

CLIMATE AND FISHERIES ON THE SOUTH EAST AUSTRALIAN CONTINENTAL SHELF AND SLOPE

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Project No. 96/149



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NON-TECHNICAL SUMMARY

96/149 CLIMATE AND FISHERIES ON THE SOUTHEAST AUSTRALIAN SHELF AND SLOPE

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Objectives

To assist in developing better management models for temperate Australian fisheries by assessing the role of oceanographic and climatic variability on historical changes in SE Australian fish stocks by:

- 1) Developing indices of deepwater productivity and temperature, based on physical and chemical analyses of the growth rings of bamboo coral.
- 2) Developing time series of relative growth for long-lived fish species on the shelf and slope in the SEF.
- 3) Developing times series of temperature for the SE Australia shelf off Tasmania and NSW from the growth rings of mollusc shells.
- 4) Examining statistical relationships among: the above environmental and fishery indices; available records of climate from the Maria Is. station; terrestrial records of regional rainfall, wind, and temperature; apparent recruitment to orange roughy from ageing data; and long-term records of fish landings in the SEF.

Non-technical summary

There is considerable evidence of the impact of climate variability on Australian fisheries. To further these investigations, we attempted, first, to develop proxy indices of environmental and biological conditions, and second, to relate these to each other.

Several attempts to create these proxy indices proved unsuccessful or less successful than originally hoped. There was insufficient molluscan material in Australian museum collections from shallow (shelf) habitats to develop climate indices from this material. Using material from bamboo corals (*Keratoisis* sp), which was collected at ~ 1000 m, we were able to construct time series of temperature from concentration anomalies of strontium. However, the banding in the corals proved not to be annual, so the 'time' series could not be readily assigned to particular dates, rendering it of little value. Thus, corals with between 300 and 400 rings across their base were carbon-14 dated to be only about 100 years old.

To obtain indices of biological conditions as encountered by major commercial fish species during their early life history, we measured the widths between the first 5 to 8 annuli as indices of their growth during these first years of life. This was carried out for 8 long-lived fishes living on the continental shelf and slope off southeastern Australia. However, little relationship was found between the relative growth experienced in particular years by different age classes of the same species nor were common long-term patterns found between species. Comparison was made between these time series and time series of wind, rainfall and temperature from the region. The results were negative.

Electron microprobe scans were carried out across otoliths of orange roughy to measure concentrations of micro-constituents over their life history. The concentrations of some micro-elements have been shown to indicate environmental temperature or trophic status, so these time series were compared with the regional environmental time series. The results strongly suggest substantial climate variability at orange roughy depths, which is now the subject of on-going discussion with regional oceanographers. The scans also indicate that roughy live much longer lived than previously thought. Our data, confirmed by several methods, indicate roughy do not reach sexual maturity until an age of about a century, and reach a maximum age of perhaps 500 years. These results fundamentally affect the management and conservation status of roughy stocks, and perhaps of other deepwater fishes.

Our evaluation of climate variability in the SE Australian region, based on available climatological time series, strongly suggests two major influences, not previously considered.

First, there is pervasive evidence of a quasi-decadal variation in the strength and annual persistence of regional (zonal west) winds. This variability correlates with year-class strength in a number of stocks we've examined, including gemfish, and may also be evident in other parts of the world. We see evidence of similar variability off South America, for example. The quasi-decadal variation appears to be at least partly a function of solar (sunspot) variations.

Second, we found evidence of a long-term (since 1920s, at least) southward shift in the Australian sub-tropical ridge, which has resulted in a poleward shift in the dominant

wind bands and which probably has affected local rainfall. This shift will strongly affect fish stocks that depend on wind forcing for either nutrient regeneration or dispersal, and also is likely to have long-term effects on terrestrial ecosystems. The underlying cause of this shift is uncertain, but this shift is consistent with the most recent climate change models. The shift, its underlying causes and its implications are currently being discussed with Australian climatologists.

In conclusion, our study, which by design was wide-ranging, also proved to be preliminary but very promising, in the sense that there is obvious merit in re-evaluating available fisheries data in the light of climate variation. Clearly this will require further work. Our revised estimates for the age of orange roughy will also require further investigation; these results have potentially profound implications for the management and ecology of deepwater fisheries.

1. INTRODUCTION: BACKGROUND & NEED

The history of fisheries is replete with examples of massive change to fish stocks. Some better known examples are the collapse of the California sardine, which was the largest fishery in the western hemisphere in the 1930s and 1940s, and the recent collapse of the northern (Grand Banks) cod stock. On a smaller scale, but of more local interest, the collapse of eastern gemfish led to that fishery's closure for the past several years.

The relative contribution of fishing pressure and climate to these changes is a key issue: fishers usually blame the environment, conservationists usually blame the fishing industry, and almost always there are too few reliable data to prove the case one way or the other. However, there is a growing consensus (1) that management models based on the simple assumption of fished populations being at equilibrium are not generally tenable, and (2) that management could be substantially improved if the effects of climate on productivity could be factored into the models. It is noteworthy that two of the best, internationally recognised examples of the use of this 'better' approach are from Australia: the use of rainfall data to predict northern prawn catches and use of the El Nino-Southern Oscillation Index to predict western rock lobster yields.

To implement this approach in other fisheries requires information on fish stocks and good environmental records. Catch and effort for the last 90 years (N. Klaer, unpubl. data, CSIRO) indicate there have been large changes in the catch composition of SE fisheries. Flathead, latchet, and Chinaman leatherjacket dominated commercial landings from the NSW shelf in the decade after World War I, but declined markedly in succeeding decades until, after World War II, they were replaced almost entirely by morwong and redfish. Eastern gemfish, which was fished off the coast of NSW until the recent closure, was caught abundantly from surface waters around Tasmania around the turn of the century, but then virtually disappeared from these waters. For orange roughy, catch-at-age analysis suggests there has been an ~20 year hiatus in recent recruitment, for reasons we do not understand (D. Smith, CAF, VML, unpubl. data).

At the same time, recent short-term studies clearly link changes in at least some SE Australian stocks with climate variability. Catches of Tasmanian rock lobster, abalone and a variety of finfishes correlate with variations in the local wind fields, sea surface temperatures and surface productivity (Harris et al. 1988; Thresher 1994, in prep.). However fish landings for most species depends on a number of factors in addition to fish abundance, e.g. market factors, changes in fish availability, in fishing grounds and fishing technology and practices. Recruitment time series are therefore invaluable, but there are few recruitment time series of reasonable length (i.e. >20 years) for southeast Australian species.

Similarly, climate analyses require environmental data that is good quality, long duration and representative of the region. However, the only instrumental record we have for the

region is the CSIRO shelf monitoring station at Maria Island (Tasmania), where temperature, salinity and nutrients have been measured for the past 50 years. Although of considerable value, that data set is neither long enough nor geographically representative enough to compare reliably with historical fish catches.

To progress in understanding interactions between fisheries and environment in an area where there is a paucity of data, one must attempt to find proxy data sources. There are relatively few such data sources but they have proved immensely valuable. Examples include the record of fish populations laid down in anoxic sediments, such as off California, Peru and southwest Africa (Soutar and Isaacs 1969; Shackelton 1987), records of sea temperature laid down in corals and the record of fish growth that can be extracted from the width of the initial growth rings of long-lived fishes (Boehlert et al. 1989).

To assess the role of the marine environment in determining fish abundance and productivity, long-term data on recruitment, fish productivity (i.e. growth rate and recruitment) and the environment are needed. However, changes in fish growth rate over time can be assessed from analysis of the otoliths of long-lived fish species (Boehlert et al. 1989). Environmental data can be obtained for the SE Australian region by use of proxy records. Information on seawater temperature and water mass composition can be obtained from analysis of carbonates in sediments, coral skeletons and mollusc shells. The time series obtained with these techniques can be used to determine if major changes in southern Australian fisheries coincided with (and hence were presumably caused by) changes in the marine environment.

This study attempted to obtain a solid information base on marine environmental variability in southern Australia for the last 100-150 years. This will be compared with changes in the productivity (i.e. growth and/or recruitment) of several long-lived commercial fish stocks as well as with historical changes in catch. In this way, we can begin to disentangle the effects of fishing from the effects of the environment on biomass and catches.

2. OBJECTIVES

To assist in developing better management models for temperate Australian fisheries by assessing the role of oceanographic and climatic variability on historical changes in SE Australian fish stocks by:

- 1) Developing indices of deepwater productivity and temperature, based on physical and chemical analyses of the growth rings of bamboo coral;
- 2) Developing time series of relative growth for long-lived fish species on the shelf and slope in the SEF;

- 3) Developing times series of temperature for the SE Australia shelf off Tasmania and NSW from the growth rings of mollusc shells; and
- 4) Examining statistical relationships among: the above environmental and fishery indices; available records of climate from the Maria Is. station; terrestrial records of regional rainfall, wind, and temperature; apparent recruitment to orange roughy from ageing data; and long-term records of fish landings in the SEF.

3. METHODS

Fisheries and environmental data

To obtain time series for the productivity of long-lived fishes in the southeast region, we reconstructed their growth rates during the first years of life based on the width of the initial annual growth rings in their otoliths. By using fish of a known age, this approach can be used to reconstruct historical changes in rates of fish growth, which may be related to changes in environmental conditions and population density, as shown by Boehlert et al. (1989) for long-lived deepwater species of *Sebastes*.

There are extensive collections of otoliths for 8 long-lived SE(T)F species at the Central Ageing Facility (CAF) (Queenscliff, Victoria): orange roughy; warty, smooth, black, and spikey oreos; nannygai or east coast redfish; jackass and banded morwong. They had all already been aged (Smith and Stewart 1994, Smith et al. 1995, Stewart et al. 1995).

For each species, the width of the first 5-8 growth increments was measured (i.e. where growth was most rapid, enabling them to be readily measured). The increments were measured for about 10 fish for each decade, extending back to the maximum effective age of the species. For each species, the effect of different mean rates of growth during the first years of life was factored out by subtracting out the mean increment width and dividing by the standard deviation, so the increment anomalies were expressed in standard deviation units.

We compiled environmental data for wind at Macquarie Island, local wind and Tasmanian rainfall, some of the few long-term records available for the Southern Ocean region. Tasmanian rainfall is by far the longest continuous data set for the region, going back to the 1880s.

Proxy environmental data

It was proposed that proxy data for environmental variability would be obtained from two groups of temperate, skeleton-building organisms: deepwater corals and shelf-dwelling molluscs.

Several species of deepwater coral are found on the seamounts off southern Tasmania where orange roughy are fished. These are sometimes brought to the surface in roughy trawls, and we have collected a number of specimens of the bamboo coral, *Keratoisis sp.* Between 300 and 400 rings were counted on two specimens.

Age validation was carried out by ^{14}C dating material from the core and outer edge of these corals; the difference between these dates is the estimated age of the specimen. (The ^{14}C at intermediate water depths is already some hundreds of years old, so a single measurement of ^{14}C age from the core of the coral cannot be used to provide an absolute age estimate.) Initial age estimates for two specimens were carried out as a pilot study by the Australia National University Quaternary Dating Research Centre, but the results were inconsistent, one sample appearing to be ~100 and the second ~300 years old, although both had >300 rings counted in cross-section. A second set of samples was run at the National Ocean Sciences AMS facility at Woods Hole Oceanographic Institution (USA).

Oxygen and carbon isotope anomalies and anomalies in the ratio of strontium to calcium were examined across a cross-section of a coral specimen. (^{18}O and strontium anomalies generally reflect temperature variation, whereas ^{13}C anomalies reflect metabolic and trophic status.) Sr/Ca ratios have been used as a proxy for relative water temperature in shallow-water corals (de Villiers, et al., 1995). Results of a pilot study to test the technique suggested periodic changes in water temperature over the corals' lifetime. The strontium probe techniques are virtually identical to those we have developed to analyse fish otoliths (Sie and Thresher 1992).

Environmental records from the continental shelf off Tasmania and Sydney were to be reconstructed from mollusc shells, using chemical techniques similar to those above. No colonial corals are found at shelf depths along the southern Australian coast, but the methods used to extract environmental data from mollusc shells are well established. Although none of the local common molluscs are long-lived, contacts with the SA Museum, the Australian Museum and the Museum of Victoria indicated that there are abundant shell collections for the southern Australian region that date from the late 1800s. In attempting to implement the approach, however, it appears that the extent of the museum collections was over-stated. No single museum had adequate temporal and spatial coverage for any species of mollusc. Combining samples held at different museums provided little useful gain. The only species for which adequate samples might be available was the scallop *Pecten fumatus*, but even for this species, old samples

were uncommon and most were taken close inshore, and hence would poorly represent oceanographic conditions. This section of the project was therefore not continued.

Because we were unable to develop environmental time series from shelf molluscs, we examined whether such time series could be obtained from orange roughy otoliths. We undertook full life history scans of the elemental composition of three average-sized orange roughy (~30 cm TL) collected in the Southern Zone. The Central Aging Facility estimated them to be about 40-50 years old. The electron probe microanalyzer carried out the analyses at fixed 25 μm steps along the main growth axis from the primordium to the posterior margin of each otolith. Analysis focussed on strontium (Sr), whose concentration is generally inversely correlated with water temperature. The results were compared with historical records of Tasmanian rainfall, which is correlated with wind and decreased water temperature.

Data analysis

Standard methods of exploratory data analysis and time series analysis were carried out to examine relationships among the physical and biological time series.

4. RESULTS/DISCUSSION

4.1 Critical scales of climate and oceanic dynamics relevant to fish populations

At scales longer than diurnal, temporal variability of the marine environment ranges from aperiodic events lasting only a few days (e.g., phytoplankton production and recruitment pulses, e.g., Doherty and Williams, 1988; Thresher, et al., 1989) to, perhaps, cyclic variability operating on global space and million-year time scales (Fischer and Arthur, 1977; Grigg, 1988). On an ecologically relevant scale, four broad classes of nominally periodic inter-annual variability have been identified by climatologists.

The quasi-biennial oscillation (QBO): The QBO is a semi-periodic fluctuation in zonal wind directions, surface pressures and rainfall. It has a period of about 26 months, and is manifest strongly in the equatorial stratosphere (in which wind direction switches from predominantly east-to-west to west-to-east), weakly in the northern hemisphere troposphere (accounting for about 2% of the variance in surface winds, for example) and strongly again in a variety of southern mid-latitude climate parameters (see Landsberg, 1962; Trenberth, 1980). The strength of the signal in the tropics is evidenced by, for example, stratospheric pressure variability at Balboa, Panama where, after detrending, the QBO accounts for 83% in the inter-annual variance in zonal winds since 1950.

EN-SO and associated variability: The El Niño-Southern Oscillation is a quasi-stable, longitudinal oscillation with centers of action in the tropical eastern and western Pacific. It is also the best known climate cycle. Documented teleconnection patterns include links between the Pacific, Atlantic and Indian Oceans (Latiff and Barnett, 1995) and between low and mid-latitude regions. Spectral analysis of the Southern Oscillation Index (SOI) indicates most power is in periods less than 7 years, which reflects the approximate interval between EN-SO events (mean about 4 years). However, 'strong' and 'very strong' events occur at intervals of approximately 8-12 years (Enfield and Cid S., 1991). Philander (1990) provides a good recent review of the EN-SO phenomenon, while Walsh (1978) and Glynn (1990) review its biological impacts.

Of about the same period, and perhaps related to the EN-SO, are several suggestions of oceanographic and biological cycles with a period of about 5 years. These cycles have thus far been suggested mainly for northern mid-latitude systems, including the NE Pacific (Mysak, et al., 1982) and NE Atlantic (Cushing and Dickson, 1976). In the Pacific, five-year cycles have been attributed to poleward propagation of coastally trapped Kelvin waves, whereas those in the Atlantic appear to relate to variability in circulation of zonal west winds in the Arctic polar vortex.

"Ten-year" (quasi-decadal) cycles: Cycles with a period of 10-11 years are among the most common reported in the literature, having been ascribed to everything from economic indices and agricultural harvests to atmospheric dust loads and rainfall (Burroughs, 1992). The most common mechanism cited to account for this variability is the sunspot cycle, which has a mean period of 10.6 years. Reflecting this, several reviews and workshops have dealt with the likely impacts of sunspots, and solar variability in general, on terrestrial climates (Meadows, 1975). Although attempts to link the two have generally not been viewed as widely successful or compelling, the sunspot cycle has also been invoked to account for variability in marine populations (e.g., Regner and Gacic, 1974, Southward, et al., 1975).

Recently, approximate ten year cycles have been reported for a number of oceanographic and atmospheric parameters, including North Atlantic sub-surface water temperatures (Levitus, et al., 1994), northern and southern hemisphere wind variability (Harris, et al, 1988) and rainfall patterns (Tyson, 1986). Links to marine populations have been drawn by a number of authors, including Southward, et al. (1975), Grainger (1978) and Harris, et al. (1988).

Decadal cycles: As used in the climate literature, 'decadal' refers to cycles of 20 or more years. Variability at about a twenty year scale has been reported for marine populations in both the NW Atlantic (Koslow, 1984) and north Pacific (Davydov, 1989). Recently, Latiff and Barnett (1994), among others, have examined in detail the physical basis of this variability, in large part because of widespread evidence of a marked shift in climate conditions in the north Pacific in the mid-1970s (Graham, 1994). Available evidence suggests that the cycle is driven by unstable interactions between a

large sub-tropical oceanic gyre in the north Pacific and the Aleutian Low, a quasi-stable region of low atmospheric pressure usually centered just south of the Aleutian Islands. The biological implications of the shift in the relative strength of these circulations is discussed by Polovina, et al. (1994), who also describes their impact on the Hawaiian marine fauna. Reports of approximate 20 year cycles are relatively common in the meteorological literature (Burroughs, 1992) including, for example, sub-tropical rainfall off South Africa (Tyson, 1986).

A variety of longer period cycles have also been suggested, ranging from 30 to 50 years to about 200 years. The evidence in support of these cycles is drawn from tree-ring and geological analyses, and the longer instrumental climate records (e.g., Cook, et al., 1992; Plaut, et al., 1995). None are widely accepted as well substantiated.

The mechanisms underlying climate cycles are still uncertain. Historically, when the subject of climate cycles was taken seriously (not often), they were usually attributed to external (e.g., astronomical) influences, such as the sunspot cycle. Currently, they are thought to derive from lags inherent in heat transfer between the ocean and atmosphere. Ikeda (1990), for example, suggested that an interaction between wind stress, sea ice cover and high latitude oceanic heat flux to the atmosphere amplifies weak, periodic external forcing by, for example, solar variability. Alternatively, simulations of both the Atlantic (Weaver and Sarachik, 1991, Mehta, 1991) and Pacific (Latif and Barnett, 1994) suggest that primitive equation general circulation models naturally oscillate at a variety of periods when run using mixed surface boundary conditions. The period of the oscillation varies with basin topography, as a function of the advection rate between sub-tropical and sub-polar gyres.

4.2 Climate and fisheries in south east Australia: gemfish as a case study

Recent historic climate trends, referred to generically as global climate change or greenhouse warming, have been hypothesised to lead to large changes in the distribution and abundance of terrestrial and aquatic biota. Predictions about marine species have been less detailed, reflecting uncertainties about the processes that regulate marine populations and the climate mechanisms that link the atmosphere and ocean. Although marine fisheries are routinely mentioned as being at risk due to global climate change, direct evidence for such an effect or clear indications of the causal mechanisms that might be involved have not been available. We provide a possible first example, for a commercial fishery off southeast Australia. Historically, recruitment to the stock correlated each year with the persistence over southern Australia of zonal west winds in the Antarctic circumpolar vortex, which in turn is a function of the latitude of the southern hemisphere sub-tropical ridge. Long-term records indicate the mean annual position of the ridge over eastern Australia has moved poleward nearly five degrees since the early 1900s, an observation qualitatively consistent with predictions of some

climate change models. By the 1980s, the ridge had moved far enough south that the zonal winds began largely to pass south of Australia, which correlated with an abrupt recruitment failure by the stock. Despite management attempts to regenerate the fishery, recruitment and the persistence of zonal winds since the stock collapse remain historically low. More broadly, wind is one of the factors most commonly related to recruitment variability in marine populations, and even relatively minor latitudinal shifts in wind bands could profoundly affect viability of marine stocks.

The eastern gemfish, *Rexea solandrii* (Gempylidae), constituted a 'bread-and-butter' fishery targeted by Australian commercial fishers each winter during the course of its spawning migrations along the southeast coast of Australia (Rowling, 1994). Although fished since the early 1900s, the modern fishery developed in the 1960s when the spawning migration route along the upper continental shelf was discovered. Annual catches rose to about 5000 metric tonnes in the late 1970s and were maintained for about a decade with no obvious evidence of stress on the stock (Rowling, 1990). Catches began to decline abruptly in the late 1980s (figure 2.1), however, following a series of poor year classes. Following widespread concern and at times heated discussions between fishers, fisheries managers and scientists, the fishery was formally closed in 1993. The closure was maintained until 1996, after which small (200 tonne Total Allowable Catch) annual fisheries have been intermittently permitted to allow scientific monitoring of the stock. The evidence indicates only one strong year-class since the collapse (Smith & Punt, ms), and the fishery is currently closed. Standard stock-recruitment models suggest that even with a complete closure, regeneration to pre-collapse stock levels will take several decades (Allan, 1993).

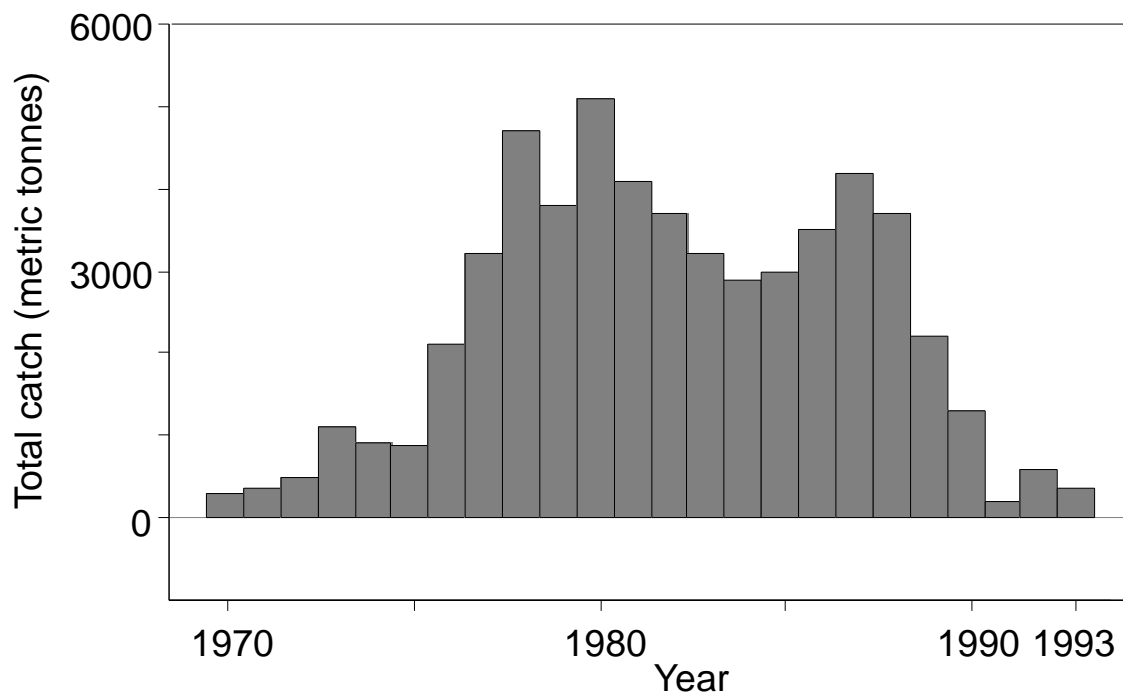


Figure 2.1 Historical landings of Eastern Australian gemfish

To assess the history of the stock, we used maximum likelihood and Bayesian methods and available data on catch rates, the fraction of the winter fishery consisting of females, and the age-composition and length-frequency of catches to estimate virgin biomass, recruitment steepness, annual recruitment anomalies, selectivity and natural mortality. For the Bayesian analysis, priors were constructed as part of the stock assessment process by a working group involving fishers, managers and scientists.

For both the maximum likelihood and Bayesian analyses, confidence intervals for population parameters are very wide for the earliest and latest years in the time series, due to the small number of years over which year-class strength could be evaluated. However, overall the time series of recruitment anomalies (deviations from the underlying stock-recruitment relationship) are very similar in both analyses. Since the inception of the modern fishery, there have been two broad peaks in recruitment, in the early 1970s and 1980s, with extended periods of apparently low recruitment in the late 1960s, late 1970s and the deep trough in the late 1980s that led to closure of the fishery. The alternating pattern of a series of good and a series of poor years, at a peak-to-peak interval of about 10 years, is reflected in the stock-recruitment curve as cycles of recruitment anomalies during periods of relatively stable stock sizes.

