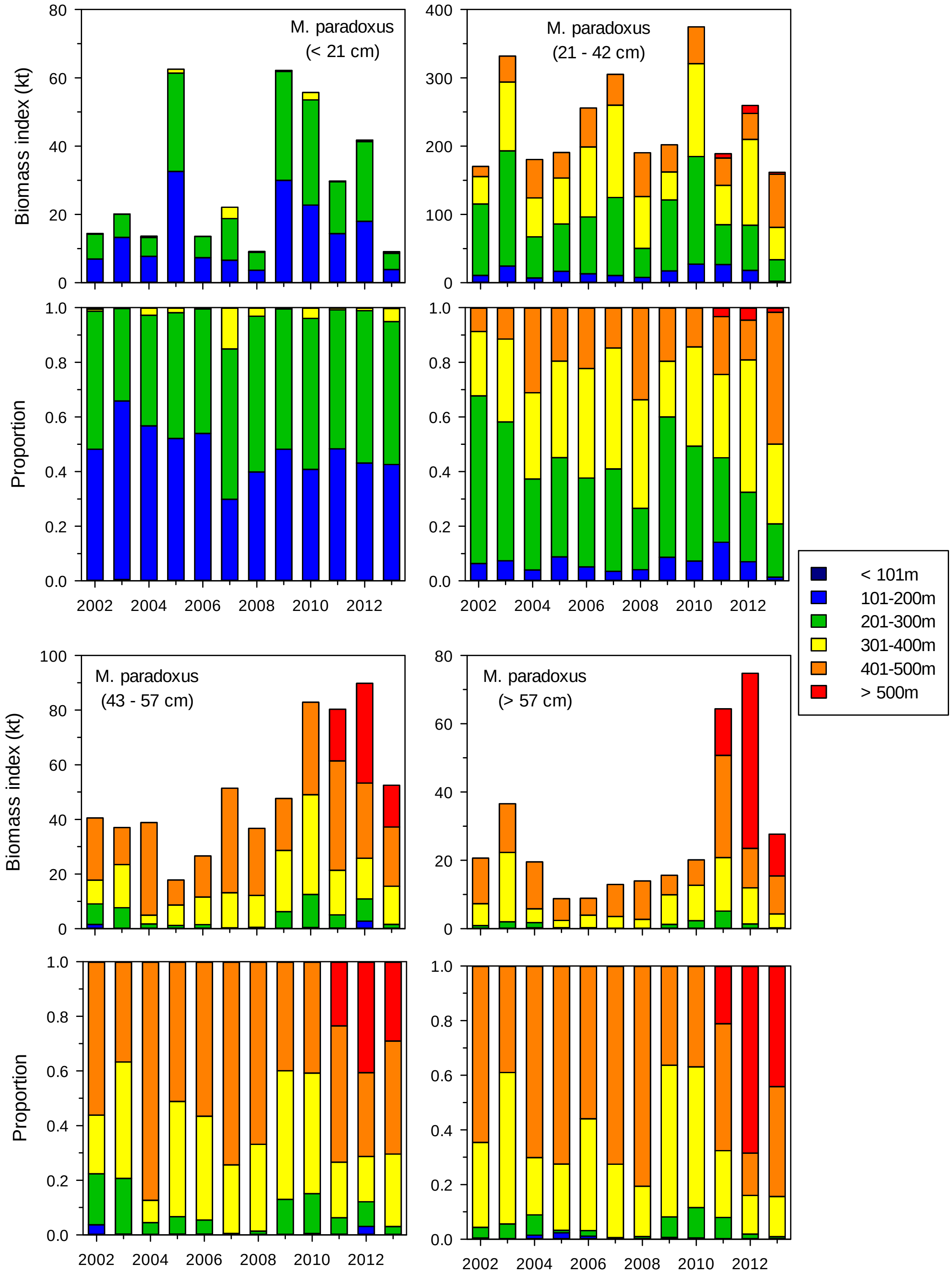

Fig. 3b: Survey biomass of deep water hake by length group and depth stratum (Depth range > 500 m first covered since 2011).

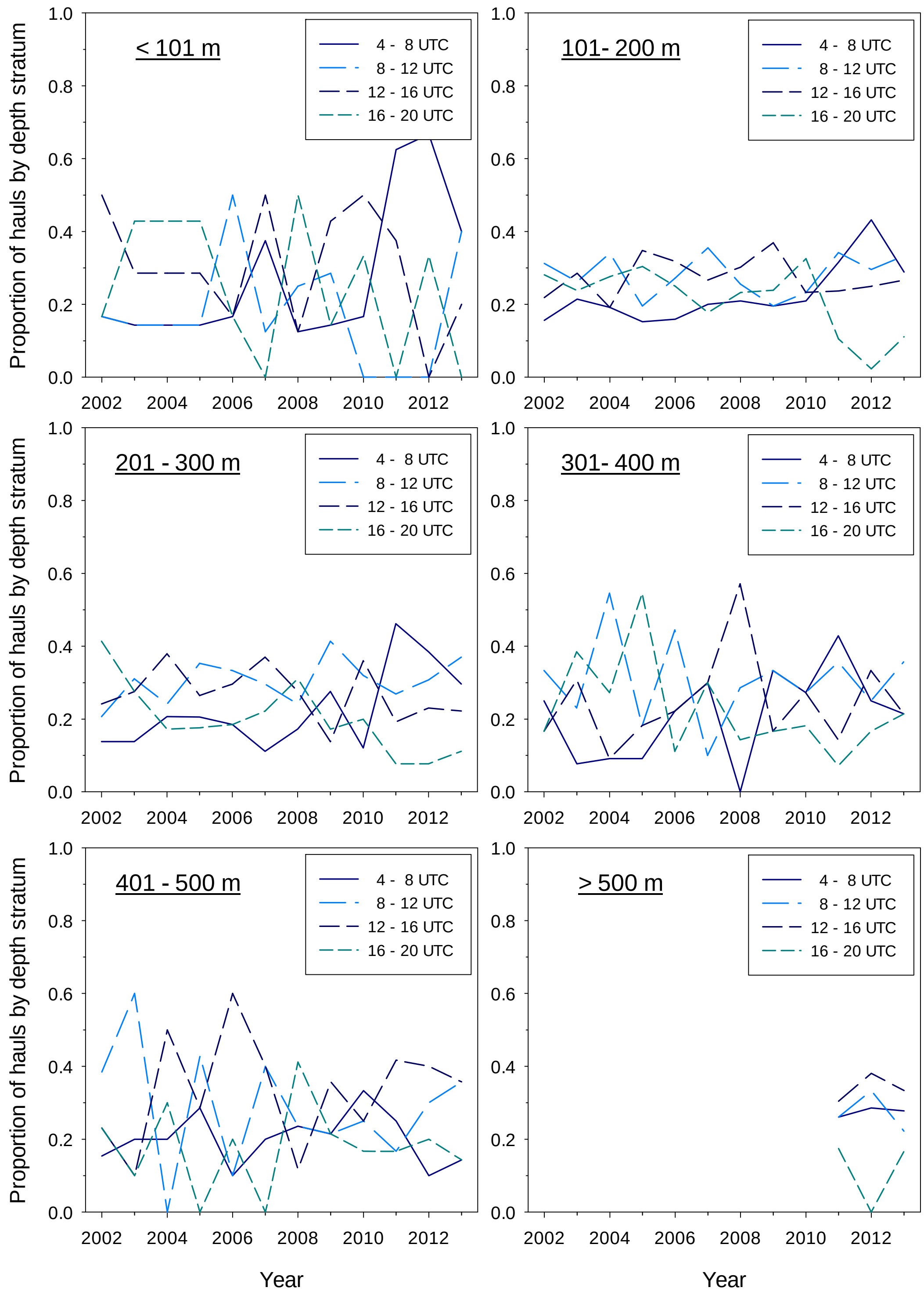

Fig. 4: Proportion of trawl stations in relation to time of day in different depth zones, 2002 to 2013.

