

RESEARCH LETTER

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Key Points:

- Growth rates of deep-sea fish proxy intermediate depth water temperature
- Long-term warming in North Atlantic but variable temperatures in South Pacific
- Parallel variability implies hemispheres respond simultaneously to forcing

Supporting Information:

- Readme
- Figure S1
- Figure S2
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- Figure S6

Correspondence to:

R. Thresher,
ronald.e.thresher@gmail.com

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Parallel decadal variability of inferred water temperatures for Northern and Southern Hemisphere intermediate water masses

Ronald Thresher¹, John Morrongiello¹, Bernadette M. Sloyan^{1,2}, Kyne Krusic-Golub³, Samuel Shephard⁴, C  il  n Minto⁵, Conor P. Nolan⁶, Francisco Cerna⁷, and Luis Cid⁷

¹CSIRO Wealth from Oceans Flagship, Hobart, Tasmania, Australia, ²Centre of Australian Weather and Climate, CSIRO, Hobart, Tasmania, Australia, ³Fish Aging Services Pty. Ltd., Portarlington, Victoria, Australia, ⁴School of Biological Sciences, Queen's University Belfast, Belfast, UK, ⁵Marine and Freshwater Research Centre, Galway Mayo Institute of Technology, Galway, Ireland, ⁶Irish Sea Fisheries Board (BIM), Dun Laoghaire, Co. Dublin, Ireland, ⁷Instituto de Fomento Pesquero, Valpara  so, Chile

Abstract We use a novel proxy (growth rates of long-lived deep water fish, orange roughy) to reconstruct inferred water temperatures of intermediate water masses in both Northern and Southern Hemispheres since the mid-1800s. The data are consistent with instrumental records showing long-term warming in the Northern Hemisphere but also indicate decadal variability of intermediate depth temperatures that is coherent across the two hemispheres. This variability correlates with the dominant subpolar annular mode in each hemisphere and implies a bihemispheric oceanic response to external forcing that influences the properties of intermediate depth water masses.

1. Introduction

The formation and circulation of intermediate depth water masses are critical elements of the global ocean circulation and biogeochemical cycles. Antarctic Intermediate Water (AAIW) forms through surface modification of up-welled circumpolar deep waters in the Southern Ocean, is subducted to a core depth of about 1000 m, and penetrates as a subsurface salinity minimum into the Northern Hemisphere while shoaling and mixing with nutrient-poor waters of tropical origin [Graham *et al.*, 2013]. In the subpolar North Atlantic, intermediate depth waters of subpolar and subtropical origin, collectively referred to hereafter as Subpolar Mode Water (SPMW), mix to dominate the water column between roughly 300 and 1110 m depth [Arbic and Owens, 2001]. Analysis of sparse subsurface data spanning the last 50 years finds variability in temperature and salinity at AAIW core depths [Gillie, 2002; Durack and Wijffels, 2010; Schmidtko and Johnson, 2012], and periodic warming and cooling in the subpolar North Atlantic superimposed on possible long-term warming [Arbic and Owens, 2001; Johnson and Gruber, 2007; Polyakov *et al.*, 2009]. However, due to the short instrumental record, it is difficult to evaluate such trends in the context of multidecadal variability.

Here we use a novel long-term data set to reconstruct, and compare across hemispheres, inferred intermediate depth water temperatures since the mid-1800s. Orange roughy (*Hoplostethus atlanticus*; Pisces, Trachichthyidae) is a globally distributed, deep water benthopelagic fish species that inhabits continental margins and oceanic seamounts worldwide at depths of roughly 400–1300 m [Branch, 2001]. Its peak abundances coincide with the core depths of intermediate water masses in both hemispheres (supporting information Figure 1). Orange roughy (hereafter roughy) are also slow growing and long lived. Radiometric analyses of acellular bony structures (otoliths) in roughy suggest maximum ages of about 200 years [Andrews *et al.*, 2009]. Like most other fish species, roughy can also be aged by counting annually formed, tree ring-like growth increments in their otoliths [Mace *et al.*, 1990; Andrews *et al.*, 2009] (supporting information Figure 2). As otolith size correlates very highly with body size in juvenile roughy ($R^2 = 0.92\text{--}0.96$) [Mace *et al.*, 1990], annual growth rates can be determined from the radial spacing between consecutive annuli. This approach is widely used and well validated in diverse fisheries studies [Morrongiello *et al.*, 2012]. The combination of long lives and well-resolvable growth increments allows reconstruction of juvenile roughy growth rates from recently collected samples that could span the last two centuries. As growth rates in fish are largely determined by environmental conditions (most notably water temperature and food availability [Wootton, 1998]), we