The biological basis of the recruitment anomalies in gemfish is not known. Comparison of the recruitment time series with available climate data, however, indicates a high level

of coherence with variations in southeast Australian winds (Figure 2.2). The magnitude of these winds, quantified as the number of days per year of 'strong zonal west winds' over Tasmania (far southeast Australia), has been related to recruitment of several southern Australian stocks, including shellfish and both marine and freshwater fin fishes (Harris, et al., 1988; Thresher, 1994, in prep). The correlation between the zonal west winds and gemfish recruitment anomalies is highly significant ($R^2 = 0.28$, $p < 0.01$, $n = 24$ years), when poorly defined year-classes at the beginning and end of the recruitment time series (pre-1970 and post-1994) are excluded from the analysis. The mechanisms linking the zonal winds to recruitment have not been examined for any Australian stock, but are likely to be similar to those shown to underlie wind-recruitment relationships in other marine species.

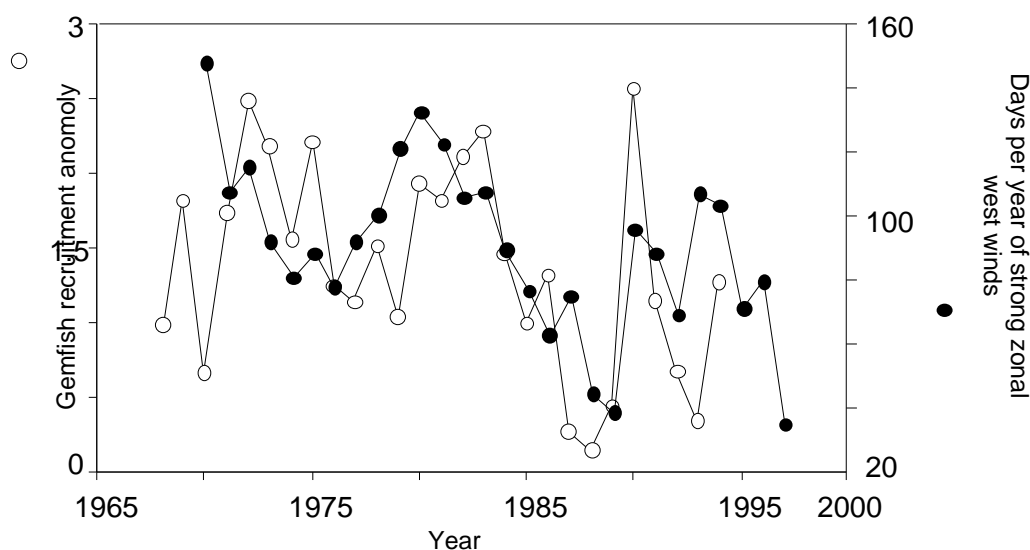


Figure 2.2. The relationship between number of days per year of strong zonal west winds (solid symbols) and gemfish recruitment, as determined from cohort analysis (open symbols)

The quasi-decadal pattern of alternating intervals of good and poor recruitment and the exceptionally poor recruitment in the late 1980s are both reflected in the long-term wind records (Figure 2.3). As previously noted by Harris, et al. (1988), the frequency of strong zonal west winds off southern Australia has oscillated at a period of about 10 years since at least the early 1940s, when records were first available. This periodic variability has been independently reported for or is evident in other climate parameters in the southern mid-latitudes, including sea level pressure differences off South Africa (Tyson, 1990) and southern Australia (Pook, 1994) and rainfall off South Africa, New Zealand and southern Australia (Bowen, 1975; Vines, 1980). The variability in pressure, wind and rainfall since the 1940s are broadly coherent, suggesting a common

underlying mechanism. The downturn in gemfish recruitment in the late 1980s coincides the lowest trough in this time series since records were started. The subsequent peak in the frequency of zonal winds in the mid-1990s is also low, with values that correspond to previous troughs rather than previous peaks. Data for 1997 indicate the current trough will be at least as deep as that in the late 1980s.

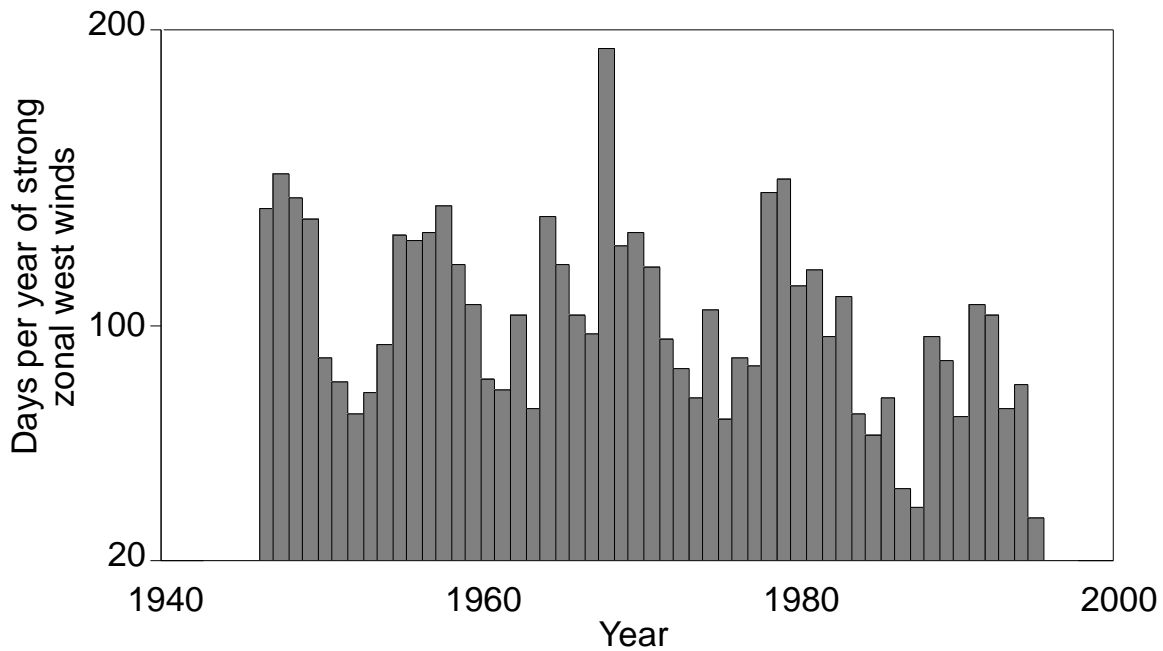


Figure 2.3. Periodicity of SE Australian Zonal West Winds

The long-term pattern of wind and recruitment suggests two underlying processes: a 'regime shift' in the late 1980's from locally strong to locally weak zonal winds, and an oscillator with a period of about 10 years. The latter approximates and is in phase with the sunspot cycle (see also Kidson, 1925, but also Pittock, 1978). The 'regime shift' is apparently due to changes in the position of the Australian sub-tropical ridge. The zonal winds are the northern margin of the 'roaring forties', and are due to the steep pressure gradient between this ridge and the sub-Antarctic trough. Intra-annual variability in the frequency of strong winds in southern Australia is a well known consequence of the seasonal latitudinal migration of the ridge (Pittock, 1973); comparison of annual values for the winds and the mean latitude of the ridge (L) indicates a longer term relationship as well (correlation between wind and L significant at $p < 0.001$, $R^2 = 0.32$, $n = 52$ years). Both intra- and inter-annually, poleward movement of the ridge corresponds with the zonal wind band moving south of the Australian continent and a slackening of local winds.

Records for L compiled since the early 1900s (Figure 2.4) indicate a long-term movement of the sub-tropical ridge when over eastern Australia to higher latitudes, with the rate of change increasing in the 1970s. Since record keeping started, the mean annual position of the ridge has moved nearly 5 degrees to the south. This long-term trend, previously noted by Das (1956) and Van Loon, et al. (1993), is also reflected in mass balance changes in New Zealand glaciers (Fitzharris, et al., 1992) and gridded sea level pressure data for the Australian region (Whetten, pers. comm.). The cause for the poleward movement is not known, but a latitudinal shift in the high pressure belt has been predicted under greenhouse conditions both on theoretical grounds and by general circulation models applied to the Australian region (Whettan, et al., 1994).

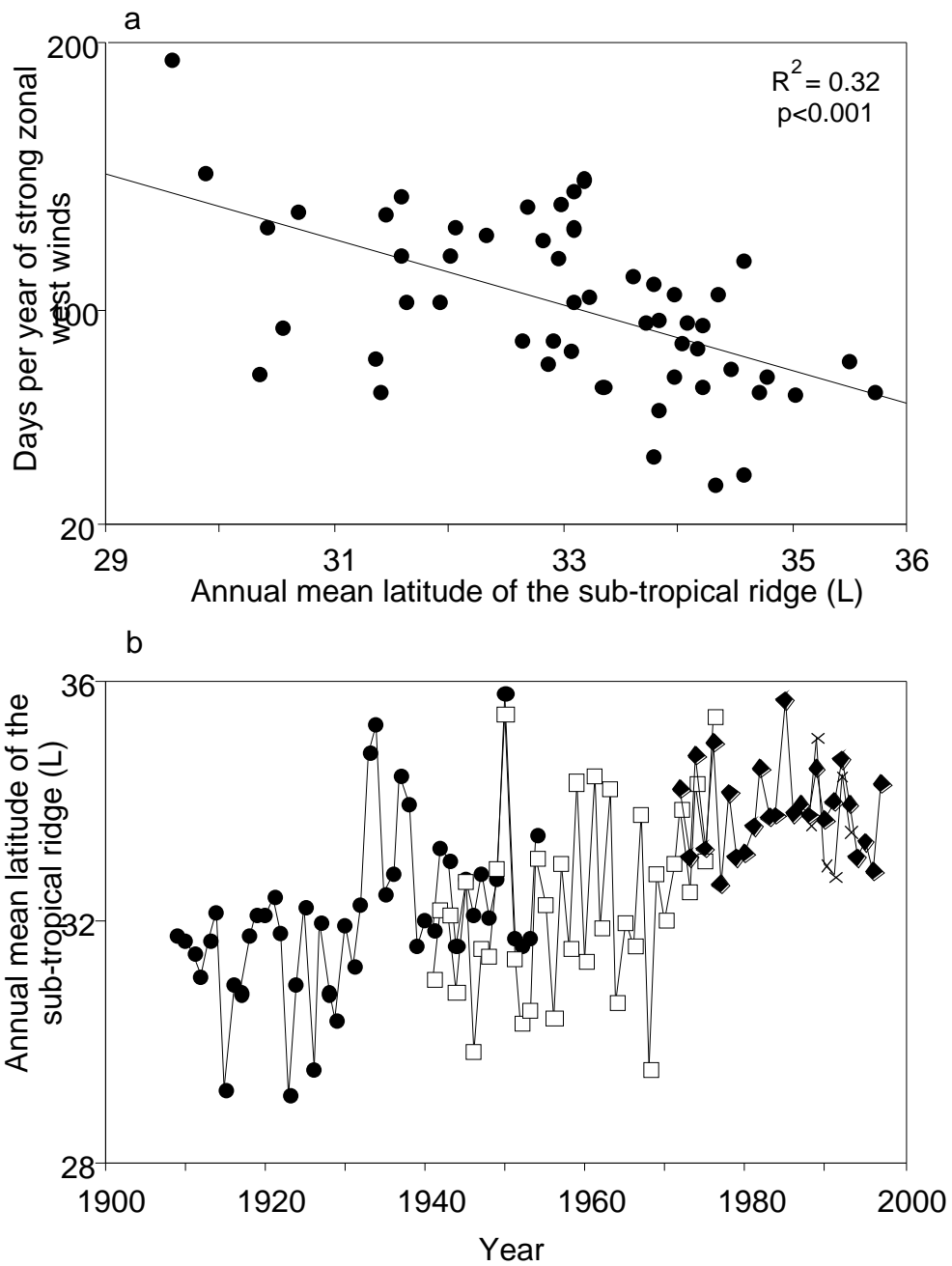


Figure 2.4. a. Correlation between latitude of the sub-tropical ridge and zonal winds in SE Australia. b. Annual mean latitude of the sub-tropical ridge since data were first collected in 1908, compiled from four different data sets

The regime shift in the late 1980s, and associated stock collapse, appear to be local manifestations of this long-term trend, as the northern limits of the zonal westerlies finally move too far south to support the stock. In the longer term, more frequent bouts of strong zonal westerlies in the southern Australian region coincide both with historical perceptions of the area as being cold, wet and windy, and with records of gemfish catches early in the century that indicate a stock that was much larger and more widespread than at the onset of the modern fishery (Johnston, 1883; Blackburn, 1979). Similar declines that have been reported for other temperate Australian stocks are attributed to over-fishing, but may also have a component attributable to recent climate changes. More broadly, the widespread observation of correlations between winds and recruitment or catches of marine stocks suggest that even relatively slight changes in the zonal distribution of pressure belts could have a substantial impact of fisheries yields and the viability of marine populations.

4.3 Evidence for physical forcing of climate cycles in south east Australia: Correlations between sunspot numbers and hemispheric circulation indices for the southern polar vortex

Atmospheric circulation in the southern mid-latitudes is dominated by strong circ-Antarctic zonal west winds (ZWW) over the latitude range of 35 to 60 degrees. These winds exhibit coherent seasonal and inter-annual variability, which has been related both to Antarctic (e.g., polar ice) and low latitude climate (e.g., EN-SO) parameters (Carleton, 1989, Pook, 1994). Historical and recent studies suggest that at its northern margins, variability in the ZWW has a strong quasi-decadal component. I test this by re-constructing variation in the Australian ZWW since 1861 using differences in monthly mean sea level pressure (MSLP) between Sydney and Hobart. The winter component of the time series exhibits marked quasi-decadal variability that approximately tracks the sunspot cycle. Compilation of time-series for Australia, South Africa and South America suggests coherent, in-phase variation of the ZWW around the hemisphere, that correlates highly with the sunspot cycle and may reflect solar-correlated expansion and contraction of the southern polar vortex.

The strength and persistence of the southern hemisphere ZWW affects rainfall, temperature and oceanic circulation in the mid-latitude regions of Australia, New Zealand, South America and South Africa, with likely flow-on effects to coastal and terrestrial ecology (Harris, et al., 1988; Thresher, 1994). Reported modes of variability include strong bi-annual seasonal variation, the quasi-biennial oscillation (QBO), and SOI-like variability at periods of 4-6 years (Trenberth, 1976, Swanson and Trenberth, 1981, Pook, 1994, Villalba, et al., 1997). More broadly, several studies suggest a quasi-decadal variability to the ZWW and associated climate parameters (Vines, 1980, 1985;

Tyson, 1986). The most recent example is a forty-year time-series of a semi-quantitative index of the annual persistence of strong ZWW in the southeast Australian region (Harris, et al., 1988). This periodic variability in the ZWW has since persisted through another decade (Figure 3.1). It is highly correlated with the sunspot cycle ($r = 0.34$, $n = 53$ years, $p = 0.014$).

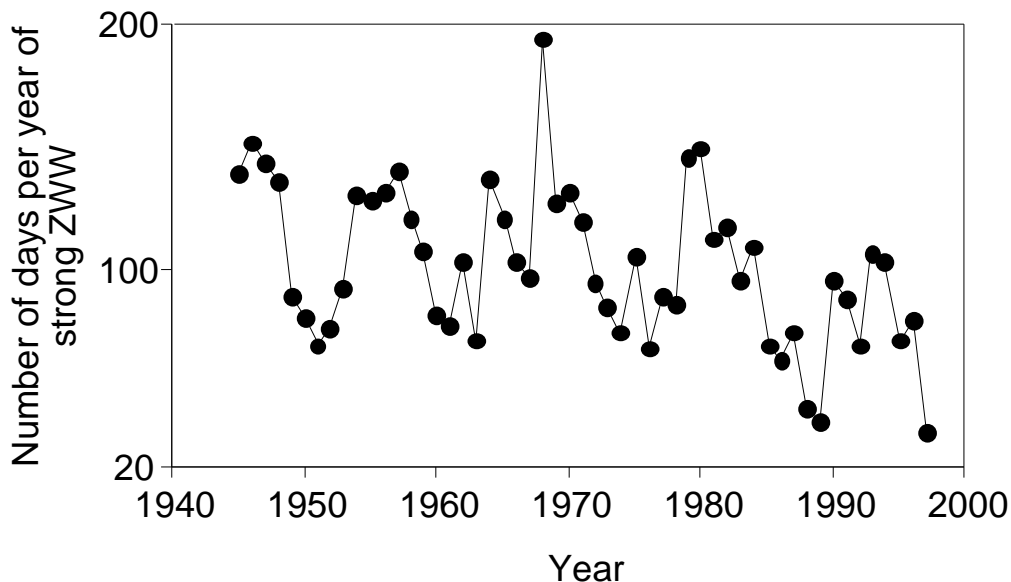


Figure 3.1. Number of days per year of strong zonal west winds over the south east Australian region, compiled from daily sea level pressure charts and based on criteria of Harris, et al. (1988)

Despite recent evidence of sunspot effects on terrestrial climate (Van Loon and Labitzke, 1988, 1994; see Kerr, 1995), reports of such an association have a long and chequered history (Anonymous, 1982; Burroughs, 1992). A frequent criticism has been the lack of persistence of the association over time (Pittock, 1978). To determine the stability of the signal while also removing subjectivity from the observations, I reconstructed the southeast Australian wind variability from monthly MSLP data compiled and checked through 1989 by CSIRO Atmospheric Research. The difference in annual MSLP between Sydney and Hobart (S - H MSLP difference) correlates highly with the reported ZWW variability ($r = 0.70$, $n = 44$ years, $p < 0.0001$) and exhibits the same recent periodicity. The MSLP data span 1861 to 1989, with only a few gaps. For purposes of analysis, three gaps of one month only were filled by interpolation; longer gaps were left as missing data.

The complete time-series, which is equivalent to Trenberth's (1976) Z5, exhibits only weak quasi-decadal variability over the long term. However, the ZWW in southeastern Australia are predominantly a winter feature, coincident with seasonal latitudinal migration of the sub-tropical ridge (STR) (Kidson, 1925, Pittock, 1983). During

summer, the STR is located at 35 - 40° S, and the ZWW band is predominantly south of the Australian continent. Analysis of the annual cycle of S-H MSLP differences summed over the 129 year time series suggests the year can be divided into an extended winter period of large pressure differences, from May through November, and an extended summer period of small pressure differences, from December through April, between which the transition is relatively abrupt. Peaks in the extended winter S-H MSLP difference, as assessed from lightly smoothing the data (using a three point unweighted moving average), closely approximate the sunspot peaks; over 9 cycles for which the MSLP data are available, the difference ranges from 3 years before to 1 year after the solar peak (mean = 0.7 years before) (figure 3.2). Nonetheless, the correlation with the sunspot cycle is weak ($r = 0.06$, NS). This reflects both the noisiness of the MSLP data and differences in heights of the solar peaks not tracked by the height of the MSLP peaks; re-analysis using smoothed MSLP differences and sunspot cycles normalised to a mean of zero and variance of one increases the significance of the correlation to $p = 0.021$.

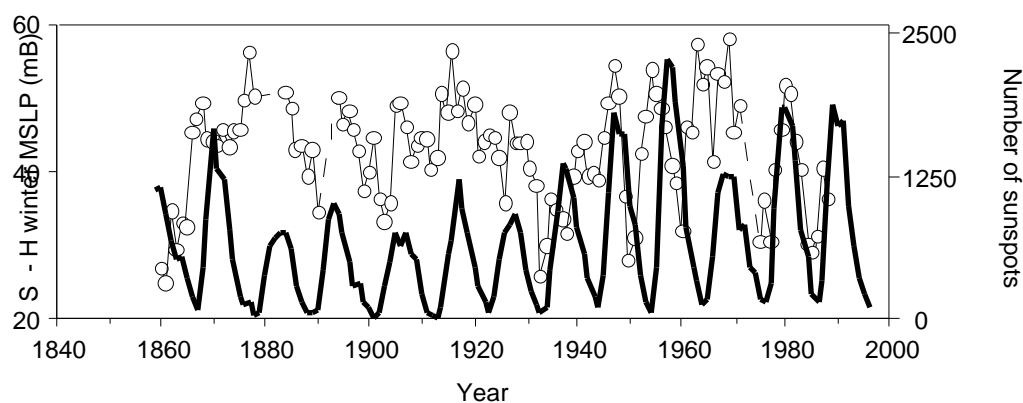


Figure 3.2. Correspondence between annual differences in MSLP between Sydney and Hobart, smoothed using a three-point unweighted running mean, and the sunspot cycle

Quasi-decadal variability in the ZWW has also been suggested for South Africa (Tyson, 1986). To assess the geographic extent of a coincidence between the ZWW and the sunspot cycle, I combined the South African and an Australian mid-tropospheric pressure time-series (Pook, 1994), each independently derived as an index of the regional ZWW, and derived a third time-series for South America from MSLP data, obtained from the NOAA National Climate Data Center. Because the interest is in the westerly winds, I used the longest time series available for a South American south west coast station (Valparaiso, 39.6° S), extracted the annual winter (JJA) monthly mean, and subtracted from it the equivalent mean for Stanley (51.7° S). The South African and Australian time series independently correlate with the sunspot cycle ($r = 0.70$, $n = 18$ years, $p = 0.0008$ and $r = 0.56$, $n = 19$ years, $p = 0.011$, respectively); the South

American MSLP time-series does not correlate with the solar cycle ($r = 0.09$, $n = 34$ years, NS), but does so if smoothed using a three-point unweighted running mean ($r = 0.44$, $p = 0.011$)(figure 3.3). This is similar to the correlation between sunspots and the S-H MSLP difference, contrasts with the closer match for the mid-tropospheric data, and perhaps indicates a solar signal that is principally evident in the troposphere (Van Loon and Labitzke, 1984) and transferred with some distortion to sea level. The African, Australian and South American time-series are by chance largely complementary, and jointly span the period from 1923 to 1990 (with a gap in 1957 and in 1966/67). In combination, they strongly suggest a correlation between the ZWW and the sunspot cycle that is in phase around the hemisphere and has been stable over the 67 year interval.

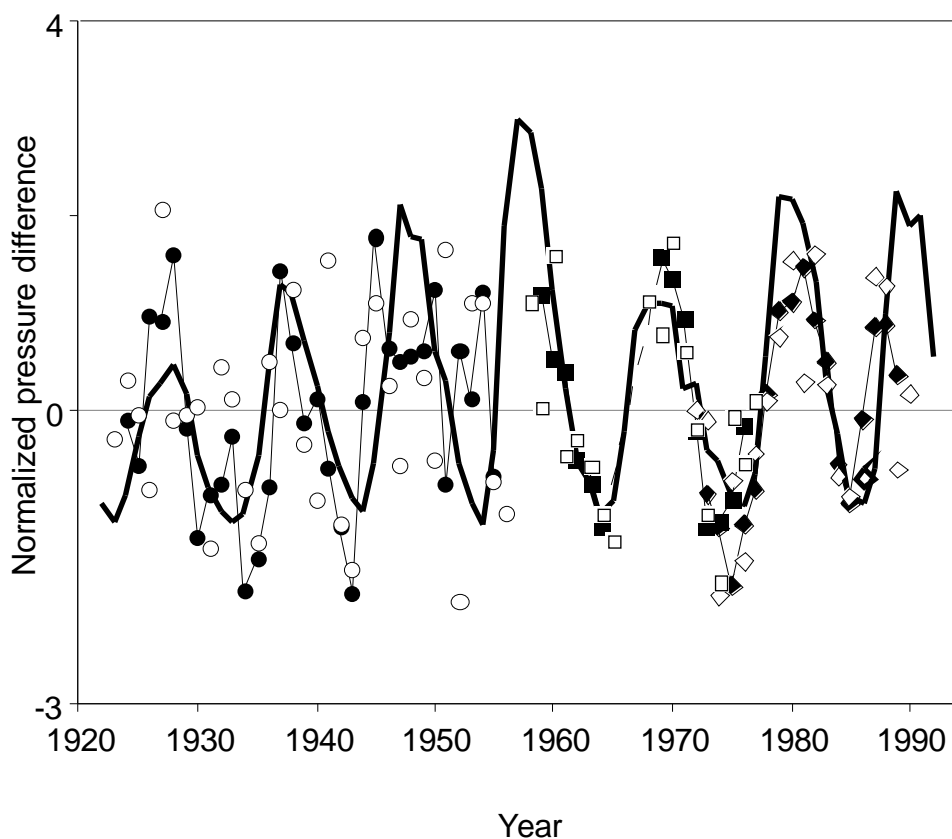


Figure 3.3. Correspondence between the sunspot cycle (heavy line) and MSLP indices of the Antarctic zonal winds in South America (circles), South Africa (squares) and Australia (diamonds). Open symbols are the raw values; solid symbols connected by lines are the three-point unweighted running means

Variation in the ZWW at the northern margin of the wind zone could result from either or both increased wind velocity or a shift in the location of the zone. There is no indication of a correlation between the sunspot cycle and the annual, winter or summer wind run at Macquarie Island (54° S) for the interval 1952 to 1979 ($n = 28$ years, all

correlations NS); artifacts in the wind run time-series introduced in 1979/1980 and 1991/1992 preclude using the full time-series to test the hypothesis further. To test whether the northern margin of the ZWW shifts with the sunspot cycle, I measured the latitude of maximum SLP along the Australian eastern seaboard (longitude 150 W) from daily charts provided by the Australian Bureau of Meteorology (BoM) and used these data to compute the monthly, seasonal and annual mean latitude of the Sub-tropical Ridge (L) for 1973 to 1997. Annual mean values of L measured from the SLP charts are almost identical to those published by the BoM for 1988 to 1993, and as calculated by Pittock (1983) from instrumental records to 1977.