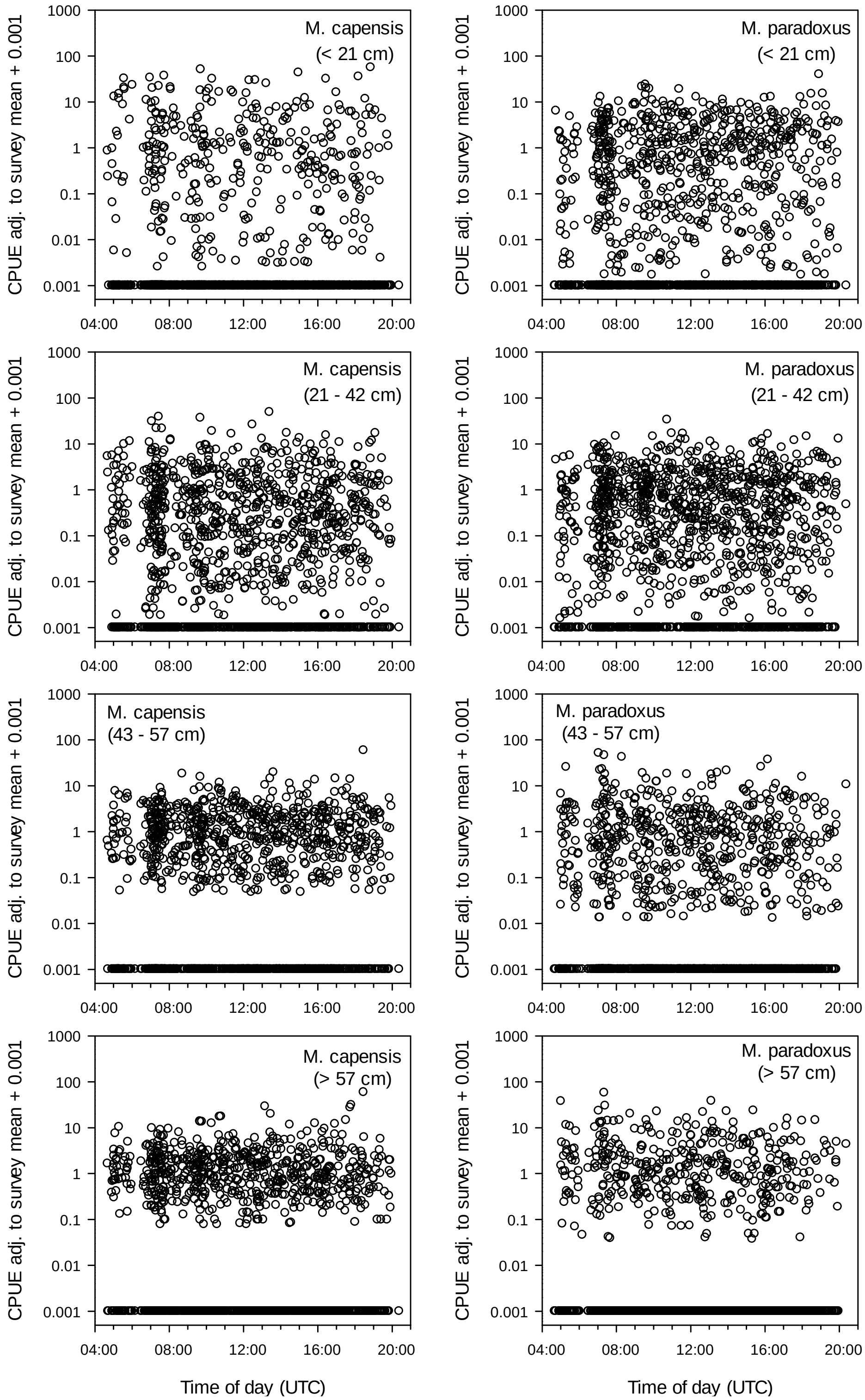

Fig. 5: Survey CPUE of shallow and deep water hake by length group adjusted to survey mean in relation to time of day, 2002 to 2013.

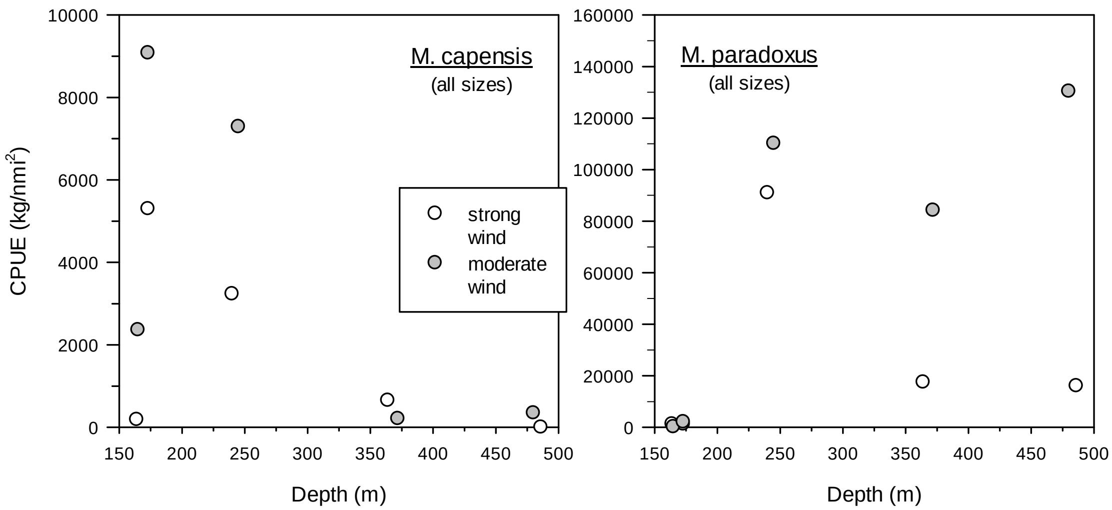

Fig. 6: Comparison of survey CPUE of shallow and deep water hake at five locations in the southern survey area sampled twice during contrasting wind conditions in 2003.

