Classification of Fiordland Marine Environments and Their Use as Surrogates Measures of Biodiversity

FINAL REPORT
Modelling of Biological Parameters, Ground-Truthing, and Classification of Physical Environmental Types

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Introduction

The development of environmental classification systems holds the potential to assist in managing biodiversity on regional scales (Belbin 1993). One approach for developing environment classifications uses relationships established between multiple physical factors, which are typically continuous at some resolution, and limited biological information as means to use physical environmental types as a proxy for biodiversity patterns (Roff 2000, Roff, et al. 2003). Environmental classification systems can have numerous applications to support management decisions and better understand spatial relationships between physical habitat types and biological parameters (e.g. Ward, et al. 1999, Edgar, et al. 2000).

In New Zealand, several initiatives for developing classifications for terrestrial, freshwater and marine environments have created such "spatial frameworks" for better understanding the pattern of physical environmental types and potential associations with aspects of biological diversity (e.g. Leathwick, et al. 2004, Snelder, et al. 2005). A classification of marine environments for the entire New Zealand region has been developed at a resolution of 1 km^2 (Snelder, et al. 2005), however this resolution omits detail of some coastal areas such as the Marlborough Sounds and Fiordland, where there are numerous narrow inlets and channels and interspersed islands. For this reason, a finer resolution classification was developed for Fiordland (Wing, et al. 2003).

As the utility of a physical environment classification depends on its ability to represent different aspects of marine biodiversity, a study of the relationships between individual physical predictor variables and biological information of population-, species-, and community-levels of organisation was required. In this study, statistical techniques were used to establish relationships between physical environmental variables and biological attributes to map predictive surfaces. These predictive layers were then re-sampled in an independent "ground-truthing" survey which was used to verify how well statistical predictions based on physical variable matched observed patterns at different levels of biological organisation. Results of the statistical modelling was used to develop a multivariate classification of physical environmental types, which was then analysed in terms of the biological patterns represented at different levels of detail in the classification. These results are discussed in the context of the utility of environmental classifications as surrogate measures of biodiversity for coastal marine systems.

Part 1. Statistical Relationships between Biological Response Variables and Physical Environmental Factors and Ground-Truthing of Predictive Modelling

Data Sources & Methodology

Data Layers of Physical Environmental Parameters. Pre-screening of 12 data layers of physical environmental parameters available for the Fiordland region was conducted to remove parameters that were strongly correlated. This analysis reduced the number of data layers to 9, which were then to be used as correlates with biological data sets. Data resolution for continuous grids was 50 m, covering inner fjord regions to the entrance of individual fjords and complexes (Table 1).

Bathymetry for the Fiordland region was constructed by digitising available fair sheets from nautical surveys for the region. This information was captured from chart scales of 1:10,000, 1:25,000, and 1:50,000 from 31 charts. Capture of data points from fair sheets was done with several criteria, including priorities for points in the depth range of 0-50 m, medium priority for ranges of 50-100 m and low priority for depths > 100 m. Data capture was also done to represent irregular relief, with lesser priority to areas of flat bottom. The coastal fringe was also digitised (depth = 2). This data capture process comprised 48,400 points, with various data resolution depending on the area. Overall, the data density is approximately 50 m, of which a bathymetry model was created at this resolution in a Geographic Information System (GIS). Additional layers of slope and aspects were also calculated in the program at the same resolution (i.e. 50 m).

Physical oceanographic data from Conductivity, Temperature, Depth (CTD) surveys collected during University of Otago research cruises in 1998, 1999, 2000, and a Department of Conservation/University of Otago cruise in 2002 were combined with a high resolution survey conducted in November 2003 (funded through Ministry for the Environment/Ministry of Fisheries). CTD data were post-processed to provide values for surface salinity of the top two meters of the water column, effective freshwater depth (EFD), a stratification metric (PEA), and a water column mixing index (1-PEA/PEA_{max}) for 112 cast positions. These data were interpolated using a distance-weighted cost function constrained to the coastline. This provided a consistent smoothing algorithm across the complex Fiordland topography at a resolution of 50 m. Further information of the individual data layers and calculations is provided in Wing, et al. 2003, 2004.

