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Oceanic evidence of climate change in southern Australia over the last three centuries

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[1] Chemical analysis of deepwater octocorals collected at 1000 m depth off southern Australia indicates long-term cooling, beginning in the mid-18th century. This cooling appears to reflect shoaling of isotherms along the continental shelf, that can be related statistically, observationally and by modeling to increasing coastal sea-surface temperatures, that in turn reflect a poleward extension of the SW Pacific boundary current (the East Australian Current). The oceanographic changes implied by the coral record suggest climate change in temperate Australia starting about the time of European settlement. Correlations between temperate Australian and Antarctic indices suggest these long-term changes might also be relevant to Antarctic climate. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; *KEYWORDS:* Coral age validation, Australia, Coral chemistry, Southern Ocean, Sub-tropical ridge, Climate proxy. **Citation:** Thresher, R., S. R. Rintoul, J. A. Koslow, C. Weidman, J. Adkins, and C. Proctor (2004), Oceanic evidence of climate change in southern Australia over the last three centuries, *Geophys. Res. Lett.*, *31*, L07212, doi:10.1029/2003GL018869.

1. Introduction

[2] Information spanning more than the last few decades on oceanographic variability in the southern extratropics is sparse. This lack of long-term information hampers interpretation of recent changes in regional oceanographic and climate indices [e.g., *White and Peterson*, 1996; *Thomson and Solomon*, 2002], and has prompted analysis of proxies to provide a context for these observations [e.g., *Fitzharris et al.*, 1997; *Budd*, 2000]. Coral chemistry provides a more direct means of assaying long-term oceanic variability than many other proxies, but has not previously been used in southern temperate regions. Here, we examine ontogenetic variability in the Mg/Ca ratios of two specimens of a deep-water octocoral, collected off the SE coast of Australia. The SE coast of Australia is oceanographically dynamic, close to the sub-tropical convergence and influenced by the SW Pacific boundary current, the East Australian Current [*Rintoul and Bullister*, 1999; *Cresswell*, 2000]. Mg/Ca ratios in octocorals increase with temperature [*Velmirov and Bohm*, 1976; *Weinbauer et al.*, 2000] and hence the variability observed in the corals could indicate long-term trends in regional oceanography and climate.

2. Samples, Ageing and Specimen Analysis

[3] Analyses are based on two live-collected specimens of the deep-water octocoral, *Keratoisis* spp. (Family Isididae, Order Gorgonacea). One (K2) was collected at the Cascade Plateau (43°53′S, 150°25′E), SE of Tasmania, in late 1992-early 1993 and the other (K4) at the "Southern Hills" region, south of Tasmania (44°20′S, 147°10′E) in November, 1992. Field notes and video surveys suggest both samples were taken at about 1000 m depth.

[4] Coral ages were determined using four techniques. Three gave ages that were in good agreement. Octocorals have been verifiably aged by counting growth circuli [*Grigg*, 1974; *Andrews et al.*, 2002]. We counted 338 to 340 circuli in K2 and 316 to 364 in K4. Two other, similar sized specimens collected in the same areas had circuli counts of 405–413 (K1) and 360–385 (K3). There was no correlation between circuli spacing and distance from the center of either K2 or K4, suggesting growth rates that have been relatively constant with colony age. Radiometric ages were obtained using two separate decay schemes. ^{210}Pb activities from the inner 12 mm of sample K2 are all the same value within error (0.126 ± 0.004 dpm/g) and indicate that the initial excess (0.294 ± 0.006 dpm/g) has decayed back to secular equilibrium (Figure 1a). As ^{210}Pb has a 22-year half life, the inner portion of K2 must be older than about 110 years. Extrapolating the 50 μm/year growth rate indicated by the outer three ^{210}Pb points implies that the coral is about 400 years old in the center. Uranium series data from two samples in K3 also constrain its age. If the initial ^{230}Th/^{232}Th ratio did not change during the coral's lifetime, then based on a development diagram (Figure 1b) the outer sample from K3 can not be older than about 270 years and the interior sample can not be older than about 360 years. Given the large sample masses required by both techniques produce ages averaged over several decades, the ^{210}Pb data from K2 and the U-series data from K3 appear to be in good agreement with the circuli counts. Ages of 300–500 years are also indicated by work on the same genus in New Zealand [*Tracy et al.*, 2003].