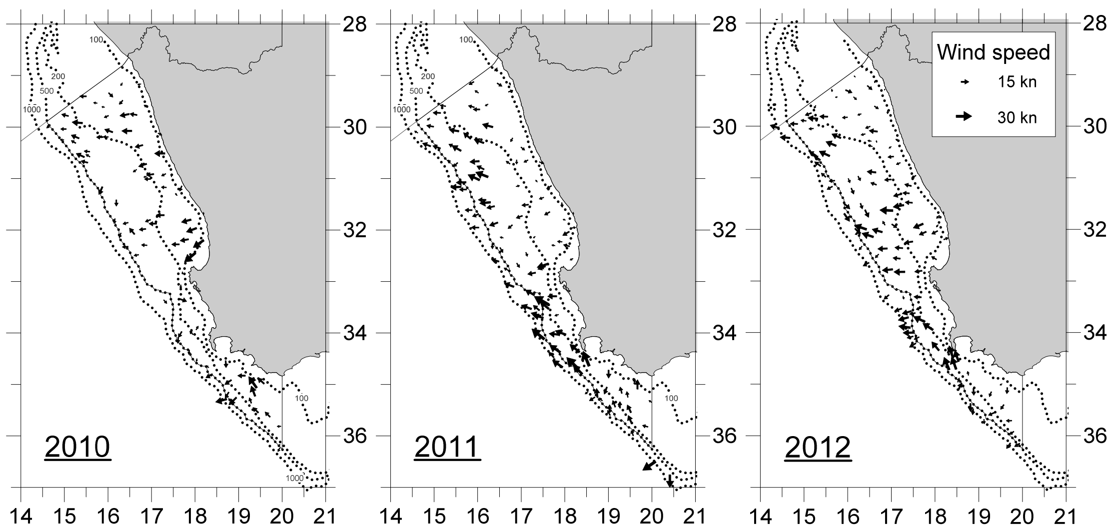

Fig. 7: Wind conditions at trawl stations during the surveys in 2010, 2011 and 2012.

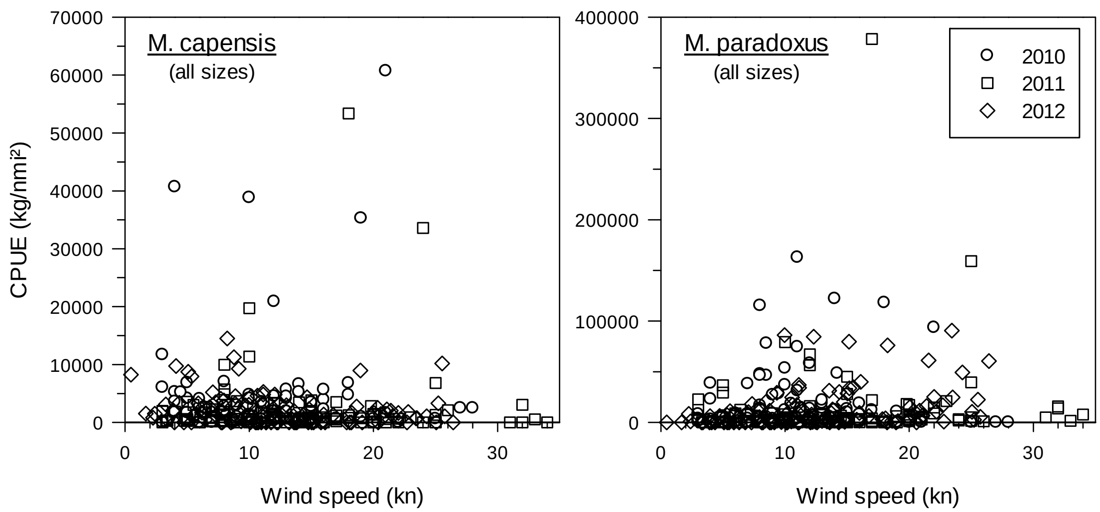

Fig. 8: Survey catch rates of shallow and deep water hake in relation to wind speed in 2010, 2011 and 2012.

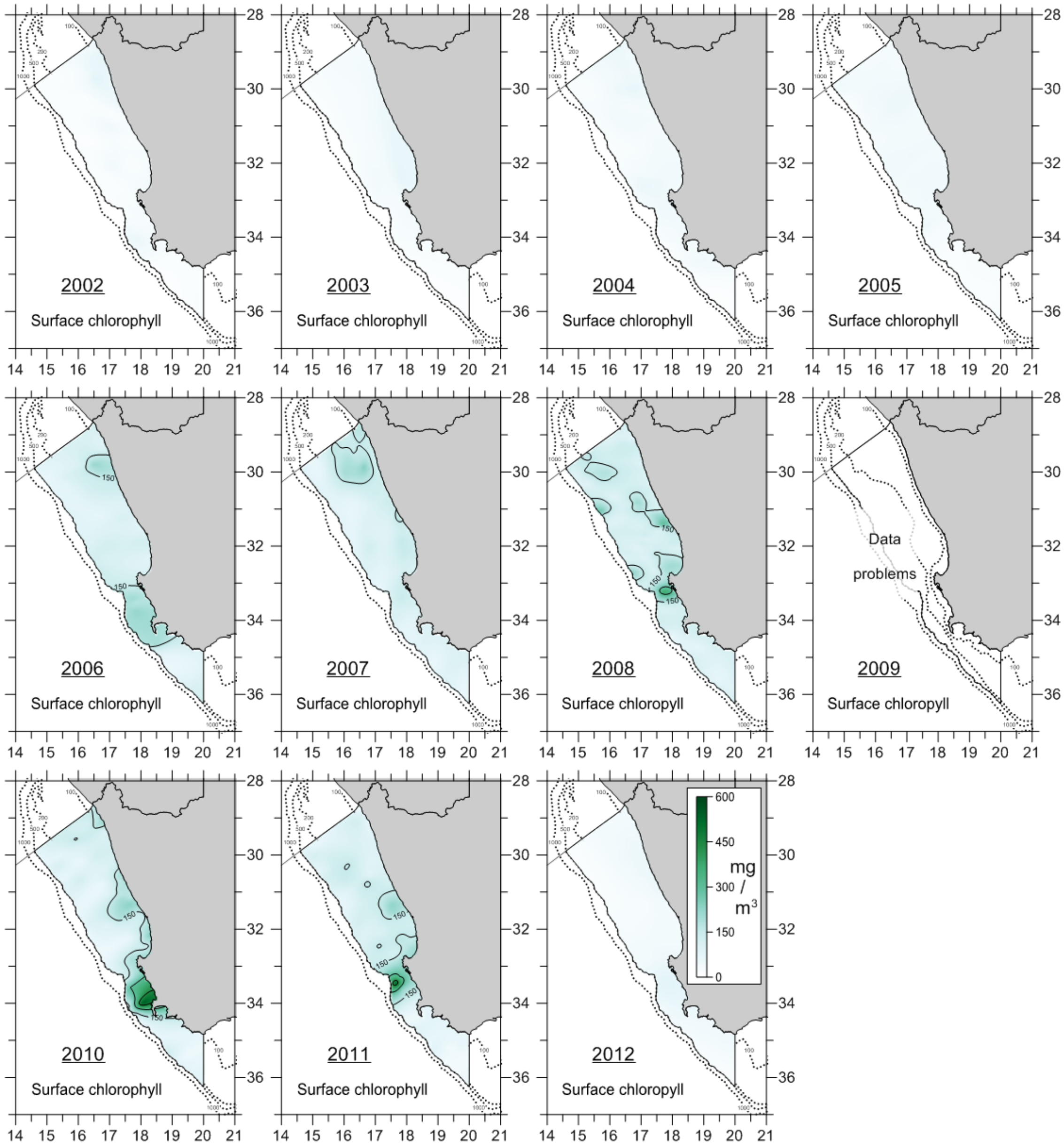

Fig. 9: Surface layer chlorophyll concentration (sum for the upper 100 m) measured at trawl stations for the surveys in 2002 to 2013 (no data available for 2013).

