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Prediction of year class strength in southern blue whiting (*Micromesistius australis*) in New Zealand waters

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EXECUTIVE SUMMARY

The number of 2 year old fish in the Campbell Island stock of southern blue whiting, as estimated from an assessment model, varied over 100-fold since 1970. A number of environmental variables were analysed to determine whether they could predict this large variation in year class strength. Two separate analyses were carried out. In the first, estimates of year class strength over the period 1977 to 1992 were modelled as a continuous variable using multiple regression. Three environmental variables explained 86% of the variation in year class strength. However, the predictive powers of the model for 1970 to 1976 and 1993 to 1994 was poor. This poor predictive power may be due to errors in the original estimated year class strengths or to spurious correlations arising from the large number of environmental variables and short time series of recruitment data.

In the second analysis, estimates of year class strength for 1970 to 1994 were categorised into weak, medium, and strong, and modelled as a discrete variable using multiple discriminant analysis. Three environmental variables were selected into the model and classified more than 88% of the year classes into the correct year class using re-substitution. The predictive power of the discriminant function was tested using a cross-validation procedure which resulted in 20 (76%) of the year class strengths being correctly classified. Several of the misclassified years were from the less reliable part of the data set, and no year classes were misclassified from weak to strong or vice versa.

In both models, southern blue whiting year class strength was negatively correlated with anticyclonic, stable atmospheric conditions centred over the Campbell Plateau. The underlying water circulation patterns over the Campbell Plateau, and the influence of climate on its variability, are poorly understood. The reasons for the high variability in the year class strength are therefore unclear.

INTRODUCTION

Southern blue whiting (*Micromesistius australis* Norman) is an important commercial species in New Zealand waters. The fishery was developed in the early 1970s by the Soviet fleet and since then landings have fluctuated considerably, averaging about 20 000 t and peaking at over 75 000 t in 1992 (Figure 1). The fishery targets southern blue whiting when they aggregate to spawn on the Campbell Island Rise, Bounty Platform, Pukaki Rise, and the Auckland Islands Shelf (Figure 2). Fish from these four grounds appear to form separate stocks (Hanchet 1998a), and are treated separately for stock assessment and management purposes.

Annual stock assessments have been carried out for this species since 1990. Early assessments used age structured stock reduction analysis fitted to CPUE data and assumed deterministic recruitment (Hanchet 1991). More recently, time series of catch-at-age data have been developed, and these have allowed the development and use of more complex catch-at-age models such as separable Sequential Population Analysis and VPA (Hanchet 1998b). These models typically estimate large (100-fold) annual fluctuations in year class strength. Because of this large variation, and the increased reliance of the fishery on the recruiting year classes, it is important to be able to predict recent year class strengths for use in short-term projections of biomass and yields.

The influence of ocean climate on fish populations has been known for a long time, and has been the focus of research for the last two decades (e.g., Cushing 1982, Beamish & McFarlane 1989, Beamish 1995). Many studies have attempted to link variability in year class strength to climatic factors (e.g., Hollowed & Woosher 1992, Megrey *et al.* 1995). Some studies were unable to establish strong environmental links to recruitment, and in others, although initially successful, the correlations have broken down over time (*see* Walters & Collie 1988, Mann 1993). Establishing causal links between recruitment indices and climate variability has often proved difficult because factors influence recruitment in complex ways. Changes in sea temperature can affect fish recruitment patterns through changes in larval and juvenile growth rates or mortality rates, primary production, feeding rates and dispersion or aggregation of predators and prey (Mann 1993, Renwick *et al.* 1998).

Although some authors have criticised the continued search for recruitment predictors because of biases, measurement error (in both environmental variability and biotic response), and the likelihood of spurious correlations (Walters & Collie 1988), others have advocated continued use of correlative studies as long as they are based on a sound conceptual framework and judicious use of statistical methods to avoid spurious results (Tyler 1992).

Two studies have examined factors that might affect year class strength in southern blue whiting. Shpak & Kuchina (1983) examined the effect of micro-circulation and temperature on the number of spawners and the resulting egg densities on the Bounty Platform during the period 1973 to 1976. They postulated that average temperatures and anticyclonic (stable) water circulation patterns were most favourable for the reproduction of southern blue whiting. Hanchet (1993) found that the estimated number of 2 year olds in the Campbell Island stock between 1982 and 1992 was positively correlated ($r^2 = 0.64$) with September sea surface temperatures (SST) in the year they were spawned. However, the temperatures came mainly from commercial fishing vessels and were possibly unreliable, and no other environmental variables were examined.

Although model estimates of the number of 2 year olds exist for three stocks of southern blue whiting (Campbell Island Rise, Bounty Platform, and Pukaki Rise), it was decided to focus this study on the Campbell Island stock. This is because historically most fishing has been carried out on this stock, the time series of year class strengths is more extensive for this stock, and the meteorological station at nearby Campbell Island provided additional environmental data on local climate in the area.

The aim of the current work was to determine whether year class strength from the Campbell Island Rise could be predicted from environmental data. We initially identified the critical periods of the life history of southern blue whiting which may influence its survival rates between years. Next, we summarised what is known about its physical environment and identified appropriate spatial and temporal scales for the environmental factors that might be influencing year class strength. Lastly, we compared the time series of selected environmental variables with the time series of year class strength.

BACKGROUND

Early life history

Spawning occurs mainly in August on the Bounty Platform and September on the Pukaki Rise, Auckland Islands Shelf and Campbell Island Rise (see Figure 2). Spawning around the Campbell Island area occurs in midwater over depths ranging from 450 to 600 m (Ingerson & Hanchet 1995). Few data are available on the early development and/or distribution of juvenile southern blue whiting. However, the early life history of the closely related blue whiting (*M. poutassou*) has been studied extensively in the northeast Atlantic (Bailey 1982), and the following account is taken from his review. The eggs of blue whiting are positively buoyant, and take about 5 days to hatch at 10 °C. Blue whiting larvae start feeding about 6 days after hatching. Young larvae feed on young stages of small crustaceans, particularly copepod eggs and nauplii, and older larvae feed more on copepodities. Larval growth rate is estimated to be 3–5% in length per day. The larvae appear to ascend as they grow, and 1–2 months after spawning are confined mainly to surface waters. The juvenile fish are believed to remain in midwater until about the end of their first summer when some become distributed close to the seabed.

The early life history of southern blue whiting is probably very similar. Based on the hatching time-water temperature relationship given by Bailey (1982), southern blue whiting eggs are predicted to take about 7 days to hatch (the typical mixed layer winter water temperature on the Campbell Plateau is about 7 °C; NIWA, unpublished data). There have been no juvenile fish surveys carried out in the area. Despite a large number of bottom trawl surveys carried out throughout the year in the area (e.g., van den Broek *et al.* 1984, Hatanaka *et al.* 1989, Hurst & Schofield 1995), southern blue whiting are rarely caught until they are over 1 year old. Only one trawl shot, in April 1982 in 270 m on the northern edge of the Campbell Island Rise, has caught reasonable numbers of 0+ fish (n = 138), and these had a modal fork length of 120 mm (van den Broek *et al.* 1984).

However, large numbers of 0+ southern blue whiting have recently been reported in the diet of the black-browed albatross (*Diomedea melanophrys impavida*) and rockhopper penguins (*Eudyptes chrysocome*) breeding at Campbell Island (Cherel *et al.* 1999). Black-browed albatross preyed upon a single size class of fish with a mode at 80 to 90 mm standard length (90–100 mm fork length). Satellite tracking showed that, on short trips breeding albatrosses foraged within the 1000 m depth contour in the subantarctic zone north of Campbell Island. The limited foraging range and diving ability of both species during chick rearing, together with the presence of large numbers of fish in their diet, suggest that 0+ southern blue whiting occur in dense schools in the upper few metres of the water column near Campbell Island during the summer months.

Physical setting

The hydrology of the area south of New Zealand has been summarised by Burling (1961) and Heath (1975, 1981). The general eastward circulation of water south of New Zealand is complicated by the influence of the Campbell Plateau, an extensive underwater platform extending south of the New Zealand land mass. The resulting bathymetric diversion of the flows leads to a complex circulation, but at the same time limits any large temporal variability in the position of the fronts (Heath 1981). Two major fronts and three major water masses occur in this area (Figure 3). Warmer, more saline, Subtropical Water to the north is separated from cooler, less saline, Subantarctic Water to the south by the Subtropical Front, which extends east through the Snares Trough and then north along the east coast of the South Island as the Southland Front (Heath 1981). The Subantarctic Front extends along the southern and eastern flank of the Campbell Plateau and separates Australasian Subantarctic Water to the north from Circumpolar Subantarctic Water to the south. The associated flow is the Constricted Current discussed by Burling (1961).