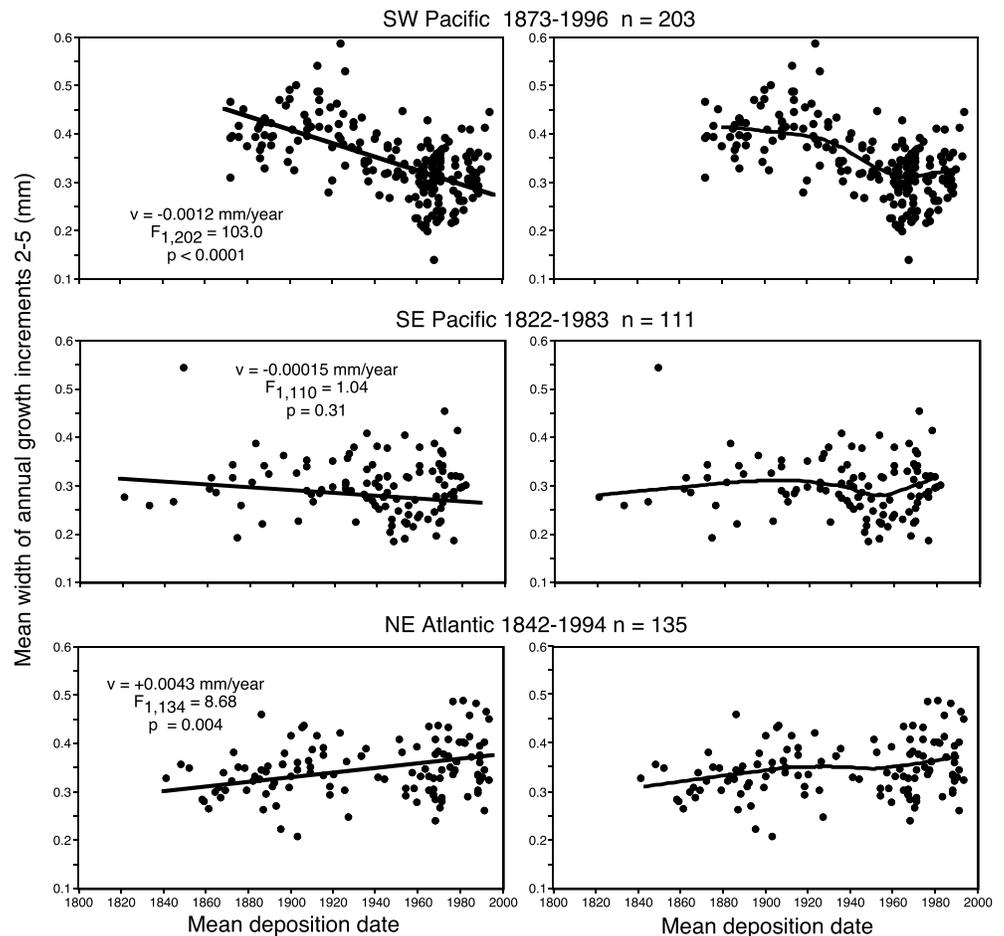


Figure 1. Long-term trends in juvenile growth rates for orange roughy as inferred from the widths of annuli deposited in their otoliths in growth years 2–5 inclusive. Linear regressions are significant over time for the SW Pacific and NE Atlantic. Curved lines in right-hand figures are running means of the same data, obtained by filtering the data using a Lowess Filter, tension 66.

compared roughy growth rates across sites as a possible proxy for long-term spatial and temporal variability of the intermediate water masses in which the fish reside.

2. Material and Methods

We analyzed historical growth rates for three populations—off Chile (SE Pacific) and Tasmania (SW Pacific) in the Southern Hemisphere and from the Irish Slope (NE Atlantic) in the Northern Hemisphere (supporting information Figure 1)—using otoliths obtained from fisheries studies. We hypothesized that growth records from the Chilean and Tasmanian samples would be similar, as both reside in AAIW, the former closer to the likely formation area [Hartin *et al.*, 2011; Holte *et al.*, 2012]. The Irish Slope sample was a designed out-group for this comparison, given its provenance in a North Atlantic-sourced intermediate water (SPMW). Increment widths were measured for annuli between ages 2 and 5 years inclusive, formed during the juvenile's benthic phase [Mace *et al.*, 1990; Shephard *et al.*, 2007], and averaged to determine a mean juvenile growth rate for each individual (supporting information Figure 2). Counts of annuli combined with the known dates the fish were collected suggest that the reconstructed growth histories span 1832–1983, 1873–1996, and 1842–1994 for the SE Pacific, SW Pacific, and NE Atlantic, respectively. Counting errors due to narrow increments near the margin of otoliths from the oldest fish are likely to introduce an age uncertainty of about ± 6 years, reducing to ± 2 year in the youngest fish examined (15–20 years old) (supporting information Figure 4). Because of this inaccuracy, comparisons among sites and with environmental factors should only be considered at decadal time scales.

