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AGGREGATIONS OF CORY'S SHEARWATERS (*CALONECTRIS DIOMEDEA*) AT GULF STREAM FRONTS

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Seabirds are adapted to marine communities where prey concentrations are patchy and short-lived. Hydrographic events and physical properties of water masses combine to influence the distribution and abundance of lower trophic level prey organisms. These processes may also account for some, and occasionally most, of the variation in the abundance and distribution of seabirds. Seabird faunas have been related to sea-surface temperature (Murphy 1936, Bourne *in* Palmer 1962, Ashmole 1971, Watson 1975) or to water masses defined by surface temperature and salinity (Pocklington 1979), and several investigators have related the distribution of individual seabird species to sea-surface temperature and major current systems (e.g., Szijj 1967, Jehl 1973, Gould 1983). However, few studies have correlated smaller-scale variation in seabird abundance with the distribution of physical processes (e.g., Brown 1980a). Recently, oceanographic research on specific hydrodynamic features has enabled ornithologists studying marine birds to investigate and interpret such interactions simultaneously (Brown 1980b).

Hydrographic fronts that occur at adjoining water masses of differing densities (temperature and/or salinity) are one example of small-scale physical oceanographic events (Stommel 1963, Haury et al. 1978), and seabirds have been associated with fronts at the edge of the continental shelf in the Bering Sea (Kinder and Coachman 1978, Iverson et al. 1979, Schneider 1982, Kinder et al. 1983), Ross Sea (Ainley and Jacobs 1981), and Northwest Atlantic (Brown 1977, Fournier 1978, Orr et al. 1982). The association of seabirds with fronts in the South Atlantic Bight region (Cape Hatteras, North Carolina to Cape Canaveral, Florida) has not been reported previously.

Cory's Shearwaters (*Calonectris diomedea*) inhabit warm temperate and subtropical seas and breed north of the equator on islands of the eastern Atlantic and Mediterranean (Cramp and Simmons 1977). Nonbreeders disperse to the western Atlantic, including the continental shelf of the southeastern United States, during summer and fall (Clapp et al. 1982). Here, we present evidence that Cory's Shearwaters aggregate at Gulf Stream surface thermal fronts during summer and fall at the shelf break in the southern portion of the South Atlantic Bight. We offer hy-

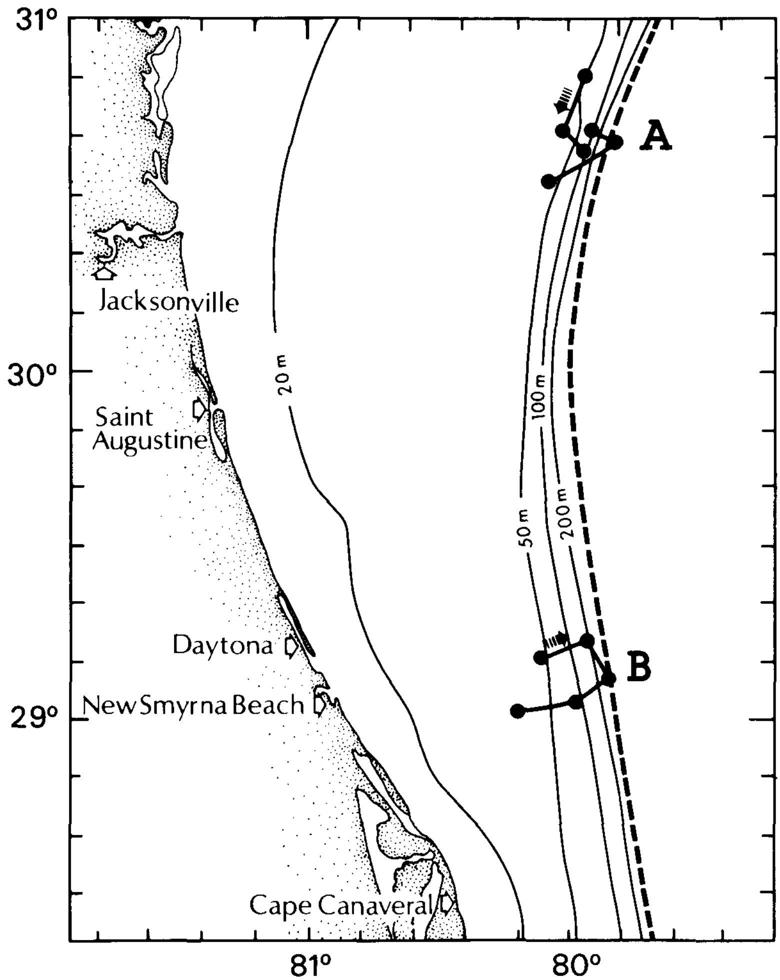

FIG. 1. Map of southern South Atlantic Bight with 13 July 1983 (A) and 1 Oct. 1983 (B) cruises indicated with arrows. Annual mean position of western Gulf Stream surface thermal front is shown by dashed line. Depth contours are indicated by solid lines.

