COASTAL UPWELLING IN THE NORTHWESTERN GULF OF GUINEA

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ABSTRACT
Previous investigators have concluded that upwelling occurs in the northwestern Gulf of Guinea during the late northern summer months. Some investigators have qualitatively related the seasonal upwelling to average conditions in the wind field. A distinction is made in this paper between "wind-driven" and "current-induced" upwelling, and the role of each is delineated as it relates to the oceanic conditions in the northwestern Gulf of Guinea. Wind-driven upwelling is found to be a seasonal supplement to the current-induced upwelling that is present most of the time. The ecological significance of the two types of upwelling and of advection in superthermocline waters is discussed and its relation is shown to biological data obtained on three cruises of the R/V GERONIMO.

INTRODUCTION
Upwelling is one of several oceanic processes which are thought to have a significant effect on the distribution of pelagic fishes. It apparently influences distribution of fish by modifying environmental conditions to which the fish are sensitive and by increasing the nutrient content of the euphotic zone, which leads to increased productivity throughout the food web. The Tropical Atlantic Biological Laboratory (U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries) has completed three cruises to the northwestern Gulf of Guinea, during which its research vessel, the GERONIMO, investigated the relation between the distribution of tuna schools and seasonal upwelling believed to exist there. This report describes and interprets the resulting oceanographic observations which relate to upwelling.

THE AREA OF INVESTIGATION
The northwestern Gulf of Guinea (Fig. 1) is strongly influenced by general meteorological and oceanic conditions of the Gulf of Guinea and some unique local conditions.
TABLE 1

PERCENTAGE FREQUENCY OF ALL SOUTHWEST (OCTANT) WINDS AND THOSE IN THE 11- TO 16-KNOT AND 17- TO 27-KNOT RANGES IN THE NORTHWESTERN GULF OF GUINEA

(Data for winds from Publication No. 700, Part IV, U.S. Naval Oceanographic Office [1963] and from communication with that office)

<table>
<thead>
<tr>
<th></th>
<th>Cape Palmas</th>
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<th>Cape Three Points</th>
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<th>Bight of Benin</th>
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<tr>
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Meteorology.—Longhurst (1962), in a summary of climate in the Gulf of Guinea (5°S to 15°N), related the seasonal weather pattern to the movement of the intertropical convergence. When the convergence is in the northern portion of its range (northern summer), southwest winds predominate in the Gulf of Guinea and the area experiences frequent rainfall, with a maximum amount coincident with the passage of the convergence over a given area. When the convergence lies in the southern portion of its range (northern winter), northeast winds are prevalent near the coast and rainfall is light.

When the intertropical convergence lies well to the north of the northwestern Gulf of Guinea, the Coriolis parameter should produce a westerly wind component yielding southwest winds. A summary of sea surface wind data (Table 1), however, revealed that southwest winds were present in all months and their percentage frequency increased only slightly in July-September, when the convergence lay farthest north. Southwest winds are of particular significance in the region because they are the most effective in producing upwelling along the coast east of Cape Palmas and Cape Three Points, where the surface water is coolest during the late northern summer months.

Oceanography.—The eastward-flowing Guinea Current strongly influences the surface and near-surface waters of the northwestern Gulf of Guinea.
The current is an extension of the Equatorial Countercurrent and the Canary Current (Fig. 1), both of which contribute amounts of water that vary seasonally. Both currents appear stronger in the northern summer months; consequently the Guinea Current is stronger during that period also (Longhurst, 1962).

Variations of velocity of the Guinea Current apparently include reversals (from eastward to westward) near the coast. Longhurst (1962) stated that the frequency of reversal of the Guinea Current is probably determined by variations of the Equatorial Countercurrent, the Canary Current, and the flow of Benguela water into the Gulf of Guinea. He listed the tri-monthly frequency of reversals observed in the Cape Palmas–Cape Three Points area, on the basis of current charts of the British Meteorological Office. Donguy & Privé (1964) showed reversals in their computed geostrophic surface currents in the area off Abidjan in May–June and September–October, 1962. Boisvert (1967) showed the percentage frequency and average speed of the Guinea Current in three principal directions: NE, 16 per cent, 0.7 kt; E, 37 per cent, 0.9 kt; SE, 19 percent, 0.7 kt. All other directions (octants) were 5 per cent or less. He stated that: "The Guinea Current appears constant in direction except during December through February, when easterly winds reduce the speed and cause the current to become variable and at times to reverse; when reversed, the flow seldom exceeds 1 knot."