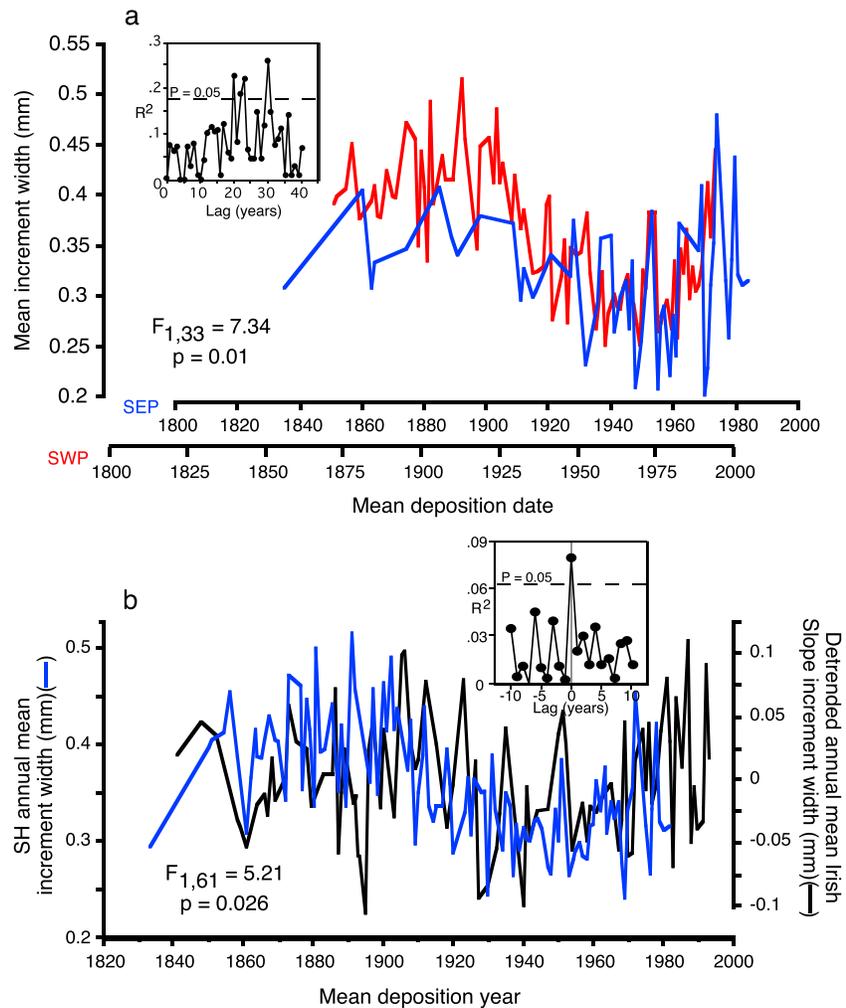


Figure 2. (a) Comparison of annual mean growth rates (increment widths) for SE (blue line) and SW (red line) Pacific juvenile orange roughy, the latter lagged by 22 years based on highest sustained cross correlation in a lag analysis spanning 0 to +40 years (inset box). Lagged growth rates correlate at $p = 0.01$. (b) Comparison of annual mean growth rates of juvenile orange roughy from NE Atlantic (black line) and pooled Southern Hemisphere (SH) (blue line) populations (see text), at a lag of 0 years based on the highest cross correlation in a lag analysis spanning -10 to +10 years (inset box). Irish Sea data have been detrended to remove the long-term linear increase in growth rate over time. Annual mean growth rates correlate across hemispheres at $p = 0.026$.