Data layers for aspects of wave climatology for the Fiordland coastline were developed using the SWAN (Simulating WAves Nearshore) wave model. This model uses

information of offshore swell conditions (Gorman, et al. 2003[a,b]) and local bathymetry information to characterise processes leading to spatial variability in wave climate, including shoaling, wave breaking, energy dissipation, reflection and refraction (e.g. Kirby and Dalrymple 1983, Holthuijsen et al. 2000). In addition this model provides for the spatial resolution (50 m) that we require for defining physical drivers of biodiversity patterns in this region. The SWAN model provided values for significant wave height (H_{sig}) and orbital velocity at the seabed (U_{bot}) at a maximum resolution of 50 m. Three additional physical data layers were available for wave statistics (i.e. orbital velocity on the bottom (U_{bot}), transport, and wave force), however, in the inner fjord region, several of these variables dropped to zero and showed very little spatial variation. As these parameters were also strongly correlated with H_{sig}, it was considered that variations in H_{sig} captured most of the environmental pattern observed across the Fiordland region.

Table 1. Physical environmental variables for Fiordland used in the statistical modelling of biological parameters (details for individual data layers in Wing, et al. 2004, 2005).

Environmental variable	Abbreviation	Description	Units
Depth	bathy	Bathymetry grid (50 m resolution)	m
Slope	slope	Slope calculated from adjacent cells of the bathymetry grid	degrees from horizontal
Yearly Mean Solar Radiation	Solar_global	Total annual solar radiation potential	$Wh \cdot m^{-2} \cdot day^{-1}$
Annual Solar Standard deviation	Solar_direct	Variation of yearly mean solar radiation, indicating regions with higher variance of the light environment	$Wh \cdot m^{-2} \cdot day^{-1}$
Significant Wave Height	H_{sig}	Values derived from SWAN wave climate model	m
Surface Salinity	surf_sal	Mean salinity in upper 2 m of water from CTD surveys 1998, 1999, 2002, and 2003	psu
Effective Freshwater Depth	EFD	Integration of the amount of freshwater throughout the water column, proxy for the strength of estuarine circulation	m
Potential Energy Anomaly	PEA	Measure of relative stratification of the low salinity surface layer	$J \cdot m^{-3}$
Mixing	Mixing	Normalised index of 1 minus the ratio of PEA to maximum PEA, where 1 refers to perfectly mixed and 0 refers to perfectly stratified	dimensionless

Data on the mean solar irradiance in the fjords was modelled using r.sun within the GRASS open source GIS package (Hofierka and Suri 2002). In this program solar geometry and the interaction of solar radiation with the atmosphere is based on the work of Krcho (1990), Jenco (1992) and Kittler and Mikler (1986). The model considers the effect of local topography, derived from the 10 m LINZ contours, on shadow formation and computes daily sums of solar irradiance. A detailed methodology for the model can be found in Neteler and Mitasova (2003). This model provides information on the yearly mean solar radiation and the annual solar radiation standard deviation (as a measure of the variation in the light field) in units of $Wh \cdot m^{-2} \cdot day^{-1}$ (Table 1). These variables were included for their potential to correlate with primary production, but may also be a proxy for light environments that may potentially affect the recruitment of sessile invertebrates.

Detailed information for data sources for data layers and computations can be found in Wing, et al. 2004, 2005).

