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Predicting the Distribution and Abundance of Emperor Fishes (*Lethrinus* spp.) in the Arabian Sea Using Two-Stage Generalized Additive Models and a Geographic Information System

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التنبؤ بتوزيع ووفرة أسماك الشعري (*Lethrinus* spp.) في بحر العرب بإستخدام النموذج الإضافي المعمم (GAM) ونظم المعلومات الجغرافية(GIS)

لبنى الخروصي

الخلاصة: تم تحليل البيانات المتعلقة بتوزيع ووفرة أسماك الشعري *(Lethrinidae)* على طول الساحل العماني المطل على بحر العرب حيث تم أخذ هذه البيانات من بيانات معدل الصيد لكل وحدة جهد لقطاع الصيد التجاري خلال الفترة من ١٩٩٦ الى ٢٠٠٤ و ٢٠٠٥م على التوالي. كما تم استخدام النموذج الإضافي المعمم (GAM) خلال مرحلتين لإكتشاف إختلافات الوفرة مع التغيرات البيئية. ودلل نموذج (GAM) على أن أفضل أنماط الوفرة والتوزيع النوعي تحققت في شهري أغسطس وأكتوبر وعند درجة حرارة سطح البحر (SST) بين ٢٥-٢٧ وخطوط الطول بيـن ٥٠°٥٧’غرباً –٥٠°٥٨’ شرقاً. وتم إستخدام تقنية نظم المعلومات الجغرافية ArcGIS-٩ كمساعد لتوضيح الاتجاهات الموسمية التي لا تظهر للعيان عن طريق التحليل الإحصائي بطريقة GAM . و يتضح من الشبكات المكانية أن الوفرة تتزايد عندما تكون درجة حرارة سطح البحر أكثر دفئا وذلك خلال الفترة من أغسطس/سبتمبر إلى يناير، ومن جهة أخرى تنخفض خلال فترة الرياح الموسمية الجنوبية الغربية في يونيو- أغسطس حيث تنخفض درجة حرارة سطح البحر إلى أقل من ٢٥ درجة مئوية. وتؤكد النتائج المستخلصة من تحليل بيانات عام ٢٠٠٥م على صحة النتائج الأصلية للبيانات خلال الفترة من ١٩٩٦-٢٠٠٤م كدلالة على صحة التوقعات المنبثقة من النماذج الأصلية. وتعتبر الطرق المستخدمة في هذه الدراسة خطوة أساسية باتجاه تطوير الطرق الإحصائية والمكانية الواضحة والصحيحة لتوقع أداء الثروة السمكية.

ABSTRACT: The distribution and abundance of emperor fishes (Lethrinidae) along the Arabian Sea coast of Oman were analysed from commercial catch-per-unit-effort data for the periods 1996–2004 and 2005, respectively. Two-stage generalized additive models (GAM) were used to detect trends in abundance relative to environmental variables. The GAM that included month (positive in August and October), sea surface temperature (SST; positive at 25–27°C) and longitude (positive between 57°50’ E–58°50’ E) explained the highly variable distribution and abundance patterns best. ArcGIS-9 was used as an auxiliary to visualize seasonal trends that could not be seen from the statistical GAM analysis. From the spatial grids, it appeared that abundance increased with warmer SST encountered in August/September to January but was lower during the SW monsoon in June–August when the SST decreased below 25°C. The results emanating from the analysis of the 2005 data confirmed those from the original 1996–2004 data, suggesting that predictions from the original models were relatively robust. The synthesis of methods used in this study is a major step towards developing statistically robust and spatially explicit methods for predicting fisheries performance.

Keywords: Emperor (*Lethrinus*), generalized additive model (GAM), geographical information system (GIS), sea surface temperature (SST), Catch per unit effort (CPUE).

Introduction

Emperor fishes of the genus *Lethrinus* are found only in the tropical and subtropical Indo-Pacific region, except for one species that occurs in the eastern Atlantic (Randall, 1995). They are carnivorous, bottom-feeding coastal fishes, usually associated with coral reefs or rocky substrata, or nearby sand, rubble or weedy bottoms. Randall (1995) lists 7 *Lethrinus* spp. from the coast of Oman, where they make up a significant proportion of catches made by traditional and industrial fishing fleets. The most common

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emperor species on local Omani markets is *Lethrinus nebulosus*, which reaches a maximum size of 80 cm, and is caught from the shore down to depths of at least 75 m (Randall, 1995).

The emperor is an important commercial reef fish (demersal fish) in the Sultanate of Oman, locally referred to as sheiry. Both industrial trawlers and the traditional fishing sector catch emperor. Total landings of emperor during 2005 were 9235 MT with a value of 53 million Omani rails. Emperor contribute around 5.8 % to the total landings and 6.4% to the total value of the fisheries economy. In addition, the emperor fishes contribute approximately 25% to the total demersal landings in terms of both quantity and value (MAF, 2005).

The distribution, biology and fisheries of commercially important emperor fishes (Lethrinidae) along the Arabian Sea coast of Oman have formed the basis of two recent Ph. D. studies (Al-Kharusi, 2006; Al-Mamry, 2006). Age, growth and reproductive biology of spangled emperor *Lethrinus nebulosus* were described by Al-Mamry *et al. (*2007), and yield per recruit models further suggested that the species is underexploited in the region (Al-Mamry *et al*., in press). Using a different approach, Al-Kharusi and Jarvis, (2007) used commercially derived catch-per-unit-effort (CPUE) data, geographical information systems (GIS), and generalized additive modeling (GAM) to explore the relationships between emperor distribution and abundance in the Arabian Sea, and environmental variability. GAM techniques are able to deal with non-linear relationships between an independent variable such as fish abundance and multiple environmental variables at the same time (Swartzman *et al.,* 1992).

Although GAMs are useful predictive tools, observations of catches are often characterized by a large number of zeroes in space and time – this could account for the small proportion of variance explained in some models (Bellido, 2002; Sacua, 2005; Welsh *et al*., 1996). To overcome this effect, a 2-stage approach may be used, in which the first stage models the probability of fish being present using binomial presence/absence data, and the second stage models the observed fish abundance, where they are present, assuming a Gaussian error distribution (see Barry and Welsh, 2002; Barratt *et al.,* 2002). The outputs of the two stages can be combined through multiplication to estimate the expected abundance. Once such a model has been generated, the standardized catch rates (or abundance index) can be spatially interpolated by applying the fitted model to the environmental grids within the study area using GIS (see Stoner *et al*., 2001).

