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THE CHEMICAL AND BIOLOGICAL EFFECT OF A GULF STREAM INTRUSION OFF ST. AUGUSTINE, FLORIDA

Larry P. Atkinson, Gustav-Adolf Paffenhöfer, and William M. Dunstan

ABSTRACT

During a 3-day anchor station in shelf waters off St. Augustine, Florida we observed the effect of an intruding mass of deeper Gulf Stream water. The shelf waters were relatively low in nutrients and salinity while the Gulf Stream waters were high in salinity and nutrients. Onshore currents correlated with increases in nitrate and chlorophyll concentrations.

The advection of higher nutrient Gulf Stream water coincided with high chlorophyll ($\sim$ mg chl a m^{-3}) concentrations and dense populations of *Phaeocystis pouchetii* (up to $3.12 \times 10^6 1^{-1}$). Zooplankton sampling was impossible in the bottom layer because of the dense *Phaeocystis* bloom. The dominant zooplankton in the upper layer was the doliolid *Dolioletta gegenbauri f. tritonis*. Concentrations reached 1561 m^{-3}.

The intrusion of cold, deeper, nutrient-rich Gulf Stream water onto the continental shelf off the southeastern United States was recognized over 38 years ago by anomalous nearshore temperatures in the summer (Green, 1944). Later Taylor and Stewart (1959) hypothesized that the process is wind dependent and occurs predominantly in July, August, and early September. More recent data indicate that deep, nutrient-rich waters advect onto the shelf many times during the year; although the nearshore effect, as expressed by temperature anomalies may be seen only in July, August, or September. It is also becoming evident that these intrusions supply a significant amount of nutrients relative to land runoff and are a major factor controlling phytoplankton production (Dunstan and Atkinson, 1976). By intrusions we refer to the advective movements of deeper, cold Gulf Stream water into the shelf waters. Although the advection can be forced by wind, eddies, meanders, or density motions, the result is the same. Intrusions were reviewed by Bumpus (1973) and by Blanton (1971).

To determine the short-term effects of an intruding water mass, a series of stations were occupied to determine the horizontal and vertical distribution of associated chemical, physical, and biological properties. This was followed by an anchor station to observe the local time change in these properties. The anchor station was in 38 m of water at a point (by chance) through which the higher nutrient water appeared with a tidal frequency.

This paper describes the hydrographic conditions before and after the anchor station, followed by hydrographic data taken during the anchor station. The hydrographic data are discussed in detail because interpretation of the biological data depends on knowledge of the resident water mass. The biological observations are then discussed.

METHODS

Choice of Area and Observational Plan

From experience we knew that intrusion features could be expected off the Florida shelf during the early spring and that the weather would be moderate. Considering these factors we established an anchor station off St. Augustine, Florida, at a depth of 38 m (Fig. 1, Station 7). Before occupying this station, we ran a small grid of stations (pre-anchor station observations) to determine the spatial distribution of properties. The anchor station was then
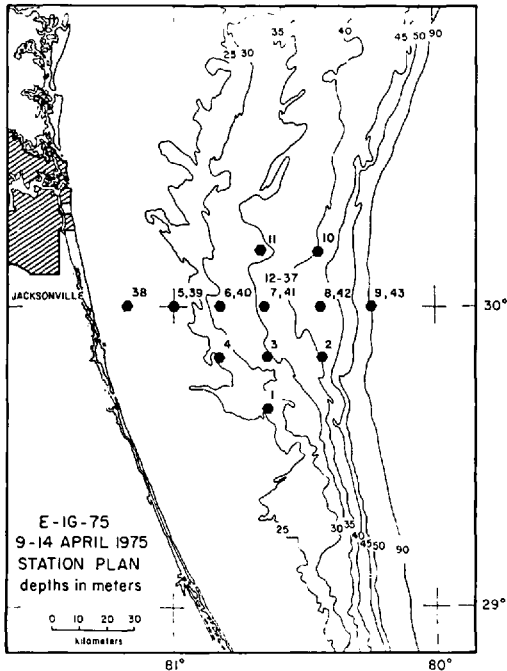
Figure 1. Study area off the Florida coast. Numbers adjacent to station locations refer to station number.

occupied for 3 days followed by an onshore-offshore section (Stations 38–43) through the previous anchor station.

Surface Current

Surface currents (5 m) were continuously recorded with a Bendix Q-15 ducted impeller current meter while the ship was at anchor. A second Q-15 was placed at 25 m but, unfortunately, it repeatedly tangled in the anchor line and had to be retrieved. Data was collected onboard continuously on a Rustrak recorder. Ship's yawing was noticeable in the recording and for purposes of analysis the velocity every 15 min was determined by hand smoothing.

Water Sample Casts

Standard 1.7- and 5-l Niskin bottles were used for the bottle casts. The placement of the bottles was determined by the vertical

structure observed in the STD cast with emphasis on the lower layer.

CSTD

Prior to bottle casts, a CSTD profile was taken with an Interocean CSTD probe. The data were analog recorded and digitally printed. The CSTD was calibrated for salinity and temperature against the near bottom sample from the subsequent bottle cast.

Nutrients

Phosphate and silicate were determined using standard methods (Strickland and Parsons, 1972). Nitrate was determined using an improved cadmium wire reduction technique (Gardner et al., 1975).

Data Storage

All of the basic hydrographic data are available from the National Oceanographic Data Center (request EASTWARD Cruise E-1G-75). All of the data appear in a technical report (Atkinson et al., 1977).