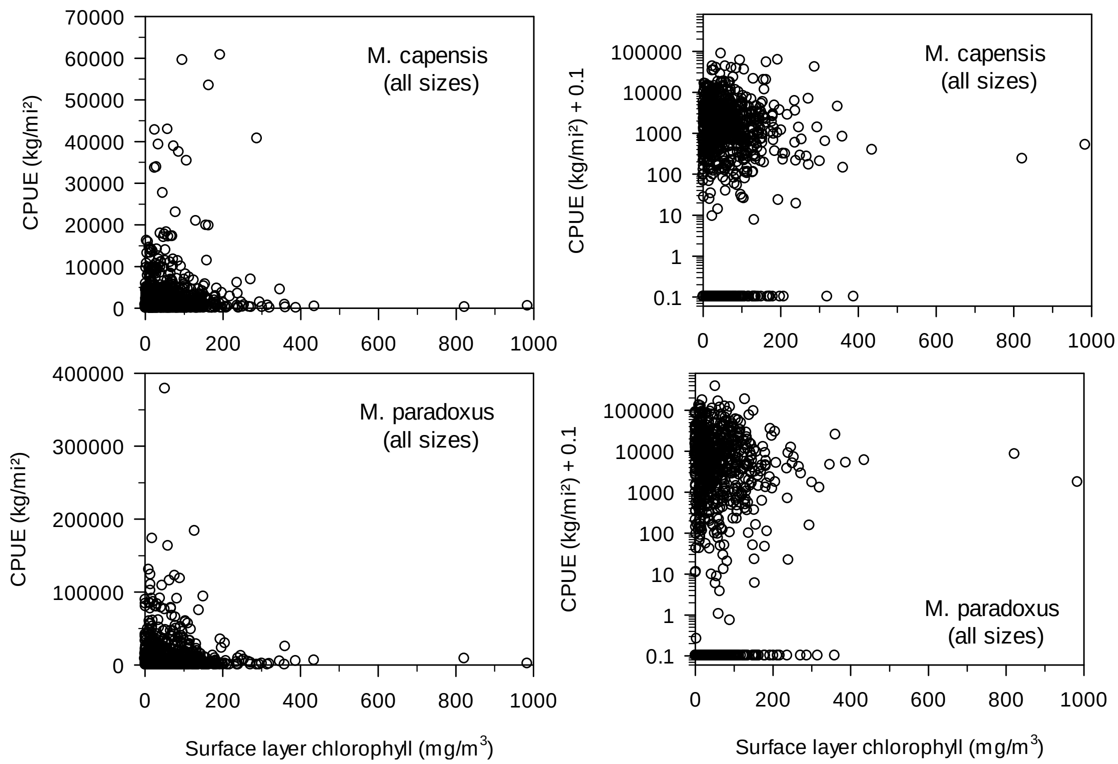

Fig. 10: Survey catch rates of shallow and deep water hake in relation to surface layer chlorophyll concentration, 2002 to 2008 and 2010 to 2012.

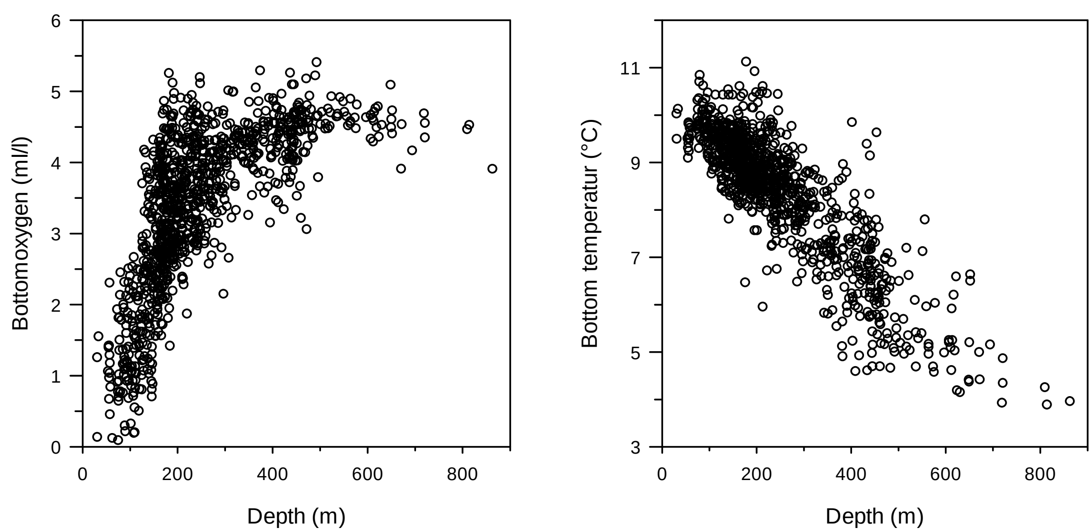

Fig. 11: Oxygen content and temperature in the bottom layer in relation to depth, 2002-2012.