The Australasian Subantarctic Water is formed to the west of New Zealand by the mixing of Subtropical Water and Circumpolar Subantarctic Water (Heath 1981), where it is also known as Subantarctic Mode Water. Australasian Subantarctic Water on the Campbell Plateau appears to be cooler and less saline than further west. The reasons for this are unclear. Burling (1961) postulated the presence of a counter-clockwise gyre (the Bounty-Campbell Gyre), centred on the northern Campbell Plateau, that resulted in the advection of cooler less saline water south onto the Campbell Plateau. Heath (1975) found evidence of a weak anticlockwise movement centred on 47° S and 171° E, that he stated was in a similar location to the Bounty-Campbell Gyre given by Burling (1961). However, Heath (1981) later concluded that the reduced salinity (and presumably temperature) on the Campbell Plateau was a result of excess precipitation over evaporation, and made no reference to the Gyre. A current research project is examining the circulation over the Campbell Plateau (Anon 1998). Preliminary results from research voyages in May, September, and October 1998, based on ADCP surface velocities and geostrophic flows, showed strong flows along the southern flank of the Campbell Plateau (Burling's constricted current), and a weaker westward flow of water along the northern flank of the Campbell Plateau, to the north of the Pukaki Rise (M.Morris, NIWA, pers. comm.). Circulation over the Campbell Plateau itself was generally weak, with postulated southward flows occurring to the west of the Pukaki Rise and eastward flows between the Pukaki Rise and Campbell Island Rise, and westward flows over the Campbell Island Rise itself. These observations are suggestive of weak anticyclonic circulation over the Pukaki Rise and Campbell Island Rise, but do not support the larger scale hypothesised Bounty-Campbell Gyre (M.Morris, NIWA, pers. comm.).

Heath (1981) also noted that water over the Campbell Plateau had weak thermal structure brought about by enhanced mixing over shallow depths. During winter, water was well mixed and nearly isothermal in the upper 300 m. Isothermal water down to depths of 500 m has also been recorded during the recent surveys (NIWA, unpublished data).

In middle latitudes, much of the seasonal to interannual variability in the ocean climate is thought to be forced by changes in the atmospheric circulation (Lau 1997). The atmosphere modifies the upper layers of the ocean mainly through heat and momentum transfers at the ocean surface. Changes in these transfers cause variations in the temperature and depth of the ocean mixed layer, which may affect the stability and rate of mixing in the water column, and the distribution of nutrients and primary productivity.

Little is known about the inter-annual variability in the circulation or hydrology within the area. Farkas (1972) presented SST data from Perseverance Harbour on Campbell Island (collected by the bucket method). After eliminating seasonal variation (by using 12-monthly running means) she found between year variations of less than 1 °C. She compared meridional pressure gradients centred on Campbell Island with SST, but found October variations were small and negatively correlated. She did not attempt to relate SST variations to watermass circulation. SSTs recorded from trawl surveys carried out in the same season have also differed by less than 1 °C between years (NIWA, unpublished data).

Primary productivity

Heath & Bradford (1980) examined the distribution of chlorophyll *a* and factors affecting phytoplankton production over the Campbell Plateau. They found that chlorophyll *a* reached maximum concentrations in areas shallower than 450 m (e.g., west Pukaki Rise, north Campbell Island Rise, and north Bounty Platform) and was generally low elsewhere. They concluded that the water column stability was insufficient to support high phytoplankton production over the deeper regions of the Plateau, because phytoplankton were mixed below the critical depth where photosynthesis could occur. However, in the shallower regions the seabed acted in a similar way to a seasonal thermocline and retained the phytoplankton in shallow enough water for maximum production to be maintained. Areas of high zooplankton biomass were found only downstream of the areas of primary productivity.

METHODS

Recruitment time series

Estimates of the relative number of 2 year olds were obtained using separable Sequential Population Analysis, an age structured population model which has been used in stock assessments of southern blue whiting since 1994 (Hanchet & Haist 1994, Hanchet 1998b, Hanchet *et al.* 1998). The model was fitted to the catch history for 1972 to 1996, catch at age data (age 2 to 20+) for 1979 to 1996, CPUE indices for 1986 to 1996, and adult acoustic abundance indices from 1993 to 1995 following Hanchet (1998b). The proportion of the catch on the Campbell Island ground from 1972 to 1978 is unknown and for the analysis was assumed to equal the average from 1978 to 1996. Although the true proportion may be different from this, Hanchet (1998b) showed that the biomass and year class strength estimates from the model were relatively insensitive to the value used. Model estimates of the relative number of 2 year old fish in the population were obtained for 1972–96 (Figure 4).

Because catch at age data were not available for the earlier years, and the proportion of the commercial catch taken from the Campbell Plateau during those years is unknown, there is some uncertainty surrounding the early estimates of year class strength. The strength of the most recent 1–2 year classes are also poorly estimated by the model. The most reliable estimates of 2 year olds are therefore available for 1979 to 1994 (the 1977 to 1992 year classes). Although there is uncertainty surrounding the estimates of year class strength from the other years, they are probably qualitatively correct (i.e., the strong year classes probably are strong and the weak year classes probably are weak). The estimates of year class strength from all years were therefore divided qualitatively into weak, medium, and strong categories using the levels shown in Figure 4.

The stock assessment model assumes that no stock-recruitment relationship exists over the range of stock sizes experienced during this period. The model suggests a large decline in biomass from 1982 to 1993 followed by a large increase from 1993 to 1996. There was no obvious trend in recruitment over this period and so a possible stock recruitment relationship has not been considered further in the study.

Identification of spatio-temporal scales

The critical period of life that determines year class strength, if there is one, is not known for either of the *Micromesistius* species. For many other marine teleosts the critical period is believed to be during the first 6 months of life (e.g., Francis 1993, Megrey *at al.* 1995, Renwick *et al.* 1998) when fish are probably most vulnerable to changes in temperature and circulation patterns that may lead to unfavourable conditions for growth and survival. The recruitment estimates from the model were therefore lagged 2 years so that they represented the year that the fish were spawned. In doing this we have made the assumption that the relative abundance of 2 year olds is the same as that of 0+ fish.

Based on seabird diet research (Cherel *et al.* 1999), it appears that at least some 0+ southern blue whiting are located in the surface waters near Campbell Island. Further evidence that they remain close to the spawning ground is that by September large numbers of 1 year old fish may be found on the bottom in a depth of 300 m around the northern and eastern edge of the Campbell Island Rise (Grimes & Hanchet 1999). The geographic region of interest therefore spanned the area surrounding Campbell Island.

Environmental data sets

A number of environmental predictors were examined. Weather patterns were identified using the frequency of occurrence (days per month) of 12 synoptic weather patterns for the New Zealand region. The patterns were derived from a cluster analysis of 40 years' data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay *et al.* 1996). The 40 year time series is an extension of earlier work (Kidson 1994). The field analysed was 1000 hPa height, which is analogous to the mean sea-level pressure field. Cluster mean flow patterns are illustrated in Figure 5.

Several variables were associated with the structure of the lower atmosphere. The variable "thick" measures the mean temperature in the lowest 5 km of the atmosphere. It is calculated as a height difference (or thickness) between two fixed pressure surfaces. Thickness advection (T.adv) measures the relative change in temperature (thickness) as a result of transport by the wind (advection) of warmer or cooler air. Surface vorticity (S.vort) represents vorticity near the Earth's surface, and is a measure of the intensity of depressions and anticyclones. V.adv5 represents the relative change in vorticity resulting from advection at about 5 km above the ground. Both T.adv and V.adv5 are important factors in the development and decay of storms.

As well as the synoptic typing described above, low-level flows in the region just south of New Zealand were described using a principal component analysis (PCA) of monthly mean 1000 hPa heights from the 40 year NCEP/NCAR reanalyses. The leading three patterns and their associated amplitude time series were used in the analysis, capturing 94% of the variance in the region from 35 to 60° S, 150 to 170° E. As is typical of PCA over small regions of spatially homogeneous data (Richman 1986), the patterns depict an in-phase change over the whole grid, followed by zonal and meridional gradients (Figure 6).

Surface wind flows were also characterised in terms of mean north-south and east-west sea-level pressure differences (Z1, M1, etc., as in Trenberth 1976). Lastly, the Southern Oscillation Index (SOI) was included and was calculated as the normalised monthly mean Tahiti minus Darwin sea level pressure (MSLP) difference. The complete set of environmental predictor variables is shown in Table 1.