[5] We also attempted to age the corals using radiocarbon. However, the age estimates obtained (K2 80 yo; K4 130 yo, both ±50 y) conflict with those we obtained using other methods. As explained below, the conflicting age

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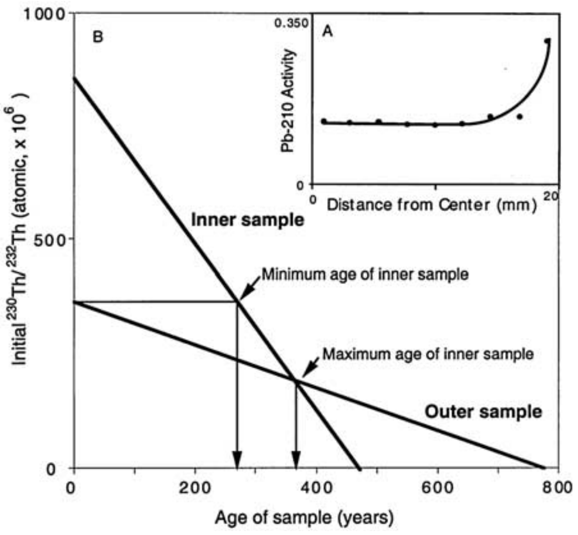

Figure 1. (a) ^{210}Pb activity as a function of position along the axis of K2. Line indicates fitted exponential decay curve. Points at secular equilibrium are $\geq$ about 110 years old. (b) Development diagram for K3. Sample ages and initial ^{230}Th/^{232}Th ratios are constrained by the intersection of the wedges coupled with stratigraphic constraints [see *Cheng et al.*, 1995]. The y-intercept is the measured thorium isotopic composition and the x-intercept is the age if the initial ^{230}Th/^{232}Th ratio were zero, the maximum possible age. The slope is a function of the ^{238}U/^{232}Th ratio, the higher the value, the steeper the slope.

estimates are likely due to changes in the ^{14}C reservoir age of the ambient water during the coral's lifetimes.

[6] Chemical analysis was done by probe microanalysis, on sections immediately distal to those that were aged, using a JEOL 8900R electron probe at CSIRO Mineral Products. Procedures are similar to those detailed in *Gunn et al.* [1992]. The concentrations (% dry-weight) of Mg and Ca were measured at 100 μm intervals from the coral's central pore to its outer margin, and converted to molar ratios. The measured concentrations (Mg, 1.49–2.25%; Ca, 33.6–37.7%) are similar to other biogenic calcites, are more than 10 times higher than the elements' minimum detection limits, and were measured with an instrumental accuracy of about 2%. ^{18}O isotope analysis of K2 was done at 0.85 mm intervals from the coral's center to edge and again at 50 μm intervals for the outermost 1.5 mm, using the VG Prism stable isotope mass spectrometer at the NOSAMS facility, Woods Hole. The analytical precision of the instrument is ±0.08 ppt, based on daily analysis of NIST carbonate standards.

3. Long-term Changes in Coral Chemistry and Links to Oceanographic and Climate Variability

[7] Mg/Ca ratios decline significantly ($P \ll 0.001$) from the core to the margin in both K2 and K4 (Figure 2), suggesting long-term cooling at depth off the SE coast. We tested this hypothesis in K2 using an independent biothermometer - ^{18}O ratios - across a section immediately adjacent to that used for probe analysis. Delta^{18}O values increase significantly ($p < 0.001$) across the section (Figure 2), also indicative of cooling. The plot of delta ^{18}O broadly matches that of the Mg/Ca ratios ($R^2 = 0.27$, $P < 0.0001$); differences could be real, but are also likely to reflect the relatively coarse spatial scale at which ^{18}O was analysed over most of the coral and its relatively large measurement error. Assuming no age-related distortion due to vital effects or salinity (which would vary <0.3 ppt at these depths), the slope of ^{18}O against coral radius suggests ambient temperature at 1000 m has declined about 1.1 C° (0.79–1.43°, based on the 95% CI of the slope), using the calibration in *Druffel* [1997] of 0.22 ppt/C°. The change in Mg/Ca ratios suggests a larger decline (2.6° in K2, and 1.3° in K4, 95% CI for both ca. 0.8°), but is based on a mean calibration (0.005/C°) for shallow water species [*Weinbauer et al.*, 2000]. High frequency variability in the Mg/Ca ratios is consistent with a four-year record of near-bottom temperatures at 994 m depth near the coral sites (44°6.70′S, 146°13.08′E), which shows variability of 0.5–1.0°C on periods ranging from semi-diurnal to interannual.

