Exchange through a Barrier Island Inlet: Additional Evidence of Upwelling off the Northeast Coast of North Carolina

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ABSTRACT

During the period 20 June–2 July 1973, hydrographic data were collected at Oregon Inlet, N. C. An examination of the water temperature time-history record at three stations in and near the inlet show 1) that in two periods with predominately southerly winds, the temperature fluctuated in the range from 13.7° to 27.5°C with an apparent tidal periodicity; 2) that for nearly 48 h between these two periods and with northeasterly winds, a nearly constant temperature of 22.0° to 22.5°C was maintained in spite of normal tidal fluctuations; and 3) this constant temperature period is bracketed by two 24 h transitional periods that are initiated almost coincidently with wind directional changes. It appears that the sequence and relationship of these wind and water temperature data may be explained by and provide additional evidence and documentation of wind-induced upwelling along the northeastern North Carolina coast previously reported by Wells and Gray (1960), Carter, Pritchard and Carpenter (1966) and Boicourt (1973). Indeed, an important conclusion that can be drawn from this sequence and relationship of data is that temperature, salinity and current velocity records in and near a barrier island inlet can furnish much information about the exchange and mixing processes on the adjacent continental shelf, especially when there are large differences in temperature and salinity between the sound and shelf waters.

1. Introduction

During the period from 20 June–2 July 1973, hydrographic data were collected near Oregon Inlet, N. C., as part of an investigation (Singer and Knowles, 1975) to determine the circulation in the Oregon Inlet, Croatan and Roanoke Sounds complex, and the source of salt water entering Albermarle Sound (Fig. 1).

The data were recorded at 5 min intervals during the research period by bottom mounted film-recording sensors at five stations (Fig. 2). Station 1 sensors recorded tidal and temperature data; Station 2a sensors recorded temperature data only; Station 3a sensors recorded tidal, temperature and current velocity data; and Stations 6 and 7 sensors recorded temperature and current velocity data. The respective depths for these instruments are given in Table 1. In addition, vertical profiles of temperature and salinity were recorded periodically at Station 1 and Station 5 using a portable CTD unit.

2. Results

Fig. 3 is a time-history record of the water temperature fluctuations at Stations 1, 2a and 3a recorded during this period; also included for reference are wind data from the Oregon Inlet Coast Guard Station, tidal data from Station 1 and flood-ebb current meter data from Station 3a. Wind direction is the direction from which the wind blows (i.e., southerly winds blow from the south) and is shown in Fig. 3 in vector form with north to the top of the page.

To facilitate the discussion of the temperature time series, five time intervals (A through E) are identified in Fig. 3 which seem to reflect distinct, wind-related features in the record. An examination of these intervals shows the following general features:

1) Time intervals A and E show a periodic fluctuation in temperature ranging from 15.6° to 27°C in A and from 13.7 to 27.5°C in E during southerly winds (except

TABLE 1. Approximate depths at instrument stations.

Station	Approximate depth (m)
1	6.4
2a	5.5
3a	4.0
6	2.7
7	4.0

for two brief periods in E); this fluctuation is tide related with the warmer waters having temperatures characteristic of sound waters, and the colder waters that of mid-shelf subsurface waters.

2) Time interval C shows a nearly constant temperature period with a range from 22.0° to 22.5°C at Station 1 and less than 0.5°C higher at stations 2a and 3a during northeasterly winds; the constant temperatures are maintained apparently in spite of the tide.

3) Time intervals B and D show the transitional periods that seem to be initiated by wind directional changes; the temperature records appear to be under some tidal influence.

In addition, there appears to be some correlation between the observations at the inlet and the temperature record at Station 6 in the sound (Fig. 4). This is noted as an abrupt decrease in the sound temperature at the beginning of time interval C (the constant temperature period) with some fluctuation during this period, and an increase in the sound temperature at its conclusion. Finally, Station 7 (the station furthest from the inlet) exhibits a general warming trend over the period of the study and is apparently least affected by the events at the inlet.

It should also be pointed out that air temperature fluctuations during this period were essentially the same as with those days both preceding and following it (Fig. 4). The decrease in air temperature on 23 June was in conjunction with a period of heavy rains.