Al-Kharusi and Jarvis (2007), found year, month, latitude, sea surface temperature (SST) and depth to be significant explanatory variables in their best fit GAM model of *Lethrinus* abundance. They recommended that the robustness of the original models (based on 1996–2004 data) be tested using subsequently data and that spatial predictions be attempted; these recommendations are consistent with the goal of fish habitat studies, which is not only to describe the trends in the modeled data, but also to make predictions which may be valid for given temporal and spatial scales (Hilborn and Walters, 1992). Similar, comparison between the outputs of original GAM models and new GAM models developed from test data, collected subsequently, was done by Stoner *et al*. (2001) for winter flounder.

In the present study, the earlier dataset (1996–2004; see Al-Kharusi and Jarvis, 2007) and new data collected in 2005 were treated separately and subjected to a 2-stage GAM approach. The steps undertaken were: a) to develop separate 2-stage GAMs for the 2 datasets to establish statistically significant environmental trends relative to fish abundance; b) to include these trends into predictive models that could be compared, and c) to transfer the model outputs to a GIS grid to visualize spatial trends that could not be seen from the statistical GAM analysis.

Materials and Methods

The study area and the physical oceanography of the Arabian Sea coast of Oman was described in Al-Kharusi and Jarvis, (2007) and are not repeated here. Important though, is that the particular focus area was between 17º30’–21º00’N and 53º00’–59º30’E, and that the area was divided into blocks of 30×30 nautical miles, each then sub-divided into nine smaller areas of 10×10 nautical miles for statistical purposes (Fig. 1).

The dataset for the 1996–2004 period was identical to that used in Al-Kharusi and Jarvis, (2007), i.e., commercial emperor catch and effort data from the Statistics department of the Ministry of Fisheries Wealth, SST data from the PO-DAAC physical oceanographic website measured in Celsius, and depth from digitized Omani charts measured in meters . The

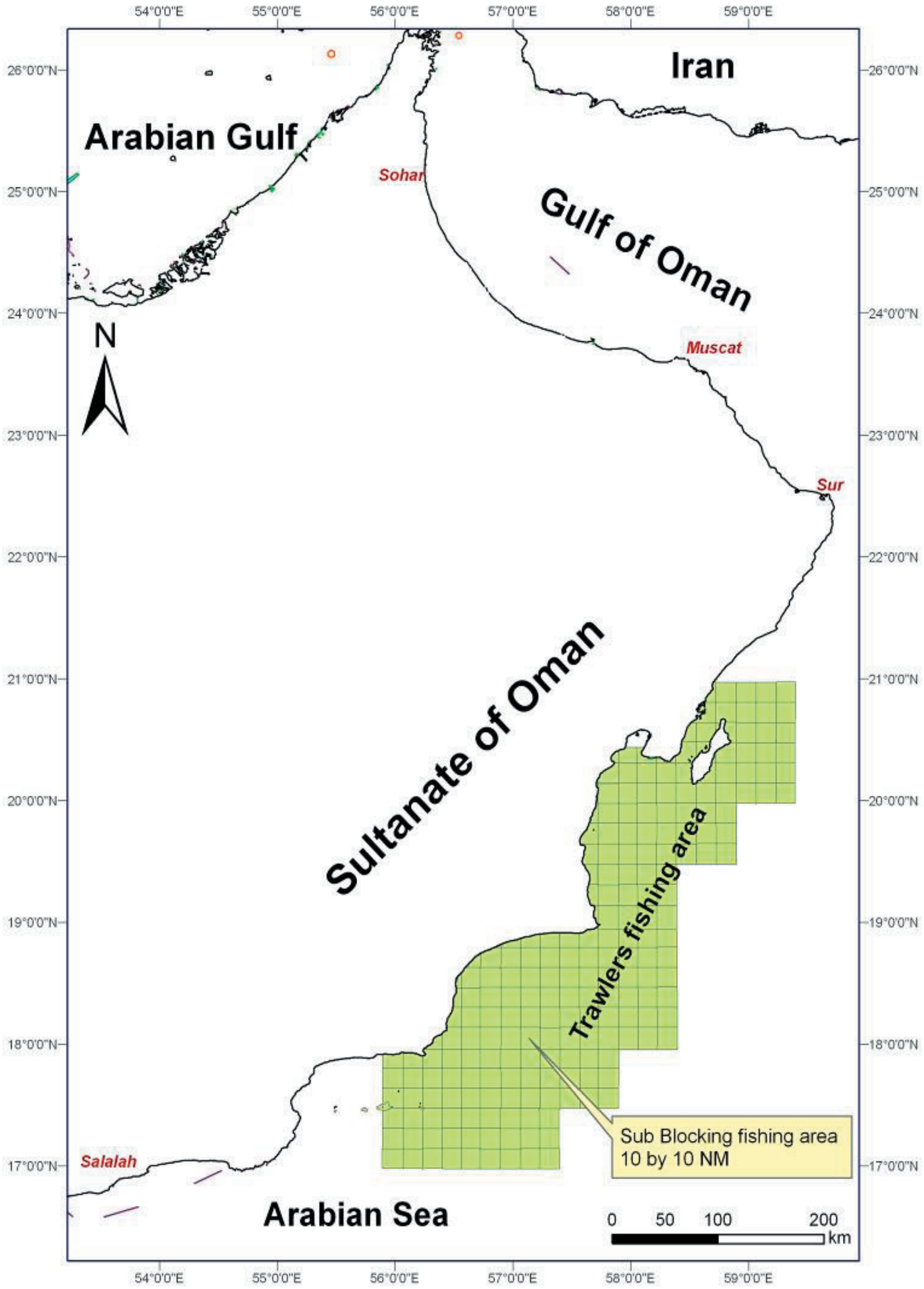


Figure 1. Trawl fishing grounds in the Arabian Sea off Oman, showing the grid blocks used in the study.

data for 2005 were also obtained from the same source and used for comparison with the output of GAM model employed for 1996-2004 data. Catch Per Unit of Effort (CPUE; kg/day), calculated as total catch over all fishing blocks divided by fishing days, was used as an index of abundance. The emperor CPUE data sets were imported from a custom-designed Microsoft Access^{TM} database and integrated into ArcGIS^{TM}, and located using the centroid sub-block of 10×10 nautical miles.

For the GAMs, data sets for 1996-2004 and for 2005 were separately imported from Excel into Brodgar 2.5.2 software (www.brodgar.com), using covariate data held in GIS and R (Venables and Dichmont, 2004). A cubic smoothing spline method available in Brodgar was used to smooth variables, using cross validation to find the optimal degrees of freedom (df) for each model.

