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Investigating bomb radiocarbon transport in the southern Pacific Ocean with otolith radiocarbon

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ABSTRACT

To explore the transport of carbon into water masses from the surface ocean to depths of ~1000 m in the southwest Pacific Ocean, we generated time series of radiocarbon ($\Delta^{14}C$) from fish otoliths. Otoliths (carbonate earstones) from long-lived fish provide an indirect method to examine the "bomb pulse" of radiocarbon that originated in the 1950s and 1960s, allowing identification of changes to distributions of ^{14}C that has entered and mixed within the ocean. We micro-sampled ocean perch (*Helicolenus barathri*) otoliths, collected at ~400–500 m in the Tasman Sea, to obtain measurements of $\Delta^{14}C$ for those depths. We compared our ocean perch $\Delta^{14}C$ series to published otolith-based marine surface water $\Delta^{14}C$ values (Australasian snapper (*Chrysophrys auratus*) and nannygai (*Centroberyx affinis*)) and to published deep-water values (800–1000 m; orange roughy (*Hoplostethus atlanticus*)) from the southwest Pacific to establish a mid-water $\Delta^{14}C$ series. The otolith bomb ^{14}C results from these different depths were consistent with previous water mass results in the upper 1500 m of the southwest Pacific Ocean (e.g. World Ocean Circulation Experiment and Geochemical Ocean Sections Study). A comparison between the initial $\Delta^{14}C$ bomb pulse rise at 400–500 m suggested a ventilation lag of 5 to 10 yr, whereas a comparison of the surface and depths of 800–1000 m detailed a 10 to 20 yr lag in the time history of radiocarbon invasion at this depth. Pre-bomb reservoir ages derived from otolith ^{14}C located in Tasman Sea thermocline waters were ~530 yr, while reservoir ages estimated for Tasman Antarctic intermediate water were ~730 yr.

1. Introduction

Atmospheric testing of thermonuclear weapons in the 1950s and 1960s generated large amounts of radiocarbon. This 'bomb pulse radiocarbon' can be used to trace carbon through the environment, enabling global oceanic circulation patterns to be detected and mapped (e.g. Broecker and Peng, 1982; Nydal, 2000). Atmospheric concentrations of radiocarbon ($\Delta^{14}C$) began increasing worldwide in 1955, while in ocean surface waters the increase was delayed until about 1958 (e.g. Broecker and Peng, 1982; Nydal, 2000). The extended time since atmospheric thermonuclear testing largely ceased in 1963 makes the bomb ^{14}C tracer a powerful device for examining the temporal evolution of ^{14}C and therefore carbon distribution in the ocean (e.g. Druffel, 2002; Jenkins et al., 2010; Key et al., 2004). Radiocarbon, along with physical and geochemical tracers such as salinity, temperature, density, oxygen, stable carbon isotopes, and silicates have vastly improved our understanding of ocean circulation and current dynamics, particularly in the southwest Pacific Ocean (Bostock et al., 2013; Ganachaud et al., 2014; Sokolov and Rintoul, 2000). Our research aims to produce a record of ^{14}C transport from surface waters to depths approaching 1000 m in the oceanic water column of the southwest Pacific.

1.1. Environmental and biological variability of radiocarbon

Levels of ^{14}C in the atmosphere and ocean differ due to the balance between $^{14}CO_2$ inputs to the ocean, the production of ^{14}C in the atmosphere (e.g. anthropogenic inputs, cosmic ray interactions), and ^{14}C exchange with the deep ocean (e.g. circulation inputs, ^{14}C decay) (Broecker and Peng, 1982; Kalish, 2002a). Radiocarbon concentrations (in both the atmosphere and ocean surface waters) exhibit a slight decline due to the increase in fossil fuel burning (Suess Effect; Suess, 1953) from ca. 1880 until about 1955, after which bomb ^{14}C increase disrupts this trend (Broecker and Peng, 1982; Druffel, 2002; Kalish, 2002a). Differences in advection and degrees of vertical mixing contribute to the spatial variability of ^{14}C in marine waters. This is especially evident in surface

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waters where gas exchange is greatest and upward mixing of subsurface waters depleted in ^{14}C occurs (Broecker and Peng, 1982; Druffel, 2002).