For the 26-year interval, the sunspot cycle does not correlate with the annual or summer (JFM) mean L, but tends to vary anti-phasically with its winter (J-O) mean position ($r = -0.34$, $p = 0.094$). Weakly smoothing the latitude data (three point unweighted running means) increases the significance level of the correlation with the winter position to $p = 0.008$ ($r = -0.52$) (figure 3.4). The smoothed data also suggests a in-phase correlation between sunspots and the summer mean L, though the correlation is not significant ($r = 0.27$, NS). The negative correlation between sunspots and the winter mean L and the weak positive association with the summer mean L results in a positive correlation between the sunspot cycle and the smoothed annual range of L each year ($r = 0.45$, $p = 0.028$).

Variation in ZWW indices that is in phase across Africa, Australia and South America and the solar-correlated movement of the STR suggest a hemisphere-wide, sunspot-correlated expansion and contraction of the southern polar vortex. A similar effect has been proposed for the north polar vortex (Angell, 1992, Van Loon and Latitzke, 1994), and has previously been suggested for the southern hemisphere. Kidson (1925) reported highly significant correlations between sunspot numbers and Australian rainfall, L over eastern Australia, the rate of movement of the sub-tropical anticyclones, and the annual range of L, for the interval 1891 to 1921. The correlation between sunspot numbers and annual range of L is almost identical to that I found using recent data. Although Kidson's correlation was subsequently discounted (Pittock, 1978), my analysis suggests this may have been premature.

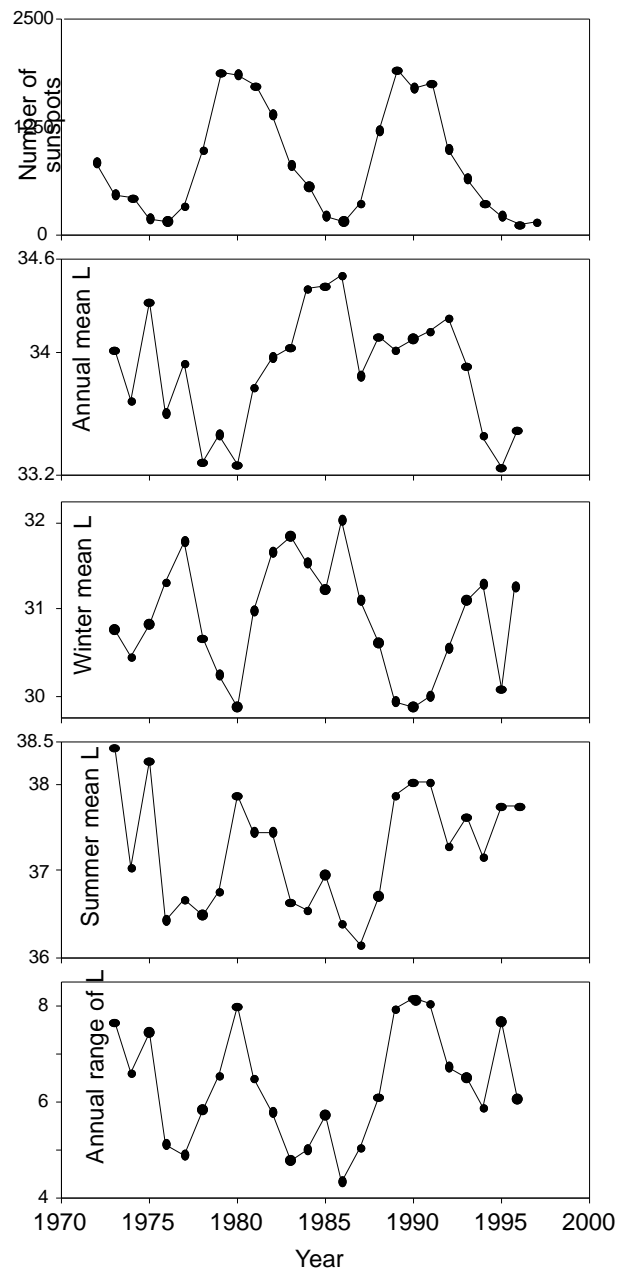


Figure 3.4. Relationship between the sunspot cycle and summer, winter and annual mean latitude of the Australian sub-tropical ridge

There are four likely reasons why there have not been more reports of solar-correlated variability in ZWW circulation. First, available time-series for zonal circulation are relatively short and based on few stations, particularly in the Southern Ocean. Second, the correlation appears to be strongest along the margin of the polar vortex, and may be conspicuous over only a narrow latitude range. Third, the sub-tropical ridge over Australia has shifted nearly 4 degrees polewards since the 1920s (Das, 1956). Consequently, the continental area affected by sunspot-correlated climate variability has probably decreased and its influence on regional rainfall, for example, is likely to have weakened in recent decades. Fourth, the correlation between L and the sunspot cycle differs in sign between winter and summer, as does the correlation between sunspots and S-H MSLP differences (positive in winter, but negative for the summer months; $r = -0.22$, $n = 113$ years, $p = 0.017$). The winter and summer correlations with the sunspot cycle largely cancel each other when summed over the year, so that analyses of annual mean data may not be informative at this time scale.

4.4 Possible global links of south east Australian quasi-decadal climate variability

Natural temporal variability - its scales, causes, and consequences for population and ecosystem dynamics - constitute a large portion of ecological research. A particularly intriguing aspect of this variability is evidence of apparently quasi-stable oscillations in abundance. Classic studies, featuring in elementary ecology texts, have explored empirically and theoretically the within- and among- species conditions that result in stable and unstable population oscillations. However, even for well known examples of natural quasi-stable oscillations (e.g., the Canadian hare-lynx cycle), the extent to which these oscillations derive from intrinsic factors, as opposed to environmental forcing, remains uncertain (Finerty, 1980).

Perhaps the best known example of natural population cycles operating at a time scale greater than a few years is the 'ten year' cycle characteristic of a variety of northern temperate mammals and birds, of which the hare-lynx cycle is one example. Trapping records for Canadian mammals spanning more than two centuries indicate periodic peaks and troughs in catches of a variety of unrelated species. Classic studies by Elton and Nicholson (, e.g., 1942) document that these cycles of apparent abundance have a period of 8-12 years, are broadly in phase among diverse species, cover large areas, and occur mainly in mid-latitude populations (see reviews by Keith, 1963, Finerty 1980). Similar cycles have been suggested for related species in northern Russia (Keith, 1963, Bulmer, 1974). Although the extensive trapping efforts on which initial analysis was based were phased out early in the twentieth century, small scale studies confirm that this cycle is still evident in Canadian hare populations, for example, through to at least the 1980's (Brand, et al., 1976, Krebs, et al., 1986).

As early as 1931, ten year cycles had also been suggested for a Canadian anadromous fish stock (Phelps & Belding, 1931); suggestions of similar cycles in marine species date from at least 1879 (Regner and Cacic, 1974). Although the Canadian observation was

noted in the terrestrial ecological literature (Bulmer, 1974), little significance was attached to it. Nonetheless, approximate 10 year cycles of abundance or recruitment (year-class strength) have subsequently been suggested or implied for a variety of marine and anadromous populations. These include fish and invertebrates, and species in the Atlantic and Pacific Oceans and in the northern and southern hemispheres (Table 1). The longest modern time series is for Irish Sea herring, catches of which vary cyclically at a period of 10-11 years since at least 1892 (Grainger, 1978). Although quasi-decadal cycles as well defined as those of the herring are clearly not the norm for most marine stocks, a review of the fisheries data suggests a number of other examples of species varying in abundance similar cycle of recruitment variability or apparent abundance is common, if far from universal. Fisheries data overall suggest a pattern similar to that drawn by terrestrial ecologists for Canadian populations, i.e., a common, but not universal, quasi-decadal cycle of apparent abundance that is broadly in phase over large areas and among diverse populations. A direct comparison between the population cycles of marine stocks and Canadian mammals is difficult because the time series overlap only slightly (those for marine stocks typically more recent). However, qualitative and small scale quantitative data allow approximate tracking of snowshoe hare cycles to the 1980's, which can be compared with the longest of the recent marine data sets. Such a comparison suggests that the 'ten year' cycles of at least these two species have been in approximate phase since at least the late nineteenth century.

However, marine and terrestrial manifestations of this 'ten year' cycle appear to differ fundamentally in geographic distribution: among terrestrial species, such cycles have been demonstrated only from the northern hemisphere, whereas similar cycles among fished stocks have been suggested for mid-latitude populations in both hemispheres. If, as implied above, the cycles in marine and terrestrial populations result from similar, if not the same forcing functions, then temperate southern hemisphere mammals and birds should also fluctuate in abundance over an approximate ten year period. Moreover, as in marine stocks, these cycles should be approximately in phase with those in northern hemisphere species.

I tested this hypothesis by seeking data on southern hemisphere mid-latitude mammals that are ecologically similar to the Canadian snowshoe hare and lynx. The longest time series available was for two species of Tasmanian wallabies, medium-sized, browsing herbivores common in forested and mixed forest-field environments (Strahan, 1983). The two species were hunted as agricultural pests from 1923 to 1982, with bounties paid on carcasses. Bounty records were available for the two species (in many years, only as pooled data) from the Tasmanian Department of National Parks and Wildlife (Anonymous, 1984). Fast Fourier analysis of the raw data indicates peaks in the power spectrum at periods of 8-10 and 12-13 years. To compare this time series with those of the Canadian species, I detrended the wallaby data and compared it with the snowshoe hare data for the 60 year period of overlap in the two data sets (1923-1982). Although variability in the wallaby data is less extreme than among hares, peaks and troughs in the two series largely coincide and the two correlate significantly ($r_s=0.29$, $p<0.05$).

The Canadian cycle is also strongly manifest in catches of the hare's principal predator - the northern lynx. Information on wallaby predators is sparse. Although a government bounty was also paid on thylacines, this system competed with bounties paid by individual property owners, such that state records are conspicuously incomplete (Guiler, 1985). However, data for individual properties over a 40 year period in the late 1800's are consistent with an approximate ten-year cycle to bounties paid (see fig. 6.2 in Guiler, 1985).

Quasi-decadal Climatological Cycles

The principal characteristics of the quasi-decadal cycles of fished and terrestrial populations appear to be similar, including indications of a bi-polar distribution. The breadth of habitats, geographic spread and diversity of species involved in these cycles, as well as indications of similar phase relationships across habitats, suggests the oscillation is not likely to be the result of features intrinsic to populations or species (e.g., Hastings and Higgins, 1994). Rather, it implies a response a pervasive external forcing function.

The possibility that external factors (e.g., plant biomass, weather, fire frequency, sunspots) account for the quasi-decadal Canadian mammal cycle has been generally discounted on the basis of weak correlations and the absence of any evident, suitably pervasive forcing factor (Arditi, 1979, Finerty, 1980, Keith, 1990). Hence, emphasis has been placed, both theoretically and empirically, on biotic interactions and intrinsic population dynamics (Finerty, 1980, Arcakaya, 1992). In contrast, fisheries studies in general assume that recruitment varies primarily, if not wholly, due to environmental influences. This is in part because changes in parental biomass often appear to have little effect on recruitment, and in part because of a perception that due to their very high fecundity, even slight variations in the egg and larval mortality of marine species could result in large fluctuations in recruitment (Koslow, 1992). Consequently, numerous studies have sought environmental features that correlate with changes in the abundance or recruitment of marine stocks (reviewed by Laevestu, 1993), and most studies suggesting 'ten-year' cycles in marine and anadromous species also suggest an external forcing function.

On local scales and, typically, dealing with changes in abundance of only one species, cyclic fluctuations of marine stocks have been linked to water temperature, salinity, rainfall (= freshwater discharge), sea ice cover, current patterns, winds and sunspot cycles (refs from Table 4.1). However, the possibility that large scale climate variability is responsible for quasi-decadal cycles in marine stocks has been independently raised for both the Pacific and the Atlantic Oceans and in the northern and southern hemispheres. Specifically, changes in fish abundance have been linked with 11-12 year cycles in the position of the Aleutian low and the frequency of strong

winds in the Alaskan Gulf (Favorite, 1985), with sea surface temperature and atmospheric circulation across the North Atlantic (Koslow, et al., 1987), to the occurrence of 'Benguela Ninos' (up-welling events), the EN-SO cycle, and the strength of the Antarctic zonal west winds in the South Atlantic (Taunton-Clark and Shannon, 1988, Harris, et al., 1992), and to an 11-year cycle in the frequency of strong zonal winds off SE Australia (Harris, et al., 1988, Thresher, 1994). Instrumental records support a hypothesis that these are manifestations of large scale features with global impacts, if perhaps also with peak actions at mid-latitudes of both hemispheres.

In the southern hemisphere, a circum-polar ten-year cycle in mid-latitude rainfalls (Vines, 1980, Vines and Tomlinson, 1985) has been linked to variation in atmospheric pressure gradients (geopotential height anomalies) off South Africa (Tyson, 1986), which in turn matches similar data off southern Australia (Pook, 1992). In combination, the South African and Australian data suggest cyclic variation in pressure gradients across the southern polar vortex spanning about 30 years. Tyson (1986) attributes this cycle to 'longitudinal oscillations in the position of standing wave 3 in the southern hemisphere westerlies'. Standing wave 3 (SW3) accounts for the second largest component (after wave 1) of the variance in the climatological mean amplitude of the 500 mb geopotential height at 50°S, reaches its maximum interannual variability between 45°S and 55°S, and has quasi-stationary ridges close to areas with evident quasi-decadal cycles in marine populations (Van Loon and Jenne, 1972, Trenberth, 1980).

In the northern hemisphere, quasi-decadal cycles has been suggested for a variety of mid- to high latitude climate and oceanic variables, including sea-ice cover, air temperatures, sea level pressure (Ikeda, 1990), extent of the northern polar vortex (Angell, 1992), North Atlantic sea water temperatures (Levitus, et al., 1994), and background thickness of the 1000-500 hPa field for the area north of 20°N (Wallace, et al., 1993). Ikeda (1990) suggests the cycle is manifest primarily in the first empirical orthogonal function (Y1) derived by Trenberth and Paolino (1981) to describe the dominant modes of interannual variability in the northern hemisphere sea level pressure fields. This function explains about 20% of the variance in the annual mean pressure field, has a dominant low anomaly in the Arctic and two minor high anomalies over the Pacific and Europe, and is associated with weakening and strengthening of zonal west winds in the sub-arctic (Ikeda, 1990). In that regard, the approximate 10 year cycle of wind strength in the Gulf of Alaska correlates with Y1 pressure variations, but only when the winds are lagged by 2 or 3 years. The quasi-decadal variability in North Atlantic sub-surface water temperatures described by Levitus, et al. (1994) also broadly correlates with Y1, though the authors note its spatial and temporal pattern is similar to another component of the northern teleconnection field, known as the East Atlantic Oscillation.

Independent suggestions of quasi-decadal cycles for climate variables in both the southern and northern mid-latitudes are consistent with the suggested bi-polar distributions of quasi-decadal oscillations of animal populations. The similarity in

period and phase between cycles of northern and southern mid-latitude populations, however, implies a coupling between climates of the two polar regions tighter than previously suggested (e.g., Knox et al, 1988). Although records are too short to draw strong conclusions, instrumental data are consistent with such a coupling. Quasi-decadal variation in atmospheric pressure differentials across the southern zonal westerlies correlates significantly with several Northern hemisphere climatological time series, including the size of the north polar vortex ($r_s = 0.34$, $p = 0.06$, at 0 lag; $p < 0.01$ when the southern time series is lagged by 1 and 2 years), Y1 ($r_s = -0.54$, $p < 0.05$), and sub-surface North Atlantic water temperature ($r_s = 0.45$, $p < 0.02$). As well, the pattern of interannual variability in wind strength in the Gulf of Alaska (Favorite and Ingraham, 1977) is strikingly similar to that in the intensity of zonal west winds along the south coast of Australia. Extrapolation of the quasi-decadal cycles proposed independently for each suggests that wind variability in the two hemispheres is nearly in phase, though the seven year overlap in the time series is too short to test this directly.

Correlations between Climatic and Animal Population Dynamics

The review above suggests a complex of co-varying climatic and oceanic parameters, that spans mid-to-high latitudes in both hemispheres. Secular variation of this elements in this complex correlates variously with changes in the apparent abundance or recruitment of a number of fished stocks, including Dungeness crab, NW Atlantic cod, Bay of Fundy scallops, European eels, and most SE Australian stocks exhibiting quasi-decadal variability. These correlations and the latitudinal distributions of the climate variables suggest strongly a link between the dynamics of mid-latitude animal populations and a bi-polar climate oscillation manifest in, for example, Y1 in the Northern Hemisphere and SW3 in the Southern Hemisphere. Nonetheless, there are three reasons for caution in concluding that a complex involving Y1, SW3 and the polar winds underlies all quasi-decadal variations in animal populations. First, most time series are very short. Second, oscillations in the abundance of a number of species (e.g., snowshoe hare and Irish Sea herring) do not clearly correlate with any of these climate variables. And third, spectral analysis of the entire Y1 time series (1925-1977) indicates peak power at a period of 6-7 years, not 10 years (Trenberth and Paolino, 1981). This appears to conflict with the long-term quasi-stability of the ten-year oscillations among terrestrial mammals, in particular, and fished stocks such as the Irish Sea herring. The implication is that although Y1 and its associated climate variables may underlie much of the observed animal variability, it is not the sole factor involved.

An explanation for this apparent mis-match is suggested by the work of Wallace, et al. (1993), who distinguish between two components to the northern hemisphere geopotential field variability - a 'background field', which is manifest year-round, but is most clearly evident in the summer 1000-500 hPa thickness poleward of 20°N, and a 'teleconnection pattern', which dominates both the winter and annual mean pressure

fields. Wallace et al (1993) suggest that the teleconnection pattern is associated with regional centers of action, strong horizontal gradients and geostrophic winds, and is a signature of dynamical processes in the northern polar climate, whereas the much lower amplitude variability in the background field reflects hemispherical mean conditions and, as such, is a more passive thermodynamic response to perturbations in the radiation and/or surface energy balance. Data in Wallace, et al (1993) indicate quasi-decadal variability in the background thickness field, similar to that reported for components of the teleconnection pattern, e.g., Y1. However, the time series are wholly uncorrelated (maximum correlation with Y1 at any lag between ± 5 years, $r_s = -0.05$, overlap period 1946-1977), i.e., the two components appear to be oscillating independently. More to the point, secular variation in the background thickness field correlates highly with snowshoe hare abundance ($r_s = 0.61$, $P < 0.001$). Since 1946, 4 peaks and 3 troughs in the summer thickness field poleward of 20°N match ± 1 yr those in relative hare abundance (Figure 7).

Although the time series is too short for strong conclusions to be drawn, three additional observations also suggest a relationship between the animal population cycles and variations in the background thickness field. First, temporal variation in the background field reflects hemispheric mean conditions, but the amplitude of the signal increases with latitude (Wallace, et al., 1993); the prevalence of oscillations in both the mammal and fished populations also appears to increase with latitude in the northern hemisphere. Second, interannual variability in the background field is slight relative to that of the teleconnection pattern, and hence is masked in annual mean data; this could account for the failure of previous efforts to link oscillations in hare abundance to conventional indices of interannual climate variability. And third, independent observations by climatologists and mammal ecologists suggest a mechanism that links the background field with fluctuations in snowshoe hare populations. Wallace, et al. (1993) note similarities between variability of the background field and the interannual and seasonal variability in northern hemisphere snow cover; recent studies on hare fluctuations indicate declines are proximately caused by food shortage, which is directly affected by snow depth (Keith, 1983, 1990).

Peaks and troughs in the interannual variability of the north polar background field since 1946 also coincide ± 2 yrs with those in the annual Tasmanian wallaby kills (note on stats), which implies a southern hemisphere climate analogue. Such a signal may be evident in Tasmanian summer rainfall data. December rainfall data for SW Tasmania since 1899 shows evidence of a quasi-decadal cycle, but this cycle is not phase-locked with that in the south polar winds ($r_s = -0.07$, $n = 37$ yrs, both variables lightly filtered using 3-pt unweighted running mean). However, it does correlate with interannual variability in the north polar summer thickness field ($r_s = -0.30$, $p = 0.05$, $n = 44$ years), albeit negatively. Completing the circle, the Tasmanian summer rainfall signal correlates with relative abundance of Canadian snowshoe hares, when the latter is lagged half a wavelength (5 years) ($r_s = 0.37$, $p < 0.01$, $n = 52$ years).

Roles of External and Internal Forcing

Correlations between mid-to-high latitude 'ten-year' cycles among climate parameters and animal populations in both hemispheres suggest an oscillating global forcing function, perhaps with greatest effect at mid-to-high latitudes. Two broadly different mechanisms have been suggested to account for such oscillations: external forcing and internal oscillations in atmosphere-ocean circulation.

Regarding the former, cycles with a period of 10-11 years are among the most common reported in the literature on climate variability, having been ascribed to everything from economic indices and agricultural harvests to atmospheric dust loads and rainfall patterns (Burroughs, 1992). The most common mechanism cited to account for this variability is the sunspot cycle, which has a mean period of 10.6 years. Reflecting this, several reviews and workshops have dealt with the likely impacts of sunspots, and solar variability in general, on terrestrial climates (Anonymous, 1982). Although a number of studies have provided often extensive statistical evidence for an impact of solar variations on terrestrial climates (reviewed by Burroughs, 1992), attempts to link the two have generally not been viewed as widely successful or compelling. This is in part because the suggested climate cycles themselves have often proven ephemeral, in part because of the slight amplitude of the solar signal (see, however, Ikeda, 1990), and in part because instrumental records are not often long enough for a statistically robust analysis (Pittock, 1983, Burroughs, 1992).

An alternative hypothesis is that stable 'ten year' oscillations derive from internal climate dynamics. The potential for this is well demonstrated, as in, for example, oscillatory behavior of northern hemisphere teleconnection patterns (Wallace and Gutzler, 1981).

The best known of these climate oscillations is the El Nino-Southern Oscillation, a low latitude quasi-stable, longitudinal oscillation with centers of action in the eastern and western Pacific. Documented teleconnection patterns include links between low to mid-latitude centers of action in both the Pacific and Atlantic Oceans, which could provide a mechanism for the poleward propagation of EN-SO cycles (see also Mehta, 1992). However, spectral analysis of the Southern Oscillation Index (SOI) indicates most power is in periods less than 7 years, which reflects the approximate interval between EN-SO events (mean approximately 4 years). Nonetheless, three observations suggest a relationship between the tropics and a 'ten-year' mid-latitude climate cycle. First, although EN-SO events occur at relatively high frequency, 'strong' and 'very strong' events occur at intervals of approximately 8-12 years (Enfield and Cid S., 1991). Second, annual mean variation in the SOI correlates with the pooled time series of pressure gradient variability in the southern polar vortex and the size of the north polar vortex (SOI vs. south polar geopotential height anomalies, $r_s = -0.36$, $p < 0.05$, $n = 32$

years; vs. size of north polar vortex, $r_s = -0.44$, $p < 0.005$, $n = 42$ years). And third, time series for at least some tropical species suggest a strong association with mid-latitude climate variability, despite the distances and very different habitats involved. The implications are that tropical oscillations reflect quasi-decadal variability at mid-latitudes, but are not dominated by it and probably are not causative.

Another approach is suggested by recent analyses of air-ocean circulation models in the light of suggested decadal oscillations in climate and oceanic parameters. Two recent models have been proposed that could produce such oscillations. One (Ikeda, 1990) is based, in part, on an interaction between wind stress, sea ice cover and high latitude oceanic heat flux to the atmosphere that amplifies weak, periodic external forcing by, for example, solar variability. Analysis of this model also suggests that the Eurasian Basin may have a decadal self-oscillation period, which could respond to irregularly occurring, major external forcing events to generate a quasi-stable ten year cycle even in the presence what is otherwise white-noise external or internal forcing. The second model (Weaver and Sarachik, 1991) independently pursues the latter approach, suggesting that under steady external forcing a primitive equation general circulation model for the North Atlantic oscillates at an approximate ten year period when run using mixed surface boundary conditions. The period of the oscillation varies slightly with basin topography, as a function of the advection rate between sub-tropical and sub-polar gyres, but is also robust under a variety of model conditions, including two hemisphere models. More generally, Mehta (1991,1992) has shown that two hemisphere, primitive equation coupled ocean-atmosphere models can oscillate stably over a range of periods, from a few weeks to several decades, given mean meridional circulations.