The GAMs used to estimate environmental effects on relative emperor abundance were fitted with Binomial, Gaussian and Quasi-Poisson error distributions, respectively, and a step-wise fitting procedure was used to remove insignificant variables and maintain a level of significance of $P<0.001$. The model fits were evaluated using R^2 and deviance reduction (R^2 = 1–residual deviance / null deviance), and the Akaike Information Criterion (AIC = (Deviance + 2*df) / n; Akaike, 1973).

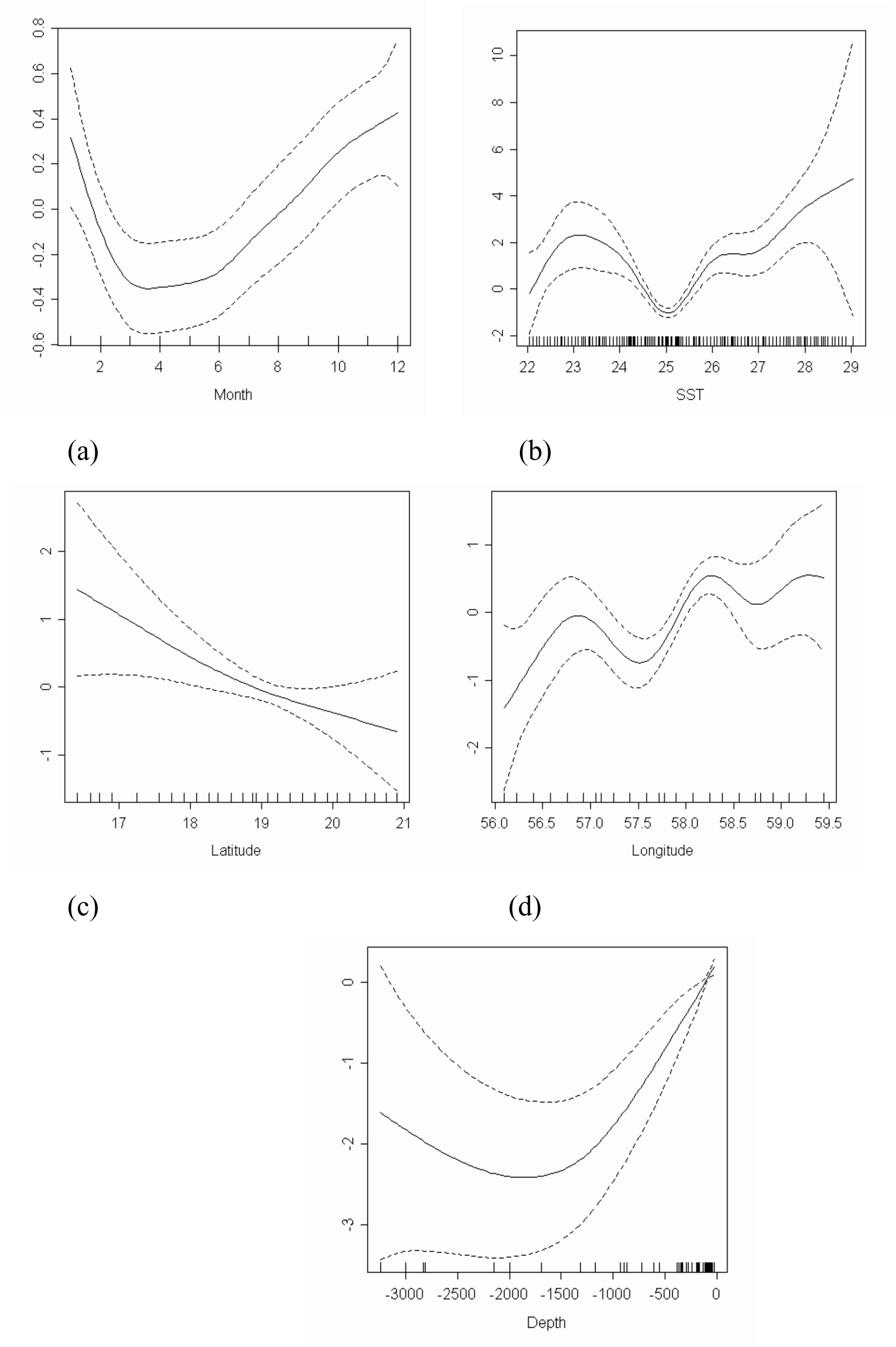
In the first stage (binomial) model, emperor distribution was determined after converting CPUE data into binary form (1=present and 0=absent), using a binomial distribution with 'logit' link function. This model provided estimations of the probability of emperor presence on a geographic basis. In the second stage model, the CPUE values were used on the "presence" matrix with Gaussian (or quasi-Poisson) error distributions and 'identity' link function. This second model quantified the strength of the presence in areas where emperors were present, and the combined outputs of the two-stage model, probability and prediction, were multiplied in order to estimate expected abundance.

The GAM output plots are shown as the best fitting smoothers for the effects of all the explanatory variables included in the model. The dotted lines represent the 95% confidence intervals and the tick marks on the x-axis called rug indicate the number of data points available for different values of x. The partial components, as represented by y-values on the GAM plots, express the relationship between the link function of the response variable and each of the variables included in the model.

The continuous probability grids of emperor presence were then generated from the GAMs and transferred to ArcGIS-9 software (ArcMap) (ESRI) to plot the results.

Table 1. The GAM model specifications for Binomial Gaussian and Quasi-Poisson error distributions for the 1996-2004 data, showing the degrees of freedom (df) and probability (p) for each variable, and the R^2 and AIC statistics for the best fit.

Variable	Binomial R^2 = 15 AIC = 0.98		Gaussian R^2 = 25 AIC = 424		Quasi-Poisson R^2 =50 AIC = 0.89	
	df	**p-value**	**df**	**p-value**	**df**	**p-value**
Month	4	3.4951e-05	5	1.4284e-08	4	<0.001
SST	6	< 2.22e-16	8	< 2.22e-16	4	< 2.22e-16
Longitude	7	5.1351e-06	4	0.020	1	0.03
Latitude	2	0.000	1	0.013	4	<0.001
Depth	2	8.927e-10	2	0.687	4	0.0.01
Gaussian	CPUE ~ + s (Month) + s (Latitude) + s (Longitude) + s(Depth) + s(SST)					
Binomial	PA ~ + s (Month) + s (Latitude) + s (Longitude) + s (Depth) + s (SST)					
Quasi-Poisson	CPUE ~+s(Year) + s(Month) + s(SST) + s(Depth) + s(Latitude) +s(longitude)					



(a) (b)

(c) (d)

(e)

Figure 2. Output of the binomial presence/absence model (GAM) using the 1996-2004 data. The effects of explanatory variables are shown for (a) month, (b) SST, (c) latitude, (d) longitude and (e) depth.

