Forage fish of the Pacific Rim as revealed by diet of a piscivorous seabird: synchrony and relationships with sea surface temperature

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Abstract: We tested the hypothesis of synchronous interannual changes in forage fish dynamics around the North Pacific Rim. To do this, we sampled forage fish communities using a seabird predator, the rhinoceros auklet (*Ce ca -ce ata*), at six coastal study sites from Japan to California. We investigated whether take of forage fishes was related to

Introduction

An extensive body of literature compares population study. Therefore, we derived SST indices from the Advanced Very High Resolution Radiometer (AVHRR) satellite remote sensing system (9 km $\times$ 9 km cells; poet.jpl.nasa.gov/), available since 1985. We computed 3-month seasonal indices for a 50 km radius around each site (excluding land), comparable with auklet foraging ranges around the colonies (Kato et al. 2003; McFarlane-Tranquilla et al. 2005). AVHRR data were fairly complete within the 50 km radius around most sites in most months (see Appendix A). We compared satellite-derived SST with in situ measurements where possible (Appendix A). All correlations were highly significant, though less so as the year progressed, which we interpreted as reflecting the effects of insolation.

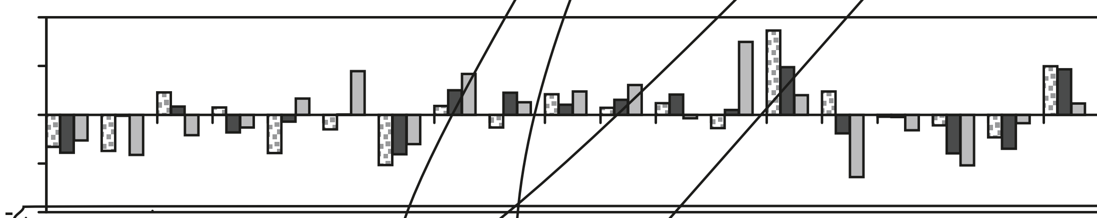
Forage fishes

Fishes were sampled by a piscivorous, diving marine bird (rhinoceros auklet), which is closely related to puffins and ranges throughout the North Pacific Rim. This seabird can forage to depths of 60 m, but has mean dive depths of 10–30 m (Burger et al. 1993; Kuroki et al. 2003). Fishes were collected from auklets provisioning offspring in summer (June–August), either by netting or hand-capturing the adults as they returned to the colony. Fishes were measured, weighed, and identified to species. Rhinoceros auklets are "multiple prey loaders", which typically bring 1–10 prey back to the colony in their bill following a foraging bout.

We used percent number of prey species, since we were interested in community composition. As multiple prey from one bill load are not statistically independent, individual prey items were summarized in terms of a bill-load sampling unit (Appendix B, Table B1). We calculated the proportion diet composition by number for each bill load averaged over each year as an index of prey harvest (or take). Forage communities were described using the entire time series available at each site, in some cases dating back to 1976.

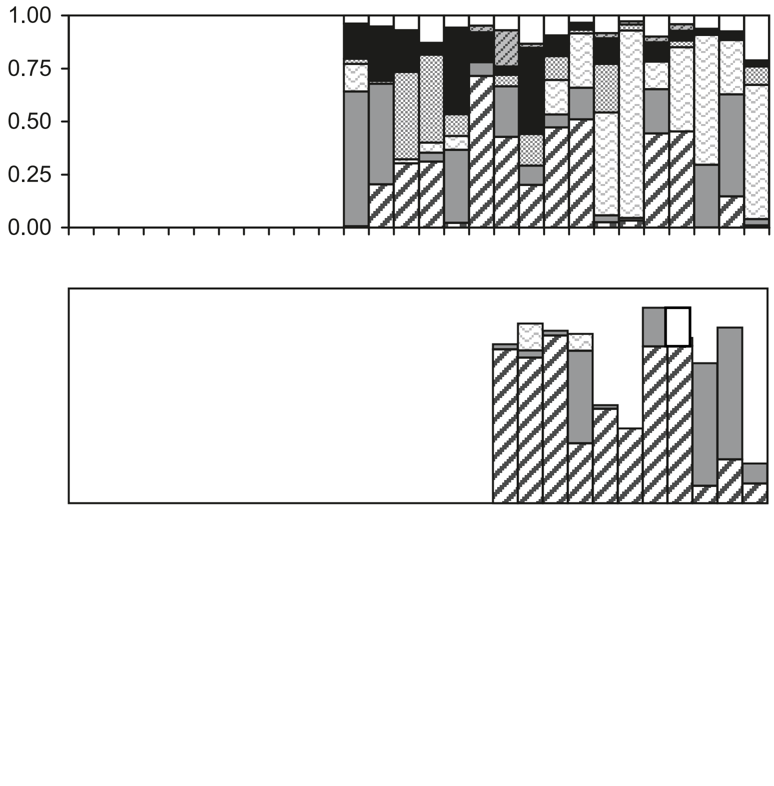
Statistical analysis

Since fish data were expressed as proportions, we used a logit-transformation (ln[/(1 –)]) prior to analysis, where



for years in which sampling took place at all sites for 1994–2003. Species richness was calculated for each site using fish species that made up ≥10% of predator diet in at least 1 year. For SST indices and the predominant prey at each site, we used linear and quadratic regression to infer trends between years. Time series were tested for first-order effects of serial autocorrelation (Prais–Winsten regression for small sample sizes). No autocorrelation coefficients were significant (all > 0.5). Series were detrended if necessary by taking residuals. We then used Spearman's rank correlations to examine spatio-temporal concordance of ocean conditions and take of primary forage fish species at each location.