We chose to examine environmental factors over the nine month period July to March, covering the period immediately before spawning until the end of the first summer. This period was divided into three seasons; winter (July-September), spring (October-December), and summer (January-March) following Francis (1993).

Statistical analysis

Two analyses were carried out: the first used estimates of year class strength as a continuous variable for 1977 to 1992, and the second used the estimates of year class strength qualitatively (weak, medium and strong) from 1970 to 1994 (see Figure 4). Recruitment data are usually lognormally distributed, so year class strength was transformed using natural logarithms before analysis (following Francis 1993, Megrey *et al.* 1995). For the shorter data set, firstly a Pearson's correlation analysis was used to determine the correlation of each environmental variable with year class strength. Next a stepwise multiple regression analysis was carried out to identify the variables which explained most of the variation in year class strength. Because of the large number of predictor variables compared to the small number of observations, many variables could explain a small amount of variation in the year class strength. Therefore, the probability of entry of a predictor variable to the model was set at 0.01, and the probability of exit was set at 0.15 (following Megrey *et al.* 1995, Renwick *et al.* 1998). (That is, a predictor variable entered the model only if it was significant at the 1% level, and was retained in the model only if it was significant at the 15% level.) Finally, a multiple regression was carried out to determine the coefficients of the predictor variables selected in the stepwise procedure, and to obtain r^2 and adjusted r^2 values for the model. Auto-correlation of the residuals was examined using the Durbin-Watson statistic. The regression model was then used to predict year class strengths for 1970–76 and 1993–94, and to compare these with the estimates from the population model.

The longer time series of recruitment data (1970–94) was analysed using multiple discriminant analysis with the STEPDISC, DISCRIM, and CANDISC procedures of SAS (SAS Institute 1988). Initially a stepwise discriminant analysis (STEPDISC) was carried out to identify which variables significantly improved the discrimination between year class strength ($P < 0.05$). Again, because of the large number of predictor variables, the probability of entry of a predictor variable to the model was set at 0.01, and the probability of exit was set at 0.15. Then a discriminant function analysis (DISCRIM) used most important predictor variables selected in the stepwise procedure to determine class rules. Because the three levels of year class strength were ordinal (i.e., ranked from low to high) only one discriminant function was computed.

Classification success was determined using both resubstitution and cross-validation procedures (SAS Institute 1988). In resubstitution, the training data set is used to both produce and to test the discriminant function. In cross-validation, each year class is removed from the data set in turn and then classified into the class rules determined by the remaining year classes. This is a more reliable measure of the predictive power of the model (SAS Institute 1988). The probability of classification by the discriminant function into each year class was examined to determine which years were incorrectly classified using both re-substitution and cross-validation procedures. Finally, a canonical discriminant analysis (CANDISC) was carried out using only the variables selected above to determine the coefficients of the predictor variables in the discriminant function and to compare the class means. Four multivariate statistics (Wilk's Lambda, Pillai's Trace, Hotelling-Lawley Trace, and Roy's Greatest Root with F approximations) were used to test the hypothesis that the class means were equal (SAS Institute 1988).

RESULTS

Correlations

Correlations of year class strength with the seasonal environmental variables are shown in Table 2. The most significant correlations were with variables from winter and spring, though no variables were significant with the same sign over more than one season. The highest correlation was with winter PC 1 ($r = -0.73$), which is an anticyclonic air pressure system situated over the Campbell Plateau (see Figure 5). This variable was strongly negatively correlated ($r = -0.84$) with Auckland–Christchurch pressure difference (Z1), and strongly positively correlated ($r = 0.77$) with the frequency of high pressure systems to the southeast of Cook Strait (HSE) as well as a number of other environmental variables (Table 3).

A number of other studies have shown that year class strength is correlated with sea surface temperature, so all available sea surface and air temperature data were examined for consistency. Gridded SST and observed SST and air temperature from Campbell Island showed consistent patterns over time (Figure 7). Mean seasonal temperatures were all highly correlated with each other ($P < 0.01$) for each season except spring. However, none of the temperature variables were correlated with year class strength (Table 2a, 2b).

Multiple regression analysis

Three variables (winter PC 1, summer TSW, and winter M2) entered the model, and together explained 86% of the variation in year class strength (Table 4). First-order auto-correlation of the residuals from the regression was not significant ($P > 0.05$). Winter PC 1 had a negative relationship with year class strength (Figure 8a), and by itself explained 53% of the variation in year class strength. Summer TSW had a positive relationship with year class strength (Figure 8b), and by itself explained 36% of the variation in year class strength. The predicted and observed year class strengths from the full model are shown in Figure 9. The model appears to fit the strong and weak year classes particularly well over the period of the model. However, the model performs poorly when used to predict the early (pre-1977) and later (post - 1992) year class strengths.

Multiple discriminant analysis

Three variables (winter Z1, summer CI gSST, and spring R) were selected using the stepwise discriminant analysis. Using a discriminant function based on these three variables, 22 (88%) of the year class strengths were correctly classified into one of the three categories (Table 5). All the strong year classes were correctly classified by the model. The three years which were misclassified were all in the early part of the dataset (Table 6): 1971 and 1975 were misclassified as low year class strengths, and 1970 was misclassified as an average year class strength.

When the cross-validation procedure was used the overall classification success dropped to 19 (76%) (Table 7). Classification of weak and strong year classes was again good with only one year misclassified (as a medium) in each case (*see* Table 6). Four of the medium year classes were misclassified, two as strong and two as weak. Three of these years were from either the earlier or the later, less reliable, part of the data set.

Canonical discriminant analysis showed that the discriminant function was significant ($P < 0.01$; Likelihood ratio test). All four multivariate tests indicated significant differences in the class means between year class strengths ($P < 0.001$). The raw and standardised coefficients of the variables are shown in Table 8 and the class mean scores in Table 9. Winter Z1 and summer CI gSST were the most important variables, and both had a positive relationship with year class strength.

DISCUSSION

The multiple regression model had good explaining power for the short data set but poor predictive power for the earlier and later years. This could be because the year class strengths in the other years were poorly estimated by the population model. Spurious trends in recruitment could be generated from incorrect parameter estimates used in the age structured analysis to produce the original year class strength estimates (Megrey *et al.* 1995). These include incorrect estimates of natural mortality, weight at age, incorrect catch history, errors in the catch at age through ageing and sampling errors, observation error in the catch per unit effort and acoustic abundance indices, and model mis-specification. However, the sensitivity of the model results to changes in the parameter estimates and weightings given to the various indices are routinely examined in stock assessments of southern blue whiting, and estimates of year class strength appear reasonably robust (Hanchet & Haist 1994, Hanchet 1997, Hanchet *et al.* 1998). Furthermore, Hanchet (1998b) compared year class strengths from four different age structured models including Virtual Population Analysis and stock reduction analysis with various maximum likelihood and least squares estimators, and although historical biomass varied considerably between the models, the year class strengths were qualitatively similar. In general, the signal in the catch at age data is so strong and consistent between years that the estimates of year class strength are qualitatively reliable.

Another reason for the poor predictive power of the regression model is the large number of environmental variables used in the analysis, and the relatively short time series of data on which it is based. In the analysis a large number of environmental variables were scanned to determine which provided the best fit, and in doing so it is possible that spurious correlations may have been developed (Tyler 1992, Francis 1993). Although protection against Type 1 error is possible in a univariate analysis (i.e., by adjusting significance levels using the Dunn-Sidak method) (Francis 1993), it is not possible to carry out a similar approach in the multiple regression analysis used here.

Division of year class strength into the three categories of weak, medium and strong allowed the development of a longer data set and appeared to result in a more robust analysis. Classification success using both re-substitution and cross-validation was greater than 75%, and there were no misclassifications from weak to strong or vice versa. In particular, most of the strong year classes were predicted correctly by the model.

Although the final variables used in the two models were different there was some consistency between the two analyses. The two most important predictor variables (PC 1 and Z1) were negatively correlated ($r = -0.86$). PC1 was also correlated with a range of other variables that are indicative of an anticyclonic weather pattern over the Campbell Plateau that would lead to anticlockwise winds and generally more stable, warmer climatic and possibly marine conditions. However, southern blue whiting year class strength was negatively correlated to this suggesting that less stable, cooler conditions are more suitable for stronger year classes.

Heath & Bradford (1980) showed that maximum primary production on the Campbell Plateau occurred over the shallower areas to the north of the Campbell Island Rise and west of the Pukaki Rise, and that the highest zooplankton biomass was immediately downstream of these. The optimal location for larval and juvenile southern blue whiting should therefore be close to these areas, although predation there may also be higher (Cherel *et al.* 1999.). We hypothesise that circulation patterns which transported eggs and larvae to the area to the north of the Campbell Island Rise, and retained them there, would be important predictors of year class strength. Unfortunately, the underlying water circulation over the Campbell Plateau area is poorly known, and is currently under investigation (Anon 1998). Once the baseline data are collected it may be possible to speculate on how particular climatic conditions may change the underling circulation patterns and therefore influence year class strength.