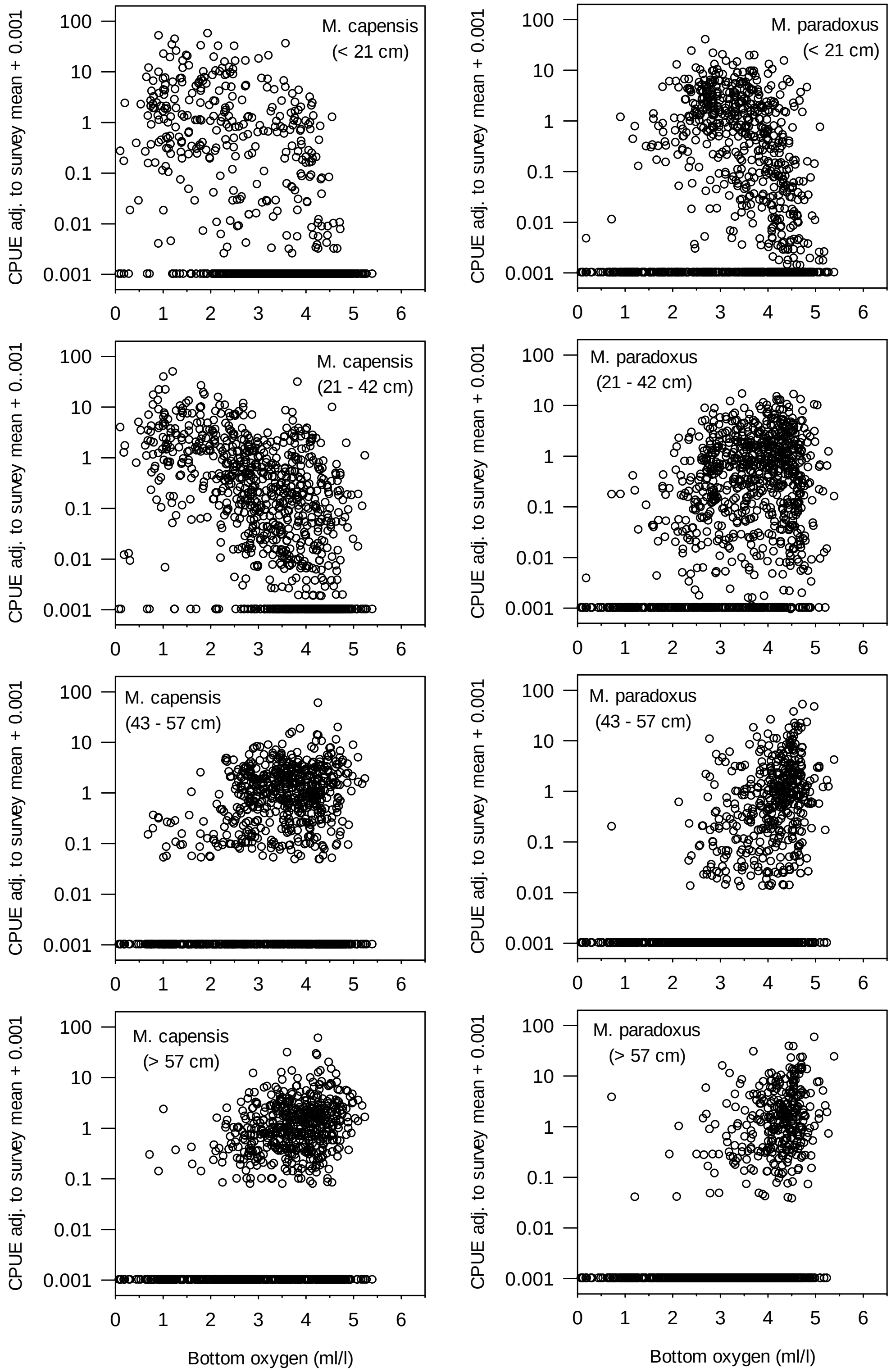

Fig. 12: Survey catch rates of shallow and deep water hake in relation to oxygen content in the bottom water, 2002 to 2012.

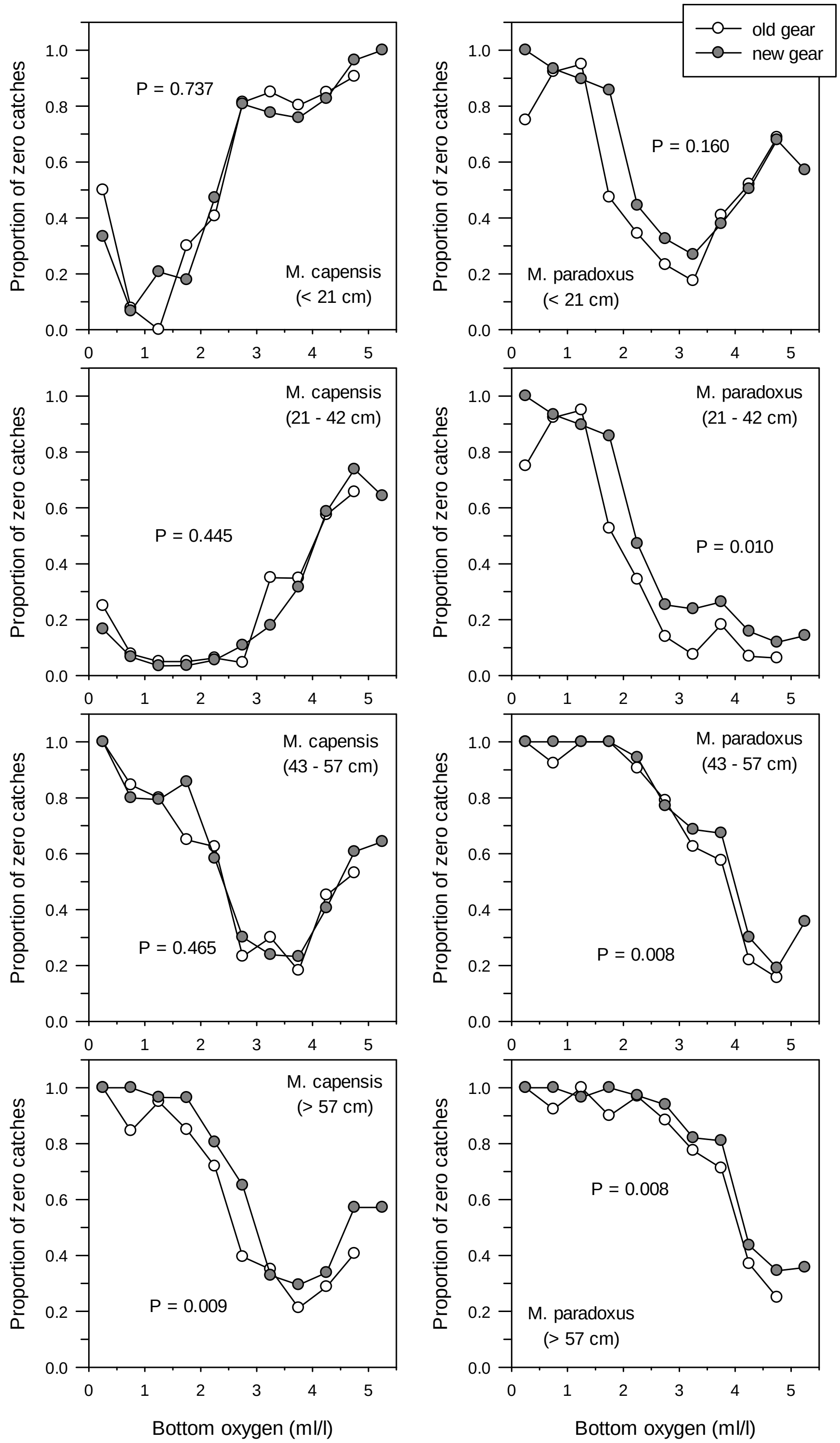

Fig. 13: Proportion of tows with zero catches of shallow and deep water hake by length group and survey gear in relation to oxygen content in the bottom water, 2002 to 2012 (P values refer to level of significance in paired t-tests for the difference between the old and the new survey trawl).