The data on which the concept of current reversals is based are either point observations or isolated sections perpendicular to the coastline. Such data do not provide a clear description of the reversals in the alongshore...
direction. Cyclonic eddies between the Guinea Current and the coast could yield the same point data or sections and be misinterpreted as current reversals. In fact, there is reason to expect the formation of such eddies downstream from Cape Palmas and Cape Three Points; therefore, the existence of current reversals must be considered hypothetical.

The southern boundary of the Guinea Current is a shear zone between it and the westward-flowing South Equatorial Current (Benguela Current, according to Boisvert, 1967). The position of the shear zone varies seasonally by about 100 miles. Boisvert (1967) gave the average seasonal position of the southern boundary on the 10°W meridian as 2.5°N in November-March, 4.0°N in April-June, and 3.5°N in July-October. Contours of current speed in the South Equatorial Current (U. S. Naval Oceanographic Office, 1965) between the equator and the shear zone showed that it was stronger during the July-October period, corresponding with the strongest period of the Guinea Current.

The Equatorial Undercurrent has been more extensively studied than other subsurface currents that influence the circulation of the Gulf of Guinea. This eastward-flowing current was found to extend into the Gulf as far as São Tomé (about 6°E) in February-April (Rinkel, Sund & Neumann, 1966). Donguy & Privé (1964) stated that the Equatorial Undercurrent does not extend eastward to the longitude of Abidjan (4°W), but one of the vertical salinity sections they published clearly indicated its presence at that longitude. Although the current does not directly enter the area of the present investigation, the high-salinity water it transports may spread throughout the region between the equator and the African zonal coastline.

The spreading of Equatorial Undercurrent water in the northern Gulf of Guinea may be accomplished in part by the westward-flowing Guinea Undercurrent. Smith (1966) concluded that the Guinea Undercurrent was present in October 1963, between 2° and 3°N, on the basis of the distribution of high salinities on the 250 cl/ton surface. He favored the eastern South Atlantic as the source of the high-salinity water in the current, but suggested the Equatorial Undercurrent as an alternate source.

Little is known about other subsurface currents in the northwestern Gulf of Guinea. Donguy & Privé (1964) described a general reversal of current direction, from eastward to westward, at about 100 m between Abidjan and the equator; they computed the westward currents at less than 20 cm/sec between 100 m and 300 m.

Water Masses.—The water masses present in the upper 700 or 800 m in the northwestern Gulf of Guinea are Tropical Surface Water (superthermocline water, upper 50 m or so) and South Atlantic Central Water (defined by a temperature-salinity regression, 50-800 m). Berrit (1961) subdivided
the Tropical Surface Water into “categories” based on sea surface temperature and salinity ranges as follows: Guinean Water (> 24°C, < 35‰); Tropical Water (> 24°C, > 35‰); Benguelan or Canary Water (< 24°C, > 35‰); and an unnamed category (< 24°C, < 35‰). According to Berrit, Guinean Water is formed in amounts that vary seasonally, principally off Liberia and in the northeastern Gulf of Guinea (Bay of Biafra). Tropical Water is formed in the open sea in the intertropical zone. Benguelan or Canary waters are advected (beneath the surface) into the Gulf of Guinea from their respective formational zones to the south and north of the limits of the Tropical Water body. The unnamed category of water was believed by Berrit (1961) to have been formed from the mixing of Sassandra River runoff with cool, saline, surface waters (assumedly upwelled) in the immediate area. The unnamed category was found by Berrit only in the Cape Three Points–Cape Palmas area and for short periods only, during July-September.

Upwelling

The term “upwelling” is commonly used to describe a wide variety of conditions involving upward transport of water in the sea, and frequently is misused in describing effects of the process, rather than the process itself. Various explicit and implicit definitions have been published. Smith (1964) surveyed the literature on upwelling and suggested the following definition as the most acceptable: “An ascending motion of some minimum duration and extent by which water from subsurface layers is brought into the surface layer and is removed from the area of upwelling by horizontal flow.”