Results

GAM fits to 1996–2004 and 2005 data

The best-fit binomial models for the 1996–2004 data had an R^2 of 15% (Table 1), with 4 degrees of freedom for the optimal GAM for month ($P < 0.001$). The smoother for partial effect of month indicated that it is an important variable with a seasonal effect – positive in August and October, and negative in March and April (Fig. 2a). The optimal GAM for SST (df = 6, $P < 0.001$; Table 1) and the smoother for partial effect of SST suggests that emperors prefer areas where SST ranges between 25 and 27˚C (Fig. 2b). Longitude was also significant (df = 7, $P < 0.001$; Table 1), with a positive effect between 57º50’ E and 58º50’ E (Fig. 2c), but neither latitude nor depth were important explanatory variables (df = 2; Figs 2 d & e).

The stage-2 Gaussian model for 1996–2004 data could explain 25% of the variance of emperor CPUE (Table 1), and the smoother for the partial effect of month indicates a positive seasonal effect for August to October and a negative effect for March to April (df = 5, $P<0.001$; Fig. 3a). SST was the most important explanatory variable in the Gaussian model (df = 8, $P<0.001$), with a strong positive effect between 25 and 27°C (Fig. 3b). Neither latitude, longitude nor depth were important in terms of error distribution or p-value (Table 1; Figs 3 c-e).

The best-fit quasi-Poisson models for the 1996–2004 data had an R^2 of 50% (Table 1), with 4 degrees of freedom for the optimal GAM for month ($P < 0.001$). The smoother for partial effect of month indicated that it is an important variable with a seasonal effect – positive in August and October, and negative in March and April. The optimal GAM for SST (df = 4, $P < 0.001$; Table 1) and the smoother for partial effect of SST suggests that emperors also prefer areas where SST ranges above 25 and less 27˚C. Latitude was also significant (df = 4, $P < 0.001$; Table 1), with a positive effect, but neither longitude nor depth were important explanatory variables ($P > 0.001$).

The GAM fits for the 2005 data could explain 20% of the variance in the binomial and Gaussian models, respectively, and in the Quasi-Poisson model used to validate the results it could explain 40% of the variance (Table 2). The SST effect was present in all three models (Table 2), and the optimal three GAMs for CPUE contained a smoothing function for SST (df = 5, $P<0.001$). Figure 4 shows the probability prediction estimates of emperor abundance distribution for 2005, and the smoother for the partial effect of SST indicates a positive effect on CPUE between 25˚C and 27˚C (Fig 3-b). This compares well with the results of the 1996-2004 models.

Spatial interpolation of GAM outputs to GIS

Having generated the GAMs, the three indices (presence/absence, predicted CPUE in kg/day, and expected abundance) were interpolated by transferring the models to ArcGIS-9, to illustrate seasonal (monthly) variation on a geo-referenced scale. The probabilities of occurrence were divided into 5 groups from 0 to 1 to illustrate the probability distribution. For the 2005 presence/absence model, the interpolation suggested a spatial distribution pattern in which season played a strong role: during September to January (excl. November) there was a high probability of occurrence compared to lower probabilities in particularly March, May and June (Fig. 5).

The spatial interpolation of the predicted CPUE in kg/day in 2005 (Fig. 6) also showed a seasonal distribution pattern – predictions of CPUE more than 1 kg/day were more abundant from August to January, while February to July CPUE predictions were lower, except during June. Interpolation of the absence/presence × CPUE model (Fig. 7) showed a similar pattern to that of the predictive CPUE (in Fig. 6), with higher abundance expected between August and January.

Spatial interpolation of the quasi-Poisson output for 1996–2004 data (absence/presence × CPUE) also showed clear seasonal patterns (Fig. 8), and therefore all the above interpolations (for 2005 and for 1996–2004) suggested a strong seasonal effect on the distribution and abundance of emperor fishes in the Arabian Sea.

The accuracy of the models’ spatial and temporal predictions was assessed by comparing them with average of CPUE from fishing operation records. This process was undertaken using the Gaussian model to predict emperor abundance for each fishing block. The relationship between predicted abundance and average trawler CPUE (Fig. 9) was reasonably well supported; low predicted abundance resulted in a lower CPUE values, and higher predicted abundance resulted in higher CPUE values in the range between zero and >10 kg/day.

Discussion

Al-Kharusi and Jarvis (2007) reported on space-time distribution of *Lethrinus* in the Arabian Sea, and based on the 9 year database for 1996–2004 (identical to