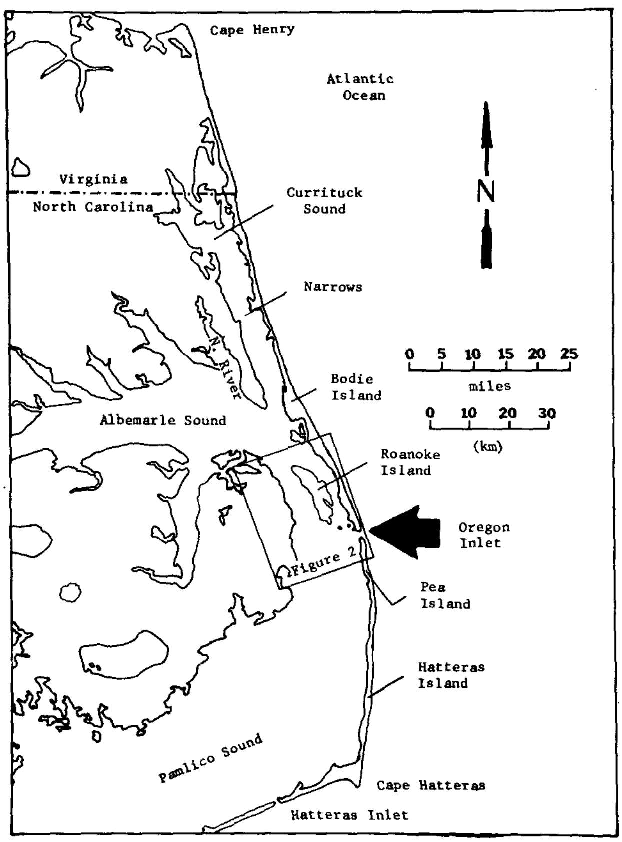

FIG. 1. Location of study area along the North Carolina coast.

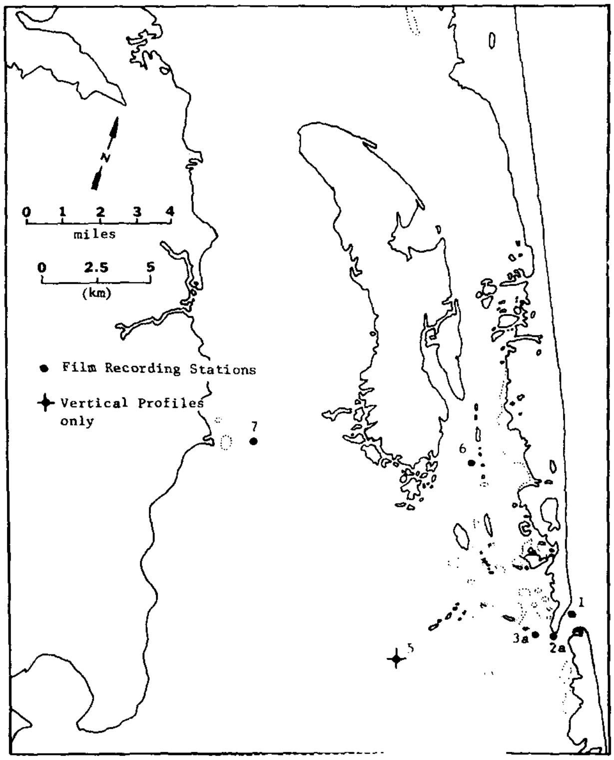

FIG. 2. Location of bottom mounted thermographs (20 June–2 July 1973).

As was mentioned briefly above, during the period of constant water temperatures (interval C) normal tidal currents were observed at the inlet. There were no missed floods or missed ebbs; however, somewhat longer floods were observed during this period than either preceding or following it as can be seen from the current meter record for Station 3a (the dashed lines indicate a best estimate of speeds beyond the maximum recorded by the current meters) and the tidal record for Station 1 (Fig. 3).

Vertical profiles of temperature and salinity made using a portable CTD unit at Stations 1, 2a, 3a and 5 beginning on 26 June and running through 29 June (i.e., covering only the period of constant temperature and as its effects subsided) tend to confirm the results of the bottom-mounted sensors. Furthermore, they help identify the source of the constant temperature water, as will be discussed below.