The suggestions that atmosphere-ocean dynamics amplify the weak solar signal (Ikeda, 1990) and that thickness of the northern hemisphere background field is a thermodynamic response to perturbations in the radiation and/or surface energy balance (Wallace, et al., 1993) both appear to be consistent with a link between quasi-decadal terrestrial cycles and solar variability. However, recent observations indicate cyclic variability in the different parameters is not closely related. Peaks in the summer thickness field, for example, lag the sunspot cycle by +3-4, +2, +1 and 0 years, in order from the mid-1940's to 1980, suggestive of a progressive alignment of cycles of similar period, rather than causation. Similarly, peaks in the sunspot cycle coincide with peaks in the Y1 component on the northern teleconnection field variability in the 1930's and 1940's, but with troughs in the 1950's and 1960's. Wildlife and fisheries data are also not strongly supportive of an effect of the sunspot cycle (though see Currie, et al., 1993, for an alternative view). The possibility that the hare-lynx cycle is a response to sunspot cycles was considered shortly after its discovery, but rejected on the basis of an inconsistent match over the 200-year time series (Moran, 1949).

The generality of this conclusion is difficult to determine, given the diversity of populations and climate parameters that appear to exhibit similar quasi-decadal

variability, not all correlated, and the relatively short time series available for most data sets. However, it is a reasonable hypothesis that apparent correlations between solar variability and climate are not causative, but instead reflect irregular detection of a relatively subtle internal climate oscillation, along the lines suggested by the atmosphere-ocean models described above. van Loon and Labitzke (1988) note this possibility in a paper considered the strongest evidence to date of a link between climate and sunspot cycles, but discount it on the basis of 'no obvious explanation' for the internal oscillations. In the light of the proposed atmosphere-ocean models, this problem may not longer apply. Nor is the time series examined by van Loon and Labitzke (1988) long enough to distinguish between a relationship with solar variability or, for example, variation in the north polar background field. In that regard, a suggestion that the magnitude of 'solar cycle' varies latitudinally in the northern hemisphere (Currie, 1979) is intriguing in the light of similar latitudinal gradations in both the 'ten year' cycles of animal populations and the magnitude of fluctuations in the north polar background thickness field (note on Atlantic vs Pacific).

Table 4.1. Literature reports of approximate ten-year cycles of recruitment or abundance in marine and anadromous populations

Ocean	Species	Period (yrs)	Reference
<u>Marine Teleosts</u>			
NE Atlantic	Clupea harengus	11	Jensen (1927)
		11.2	Currie, et al.(1993)
		10	Grainger (1978)
NE Atlantic	Sardina pilchardus (egg abundance)	8, 11	Regner & Gacic (1974)
		11	Southward, et al. (1975)
NW Atlantic	Gadus morhua (17th & 18th centuries)	11.2	Currie, et al. (1993)
		10-20	Koslow, et al. (1987)
NW Atlantic	Melanogrammus aeglefinus	12-18	Koslow, et al. (1987)
SE Atlantic	Sardinops ocellatus	10	Shannon, et al. (1988) Tauton-Clark & Shannon (1988)
NE Pacific	Theragra chalcogramma	11	Bulatov (1989)
SW Pacific	Rexea solandri	10	Thresher (1994)

Marine Invertebrates

NE Atlantic	Zooplankton abundance	11	Southward, et al (1975)
NW Atlantic	Placopecten magellanicus	9	Caddy (1979)
NE Pacific	Cancer magister	10	Botsford (1986)
W Pacific	Asterias amurensis	10	Nojima, et al. (1986)
SW Pacific	Jasus novaezelandiae	11	Harris, et al. (1988)
SW Pacific	Pecten fumatus	10	Thresher (1994)

Anadromous and Freshwater Teleosts

NE Atlantic	Salmo salar	8 - 11 10	Berg (1935) Gee & Milner (1980)
NW Atlantic	Salmo salar	10 9.6 10	Phelps & Belding (1931) Huntsman (1937) Kerswill (1955)
NE Pacific	Oncorhynchus spp.	10	Botsford, et al. (1982)
NW Pacific	Oncorhynchus gorbuscha	11	Birman (1976)

4.5 Extreme longevity of the commercially harvested deepwater fish, *Hoplostethus atlanticus* (Trachichthyidae) and evidence of significant environmental variability at roughy depths

Orange roughy (*Hoplostethus atlanticus*) is a globally distributed deepwater (600-1500 m) species that is subject to recent commercial fishing in Australia, New Zealand and Namibia; exploratory fishing has also been undertaken in the North Atlantic, North Pacific and Indian Oceans. A key issue regarding sustainable exploitation and ecosystem impacts is the species' maximum age and age at sexual maturation. Correlations between environmental variability and ontogenetic variation in the composition of roughy otoliths, and analysis of rates of otolith deposition suggest roughy are much longer lived than previously estimated, reaching sexual maturity at an age of 80-120 years. Maximum ages, estimated by C-14 analysis of roughy otoliths and comparison of strontium patterns in otoliths with those of radiocarbon-aged deepwater

corals, is 400-600 years. This places orange roughy among the longest lived vertebrates thus far reported and has substantial implications for the sustainability of the fisheries and fisheries impacts on deep-water ecosystems.

Orange roughy is a deep-bodied, robust fish that reach sexual maturity at a standard length of about 30 cm and reach a maximum length of 50-60 cm, depending upon locale. Since 1980, major fisheries for the species have developed in the southern hemisphere, and exploratory fishing has been undertaken in the northern hemisphere. At present, it constitutes the basis for the deepest commercial fishery, with trawlers routinely fishing to 1000 m and harvesting up to about 100,000 tons annually. Sustainable yield estimates are based in large part on age estimates which, however, are controversial (Gauldie, 1998). Original estimates of age and growth rate were based on conventional enumeration of macroscopic annuli visible on roughy otoliths, and suggested sexual maturation at 9-12 years and a maximum age of 20-25 years (Kotlyar, 1980; van den Broek, 1983), indicating relatively productive stocks. The aging protocol was never validated, but the estimates are consistent with counts of assumed daily growth increments in the otoliths and expectations based on the physiology of otolith deposition (Romanek and Gauldie, 1996). They are not consistent, however, with counts that can range up to several hundred depending upon the criteria used to define an 'annual' increment, size-frequency distributions of landed fish that show no evidence of either the modal progression that would be expected for a relatively rapidly growing fish or a downwards shift in mean size as the fishery becomes progressively dependent on newly recruits (Francis and Smith, 1995), and with localised fisheries that in many instances disappear after only a few years of harvesting. Radiometric aging using the ^{210}Pb : ^{226}Ra disequilibrium subsequently suggested sexual maturation at about 30 years of age and a maximum age of at least 150 years (Fenton, et al., 1991). The physical basis for these estimates has been questioned by Gauldie and Crenner (in press), who shows that a transitional element in the decay sequence (radon) is likely to diffuse out of otoliths, which are porous structures (Proctor and Thresher, 1998). This implies the radiometric ages are under-estimates. However, Gauldie (pers. comm.) also suggests selective up-take of lead isotopes by roughy otoliths, which saves the hypothesis of fast growth and low maximum ages.

We examined ontogenetic variability of two elements in the otoliths of orange roughy to assay scales of environmental variability at roughy depths in the southern Australian region. To minimise effects of potential confounding factors, we restricted the analysis to three pre-maturation (about 30 cm) males all drawn from a single site (Maatsuyker island fishery) at the same time (August 1996). Procedures for otolith extraction, preparation and analysis follow Gunn, et al. (1992). Ontogenetic variation was assayed at a series of equally-spaced points along the curved long growth axis of each otolith, mapped as a series of short, straight transect lines. Length of the ontogenetic series differed among individuals, in part due to differences in absolute otolith size and shape and in part to slight differences in the way each otolith was sectioned. Element concentrations were measured using a JEOL electron probe microanalyser, using a beam

diameter of 14 microns, point spacing of 25 microns (center-to-center), and a beam power density of $2.44 \mu\text{W}\mu\text{m}^{-2}$. Analysis of the first three specimens was limited to strontium (Sr) and calcium (Ca), which are unaffected by specimen handling and which have been suggested vary with water temperature (reviewed by Thresher, in press). Subsequently, we also measured concentrations of phosphorous (P), on the basis of an apparent relationship between regional levels of water column productivity and P concentrations in otoliths (Thresher and Proctor, in prep).

Sr series for the three individuals examined differed markedly when aligned from the otolith center, but were strikingly similar when aligned from the margin and linearly stretched (due to the unequal series length) for maximum overlay (Figure 5.1a). For roughly the outer 2/3s of the otoliths, the three life history scans correlate highly ($p < 0.01$ for all three pair-wise comparisons, based on data re-sampled from the overlaid plots at 64 uniformly spaced intervals, after filtering each individual scan using a three-point unweighted running mean); interior of this point they differ substantially in length and pattern, although all three exhibit a pair of peaks in Sr values close to the primordium that our unpublished data suggests is a 'juvenile' signature. The common pattern in the outer otoliths suggests a response to environment variability. We tested for this by producing a consensus Sr life history scan by averaging the values for the three fish and comparing it with local environmental records. The consensus pattern correlates highly with annual Tasmanian rainfall records ($p < .0001$, $n = 64$ years) (Figure 5.1b), back to about 1920. The longest individual scan (specimen #156) extends the correlation back to the mid-1890s (Figure 1c). Variations in rainfall in SW Tasmania reflect the strength of the Antarctic zonal west winds (Shepard, 1995) and hence are likely to be an index of wind forcing and turbulence in the areas inhabited by orange roughy. How these affect Sr concentrations in roughy otoliths is still uncertain, but the literature suggests it is likely to be mediated by fish growth rate, water temperature, or both.

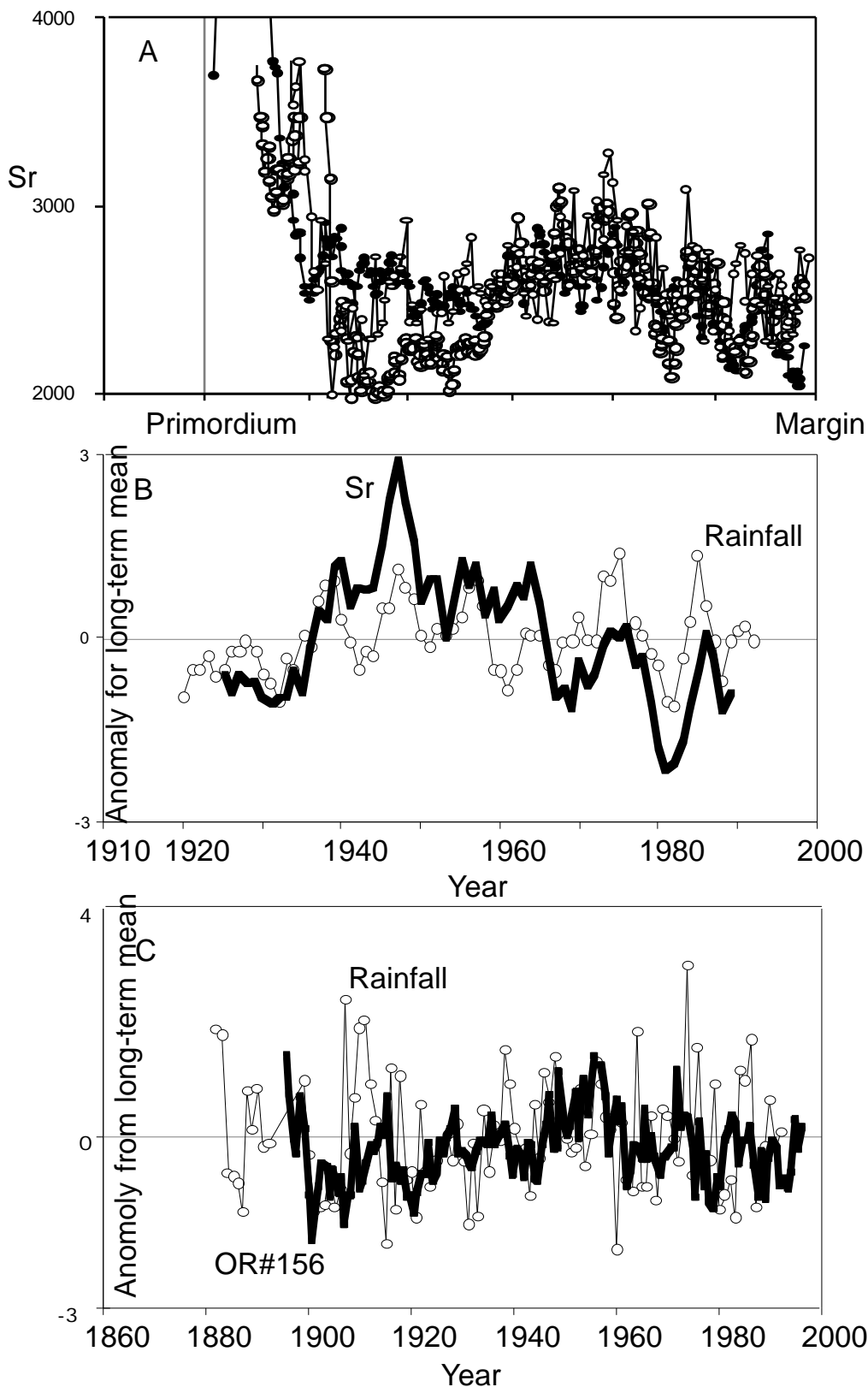


Figure 5.1. Coherence pattern and correlation with rainfall between Sr life history scans circa 30 cm orange roughy

The common pattern of otolith composition and its correlation with climate variability implies significant environmental variation at the depths inhabited by roughy. It also implies ages considerably greater than previously suggested. Reasonable interpolation of the life history scans relative to the rainfall history suggests the males examined ranged in age from 80 to about 130 years, which is three times longer than suggested by radiometric techniques and an order of magnitude greater than the age suggested by enumeration of external annuli or counts of assumed daily increments. As the fish examined were only about 30 cm long, it also implies that the maximum age of the fish, which can reach 60 cm, is considerably greater than 150 years.

We tested these hypotheses three ways:

1. We generated a second, potentially independent environmental proxy in roughy otoliths by measuring P concentrations along the growth axis of two additional circa 30 cm males collected at Maatsuyker in August 1998. Sr and P concentrations did not correlate in either individual, but the pattern of variability in P was similar in both (correlation after re-sampling linearly stretched and overlaid plots, $p = 0.08$, $n = 131$ points). On the basis of a possible relationship between productivity and P in otoliths, we compared a consensus P life history scan for the two fish with the Southern Oscillation Index (SOI), after first differencing both series and smoothing them using a three-point unweighted running mean. The coincidence between the SOI time series and the P life history scan is striking (Figure 5. 2) and highly significant ($p = 0.0014$, $n = 115$ years). The correlation implies the two roughy were approximately 110 years old, i.e., about the same age estimated for similar sized fish from the relationship between temperature/rainfall and Sr concentrations.

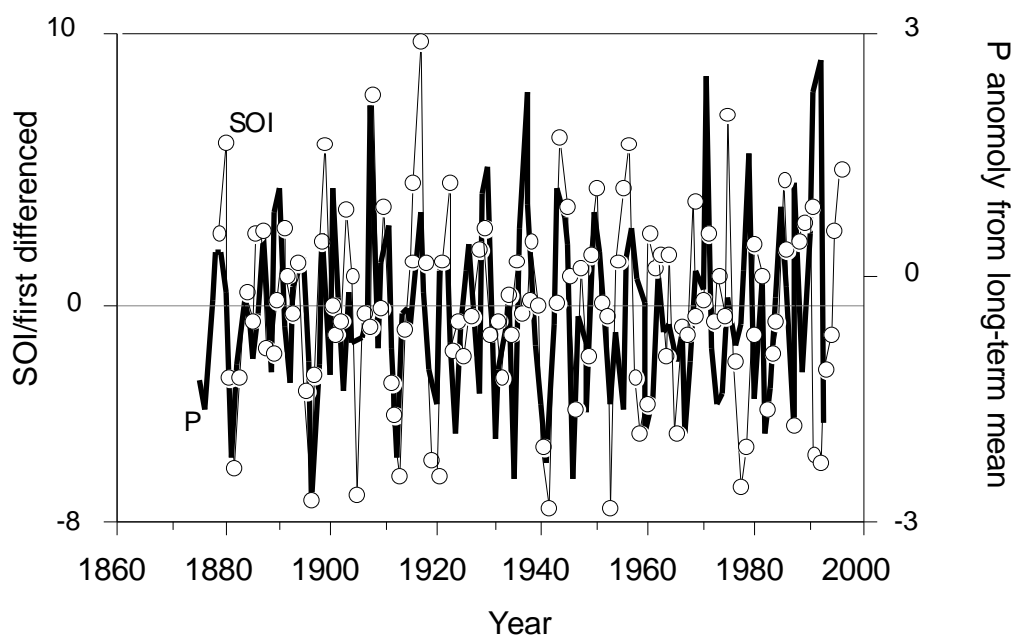


Figure 5.2. Relationship between the Southern Oscillation Index (SOI) and the mean P life history scans of two Maatsuyker orange roughy

2. We directly measured the otolith growth rate. If 30 cm roughy are ten years old, then annual growth along a 6 cm otolith axis should be about 600 microns; the otolith of a thirty year-old fish should grow about 200 microns annually; and that of a hundred year-old fish should grow about 60 microns annually. These predictions assume a constant growth rate to sexual maturity, which is consistent with both the 'climate-based' age estimates and previous studies using growth increments (Gauldie, et al., 1989) and radiometric techniques (Fenton, et al., 1991). We measured otolith growth rate by comparing Sr plots of males caught at Maatsuyker in August 1998 with those taken in August 1996 and determining the extent to which the Sr scan had been extended in the two year interval. Both of the 1998 fish had Sr life history scans that were similar to each other and to the 1996 fish. For purposes of obtaining the most accurate measurement of otolith growth, which is critically dependent on the alignment of the Sr plots, we chose for the comparison the 1996 and 1998 fish that had the most similar Sr trajectories (Figure 3). The correlation between the two Sr life history scans is significant at $p < 0.0001$ ($n = 72$ points corresponding to annual intervals, re-sampled from the optimally overlaid plots). The growth axis of the 1998 specimen, from the primordium to the position that corresponds to the outermost point of the 1996 specimen, was 6,517 microns. Hence, the predicted growth over the subsequent two years is 1,304 microns for an assumed age of 10 years (based on Gauldie, et al., 1989), 650 microns for an assumed age of 20 years (from Mace, et al, 1990), 343 microns for an assumed age of 35 years (based on Fenton, et al., 1991) and 130 microns based on an assumed age of 100 years. The measured difference between the 1996 and 1998 specimen is

143.5 microns (Figure 5.3), which is within measurement error of the prediction based on 100 year-old fish

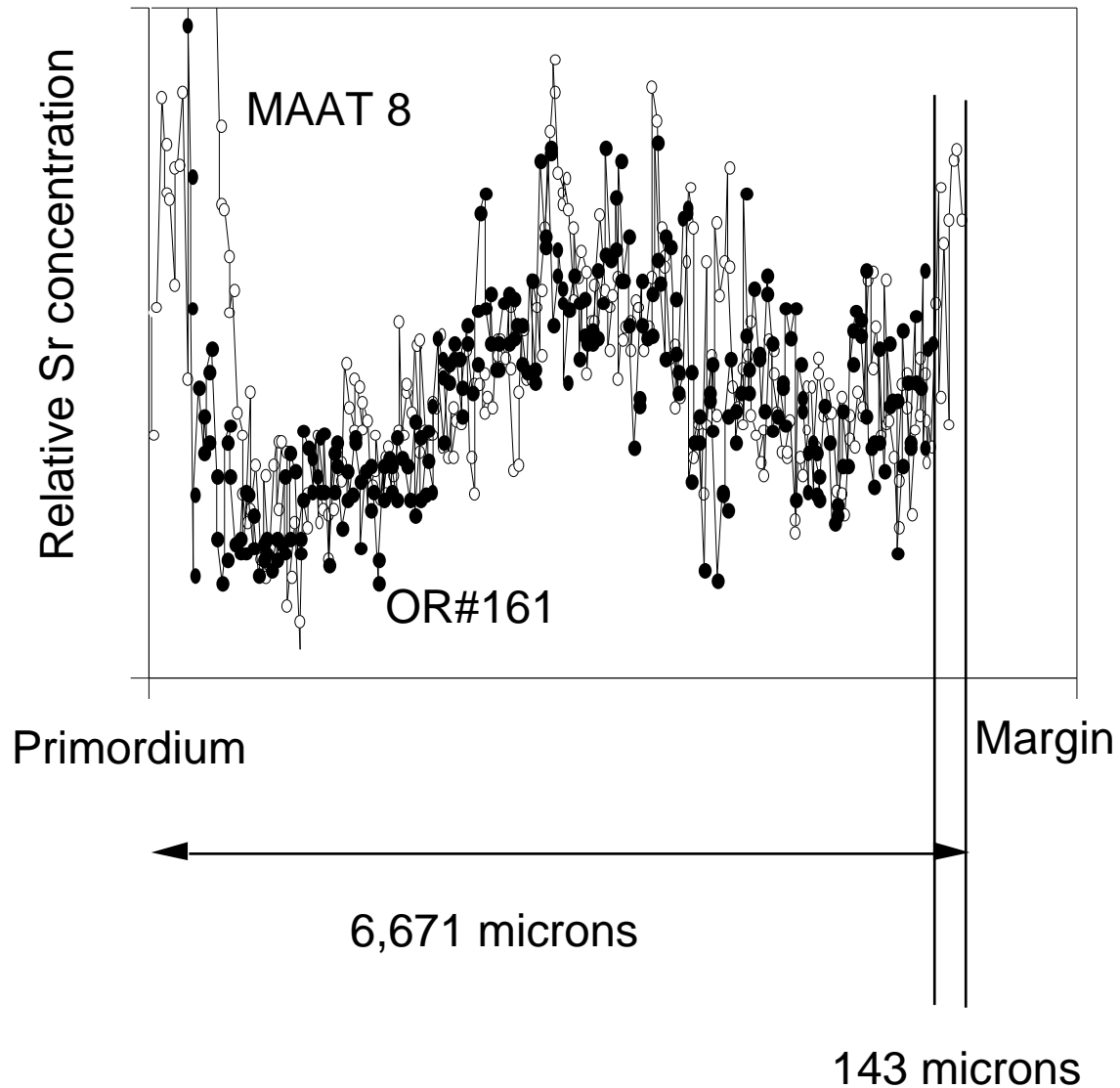


Figure 5.3. Marginal growth of the Sr life history scan for circa 30 cm orange roughy, based on comparison of two individuals collected at a two year interval

3. Finally, we sought to determine maximum roughy ages directly using radiocarbon techniques. For ^{14}C analyses, 10 mg samples were taken from the center and margins of four roughy ranging in standard length from 20.5 to 51.5 cm, caught at the Cascade Plateau (near Maatsuyker). ^{14}C age estimates for the margin indicate reservoir carbon age; the difference between age estimates for the center and margins indicates absolute age of the specimen. The data suggest absolute ages of 40-50 cm

fish in the range of 600 to 700 years, but also reservoir ages of 105-325 years, which is lower than expected based on oceanographic sampling in the area and the depth strata occupied by the fish (Lassey, et al., 1990). The low reservoir age very likely reflects a contribution of diet (which is based on vertically migrating prey, that would have very low reservoir ages) to otolith carbon and may be valid, but also could be biased by post-bomb ^{14}C regeneration. To get around this problem, we aged the large roughy indirectly by comparing them with antipatherian corals (*Keratoisis* sp.) collected at the Cascade Plateau in 1996, at about 1000 m depth, i.e., below the depth of bomb effects, for which ^{14}C age estimates should be valid. Two coral sections were aged and also sampled for ontogenetic variability in Sr concentrations. Sr concentrations (or more specifically Sr/Ca ratios) in corals have been previously identified as a bio-thermometer (Beck, et al., 1992). We optimally aligned the Sr pattern in the two coral examined with that of a 51 cm orange roughy collected at the Cascade Plateau (Figure 5.4). Both correlations were highly significant (K-1: $p < 0.05$, $n = 41$ points; K-2: $p < 0.001$, $n = 41$ points). K-1 overlaid 11% of the outermost Sr life history scan of the roughy, whereas K-2 overlaid 23% of the life history scan. C-14 age estimates for the two corals were 110 and 210 years, respectively, in both cases ± 50 years. On the basis of these ages, the amount of overlap between the corals and the roughy Sr plots, and our age estimates for 30 cm fish, we estimate the total age of the 51 cm roughy at 450-500 years.