Data layers provided contrasting patterns of longitudinal (i.e. inner to outer fjord) and latitudinal (i.e. north to south) gradients across the region. For example, patterns of surface salinity showed gradual gradients from lower salinity occurring in inner fjord regions and relatively higher salinity in outer fjord regions. Another example of variations from fjord to fjord, but also for region within fjords for a given variable was illustrated with depth, where there was a tendency to have shallow regions along the coastal segment, with larger shallower areas in inner and outer fjord regions, and near island groups (Figure 1A). Yearly mean solar radiation, in contrast, showed a more consistent pattern across the Fiordland region, where the south-facing sides of the fjords tended to have lower solar radiation, and this trend tended to be accentuated in inner fjord regions (i.e. lower levels of light in inner fjord regions)(Figure 1B). This combination of these different environmental variables provided a means to be able to distinguish relationships for a suite of environmental variables with a reduced amount of spatial autocorrelation to model biological attributes.
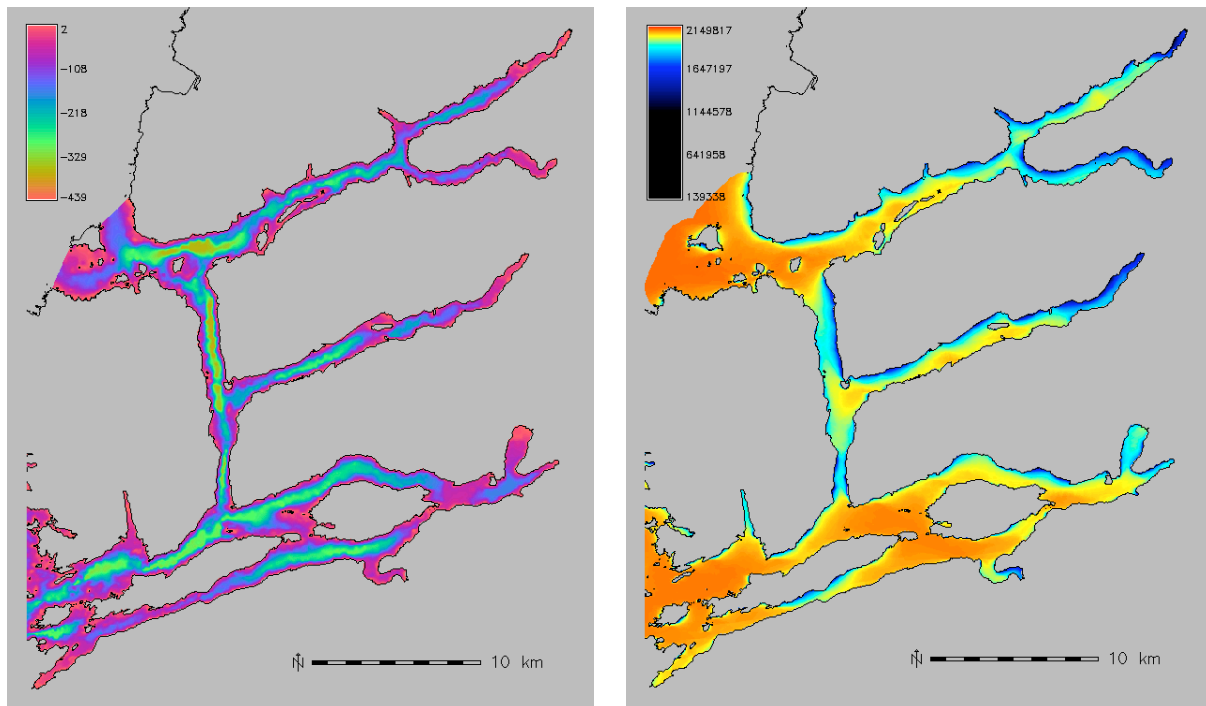
A. Depth (m)   **B. Annual solar radiation (Wh·m⁻²·day⁻¹)**

Figure 1. Example physical data layers of (A) depth and (B) yearly mean solar radiation for the Breaksea and Dusky Sound complex (Wing, et al. 2004).