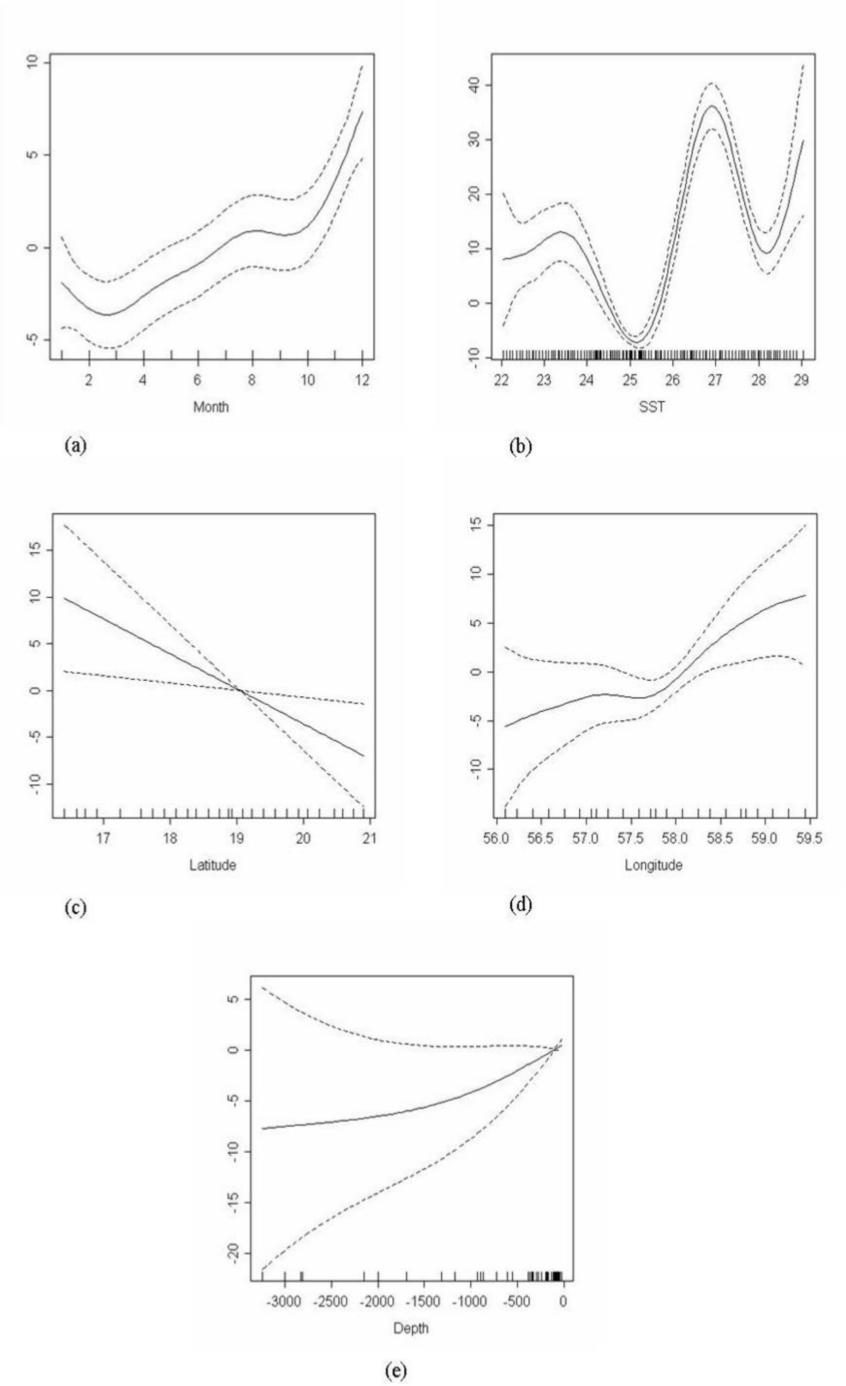


Figure 3. Output of the Gaussian abundance model (GAM) using the 1996-2004 CPUE data. The effects of explanatory variables are shown for (a) month, (b) SST, (c) latitude, (d) longitude and (e) depth.

Table 2. The GAM model specifications for Binomial, Gaussian and quasi-Poisson error distributions for the 2005 data, showing the degrees of freedom (df) and probability (p) for each variable, and the R^2 and AIC statistics for the best fit.

Variable	**Binomial** $R^2 = 20$ **AIC = 1.2**		**Gaussian** $R^2 = 20$ **AIC = 1.98**		**Quasi-Poisson** $R^2 = 40$ **AIC = 0.96**	
	df	**p-value**	**df**	**p-value**	**df**	**p-value**
Month	έ	έ	5	0.039	6	3.0248e-11
SST	5	3.7468e-07	5	0.005	5	1.8874e-05
Longitude	8	0.00	7	0.000	8	1.6723e-09
Latitude	4	0.017	έ	έ	4	0.003
Depth	6	0.004	έ	έ	2	0.002
Binomial	PA ~ + s (Latitude) + s (Longitude) + s(Depth) + s(SST) + Month					
Gaussian	CPUE ~ + s (Longitude) + s (SST) + s (Month) + Latitude + Depth					
Quasi-Poisson	CPUE ~ + s (Latitude) + s (Longitude) + s (Depth) + s (SST) +s (Month)					

Key: έ = error for parametric component.

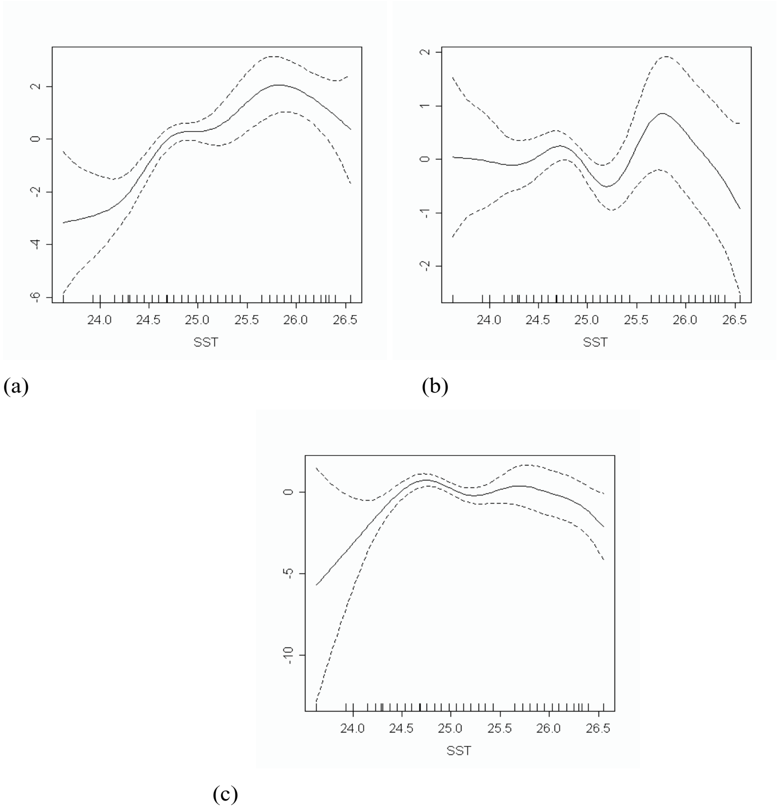


Figure 4. Output of the presence/absence, Gaussian and quasi-Poisson models (GAM) as fitted to the partial effects of the SST predictor variable for emperor abundance in 2005.