In the northwestern Gulf of Guinea, conditions which may be interpreted as evidence of coastal upwelling could be produced by either one of two processes, or by both. These processes are: (1) the rise of water toward the surface to replace locally wind-driven offshore transport, and (2) the inclination of the field of mass in geostrophic adjustment to the eastward-flowing Guinea Current. In this paper, I distinguish between the two processes by the use of the terms “wind-driven” and “current-induced” with the term “upwelling.” The vertical transports produced by the two processes differ significantly. Wind-driven upwelling requires continuous vertical transport, as long as the appropriate wind component exists. Conversely, current-induced upwelling requires no vertical transport (theoretically) once geostrophic balance has been established with a current parallel to the coastline. In the real ocean, however, true geostrophic balance is never realized, because molecular and eddy viscosity lead to cross-isobar flow with an upwelling component. The resolution of the role of each process (wind-driven and current-induced upwelling) in producing the observed oceanic conditions is one of the goals of this study.
Evidence of coastal upwelling—which might be expected in the northwestern Gulf of Guinea—would be the occurrence of cooler, more saline water containing less dissolved oxygen and more dissolved phosphate than are usually found at a given depth. On a plot of one of these variables at constant depth, such evidence would appear as onshore-offshore gradients of the variable, with the unusual values near shore. The salinity criterion specified above becomes ambiguous if the water is transported from a depth greater than that of the salinity maximum (Fig. 2), but temperature can be used to help resolve such cases because its vertical distribution is essentially monotonic. The concentrations of oxygen and phosphate are not reliable indicators of upwelling near the surface of the sea, because, once there, the concentrations are subject to rapid modification by biological processes.
FIGURE 3. Cruise tracks and time periods of portions of R/V GERONIMO cruises 3, 4, and 5 (Tuna Surveys 1, 3, 4, and 6) in the northwestern Gulf of Guinea. Dots designate BT stations; crosses are hydrographic stations. Arrows signify general directions in which the tracks were run.
**OBSERVATIONS**

Portions of cruises 3, 4, and 5 of the R/V GERONIMO were conducted in the northwestern Gulf of Guinea. The positions of the stations and the time periods of the portions of those cruises selected for this study (tuna surveys 1, 3, 4, and 6) are shown in Figure 3. Figures 3-5 and 7-15 have been taken from atlases of oceanic conditions, which were prepared for the tuna survey portions of each of these cruises (Goulet & Ingham, 1968; Ingham, Goulet & Brucks, 1968; Brucks, Ingham & Leming, 1968). Tuna surveys (TS) 1 and 6 were conducted in the “warm season” (10-21 February 1964, and 14-23 March 1965), and TS 3 and 4 in the “cool season” (5-23 August and 26 September–13 October 1964); the terms for seasons refer to sea-surface temperatures (Berrit, 1962).

Evidence of coastal upwelling on the sea surface was found in the eastern half of TS 3 and the western half of TS 4 (Figs. 4 and 5). On TS 3, appropriate onshore-offshore gradients of temperature and salinity were present, but on TS 4 only the temperature distribution indicated upwelling.

The observed body of low-salinity, cool surface water in the western half of TS 4 (Figs. 4 and 5) probably was the result of advection of mixed effluent from the Sierra Leone–Liberia area into an area of upwelling southeast of Cape Palmas. The following observations support this contention:

1. The coastal rivers of Liberia, Sierra Leone, and western Ivory Coast are relatively short, with steep gradients draining the highlands (500-1,000 m) of the Nimba and Loma mountains. Jackson (1961) showed average minimum air temperatures at stations in the highlands as low as 20°C in September. The coastal rivers, therefore, could transport cool water rapidly to the sea in periods of high runoff.

2. The period of heaviest rainfall (and maximum runoff) in the watershed is July–October; about 300-400 mm of rain falls each month in the period. A report of the hydrology of 10 Liberian rivers for April 1960 through March 1961 (Stanley Engineering Company of Africa, 1961) showed the maximum daily discharge rates—ranging individually from 433 to 82,400 ft³/sec (12 to 2333 m³/sec)—between 19 August and 26 September.

3. The salinity distribution (Fig. 5) and the topography of the 34.8‰ isohaline surface, arbitrarily taken as the lower limit of the mixed effluent (Fig. 6), showed that the lowest salinities and the greatest thickness of the low-salinity lens extended eastward from a region about 30 to 50 miles off Cape Palmas. This finding indicated that the mixed effluent either was advected from the Liberia–Sierra Leone area or (less likely) flowed southwest from the Sassandra River before being caught up in the Guinea Current.
FIGURE 4. Temperatures (in °C) at the surface of the sea (0-3 m) in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
FIGURE 5. Sea-surface salinities (in ‰) in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
4. The sea-surface temperature distribution (Fig. 4) showed the lowest temperatures (< 20°C) near the coast east of Cape Palmas to be not in correspondence with the lowest salinities—an indication of probable upwelling, also.