Zooplankton Sampling

Zooplankton were collected with a cylinder-cone net of 50-cm mouth-diameter and 253-μm mesh. The filtering to mouth area ratio was 8:1. The front of the net was held in a wide frame to decrease net avoidance by zooplankton. A TSK-flowmeter was placed in and outside the net mouth to determine the amount of water filtered. The inside flowmeter reading was always within 85% of that of the outside flowmeter (Smith et al., 1968) indicating clogging did not occur.

All zooplankton tows were taken at the anchor station. Each tow was oblique (surface to 10–12 m depth to surface). The speed of the current along the boat ranged from 0.4 to 1.2 knots. The volume of seawater filtered varied from 3.5 to 21.2 m^3.

The samples were immediately preserved in 2 to 3% buffered formaldehyde and within
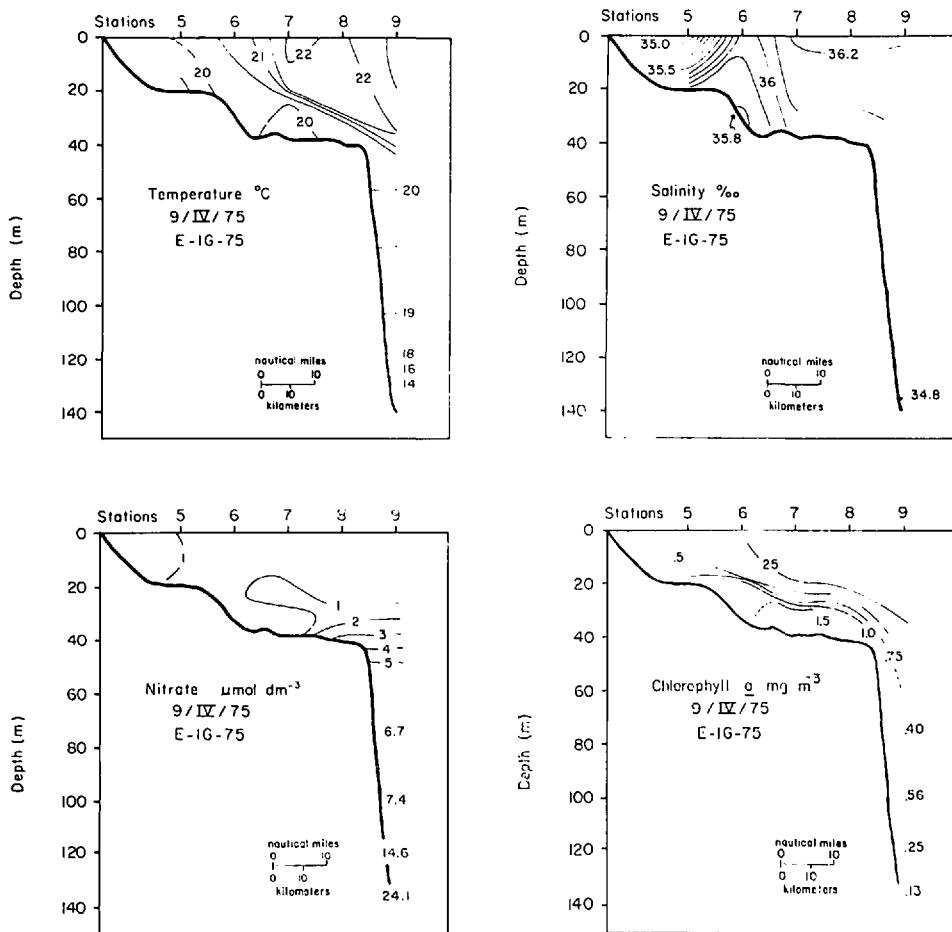
Figure 2.   Onshore/offshore vertical sections before the anchor station.

4 weeks were transferred into glycolphen-oxetol (Steedman, 1974). If necessary, samples were split with a Folsom plankton splitter. One eighth to entire samples were counted.

Chlorophyll *a* and Phytoplankton

Chlorophyll *a* was determined fluorometrically using an extraction method adapted from Yentsch and Menzel (1963). Samples for phytoplankton counts were preserved in Lugol's solution modified by Utermöhl (1958).

RESULTS

Observations Prior to the Anchor Station

The onshore-offshore vertical section (Fig. 2) taken prior to the anchor station shows the presence of a nearshore mass of fresher water representing the effect of coastal runoff. Offshore of station 6, the waters are predominantly of Gulf Stream origin. The high nitrate concentrations in particular are indicative of deeper Gulf Stream water. The intruding Gulf Stream water is in the 20–21.5°C temperature range
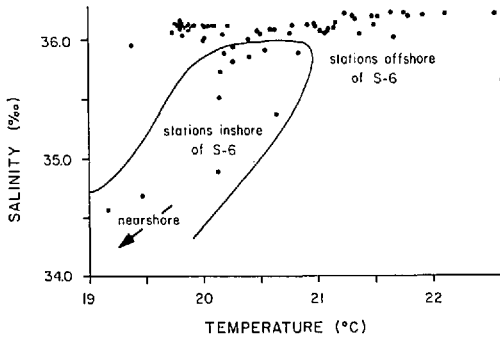
Figure 3.   Temperature-salinity diagram.

and it is noted there are three water masses at 20°C in the Figure 2 temperature section.