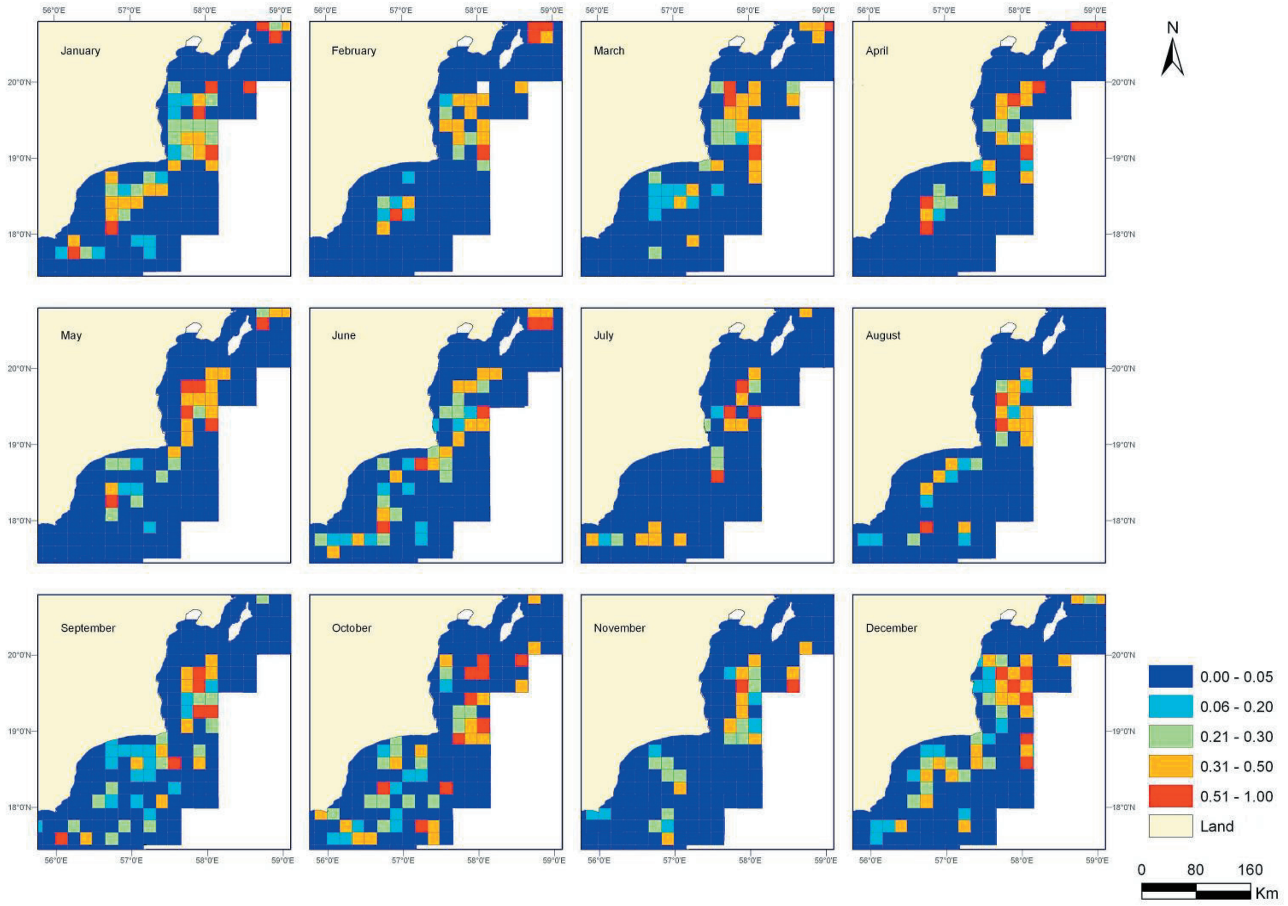


Figure 5. The probability distribution (binomial, presence/absence) of emperors estimated by month for 2005 after interpolation to ArcGIS-9.

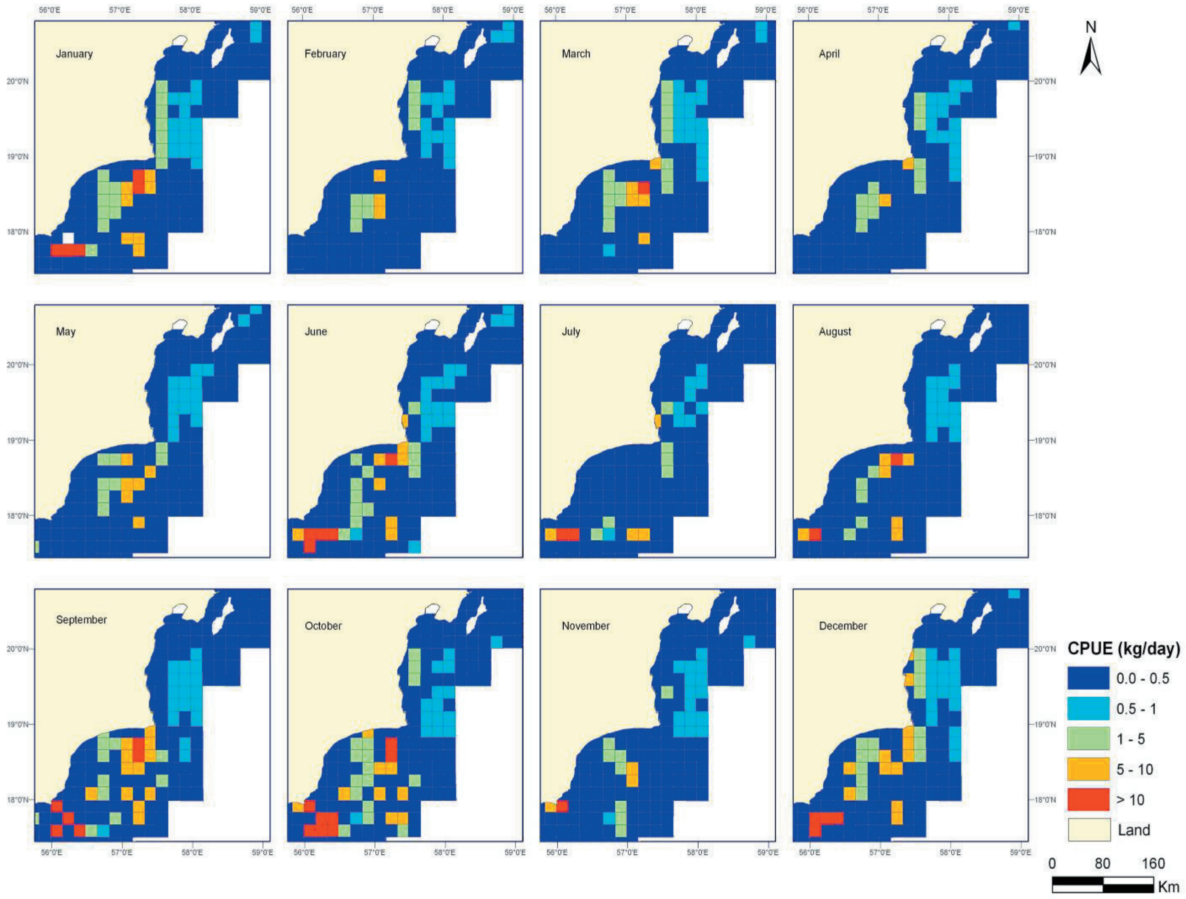


Figure 6. The predicted relative emperor abundance in kg/day (Gaussian) estimated by month for 2005 after interpolation to ArcGIS-9.