The water categories (Berrit, 1961) present on the sea surface during TS 1, 3, 4, and 6 were as follows:

- **TS 1**                                Guinean Water
- **TS 3, western half**                   Guinean Water
- **TS 3, eastern half**                   Benguelan or Canary Water (upwelled)
- **TS 4, western half**                   unnamed category
- **TS 4, eastern half**                   Guinean Water
- **TS 6, nearshore**                      Tropical Water
- **TS 6, offshore**                       Guinean Water

The category present in the eastern half of TS 3 (in the upwelling area) probably was Canary Water rather than Benguelan Water, since the prevailing surface currents are from the west and northwest (Boisvert, 1967; U. S. Naval Oceanographic Office, 1965). The thermocline topography (Fig. 8) suggests currents from the west during the survey.

The distributions of temperature and salinity on the 20-m surface lead to a different conclusion regarding coastal upwelling. The temperature distributions (Fig. 7) showed strong onshore-offshore gradients in TS 1, 3, and 4, but weak ones in TS 6. The difference in temperature across the gradient was about the same (5 to 7°C) on TS 1, 3, and 4, but the temperatures were about 5° higher in TS 1. Thermocline topographies (Fig. 8) showed well-defined slopes for TS 1, 3, and 4, but no regular slope for TS 6. The horizontal temperature gradients seen on the 20-m surface in TS 1, 3, and 4, therefore, were traces of the intersection of the thermocline with the 20-m surface.

The distribution of salinity on the 20-m surface (Fig. 9) showed an onshore-offshore gradient and higher salinities nearshore in each survey.
FIGURE 7. Temperatures (in °C) at the 20-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
FIGURE 8. Depth (in m) of the thermocline in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
FIGURE 9. Salinities (in %o) at the 20-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
Figure 10. Concentrations (in ml/l) of dissolved oxygen at the 20-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
FIGURE 11. Concentrations (in μg-at/1) of dissolved phosphate at the 20-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
Closely paralleling the distribution of temperature, the highest salinities (> 35.8\%\(\text{o}\)) and strongest gradients were found during TS 3 and 4, and the weakest gradients during TS 6.

Coastal upwelling during TS 1, 3, and 4 was shown clearly by the distributions of temperature and salinity on the 20-m surface. Although other variables were less reliable indicators, additional evidence of upwelling was found in distributions of dissolved oxygen and phosphate (Figs. 10 and 11). Onshore-offshore gradients, with lower oxygen and higher phosphate values nearshore, were present during TS 3 and 4. In the western half of TS 4, there were unusually low oxygen and high phosphate concentrations. Such anomalous values could not have been the result of upwelling, because observed temperatures were not commensurate with those of the deeper water (at about 200 m) which ordinarily contains equally low oxygen and high phosphate concentrations. The anomalous concentrations probably were the result of the sinking of particulate organic material from the mixed effluent found near the surface. This contention is substantiated by entries in the personal log of the field-party chief of the cruise (personal communication, John W. Van Landingham, Physical Scientist, Tropical Atlantic Biological Laboratory, Miami, Florida, July 1968), which described large areas of turbid water containing blooms of phytoplankton.

The distributions of properties on the 50-m surface showed a decrease in the strength of horizontal gradients (therefore in the inclinations of water strata) associated with upwelling. Temperature gradients on the 50-m surface (Fig. 12) had the same direction as those on the 20-m surface, but magnitude was reduced to differences of about 2\(\text{\textdegree}\) instead of 5\(\text{\textdegree}\) across the gradient. Weak salinity gradients were found in the western half of TS 3 and in TS 6 (Fig. 13). The lack of well-defined gradients was due partly to the salinity maximum layer near the 50-m surface. Onshore-offshore gradients of oxygen concentration, with lower values nearshore, were found in each survey (Fig. 14), but they were weak and poorly defined in TS 1. Gradients of dissolved phosphate, directed oppositely to the oxygen gradients, were found in TS 3, 4, and 6 (Fig. 15). Generally the oxygen gradients were better defined than those of phosphate.

At the 100-m depth, no significant onshore-offshore gradients of temperature, salinity, oxygen, or phosphate appeared, which indicates that the limit of influence of upwelling lay somewhere between depths of 50 and 100 m.