Unlike results of other studies in New Zealand (Francis 1993, Renwick *et al.* 1998, Livingston, NIWA, pers. comm.) correlations of year class strength with sea surface temperatures were weak. Stronger year classes appeared to be associated with cooler winter SSTs observed at Campbell Island over the few years where data were available (see Table 2b), but this correlation was not significant. Summer gridded SST entered the model in the discriminant analysis, but strong year class strength was associated with warmer summer temperatures (3–6 months after spawning).

The results of the present study are different from those of Shpak & Kuchina (1983) and Hanchet (1993). Shpak & Kuchina (1983) studied the Bounty Platform stock and concluded that average water temperatures and anticyclonic circulation patterns were most favourable for reproduction of southern blue whiting. In the present study, year class strength on the Campbell Island stock was negatively correlated with anticyclonic weather patterns. Hanchet (1993) found a positive correlation between September SST and Campbell Island year class strength. However, his results were based on a short time series, and the temperature recordings came mainly from commercial fishing vessels which were possibly unreliable.

Although the causal relationship between the year class strength and the environmental variables is unknown, the predictive capabilities of the discriminant function appeared to be good. The ability to predict year class strength, even at the gross levels used here, is important for stock projections which normally assume some mean recruitment level (e.g., Hanchet 1997). As our understanding of the circulation patterns surrounding the Campbell Plateau area improves, we may be able to understand better the effects of climatic forcing on the underlying circulation and perhaps understand better the reasons for the variability in southern blue whiting year class strength.

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REFERENCES

Anon. 1998: Measuring southern ocean currents. *Seafood New Zealand 6 (4): 26.*

Bailey, R.S. 1982: The population biology of blue whiting in the North Atlantic. *Advances in marine biology 19:* 257–355.

Beamish, R.J. (Ed.) 1995: Climate change and northern fish populations. *Canadian Special Publication of Fisheries and Aquatic Sciences 121.* 739 p.

Beamish, R.J. & McFarlane, G.A. (Eds) 1989: Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. *Canadian Special Publication of Fisheries and Aquatic Sciences 108.* 379 p.

Burling, R.W. 1961: Hydrology of circumpolar waters south of New Zealand. *New Zealand Oceanographic Institute Memoir 10.* 66 p.

Cherel, Y., Waugh, S., & Hanchet, S.M. 1999: Albatross predation of juvenile southern blue whiting *Micromesistius australis* on the Campbell Plateau. *New Zealand Journal of Marine and Freshwater Research 33:* 437–442.

Cushing, D.H. 1982: Climate and Fisheries. Academic Press, London. 373 p.

Farkas, E. 1972: Sea surface temperatures and atmospheric circulation anomalies south of New Zealand during 1957 to 1966. *New Zealand Journal of Marine and Freshwater Research 6:* 133–147.

Francis, M.P. 1993: Does water temperature determine year class strength in New Zealand snapper (*Pagrus auratus,* Sparidae)? *Fisheries Oceanography 2:* 65–72.

Grimes, P. & Hanchet S.M. 1999: Acoustic biomass estimates of southern blue whiting (*Micromesistius australis*) from the Bounty Platform and Pukaki Rise, August-September 1997. N.Z. Fisheries Assessment Research Document 99/12. 28 p.

Hanchet, S.M. 1991: Southern blue whiting fishery assessment for the 1991–92 fishing year. N.Z. Fisheries Assessment Research Document 91/7. 48 p.

Hanchet, S.M. 1993: Southern blue whiting (*Micromesistius australis*) fishery assessment for the 1993–94 fishing year. N.Z. Fisheries Assessment Research Document 93/17. 56 p.

Hanchet, S.M. 1997: Southern blue whiting (*Micromesistius australis*) fishery assessment for the 1996–97 and 1997–98 fishing years. N.Z. Fisheries Assessment Research Document 97/14. 32 p.

Hanchet, S.M. 1998a: A review of southern blue whiting (*M. australis*) stock structure. N.Z. Fisheries Assessment Research Document 98/8. 28 p.

Hanchet, S.M. 1998b: Documentation of the separable Sequential Population Analysis used in the assessments of southern blue whiting (*M. australis*), and a comparison with other models. N.Z. Fisheries Assessment Research Document 98/33. 22 p.

Hanchet, S.M. & Haist, V. 1994: Southern blue whiting (*Micromesistius australis*) fishery assessment for the 1994–95 fishing year. N.Z. Fisheries Assessment Research Document 94/22. 41 p.

Hanchet, S.M., Haist, V. & Fournier, D. 1998: An integrated assessment of southern blue whiting (*M.australis*) from New Zealand waters using separable Sequential Population Analysis. *In:* Funk, F., T. J. Quinn II, J. Heifetz, J. N. Ianelli, J. E. Powers, J. F. Schweigert, P. J. Sullivan, & C. -I. Zhang, (eds) Fishery stock assessment models. Alaska Sea Grant College Program Report No. AK-SG-98-01, University of Alaska Fairbanks, 1998.

Hatanaka, H., Uozumi, Y., Fukui, J., Aizawa, M., & Hurst, R.J. 1989: Japan-New Zealand trawl survey off southern New Zealand, October–November 1983. *N.Z. Fisheries Technical Report No. 9.* 52 p.

Heath, R.A. 1975: Oceanic circulation and hydrology off the southern half of New Zealand. *New Zealand Oceanographic Institute Memoir 72.* 36 p.

Heath, R.A. 1981: Oceanic fronts around southern New Zealand. *Deep-sea Research 28A:* 547–560.

Heath, R.A. & Bradford, J.M. 1980: Factors affecting phytoplankton production over the Campbell Plateau, New Zealand. *Journal of Plankton Research 2:* 169–181.

Hollowed, A.B. & Wooster, W.S. 1992: Variability of winter ocean conditions and strong year classes of Northeast Pacific groundfish. *ICES Marine Science Symposium 195*: 433–444.

Hurst, R.J. & Schofield, K.A. 1995: Winter and summer trawl surveys of hoki south of New Zealand. *N.Z. Fisheries Technical Report No. 43.* 55 p.

Ingerson, J.K.V. & Hanchet, S.M. 1995: Catch per unit effort (CPUE) analysis of the Campbell Island Rise southern blue whiting (*Micromesistius australis*) fishery from 1986 to 1994. N.Z. Fisheries Assessment Research Document 95/21. 15 p.

Kalnay, E. et al., 1996: The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77: 437–471.

Kidson, J.W. 1994: An automated procedure for the identification of synoptic types applied to the New Zealand region. *International Journal of Climatology 14*: 711–721.

Lau, N.C. 1997: Interactions between global SST anomalies and the midlatitude atmospheric circulation. *Bulletin of American Meteorological Society 78:* 21–33.

Mann, K.H. 1993: Physical oceanography, food chains, and fish stocks: a review. *ICES Journal of Marine Science 50:* 105–119.

Megrey, B.A., Bograd, S.J., Rugen, A.B., Hollowed, P.J., Macklin, S.A., Schumacher, J.D., & Ingraham Jr., W.J. 1995: The exploratory analysis of associations between biotic and abiotic factors and year class strength of Gulf of Alaska walleye pollock (*Theragra chalcogramma*). *In* Beamish, R.J. (Ed.). Climate change and northern fish populations. *Canadian Special Publication of Fisheries and Aquatic Sciences 121:* 227–243.

Renwick, J.A., Hurst, R.J., & Kidson, J.W. 1998. Climatic influences on the recruitment of southern gemfish (*Rexea solandri*, Gempylidae) in New Zealand waters. *International Journal of Climatology 18:* 1655–1667.

Richman, M.B., 1986: Rotation of principal components. *Journal of Climatology* 6: 293–335.

SAS Institute 1988: SAS/STAT user's guide, release 6.03 edition. Cary, NC: SAS Institute Inc., 1988. 1028 p.

Shpak, V.M. & Kuchina, V.V. 1983: Dynamics of abundance of southern putassu. *Biologiya Morya 2*: 35–39. (Translation held in NIWA library, Wellington.)

Trenberth, K.E. 1976: Fluctuations and trends in indices of the Southern Hemisphere circulation. *Quarterly Journal of the Royal Meteorological Society* 102: 65–75.