3. Results and Discussion

Juvenile growth rates vary widely among individuals at all sites, but mean increment width was similar for all three, averaging about 0.3 mm (Figure 1). Growth rates have increased significantly over time in the NE Atlantic samples (Regression $F_{1,134} = 8.68$, $p < 0.005$) but decreased in both Southern Hemisphere populations, albeit significantly only for the Tasmanian samples ($F_{1,202} = 103.0$, $p < 0.0001$; for Chilean samples, $F_{1,77} = 2.78$, $p < 0.1$). The slopes of the growth rate versus date regressions differ among sites at $p < 0.0001$ (analysis of covariance $F_{1,416} = 74.8$). Running means of the data for each site suggest a second-order temporal trend in growth rates (Figure 1), which we extracted by calculating residuals about the linear growth rate versus date regression (supporting information Figure 5a). Although the amount of variance accounted for is small, all three sites exhibit parallel second-order trends in individual mean growth rates: increasing from the early-to-mid 1800s, peaking in the early 20th century, falling and reaching a low between 1940 and 1970, and then increasing again through the 1980s and 1990s (supporting information Figure 5b).

Temperature is likely to be a major determinant of growth rates in roughy, as it is in other poikilotherms [Portner and Farrell, 2008]. We test this by comparing recent interannual variability in growth rates with instrumental records at intermediate depths in the North Atlantic since the 1930s and the SW Pacific since the

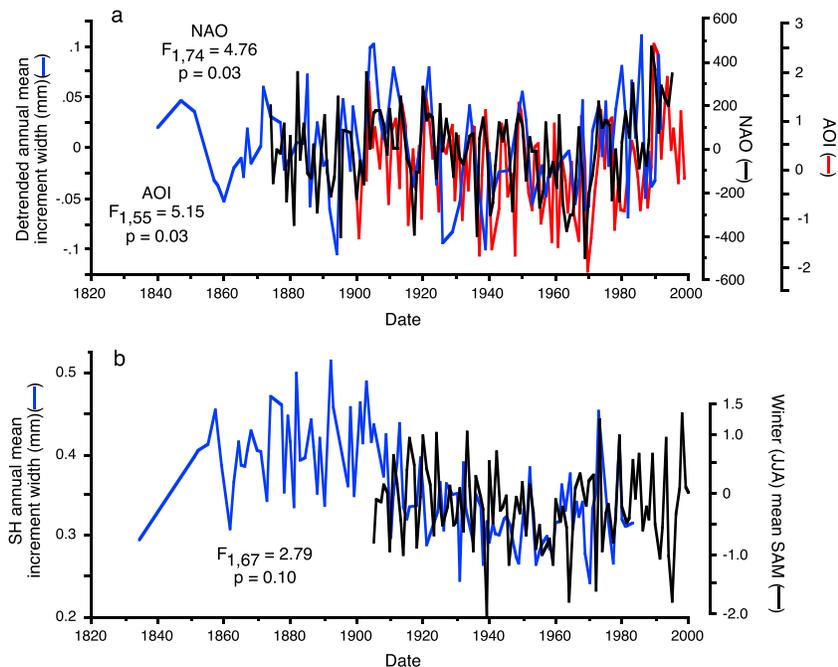


Figure 3. (a) Comparison of reconstructed North Atlantic Oscillation Index (NAO) (black line) and Arctic Oscillation Index (AOI) (red line) with detrended annual mean juvenile growth rates for NE Atlantic orange roughy (blue line). NAO data are from www.cru.uea.ac.uk/~timo/datapages/naoi.htm. AOI data are from jisao.washington.edu/ao/aojfm18992002.ascii. The association with the NAO is consistent with preliminary analysis of stable oxygen isotopes ($\delta^{18}\text{O}$), an independent temperature proxy in biogenic carbonates, in the otoliths of Irish Slope roughy, which also suggests a positive relationship between temperature at roughy depths and the NAO (R. Rickaby et al., personal communication, 2013). (b) Comparison of reconstructed winter (June–July–August) mean Southern Annular Mode (SAM) (black line) with annual mean Southern Hemisphere (SH) growth rates of juvenile orange roughy (blue line). Growth rates tend to correlate with the winter SAM over the full time series ($p = 0.10$) and correlate significantly after 1940 ($p = 0.04$). The SAM index is from Jones et al. [2009]. All three climate indices are lagged by 2 years to align with the mean deposition date of the growth increments.

1960s supporting information Figure 6). There are too few historical deep water temperature records for the SE Pacific to warrant a comparison. As predicted, growth rates track historical SPMW mean temperatures through most of the time series, diverging only in the 1980s. A similar pattern is evident in the SW Pacific, particularly after 1960 (supporting information Figure 6b); regional instrumental records prior to the 1960s are sparse. A longer term comparison in the SW Pacific can be made using Mg/Ca ratios in deep water gorgonians collected at the roughy fishing grounds and depths as a proxy for water temperatures [Thresher et al., 2010]. Gross trends in juvenile roughy growth rates parallel trends in the coral proxy since 1870 (supporting information Figure 6c). Although there is a clear link between growth rates and temperature, there are insufficient data to determine whether this is a direct effect, or indirect, e.g., mediated by temperature impacts on food availability.