potheses to explain why these aggregations occur, and discuss the possible relationships of hydrographic structure to biological processes at the front.

METHODS

Study area.—Research was conducted in the southern South Atlantic Bight region off northeast Florida and southeast Georgia (Fig. 1). The region is characterized by a wide, shallow continental shelf that narrows considerably at the southern and northern extremes

TABLE 1

SPECIES COMPOSITION OF SEABIRDS OBSERVED DURING JULY AND OCTOBER 1983 SURVEYS OF THE SOUTH ATLANTIC BIGHT OUTER SHELF

	July			October		
	N	% of transects observed on	% of all birds seen	N	% of transects observed on	% of all birds seen
Calonectris diomedea	81	36	82	199	50	98
Puffinus lherminieri	6	16	6	3	50	1
Phaethon lepturus	1	4	1	0	0	0
Sterna maxima	1	4	1	0	0	0
Sterna hirundo	1	4	1	0	0	0
Sterna anaethetus	8	8	8	2	33	1
Sterna spp.	1	4	1	0	0	0

near Cape Canaveral, Florida, and Cape Hatteras, North Carolina. In this region, surface-slope waters are absent and warm oceanic (i.e., Gulf Stream) water interacts directly with shelf waters. Mixing regimes segregate shelf waters into inner-shelf (0–20 m), middle-shelf (20–40 m), and outer-shelf (40–200 m) domains. The climatology of these water masses is summarized by Atkinson et al. (1983). Transects were carried out in the outer shelf domain where variations in Gulf Stream frontal effects, occurring on time scales of 2 to 14 days, are as large as seasonal variations (Lee and Atkinson 1983). Over the outer continental shelf a southeasterly drift predominates during summer and fall. At the shelf break, however, surface currents are to the northeast due to frictional interaction with the Gulf Stream (Bumpus 1973).

Bird counts.—Counts of seabirds, including Cory's Shearwaters, were made during bimonthly surveys of the seabird fauna of the South Atlantic Bight. Observations reported here are from cruises made on 11–15 July 1983 aboard the 21-m R/V "Bluefin" (Skidaway Institute of Oceanography) and on 29 Sept.–13 Oct. 1983 aboard the 41-m R/V "Cape Hatteras" (Duke University Marine Lab). Simultaneous oceanographic measurements and seabird counts across and along the western Gulf Stream front were made on 13 July and 1 Oct. during the respective periods of these cruises (Fig. 1).

Observations of seabirds were recorded during 15-min periods (one 15-min count = one transect). Transects were made while the vessel proceeded on a constant course and heading. Ship speed during transects varied from 4.3 to 8.3 knots (6.3 to 15.3 km/h). Ship location and speed were recorded at the beginning and end of each transect. Transects were continuous and consecutive during counts across and along the front to increase spatial resolution of physical events and seabird concentrations.

All birds were counted out to a distance of 300 m from the observer within a 90° sector on the side of the ship with less sun glare. Distance was determined with a hand-held fixed-interval rangefinder made from a modified set of calipers (Heinemann 1981). Birds not in the transect zone of 300 m were counted but were not included in density estimates. Birds flying into the transect zone from the stern were excluded to avoid bias from individuals following the ship. One individual (Haney) did all of the counting.