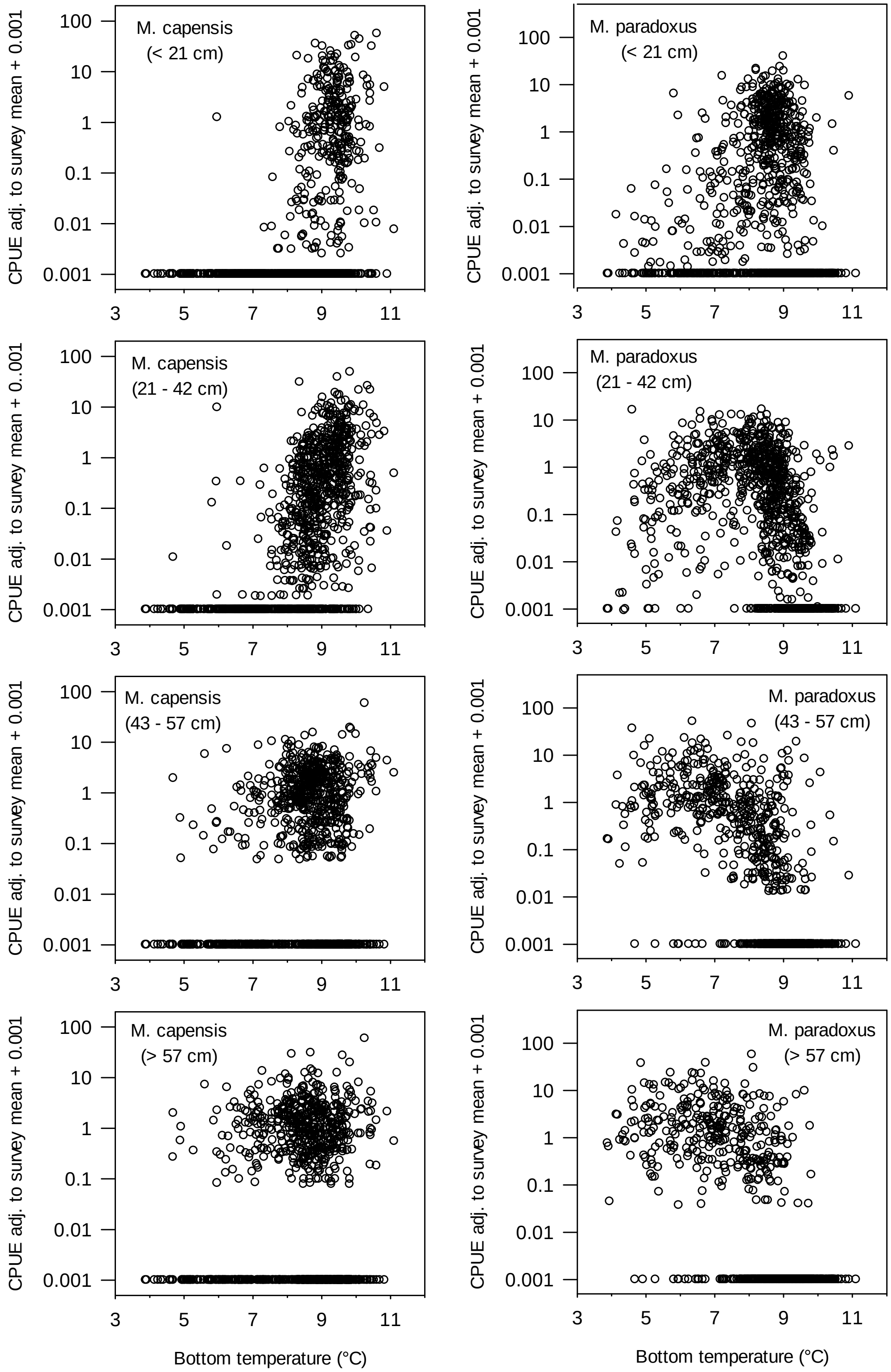

Fig. 14: Survey catch rates of shallow and deep water hake in relation to bottom temperature, 2002 to 2012.

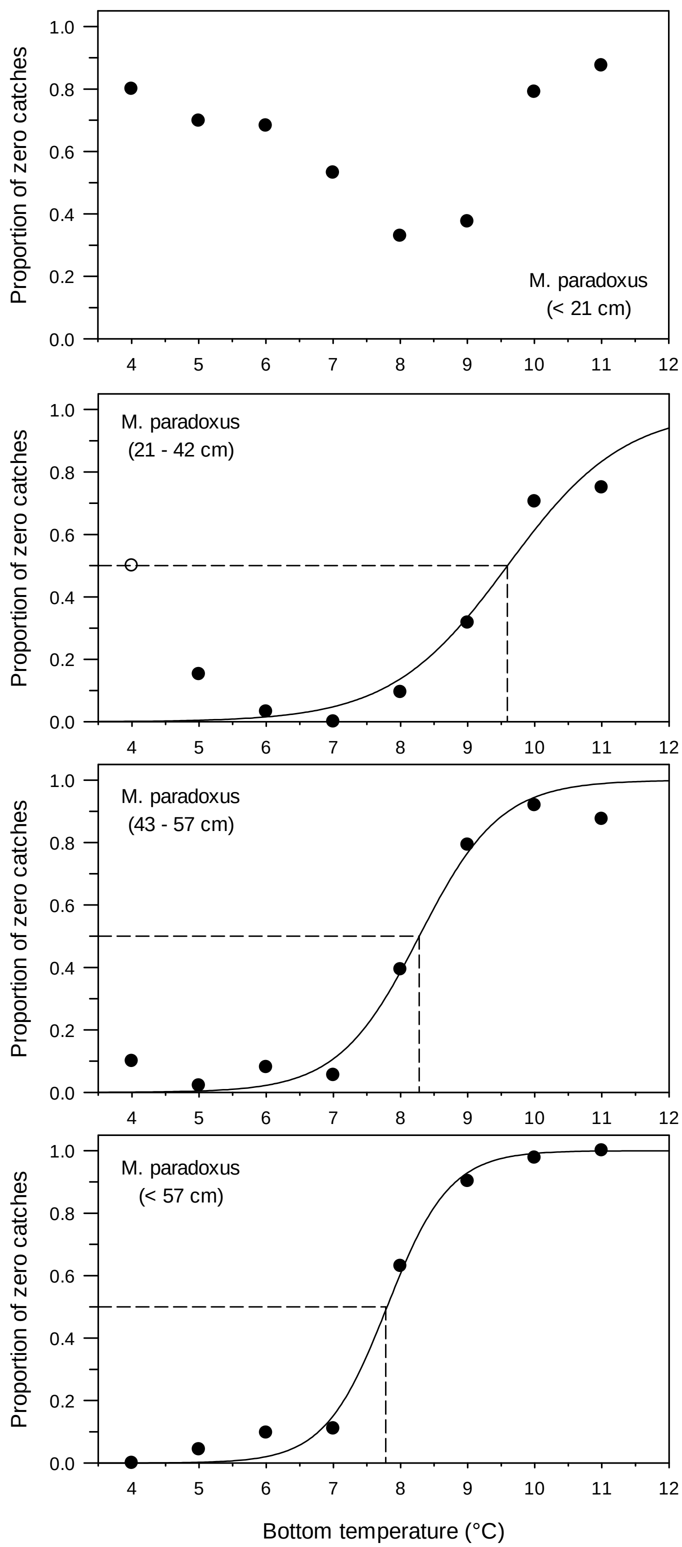

Fig. 15: Proportion of tows with zero catches of deep water hake by length group in relation to bottom temperature, 2002 to 2012 (Solid lines: two parameter logistic regressions, dashed lines: temperature at which 50 % of the catches were zero).