Relative Roles of Wind-Driven and Current-Induced Upwelling

The cooler surface water generally found near the coast in the northwestern Gulf of Guinea during the late northern summer was attributed to upwelling by Janke (1920), Varlet (1960), Berrit (1962), Longhurst
FIGURE 12. Temperatures (in °C) at the 50-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
Figure 13. Salinities (in ‰) at the 50-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
Figure 14. Concentrations (in ml/l) of dissolved oxygen at the 50-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
FIGURE 15. Concentrations (in µg-at/l) of dissolved phosphate at the 50-meter depth in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6.
(1962), and Donguy & Privé (1964). If the conditions in the upper 50-100 m of the sea during TS 1, 3, and 4 were the result of wind-driven upwelling, correlation of the distributions of oceanic properties with the observed wind field should have been possible. If wind observations collected at the same time as the oceanic observations are used to determine the role of wind-driven upwelling, the tacit assumption is that the response time of the upper layers of the ocean to changes in the wind field is short. Some recent research by Smith, Pattullo & Lane (1966) clearly demonstrated the truth of the assumption. They described a section of stations off the Oregon coast—before and after the onset of upwelling winds—in which they found coastal upwelling established to depths of about 50 m after only 76 hours. Their research also demonstrated agreement between upwelling velocities calculated from the change in depth of isopycnic surfaces (2 × 10^{-4} cm/sec offshore, to 70 × 10^{-4} cm/sec nearshore) and those calculated from wind data by using Yoshida’s (1955) equation (1 × 10^{-4} cm/sec offshore, to 85 × 10^{-4} cm/sec nearshore).

To test the hypothesis that wind-driven upwelling was responsible for the oceanic conditions observed in the northwestern Gulf of Guinea, I computed the upwelling velocity from the wind data acquired at about 400 stations on TS 1, 3, 4, and 6. The computed upwelling velocities were plotted and contoured (Fig. 16) for comparison with the fields of temperature and salinity. Yoshida’s equation (Yoshida, 1955; Smith, Pattullo & Lane, 1966) was used for the computation of upwelling velocity:

\[ W = \frac{k}{\rho f} \tau_x e^{-ky} \]

and

\[ k = f \left( gh \frac{\Delta \rho}{\rho} \right)^{-\frac{1}{\gamma}} \]

where \( W \) is the upwelling velocity, \( f \) is the Coriolis parameter, \( \rho \) is the density of the layer of water involved in the upwelling, \( \Delta \rho \) is the density difference between the layer involved in the upwelling and the layer beneath it, \( h \) is the thickness of the layer involved, \( \tau_x \) is the wind stress component parallel to the local coastline (\( \tau = \rho_{air} C_d |\vec{U}| \vec{U} \), \( C_d = \) drag coefficient = 2.6 × 10^{-3} ) taken positive for westerly winds, and \( y \) is the distance offshore perpendicular to the local coastline.

Comparison of the distributions of computed velocities of upwelling (Fig. 16) with the distributions of sea-surface temperatures (Fig. 4) revealed approximate correspondence of onshore-offshore gradient areas with upwelling velocities of about 10^{-3} cm/sec or greater, and of non-gradient areas with upwelling velocities of about 10^{-4} cm/sec, or less. The one major exception to the correspondence was in the eastern half of TS 4, where a non-
FIGURE 16. Computed velocities (in cm/sec) of upwelling in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6. Negative values indicate downwelling.
gradient temperature field corresponded with a comparatively large area of upwelling velocity greater than $10^{-3}$ cm/sec.

A similar general correspondence was found when the distributions of upwelling velocity (Fig. 16) were compared with those of temperature on the 20-m surface (Fig. 7). The correspondence broke down, however, in two subareas of TS 1 and TS 3, in which strong horizontal gradients of temperature were present, but upwelling velocities ranged from $10^{-4}$ cm/sec to zero, and below to negative (downwelling) values.

The general correspondence between the areas of temperature gradients on the zero and 20-m surfaces, and the larger computed upwelling velocities indicated that wind-driven upwelling had a part in producing the observed inclination in the temperature field. To obtain an estimate of the magnitude of the contributions of wind-driven and current-induced upwelling to the production of the observed gradients, I computed geostrophic velocities of surface currents (relative to the 100-db surface) for TS 3 and TS 4. Any increase in the inclination of the field of mass because of wind-driven upwelling would produce a corresponding increase in computed speeds of geostrophic currents. Such an increase would be either real or apparent, depending on the variation of the wind field and the time required for equilibrium to develop. One would expect the computed speeds of the alongshore (eastward) current to increase eastward into the upwelling area from the longitude of Cape Palmas and shoreward, but the distributions of computed velocities that I obtained (Fig. 17) did not reveal a pattern of increase. Unfortunately, the quality of the data—particularly those obtained from poorly planned casts at the inshore stations—may have been variable enough to conceal the expected increase in velocity.