Temperature–Salinity Relationships.—The TS relationship (Fig. 3) shows the presence of a fresher water mass westward of station 6 with temperature of 19.5 to 22°C and salinities of less than 35‰. These properties are characteristic of the nearshore water mass. The principal part of the TS curve representing offshore water is typical of the Gulf Stream (Stefansson et al., 1971). From these data it is concluded that the study area was under the influence of two water masses; one the cooler, fresher nearshore and the other Gulf Stream water of higher temperature and salinity. This argument is not trivial as nearshore water masses can easily have an offshore or Gulf Stream origin resulting from major Gulf Stream excursions (Blanton, 1971; Lee, 1975) which have been modified by atmospheric interactions.

Phosphate, Nitrate, Silicate.—Nutrients are useful in identifying or confirming the existence of certain water masses. All data show the presence of a nutrient-rich water mass offshore at greater depths (Fig. 2 for example). This is the western edge of the Gulf Stream and represents North Atlantic Central water.

Post-anchor station silicate profiles (not presented here) show the nearshore water mass having high silicate which indicates a nearshore origin. Both pre- and post-anchor
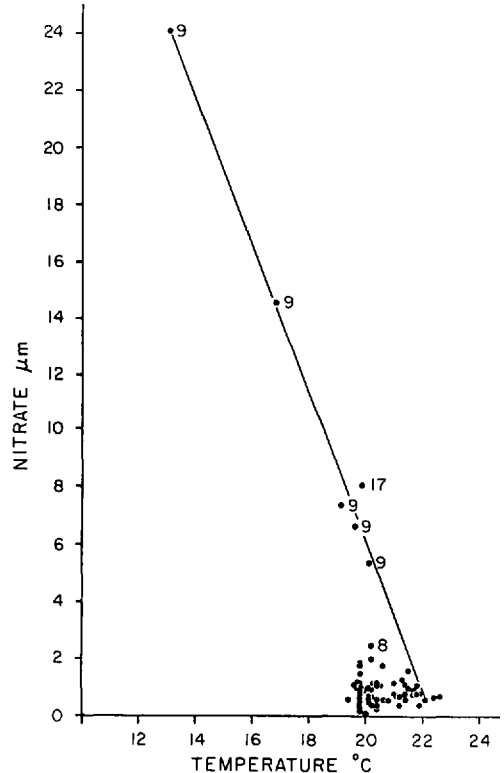

Figure 4.   Nitrate-temperature relationship. The straight line is the regression of deep water data from stations 8, 9, 17, 42, and 43 which were deep stations. The numbered data points refer to specific stations.

sections show increased silica near the bottom indicating either a nearshore or offshore source.

Nitrate–Temperature Relationships.—The temperature-nitrate plot (Fig. 4) shows a linear relationship at lower temperatures where conservative processes prevail; no light available. At temperatures above 20.5°C nitrate is uniformly low as might be expected. However, at lower temperatures two water types are evident with different nitrate concentrations: 20°C waters were observed with either 0.5–2.5 μm NO_3 or 5–8 μm NO_3. Temperature-salinity analysis indicates that low nitrate water, on the inner shelf, represents deeper water of higher
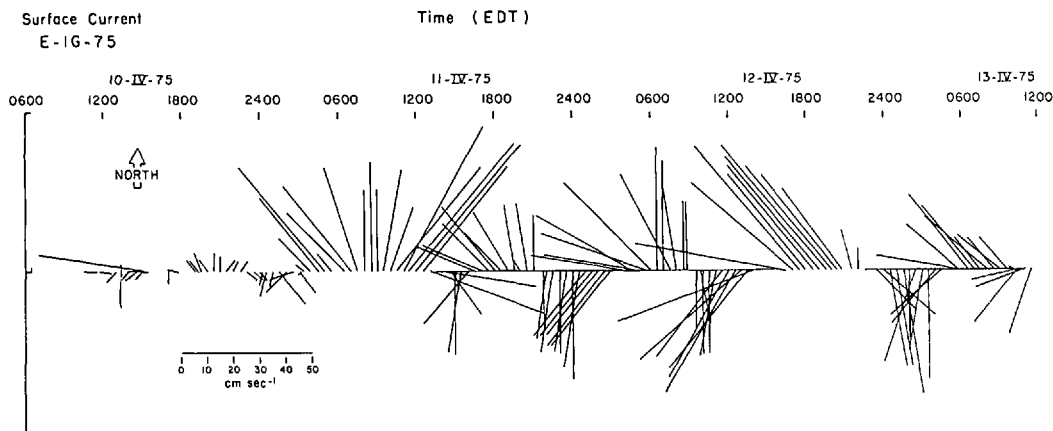
Figure 5.   Observed current at 5 m. Unfiltered data. Observations every 15 min.

nitrate content which was advected onto the shelf where the nitrate was depleted via biological activity.

Wind and Pressure.—Pressure during the observation period changed little, varying between 1000 and 1024 mb.

Winds were predominantly out of the south during the first few hours of observations. Then the direction changed to the northeast and velocities of *ca.* 10 m sec^{-1}. Early on 11 April the wind shifted again to the south and then to the southwest. During the shift to the south velocities decreased, but then with the shift to the southwest velocities reached 10 m sec^{-1} again. Winds then slowly shifted to the north to northwest during 12 April and speeds slowly decreased to 2–3 m sec^{-1}.