[8] The apparent long-term cooling evident in both corals, collected about 400 kms apart, implies a causal mechanism with broad action. Historical records for Southern Ocean temperatures at depth are sparse, but show no sign of widespread cooling of this magnitude or of a change in the horizontal distribution of water masses that would have such a large effect on water temperature. Shoaling of isotherms along the coast is a more plausible mechanism, requiring a change in depth of only a few hundred meters to

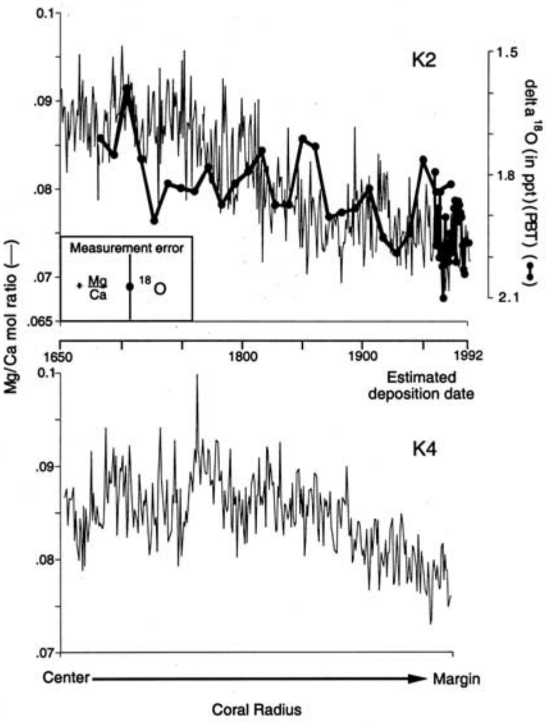

Figure 2. Mg/Ca molar ratios (thin lines) for K2 and K4, and for K2, delta^{18}O isotope ratios (heavy line and solid points), measured along radial transects of two specimens of *Keratoisis* spp. Regressions of Mg/Ca for both corals and delta^{18}O isotope ratios for K2 against coral radius are significant at $p < 0.001$.

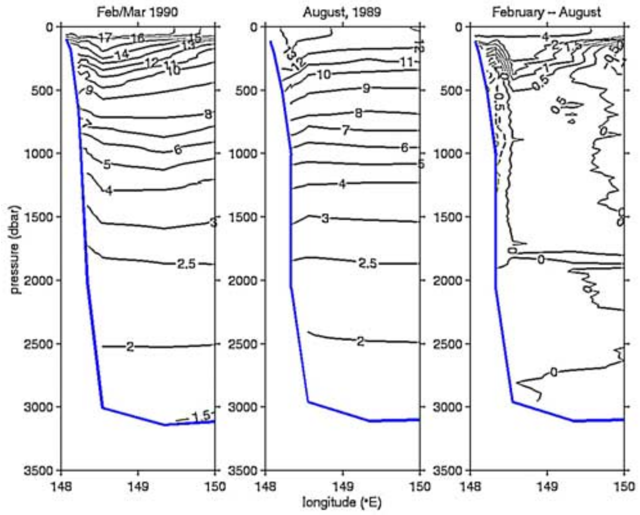

Figure 3. Potential temperature along an east-west transect along 43S, east of Tasmania during periods of (a) strong southward flow in the EAC (summer 1990 and (b) weak flow in the EAC (winter 1989). The difference is shown in (c) (negative contours are dashed).

account for the observed temperature shifts. Shoaling can also account for the mis-match, noted earlier, between the coral ages as estimated using radiocarbon (80–130 years) and the three other approaches we used, which consistently indicate ages of 300–400 years. The radiocarbon age estimate assumes a constant ^{14}C reservoir age. In the ocean, this age increases with depth; where the samples were collected, the rate of change is about 100 years per 100 m [*Lassey et al.*, 1990]. Although ^{14}C- age estimates at the margins of K2 (1055 yo) and K4 (1310 yo)(both ±50 y) are consistent with modern reservoir ages at ca. 1000 m near where the corals were collected (760–1400 yo) [*Lassey et al.*, 1990], shoaling during the coral's lifetime would have increased the reservoir age of the ambient water and narrowed the difference between the apparent ages of the corals' centers and margins. The mis-match between the radiocarbon and other age estimates suggests the shoaling has been 200–300 m. Oceanographic transects off the SE coast (Figure 3) suggest this would be equivalent to a change in temperature of 1–2°, which is consistent with the re-constructed temperature trend.