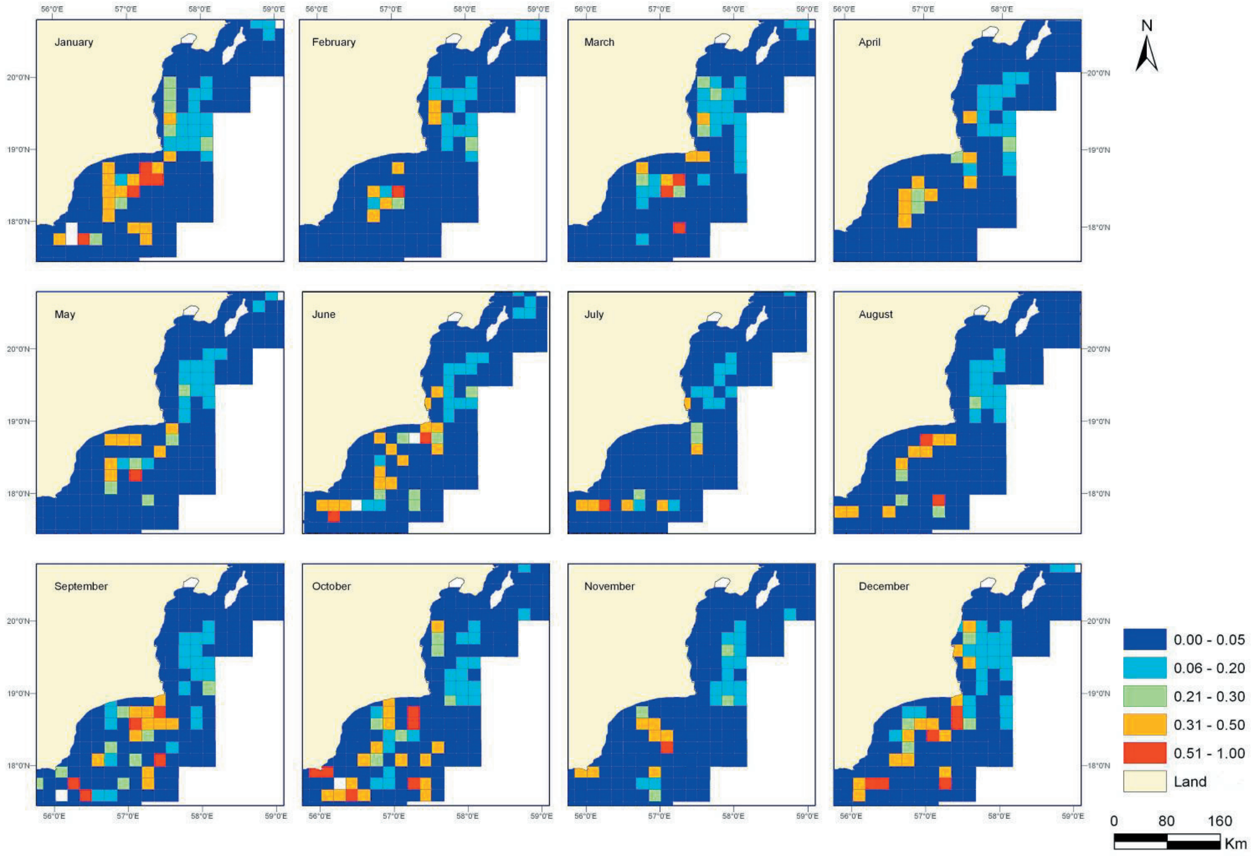


Figure 7. Probability distribution × expected emperor abundance per month for the 2005 data after interpolation to ArcGIS-9.