Comparisons among sites indicate strong similarities in trends over time (Figure 2). Annual mean increment widths correlate at $p = 0.004$ ($F_{1,33} = 9.61$) between the SE Pacific and SW Pacific when the latter is lagged by 20 to 23 years, as well as at 30 years (Figure 2a). The lag between the SE and SW Pacific otolith records matches the postventilation age of AAIW in the SW Pacific, as determined from chlorofluorocarbon concentrations [Hartin et al., 2011], and is consistent with coupling between the SE and SW Pacific via the South Pacific subtropical gyre [Judicone et al., 2007]. For comparison with the second-order NE Atlantic time series, we pooled the SE and lagged SW Pacific data sets to create a Southern Hemisphere (SH) growth rate chronology (Figure 2b). SH annual growth rates correlate with the detrended NE Atlantic time series at $p = 0.026$ ($F_{1,61} = 5.21$) uniquely at a lag of 0 years (Figure 2b).

Modeling suggests that variations in AAIW properties can have a direct effect on Northern Hemisphere climates via isopycnal advection at a lag of 10–100 years [Graham et al., 2013]. Simultaneous covariation in the Northern and Southern Hemisphere roughy populations, however, suggests that the processes that determine intermediate water temperatures in both hemispheres are responding in parallel to external forcing, e.g., solar irradiance, or to variability in atmospheric forcing [Roemmich et al., 2007]. In that regard,

growth rates of the NE Atlantic roughly since 1840 correlate significantly with the North Atlantic Oscillation (NAO), both as raw annual means ($F_{1,86} = 4.64$, $p = 0.03$) and after detrending ($F_{1,86} = 5.56$, $p = 0.02$) (Figure 3a). Since 1899, they also correlate with the reconstructed Arctic Oscillation Index (AOI) ($F_{1,55} = 5.10$, $p = 0.027$, and $F_{1,55} = 5.15$, $p = 0.027$, for raw and detrended growth rates, respectively) (Figure 3a). In the Southern Hemisphere, the pooled SH increment chronology correlates poorly with reconstructed annual mean values for the Southern Annular Mode (SAM) since 1905 ($F_{1,67} = 0.69$, not significant) but do tend to covary with the austral winter (June, July, and August) SAM over that period ($F_{1,67} = 2.79$, $p = 0.1$) (Figure 3b). The correlation is significant if we exclude from the comparison the years prior to 1940, when our sampling coverage is sparse (since 1940, $F_{1,39} = 4.63$, $p = 0.04$). Correlations with other seasons are not significant. AAIW is ventilated only during the austral winter [Sloyan *et al.*, 2010; Hartin *et al.*, 2011; Holte *et al.*, 2012], with interannual variability in its temperature (and salinity) properties previously linked to the winter SAM [Naveira Garabato *et al.*, 2009; Schmidtko and Johnson, 2012]. More broadly, NAO- and SAM-driven ocean impacts are significant in the formation regions of SPMW and AAIW, respectively, resulting in variability in formation rate and temperature and salinity properties of these middepth water masses [Visbeck *et al.*, 2003; Sallée *et al.*, 2010; Schmidtko and Johnson, 2012]. We speculate that the parallel second-order trends since the mid-1800s are an oceanic response to these subpolar annular modes, with links between them perhaps modulated by the atmospheric tropical meridional circulation [Kang and Polvani, 2011; Nguyen *et al.*, 2013].

4. Summary

The temperature records inferred from the otolith data provide a long-term context for recent observations of warming and cooling trends at intermediate water depths in the Northern and Southern Hemispheres, respectively. The roughly data confirm suggestions of long-term warming of the SPMW, as well as providing evidence of recent decadal variability, and suggest that the warming is a continuation of a trend that dates from at least the mid-1800s. In the Southern Hemisphere, annual mean juvenile growth rates for the pooled SH population decline significantly ($F_{1,108} = 46.6$, $p < 0.0001$) over approximately the same interval (1832–1981). However, the decline in temperature in the SH is conspicuously nonlinear, occurring primarily between the early 1900s and, depending on location relative to the source of the water mass, 1960 to 1980. The otolith-based time series suggests that reported middepth cooling reflects falling temperatures at around 1000 m during the early to mid-20th century, which is likely to have followed an earlier period of warming and to have slowed or reversed since the 1980s.

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