Temperature and salinity profile data from Station 1 and Station 5 are included in Figs. 5 and 6. For Station 1, the vertical profile of temperatures agree to within 1°C with the continuous temperature record shown earlier in Fig. 3 for corresponding times (the accuracy of these two units is ±0.55° and ±0.5°C, respectively). Particularly note that for Station 1 in Fig. 5, a vertically isothermal temperature of 21.4°C

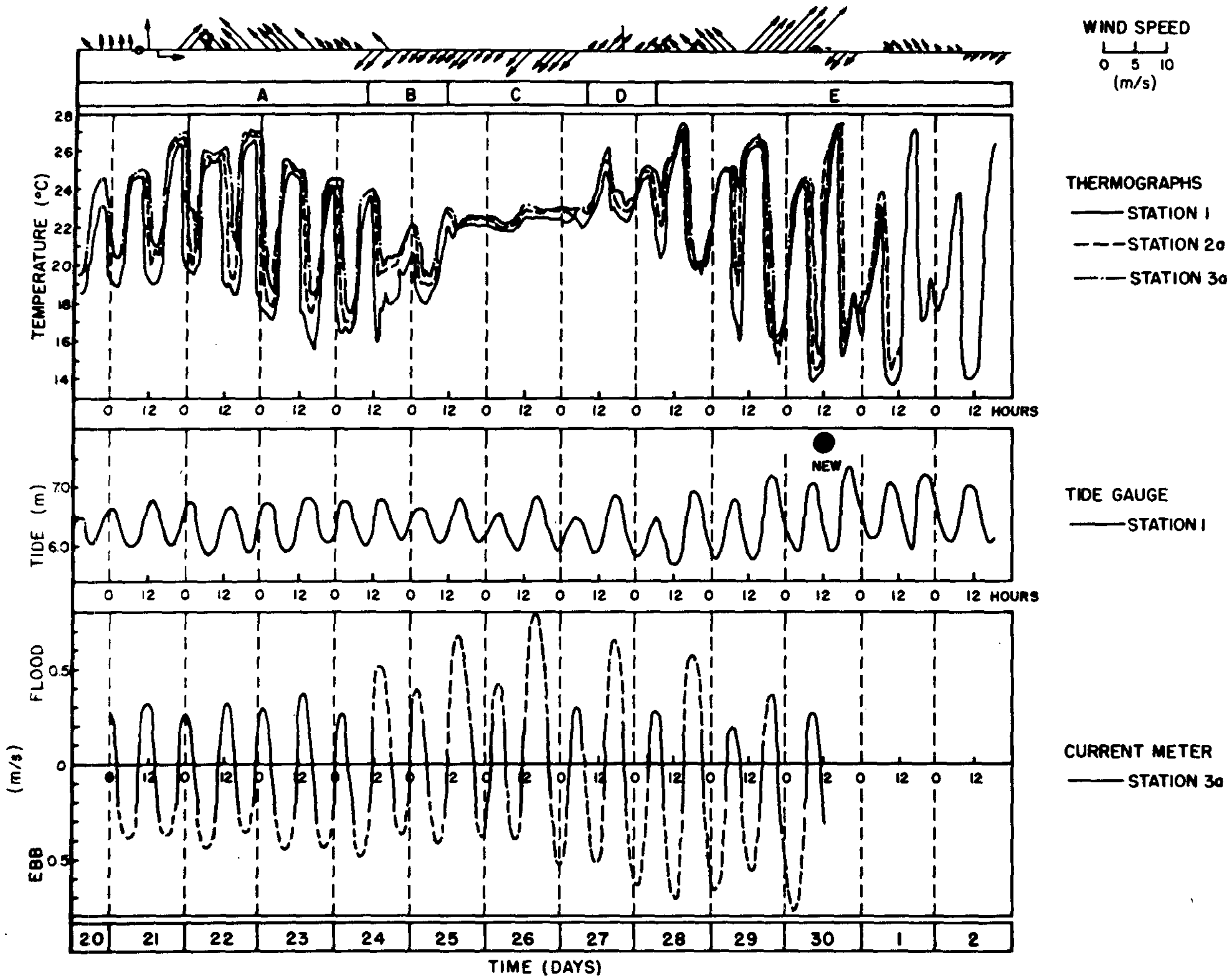

FIG. 3. Water temperature records for Stations 1, 2a and 3a, tidal data for Station 1, and the bottom mounted current meter record for Station 3a (20 June–2 July 1973). Dashed lines in current meter records represent the best estimate of the speeds beyond the maximum recorded by the current meters.

