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Modeling environmental factors affecting assimilation of bomb-produced Δ^{14}C in the North Pacific Ocean: Implications for age validation studies

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ABSTRACT

The bomb-produced radiocarbon (^{14}C) chronometer has become the gold standard for assessing the accuracy of otolith growth ring based fish age estimates. In the northeast Pacific Ocean, nearly a dozen age validation studies have been conducted, ranging from California to Alaska, most of which have relied on a single reference chronology from the Gulf of Alaska. We developed a Bayesian hierarchical model using data sets of bomb-produced radiocarbon in the northeast Pacific Ocean and investigated whether latitude and upwelling exerts an influence on the parameters that describe the rapid Δ^{14}C increase in marine calcium carbonates. Models incorporating both latitude and upwelling as linear covariates of a 4-parameter logistic model were favored based on ΔDIC statistics. There was substantial evidence to support that the timing of the Δ^{14}C pulse was advanced and that total Δ^{14}C uptake increased with increasing latitude. In contrast, increased oceanographic upwelling resulted in lower total radiocarbon input as well as a delay in the timing of the pulse curve, as was demonstrated in the upwelling dominated California Current System. Within the observed latitudinal and upwelling range of the data sets examined in this study the predicted timing of the bomb pulse curve varied by as much as 3 years, which could be misinterpreted as aging error. Our results suggest that new reference chronologies may be needed for regions of the North Pacific Ocean differing in latitude, seasonal upwelling strength and other mixing factors that can potentially change the functional form of the Δ^{14}C curve.

1. Introduction

Accurate age data are a fundamental part of estimating fish growth and the age composition of commercially exploited fish populations. Further, stock assessments and management strategies used in setting critical harvest limits for the sustainability of resources require accurate age data (Campana, 2001). Ages of most commercially important fish caught in the North Pacific Ocean and other oceans are estimated by counting (reading) visible annual growth rings in the fish's otoliths (ear stones). Accurate age estimation is often a difficult task as the interpretation of these growth rings is not always clear, and can require subjective decisions on what constitutes a year's growth. Inaccuracies resulting from incorrect assignment of age can compromise stock assessments, leading to erroneous allowable removals (Lai and Gunderson, 1987; Campana, 2001). To confirm the accuracy of age estimates, a number of age validation techniques have been proposed, including using known-age fish (Heifetz et al., 1999), radiometric studies (Andrews et al., 2009), marginal increment analysis (Cappo et al., 2000), tracking strong fish year classes (Kimura et al., 2006), and mark and recapture (McFarlane and Beamish, 1995), as well as the novel use of radiocarbon (^{14}C) derived from above-ground atomic bomb testing (Kalish, 1993). Serving as a time-stamp in otoliths of fish extant during the Cold War era, bomb-derived ^{14}C is becoming a widely used tool for fish age validation and is considered one of the best methods for this type of research (Campana, 2001; Francis et al., 2010).

During the height of the Cold War, so many nuclear bombs were exploded above ground that the amount of ^{14}C in the atmosphere and in the surface layer of the oceans was significantly raised (Nydal, 1993). In the surface waters of the oceans the increase of ^{14}C (measured as Δ^{14}C) began in the mid to late 1950s and peaked in about 1970 (Nydal, 1993). Because ^{14}C has a half-life of 5730 years, its presence remains in the Earth's atmosphere and oceans for millenniums. For fish spawned during the era of increasing marine

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bomb-derived ^{14}C, a record representing the "birth year" is preserved in its otolith core. An otolith core is material deposited in the first year of life. To validate the ages of adult fish, the increase in Δ^{14}C found in otolith cores is compared to recognized amounts in biological structures of known age. Thus, if we know the year a fish was collected and have estimated the fish's age by reading the growth rings, then we can estimate when the otolith core was laid down and, accordingly, how much ^{14}C should be in that core.

To apply this validation method two chronologies are needed. First a Δ ^{14}C "reference chronology" (a time-series of Δ^{14}C measurements) is developed from the otoliths of fish with known birth years (i.e., with no aging error). If juvenile fish collected during the era of marine ^{14}C increase are available, they can supply the known-age otoliths. In this case, the age, or birth year, of juvenile (1-year old) fish can be confirmed by fish length, spawning phenology, catch date, and the ^{14}C in the otoliths of these fish (representing their birth year) can be measured and used to provide the reference chronology. The Δ^{14}C reference chronology is then compared to Δ^{14}C measured in cores from adult otoliths whose ages are being validated, the "test specimen" chronology. Test specimens are chosen such that the range of estimated birth years spans the era of rapid marine ^{14}C increase (the late 1950s to about 1970). So, for example, if a test specimen was caught in the year 2000 and was estimated to be 40 years old via growth-ring counts (i.e., born in 1960), the specimen would be an appropriate candidate for validation testing.