[9] Oceanographic data suggest a process to account for such shoaling. Records from the Maria Island (east coast of Tasmania) hydrographic station, collected since 1941, indicate sea-surface temperatures (SSTs) along the SE Australian coast have been increasing, due to enhanced poleward flow of the warm East Australian Current (EAC) [*Harris et al.*, 1987]. Hydrographic sections show that deep isotherms along the coast shoal during periods of strong southward flow of the EAC (Figure 3), in order to satisfy the thermal wind balance. We hypothesize that the long-term cooling at 1000 m reflects a prolonged period of poleward expansion of the subtropical regime of wind stress curl forcing (i.e., Ekman pumping) and consequent enhancement of the subtropical gyre and its western boundary current, the EAC. This suggestion is consistent with evidence of a poleward shift of the annual mean latitude of the subtropical ridge (STR) over eastern Australia by about 4° longitude since the early 1900s [*Das*, 1956; *Thresher*, 2003], with a stronger EAC off SE Australia in summer [*Harris et al.*, 1987], when the STR shifts seasonally southwards, with the rapid (<two months) response of the thermocline of the Tasman Sea to local changes in wind stress curl [*Cresswell*, 2000], and with the modeled effects of a poleward displacement of the STR on regional water mass distributions [*Oke and England*, 2004].

[10] If this hypothesis is correct, then the temperature record in the outer portions of the corals should correlate negatively with SSTs off SE Australia and with the latitude of the STR, and should do so at an implied age of the corals of 300–400 years. We tested this prediction using the SST data at Maria Island (field sampling to 1990, and satellite data thereafter) and the summer mean latitude of the STR (L), from *Pittock* [1973 and pers. comm.] and *Thresher* [2003]. The comparisons are shown in Figure 4. Correlations among all three variables are significant at $p < 0.01$, after adjusting for autocorrelations [*Wilks*, 1995]. The correlations between L and SSTs and between SSTs and Mg/Ca ratios remain significant after de-trending; the correlation between L and Mg/Ca ratios weakens to $p < 0.1$, which is likely to reflect the imperfect mediating effect of SSTs. The correlation for K2 (K4) peaks in significance at an implied total age for the octocoral of 344 (300) years, assuming a constant growth rate.

4. Discussion

[11] From our age estimates, it appears that the temperatures experienced by K2 were variable, but showed no long-term trend until about 1750, declined for about 100 years, re-stabilised, and have again been declining since about 1970. The decline in temperatures at 1000 m reflected in K4, collected farther south, began about 1845, and shows no indication to present of stabilising. We hypothesise that the shallow marine and terrestrial climates of SE Australia have also been changing since the mid-18th century, as the region affected by the cold, rain-bearing zonal west winds has contracted polewards. The correlations between re-constructed water temperatures at 1000 m, SSTs and the latitude of the STR support this inference. Such changes over the last century have previously been invoked to account for drought

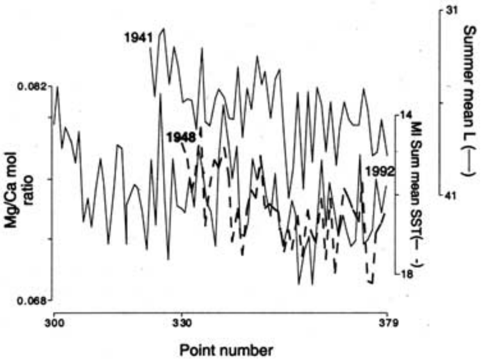

Figure 4. Comparison of K2 Mg/Ca ratios, summer (JFM) mean SST at Maria Island (MI) and summer mean latitude (L) of the STR. Note that the scales for L and SST are inverted. Dates indicate beginning and end of the time series.

in SW Australia [*Allan and Haylock*, 1993] and for the retreat of glacial termini in New Zealand [*Fitzharris et al.*, 1997]. They are also consistent with a 200-year shallow marine temperature record inferred from a high latitude scleractian coral collected off Western Australia [*Kuhnert et al.*, 1999], with evidence of long-term drying over SE Australia inferred by *Jones et al.* [2001] from declining lake levels, and with an hemispheric increase in the zonally averaged latitude of the sub-tropical wind maxima [*Gibson*, 1992] and mid-latitude tropospheric pressure [*Thomson and Solomon*, 2002]. If the poleward shift in the westerly winds was experienced across temperate Australia, it could have had a substantial impact on land use and the ecology and distributions of terrestrial and marine species, starting about the time of European settlement. Interannual differences in the mean latitude of the STR also correlate with the Antarctic Oscillation Index ($p < 0.05$) over the last 23 years, suggesting that the long-term changes evident in the corals may also be relevant to Antarctic climate.

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