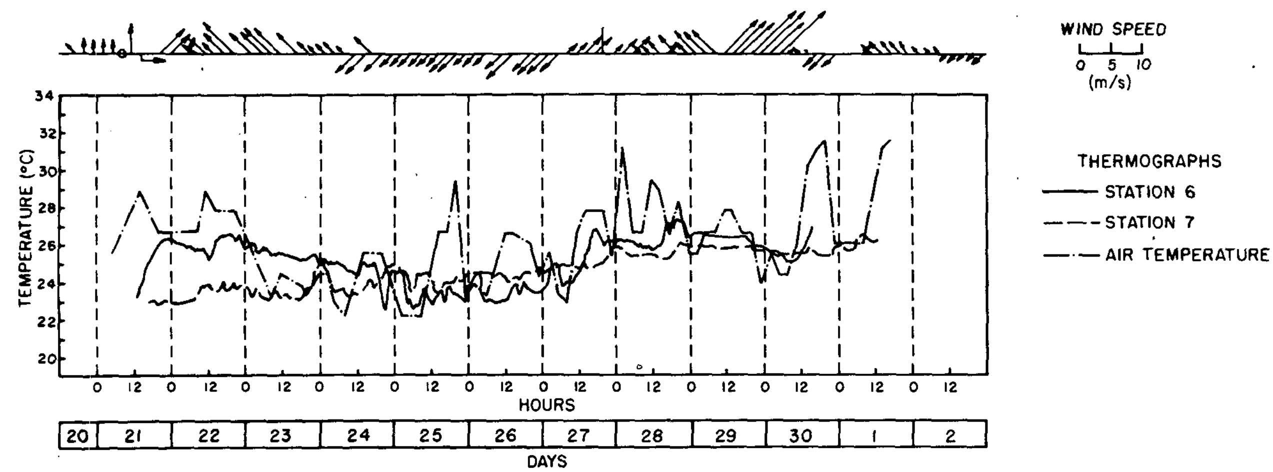

FIG 4. Water temperature records for Stations 6 and 7 and the air temperature record for the period 20 June–2 July 1973.