Since the strength and frequency of the upwelling wind vary seasonally, as does wind-driven upwelling in the northwestern Gulf of Guinea, data on average surface currents by season should show the pattern of eastward and shoreward acceleration. The seasonal portrayal of surface currents shown in U. S. Naval Oceanographic Office publication No. 700 (1965; reproduced in Fig. 18) revealed the expected pattern in July-September: surface-current speeds increased from about 1.0 kt (50 cm/sec) off Cape Palmas, where the Guinea Current enters the upwelling zone, to speeds of more than 1.7 kt (85 cm/sec) nearshore off Abidjan. In the opposite season, January-March, no such increase was evident. In each period, the average speed of the Guinea Current off Cape Palmas, between the cape and 3°N latitude, was about the same—1.1 kt (55 cm/sec). The increase in speed caused by geostrophic adjustment to wind-driven upwelling was in the magnitude of 0.5 kt (25 cm/sec). Estimates of the change in the inclination of the field of mass associated with the increase in velocity would be about $2.6 \times 10^{-7}$—for example, from $5.1 \times 10^{-7}$ at 50 cm/sec to $7.7 \times$
10^{-2}$ at 75 cm/sec. When Margules' equation and relevant values for density and latitude are used, the computed change in the inclination of the density discontinuity surface (thermocline) for the same increase in velocity is from $2.67 \times 10^{-4}$ to $4.01 \times 10^{-4}$. For an onshore-offshore transect of $10^5$ m (about 0.9° latitude), these slopes would elevate the thermocline at the nearshore end above the level at the offshore end by about 27 and 40 m for current speeds of 50 and 75 cm/sec, respectively. The computed elevations are in good agreement with onshore-offshore differences in depth of the thermocline (Fig. 8) observed during TS 1 (no wind-driven upwelling) and TS 3 and 4 (wind-driven upwelling).

The difference in elevation of the thermocline can be used as a quantitative estimate of the relative effects of wind-driven and current-induced upwelling on the thermal environment. In the late summer when the wind component of upwelling is strongest and most frequent, an elevation of the thermocline at nearshore stations of about 15 m may be expected, in addition to the norm of 25 m or so caused by the Guinea Current. The rise of the cold thermocline water to the sea surface in late summer was judged by early investigators to be the only indication of upwelling.

In summary, the wind-driven upwelling in the northwestern Gulf of Guinea is a seasonal (July-October) supplement to the current-induced up-
welling which is present most of the year, and it increases the slope of the field of mass by about 50 per cent.

**ECOLOGICAL CONSIDERATIONS**

If the thermocline is the lower boundary of the principal environment of adult surface-schooling tunas, the volume of water available to the fish in the northwestern Gulf of Guinea is a thin wedge of variable composition (Fig. 19). During TS 1, 3, and 4, the shoreward edge of the wedge was less than 10 m thick; the seaward edge was about 20 m thick during TS 1, and 30 to more than 40 m thick during TS 3 and 4. Throughout TS 6, the wedge had no regular slope; it could be described as a slab, with an average thickness of about 20 m.

The highly variable conditions in the wedge of superthermocline water were modified by: (1) advection of various categories of water into the wedge by surface currents, (2) upwelling and mixing of thermocline water into the wedge, and (3) tilting of the thermocline near the sea surface, which caused a thinning of the wedge.

The presence of four markedly different categories of surface water (Guinean, Tropical, Canary, and mixed effluent) in the wedge during the survey attests to the efficacy of advection in modifying it. Advection pro-
duced variations of about 5 degrees in temperature (24°-29°C); 2.6‰ in salinity (33.2‰ to 35.8‰); 2.8 ml/1 in oxygen concentration (2.0-4.8 ml/1); and 1.0 µg-at/l in phosphate concentration (0.2-1.2 µg-at/l).