As sampling of biological parameters was largely constrained along the coastal fringe (i.e. within 100 m of the coast), a series of circular buffers with a radius of 100 m were created along the Fiordland coastline (Figure 2). In addition, as several of the biological data sets were obtained from sampling along transects, these coastal buffers were also considered to be a measure of environmental variation at the scale of the sampling unit (i.e. the transect). Information from the physical data layers were extracted from each coastal buffer to provide means, standard deviation, minimum, maximum, and ranges for each data layer. This allowed to test for differences between sites of similar depth (at the sampling point) but with differing surrounding depths. For statistical testing of biological parameters, environmental data were extracted from sampling points and data included within coastal point buffers were attached to sampling sites.
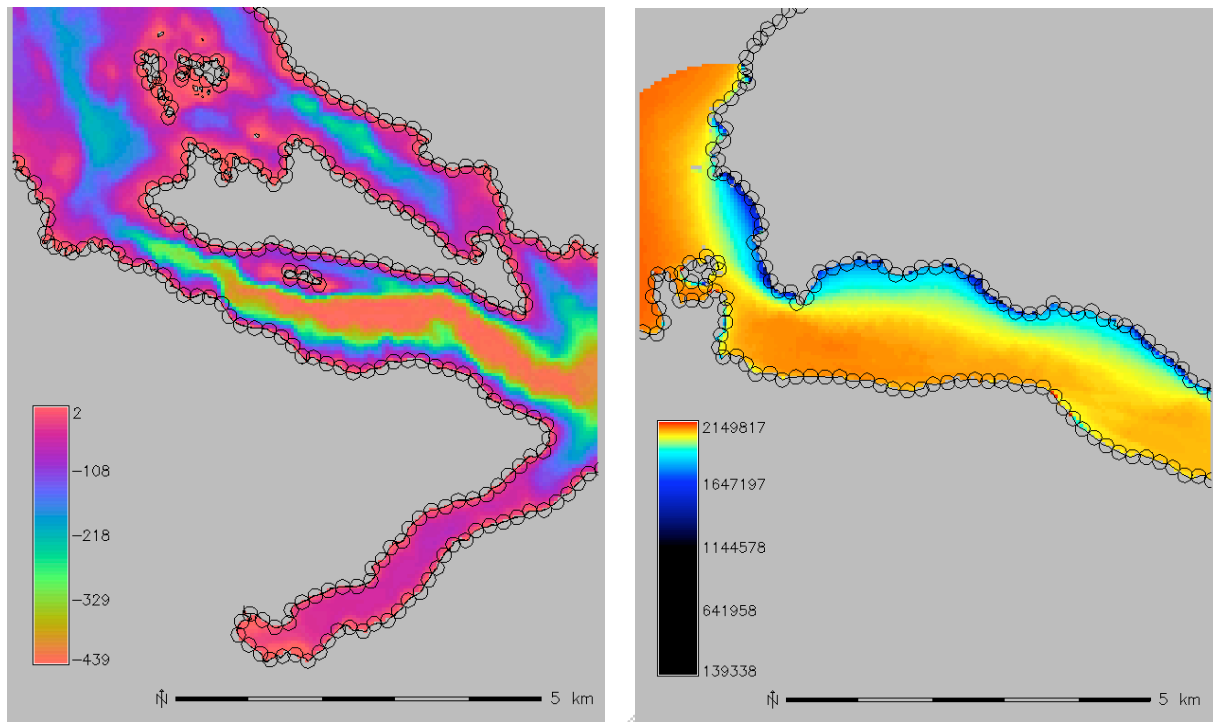
A. Depth (m)   **B. Annual solar radiation (Wh·m⁻²·day⁻¹)**

Figure 2. Detail of the coastal point buffers overlayed on the Fiordland coastline and data layers of (A) depth and (B) global sum solar radiation (Wing, et al. 2004).

Indicators of Population, Community and Species-level Biological Organisation. Biological data used to validate the relevance of the data layers of physical environmental variables were selected as indicators of different levels of biological organisation. Biological data sets that were available for modelling were obtained for reasons other than developing a classification. A measure of biological variation at the level of the population was used from surveys of sea urchin (*Evechinus chloroticus*) size frequency distributions at 24 sites obtained across Fiordland in 1998 and 1999 (Wing et al. 2000). Size frequency distributions from 10 mm to 160 mm were recorded from urchins collected at individual sites. Exploratory data analysis showed that the mean sizes were correlated with the modes, although some of the frequency distributions appeared to have multiple modes. To explore relationships between physical environmental variables and other attributes of the population size structure, the relative proportion of smaller sized sea urchins (i.e. <70 mm) and larger sea urchins (i.e. >125 mm) were also used as response variables. Mean test diameter of kina populations in the fjords is related to their growth and mean lantern index (Wing, et al. 2001)(Table 2), while the proportion of larger sea urchins was used as an indicator of adult survival and the proportion of smaller sea urchins as indicators of recruitment (survivourship) of smaller individuals in the population (Table 2).

To assess the relevance of community- and functional group-level indicators to physical environmental parameters, data on sessile suspension-feeding invertebrates (hereafter referred to as "epifauna") obtained from photographic quadrat surveys were used to derive diversity statistics and quantify the relative proportion (incidence) of major functional/taxonomic groups at 23 sites (Smith 2001). These data were collected in 1996. Diversity statistics of the variation of species density (i.e. the standard deviation of the average number of species per 0.25 m^2 quadrat) and observed species richness (i.e. number of species per site) were used as response variables. For establishing relationships of the physical environmental variables and major functional groups within the suspension-feeder assemblage, the proportion of ascidians (Phylum Tunicata) was used as a response variable. The variation in species density represents a proxy for the patchiness in epifaunal communities, which is likely to be related to physical and biological disturbance of rock wall habitats at the scale of the transect. Species richness of epifaunal assemblages has been related to recruitment of species, at the time-scale of months, but also for the accumulation of species over 1000's of years (Smith and Witman 1999, Smith 2001)(Table 2). The proportion of the number of ascidians was used as a proxy for the importance of active suspension-feeding as a functional group in these assemblages (Table 2).