Currents.—Current vectors (Fig. 5) show the tidal dominance of the surface current. As might be expected the proximity of the Gulf Stream resulted in occasional strong currents to the north. However, an analysis of the E–W and N–S components shows a net westerly drift while the N–S components show a net near zero. Winds seem to have had some effect on the observed currents. The strong north wind on the 11th stalled the current system. During the 12th the southerly winds appeared to intensify the

northerly currents and eliminate the reversal that was typically observed.

Temperature–Salinity.—The temperature variations (Fig. 6) were most extreme in the surface layers above 20 m. The periodic appearance of a thermocline accompanied at times the appearance of a surface layer of relatively warmer, more saline water. Colder surface water was of consistently lower salinity. By reference to the TS diagram (Fig. 3) it is clear that the colder, fresher surface water is from regions west of the anchor station. Likewise, the warmer, more saline water is from the east.

Nitrate, Phosphate and Silicate.—The temporal changes in the vertical structure of nitrate, phosphate and silicate (Fig. 7) show little change in the surface layers but periodic changes in the concentrations nearer bottom. The change in the vertically integrated amounts show the temporal change more clearly (Fig. 7). Integrated phosphate varied from 2 to 17 mmol m^{-2} in a 12-h period with remarkable regularity. Integrated silicate and nitrate varied from 20 to nearly 200 mmol Si m^{-2} and 10 to 80 mmol NO$_3$ m^{-2} respectively with little obvious periodicity or correlation to phosphate.

The periodic variation of phosphate relative to nitrate implies that its concentration

Temperature °C　　　　　　　　　　　Time (EDT)

Salinity ‰　　　　　　　　　　　　Time (EDT)

Chlorophyll a (mg m⁻³)　　　　　　　Time (EDT)
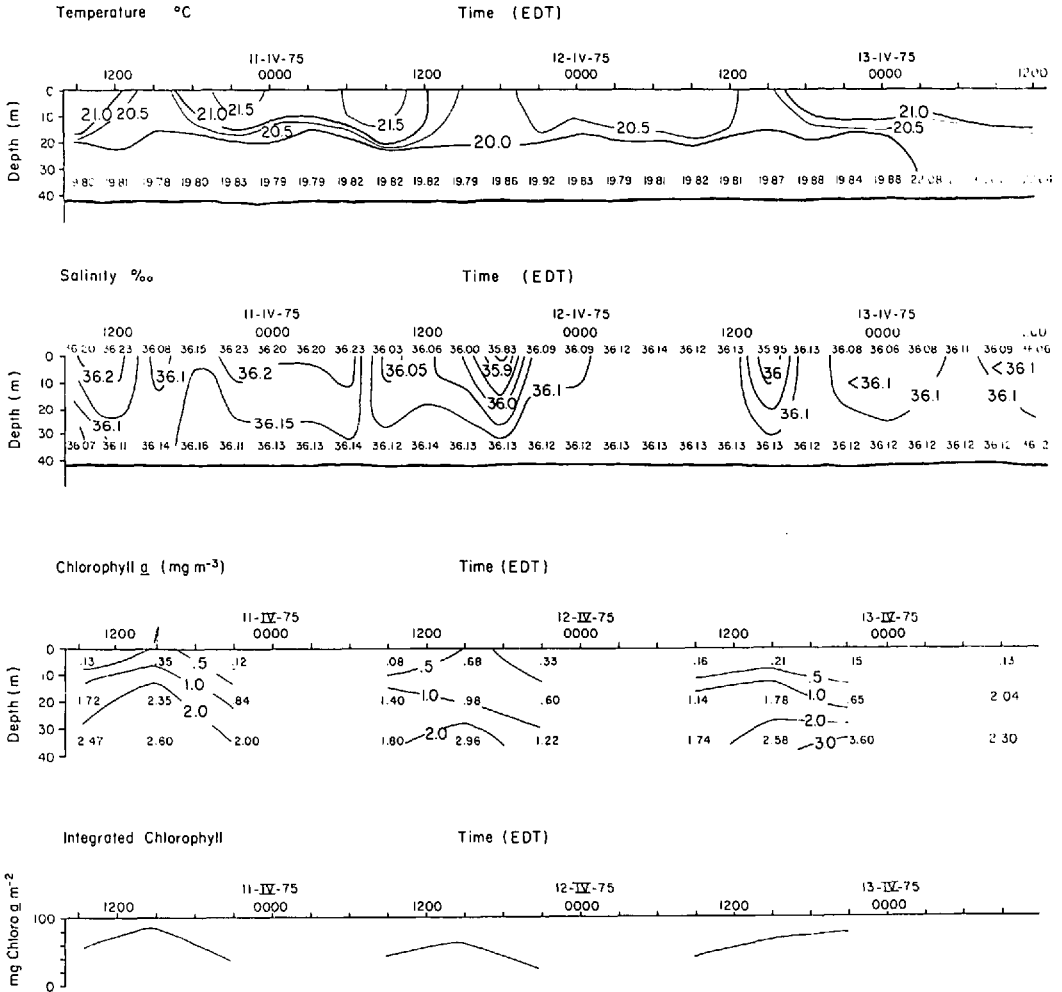
Integrated Chlorophyll　　　　　　　Time (EDT)

Figure 6. Time change in temperature, salinity, chlorophyll *a* and integrated chlorophyll. Observed near bottom temperature and surface and near bottom salinities are shown.

changes were controlled more by advection than were nitrate. This conclusion is derived from the temporal phosphate and nitrate observations and the fact that the anchor location was repeatedly invaded by a front separating onshore and offshore water with the offshore water relatively higher in nutrients. Thus movement of the intrusion periodically advected phosphate into the observation area. The relative depletion of nitrate is reflected in the low nitrate to phosphate ratio in the water column of 7 to 8 (N:P). When the nitrate concentration did occasionally rise with phosphate the N:P ratio increased. This indicates that nitrate is also being advected onshelf but biological assimilation is usually depleting it relative to phosphate.