Advection yields broad, ill-defined zones of enrichment and increased production, except in situations where radically different, nutrient-rich bodies of water are advected. Such a body of water was the mixed effluent, well defined in terms of salinity, that was present in the western half of TS 4 (Figs. 5 and 6). The effluent corresponded with low oxygen and high phosphate concentrations at the 20-m surface (Figs. 10 and 11), higher zooplanktonic standing stock in the surface layer (Fig. 20), and a greater concentration of tuna schools (Fig. 21)—33 schools in the western half of TS 4, against 17 in the eastern half, and 15 in the western half during TS 3. The implication of these conditions is clear. Increased primary and secondary production in the mixed effluent led to the concentration of tuna schools.

Wind-driven upwelling influenced conditions in the wedge in the eastern portion of TS 3 and to a lesser extent in the western portion of TS 4. In the former area, the wedge was thinned and thermocline water was mixed into it, as evidenced by the wide separation on the sea surface of isotherms usually closely packed in the thermocline (Fig. 4). The increase in nutrient content of the euphotic zone, which resulted from the introduction of thermocline water, apparently led to increases in primary and secondary production (Fig. 20), and should have led to an eventual increase in the abundance of forage for tunas and other pelagic predators. Increases in
FIGURE 20. Zooplanktonic standing stocks (in ml/1000 m$^3$) in the surface layer of the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6. (From Mahnken, Jossi & McCabe, 1969.)
FIGURE 21. Tuna schools seen or sampled in the northwestern Gulf of Guinea during Tuna Surveys 1, 3, 4, and 6. (□ = skipjack; ◊ = yellowfin; ▽ = little tuna.)
nektonic forage, however, generally follow the upwelling in time, and are displaced from it in space. If the time required for the increase in forage concentrated by zooplanktonic blooms resulting from upwelling is estimated at about 30 days (based on estimated and measured values of reproduction and succession in temperate-zone environments as cited by Moore [1958]), and if 0.9 kt is assumed as the average rate of flow of upwelled water eastward (Boisvert, 1967), then forage concentration resulting from the upwelling would be about 650 nautical miles east of the site of upwelling. Unfortunately, this concept of downstream displacement did not enter into the planning of the tuna surveys. The association of distribution of fish schools with zones of upwelling, therefore, could not be made with the acquired data—if productivity initiated by upwelling is the basis of the association.

Upwelling can concentrate tuna schools in another way—by producing a zone of abrupt transition (front) between normal surface water and upwelled water. Because of the convergence involved in the formation of fronts, they become concentrating mechanisms for plankton and floating detritus which, in turn, leads to the concentration of nektonic forage. The abrupt temperature gradients of fronts may also serve as physiological barriers for surface-schooling tunas. Only one front generated by upwelling was observed during the tuna surveys; it was close to the coast in the western half of TS 4. The front was so near shore that we could not determine whether it was a factor in concentrating schools of tuna. In the eastern half of TS 3, the surface zone of transition around the upwelling area did not contain gradients steep enough to constitute a front. Apparently, intensity was lacking or upwelling was not recent.

Current-induced upwelling, present throughout TS 1, 3, and 4, modifies the superthermocline environment by reducing its thickness and by drawing up nutrient-rich water into the euphotic zone. In contrast with wind-driven upwelling, no continuing upward flow of water is involved, theoretically, in current-induced upwelling after geostrophic balance has been established. Consequently there would be no continuing vertical transport of nutrients. In fact, a cross-isobar flow exists in geostrophic balance, but that flow would be considerably weaker than the one involved in wind-driven upwelling. Wyrtki (1961) estimated flow through the thermocline at 1 to $5 \times 10^{-5}$ cm/sec. Assuming that his values represent cross-isobar flow, wind-driven upwelling apparently yields vertical flow rates, as computed in the present study, 100 to 1000 times as great.

Another, more important, source of nutrient renewal is produced by current-induced upwelling. The currents involved continuously advect water that may be rich in nutrients into the region of upwelling and the euphotic zone. This advection may create a nutrient "conveyor belt" on which pri-
mary production occurs wherever the belt is shallow enough to receive sufficient illumination. The nutrient renewal so provided depends on the recent history of water entering the region of upwelling—if, for example, the water recently passed through a euphotic zone elsewhere, it would not be rich in nutrients but would carry plankton instead.

A promising association was found in TS 4 between distribution of tuna schools and the mixed effluent, but in the remaining surveys the relations between distributions of tuna schools and oceanic conditions were not as straightforward. No concentrations of tuna schools were found in TS 1 and 3. Current-induced upwelling was present in both surveys, but concentrations of zooplankton were relatively low except near the eastern edge of each survey area, probably as a consequence of the time lag between upwelling and secondary production. Accordingly, the associated concentration of forage nekton and tuna schools could be expected even farther to the east.

