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SHORT NOTE

Fronts and Seabird Aggregations in the Southeastern Bering Sea

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ABSTRACT: A number of recent studies suggest that biological activity may be enhanced at fronts, which mark the boundary between water masses. Concurrent bird and physical oceanographic data were collected along a transect that crosses 3 fronts in southeastern Bering Sea. A simple regression-against-distance model was used to describe location and structure of bird aggregations along this transect. Significant bird aggregations coincided with 2 of the 3 fronts, 1 at the shelf break and 1 associated with the 50 m isobath. Aggregations at the shelf break front were composed of surface foraging birds (fulmars and petrels). Aggregations near the shallow sea front were composed of subsurface foraging birds (murres and shearwaters). The sizes of these aggregations suggest that high rates of carbon flux to upper trophic level consumers may occur in limited areas.

Enhanced biological activity has been frequently postulated at fronts (Uda, 1938; Pingree et al., 1974) based on the intensified physical processes at these water mass boundaries (James, 1978; Simpson and Pingree, 1978). Most biological studies have focused on primary production (Pingree et al., 1975; Fournier et al., 1977; Iverson et al., 1979a), and on mechanisms of nutrient regeneration (Floodgate et al., 1981). Increased consumer activity at fronts may result from increased primary production, or from secondary concentrating mechanisms at fronts, in the absence of increased phytoplankton production. Qualitative effects have been reported for several consumer groups (Holligan, 1981), including marine birds (Brown, 1980; Ainley and Jacbos, 1981). For mobile marine consumers such as seabirds, numbers or biomass may not be correlated with feeding activity. For seabirds, feeding (coalescing) and post-feeding (dispersing) aggregations are recognizable by the decrease in density as one moves away from the center of activity (Hoffman et al., 1981). This paper describes the location and structure of pre- and post-foraging seabird aggregations, relative to fronts and chlorophyll maxima encountered along a 534 km transect across the Bering sea shelf.

Concurrent bird and physical oceanographic data were collected from 31 May to 3 June, 1981 as part of a multidisciplinary investigation of the Processes and Resources of the Bering Sea Shelf (PROBES). CTD (conductivity-temperature-depth) casts were made at 25 km intervals along a well-studied transect which runs from 54° 51′ N, 167° 52′ W to 58° 29′ N, 162° 09′ W, or roughly northeast toward Cape Newenham from a point beyond the shelfbreak. The transect lies midway between the Alaska Peninsula and the Pribilof Islands. Chlorophyll *'a'* concentrations were measured fluorometrically in surface hydrocasts at each station. Bird counts were made while underway between stations, from dawn to dusk. Four to 6 ten-minute counts were made per hour. All birds except ship-followers were recorded in a 90° sector extending 300 m forward and abeam. Ship location was recorded at the start and end of each count in order to compute the area scanned during each count. Fronts were defined by computing the variance in temperature and salinity between adjacent stations, using ten meter depth intervals to pair measures from adjacent stations. The formula used was:

$$\Delta U^2 = (d-1)^{-1} \sum^{d} ({}_xU_i - {}_yU_i)^2$$

U = temperature or salinity; d = number of 10-m depth intervals; i = depth in tens of meters; x and y are adjacent stations.

This statistic has a maximum value between stations with high horizontal gradients, i. e. at fronts; it has a low value when adjacent stations have homogeneous temperature or salinity structures. Temporal variation included in this measure was checked by computing the variance between repeated CTD casts at the first two stations on the line.

A simple regression against distance model was used to distinguish aggregations from passing flocks and background variation in counts. Aggregations

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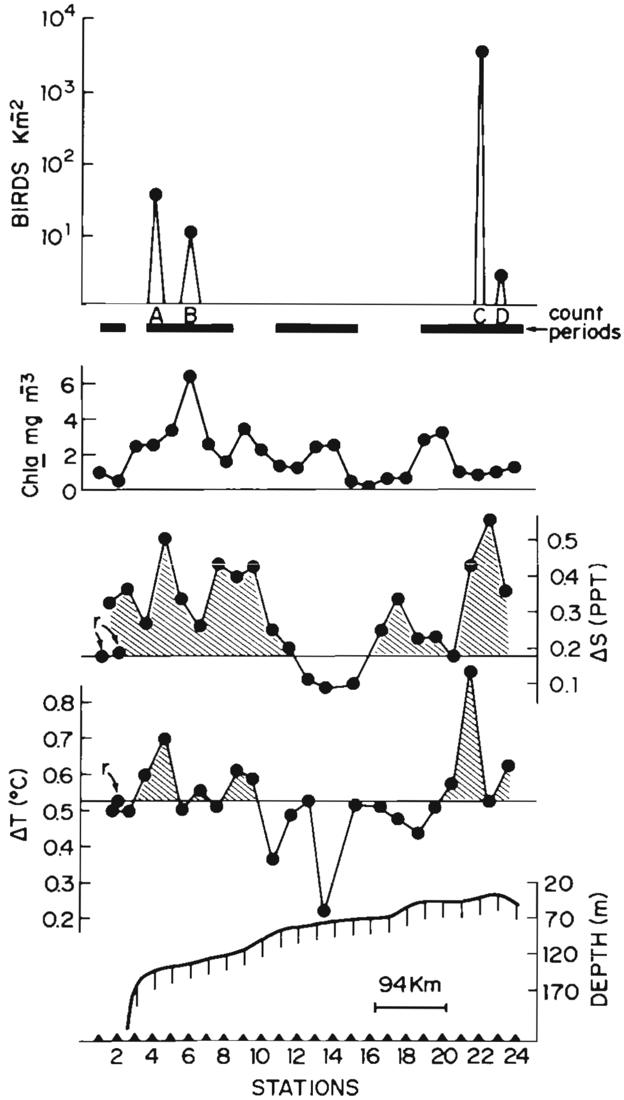