Considering the above it is probable that we observed the onshore advection of nutrient-rich water at a rate such that nitrate consumption exceeded the diffusive and advective supply relative to phosphate. Presumably higher advection rates would have
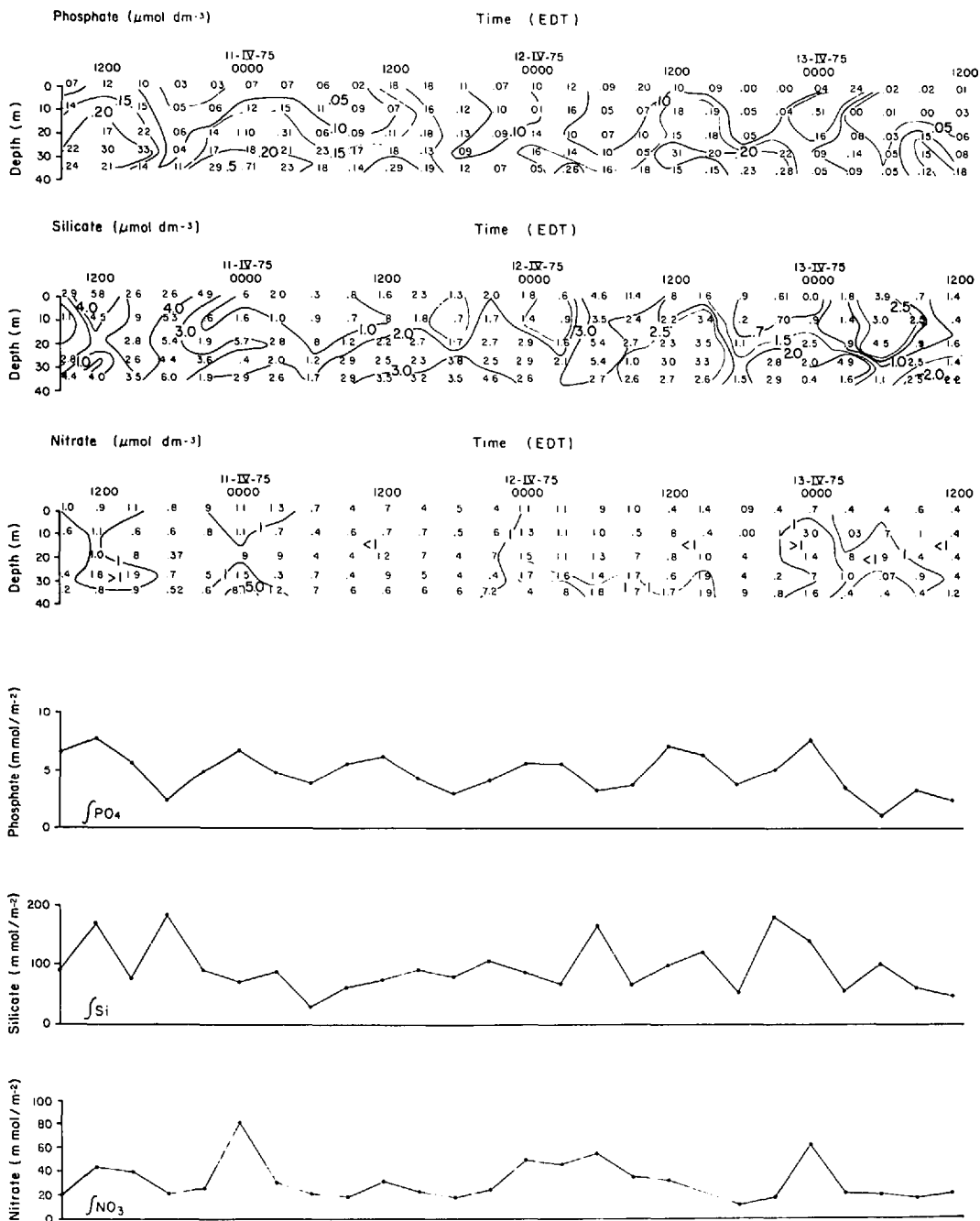
Figure 7. Time change in nitrate, silicate, phosphate, and depth integrated phosphate, silicate, and nitrate.
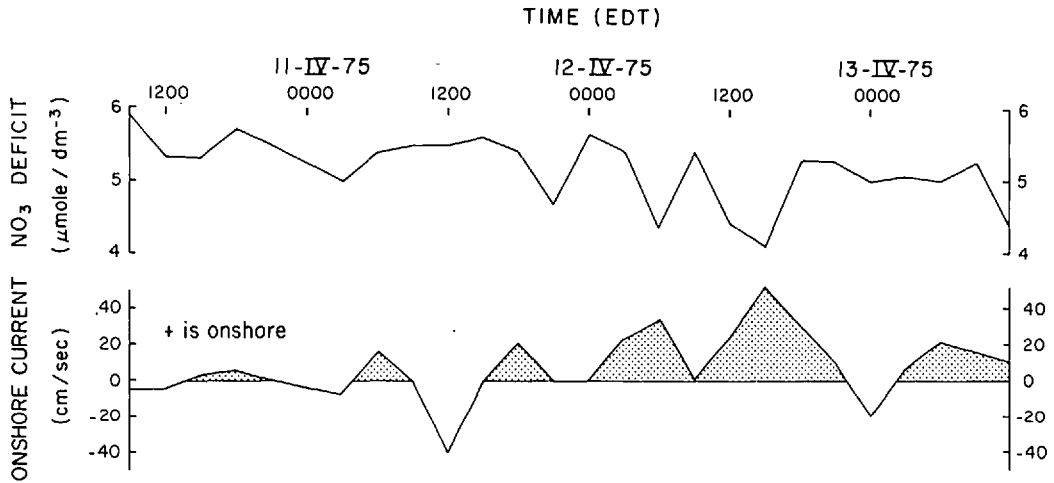
Figure 8.   Time change in near bottom nitrate deficit and the onshore current component.