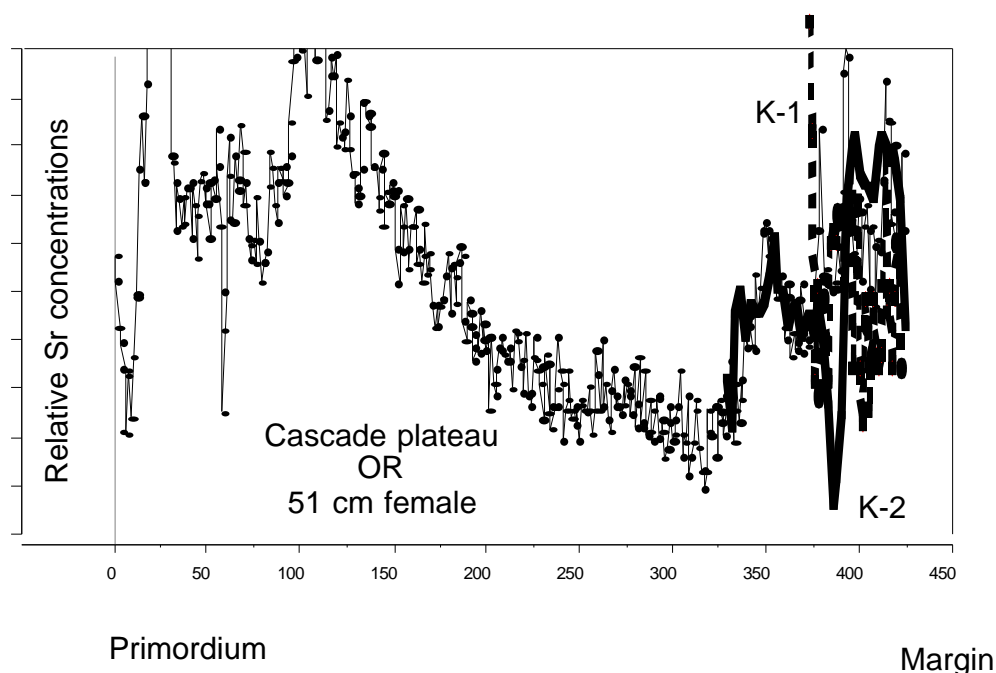


Figure 5.4. Comparison between the Sr life history scan of a 51 cm orange roughy, collected at the Cascade Plateau, with Sr plots of two deep water corals, aged using C-14 to be 110 (K-1) and 210 (K-2) years old, also collected at Cascade Plateau

We conclude that all three tests are consistent with an age at sexual maturity for orange roughy of about a century, and a maximum age of 400-500 years. Although any one could be criticized on various grounds, the consistency of results across all of the tests lends credence to the overall estimate of extreme longevity in the species. This longevity is also consistent with the stability of size frequency distributions for catches of the species, and with age-estimates obtained by radiometric techniques assuming either a degree of biasing due to radon loss (Gauldie and Crenner, in press) or inherent conservatism in applying the technique (G. Fenton, pers. comm.).

Roughy that live to half a millennium and perhaps longer (North Atlantic fishes reach a size of more than 60 cm, which is much larger than any fish we have thus far examined) places them among the longest-lived vertebrates yet reported. This extreme age implies extremely low rates of adult mortality, which is consistent with a species that is near the top of its trophic pyramid (Koslow, 1996). The age of the fish and the correlations between the composition of its otoliths and climate/oceanographic variability suggest the possibility of constructing a proxy for variability in the Southern Ocean spanning the last several hundred years. The age of the fish also has significant implications for the commercial harvest of the species. An age at sexual maturity that is three times that currently used to calculate sustainable yields imply those yields need to be reduced a corresponding amount, which may render some fisheries uneconomic. The long generation time may also imply very infrequent recruitment events, which is consistent with the few juveniles that have thus far been found (Francis and Smith, 1995) and which may require a reconsideration of the models used to estimate safe minimum biomass. More fundamentally, what may well turn out to be short term exploitation of a fish that lives for centuries will result in effectively a permanent change in the dynamics of upper slope communities and in that sense may be more similar to and should be assessed as a form of resource mining, rather than conventional harvesting of a renewable resource. The same may be true for other recently exploited deep-water fish species, such as oreo dories (Oreostomatidae) and Patagonian toothfish (Nototheniidae).

4.6 Other proxy environmental time series

Deepwater corals

Although environmental time series have been successfully obtained from shallow-water corals, they have never previously been obtained from a deepwater organism. We attempted to derive such a time series from the bamboo coral, *Keratoisis* sp., which is obtained incidentally by trawlers fishing for orange roughy on seamounts around Tasmania. Several large specimens were obtained that had ~300-400 growth rings when examined in cross-section near the base. Analyses of oxygen and carbon isotope anomalies and the concentration of strontium from a transect along the axis of a specimen showed apparent associations between these properties. ^{18}O and strontium

anomalies generally reflect temperature conditions, whereas ^{13}C tends more to reflect metabolic and trophic status.

Unfortunately, ^{14}C dating carried out on the bamboo coral did not confirm that the growth bands were annual. Tests carried out at the Australia National University Quaternary Dating Research Centre were initially inconsistent: the difference in age between material from the core and outer edge was ~300 years for one coral and ~100 years for a second, although both had 300-400 growth rings. A potential problem was noted in the sample analysis for the coral aged to 300 years. A second set of samples was run subsequently at the National Ocean Sciences AMS facility at Woods Hole Oceanographic Institution (USA), which indicated an age of ~80 years. Thus it appears that the bands are not annual, making determination of the age of the organism at various points along the cross-section of the trunk highly uncertain. Given our apparent inability to calibrate the age of the growth bands, no further micro-chemical analyses were carried out on the deepwater corals.

However, we note that the time series of anomalies in Sr concentration across one of the corals (specimen K1) appeared to be associated with the time series for southwest Tasmanian rainfall and the Sr anomalies in the orange roughy otoliths (see above). Based on this association, the age of the coral appeared to be approximately one hundred years, consistent with the C-14 age determination.

Growth variability of deep and shallow water fishes, inferred from otolith growth increment analysis

Up to the first 8 growth increments were measured for 8 species (banded morwong, jackass morwong, black oreo, smooth oreo, spiky oreo, warty oreo, redfish and orange roughy), which provided time series of growth during the early life history that extended as far back as 1861 (Table 6.1).

Table 6.1. The species examined for growth increment analysis, number of otoliths examined from each, years of their collection and their birthdates

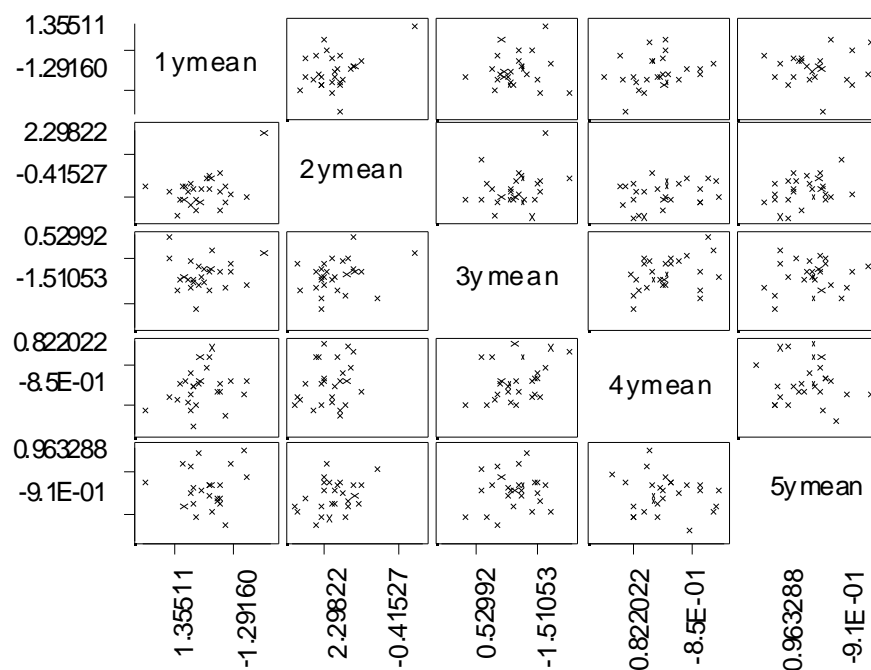
Species	Number	Years of collection	Years of birth
Banded morwong	75	1996	1912-1992
Jackass morwong	40	1993, 1994, 1996	1954-1992
Black oreo	52	1991, 1993	1891-1982
Smooth oreo	61	1987, 1991, 1993	1916-1980
Spiky oreo	56	1989	1861-1984

Warty oreo	66	1988	1888-1981
Redfish	84	1992-1995	1949-1993
Orange roughy	113	1995-1996	1871-1976

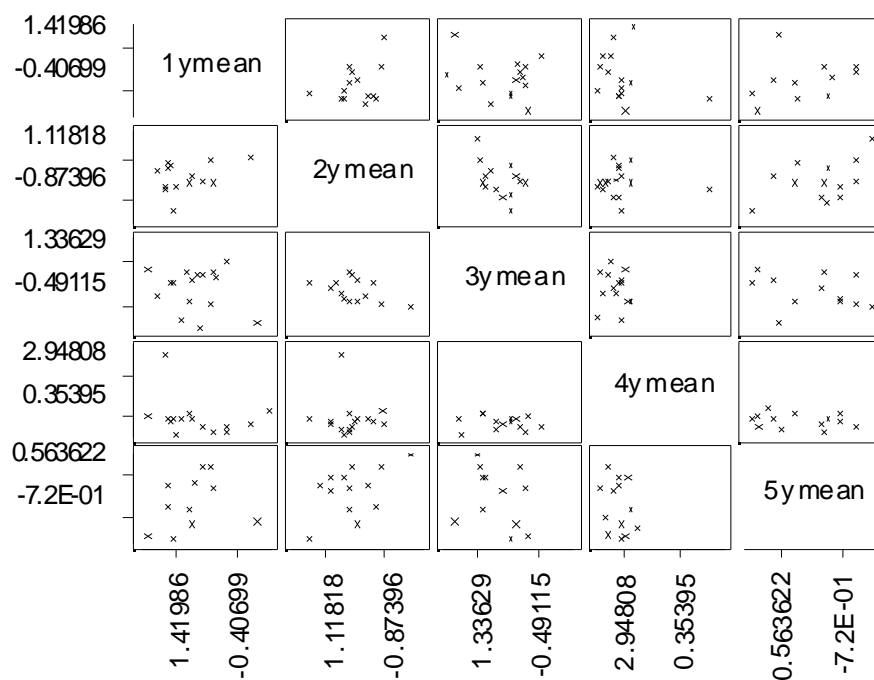
Exploratory data analyses were carried out to assess relationships of growth anomalies (i.e. years of relatively good or poor growth) within species, between species and between growth anomalies and climatic indices. Plots of relative growth for a particular year between different year-classes within species exhibited surprisingly little correlation (Figure 6.1, Table 6.2).

Figure 6.1. Plots of mean annual growth increment anomalies for one year-class against another within species.

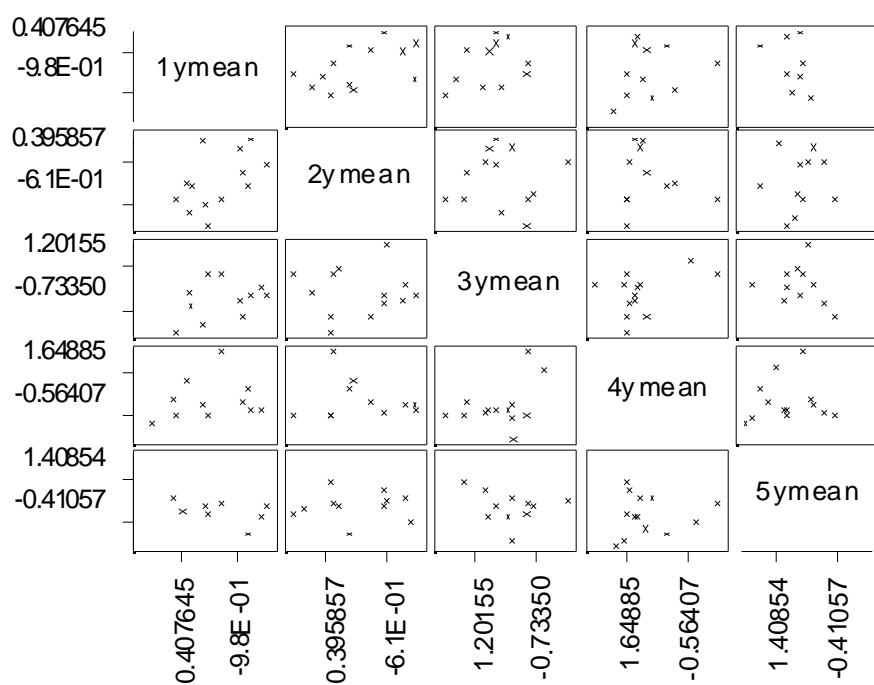
Banded morwong, 1-6 observations in each mean



Black oreo, 1-4 observations in each mean



Jackass morwong, 1-6 observations in each mean



Redfish, 1-8 observations in each mean

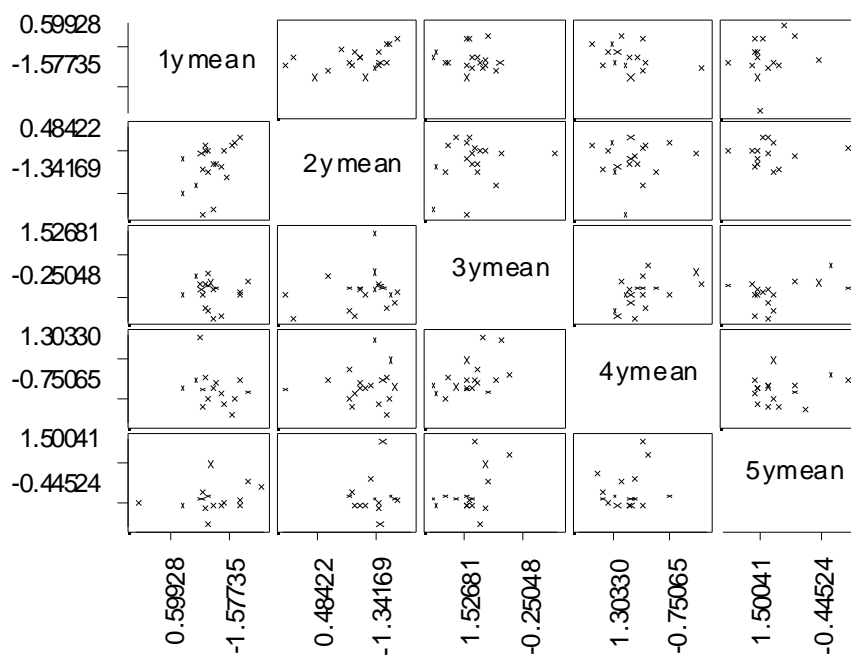


Table 6.2. Pearson correlations between mean annual growth anomalies for one year-class (Y) against another within species. The correlations are based on differing numbers of observations with pairwise deletion of missing values. The correlations correspond to the plots of means in Figure 4

Banded morwong

	Y1	Y2	Y3	Y4
Y2	0.401			
Y3	0.059	0.263		
Y4	0.242	0.246	0.355	
Y5	0.061	0.343	0.087	-0.132

Black oreo

	Y1	Y2	Y3	Y4
Y1	0.354			
Y2	-0.179	-0.469		
Y3	-0.265	-0.070	-0.081	
Y4	0.278	0.490	-0.264	-0.243

Jackass morwong

	Y1	Y2	Y3	Y4
Y1	0.522			
Y2	0.331	0.006		
Y3	0.208	-0.124	0.433	
Y4	-0.402	0.120	-0.235	0.047

Orange roughy

	Y1	Y2	Y3	Y4
Y1	0.046			
Y2	-0.253	0.143		
Y3	-0.090	0.079	-0.074	
Y4	0.175	0.240	-0.077	0.103

Redfish

	Y1	Y2	Y3	Y4
Y1	0.445			
Y2	-0.072	0.204		
Y3	-0.345	0.073	0.487	
Y4	0.250	0.061	0.429	0.185

Smooth oreo

	Y1	Y2	Y3	Y4
Y1	-0.152			
Y2	-0.363	0.316		
Y3	0.600	0.065	-0.055	
Y4	-0.104	0.255	-0.410	-0.146

Spiky oreo

	Y1	Y2	Y3	Y4
Y1	-0.426			
Y2	-0.300	0.056		
Y3	0.258	0.228	-0.249	
Y4	0.125	0.314	0.208	0.032

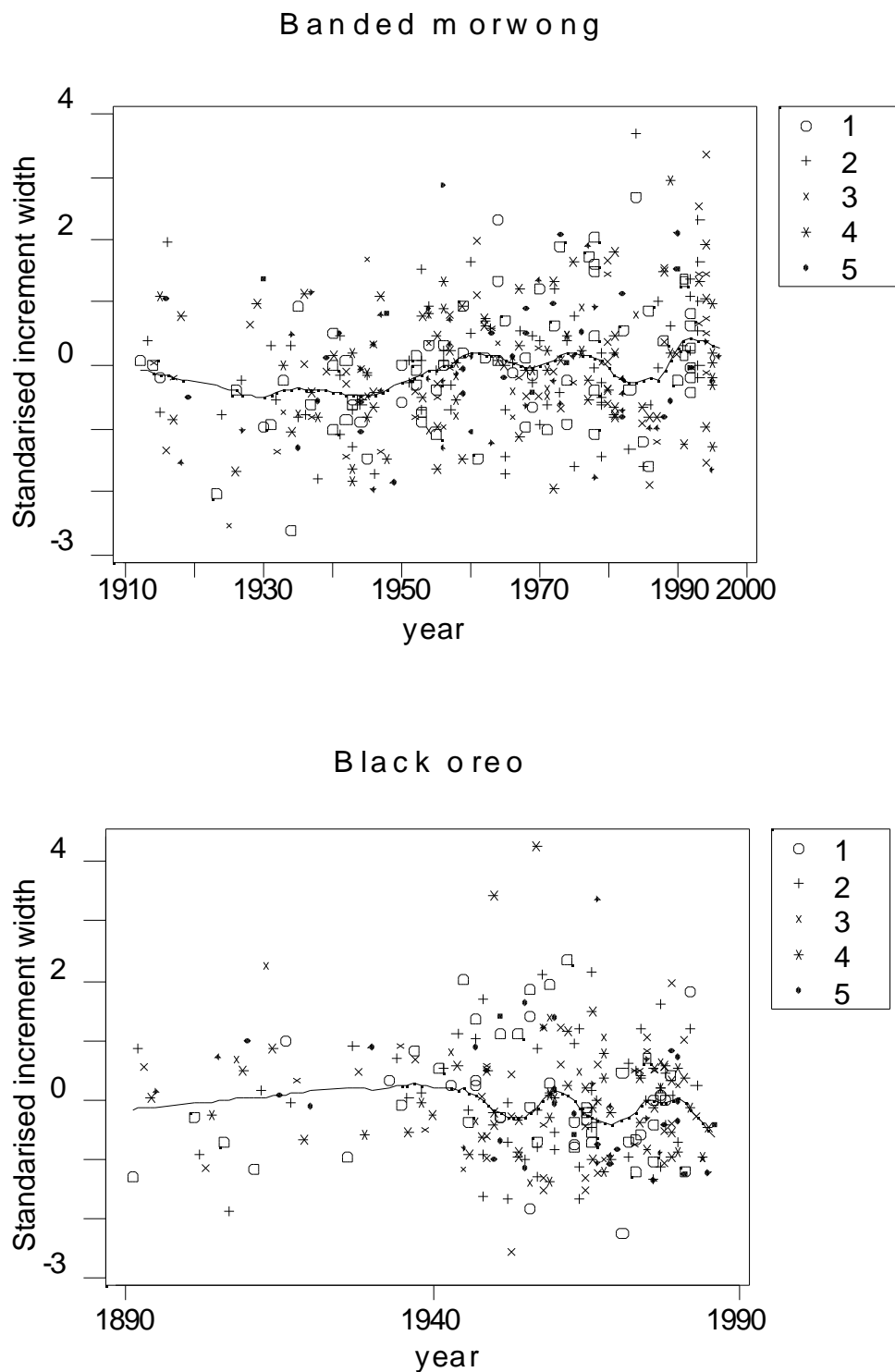
Warty oreo

	Y1	Y2	Y3	Y4
Y1	0.337			
Y2	-0.131	0.668		
Y3	0.450	-0.203	-0.198	
Y4	-0.246	0.049	0.484	0.193

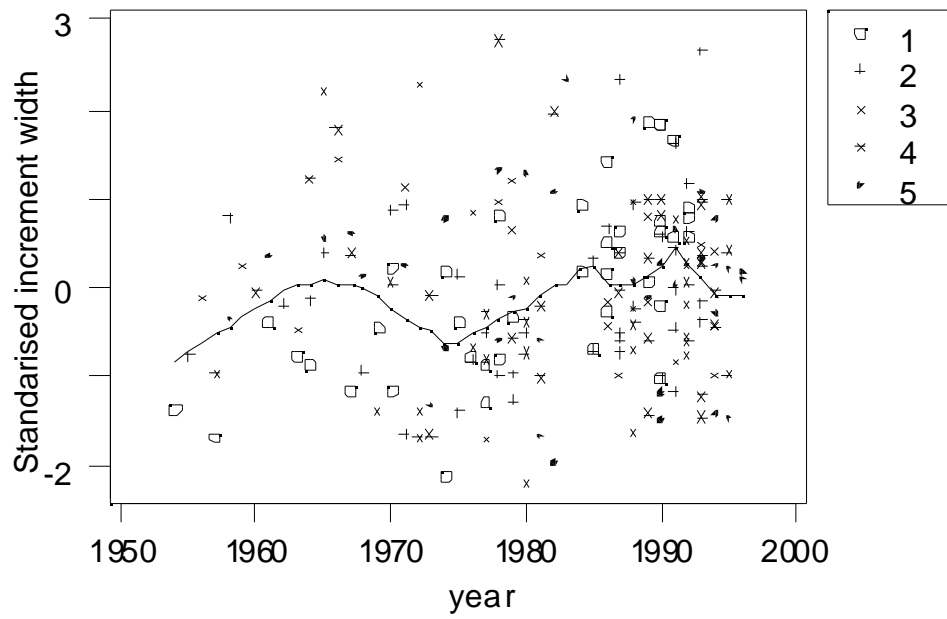
Twenty-nine out of the 80 correlations are negative, confirming the general impression of very weak association seen in the plots in Figure 4.

The time series of growth anomalies were then plotted with a lowess smoothing function to highlight low-frequency trends (Figure 6.2). There was little consistency in the trends between species. Some curves appear to be flat in the last two decades whereas others are not; some of the overall trends are down, while others are up.