Physical measurements.—For chlorophyll measurements, a Model 10-070 Turner Design flow-through fluorometer with infrared sensitive photomultiplier was used with a standard Blue lamp and 5–60 excitation/2–54 emission filter assembly specific for chlorophyll *a*

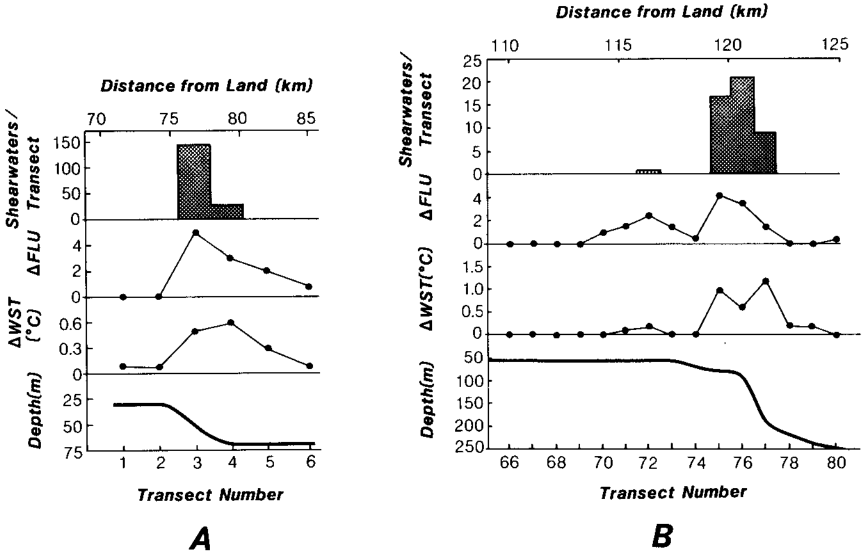

FIG. 2. Relationship of Cory's Shearwater abundance to environmental changes at Gulf Stream surface thermal front on 1 Oct. 1983 (A) and 13 July 1983 (B).

(Strickland and Parsons 1972). Seawater was obtained from a through-hull pumping system with intake at a depth of three m. Water was directed through a debubbler before it entered the fluorometer. Because all readings were made during daylight hours (0700–1500 EDT), no corrections are made for day–night changes in fluorescence to chlorophyll *a* ratios (cf. Kiefer 1973). Simultaneous temperature measurements were obtained with a towed Wheatstone bridge thermistor. Temperature and fluorescence measurements were recorded simultaneously on a Esterline-Angus MS-412B Mini–Servo chart recorder. Concurrent depth measurements were made with a SIMRAD EL fathometer set to two m sensitivity scale.

Data analyses.—Seven environmental variables were compared to an index of the abundance of Cory's Shearwaters (birds/transect). Depth (DEP) and change in depth (ΔDEP) were measured to the nearest two m for each transect. Distance from land (DFL) and distance from the Gulf Stream front (DFF) were measured to the nearest two km using NOAA Gulf Stream System Flow Charts obtained from infrared satellite data. The temperature of the water surface (WST) and change in water surface temperature (ΔWST) were measured to the nearest 0.1°C. Change in fluorescence (ΔFLU) was calculated to the nearest 0.1 relative fluorescence unit (Strickland and Parsons 1972).

Relationships among the seven environmental variables and between these variables and the abundance of Cory's Shearwaters were assessed with correlation analysis (r). The data were not transformed. The non-parametric Mann-Whitney U-test was used to test for significant differences between Cory's Shearwater abundance in near-front (<4 km from the front) and other transects (≥4 km from the front). For the purposes of this test the front was defined as that location with the highest change in water surface temperature (transect 77 on 13 July and transect 4 on 1 Oct.). Statistical significance was set at $P < 0.05$.

RESULTS

Cory's Shearwater was the dominant species of seabird recorded during the two cruises, constituting 82% of all seabirds seen on 13 July (N = 25

TABLE 2

CORRELATIONS OF THE ABUNDANCE OF CORY'S SHEARWATERS (BIRDS/TRANSECT) AND ENVIRONMENTAL VARIABLES MEASURED ON 13 JULY 1983 CRUISE TRACK (DF = 23)

Variable	*r*	*P*	$\bar{x} \pm$ SD	Range
DEP[a]	0.14	NS	144 ± 77	50–250
ΔDEP	−0.03	NS	12 ± 19	0–80
DFL	0.12	NS	115 ± 5	108–126
DFF	−0.46	<0.05	5.3 ± 3.8	0.0–16.0
WST	0.05	NS	27.8 ± 0.8	26.7–29.0
ΔWST	0.87	<0.001	0.2 ± 0.4	0.0–1.3
ΔFLU	0.54	<0.01	0.9 ± 1.2	0.0–4.2

[a] Abbreviations are explained in the text.

transects) and 98% of the total on 1 Oct. (N = 6) (Table 1). It was the only species exhibiting significant relationships to the Gulf Stream front.