resulted in a more periodic variation in nitrates, as observed in phosphate, and the N:P ratio would have been higher.

The Nitrate Deficit.—As previously discussed the deeper water has oceanic origins. It was also apparently deficient in nitrate nitrogen. To determine the nitrate deficiency the nitrate:temperature data in deep water was regressed (Fig. 4). Stations 8, 9, 17, 42 and 43 were included in the regression. The regression equation is:

Predicted Nitrate = 56.9 − 2.6 × Temperature.

Using this equation the nitrate deficit (predicted nitrate-observed nitrate) can be calculated.

Looking at the nitrate deficit at 20.5°C at Stations 7, 8, and 9 will indicate the time change in the nitrate deficit since it is hypothesized that these waters are undergoing strong vertical and horizontal motions. The nitrate deficit at Stations 7, 8, and 9 at the depth of the 20.5°C isotherm is 3.3, 2.4, and 0 μm, respectively. It is our conclusion that this shows the time dependent uptake of nitrate. These waters, all having the same initial nitrate concentrations, have lost progressively greater amounts proportional to their distance from the shelf break.

Figure 8 shows the time change in the nitrate deficit of the bottom samples during the time series stations and the onshore component of the surface current. While we are not implying the bottom current is coherent with the surface, it is notable that with the increasing onshore flow the nitrate deficit decreased.

Phytoplankton Observations.—The vertical distribution of chlorophyll (Fig. 2) shows the nearshore maximum associated with freshwater and the offshore sub-surface maximum associated with the intruding water. The sub-surface chlorophyll does not correlate with the nitrate maximum but appears on the leading edge of it. This may imply that the onshore motion is such that the phytoplankton cannot respond to the increased nitrate quickly enough to consume it.

A distinct diurnal change in chlorophyll *a* concentration was found in surface waters during the first 2 days at anchor station (Fig. 6). Chlorophyll *a* varied with tide and attained highest values during the early afternoon. The higher chlorophyll values coincided with lower surface temperatures and lower salinities. Each time a sample was taken we found an increase of chlorophyll *a* with depth. Concentration at 35 m were at

times more than 20-fold greater than surface values.

These rather high chlorophyll a values (3.6 mg m^{-3}) were attributed to the haptophycean *Phaeocystis pouchetii* Hariot (Lagerheim). This alga completely dominated the deep, cold water, forming colonies exceeding 5 mm in width and densities as high as 3.12×10^6 l^{-1}. Concentrations of phytoplankton species which were found in the surface waters, such as *Rhizosolenia alata, R. stolterfothii, Nitzschia seriata, Eucampia zoodiacus,* and some small pennates, dinoflagellates and coccolithophore, reached concentrations of 0.1×10^6 cells l^{-1} in the *Phaeocystis* dominated water.

Zooplankton Observations.—It was our intention to sample the entire water column and the surface layer separately every 3 h to detect if changes in zooplankton composition and concentration occurred in intruding and in surface water. However, the first three tows indicated the presence of large amounts of *Phaeocystis* sp. below 15-m depth which clogged the net; thus we could sample only the upper 10 to 15 m.

Most samples were dominated by gelatinous zooplankton (Fig. 9) including large numbers of doliolids (almost exclusively *Diolioletta gegenbauri f. tritonis*), salps (*Thalia democratica*) and appendicularians (*Oikopleura* sp.). The concentration of doliolids was at times enormous, reaching a peak of 1561 individuals m^{-3}. Most of the doliolids were present as gonozoids.

The densities of all zooplankton groups varied considerably during the 69 h of sampling, declining during the last 12 h. To correlate the concentrations of the dominant groups among each other we performed regression analyses. The concentrations of doliolids and larvaceans did not correlate well ($r = 0.410$, $p < 0.001$). Correlations between densities of chaetognaths and larvaceans ($r = 0.876$, $p < 0.001$) and chaetognaths and copepods ($r = 0.882$, $p < 0.001$) were significant. This may point to an association of chaetognaths and their most abundant prey. Most of the copepods

Table 1. Concentrations of dominant zooplankton in replicate tows (number $\times$ m^{-3})

	Dolio-lids	Salps	Cope-pods	Larva-ceans	Chaeto-gnaths
April 10, 1975					
0620 hours	158	47	351	91	29
0630 hours	185	43	438	114	33
April 13, 1975					
0920 hours	59	21	120	12	14
0935 hours	416	12	214	22	23
1140 hours	29	4	72	14	11
1150 hours	26	4	80	15	20

were of the genus *Paracalanus*, the body length of which did not exceed 0.9 mm. Most of the larvaceans had a body length of 1 mm or less. Thus both forms were of a size which could be readily ingested by larger chaetognaths such as *Sagitta enflata.*

The changes in the concentrations of the dominant forms could not be related to tidal currents, chlorophyll a or light.