Relevance of the physical environmental layers with individual species was evaluated using data from fish surveys conducted across Fiordland and the outer coast (Francis, et al. 1985, 1986). Survey sites with physical data available for developing statistical models were limited to 33 sites. Models were selected for individual fish species, including butterfly perch (*Caesioperca lepidoptera*), scarlet wrasse (*Pseudolabrus miles*), and blue cod (*Parapercis colias*). Abundance data were standardised using a z-score transformation (i.e. difference from the mean and dividing by the standard deviation), which provides a mean of 0 and a standard deviation of 1. This was done in order to provide a relative scale to be able to compare across species but also to compare with data from the "ground-truthing" of the model predictions (see below), which used a slightly different methodology. These species were selected based on their different ecological roles and potentially different relationships with physical environmental variables (Table 2).

Table 2. Description of biological response variables used in the statistical modelling to validate the physical data layers of the regional-scale Marine Environment Classification for Fiordland.

Variable	Description	Indicator
avesize	Average size of sea urchins (*Evechinus chloroticus*)	Sea urchins have been identified as strong interactors of benthic environments (Lawrence 1975) and demonstrated to track changes in benthic productivity (Ebert 1980). Mean size of urchin population size structure serves as a proxy for growth, Aristotle's lantern index and calorific content of gut samples (Smith 2003, Data Source, Wing et al. 2001)
M70	Proportion of sea urchin sizes <70 mm for *Evechinus chloroticus*	Proportion of smaller size classes within the population size structure of kina can be an indicator of the relative strength of recruitment and/or early survivourship to individual sites (Data Source, Wing et al. 2001)
G125	Proportion of sea urchin sizes >125 mm for *Evechinus chloroticus*	Proportion of larger size classes of kina can be an indicator of areas with relatively higher survivourship and growth (Data Source, Wing et al. 2001)
StdevD	Standard deviation of species density/0.25 m^2	Measure of variation in species density, indicating the relative patchiness the species aggregations at a site, often reflecting biological and physical disturbance at the scale of the transect (Data Source: Smith and Witman 1999, Smith 2001).
S_{obs}	Observed species richness of sessile epifaunal invertebrates	Number of species observed at an individual site, a diversity measure relevant to the scale at which species are incorporated over 10's of metres (Data Source: Smith and Witman 1999, Smith 2001).
Ascidiacea	Proportion of ascidians (Phylum Tunicata) of the total number of species in the assemblage, indicating relative predominance of taxa	Ascidians can form a significant component of fouling communities and are characterised by being relatively long-lived and having short-distance larval dispersal. These organisms are generally active suspension-feeders, playing a different functional role in epifaunal invertebrate assemblages. (Data Source: Smith, *unpublished data*).
SCL	Relative abundance of butterfly perch (*Caesioperca lepidoptera*) transformed using z-score	A suspension-feeding fish, commonly associated with deep reefs and galleries, possibly reflecting the availability of larger planktonic food resources (Data Source: Francis et al. 1985, 1986)
LPM	Relative abundance of scarlet wrasse (*Pseudolabrus miles*) transformed using z-score	A benthic carnivore of smaller invertebrates, where abundance patterns may reflect the quality and quantity of these food resources (Data Source: Francis et al. 1985, 1986)
PPC	Relative abundance of blue cod (*Parapercis colias*) transformed using z-score	A benthic carnivore of medium to larger benthic invertebrates, including kina, thought to have a relatively strong site affinity as adults, possibly reflecting adult habitat selectivity (Data Source: Francis et al. 1985, 1986)

Statistical Approach for Ground-Truthing. Predictive models were used to test the accuracy of these against an independent data set obtained during a research cruise in November 2002. Data for ground-truthing predictive models of sea urchin size structure, epifaunal invertebrate diversity, and relative abundance of reef fishes were obtained using similar methods as original data sets used to generate the predictive models (above). A slightly different methodology was used for obtaining information on reef fish abundance, where calibrated timed swims were used instead of transect methodology used in the 1985/86 data set (Francis et al. 1989). These data provided similar estimates of abundance without the potential artefact of disturbance of using tape transects. Reef fish data obtained in 2002 were z-score transformed, as the 1985/86 data set, which provided a comparable measure for testing relationships between predicted and observed relative abundance of reef fishes.