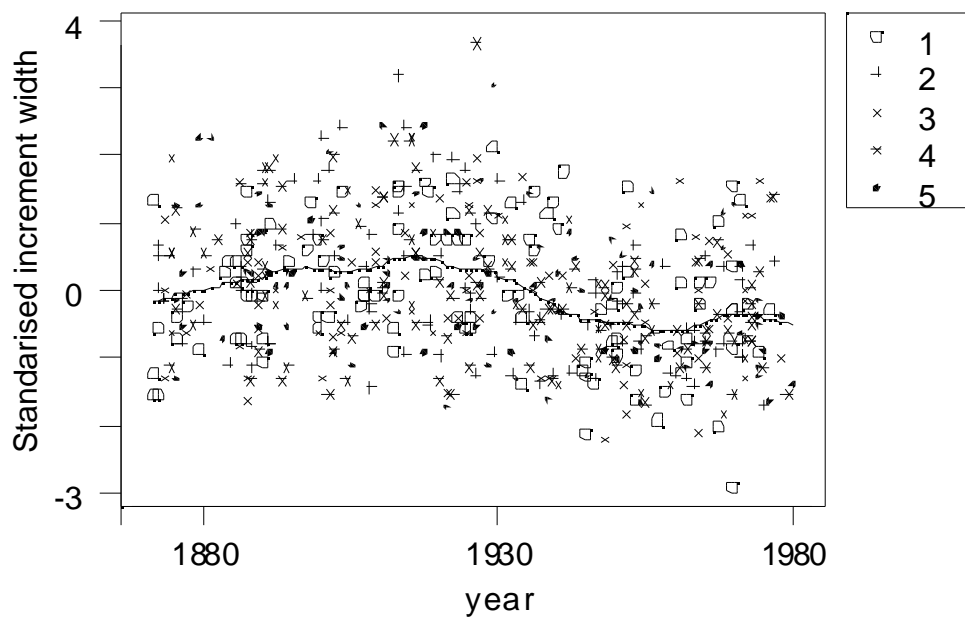
Figure 6.2. Standardized increment widths plotted against year with lowess curve based on fraction $f = 0.2$. Separate increment numbers are identified by different symbols



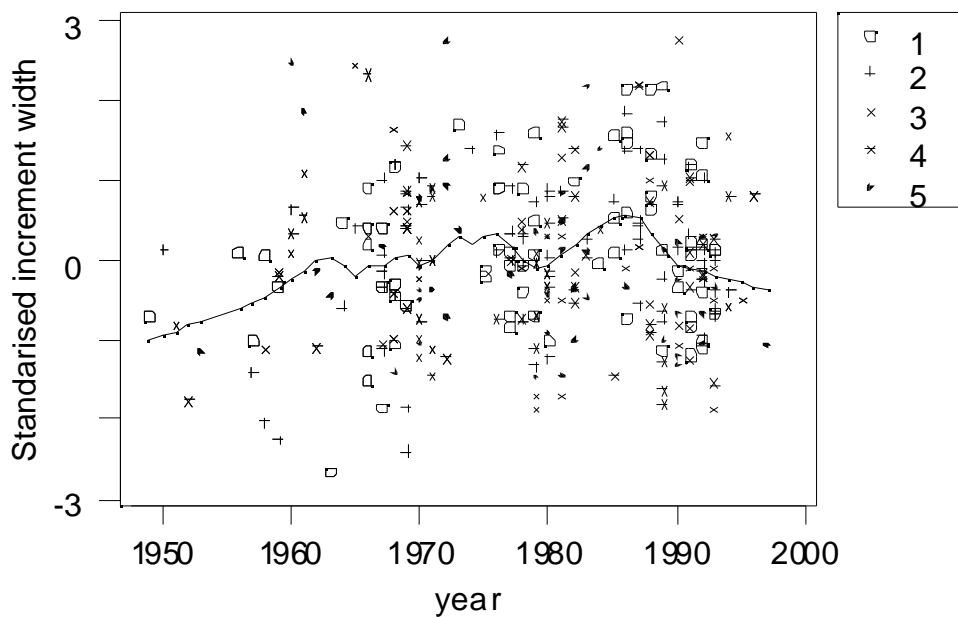
Jackass morwong



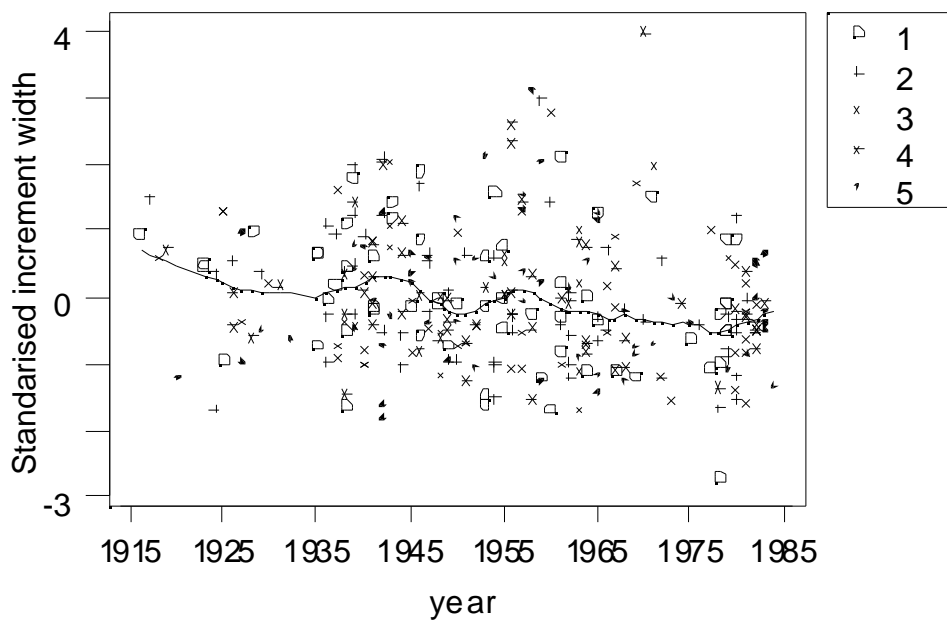
Orange roughy



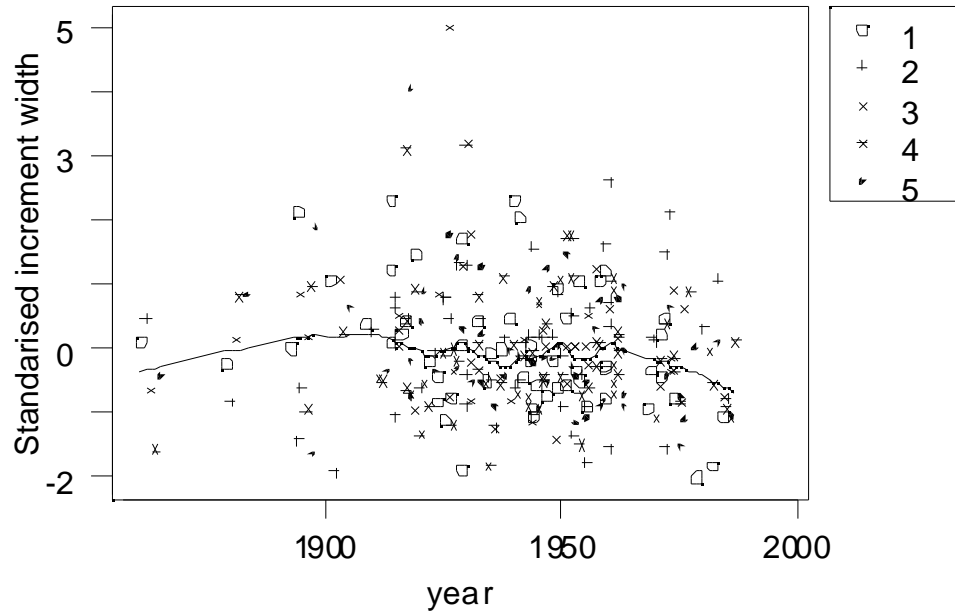
Redfish



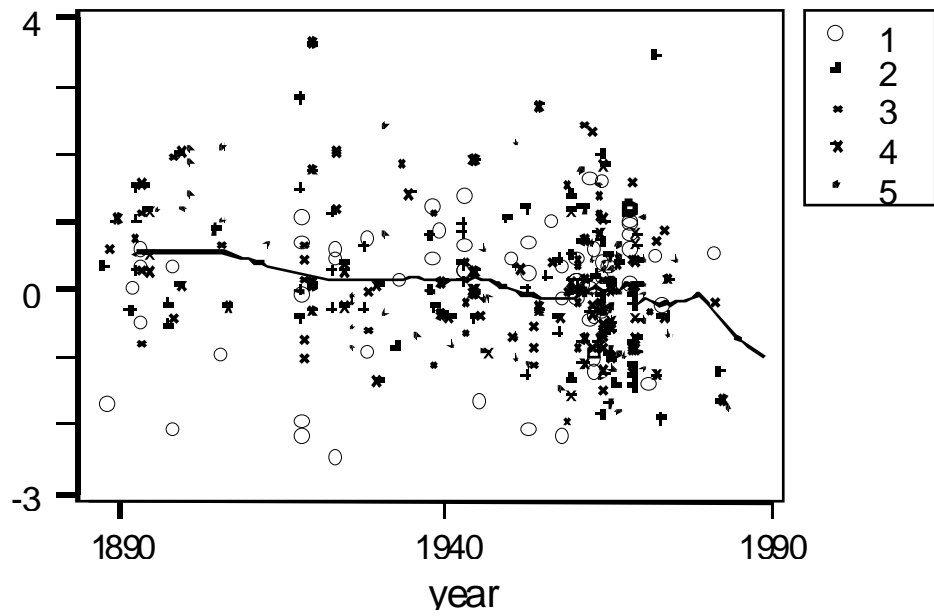
Smooth oreo



Spiky oreo



Warty Oreo



We next examined relationships between the lowess-smoothed data and four climate indices: the southern oscillation index, wind, SW Tasmania rainfall, and position of the subtropical ridge. None of the results were significant.

Results of the growth increment analyses were disappointing. The lack of significant relationships may be attributed to one or more of several factors:

- excessive measurement error relative to the growth ‘signal’;
- error and/or bias in the ageing of the fish, which the previous analyses indicate may be a problem in ageing such long-lived fishes, which could smear any ‘signal’; and
- lack of significant relationship between relative growth among different age-classes of these species or between them during their early life history or between their growth and available climate indices.

BENEFITS

The major thrust of this project was to determine if there were proxy indicators of environmental variability in both shallow and deep southeast Australian marine environments, which might bear on both fisheries production and understanding environmental variability. To that end, we reviewed available information on environmental variation in the region, sought proxies in shallow water bivalves and fishes and in deep-water corals and fishes, and then compared these time series to assess their utility as proxies and, potentially, predictors of climate and fisheries yields.

The main results were in part negative (shallow water bivalve samples not adequate for analysis, increment analysis of corals and fishes show no evident patterning), but also very strongly positive.

First, we found evidence of both medium and long-term climate variation in the region. The quasi-decadal variation in regional winds has substantial implications for regional ecosystems and, in the case of several marine stocks, fisheries yields. We are working with CSIRO Atmospheric research to attempt to further define and evaluate the underlying climate signal, and have spoken repeatedly with SEF fisheries managers about potential implications for local fisheries management. The effects of the long-term climate changes, in the form of a century long shift in the latitude of the Australian sub-tropical ridge, is also subject to on-going discussions with CSIRO Atmospheric research. The signal shows up in gridded sea level pressure maps of Australia, and could be a logical consequence of climate change models, not yet factored into local climate predictions. We are also following this up, through collaborative efforts.

Second, our analysis of coral and roughy chemical variability strongly implies medium and long-term environmental signals in the deep (1000 m) ocean. While this is not

surprising to oceanographers, their time series are too short to realistically assess the scales of this variability. Our proxy data offers the possibility of extending temperature and productivity records back at least several centuries, and could fundamentally affect our understanding of these factors. Again, this result of our project is subject to ongoing collaboration, this time with CSIRO oceanographers working in the southern ocean.

Third, our long-term proxy data for roughy depths may have implications for recruitment variability in the species, though not in the way anticipated. Our initial expectation was that perhaps we could account for the bi-modal size frequency distribution characteristic of the species, by documenting a change in environmental factors that correlated with assumed ages and could account for a recruitment failure to cover the 'under-represented' year-classes. In fact, our data do support the idea of long-term recruitment variation in roughy, but do so by emphasising their extreme longevity and hence the likelihood that recruitment in this species is a rare event by human standards. This could well explain why scientists and fishers have found so few young roughy. Much the same is true for an Atlantic bivalve, *Arctis indicata*, which is also relatively long-lived (to about 100 years) and for which almost no new recruits have been found since the deep-water fishery for these animals began about a decade ago. As in the case of roughy, it is likely the fishery is based on 'banked' past recruitment events, and then recruitment into the fishery is either very small or, perhaps, non-existent.

Finally, results from this project could fundamentally alter the conservation status and fisheries management of roughy and other deep-water stocks. Our data strongly suggest that roughy live much longer than previously thought, and may well be the longest lived vertebrate yet found. This slow maturation and extreme longevity means that current harvests are not sustainable, and that managers may need to fundamentally re-think the way they manage such slow maturing and long-lived species. To the extent that roughy ages are typical of deep-water fishes (age estimates for oreo dories, for example, are similar to those previously made for roughy, using similar techniques; on that basis, we strongly suspect the dories also live for several centuries), fisheries based on deep-water fishes may not be exploitable using current fisheries approaches. This point has been raised with the relevant SETMAC stock assessment groups, and with the NZ Ministry of Fisheries.

FURTHER DEVELOPMENT

Four areas are worthy of further investigation.

1. The medium and long-term climate signals we have detected in the region could have substantial implications for predicting and modeling climate variability in the region. Our work, for example, re-raises the issue of a solar influence on decadal scales of

variation, which was first suggested for the southern Australia early this century, but then subsequently 'discredited'. Our work suggest this 'discrediting' was premature, and that climatologists might well consider factoring it into analyze. Development from these issues is currently the basis for discussions between us and scientists at the CSIRO Division of Atmospheric Research.

2. The extreme ages we found for orange roughy lead to two potential developments. First, the methodology we developed for evaluating these ages (seeking relationships between environmental variation and chemical proxies in otoliths) could have widespread application in fisheries. This line of research could provide an independent and statistically accurate and precise means of aging fishes in general. Because ages of fishes are fundamental to developing harvest strategies, but also often poorly validated, this potential is very worth following up. Second, these same data could be used to develop long-term proxies to hindcast climate (rainfall, wind and the Southern Oscillation Index) for the southern Australian region for the last several hundred years. These proxies would allow a much better understanding of the nature and impacts of climate and oceanographic variability in the region, which could be factored into current predictive models.
3. Because of time limitations we have only just begun evaluating fisheries statistics for possible relationships with the climate variability we document. Even a preliminary scan, however, suggest quasi-decadal variation in catches of a number of stocks. Given the potential for this relatively constant variation to influence catches, it would be highly desirable to pursue this line of inquiry, document those stocks that are affected by such climate factors, and then incorporate this information into fisheries management strategies.
4. The extreme ages we estimate for orange roughy fundamentally alters the conservation status and management-related research needs for this fishery. Given that the results are likely to be controversial, further work on this species and other deep-water species, like the oreo dories and toothfish, that might also be very long-lived, would appear to be an urgent research need for the relevant fisheries management agencies.

CONCLUSION

We found considerable evidence of the impact of climate variability on both shallow and deep-water southeast Australian fisheries. Although not all of our attempts to develop proxy time series were successful, those we did develop and our analysis of available climatological time series indicate that climate variability is a key element in many shallow water fisheries, is likely to be a major factor even for those fisheries circa 1000 m deep, and that this influence may be integrated for deep-water stocks, at least, over centuries-long time spans. We conclude that our evaluations, by design wide ranging, also proved to be preliminary, in the sense that there is considerable obvious merit in re-evaluating available fisheries data in the light of the climate variation, as well as the age of orange roughy and other long-lived deepwater species.

REFERENCES

- Angell, J.K. 1992. Relation between 300-mb north polar vortex and equatorial SST, QBO, and sunspot number and the record contraction of the vortex in 1988-89. *J.Clim.* 5:22-29.
- Anonymous, 1982. Solar variability, weather, and climate. *Studies in Geophysics*
- Anonymous, 1984. Pages 33-59 The status and management of Bennetts Wallaby (*Macropus rufogriseus*) and rufous wallaby (*Thylogale billardierii*) in Tasmania in edited by Anonymous, editor. *Kangaroo Management Programs of the Australian States*. Commonwealth of Australia, Canberra, Aust..
- Arcakaya, H.R. 1992. Population cycles of mammals: evidence for a ratio-dependent predation hypothesis. *Ecol.Monogr.* 62:119-142.
- Artidi, R. 1979. Relation of the Canadian lynx cycle to a combination of weather variables: a stepwise multiple regression analysis. *Oecologia* 41:219-233.
- Berg, L.S. 1935. Evidence on the biology of *Salmo salar*. *Izv.Vniorkh* 20:
- Birman, I.B. 1976. Minor cycles in the abundance dynamics of salmon. *J.Ichthyol.* 16:364-372.
- Boehlert, G.W., M.M. Yoklavich, & D.B. Chelton. 1989. Time series of growth in the genus *Sebastes* from the northeast Pacific Ocean. *Fish. Bull.* 87: 791-806.
- Botsford, L.W. 1986. Pages 140-153 Population dynamics of the Dungeness Crab (*Cancer magister*) in edited by G.S. Jamieson and N. Bourne, editor. *North Pacific Workshop on Stock Assessment and Management of Invertebrates*. Can. Spec. Publ. Fish. Aquat. Sci.,
- Botsford, L.W., Methot, R.D., Jr. and Wilen, J.E. 1982. Cyclic covariation in the California King Salmon, *Oncorhynchus tshawytscha*, Silver Salmon, *O. kisutch*, and dungeness crab, *Cancer magister*, fisheries. *Fish.Bull.(U.S.)* 80:791-801.

- Brand, C.J., Keith, L.B. and Fischer, C.A. 1976. Lynx responses to changing snowshoe hare densities in Central Alberta. *J.Wildl.Manage.* 40:416-428.
- Bulatov, O.A. 1989. Pages 353-357 The role of environmental factors in fluctuations of stocks of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea in edited by R.J. Beamish and G.A. McFarlane, editor. *Effects of Ocean Variability on Recruitment and an Evaluation of Parameters used in Stock Assessment Models.* Can. Spec. Publ. Fish. Aquat. Sci. 108,
- Bulmer, M.G. 1974. A statistical analysis of the 10-year cycle in Canada. *J.Anim.Ecol.* 43:701-718.
- Burnett, A.W. 1993. Size variations and long-wave circulation within the January northern hemisphere circumpolar vortex:1946-1989. *J.Clim.* 6:1914-1920.
- Burroughs, W.J. 1992. *Weather Cycles:real or imaginary?* Cambridge University Press, Cambridge, England.
- Caddy, J.F. 1979. Long-term trends and evidence for production cycles in the Bay of Fundy scallop fishery. *Rapp.P.-v.Reun.Cons.int.Explor.Mer* 175:97-108.
- Currie, R.G. 1979. Distribution of solar cycle signal in surface air temperature over North America. *J.Geophys.Res.* 84:753-761.
- Currie, R.G., Wyatt, T. and O'Brien, D.P. 1993. Deterministic signals in European fish catches, wine harvests, and sea-level, and further experiments. *Int.J.Climatol.* 13:665-687.
- Cushing, D.H. and Dickson, R.R. 1976. The biological response in the sea to climatic changes. *Adv.Mar.Biol.* 14:2-123.
- Danielson, E.F., Burt, W.V. and Rattray, M., Jr. 1957. Intensity and frequency of severe storms in the Gulf of Alaska. *Trans.Amer.Geoph.Union* 38:44-49.

- de Villiers, S., B.K. Nelson, A.R. Chivas (1995). Biological controls on coral Sr/Ca and delta18O reconstructions of sea surface temperatures. *Science* 269:1247-1249.
- Dickson, R.R., Malkki, P., Radach, G., Saetre, R. and Sissenwine, M.P. 1992. Hydrobiological variability in the ICES area, 1980-1989. *ICES Mar.Sci.Symp.* 195:
- Elton, C.S. and Nicholson, M. 1942. The ten-year cycle in numbers of lynx in Canada. *J.Anim.Ecol.* 11:215-244.
- Edwards, R.L., F.W. Taylor, and G.J. Wasserburg (1987) Dating earthquakes with high precision thorium-230 ages of very young corals. *Earth and Planetary Science Letters* 90: 371-381.
- Enfield, D.B. and Cid S., L. 1991. Low-frequency changes in El Nino-Southern Oscillation. *J.Clim.* 4:1137-1146.
- Favorite, F. 1985. A preliminary evaluation of surface winds, their anomalies, effects on surface currents, and relations to fisheries. *NWAFRC Processed Report* 85-21:
- Favorite, F. and Ingraham, Jr., W.J. 1977. On flow in northwestern Gulf of Alaska, May 1972. *J.Ocean.Soc.Japan* 33:67-81.
- Fenton, G.E., S.A. Short and D.A. Ritz. 1991. Age determination of orange roughy, *Hoplostethus atlanticus* (Pisces, Trachichthyidae) using 210Pb:226Ra disequilibria. *Mar. Biol.* 109:197-202.
- Finerty, J.P. 1980. *The population ecology of cycles in small mammals: Mathematical theory and biological fact.* Yale University Press, New Haven, Conn. .
- Frew, R.D., K.A. Hunter (1992). Influence of southern ocean waters on the cadmium-phosphate properties of the global ocean. *Nature* 360:144-146.
- Gauldie, R.W. 1998. Winding back the clock on orange roughy ages: what does it do for the allowable catch. *Seafood New Zealand, Aug.:* 42-43.

Gauldie, R.W., I.F. West and G.E. Coote. 1995. Evaluating otolith age estimates for *Hoplostethus atlanticus* by comparing patterns of checks, cycles in microincrement width, and cycles in strontium and calcium composition. *Bull. Mar. Sci.* 56: 76-102.

Gauldie, R.W., I.F. West and N.M. Davies. 1989. K-selection characteristics of orange roughy (*Hoplostethus atlanticus*) stocks in New Zealand waters. *J. Appl. Ichthyol.* 5: 127-140.

Gauldie, R.W. and M.D. Cremmer. In Press. Loss of ^{222}Rn from otoliths of orange roughy, *Hoplostethus atlanticus*, invalidates old ages. *Fisheries Sci.*

Gee, A.S. and Milner, N.J. 1980. Analysis of 70-year catch statistics for Atlantic Salmon (*Salmo salar*) in the River Wye and implications for management of stocks. *J. Appl. Ecol.* 17:41-57.

Grainger, R.J.R. 1978. Herring abundance off the west of Ireland in relation to oceanographic variation. *J. Cons. int. Explor. Mer* 38:180-188.

Guiler, E.R. 1985. *Thylacine: The tragedy of the Tasmanian Tiger*. Oxford Univ. Press, Melbourne, Vict., Aust.

Gunn, J. S., Harrowfield, I. R., Proctor, C. H., and Thresher, R. E. (1992). Electron probe microanalysis of fish otoliths - evaluation of techniques for studying age and stock discrimination. *J. Exp. Mar. Biol. Ecol.* 158: 1-36.

Harris, G.P., Davies, P., Nunez, M. and Meyers, G. 1988. Interannual variability in climate and fisheries in Tasmania. *Nature* 333:754-757.

Harris, G.P., Griffiths, F.B. and Clementson, L.A. 1992. Climate and fisheries off Tasmania - interactions of physics, food chains and fish. *S. Afr. J. Mar. Sci.* 12:585-597.

Hastings, A. and Higgins, K. 1994. Persistence of transients in spatially structured ecological models. *Science* 263:1133-1136.

Huntsman, A.G. 1937. The cause of periodic scarcity in Atlantic salmon. *Trans. Royal Soc. Can.* 31:17-27.

- Ikeda, M. 1990. Decadal oscillations of the air-ice-ocean system in the Northern Hemisphere. *Atmosphere-Ocean* 28:106-139.
- Jensen, J.C. 1927. On the influence of the quantity of spawning herrings upon the stock of the following years. *J. du Conceil* 2:44-49.
- Keith, L.B. 1963. *Wildlife's ten-year cycle*. University of Wisconsin Press, Madison, Wisc..
- Keith, L.B. 1990. Dynamics of snowshoe hare populations. *Curr.Mammol.* 2:119-195.
- Kerswill, C.J. 1955. Recent developments in Atlantic salmon research. *Atl.Salmon.J.* Jan.:26-30.
- Knox, J.L., Higuchi, K., Shabbar, A. and Sargent, N.E. 1988. Secular variation of northern hemisphere 50 kPa geopotential height. *J.Clim.* 21582:19529-18720.
- Koslow, J.A. 1992. Fecundity and the stock-recruitment relationship. *Can.J.Fish.Aquat.Sci.* 49:210-217.
- Koslow, J.A. 1996. Energetic and life-history patterns of deep-sea benthic, benthopelagic and seamount-associated fish. *J. Fish Biol.* 49(suppl. A):54-74.
- Koslow, J.A., Thompson, K.R. and Silvert, W. 1987. Recruitment to Northwest Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) stocks: influence of stock size and climate. *Can.J.Fish.Aquat.Sci.* 44:26-39.
- Kotlyar, A.N. 1980. Age and growth speed of bigheads *Hoplostehus atlanticus* Collett and *H. mediterraneus* Cuvier (Trachichthyidae, Beryciformes). Pages 68-88, in *Fishes of the Open Ocean*, P.P. Shirshov Inst. Oceanography, Moscow.
- Krebs, C.J., Boutin, S. and Gilbert, B.S. 1986. A natural feeding experiment on a declining snowshoe hare population. *Oecologia* 70:194-197.

- Lassey, K.R., M.R. Manning, R.J. Sparks and G. Wallace. 1990. Radio-carbon in the sub-tropical convergence east of Tasmania- an interim report. DSIR Physical Sciences Report.
- Laevestu, T. 1993. *Weather and Fisheries*. Fishing World Books, Cambridge, Mass..
- Levitus, S., Antonov, J.I. and Boyer, T.P. 1994. Interannual variability of temperature at a depth of 125 meters in the North Atlantic Ocean. *Science*
- Mace, P.M., J.F. Fenaughty, R.P. Coburn and I.J. Doonan. 1990. Growth and productivity of ornage roughy (*Hoplostehus atlanticus*) on the north Chatham rise. *N.Z. J. Mar. Freshw. Res.* 24: 105-119.
- Mehta, V.M. 1991. Meridional oscillations in an idealized ocean-atmosphere system. Part 1. uncoupled models. *Clim.Dynam.* 6:48-65.
- Mehta, V.M. 1992. Meridionally propagating interannual-to-interdecadal variability in a linear ocean-atmosphere model. *J.Clim.* 5:330-342.
- Moran, P.A.P. 1949. The statistical analysis of the sunspot and lynx cycles. *J.Anim.Ecol.* 18:115-116.
- Nojima, S., Soliman, F.E.-S., Kondo, Y., Kuwano, Y., Nasu, K. and Kitajima, C. 1986. Some notes on the outbreak of the sea star, *Asterias amurensis versicolor* Sladen, in the Ariake Sea, western Kyushu. *Publ.Amakusa Mar.Biol.Lab.* 8:89-112.
- Phelps, E.B. and Belding, D.L. 1931. *A statistical study of the records of salmon fishing on the Restagouche River*. New York.
- Pittock, A.B. 1983. Solar variability, weather and climate: an update. *Quart.J.R.Met.Soc.* 109:23-55.
- Pook, M.J. 1992. A note on the variability of the mid-tropospheric flow over the Southern Ocean in the Australian region. *Aust.Met.Mag.* 40:169-177.