There was poor correlation between copepod and doliolid concentrations ($r = 0.328$, $p > 0.05$). Copepods attained a maximum of 838 specimens m^{-3}. Cladocerans were extremely limited with a maximum of 9.5 specimens $\times$ m^{-3}, mostly 1 to 2 specimens $\times$ m^{-3}.

On three occasions we took duplicate tows (the second tow within 15 min of the first) to obtain a measure for the variation of concentration and composition. Except for the samples on April 13, 0920 and 0935 h, the differences between tows were small.

DISCUSSION AND CONCLUSION

Hydrographic Observations

Hydrographic data indicate that the anchor station was situated in a shelf water frontal region of horizontal temperature and salinity gradients. The water to the west of the station (nearer shore) was colder, of lower salinity, and contained low concentrations of nutrients. The water to the east of the front was relatively warmer at the surface and cooler at the bottom. Salinities were much higher as were the nutrients. At a
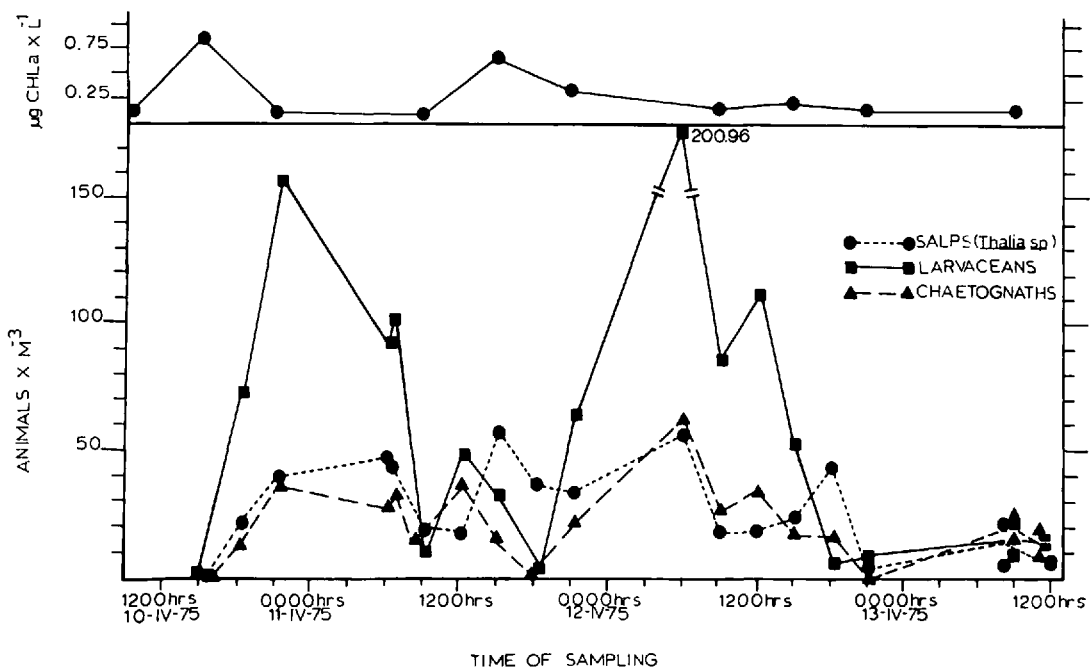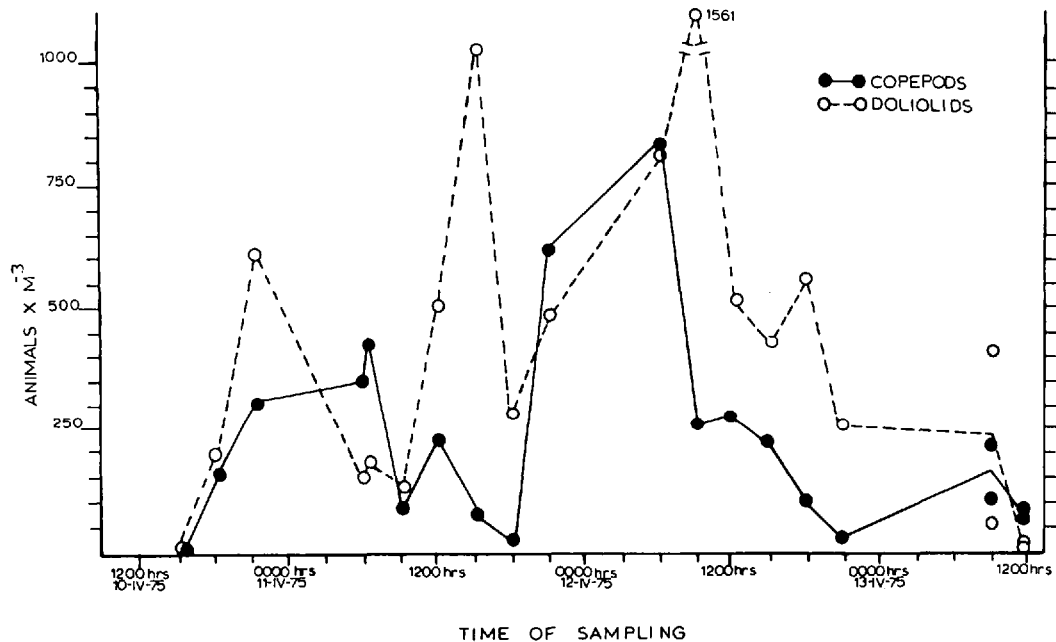
Figure 9.   Time change in concentration of abundant zooplankton groups. Data from 0–12 m oblique tow. Chlorophyll *a* concentrations are included.

depth of 5 m the currents rotated in a clockwise sense at tidal and longer time scales.