Variance among counts of Cory's Shearwaters was high. Shearwater abundance varied from 0 to 24 birds/transect ($\bar{x}$ = 3, SD = 7, N = 25) on 13 July and from 0 to 146 birds/transect ($\bar{x}$ = 29, SD = 58, N = 6) on 1 Oct. Density varied from 0 to 42 birds/km^2 ($\bar{x}$ = 5, SD = 12, N = 25) on 13 July and 0 to 97 birds/km^2 ($\bar{x}$ = 19, SD = 39, N = 6) on 1 Oct.

On 13 July and 1 Oct., aggregations of Cory's Shearwaters occurred at or near the Gulf Stream surface thermal front where the changes in water surface temperature and fluorescence values were highest (Fig. 2). On 13 July, correlations of shearwater abundance to environmental variables were significant for distance from front, change in water surface temperature, and change in fluorescence (Table 2). These three variables ac-

TABLE 3

CORRELATION MATRIX OF ENVIRONMENTAL VARIABLES MEASURED DURING 13 JULY 1983 CRUISE TRACK[a]

Variable	DEP	ΔDEP	DFL	DFF	WST	ΔWST
ΔDEP[b]	0.25					
DFL	0.73***	0.44*				
DFF	−0.41*	−0.09	−0.39			
WST	0.81***	0.32	0.76***	0.01		
ΔWST	0.32	0.07	0.22	−0.40*	0.54**	
ΔFLU	−0.06	−0.14	−0.46*	−0.43*	−0.06	0.44*

[a] Significance levels indicated as follows: * ($P < 0.05$), ** ($P < 0.01$), *** ($P < 0.001$), df = 23.
[b] Abbreviations are explained in the text.

counted for 21%, 76%, and 29%, respectively, of the variance in shearwater abundance. On 1 Oct., shearwater abundance was significantly correlated only with change in fluorescence ($r = 0.873$, df $= 4$, $P < 0.05$), which accounted for 76% of the variance in shearwater abundance. Environmental changes associated with the Gulf Stream surface thermal front showed marked intercorrelations (Table 3).

Density along near-front transects averaged 14.9 birds/km^2 vs 0.7 birds/km^2 elsewhere on 13 July and 37.7 birds/km^2 vs 0.0 birds/km^2 elsewhere on 1 Oct. Average abundance (birds/transect) of Cory's Shearwater on 13 July in near-front transects was significantly higher than in other transects (9.5 vs 0.2; $P < 0.01$, Mann-Whitney U-test, N = 8, 17, $z = 3.82$). On 1 Oct., average shearwater abundance was higher than in other transects, but not at the 5% significance level (87.0 vs 0.0; $P < 0.07$, Mann-Whitney U-test, N = 2, 4, $z = 1.62$).

DISCUSSION

Elevated levels of biological activity at fronts have been observed previously (Pingree et al. 1974, Floodgate et al. 1981, Owen 1981, Vinogradov and Shushkina 1983), and we suggest that the association of Cory's Shearwaters with the Gulf Stream surface thermal front is due to enhanced food availability. The biology of *C. diomedea* and the circulation at Gulf Stream fronts are examined in an attempt to explain further this relationship.

Physical processes occurring at the fronts were visually striking on both dates counts were conducted. The Gulf Stream side was smooth while the shelf side had capillary waves. On both occasions winds were light (< 5 knots) and oriented alongshore from the south prior to and during the study periods. The cross-shelf dimensions of the fronts were <100 m at the surface. Current shear appears to account for the physical and biological phenomena observed.

Steady wind stress can produce three-dimensional circulation if the bottom topography contains a discontinuity in gradient (Hill and Johnson 1974). Such a discontinuity can be merely a 2.6 m/10 km change in depth across the shelf. This was evident at both shelf break locations (Fig. 2). Above the edge of the shelf a convergence shear front forms and vertical transport may occur over very small horizontal distances (Fig. 3). A sharp lateral current shear associated with the thermohaline mixing regime between Gulf Stream and outer-shelf water has been documented previously by remote sensing (Maul and Hansen 1972). The dynamics of such shelf break fronts have been discussed further by Csanady (1973), Mooers et al. (1976), and Garvine (1980).