- Proctor, C.H. & R.E. Thresher. 1998. Effects of specimen handling and otolith preparation on concentration of elements in fish otoliths. *Marine Biology*, 131: 681-694.
- Regner, S. and Gacic, M. 1974. The fluctuations of sardine catch along the eastern Adriatic coast and solar activity. *Acta Adriat.* 15:3-13.
- Rhoads, D.C., R.A. Lutz (eds.) (1980). *Skeletal growth of aquatic organisms*. Plenum: N.Y. 750 p.
- Romanek, C. and R.W. Gauldie. 1996. A predictive model of otolith growth. *Comp. Biochem. Physiol.* 114: 71-79.
- Shackelton, L.Y. 1987. A comparative study of fossil fish scales from three upwelling regions. *South African Journal of Marine Science* 5: 79-84.
- Shannon, L.V., Crawford, R.J.M., Brundit, G.B. and Underhill, L.G. 1988. Responses of fish populations in the Benguela ecosystem to environmental change. *J. Cons. int. Explor. Mer* 45:5-12.
- Shepard, D.J. 1995. Some characteristics of Tasmanian rainfall. *Aust. Met. Mag.* 44:261-274.
- Sie, S. and R.E. Thresher. 1992. Micro-PIXE analysis of fish otoliths: methodology and evaluation of first results for stock delineation. *Int. J. PIXE* 2:357-380.
- Smith, D. C. and B.D. Steward. 1994. Development of methods to age commercially important dorries and oreos. Final Report to FRDC.
- Smith, D. C., G.E. Fenton, S.G. Robertson and S.A. Short. 1995. Age determination and growth of orange roughy (*Hoplostethus atlanticus*): a comparison of annulus counts with radiometric ageing. *Can. J. Fish. Aquat. Sci.* 52: 391-401.
- Soutar, A. and Isaacs, J.D. .1969. Abundance of pelagic fish during the 19th and 20th centuries as recorded in anaerobic sediment off the Californias. *Fishery Bulletin* 72: 257-273.

Southward, A.J., Butler, E.I. and Pennycuik, L. 1975. Recent cyclic changes in climate and in abundance of marine life. *Nature* 253:714-717.

Stewart, B. D. G.E. Fenton, D.C. Smith, S.A. Short. 1995. Validation of otolith increment age estimates for a deepwater fish species, warty oreo, *Allocyttus verrucosus*, by radiometric analysis. *Marine Biology* 123: 29-38.

Strahan, R.(Ed.) 1983. *The Australian Museum Complete Book of Australian Mammals*. Angus and Robertson, Sydney, Australia.

Taunton-Clark, J. and Shannon, L.V. 1988. Annual and interannual variability in the south-east Atlantic during the 20th century. *S.Afr.J.Mar.Sci.* 6:97-106.

Thresher, R.E. 1994. Climatic cycles may help explain fish recruitment in south east Australia. *Aust.Fish.* 53:20-22.

Thresher, R.E. In Press. Otolith composition as a means of stock delineation in fishes: a review and evaluation. *Fisheries Science*.

Trenberth, K.E. 1979. Interannual variability of the 500 mb zonal mean flow in the southern hemisphere. *Monthly Weather Rev.* 107:1515-1524.

Trenberth, K.E. 1980. Planetary waves at 500 mb in the southern hemisphere. *Monthly Weather Rev.* 108:1378-1389.

Trenberth, K.E. and Paolino, D.A.,Jr. 1981. Characteristic patterns of variability of sea level pressure in the Northern Hemisphere. *Monthly Weather Rev.* 109:1169-1189.

Tyson, P.D. 1986. *Climate Change and Variability in Southern Africa*. Oxford University Press, Capetown, S.Afr..

van den Broek, W. 1983. Age work reveals orange roughy live to at least 21 years. *Catch*, May:25-26.

van Loon, H. and Jenne, R.L. 1972. The zonal harmonic standing waves in the Southern Hemisphere. *J.Geophys.Res.* 77:992-1003.

van Loon, H. and Labitzke, K. 1988. Association between the 11-year solar cycle, the QBO, and the atmosphere. Part II: surface and 700 mb in the Northern Hemisphere in winter. *J.Clim.* 1:905-920.

Vines, R.G. 1980. Pages 55-66 Rainfall patterns in South Africa, South eastern Australia and New Zealand in edited by Anonymous, editor. *Proc. CNES "sun and Climate" Conference*. Centre National D'Etudes Spatiales, Toulouse, France.

Vines, R.G. and Tomlinson, A.I. 1985. The Southern Oscillation and rainfall patterns in the Southern Hemisphere. *South Afr.J.Sci.* 81:131-156.

Wallace, J.M. and Gutzler, D.S. 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Rev.* 109:784-812.

Wallace, J.M., Zhang, Y. and Lau, K-H. 1993. Structure and seasonality of interannual and interdecadal variability of the geopotential height and temperature fields in the northern hemisphere troposphere. *J.Clim.* 6:2063-2082.

Weaver, A.J. and Sarachik, E.S. 1991. Evidence for decadal variability in an ocean general circulation model: an advective mechanism. *Atmosphere-Ocean* 29:197-231.

APPENDIX 1: INTELLECTUAL PROPERTY

Basic results from the scientific analyses are the intellectual property of CSIRO, which will be made publicly available by means of consultations with industry and managers and technical publications.

APPENDIX 2: STAFF

Tony Koslow, CSIRO Marine Research (Principal investigator)

Ron Thresher, CSIRO Marine Research (Co-principal investigator)

Sandy Morison, CAF (Otolith increment analysis)

Geoff Laslett, CSIRO Maths and Statistics (Statistical consultant)

APPENDIX 3: REPORT OF THE CENTRAL AGEING FACILITY

**Measurements of early annual increments on the sagittal otoliths of
eight species of Australian temperate marine teleosts**

A. K. Morison

**Report to the
CSIRO Division of Marine Research
by the Central Ageing Facility**

October 1997

**Marine and Freshwater Resources Institute
P.O. Box 114
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Introduction

This report is the contribution of the Central Ageing Facility (CAF) of the Marine and Freshwater Resources Institute (MAFRI), towards the FRDC funded project 'Climate and fisheries on the south east Australian continental shelf and slope' being undertaken by Dr Tony Koslow and Dr Ronald Thresher of the CSIRO Division of Marine Research (Project No. 96/149).

The data reported here provide the basis for reconstructing fish growth rates using the width of the annual growth rings in fish otoliths as an index of growth. This approach can be used to reconstruct historical changes in rates of fish growth which may be related to changes in environmental conditions and population density, as shown by Boehlert *et al.* (1989) for long-lived deepwater species of *Sebastes*.

Collections of otoliths of eight long-lived species were chosen for this work. Prepared sections of previously aged material were available in the collections at the CAF for seven species: orange roughy *Hoplostethus atlanticus*, warty oreo *Allocyttus verrucosus*, smooth oreo *Pseudocyttus maculatus*, black oreo *Allocyttus niger*, spiky oreo *Neocyttus rhomboidalis*, east coast redfish *Centroberyx affinis*, and jackass morwong *Nemadactylus macropterus*. In addition, sections of otoliths of banded morwong *Cheilodactylus spectabilis* which had been prepared by the CAF and aged by Ray Murphy of the Department of Sea Fisheries, Tasmania, were returned to the CAF to allow the measurements to be made.

Methods

Otoliths do not grow uniformly in all dimensions. Growth is initially fastest in the frontal and sagittal planes, and otolith dimensions measured in these planes (anterior-posterior length and dorsal-ventral width) usually show a close correlation with fish length. Otolith growth in these planes usually slows, and may cease, as fish growth slows. However, in most long-lived species, otolith growth continues in, and becomes increasingly confined to, the transverse plane and otolith size measured in this plane (medial-lateral thickness) shows a low correlation with fish length. Therefore, to allow measurements of otolith increments to be converted to an index fish growth, all measurements of increment radius were made in either the anterior-posterior (orange roughy) or dorsal-ventral (all other species) directions.

Sagittal otoliths of redfish, jackass morwong and banded morwong were embedded in rows of 5 in blocks of polyester resin and three or four sections approximately 0.3 mm thick were cut through their centres with a modified gem-cutting saw, using a blade 0.25 mm thick. Sections were mounted on microscope slides under coverslips with further polyester resin. Sections were then viewed with transmitted light at 10 to 16 times magnification. Otoliths of orange roughy were prepared as described in Smith *et al.* (1995). Otoliths of the oreo species were prepared as described in Stewart *et al.* (1995) and Smith and Stewart (1994).

Only sections which were close to the primordium was used for measurements. For each species the width of up to the first eight increments on the otoliths of previously aged fish have been measured. The year class for each fish was calculated by subtracting the estimated age from the year of capture. Fish were grouped according to the decade in which they were born and a reading order determined randomly within each decade. Samples for which the position of increments could not be reliably determined were rejected and the next fish in the reading order selected. Increment widths were measured until either at least 10 otoliths from each decade had been measured, or all available samples for that decade had been processed, whichever came first. The number of increments measured varied among species and was limited by the narrowing of increment widths and the shift in otolith growth to the transverse plane.

Measurements were made using a customized version of the image analysis software Optimate . Previously prepared sections were viewed at an appropriate magnification with either a dissecting or compound microscope. Video cameras attached to the microscopes were used to project images onto computer monitors. Where necessary to identify the early increments, preparations were also viewed directly with the microscope. A line was drawn over the image of each prepared section from the primordium through the distal margin of the each increment. The angle of the line changed only at an increment margin, and only if necessary to pass through the next distal increment margin. The outer edge of each opaque zone, which forms the margin of each annual increment, was marked along this line. The distance from the primordium to each marked increment (increment radius) was then exported to a spreadsheet for later analysis. Increment widths were calculated as the distance to the first increment, or the distance between successive increments.

All measurements are based on increments observed in thin sections of sagittal otoliths viewed under transmitted light. Radii were measured on the posterior side of frontal sections for orange roughy, on the dorsal side of transverse sections for warty oreo, and on the ventral side of transverse sections for all other species.

The ages used to determine the year class have been derived from several previous projects, and the level of validation of the ageing method also varies among the species (Table 1). Ageing methods have been validated only for orange roughy, warty oreo and east coast redfish. However, the ageing method applied to the 3 other oreos was developed in the project that also developed the method for warty oreo. Ageing methods for the 2 morwong species are unvalidated but the sections of both species exhibit clear increments. Jackass morwong from the South East Fishery have been aged in the past using whole otoliths (Morison *et al.* 1992, Anon 1994) following the method of Smith (1982) who obtained a maximum age of 16 years for females and 11 years for males. However, a subsequent examination of otolith sections produced age estimates up to 39 years for females and 32 years for males, suggesting that the ages of older specimens has been underestimated using this method. Vooren (1977) found that the species lives to 35 years of age in New Zealand, and that otoliths of fish older

than about 15 years could not be accurately read whole. All age estimates for jackass morwong have been based on increments viewed in thin sections.

Sections of jackass morwong otoliths are comparatively opaque near the primordium where the first increment is located. As jackass morwong are spawned in late summer or early autumn, this increment is formed when the fish are less than a year old but is not often clearly visible. The first consistently identifiable increment is located further from the primordium but is formed in the second year of life. A similar pattern is observed in the otoliths of banded morwong, and it is assumed that the first increment measured on their otoliths is also formed in the second year of life.

Table 1. Validation or source of ageing method applied to study species.

Species	Validated (Y/N)	Source
Orange roughy	Y	Smith <i>et al.</i> 1995
Black oreo	N	Smith and Stewart 1994
Smooth oreo	N	Smith and Stewart 1994
Spiky oreo	N	Smith and Stewart 1994
Warty oreo	Y	Stewart <i>et al.</i> 1995
Redfish	Y	Kalish 1995
Jackass morwong	N	Morison 1996
Banded morwong	N	Unpublished

Results

Measurements were made on a total of 555 otoliths. Sample sizes ranged from 40 for jackass morwong to 113 for orange roughy and included year classes from 1871 to 1992 (Table 2). The distribution of samples was relatively uniform across decades for species such as orange roughy and banded morwong, but uneven or restricted in others (Figure 1).

Table 2. Sample size, number of increments measured, and earliest and latest year classes represented in samples.

Species	Sample size	No. increments measured	Earliest year class	Latest year class
Orange roughy	113	7	1871	1976
Black oreo	52	5	1891	1982
Smooth oreo	61	8	1916	1980
Spiky oreo	57	6	1860	1983
Warty oreo	71	5	1858	1981
Redfish	86	8	1949	1993
Jackass morwong	40	8	1954	1992
Banded morwong	75	6	1912	1992
Total	555		1871	1992

The frequency distributions of increment radii and increment widths, combining all ages for each species, are given in Figures 2-9.

The data from which these tables and figures are derived are included on the enclosed disc.

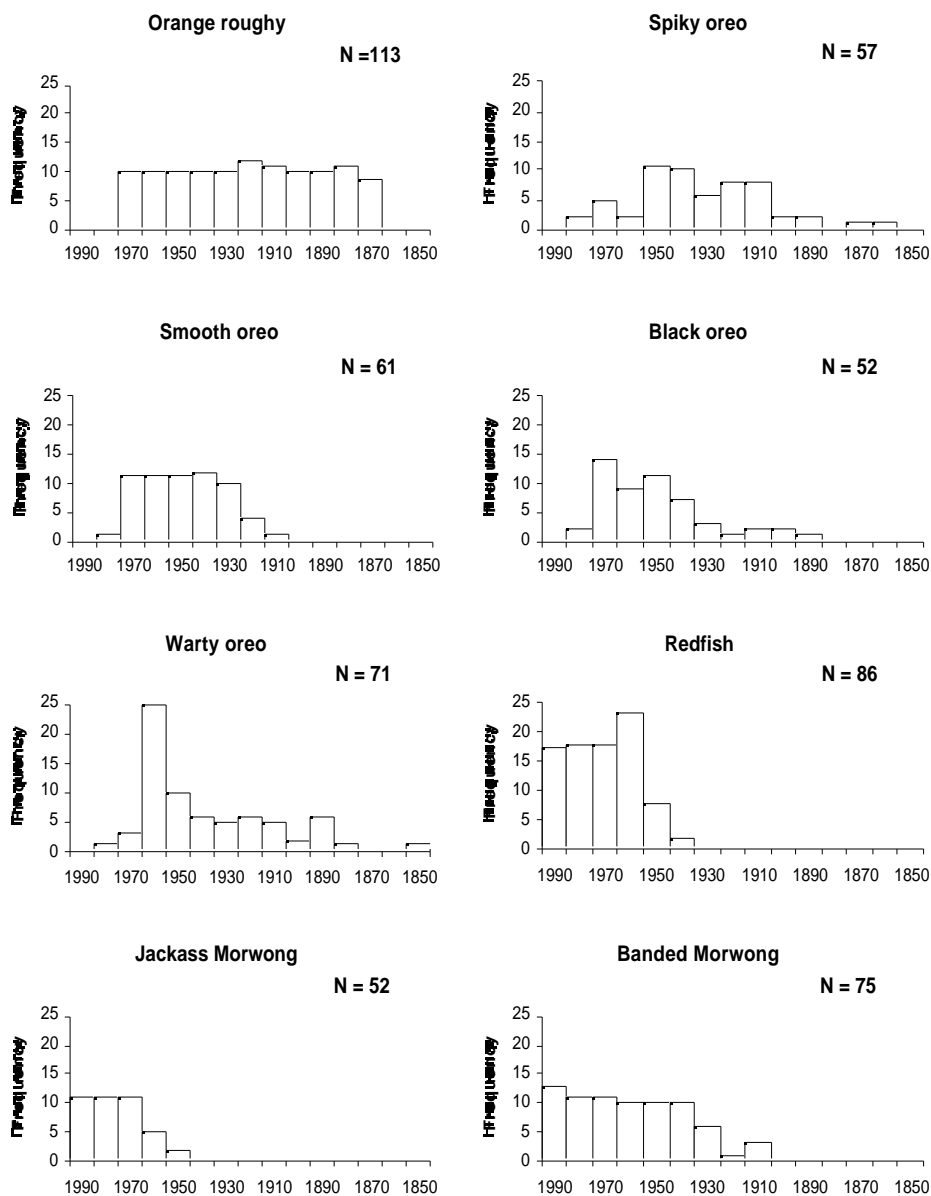


Figure 1. Birthdate distribution of samples measured by decade for each species.

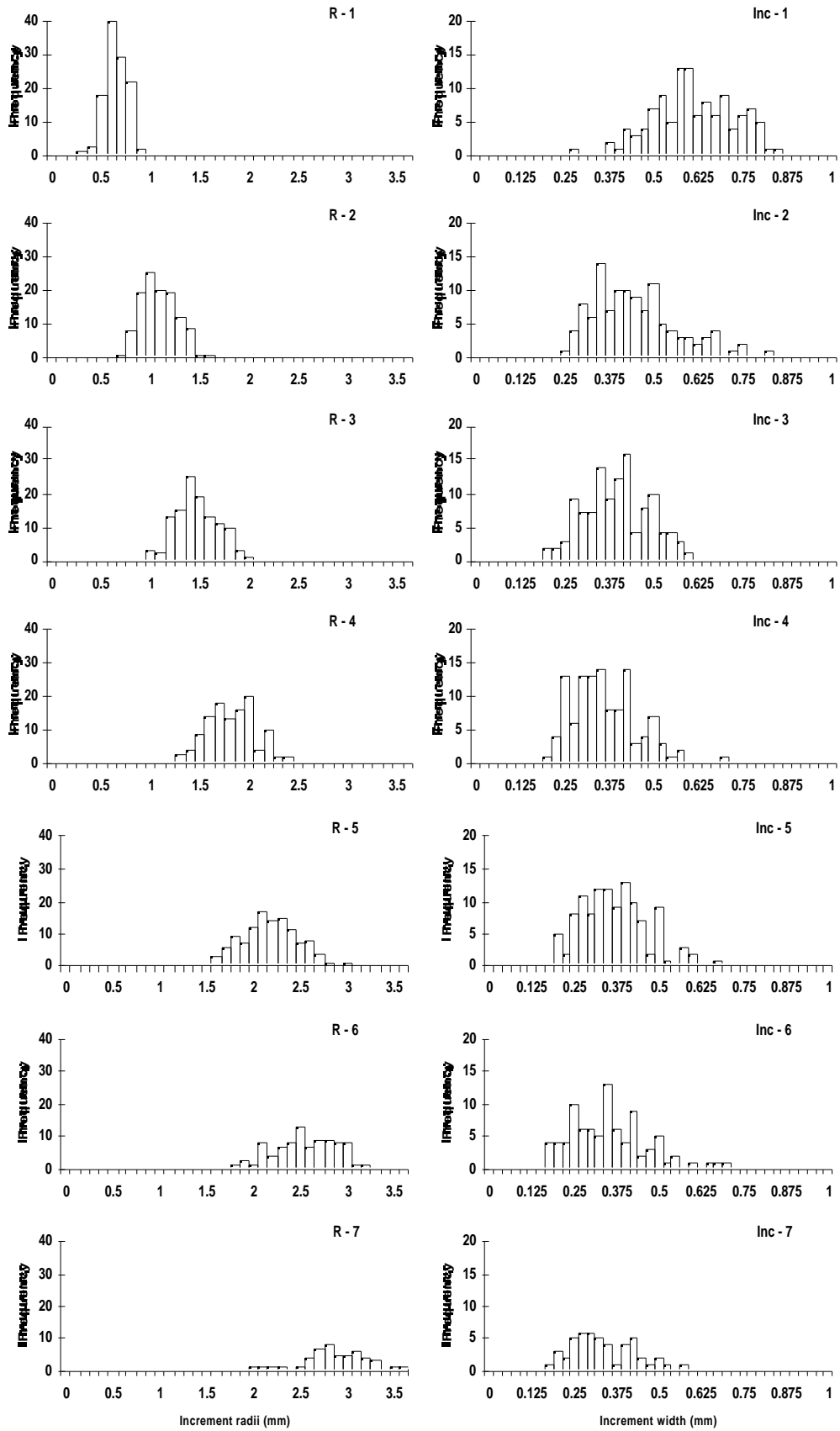


Figure 2. Frequency distributions of increment radii and increment widths for orange roughly.

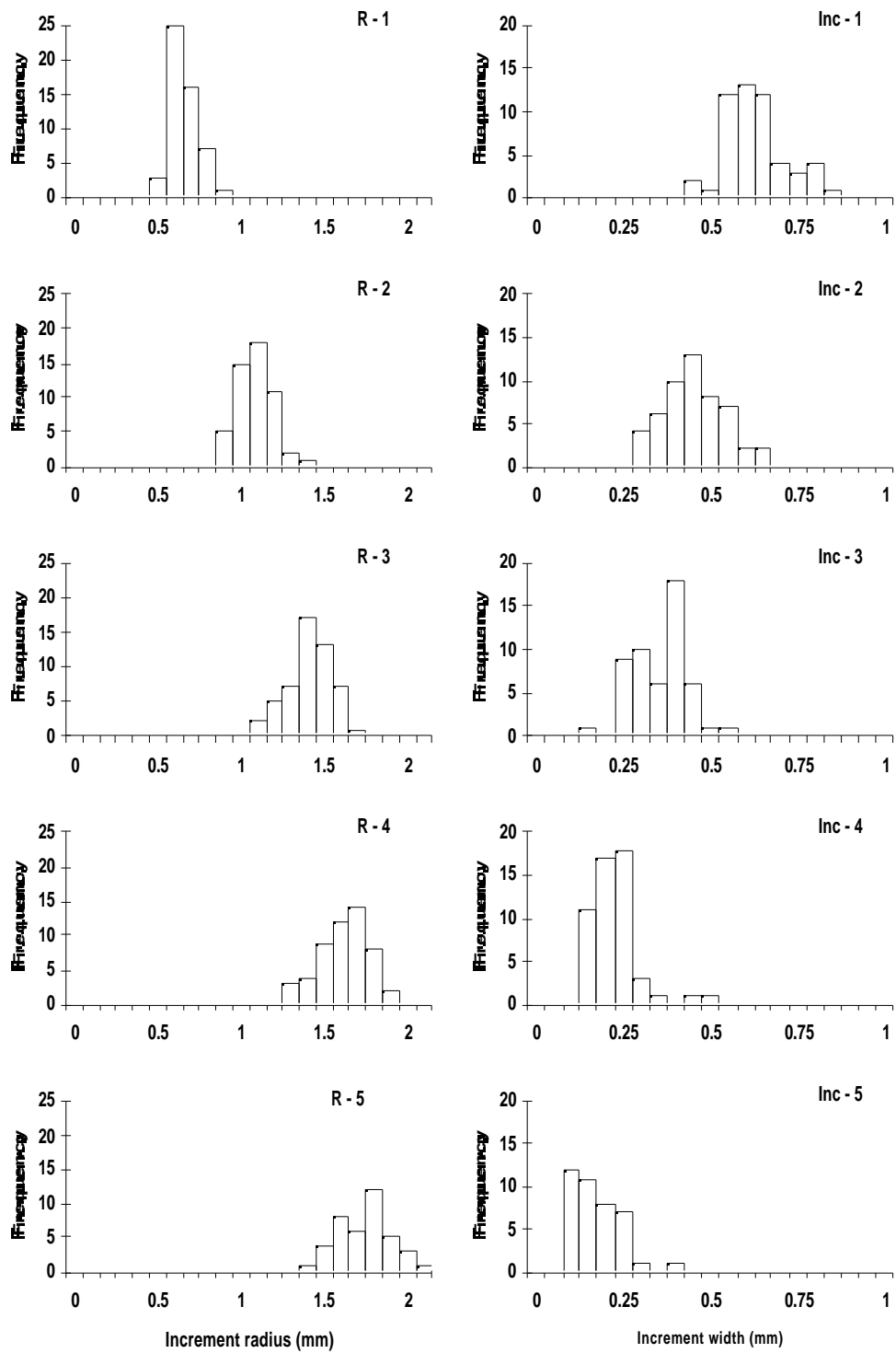


Figure 3. Frequency distributions of increment radii and increment widths for black oreo.