The net eastward movement indicated by the current meter was not evident in the hydrographic data. For example, there was little movement in the 21° isotherm during the anchor station. However the high chlorophyll concentrations imply a fairly active advection of deeper, nutrient-rich waters onto the shelf. This hypothesis is partly confirmed by the correlation of nitrate deficit to the onshore component of the current. The deficit decreases as the onshore component increases. This implies that the offshore waters have a higher nitrate concentration that approaches the concentration expected from the nitrate–temperature relationship. Thus each onshore movement advected newer, nutrient-rich water to the anchor station.

(In more graphic terms it appeared that of the Gulf Stream was positioned so that deeper waters moved vertically upward and horizontally westward onto the shelf.) This intrusion of Gulf Stream water created a front that oscillated with a tidal frequency. Taylor and Stewart (1959) and Green (1944) conclude that such "upwelling" situations are typical during summer months and imply that they would be unexpected in seasons other than summer. Our observations demonstrate that cooler, nutrient-rich water may frequently be at the shelf edge but conditions on the shelf may not be conducive to further onshore motion.

Phytoplankton

In the equatorial Pacific at depths from 5 to 50 m phytoplankton pigment fluorescence fluctuates diurnally with maxima near midnight and minima near noon (Karabashev and Solovev, 1975). In our case a maximum was observed during the afternoon. Only continuous pigment measurements over 24 h would have informed us of a possible midnight maximum which might have been obscured by tidal movements.

Blooms of *Phaeocystis pouchetii* have been repeatedly found near the British Isles (Savage, 1932; Jones and Haq, 1963). There *P. pouchetii* occurred after the diatom bloom and coincided with the spring minimum of phosphate (Jones and Haq, 1963). These authors assumed that a dormant form was part of the annual cycle. Kayser (1970) reported that *P. pouchetii* produced a form attached to substrates, releasing continuously single cells or small colonies into the water. We assume that either a dormant form or the substrate form of *P. pouchetii* was in the intrusion when it moved on the shelf, resulting in the rapid development of colonies as described by Kayser (1970).

P. pouchetii was assumed not to have a negative effect on planktonic copepods as it was found in the guts of *Temora longicornis*, *Centropages hamatus*, and *Oithona nana* (Jones and Haq, 1963). Therefore a population of copepods such as *Temora turbinata* could have existed in the intrusions described off St. Augustine, Florida.

Zooplankton

Changes in zooplankton concentrations with time during the anchor station must be interpreted with caution as the speed and direction of the current changed repeatedly during the 3 days. Copepods, chaetognaths, salps, and doliolids but not larvaceans are able to avoid nets by escape movements. The 253-μm mesh used does not quantitatively collect small copepods, chaetognaths, and larvaceans.

Large swarms of salps have been reported by Fraser (1949; 1962) and Heron (1972). Doliolids and salps may also occur in very dense patches (Braconnot, 1971). The latter seem to aggregate close to the surface during all times of the day with no subsurface maximum (Heron, 1972). Yet there exists no numerical data on the density of salps or doliolids in these swarms.

Our results show that the majority of doliolids sampled consisted of gonozoids, followed by phorozoids and oozoids. It seems that favorable environmental conditions led to (asexual) reproduction by oozoids which resulted, through phorozoids,

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in a large number of gonozoids within one to several days. *Thalia democratica* can complete a life cycle within 2 days (Heron, 1972). Under laboratory conditions the generation time of *T. democratica* ranges from 8 to 14 days at 14°C (Braconnot, 1963).

Inverse relationships occurred between salps and copepods in the California current (Berner, 1952; cited by Silver, 1975). Copepods can be scarce when salps are abundant over an extended period of time (Fraser, 1962). In seven of our 20 samples copepods were more abundant by number than the otherwise dominant doliolids. It appears therefore that we sampled a recently developed bloom of gelatinous zooplankton as copepods were still present in considerable numbers. Cladocerans were not present in appreciable numbers.

Enumerating salps and doliolids as individuals may be misleading as both, when reproduced asexually, occur in long chains up to two meters in length (D. Deibel, personal communication). Aggregation explains the difference in doliolid numbers on April 13, 0920 and 0935 h. Thus, only more sophisticated sampling or counting techniques, such as visual observations *in situ* can provide ecologically meaningful information.

The question remains open as to what caused the co-occurrence of *Oikopleura*, *Paracalanus*, and *chaetognaths.*

Larvaceans (appendicularians) may contribute significantly to the amount of prey consumed by chaetognaths, as their generation time is less than 5 days at temperatures above 18°C (Paffenhöfer, 1976; Fenaux, 1976) resulting in a rather high reproductive rate (20 to 70 offspring animal^{-1} day^{-1}).

ACKNOWLEDGMENTS

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