Tyler, A.V. 1992: A context for recruitment correlations: why marine fisheries biologists should still look for them. *Fisheries Oceanography 1:* 97–107.

van den Broek, W.L.F., Tokusa, K., & Kono, H. 1984: A survey of demersal fish stocks in waters south of New Zealand, March–May 1982. *Fisheries Research Division Occasional Publication No. 44.* 51 p.

Walters, C.J. & Collie, J.S. 1988: Is research on environmental factors useful for fisheries management? *Canadian Journal of Fisheries and Aquatic Sciences 45:* 1848–1854.

Table 1: List of environmental variables used in the analysis

CI Tav	Campbell Island average air temperature
CI gSST	Gridded SST from point nearest Campbell Island
CI oSST	Observed SST from Perseverance Harbour (Campbell Island)
TSW	"Trough in southwest flow" weather type (monthly frequency)
T	"Broad trough over New Zealand" weather type (monthly frequency)
SW	"Southwest flow" weather type (monthly frequency)
NE	"Northeast flow" weather type (monthly frequency)
R	"Ridge across South Island" weather type (monthly frequency)
HW	"High west of South Island" weather type (monthly frequency)
HE	"High east of North Island" weather type (monthly frequency)
W	"Westerly flow" weather type (monthly frequency)
HNW	"High to northwest" weather type (monthly frequency)
TNW	"Northwest flow ahead of trough" weather type (monthly frequency)
HSE	"High southeast of Cook Strait" weather type (monthly frequency)
H	"High over New Zealand" weather type (monthly frequency)
PC 1	Campbell-area 1000hPa height principal component 1 ("high")
PC 2	Campbell-area 1000hPa principal component 2 ("westerly")
PC 3	Campbell-area 1000hPa principal component 3 ("northerly")
thick	1000-500hPa mean depth at Campbell
S.vort	Mean surface vorticity at Campbell
T.adv	Mean lower-troposphere temperature advection at Campbell
V.adv5	Mean mid-tropospheric vorticity advection at Campbell
Z1	Auckland - Christchurch pressure difference
Z2	Christchurch - Campbell pressure difference
M1	Hobart - Chathams pressure difference
M2	Hokitika - Chathams pressure difference
SOI	Southern Oscillation index

Table 2: Pearson's correlation coefficients of seasonal variables with $\log_e$ YCS for the period (a) 1977 to 1992, and (b) 1985 to 1995. Bolded figures are significant ($P < 0.05$)

Variable	Winter	Spring	Summer
(a)			
CI Tav	-0.42	0.30	0.17
CI gSST	0.15	-0.19	0.33
TSW	-0.16	0.29	**0.60**
T	**0.58**	-0.13	-0.01
SW	0.47	0.09	0.06
NE	-0.03	0.23	0.34
R	-0.04	0.23	0.09
HW	**-0.51**	0.06	0.06
HE	-0.31	-0.10	0.00
W	0.48	-0.33	-0.03
HNW	0.01	**-0.57**	-0.23
TNW	0.15	0.17	0.16
HSE	**-0.62**	0.10	-0.44
H	-0.45	-0.12	-0.26
PC 1	**-0.73**	0.33	0.06
PC 2	-0.23	**-0.54**	-0.49
PC 3	-0.05	0.03	-0.20
thick	-0.23	0.29	-0.10
S.vort	**-0.51**	0.11	-0.13
T.adv	0.01	0.31	-0.07
V.adv5	0.01	0.23	0.13
Z1	**0.59**	**-0.53**	-0.26
Z2	0.12	-0.45	-0.35
M1	0.10	0.03	0.13
M2	0.21	0.00	-0.15
SOI	0.27	0.24	0.18
(b)			
CI oSST	-0.45	-0.01	-0.24

Table 3: Pearson's correlation coefficients of winter variables with PC 1, PC 2, and PC 3 for the period 1977 to 1992. Bolded figures are significant (P < 0.05)

Variable	PC 1	PC 2	PC 3
CI Tav	**0.51**	0.04	**0.65**
CI gSST	0.02	0.35	0.18
TSW	0.02	**-0.56**	-0.07
T	**-0.65**	**-0.61**	-0.17
SW	**-0.68**	-0.05	**-0.58**
NE	**0.4**	-0.3	0
R	**0.47**	-0.09	0.01
HW	0.25	0.29	-0.06
HE	0.39	0.15	**0.48**
W	**-0.56**	0.37	-0.03
HNW	-0.23	**0.72**	-0.33
TNW	-0.09	**-0.62**	0.11
HSE	**0.77**	-0.13	0.33
H	0.23	**0.83**	0.21
PC 1	1	0.11	0.28
PC 2	0.11	1	0.04
PC 3	0.28	0.04	1
thick	**0.72**	-0.02	**0.44**
S.vort	**0.68**	-0.07	**0.49**
T.adv	0.37	-0.13	**0.63**
V.adv5	-0.14	0.2	**-0.47**
Z1	**-0.83**	0.27	-0.08
Z2	-0.36	**0.85**	-0.04
M1	**-0.47**	0	**-0.81**
M2	**-0.44**	0.34	**-0.47**
SOI	0.13	-0.24	0.24

Table 4: Results of multiple regression analysis relating $\log_e$ year class strength to environmental variables for 1977 to 1992

(A) Regression

Dependent variable	r^2	Adj. r^2	Independent variable	Regression coefficient	Standard error	*t*	*p*
$\log_e$ YCS	0.884	0.855	Intercept	-1.9096	0.2908	-6.5660	0.0001
			Winter PCA1	-1.3669	0.1864	-7.3320	0.0001
			Summer Tr.SW	0.2483	0.0457	5.4320	0.0002
			Winter M2	-0.0268	0.0077	-3.4980	0.0044

(B) Analysis of Variance

Source	Sum of squares	DF	Mean Square	F	Prob > F
Model	20.949	3	6.983	30.601	0.0001
Error	2.738	12	0.228		
Total	23.687	15			

Table 5: The number of year class strengths classified by linear discriminant analysis into each year class category using resubstitution. 1, weak; 2, medium; 3, strong. Values bolded represent the number correctly classified

From category	To category			
	1	2	3	Total
1	**7**	1	0	8
2	2	**8**	0	10
3	0	0	**7**	7
Total	9	9	7	25

Table 6: Results and probability of classification by a discriminant function into year class categories using re-substitution and cross-validation procedures. *, indicates year class misclassified. Year class categories. 1, weak; 2, medium; 3, strong

Year	From YCS category	Resubstitution				Cross-validation			
		To	weak	medium	strong	To	weak	medium	strong
1972	1	2*	0.11	0.85	0.05	2*	0.03	0.92	0.05
1973	2	1*	0.70	0.27	0.03	1*	0.82	0.14	0.03
1974	2	2	0.19	0.71	0.10	2	0.23	0.65	0.13
1975	1	1	0.97	0.02	0.00	1	0.97	0.03	0.00
1976	1	1	0.60	0.39	0.01	1	0.54	0.44	0.01
1977	2	1*	0.71	0.29	0.00	1*	0.99	0.01	0.00
1978	1	1	0.97	0.03	0.00	1	0.96	0.04	0.00
1979	1	1	0.99	0.01	0.00	1	0.99	0.01	0.00
1980	1	1	0.73	0.27	0.00	1	0.71	0.29	0.00
1981	3	3	0.01	0.16	0.84	3	0.01	0.18	0.81
1982	3	3	0.00	0.00	1.00	3	0.00	0.00	1.00
1983	2	2	0.04	0.92	0.04	2	0.05	0.90	0.05
1984	1	1	0.77	0.23	0.00	1	0.59	0.41	0.00
1985	2	2	0.00	0.69	0.31	2	0.00	0.62	0.38
1986	3	3	0.00	0.29	0.71	3	0.00	0.41	0.59
1987	2	2	0.00	0.69	0.31	3*	0.00	0.38	0.62
1988	3	3	0.03	0.44	0.53	2*	0.05	0.66	0.29
1989	2	2	0.07	0.92	0.01	2	0.08	0.91	0.01
1990	3	3	0.00	0.22	0.78	3	0.00	0.32	0.68
1991	1	1	0.99	0.01	0.00	1	0.98	0.01	0.00
1992	2	2	0.04	0.91	0.04	2	0.05	0.89	0.05
1993	3	3	0.01	0.37	0.61	3	0.02	0.49	0.49
1994	3	3	0.01	0.13	0.86	3	0.01	0.16	0.83
1995	2	2	0.04	0.51	0.45	3*	0.05	0.43	0.52
1996	2	2	0.02	0.75	0.23	2	0.03	0.68	0.29

Table 7: The number of year class strengths classified by linear discriminant analysis into each year class category using cross-validation. 1, weak; 2, medium; 3, strong. Values bolded represent the number correctly classified