Turbulence and vertical transport in shear fronts may entrain organisms

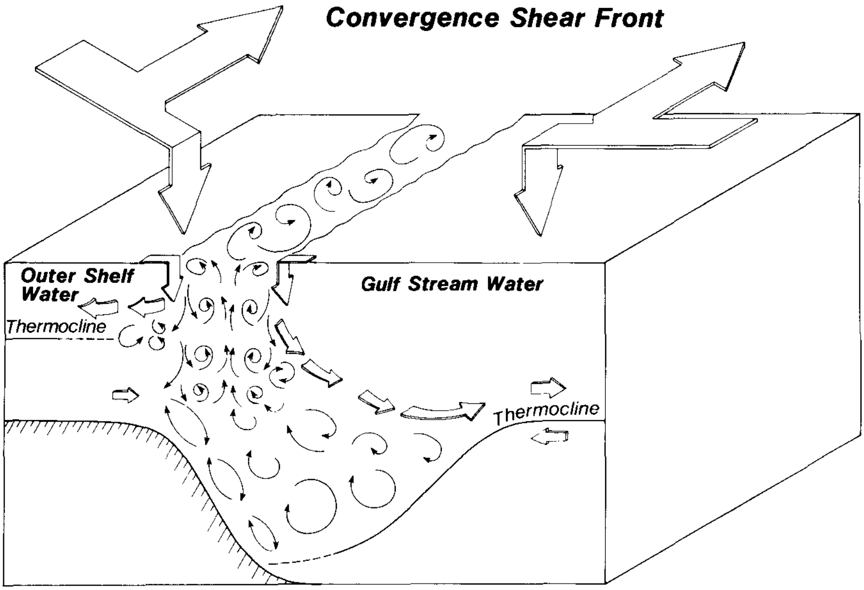

FIG. 3. Simplified representation of lateral convergence shear front at the continental shelf break. The width of the shear layer has been exaggerated to show the details of the circulation. The higher velocity of the Gulf Stream results in alongshelf turbulent dynamics that are not depicted. Typical thermocline depths are 25–40 m (outer shelf) and 75–100 m (Gulf Stream).

from depths where they would not normally be available to surface foragers. Organisms entrained from the thermocline (zooplankton, larval fish) may also be retained by the small-scale convergence zone at the shear front. Seabirds, including Cory's Shearwaters, may feed directly on the displaced organisms or on other consumers foraging at the site. The latter seems likely as Cory's Shearwaters feed mainly on actively swimming squid, crustaceans, and small fish (Clapp et al. 1982). Over half (56%) of the shearwaters observed on 13 July were sitting on the water surface, and many were submerging their heads or pecking at the surface.

Cory's Shearwaters are particularly dependent on features such as fronts that concentrate prey at the ocean surface. Unlike *Puffinus* shearwaters, *Calonectris* have long wings and weakly developed sterna, making them ill-suited for deep diving (Brown et al. 1978). Observations made on other dates (N = 55) and cruises (N = 13) in the South Atlantic Bight indicated that Cory's Shearwaters were most frequently encountered near the Gulf Stream front on the outer shelf. Shearwater abundance fell sharply when counts were continued either further offshore in the Gulf Stream or into more inshore waters. Cory's Shearwaters also continued to associate with the front during the 10–30 km east–west meanders of the Gulf Stream that occur every 2–14 days (Lee and Brooks 1979, Lee and Atkinson, 1983).

Relationships between Cory's Shearwater distribution and water-mass boundaries (fronts) have been reported by Pulich (1982), who found that Cory's Shearwaters were associated with the 35–36‰ salinity boundary in the western Gulf of Mexico but found no relationship between the occurrence of shearwaters and surface temperatures. Pulich suggested that the front at the western Gulf continental shelf break may have attracted the shearwaters along with schools of tuna and mackerel. These results, along with our data showing extended seasonal association, suggest that fronts may be important foraging areas for post- and nonbreeding Cory's Shearwaters in the western North Atlantic.

SUMMARY

The abundance of Cory's Shearwaters (*Calonectris diomedea*) in the South Atlantic Bight in July and Oct. 1983 was correlated significantly with environmental changes associated with Gulf Stream surface thermal fronts. Density of the species within 4 km of the front was 14.9–37.7 birds/km^2 vs. 0.0–0.7 birds/km^2 elsewhere ($\geq$4 km from the front). The average abundance (birds/transect) of Cory's Shearwaters on 13 July in near-front transects ($<$4 km) was significantly higher than in transects elsewhere ($P < 0.01$). The interactions of physical and biological processes that result in the association of Cory's Shearwaters with fronts are discussed.

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