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An examination of the physical variability around the Pribilof Islands in 2004

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A B S T R A C T

The Pribilof Islands form a unique ecosystem. An anti-cyclonic oceanic flow exists around the islands. Nutrients are introduced into this circulation from two sources: (1) the flow along the 100-m isobath with intrusions of nutrient-rich water in Pribilof Canyon, and (2) the westward transport and vertical mixing of middle-shelf water, which contains nutrient-rich bottom water. Enhanced tidal mixing around the Pribilofs introduces this deeper, nutrient-rich water into the euphotic zone and thus supports prolonged production around the islands. Further, the middle-shelf water that is advected into the region causes the upper 50 m of the water column around the islands to freshen throughout the summer. This enhances the frontal structure and strengthens the baroclinic flow along the 100-m isobath. The strengthening of the frontal structure can moderate ecosystem productivity by limiting the intrusion of slope water rich in nutrients and oceanic copepods.

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1. Introduction

The Pribilof Islands (Fig. 1) lie in the Bering Sea, a semi-enclosed basin separated from the North Pacific by the Aleutian Arc and from the Arctic Ocean by Bering Strait (Stabeno et al., 1999a). Almost half of the sea is comprised of a broad ($>$500 km), shallow eastern shelf, with the remainder consisting of a moderately deep basin ($<\sim$4000 m) and a narrow western shelf. This sea supports a rich and varied ecosystem including vast populations of migratory birds, marine mammals and fish (Stabeno et al., 2006). The islands support communities of Aleuts that depend on the sea for food and economic survival. Changes in climate at decadal or longer time scales could have profound consequences for both the ecosystem and economy of this productive archipelago. To be able to anticipate the effect of such changes, an understanding of the mechanisms that control the biological productivity is necessary.

The circulation in the southeastern corner of the Bering Sea basin (Fig. 1) is dominated by the Aleutian North Slope Current (ANSC) and Bering Slope Current (BSC) (Stabeno et al., 1999a). The ANSC flows northeastward along the north slope of the Aleutian Islands (Fig. 1) and turns northwestward at the shelf break to form the BSC (Stabeno et al., 2007a). Water flowing through the Aleutian Passes contributes salt, heat and nutrients to the ANSC. The water in the upper 100–200 m tends to be nutrient rich because of energetic mixing that occurs in the passes (Mordy et al., 2005; Stabeno et al., 2005). Instabilities in the BSC (Stabeno and van Meurs, 1999; Mizobata et al., 2008) and interaction of the slope flow with topography, such as Pribilof and Bering Canyons (Schumacher and Stabeno, 1998), can both result in the intrusion of nutrient-rich water onto the shelf. The flow over the southern shelf is weakly northward along the 100-m isobath and with anti-cyclonic circulation around the Pribilof Islands (Fig. 1).

Hydrography and currents differentiate the cross-shelf oceanographic structure of the southeastern shelf into three domains with distinct characteristics (Coachman, 1986; Schumacher and Stabeno, 1998; Kachel et al., 2002). A combination of tidal currents and winds results in a weakly stratified or well-mixed coastal domain ($z<\sim$50 m). Over the middle shelf domain ($\sim$50$<z<\sim$100 m), tides and winds during summer cannot stir the entire water column, resulting in a sharp, two-layered system. The outer-shelf domain ($\sim$100$<z<\sim$180 m) has a three-layered structure, with well-mixed surface and bottom layers separated by a layer of changing temperature and salinity. Transition zones separate the three domains. The inner front separates the coastal domain from the middle domain; the middle transition separates the middle domain from the outer domain; and the shelf break front separates the outer domain from the slope water (Schumacher and Stabeno, 1998; Stabeno et al., 1999b; Kachel et al., 2002).

The Pribilof Islands sit in the vicinity of the middle transition. Because of the shoaling bathymetry around the islands and their proximity to the shelf break, this region has characteristics that are unique on the shelf. Sullivan et al. (2008) have proposed that this domain be referred to as the "Pribilof Domain". Its uniqueness is a result of its geographic location. Except for the Pribilof Islands, it is only at the northern and southern extremes of the shelf break

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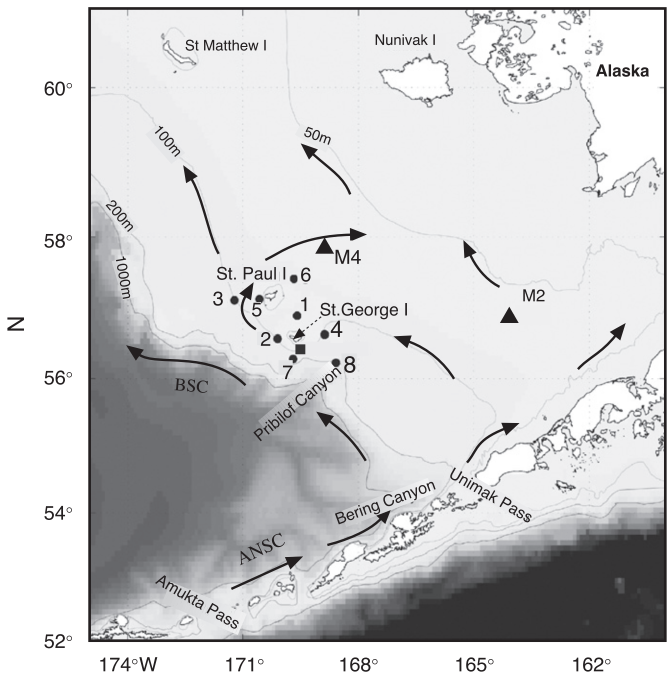