From category	To category			Total
	1	2	3	
1	**7**	1	0	8
2	2	**6**	2	10
3	0	1	**6**	7
Total	9	9	7	25

Table 8: Raw and standardised coefficients of the environmental variables in the discriminant function

Variable	Raw coefficients	Standardised coefficients
Winter Z1 (ACK-CHCH pressure difference)	0.067	1.426
Summer gridded SST	3.348	1.408
Spring “ridge on South Island”	0.249	0.861

Table 9: Class means of the discriminant function

Category	Mean
1	-1.740
2	0.1289
3	1.805

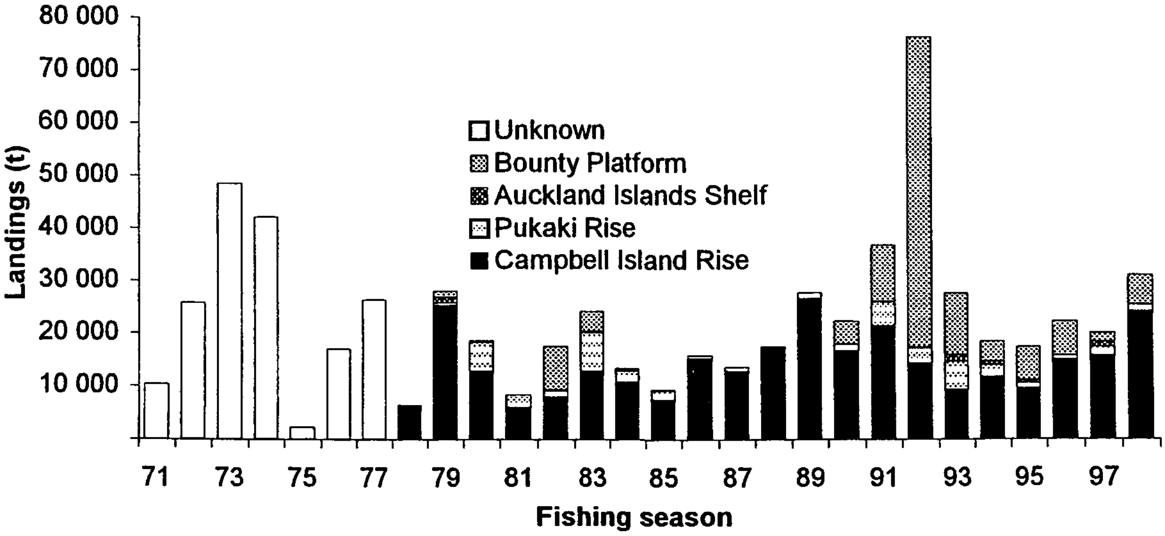

Figure 1: Annual landings of southern blue whiting (t) by the split October-September fishing year. (Note: 97, refers to the 1996–97 fishing year).

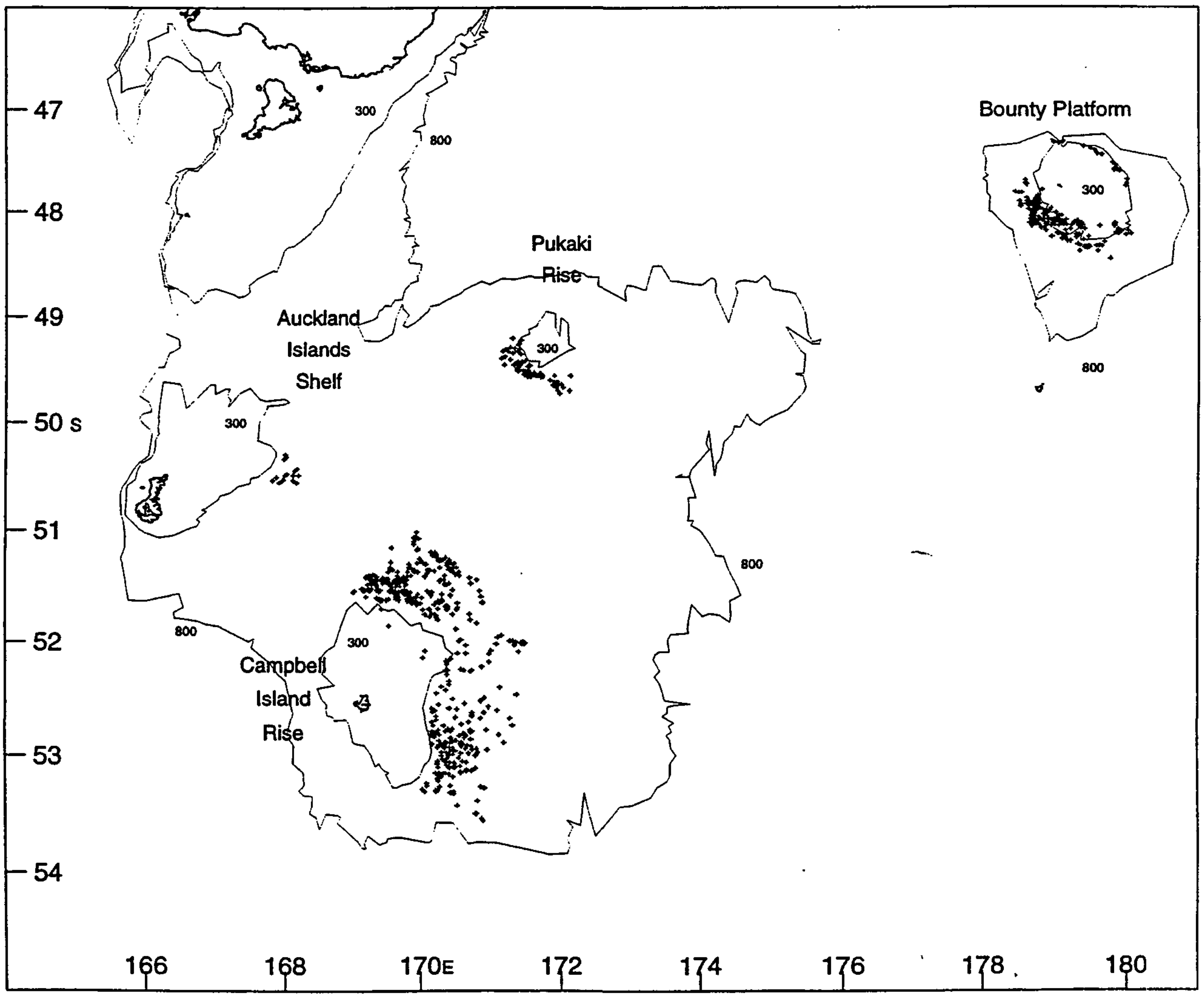

Figure 2: Position of all commercial fishing tows where spawning (running ripe) female southern blue whiting have been caught (*from* Hanchet 1998a).