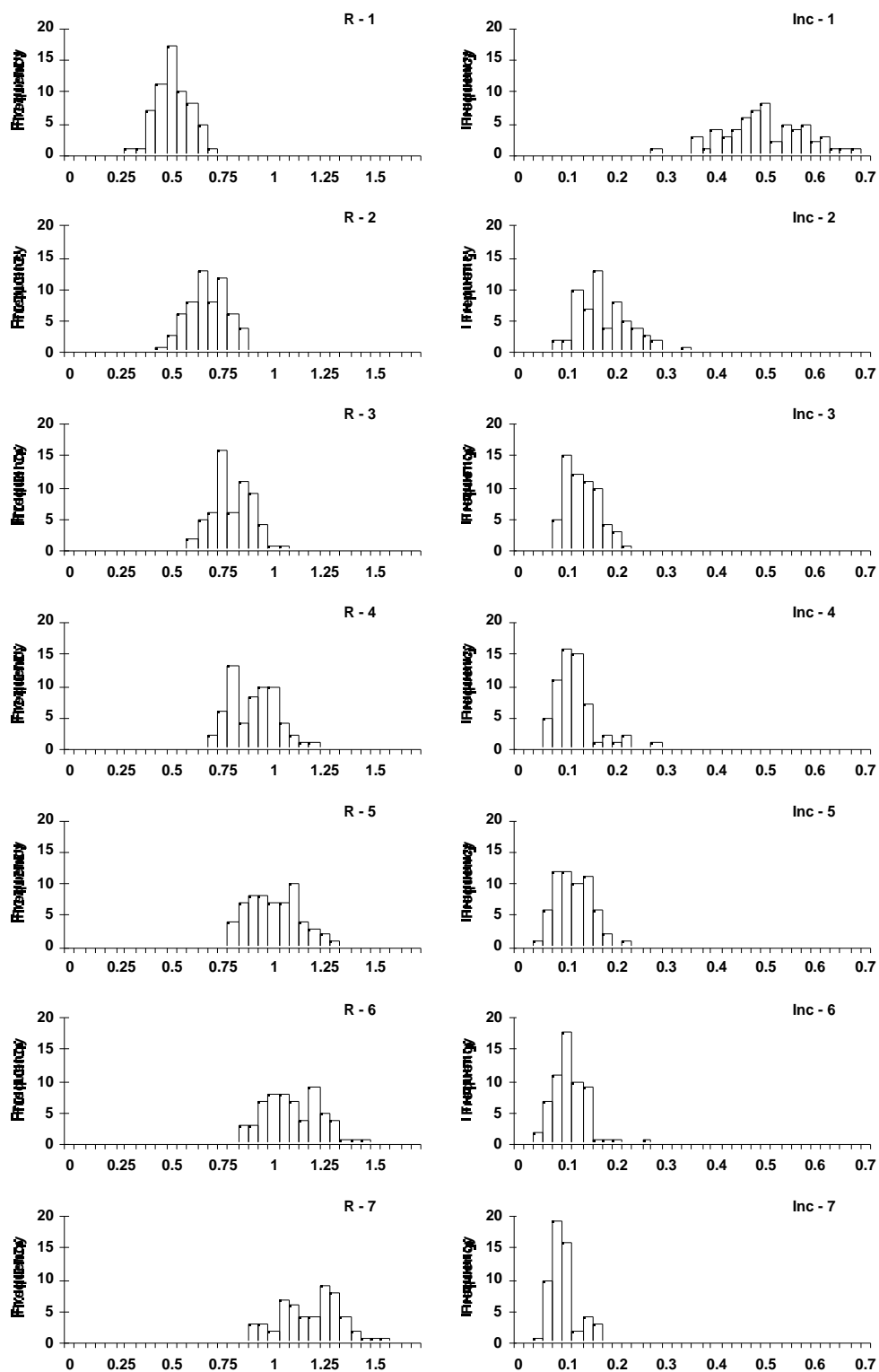


Figure 4. Frequency distributions of increment radii and increment widths for smooth oreo.

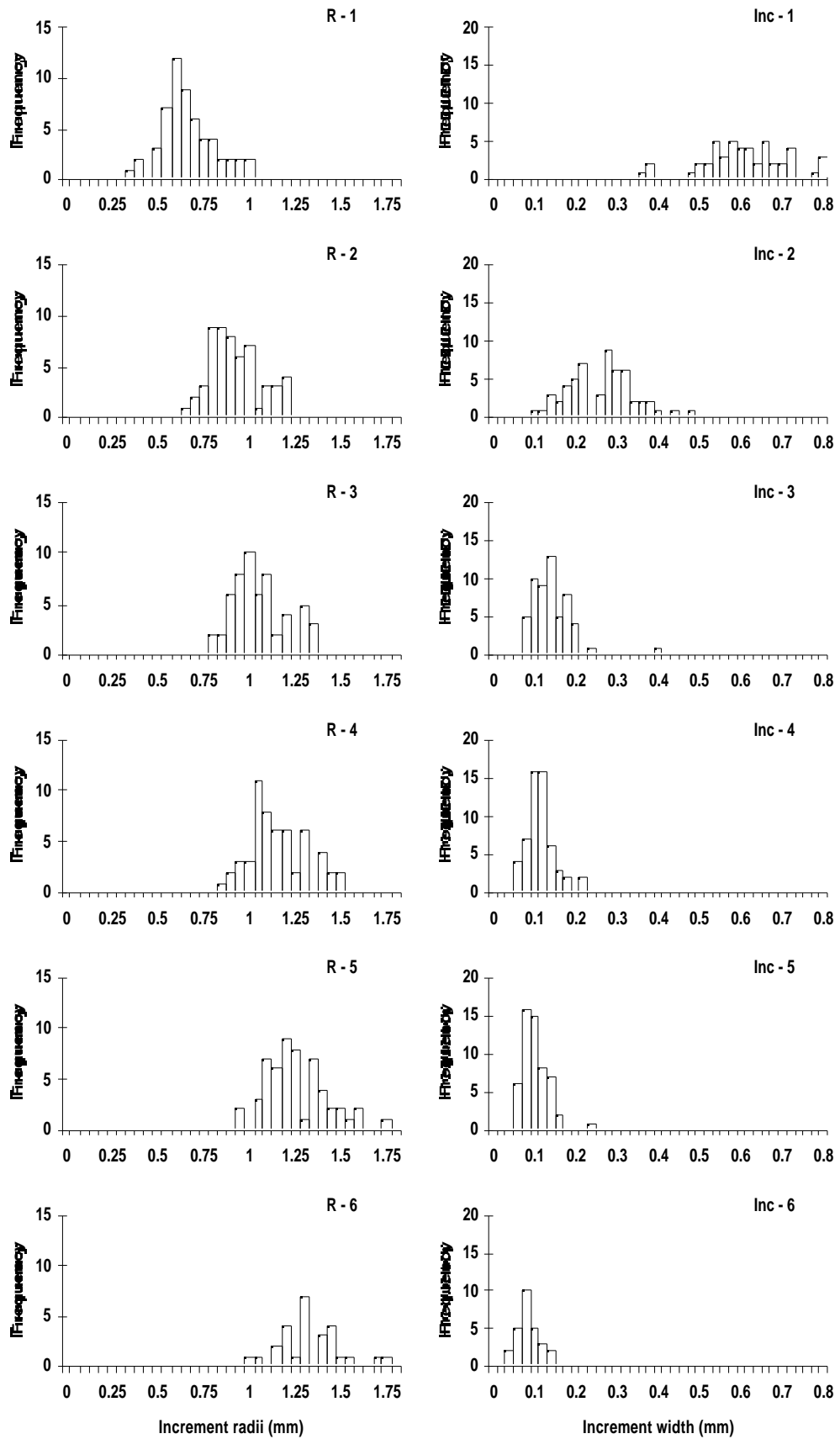


Figure 5. Frequency distributions of increment radii and widths for spiky ore.

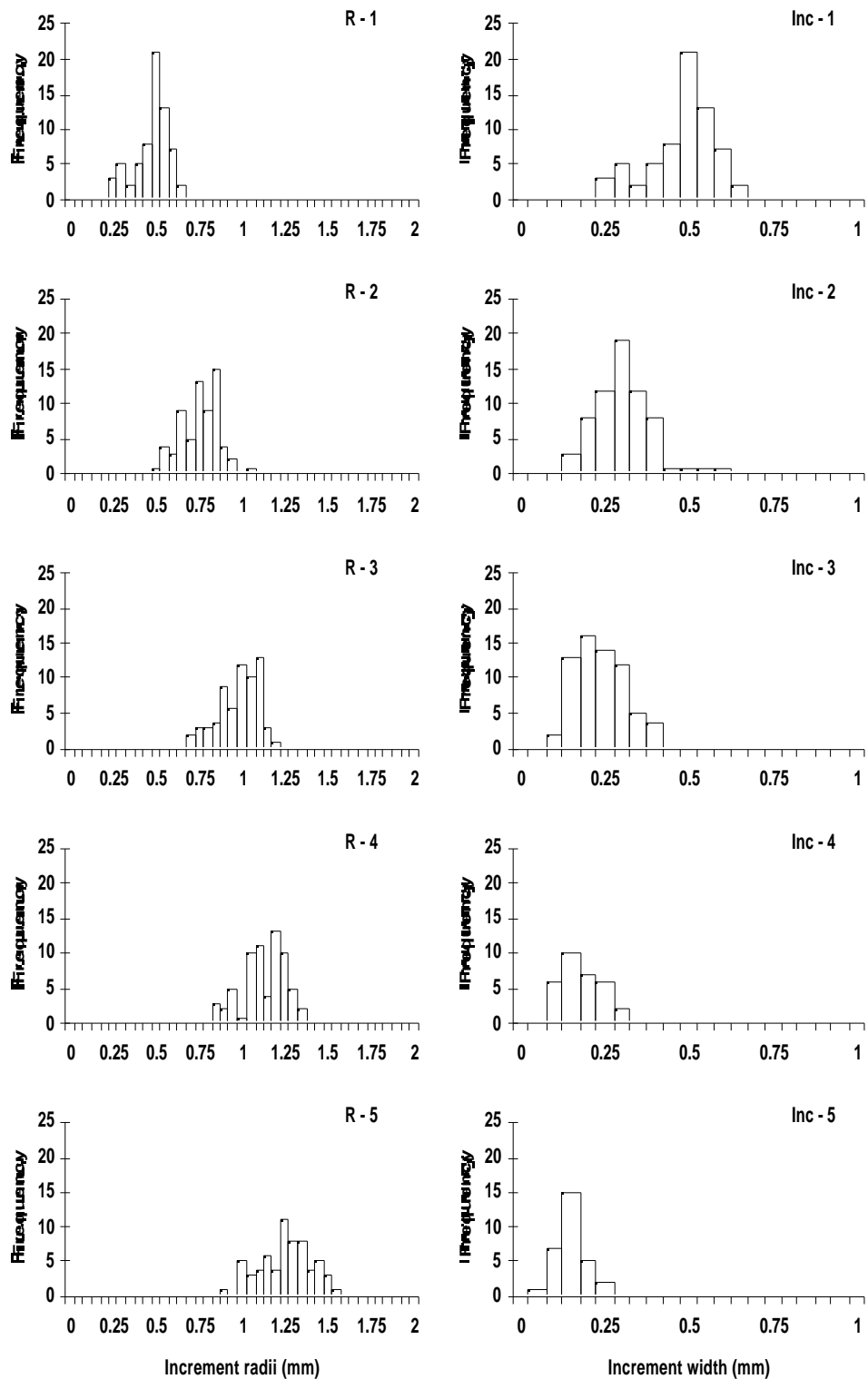


Figure 6. Frequency distributions of increment radii and increment widths for warty oreo.

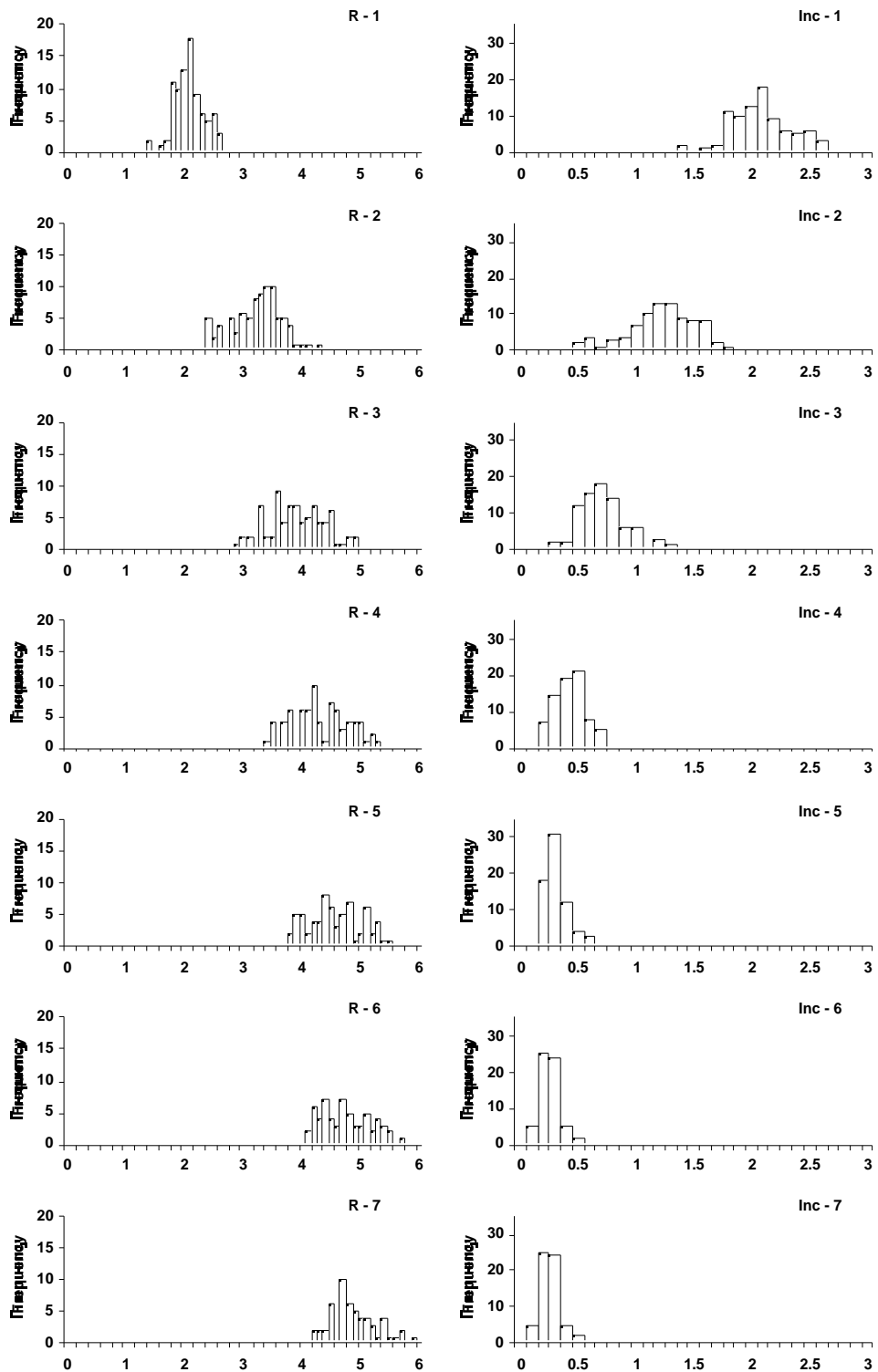


Figure 7. Frequency distributions of increment radii and increment widths for east coast redfish

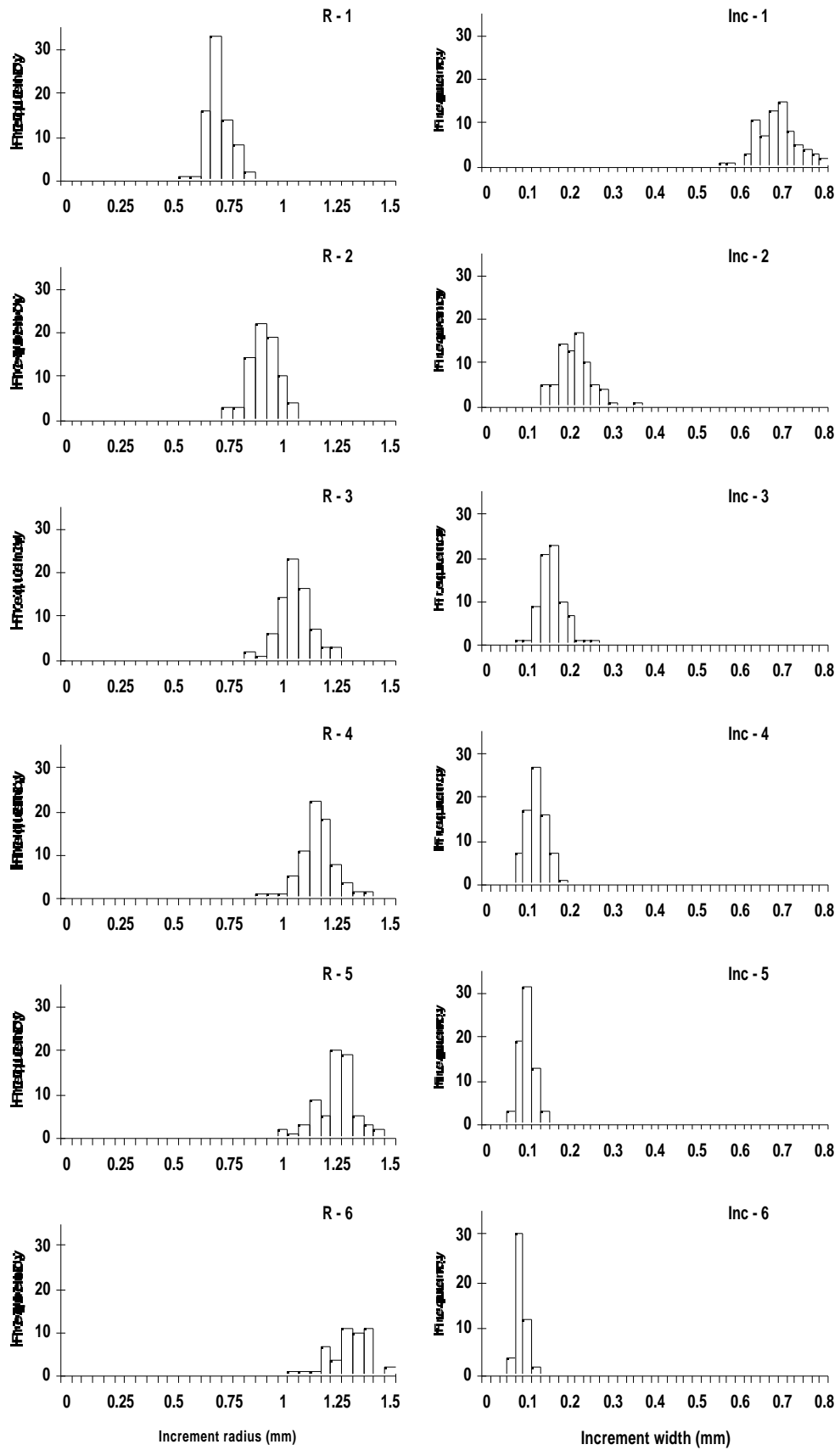


Figure 8. Frequency distributions of increment radii and increment widths for banded morwong.

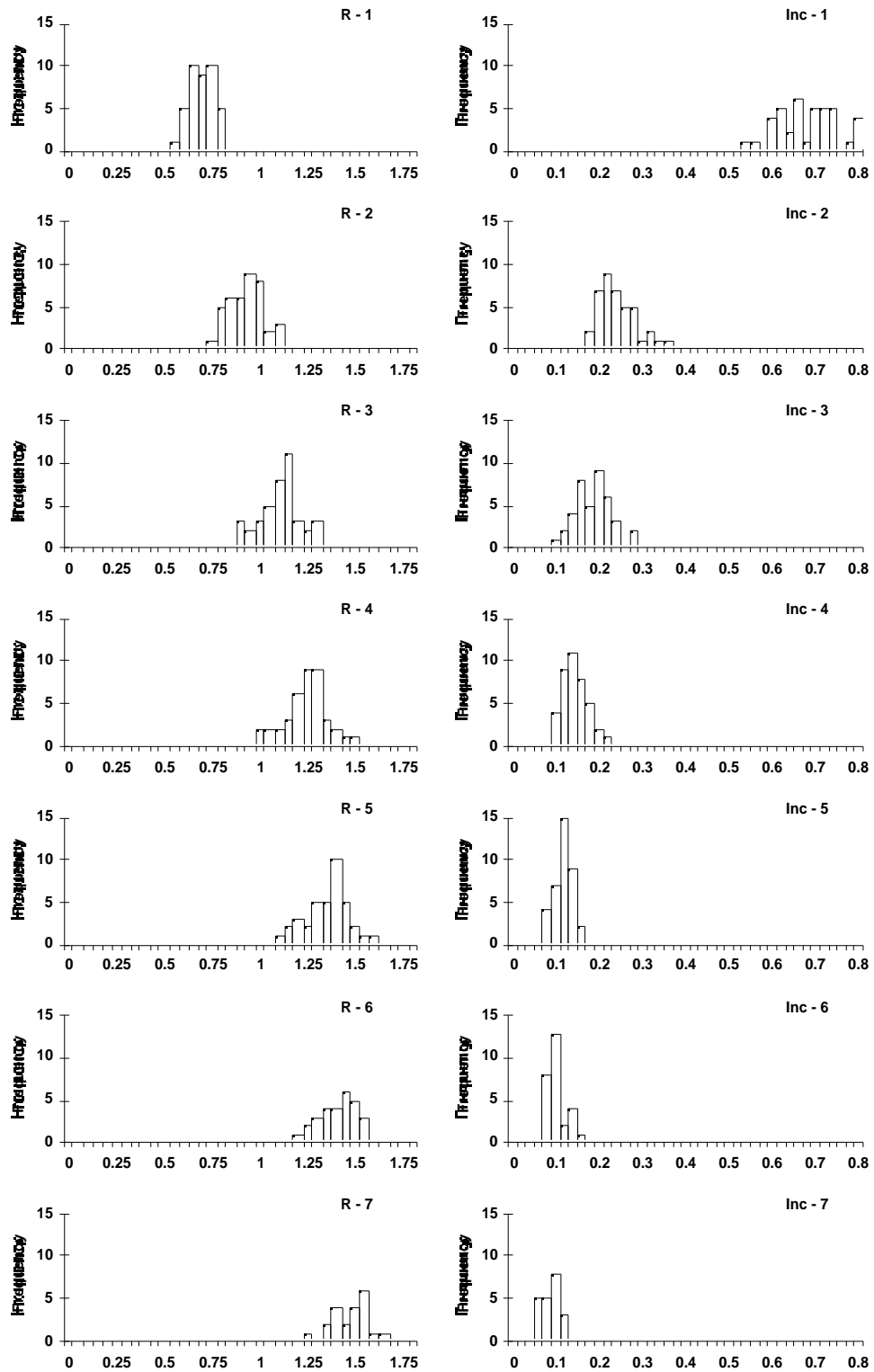


Figure 9. Frequency distributions of increment radii and increment widths for jackass morwong.

References

- Anon (1994). Jackass morwong - *Nemadactylus macropterus*. Age composition of samples submitted to the Central Ageing Facility & Length frequency data from port sampling. Report to South East Fishery Stock Assessment Group, Inshore Species Workshop, March. 1994.
- Boehlert, G. W., Yoklavich, M. M., and Chelton, D. B. (1989). Time series of growth in the genus *Sebastes* from the northeast Pacific Ocean. *Fishery Bulletin, U. S.* **876**, 791-806.
- Kalish, J.M. (1995). Application of the bomb radiocarbon chronometer to the validation of redfish *Centroberyx affinis* age. *Canadian Journal of Fisheries and Aquatic Sciences* **52**, 1399-1405.
- Morison, A. K. (1996). Age and growth of major species in the south east fishery. Marine and Freshwater Resources Institute, Department of Natural Resources and Environment, Queenscliff. 18 pp.
- Morison, A. K. Robertson, S. G., and Smith, D.C.(1992). Age determinations for jackass morwong *Nemadactylus macropterus*, tiger flathead *Neoplatycephalus richardsoni*, and eastern school whiting *Sillago flindersi* from samples submitted to the Central Ageing Facility: June 1991-July 1992 Marine Science Laboratories Internal Report, No. 201.
- Smith, D. C.(1982). Age and growth of jackass morwong (*Nemadactylus macropterus* Bloch and Schneider) in eastern Australian waters. *Australian Journal of Marine Freshwater Research.* **33**, 245-53.
- Smith, D. C., Fenton, G. E., Robertson, S. G. and Short, S.A.(1995). Age determination and growth of orange roughy (*Hoplostethus atlanticus*): A comparison of annuli counts with radiometric ageing. *Canadian Journal of Fisheries and Aquatic Sciences* **52**, 391-401
- Smith, D. C. and Stewart, B. D. (1994). Development of methods to age commercially important dorids and oreos. Final report to Fisheries Research and Development Corporation, Project 91/36. Department of Conservation and Natural Resources, Victorian Fisheries Research Institute.
- Stewart, B. D., Fenton, G. E, Smith, D. C and Short, S. A. (1995) Validation of otolith increment age estimates for a deepwater fish species, warty oreo, *Allocyttus verrucosus*, by radiometric analysis. *Marine Biology* **123**, 29-38.
- Vooren, C. M. (1977). Growth and mortality of tarakihi (Pisces: Cheilodactylidae) in lightly exploited populations. *New Zealand Journal of Marine and Freshwater Research.* **11**, 1-22.

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