Established relationships of response variables to physical environmental variables using the multi-regression (GAM) technique were used to map out predicted population, community and species-level biological parameters for sea urchins, epifauna, and reef fishes, respectively. Predictive models (based on the Generalized Regression And Spatial Prediction (GRASP) routine (Lehmann, et al. 2002) were constrained along the coastal point buffers, with the consideration that predictions beyond a 100 m from the coastline were not considered to be accurate for rocky reefs. All models had a Gaussian link function, with the exception of M70, G125 and Ascidiacea which had a binomial link function (Table 2). For the purposes of establishing statistical relationships between predicted and observed values, the constraining of predicted biological parameters to the coastal buffers was a practical way of providing predicted values to correspond with ground-truthing sites, as these locations were also within the 100 m radius of the coastal fringe. Further constraints according to substrate type were not performed for the purposes of the ground-truthing, as data collected for testing the predictive models was collected in similar habitat types.

Two regression techniques were used to characterise the relationship between predicted population, species, and community-level parameters. One involved an orthogonal regression, which allows for variation between both x and y variables with a specified error variance ratio (Legendre and Legendre 1998, SAS Institute 2003). For these tests, an error variance ratio of 1 was used, as the error variation in both predicted and observed values from the ground-truthing was assumed to be directly proportional to each other. This regression approach was considered to be a "data-driven" model to characterise the relationship between predicted values from the multi-regression modelling and those observed from the independent ground-truthing data set.

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The second method to characterise the relationship between predicted and observed biological response variables was fitting a regression of a specified slope (i.e. in this case, slope = 1) to obtain an estimate of how closely the data conformed to this model. This approach was considered to be "model-driven", as it tests a specific hypothesis about how the data of predicted and observed are to be related. Comparisons between the model of specified slope (and confidence intervals) with a line forced through the origin (i.e. slope of 1, having direct proportionality between x and y axes) would be indicative of the relative match between a perfect correlation (i.e. line with a slope of 1, forced through the origin) and those of the constant-slope model. For example, if the 1:1 correlation line was within the confidence intervals of the constant- slope model of data points, results could be considered to be not significantly different from the model of direct proportionality (i.e. the null model).

Ground-truthing sites where model predictions were available (based on the extent of the overlapping physical environmental layers) were limited to 11 sites for sea urchin size frequencies (from 24), 9 sites for epifaunal diversity (from 15), and 33 sites for reef fish assemblages (from 41 total).
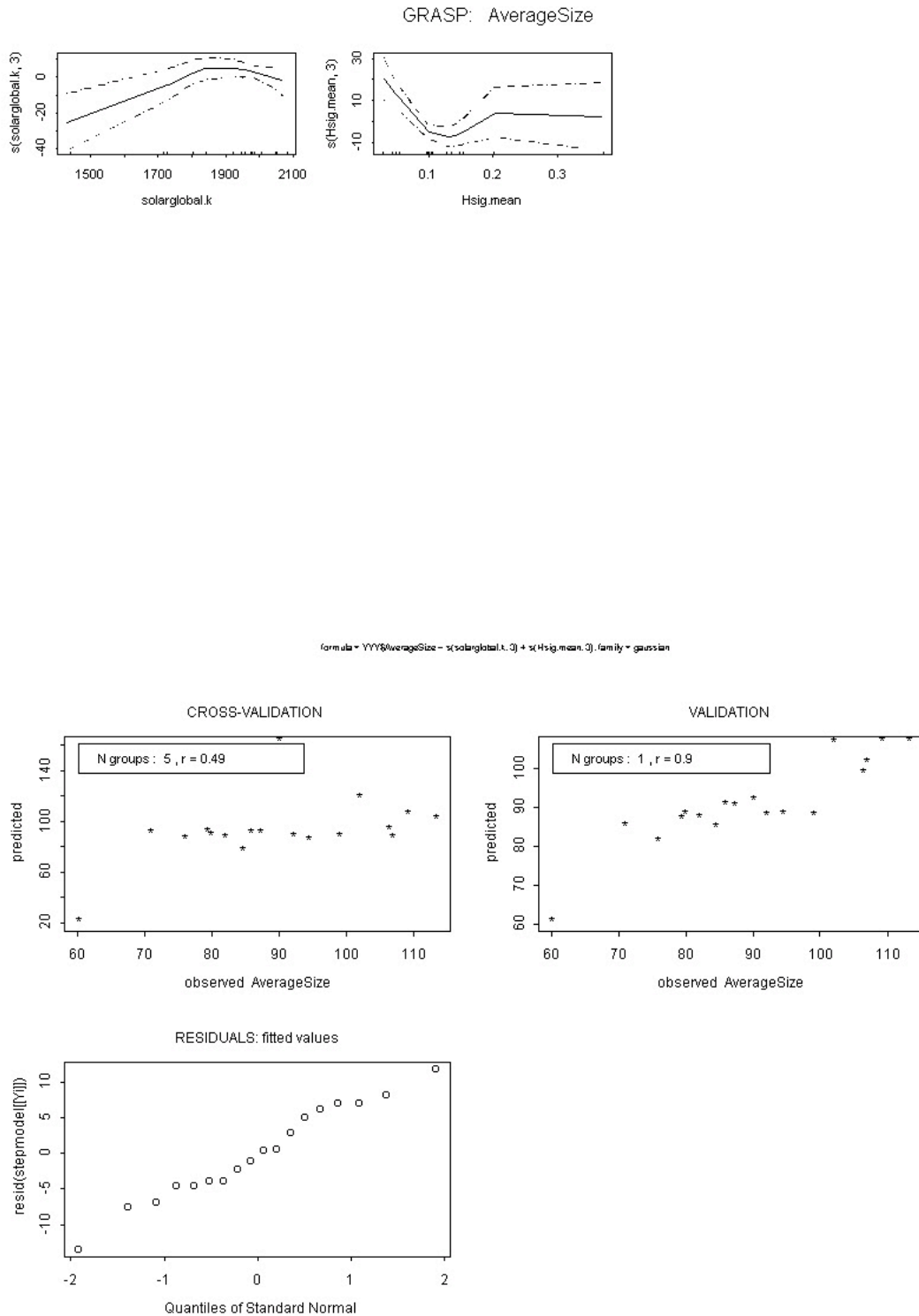