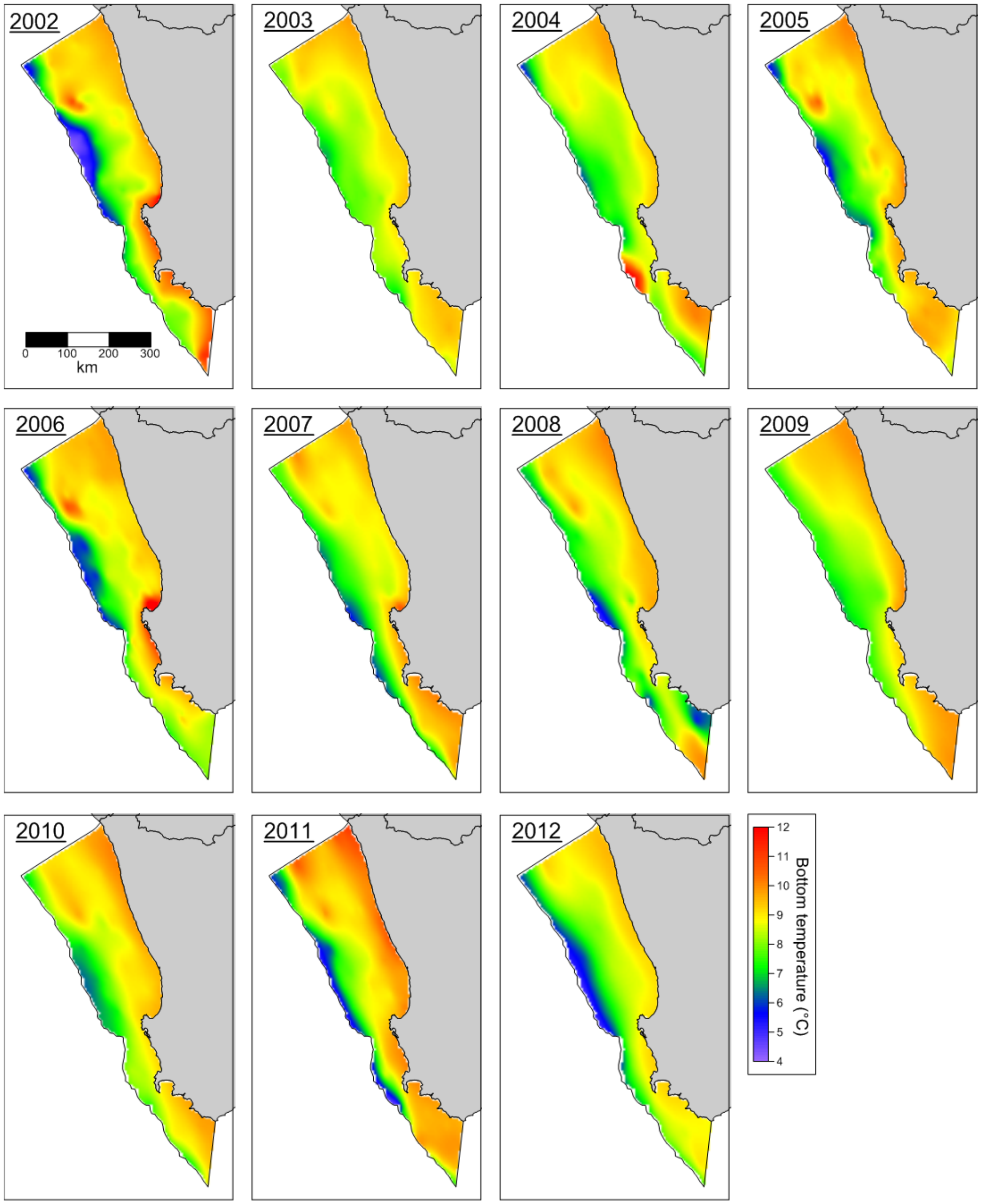

Fig. 16: Distribution of bottom temperature, 2002 to 2012 (UTM 32S projection, data interpolation with 5 km spacing using ordinary kriging and variogram models with a nugget and a spherical component (Fig. 17); domain area: 10075 km^2).

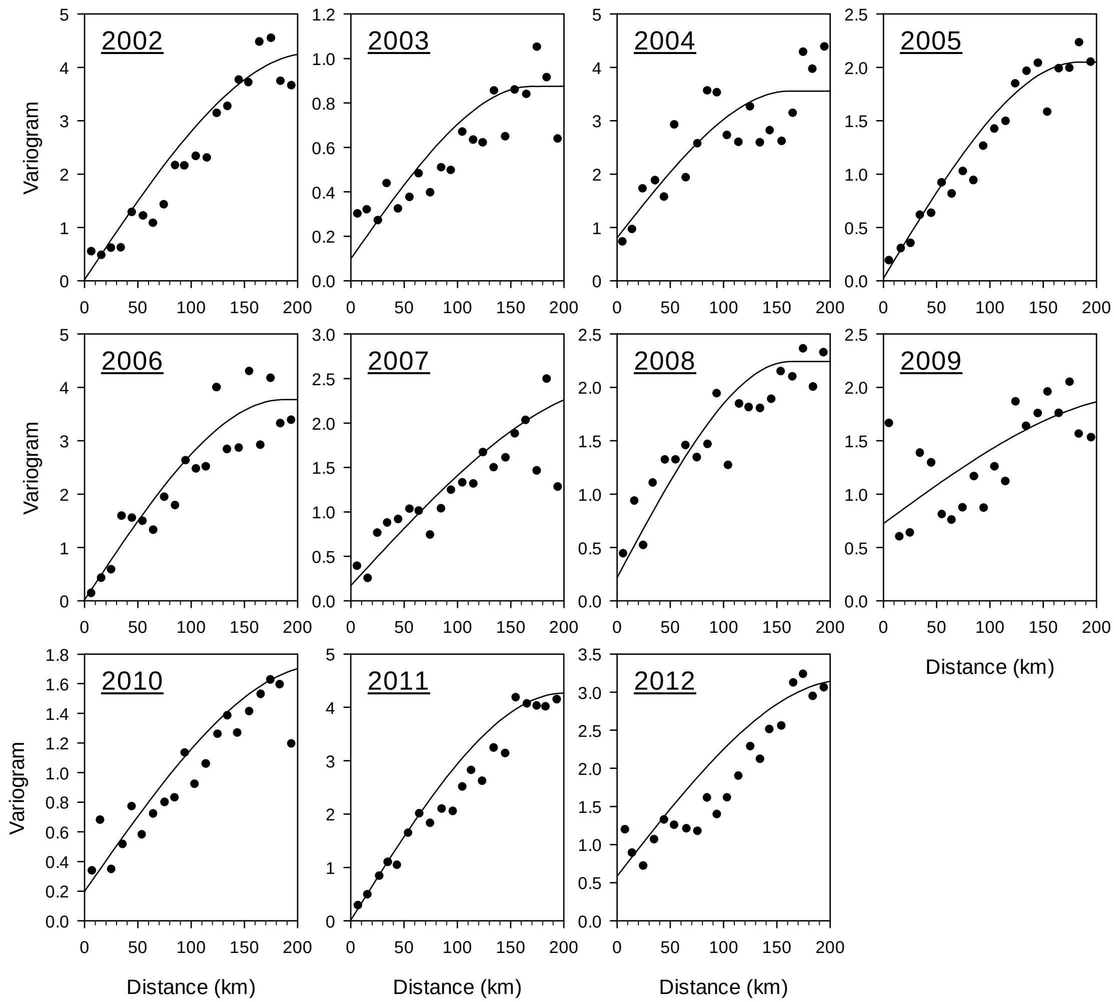

Fig. 17: Observed spatial structure of temperature (°C) in the bottom water and fitted variogram models (nugget and spherical component, number of lags: 20, lag width: 10 km), 2002 – 2012.