During TS 6, tuna schools were concentrated throughout the survey area. Attempts to explain the concentration from likely oceanic structures were futile. No upwelling was found; the superthermocline layer was occupied principally by Tropical Water with relatively high temperatures (28° to 29°C), oceanic salinities (34.6‰ to 35.4‰), low concentrations of dissolved phosphate at 20 m, and low values of zooplanktonic standing stock (Figs. 4, 5, 11, and 20). All these characteristics suggested an unproductive area, but the concentration of tuna schools was greater than in the other three surveys. The cruise report for TS 6 stated that the tuna schools were apparently migrating through the area toward the west; the fish did not linger, possibly because of unfavorable forage conditions.

Any future attempts to relate distribution of tuna to oceanic conditions in the northwestern Gulf of Guinea must overcome three major shortcomings of the 1964-65 surveys: First, the cruise track must be extensive enough to accommodate the displacement between upwelling and the resultant increases in secondary production and forage animals; second, the surveys must extend well beyond the concentrations of tuna schools, if relevant factors in their distribution are to be determined; and third, some means must be developed for assessing the distribution of forage nekton, which is probably the most significant factor in the distribution of tuna schools.

**SUMARIO**

**REVOLTURA COSTERA EN EL NOROESTE DEL GOLFO DE GUINEA**

La parte noroeste del Golfo de Guinea ha sido reconocida por muchos años como el lugar de la revoltura costera estacional. Algunos investigadores han tratado de relacionar cualitativamente la revoltura con variaciones en los vientos del oeste y sudoeste.
En el presente estudio, se encontró que la revoltura en el noroeste del Golfo de Guinea incluye dos componentes designados como “impelidos por el viento” e “inducidos por la corriente” (ajuste baroclínico del campo de masa). La revoltura a causa del viento se encontró que era un suplemento estacional (Julio-Octubre) de la revoltura inducida por la corriente, que está presente la mayor parte del tiempo. La magnitud del flujo ascendente en la revoltura inducida por la corriente ha sido estimada en $10^{-5}$ cm/sec (Wyrtki, 1961); el flujo ascendente en la revoltura impelida por el viento fue computado en este estudio (de datos sinópticos para vientos) como de $10^{-3}$ a $10^{-2}$ cm/sec. Areas de velocidad de revoltura computada igual a o mayor que $10^{-3}$ cm/sec, generalmente correspondieron a una evidencia hidrográfica de revoltura. La inclinación del campo de masa asociado con revoltura inducida por la corriente fue alrededor de $5.1 \times 10^{-7}$ y con revoltura impelida por el viento fue una cantidad adicional de alrededor de $2.6 \times 10^{-7}$.

Las inclinaciones correspondientes de la capa de descontinuidad de la densidad (termoclina) fueron $2.7 \times 10^{-4}$ y una adicional de $1.3 \times 10^{-4}$, dando elevaciones de la termoclina de 27 m y 13 m adicionales respectivamente para una sección de 105 m de largo, perpendicular a la dirección de las corrientes a lo largo de la costa. Estas elevaciones concuerdan bien con topografías termoclínicas observadas en viajes del barco de investigaciones Geronimo en el noroeste del Golfo de Guinea.

Tres procesos influyen el ambiente de supertermoclina, la productividad y la distribución de tunas que forman cardúmenes superficiales en el noroeste del Golfo de Guinea: la revoltura inducida por la corriente, la revoltura impelida por el viento y la advección. De estos, la advección fue el más efectivo en el período estudiado (viajes 3, 4 y 5 del GERONIMO en Febrero 1964, Agosto-Octubre 1964 y Marzo 1965, respectivamente). La revoltura impelida por el viento que estuvo presente en partes del viaje 4 del GERONIMO, aparentemente influyó en las concentraciones zooplanctónicas, pero no en la distribución de los cardúmenes de tunas—probablemente por la demora en tiempo y desplazamiento en espacio entre la revoltura de nutrientes y el aumento resultante en el forraje de tuna. La revoltura inducida por la corriente ocurrió durante los viajes 3 y 4 del GERONIMO, como se manifestó por la inclinación de la termoclina, pero sus efectos en la productividad y en la distribución de cardúmenes de tunas no fueron aparentes en los datos biológicos.

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