Many oceanic biological carbonates reflect ^{14}C in their surrounding environment, providing a valuable record of changes in ^{14}C over both time and space (Druffel, 2002; Kalish et al., 2001; Scourse et al., 2012). Corals are often used for this purpose (e.g. Druffel, 2002), but otoliths (fish earstones; e.g. Campana, 1997; Kalish, 1995) provide a complementary archive. Otoliths are accretionary structures of fish that are acellular and metabolically inert, permanently retaining changes in the chemical composition of the fish's environment (Campana and Neilson, 1985; Campana and Thorrold, 2001). By using the chemical composition of the otolith (e.g. levels of ^{14}C) in tandem with growth increments, temporal changes in the environment can be examined. Therefore, otoliths from long-lived fish can be used to establish pre-bomb levels of ^{14}C and to track the penetration of bomb ^{14}C through the water column on a regional scale. In contrast to coral, otoliths are able to provide records from cooler regions and throughout the water column.

Otoliths were first used as a proxy for $\Delta^{14}C$ levels in the environment in the early 1990s with reference made to the considerable potential of otolith ^{14}C for further investigation into both oceanography and global change (Kalish, 1994). Since that time, there has been a myriad of globally published research relating to $\Delta^{14}C$ in fish otoliths (primarily age validation studies: e.g. Andrews et al., 2011; Armsworthy and Campana, 2010). There has been some use, albeit limited, of otolith ^{14}C to understand ocean circulation or atmosphere/ocean flux of ^{14}C (see Campana et al., 2008; Horn et al., 2010, 2012; Kalish et al., 2001).

When developing proxy records of geochemical or oceanographic characteristics (e.g. $\Delta^{14}C$) of a marine region, it is imperative to understand the species's life history, specifically patterns of movement, diet and habitat. It is also necessary to understand the regional oceanography to give context to the proxy data. Dissolved inorganic carbon (DIC) in seawater contributes about 75% of the carbon found in otoliths; the remaining 25% of carbon is diet-based (Kalish, 1991; Solomon et al., 2006). Discounting upwelling areas, in near surface waters the relationship between ^{14}C in the environment and the otoliths is relatively simple, in part because ^{14}C in DIC equals ^{14}C in the diet as DIC enters the food chain through phytoplankton (e.g. Kalish, 1993, 1995). However, this relationship becomes more complicated when fish reside below the mixed layer (uncertainty of mixing rate at depth and limited ^{14}C data for deeper waters) and/or exhibit ontogenetic depth shifts. For example, values of $\Delta^{14}C$ measured in the otolith cores and edges of both bluenose (*Hyperoglyphe antarctica*; Horn et al., 2010) and rubyfish (*Plagiogeneion rubiginosum*; Horn et al., 2012) had completely different $\Delta^{14}C$ signatures. This was due to the juveniles of both species living in waters <200 m, while the adult fish resided in waters well below that (in depths ~600 m). Adult blue-eye trevalla also undergo extensive vertical and latitudinal migrations, which further confounds ambient water and dietary sources of carbon (Horn et al., 2010).

1.2. Proxy species

Big-eye ocean perch (*Helicolenus barathri*; here after referred to as "ocean perch") were selected as our study species for bomb ^{14}C analysis. This fish occurs in marine waters along the continental shelf of southern Australia and New Zealand in depths >350 m (Park, 1993; Smith et al., 2009). We can examine $\Delta^{14}C$ levels at depth with the otolith records from ocean perch, because these fish are demersal throughout their lives (Park, 1993; Smith et al., 2009), including feeding (Bulman et al., 2001) and reproductive strategies (Pavlov and Emel'yanova, 2013).