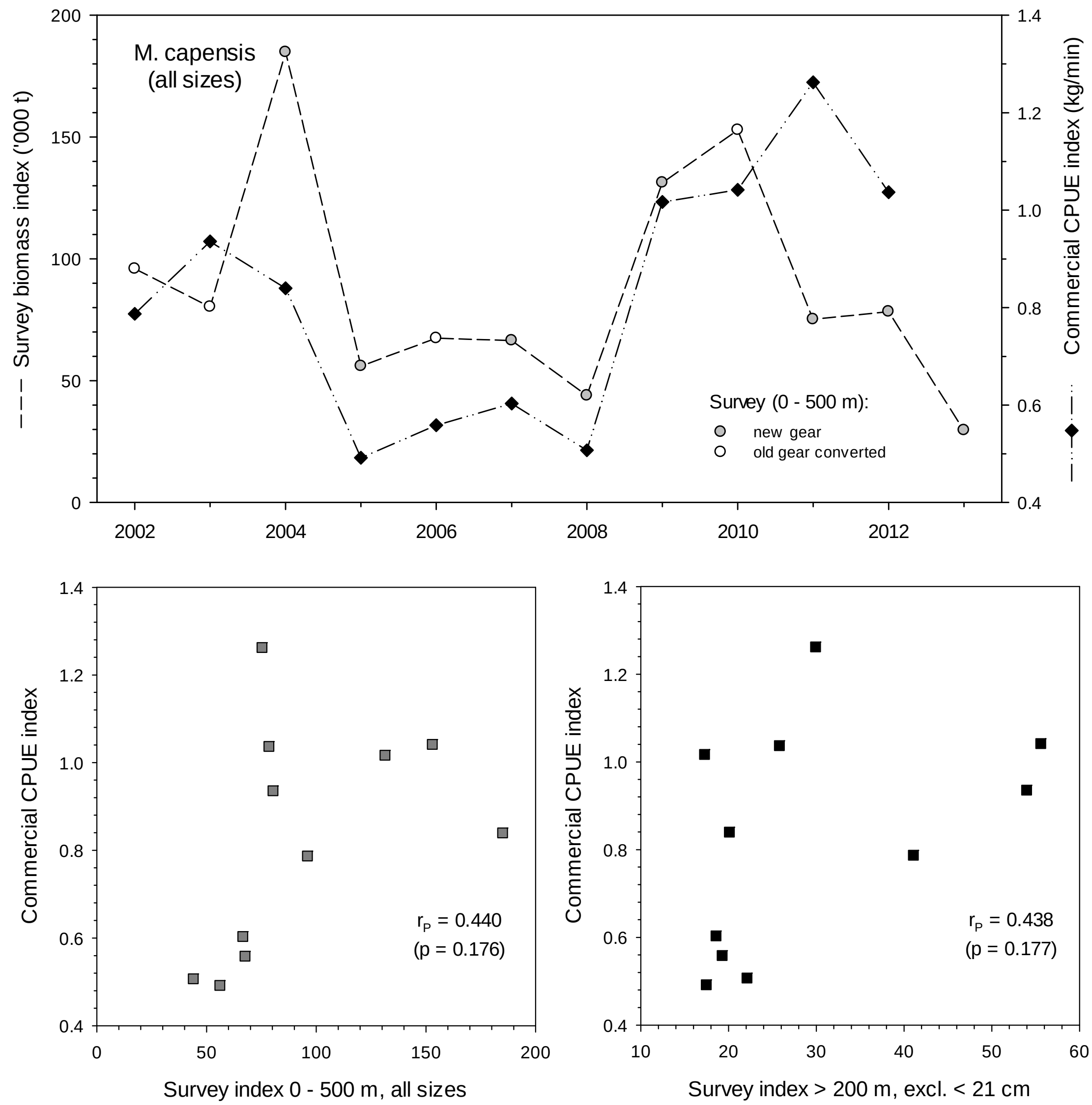

Fig. 18: Comparison of survey biomass indices with standardized commercial CPUE for shallow water hake (r_P: Pearson product moment correlation coefficient).

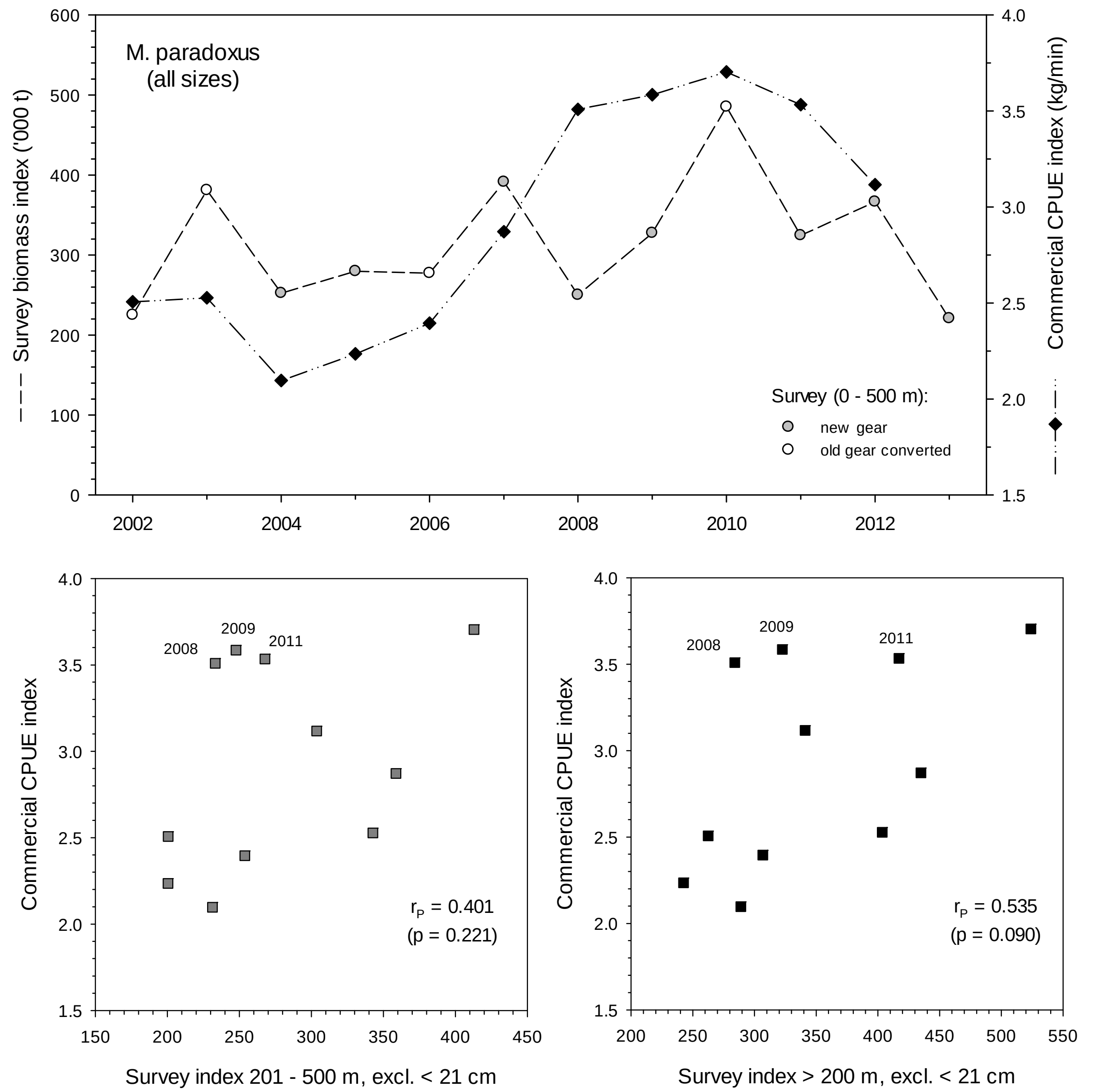

Fig. 19: Comparison of survey biomass indices with standardized commercial CPUE for deep water hake (r_P: Pearson product moment correlation coefficient).