In general terms, aging error is assessed by comparing the reference and test specimen Δ^{14}C chronologies with respect to the birth year; if the Δ^{14}C in both the reference and the test specimen chronology displays the same timing and rate of increase, then the test specimen age estimates are typically considered accurate or validated. If the timing differs, the age estimates based on growth-ring counts may be in error. A number of quantitative approaches have been proposed in the literature to derive an estimate of aging bias (Kerr et al., 2005; Kastelle et al., 2008a,b) as well as their confidence intervals (Francis et al., 2010; Kastelle et al., 2011), all of which rely on either parametric or semi-parametric means of fitting a mathematical function to the Δ^{14}C data sets. However, if the timing and/or total increase in Δ^{14}C from the test specimens differs from the reference curve, but the reference curve is based on samples taken from a geographically distinct region of the ocean, interpretation of aging error can be confounded with oceanographic properties that affect ^{14}C uptake in otoliths. Due to this possible confounding between aging error and differential radiocarbon uptake, the bomb radiocarbon age validation method relies on the assumption that the reference chronology is biologically and environmentally representative of the test specimens under evaluation. This means that in the absence of aging error, the magnitude and timing of the Δ^{14}C increase should be similar in both the reference and test chronologies. Ideally, the reference chronology and test chronology should be conspecific and from the same geographic area, but unfortunately this is rarely the case in the North Pacific Ocean since only a few teleost reference chronologies using known-age fish have been developed (Piner and Wischniowski, 2004; Haltuch et al., 2013). Potential failures in meeting this assumption have become the focus of increasing scrutiny as more research is dedicated to using this age validation method, but few studies have examined the timing and strength of the bomb-derived Δ^{14}C marine signal and its relationship across broad gradients in oceanographic processes in the North Pacific Ocean.

To consider these regional differences, our goal was to investigate potentially different timing and/or total increase in Δ^{14}C among regions of the North Pacific. We used a diverse pool of Δ^{14}C data from published literature and several unpublished datasets from the Alaska Fisheries Science Center. Our focus was to

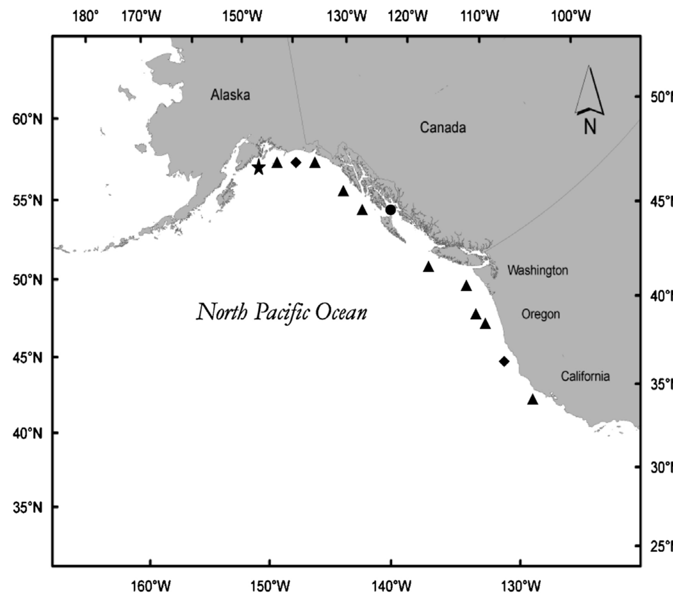

Fig. 1. Map showing the general location of 13 Δ^{14}C data sets located in the North Pacific Ocean used to develop a Bayesian hierarchical models. Star = Pacific halibut, circle = geoduck, triangles = rockfish, diamonds = flatfish.

synthesize all existing Δ^{14}C data from the northeast Pacific Ocean to describe the assimilation of bomb radiocarbon in marine calcium carbonate and to evaluate latitude and upwelling as environmental factors affecting the diffusion of ^{14}C into the marine environment and its uptake in fish otoliths. In particular, we conducted a Bayesian hierarchical meta-analysis of the relationships between Δ^{14}C data among numerous species and potential environmental factors in the North Pacific Ocean. Bayesian methods have often been used as the quantitative framework for employing meta-analysis, and numerous examples are available in the ecological (Wade, 2000; Helser and Lai, 2004) and fisheries science (Punt and Hilborn, 1997; Helser et al., 2007) literature. Bayesian methods (Gelman et al., 2004) provide a direct means of parameter estimation and quantification of uncertainty in variance components and model parameters.

2. Materials and methods

2.1. Data sets

In all, we used 13 sets of data that ranged in location from southern California to the Gulf of Alaska and represented 10 different species (Fig. 1 and Table 1). One data set consisted of Δ^{14}C measurements from the bivalve, Pacific geoduck (*Panopea generosa*) from the west coast of British Columbia, Canada (Kastelle et al., 2011) while the remainder are from finish. The data set from Pacific halibut (*Hippoglossus stenolepis*) (Piner and Wischniowski, 2004) was separated into southeastern and northern Gulf of Alaska. Samples of canary rockfish (*Sebastes pinniger*) and bocaccio rockfish (*S. paucispinis*) were separated along a large enough latitudinal gradient to divide each data set into north and south. Data sets ranged in sample numbers from 8 to 43 with estimated birth years based on growth-ring counts (except for Pacific halibut and Petrale sole, *Eopsetta jordani*), which were known-age juveniles coinciding with the era of increasing ^{14}C. Data sets contained measured Δ^{14}C values with standard errors, and approximate collection locations (latitude, often determined from a reported description of collection area). We report results as Δ^{14}C, which is normalized to 1950 and corrected for isotopic fractionation with the δ^{13}C measurement and normalized to a $\delta^{13}C_{VDPB}$