To further examine the transport of bomb ^{14}C through the water column in the southwest Pacific Ocean with otolith radiocarbon, we combined our resulting ocean perch $\Delta^{14}C$ time series with previously published otolith $\Delta^{14}C$ series from nannygai (*Centroberyx affinis*; Kalish, 1995), Australasian snapper (*Chrysophrys* (*Pagrus*) *auratus*; Kalish, 1993), and orange roughy (*Hoplostethus atlanticus*; Kalish, 2002b), as well as a hermatypic coral $\Delta^{14}C$ series (Druffel and Griffin, 2004) and a compilation of monthly resolved atmospheric ^{14}C levels in the southern hemisphere (Hua et al., 2013). These otolith series combined with the coral and atmospheric data are representative of the transport of ^{14}C from the atmosphere to oceanic depths approaching 1000 m in the southwest Pacific Ocean.

1.3. Oceanographic setting of the southwest Pacific Ocean

A brief summary of the regional oceanography (≤2000 m of the water column) in the southwest Pacific is necessary to give context to the otolith $\Delta^{14}C$ values; the following is based on Sokolov and Rintoul (2000), Ridgway and Dunn (2003) and Ganachaud et al. (2014) unless otherwise noted (Fig. 1A). The Australia/New Zealand region of the southern Pacific Ocean is primarily influenced by the South Equatorial Current (SEC) of the South Pacific Gyre (SPG) transporting three main water masses: Upper Thermocline Waters (UTW, $\sigma_\theta \sim 24.5$; origin: subducted centre of SPG), Lower Thermocline Waters (LTW, $\sigma_\theta \sim 26.2$; origin: subducted in part northeast of New Zealand) and Southeast Pacific Antarctic Intermediate Water (SP AAIW, $\sigma_\theta \sim 27.1$; origin: subducted ~50°S, 170°W–65°W) (Fig. 1A; see Bostock et al., 2013; Qu et al., 2009). The SEC turns south as it nears Australia and becomes the East Australian Current (EAC), the highly variable, western boundary current of the SPG. The EAC continues south along the Australian coast where it bifurcates into the Tasman Front (flowing eastward around northern New Zealand) and the EAC Extension (flowing southward towards Tasmania) (Fig. 1A). Lower Thermocline Waters and SP AAIW are transported south by the EAC to the Tasman Front and EAC Extension. The EAC Extension is dominated by very intense, warm-core anticyclonic eddies that can reach from the surface to abyssal depths. Around New Zealand, the Tasman Front becomes the southeast flowing East Auckland Current (EAUC) that eventually forms the East Cape Current (ECC), feeding back into the main SPG gyre after flowing east along the Chatham Rise. Anticyclonic eddies, similar to the vigorous EAC Extension warm core eddies, are associated with the flows along the north and eastern coasts of New Zealand and can extend to depths of at least 1500 m.

Three different types of AAIW are found within the Tasman Sea and along the east coast of New Zealand (Figs. 1A, 2): (1) Southeast Pacific AAIW (as above; salinity: 34.2–34.35; origin: main SPG; $\Delta^{14}C$: −120 to +55‰), (2) Tasman AAIW (salinity: 34.45–35.6; origin: Tasman Sea; $\Delta^{14}C$: −75 to −50‰ [limited data]), and (3) Southern Ocean AAIW (SO AAIW; salinity: 34.28–34.4; origin: Southern Ocean 150°E–120°W; $\Delta^{14}C$: −110 to +55‰) (Bostock et al., 2013). The AAIWs of the South Pacific are identified by the distinct salinity minimum typically found near depths of 600 to 1200 m and bounded with potential density isopycnals (σ_θ) of 26.9–27.3 (Fig. 2; Bostock et al., 2010, 2013). The saltier Tasman Sea AAIW is thought to form by mixing of older SP AAIW, that has travelled around the STG, with higher salinity thermocline waters (possibly LWT) within the recirculating central Tasman Sea (Bostock et al., 2013). Some of the Tasman AAIW flows out of the Tasman Sea eastward around the northern coast of New Zealand and east along the Chatham Rise (Fig. 2B; Bostock et al., 2013).

The specific objectives of this research were to (*i*) use carbonate from ocean perch otoliths to produce a mid-water $\Delta^{14}C$ reference record in depths >350 m for the mid-latitudes of the