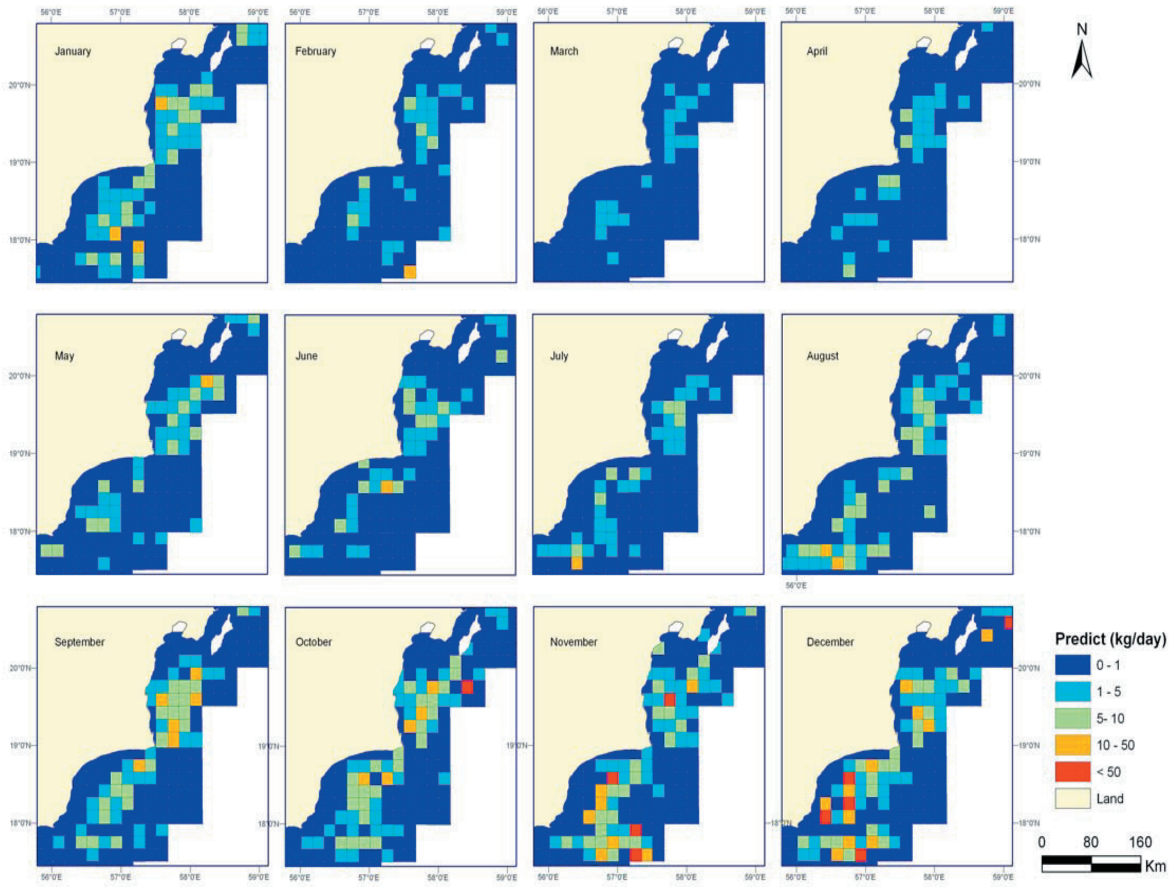


Figure 8. The predicted relative emperor abundance in kg/day (quasi-Poisson) estimated by month for the 1996-2004 data and its interpolation to ArcGIS-9.

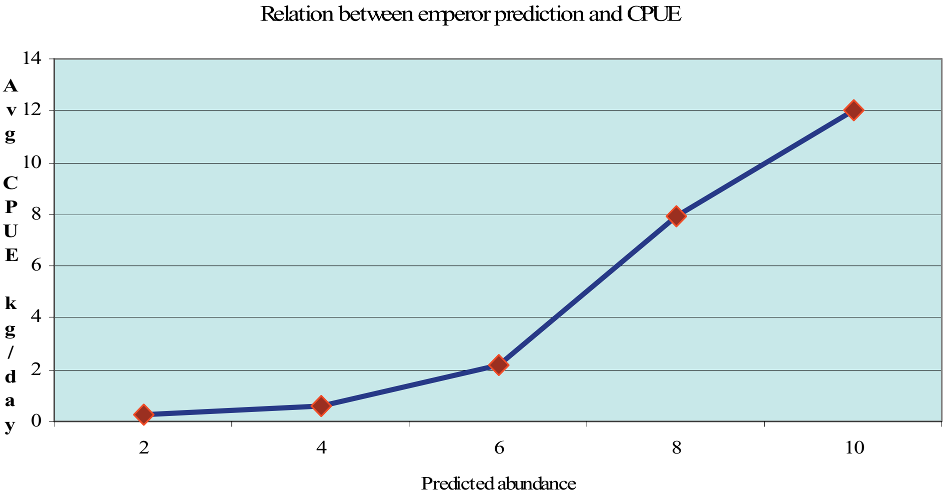


Figure 9. The relationship between the predicted abundance of emperors (Gaussian) and the raw catch per unit effort data from trawlers operating in the Arabian Sea in 2005.

the one used in the present study) and GAM analysis they could explain variations relative to year, month, latitude, SST and depth. In the present study, their work was extended by using a 2-stage GAM approach, additional data for 2005, and GIS mapping of probability predictions and estimated abundance. The rationale for extending the previous study was that fish habitat studies should not only describe trends relative to explanatory variables (in Al-Kharusi and Jarvis, 2007), but should also make predictions which may be valid for given temporal and spatial scales (this study). The methods used here (both GAM and GIS) lend themselves well to both these tasks (Swartzman *et al*., 1992; Barrat *et al*., 2002).

The catch and effort data used in this study originated from nine years of trawler catches (averaged for 1996–2004), and one year of additional data treated separately (2005). These data were obtained from government statistics for the period. Though, in general, the offshore fisheries data reported to the governments have some inaccuracies (Patterson, 1998; Groeneveld, 2003) in present study, the data obtained from the industrial trawlers are reliable as there were ministry's observers on-board the vessel.

The Brodgar 2.5.2 software used for the GAM models has been described by Smith *et al*., (2005), Sacau, (2005) and Barratt *et al*., (2002) as a public domain statistical package based on R and explicitly designed for ecological applications. In our study the Brodgar software performed adequately. Of the 3 error model fits (Binomial, Gaussian and quasi-Poisson), the quasi-Poisson resulted in the highest R^2 and lowest AIC statistics for both datasets. The quasi-Poisson model was also preferred by Al-Kharusi and Jarvis (2007), although Barrett *et al*. (2002) preferred the binomial and Gaussian models for their 2-stage GAMs of orange roughy and yellowfin tuna.

The 2-stage GAM models demonstrated non-linear and highly variable relationships between emperor spatio-temporal distribution, SST and longitude, but depth and latitude did not explain any significant amount of the variance. SST was also an important explanatory variable in the study by Al-Kharusi and Jarvis (2007) – in their model CPUE was highest at an SST of 25.5–28°C compared to 25–27°C here. Depth (<200 m) and latitude could explain some variation in the previous study, but in the present study depth was insignificant and latitude was replaced by longitude as a significant variable. These anomalies are attributed to the models and fitting procedures used – for instance, in the previous GAM the issue of zero values was not addressed in a 2-stage procedure and longitude was removed because of high co-linearity with latitude.

Based on the presence/absence model, the probability of occurrence of emperor is widespread in all months, but is greatest from September to January at an SST of 25–27˚C. Higher catches of emperor were predicted from September to January in the Gaussian model for CPUE, and the combined model (presence/absence×CPUE) indicates a large abundance of emperor in the Arabian Sea in 2005 corresponding roughly to the original data for 1996-2004 – i.e. higher abundance is predicted for June, August, September, October, December and January. These findings support previous studies that emperors prefer water at a temperature of roughly 27˚C (McIlwain *et al.*, 2006; Forster, 1984; Newman and Williams, 1997). The likely causal mechanisms linking SST and abundance of emperor, which dwell on the sea floor, may be the seasonal monsoon in the Arabian Sea, although the mechanism remains unclear. Nevertheless, upwelling pre and during the monsoon season (April to September) reduces water temperatures and may therefore influence emperor distributions.

The combination of GAM with spatially explicit GIS to visualize patterns that are unclear from GAM statistical analysis has been used successfully elsewhere (Stoner *et al*., 2001; Barratt *et al*., 2002). The study by Barratt *et al*. (2002) showed how the information can be applied to fisheries management and marine planning, i.e. in evaluation of areas for marine reserves, allocating access to fish resources, and estimating stock sizes among neighboring fishing zones or EEZs. They concluded that the models developed to date have not been rigorously tested or validated, and can only be used to assist fisheries and marine management and planning. The present study is the first attempt at combining these two methods in Oman, and although a significant step forward in the region, it should at present only be considered as a supportive tool.

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