Fig. 1. Water depth, horizontal gradients in temperature (ΔT) and salinity (ΔS), and 4 bird aggregations (A, B, C, and D) on a cross-shelf transect. Dominant bird species in these 4 aggregations are listed in Table 1. r = root mean square deviation for replicated CTD casts at one station

were measured by identifying each point with a higher bird density than that of the 4 nearest points, and testing for a significant decrease in density with increasing distance from this point. Choosing a peak count to begin analysis required dropping a degree of freedom in testing for significance. The procedure was checked by substituting random numbers for the 90 bird counts made along the study transect. Out of 18 'peaks' in the random data, only one reached significance at $p = .05$; none of the 'peaks' in the random data were significant at $p = .01$. Erroneous rejection of the null hypothesis (Type I error) occurred in 1 out of 18 cases, a value close to the expected error rate of 1 in 20 (5%). The procedure gave a measure of variance explained by distance (r^2). The rate of attenuation moving away from the peak count is the slope of the least square regression line.

Fronts were encountered at the expected (Kinder and Coachman, 1978; Coachman and Charnell, 1979; Schumacher et al., 1979) positions along the transect – at the shelf break, near the 100 m isobath, and inside the 50 m isobath (Fig. 1). Two of these fronts were crossed during daylight hours and both of these fronts showed significant aggregations of birds.

Species composition of the 4 aggregations shown in Fig. 1 are listed in Table 1. The shift from fulmars and petrels on the outer shelf to shearwaters and murres on the inner shelf is consistent with previous demonstrations of cross-shelf differences in species composition in the Bering Sea (Iverson et al., 1979b). The shearwater aggregation at the inner front (Fig. 1) was encountered at the same location 1 d later, and then again 10 d later. Large aggregations of shearwaters at the inner front are consistent with previous reports (Hunt et al., 1981) of shearwater flocks near the 50 m isobath.

Seabird aggregations coincided with chlorophyll maxima on the outer shelf (Stations 4 to 6), but not on the inner shelf (Fig. 1). Chlorophyll *a* maxima at the surface were encountered at Stations 4 to 6 (6 mg m^{-3}), Station 9 (3.5 mg m^{-3}) Station 13 to 14 (2.3 to 2.5 mg m^{-3}), Station 20 (3.2 mg m^{-3}), and Station 24 (3.2

Table 1. Significant bird aggregations for 31 May to 3 June, 1981

Station number	Patch maximum (birds km^{-2})	Attenuation coefficient (birds km^{-2} km^{-1})	r^2 (p-value)	Dominant species
4	37	− 1.7	.87 (<.05)	Northern fulmar *(Fulmarus glacialis)*
6	11	− .57	.86 (<.01)	Northern fulmar Fork-tailed storm petrel *(Oceanodroma furcata)*
22	3600	− 324	.77 (<.01)	Shearwaters (*Puffinus* sp.)
23	7	− 1.1	.95 (<.05)	Murres (*Uria* sp.)

mg m^{-3}). Increased phytoplankton concentration at the surface may play a causal role at the outer shelf front, where seabird aggregations were composed of surface foraging species (fulmars and petrels). A direct linkage through zooplankton is likely, since both fulmars and petrels can take zooplankton by pecking at the water surface. Activity at the inner front appears to have been beneath the water surface: there was no chlorophyll maximum at the surface, and seabird aggregations were composed of subsurface foragers (shearwaters and murres).

The results of this analysis from the Bering Sea indicate that fronts do play a role in precipitating bird aggregations at sea. Feeding rates at fronts deserve to be examined in light of the fact that an increase in food aggregation increases the rate at which mobile predators take prey (Ivlev, 1961). Prey aggregation and feeding rates at fronts also deserve examination in light of reported concentrations of toxic compounds at fronts (Sick et al., 1978).

Fronts are mesoscale (10 to 100 km) features and birds are large marine organisms several steps away from primary production. An association between birds and fronts is somewhat unexpected, if trophic interactions proceed at ever expanding scales of space, time and size of organism (e. g. Haury et al., 1978). Interaction along expanding scales of space and time is to be expected if diffusive forces in the water limit the rate of encounter between prey and predator. However, the positive responses of highly mobile predators to food abundance would act to foreshorten the scales of interaction. One circumstance that favors such responses is the provision of reliable cues by the environment. An organism that can increase its probability of encounter with its prey by detecting a physical cue, and holding its position relative to some physical feature, achieves a selective advantage over its conspecifics. This response, if found in an entire population of consumers, would tend to reduce the rate at which fixed carbon is dispersed away from its source of production. Foreshortening is also favored if predators can detect prey aggregations at a distance, and move rapidly toward them. Birds hold a considerable advantage in that they move through a medium in which visibility is high and viscosity is low. The fact that bird aggregations do occur at fronts, at relatively small scales, indicates that some foreshortening of the scales of trophic interaction does occur in the sea.

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