Modelling Results

Population-level Indicators.   The average size of sea urchins showed relationships with global sum of solar radiation and mean significant wave height (Hsig)(Figure 4). The trend with solar radiation was a positively increasing with increasing solar radiation, which came to a saturation point at about 1900 $Wh \cdot m^{-2} \cdot day^{-1}$. There was a steep negative relationship with mean significant wave height (H_{sig}) to approximately 0.1, where there was a levelling off and a small increase, where larger urchins which tended to occur in areas in higher wave exposure. Few sites in areas of comparatively higher wave exposure dominated this pattern with comparatively larger errors associated with the model in this part of the data range. The cross-validation and validation tests for this model had r-values of 0.9 and 0.49, respectively. The plot of the residuals for this model indicated some departure from linearity (Figure 4).

The proportion of sea urchins in the <70 mm size class showed relationships with global solar radiation, significant wave height, and mean surface salinity (Figure 5). The trend with respect to solar radiation showed a decreasing curvilinear trend with increasing solar radiation, which changed to an increasing trend beyond 1800 $Wh \cdot m^{-2} \cdot day^{-1}$.   The relationship with significant wave height (H_{sig}) showed a relatively gradual increase to a maximum of about 0.15 m, with few sites occurring above 2.0 m. The relationship with

increasing salinity to a levelling-off point at about 30 psu (Figure 5). There were few data points at salinities below 25 psu, and large error was associated with the lower part of the trend line. The cross-validation and validation tests for this model both had r-values of 0.17. The plot of the residuals for this model indicated some departure from linearity (Figure 5).

The proportion of sea urchins with a test size >125 mm at individual sites showed relationships to global solar radiation and significant wave height. The relationship showed an increasing function with solar radiation that appeared to level off at about 1800 $Wh \cdot m^{-2} \cdot day^{-1}$ and showed a slight downward trend. There were few sites located in areas with less than 1700 $Wh \cdot m^{-2} \cdot day^{-1}$, which may have contributed to the large error associated with this portion of the trend line. Statistics of the validation and cross-validation showed values of 0.75 and 0.4, respectively, and residuals showed some departure from linearity towards the high end of the residuals (i.e. > 1)(Figure 6).