Results


1.00
0.75
0.50
0.25
0.00

sisted largely of anchovy (*E g a da* in the east, *E -*
g a a c in the west), sandlance (*A d te e -*
a te in the east, *A d te e at* in the west),
Pacific saury (*C ab a a*), capelin (*Ma t*),
Pacific herring (*C ea a a*) and Pacific sardine (*Sa d -*
aga

to be positively correlated with SST. A positive relationship was observed with summer SST, yet it was not significant (Fig. 4).

Discussion

We used a piscivorous seabird to sample forage fish around the North Pacific Rim. The use of seabird diet as an indicator of prey is not a new idea (Cairns 1987; Barrett 2002; Mills et al. 2007), but this is the first study to use a single seabird species to sample multiple locations over an entire ocean basin. We found that forage species at many sites responded to marine conditions on interannual scales, although indications of lower-frequency change were strongest in the Sea of Japan. There was spatial synchrony (i.e., similarities) in the relationships between SST and certain forage fish species in seabird diet in the northeast Pacific.

Seabirds as indicators of forage fish

As indicators, ‘‘puffins’’ such as the rhinoceros auklet are especially useful in that they are abundant, widely distributed, and samples of forage fish are easily obtained by catching the birds as they return to colonies to feed dependent offspring. In a single feeding episode, puffins may also bring multiple forage fish to the nestlings. While predator-based sampling avoids certain problems inherent in studies of forage fish (e.g., patchy distributions), this technique also presents some difficult interpretive challenges given prey age or size classes and general prey preferences. If independent measures of prey abundance are available, these are valuable to calibrate predator diets. However, once preferences are well established, predator diet may be used to track dynamics of forage species (Reid et al. 1996, 2005).

Prey preferences have been examined at several of our study sites. Auklet take of juvenile rockfish in the California Current has been correlated with midwater trawl surveys for juvenile rockfish over many years (Thayer and Sydeman 2007); auklets in this region preferentially prey on rockfish when they are abundant in the ecosystem. In the Sea of Japan, auklet harvest of anchovy has been linked to annual stock size estimates (1996–2001; Deguchi et al. 2004). In both situations, the take of preferred prey was correlated with increased bird productivity (Takahashi et al. 2001; Thayer and Sydeman 2007). Unfortunately, there were no independent measures of prey availability in the environment that were available for other regions. However, in the Eastern Coastal Transition Zone (British Columbia, Canada), auklet take of sandlance has been related to the take of sandlance by other predators in the system (groundfish; Bertram and Kaiser 1993) as well as to high offspring survival (Hedd et al. 2006). Ongoing studies in the Gulf of Alaska indicate an increase in capelin since the mid-1990s (Brown 2002), similar to the trend in auklet take of capelin in this study.

Other high-lipid forage fish, though perhaps not known to be ‘‘preferred’’ as described above, may be taken opportunistically by the birds (e.g., sardine, juvenile salmon and sablefish). The appearance of such prey in the diet indicates their presence in the fish community at any given time. Thus, we interpret marine bird diet as useful for examining fish community composition in addition to its potential value as an indicator of dynamics of primary prey relative abundance in the environment. In conjunction with fisheries-independent data, an eventual goal is to use one or more marine birds and possibly other predators at multiple

Sea, and Barents Sea indicate that capelin prefer colder waters and that they are found over a wider range in cooler years (Methven and Piatt 1991; Brodeur et al. 1999; Hollowed et al. 2007). Capelin feed on euphausiids and copepods (Hart 1973), and the abundance of these species was higher at lower temperatures in the Gulf of Alaska (Wang and Foy 2006). Therefore, cooler conditions could promote capelin survival. The negative correlation of capelin with winter SSTs in the Gulf of Alaska may be related to food availability and survival prior to reaching age class 1, the age at which they are taken by auklets. This explanation is more probable than one related to direct influence of SST on spawning distribution and behavior. Capelin come inshore to spawn in late spring and early summer (Naumenko 2002), but the relationship we observed with SST occurred during winter. Most importantly, capelin do not mature before ages 2 or 3 (Brown 2002), yet our samples consisted of almost exclusively 1+ age class fish.

In the northern Gulf of Alaska, both 0 and 1+ age class sandlance were harvested by the birds, and we found a strong relationship of sandlance with spring SST. In this region, wind mixing, topographic steering, and periodic up-

Wildlife Service (CWS), Oracle Corporation, and Exxon/Mobil Corporation, crucial components in sustaining our long-term data series.

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Table B1. Sample sizes (number of rhinoceros auklet (*Ce ca ce ata*) prey loads) at each study location, 1994–2003.

Site	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
MI	180	124	68	110	305	99	106	116	95	97
SLI	38	45	32	37	77	31	46	76	54	67
TRI	85	117	107	90	88	86	83	93	110	96
SFI	61	58	59	46	70	60	33	93	53	38
ANI	25	22	26	19	24	24	34	52	46	33
TEI	88	88	66	117	112	109	109	99	78	127

Note: MI, Middleton Island; SLI, St. Lazaria Island; TRI, Triangle Island; SFI, Southeast Farallon Island; ANI, Año Nuevo Island; TEI, Teuri Island.