Fig. 1. Southeastern Bering Sea with major currents, locations of Pribilof moorings (1–8) and two long-term biophysical moorings along the 70-m isobath (M2 and M4). The square indicates the location of the ADCP mooring in 1997–1998. The two major currents in the basin are the eastward flowing Aleutian North Slope Current (ANSC) and the northwestward flowing Bering Slope Current (BSC). The weaker flow on the southeastern shelf is also indicated.

that close proximity between the basin and coastal domains occurs (Fig. 1).

The Pribilof Islands consist of four separate islands: St. Paul Island, St. George Island, Walrus Island and Otter Island. St. Paul and St. George Islands comprise over 97% of the total land area. They are separated by ~90 km, with St. George Island found farther south and closer to the shelf break than St. Paul Island. Walrus Island lies slightly east of St. Paul Island, and Otter Island lies south of St. Paul Island.

From 26 July to 20 August 2004, an interdisciplinary research cruise was conducted to examine the ecological processes that affect the productivity of Pribilof Islands' waters and the ability of this ecosystem to support zooplankton and juvenile fish, as well as the seabirds and marine mammals that consume them. This study examined physical processes, nutrient availability, primary production, zooplankton community structure and biomass, and the diets of seabirds with a goal to understand how the ecosystem would respond to climate variability.

This article focuses on the physical environment and the impact of bottom-up processes on primary production. It utilizes data from eight moorings that were deployed in the vicinity of the Pribilof Islands, two long-term biophysical moorings deployed over the middle shelf, satellite-tracked drifters, shipboard measurements and satellite images. We begin with a description of the winds and ice extent over the eastern shelf in 2004, and how ice impacted the spatial and temporal patterns of chlorophyll. We then use satellite-tracked drifters to examine the long-term mean flow around the islands compared to the flow in 2004. Next, we use data from the moorings to examine mechanisms that control flow onto the shelf and the balance between middle-shelf water and the outer shelf/slope waters. We use a hydrographic model to examine how mechanisms, particularly tides, are important to this ecosystem. Finally, we present chlorophyll patterns and relate them to physical mechanisms that are important in the bottom-up control of this ecosystem.

2. Methods

2.1. Hydrography and nutrients

Conductivity–temperature–depth (CTD) data were obtained using a Seabird SBE9plus system with dual temperature and salinity sensors. The data were recorded on downcasts, which had descent rates of 15–30 m min^{-1}. Salinity calibrations were provided by water samples taken during most of the casts. These data indicated instrument accuracy better than 0.01 psu. Data were routinely examined to remove spurious values. Water samples were collected for analysis of nutrient concentrations at 0, 10, 20, 30, 50 m and near the bottom of each CTD cast. Nutrient samples were collected using polyethylene scintillation vials and caps, pre-washed with dilute HCl and triple rinsed with sample water. Samples were stored upright in a refrigerator until they were processed, normally within 1–2 h, using an on-board Apkem RFA Model 300 automated nutrient analyzer (Whitledge et al., 1981). These *in situ* measurements also provided quality control for the time series collected by the moored nutrient sampler.

2.2. Meteorology

Weather observations are made routinely at the St. Paul airport on the southern part of the island at an elevation of 7 m; maximum elevation on the island is 180 m. Since the Pribilof Islands are low-lying islands, they cause little or no orographic effects on wind fields. While historically the frequency of weather reports was variable, data are now collected hourly.

Simulated winds (e.g., NCEP) provide a good replication of the winds in the Bering Sea (Ladd and Bond, 2002). These fields are used herein to explore spatial variability of the winds and their impact on oceanographic features through Regional Ocean Modeling System (discussed in Section 2.5).

2.3. Moorings

Eight moorings were deployed near the Pribilof Islands from the NOAA Ship *Miller Freeman* on April 30–May 1, 2004 (Fig. 1). Six of the moorings were recovered between September 30 and October 2, 2004. The releases on the other two moorings (P2 and P7) failed to respond, and, because of adverse weather, the ship could not remain on site. Mooring P7 was successfully recovered April 30, 2005. P2 was found on May 5, 2005, but unfortunately it had been dragged ~10 km by a fishing boat and was badly damaged; only the bottom three instruments were recovered. Examination of the three temperature time series from P2 indicated that the mooring was dragged in late December. Depths of the instruments from all the moorings are presented in Table 1. All instruments were calibrated before and after deployment. Each of the deployments (recoveries) was followed (preceded) by a CTD cast and a bongo tow.

Biophysical moorings have been maintained at two sites, M2 (since 1995) and M4 (since 1999), along the 70-m isobath of the southeastern Bering Sea shelf (Fig. 1). During the summer of 2004, a surface mooring was deployed at M2 and a taut wire/chain subsurface mooring was deployed at M4; during winter both sites contained subsurface moorings. Each mooring was instrumented to measure temperature, salinity, nutrients and fluorescence; the surface mooring also measured meteorological variables. Next to each biophysical mooring, a bottom-mounted, upward-looking