GRASP: AverageSize

formula = YYY$AverageSize ~ s(solarglobal.k, 3) + s(Hsig.mean, 3), family = gaussian

CROSS-VALIDATION

N groups : 5 , r = 0.49

VALIDATION

N groups : 1 , r = 0.9

RESIDUALS: fitted values

Figure 4. Multi-regression model results for the mean size of *Evechinus chloroticus*. Lines refer to the predictions for individual physical environmental variables and the dotted lines refer to the confidence intervals. Whisker plots at the bottom of each graph refer to the location of actual data points. The lower portion of the figure shows the results of the cross-validation, validation and residuals for the model.
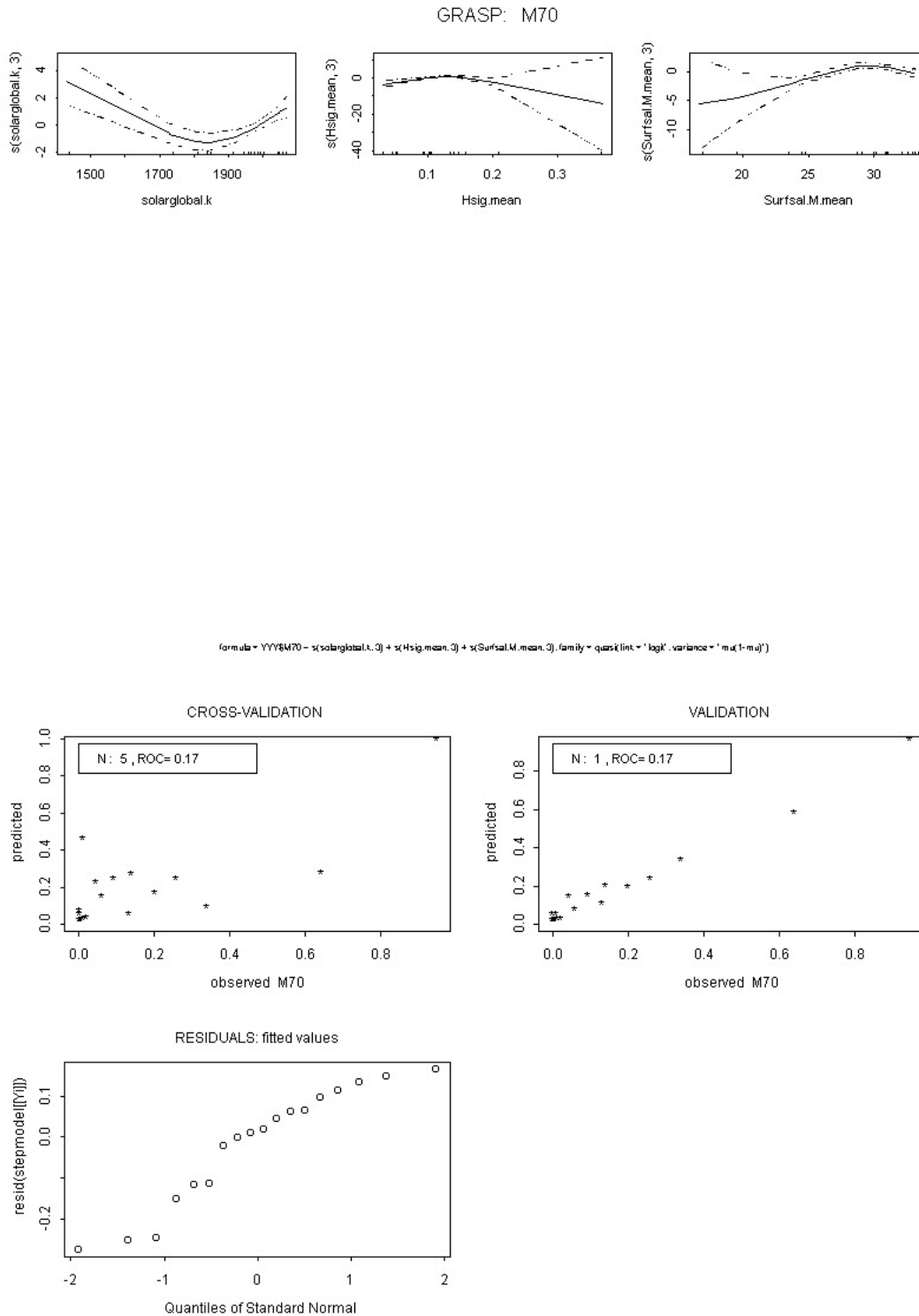
Figure 5. Multi-regression model results for the proportion of size classes <70 mm for *Evechinus chloroticus*. Lines refer to the predictions for individual physical environmental variables and the dotted lines refer to the confidence intervals. Whisker plots at the bottom of each graph refer to the location of actual data points. The lower portion of the figure shows the results of the cross-validation, validation and residuals for the model.