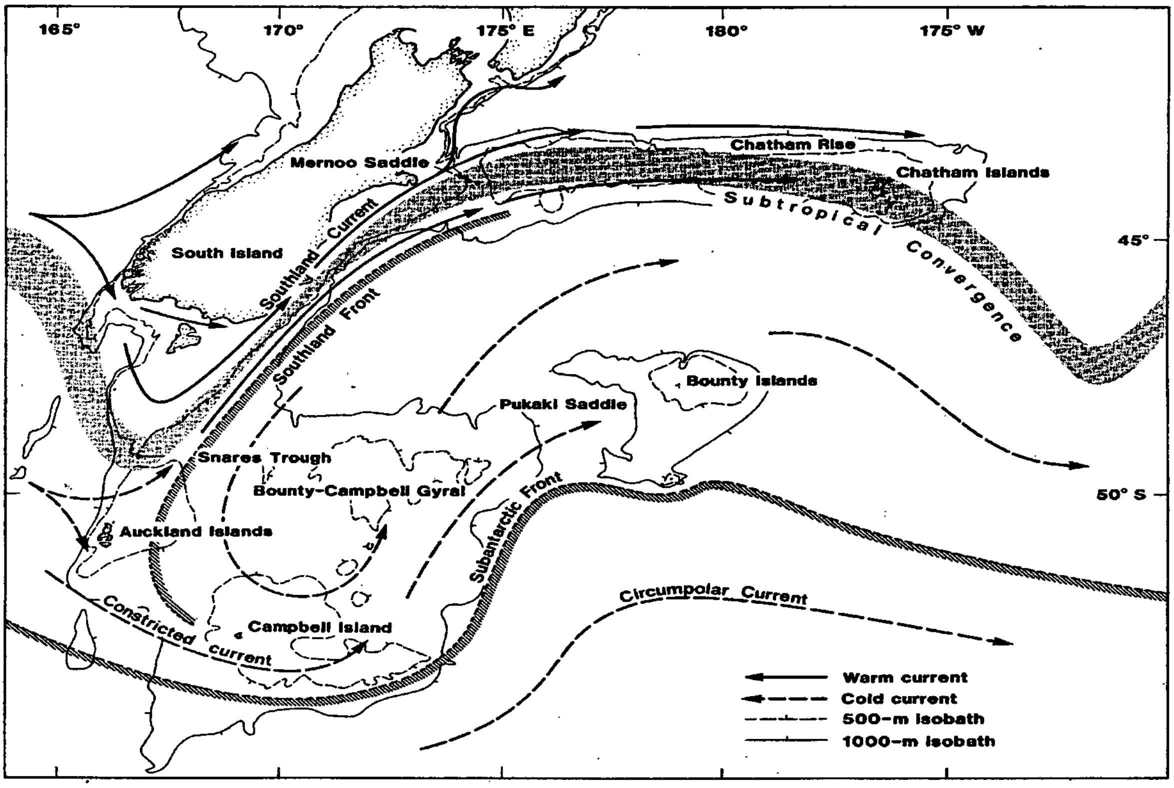

Figure 3: Major hydrological features around southern New Zealand (from van den Broek *et al.* 1984).

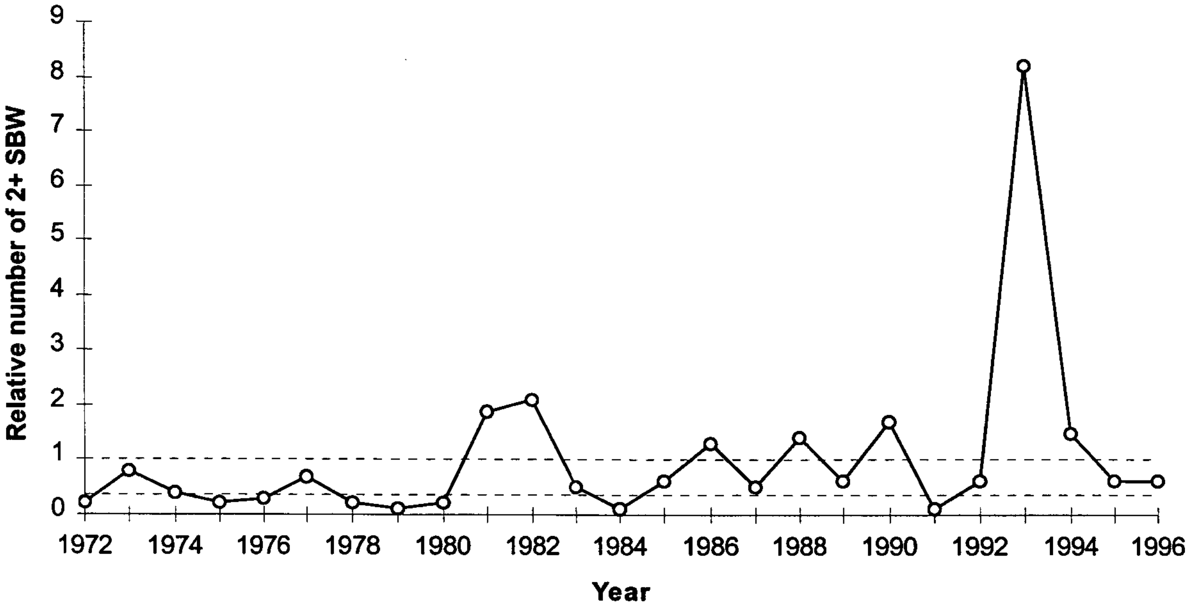

Figure 4: Estimated number of 2 year old southern blue whiting for 1972 to 1996 from the separable Sequential Population Analysis (Hanchet 1998b). Horizontal lines indicate year classes divisions into strong, medium, and weak.

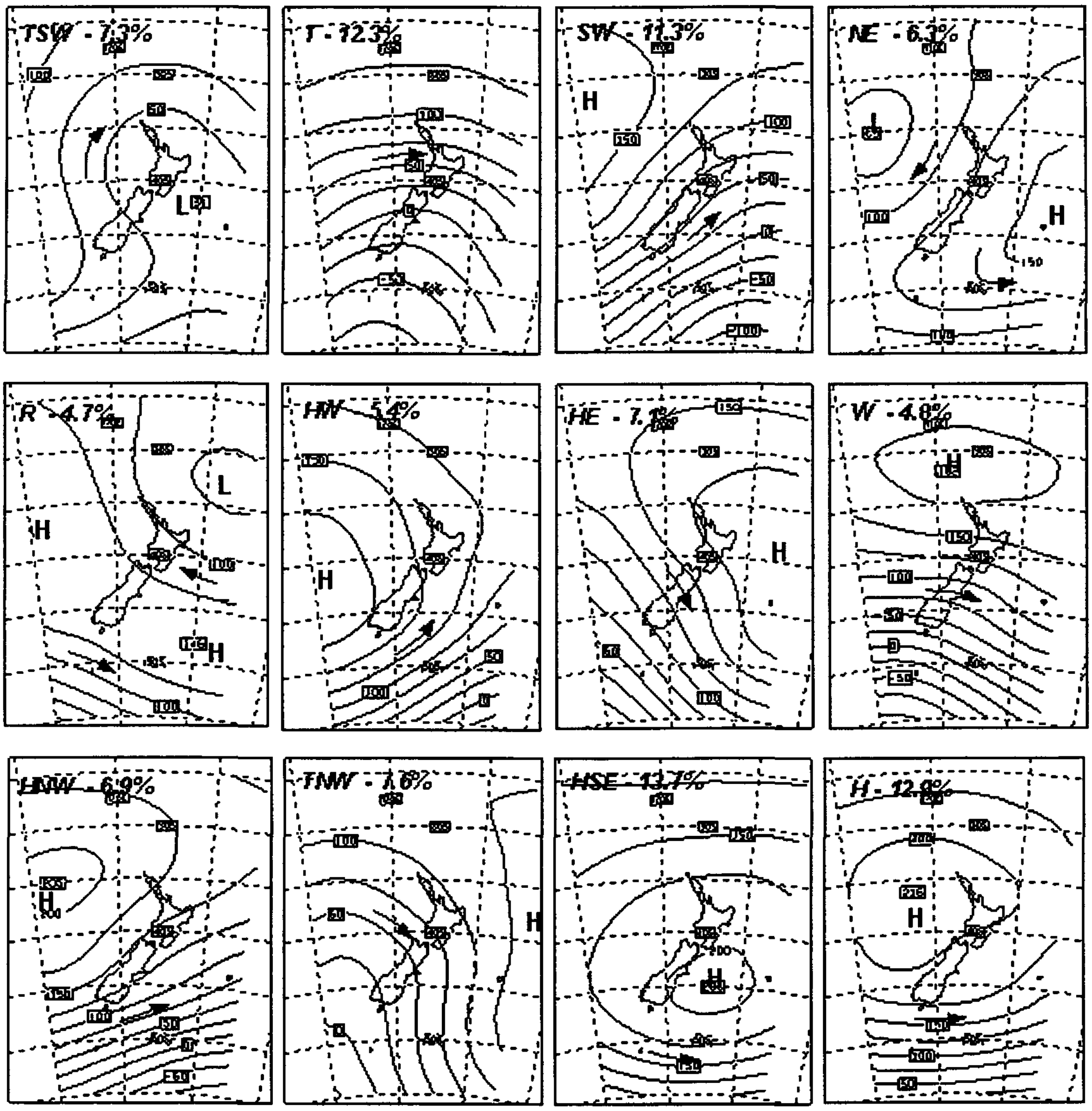

Figure 5: Cluster-mean flow patterns used to characterise daily weather types. Each day's circulation pattern was categorised as one of the above types, based on a similarity measure. The overall percentage frequency of occurrence of each weather pattern and the abbreviated label used in Table 1, is shown in the top left corner of each map.

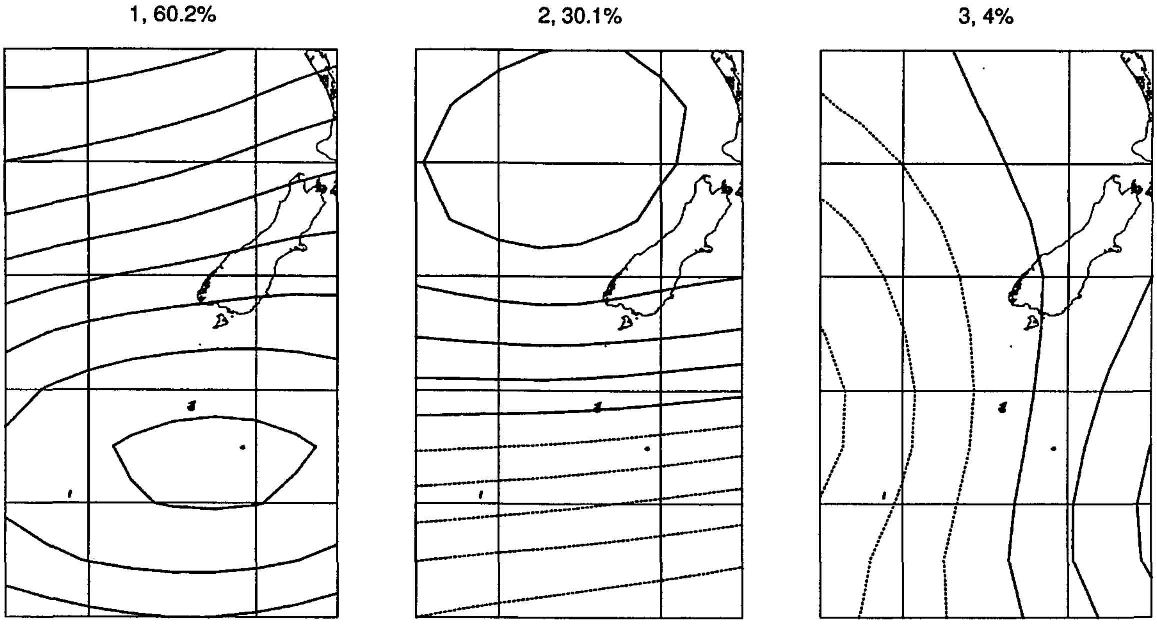

Figure 6: Spatial patterns of the first three principal components of monthly mean 1000 hPa height over southern New Zealand. Figures are the component number followed by the fraction of variance accounted for. The contour interval is arbitrary, negative contours are dashed.

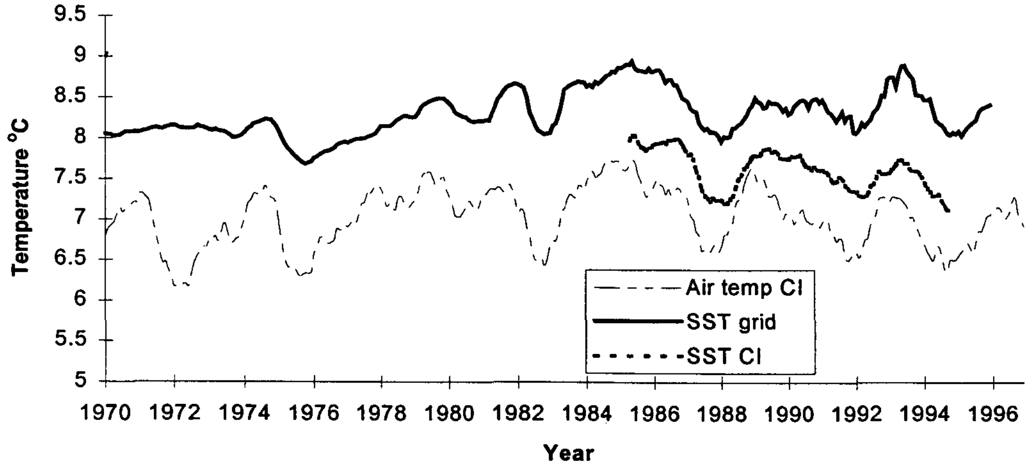

Figure 7: Mean monthly air and sea surface temperatures recorded at Campbell Island and gridded satellite SST centred on Campbell island from 1970 to 1996. All data are smoothed 12 monthly running means.

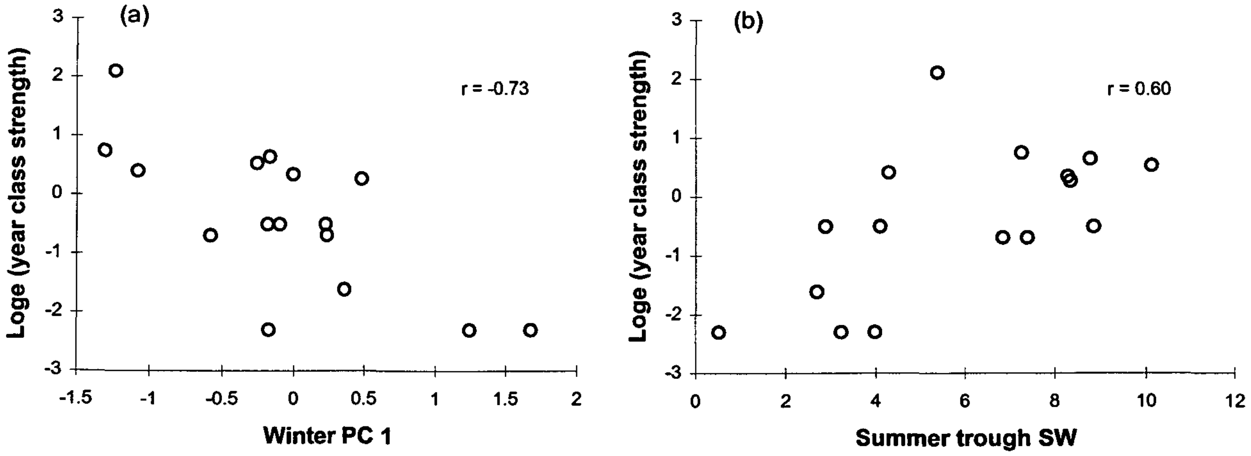

Figure 8: Univariate plots of $\log_e$ year class strength versus (a) winter PC 1 and (b) Summer TSW.

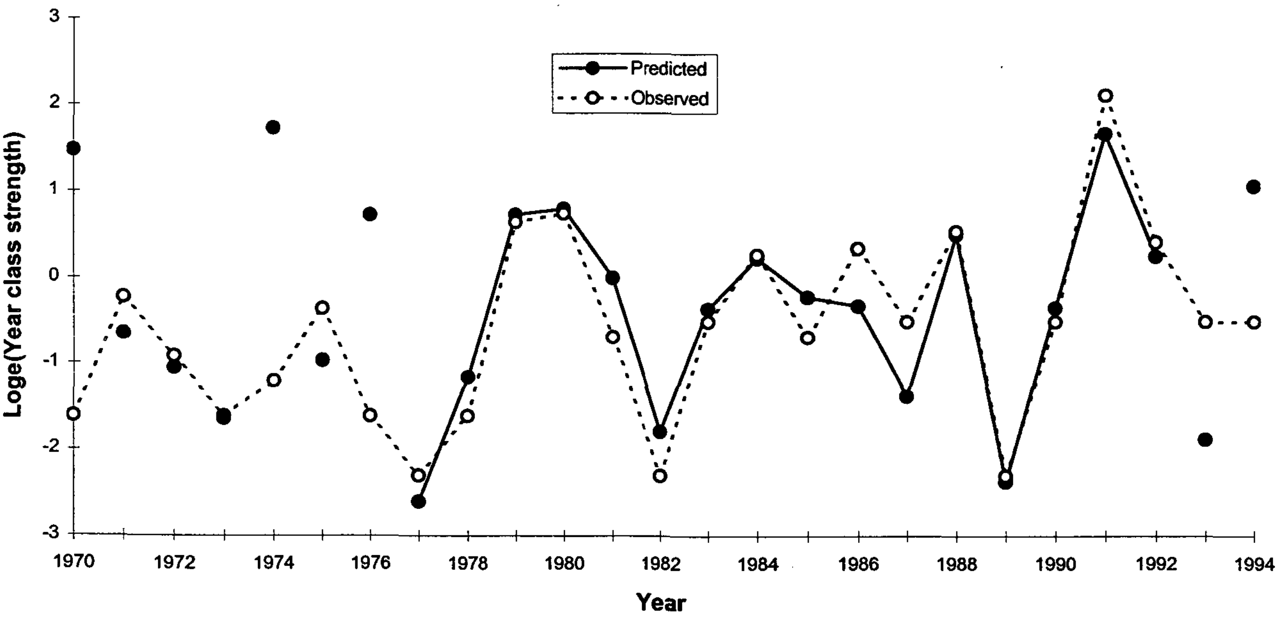

Figure 9: Predicted and observed $\log_e$ (year class strength) for 1970–94. Observed values based on the results of the population model. Predicted values were calculated using an equation based on 1977–92.