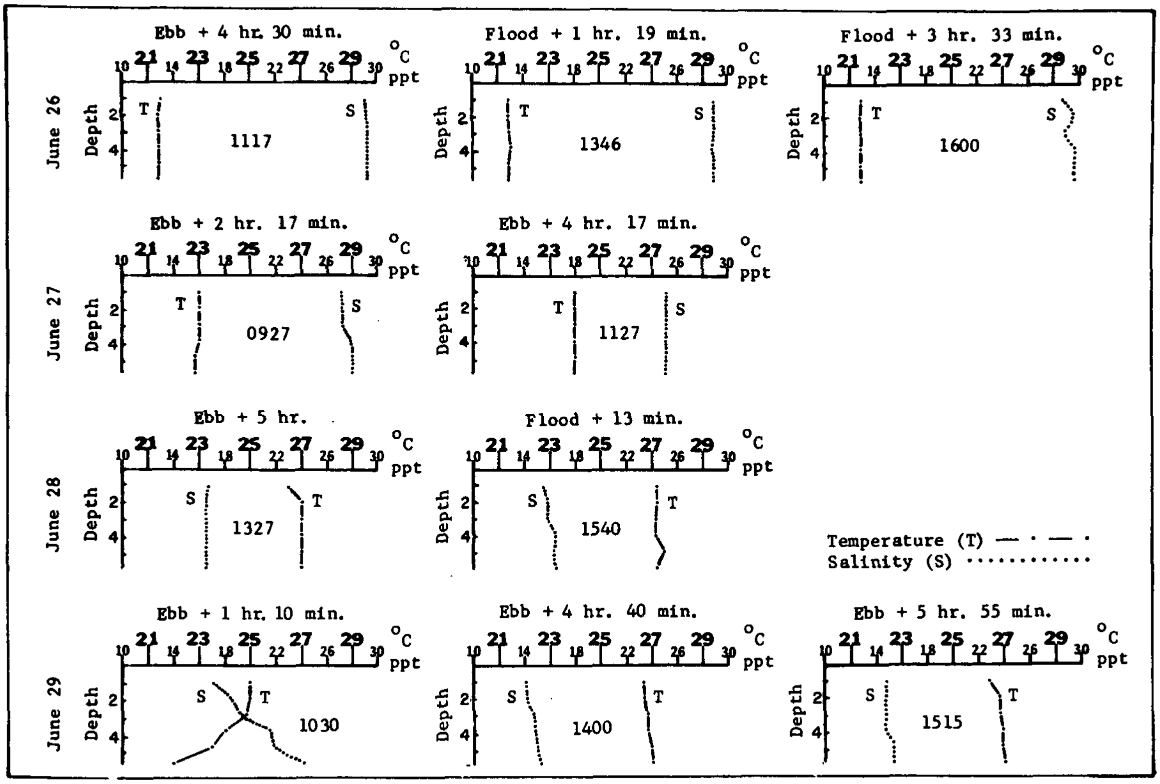

FIG. 5. Vertical profiles of water temperature and salinity for Station 1 (26–29 June 1973). Tidal states correspond to Station 3a current meters records and heights are reported in meters.

is maintained throughout the day for 26 June. This temperature profile is also independent of tidal phase and aside from being slightly lower in temperature than the bottom-mounted instrument's readings, agrees in trend with them. Note, too, that the salinity of this water remains fairly constant, ranging from 28.80 to 29.60% throughout the day, and is essentially independent of ebb or flood. Such salinities are much too high to have originated in Pamlico Sound where Jarrett (1966) has reported the average salinity to be 20%. Likewise, the temperatures during ebb are much too low for this time of year (Schwartz and Chestnut, 1973), thereby suggesting that this mass of homogeneous water was nonestuarine in origin.

Indeed, it is not unusual for surface waters in the 21–23°C range to be found off the northern North Carolina Coast at this time of year (Parr, 1933; Fuglister, 1947; Wells and Gray, 1960; Stefansson *et al.*, 1971; Boicourt, 1973); that it is present during this constant temperature period is apparent from an Airborne Radiation Thermometer Isotherm Chart for 24 and 25 June 1973 compiled by the U.S. Coast Guard Oceanographic Unit (Fig. 7). Furthermore, salinities in the 28 to 30% range are not uncommon in conjunction with these coastal waters (Boicourt, 1973); therefore, there is good reason to believe that the homogeneous waters passing through the inlet on 25–26 June were shelf surface waters moved by NE winds into position adjacent to and reaching the bottom near the coast.

In contrast, oceanic temperature <20°C for this time of year are typical of water upwelled from the mid-shelf region during periods of southerly winds (Wells and Gray, 1960; Boicourt, 1973). This could well account for the lower temperatures observed for floods during the periods of southerly winds in time intervals A and E.

Trends similar to those for Station 1 on 26 June are also noted for Station 5 (Fig. 6). In addition, note the similarity in the trends for the next three days at these two stations where there is an overall decrease in salinity and an increase in temperature. In particular, at Station 5, salinities dropped from a high of 27.7% on 26 June to range between 13.2 and 14.2‰ on 28 and 29 June. Over this same time span, temperatures rose from 22°C to range between 26 and 28°C. These latter values compare favorably with salinity and temperature data collected by Schwartz and Chestnut (1973) for this area of Pamlico Sound during the month of June 1972, which they found to range from 12.1 to 15.9‰ and from 25° to 27°C, respectively.

The change in water temperatures and salinities at Station 5 is a further indication that northeasterly winds apparently caused a rather substantial penetration of oceanic waters into this region, thereby significantly increasing the salinity and decreasing the

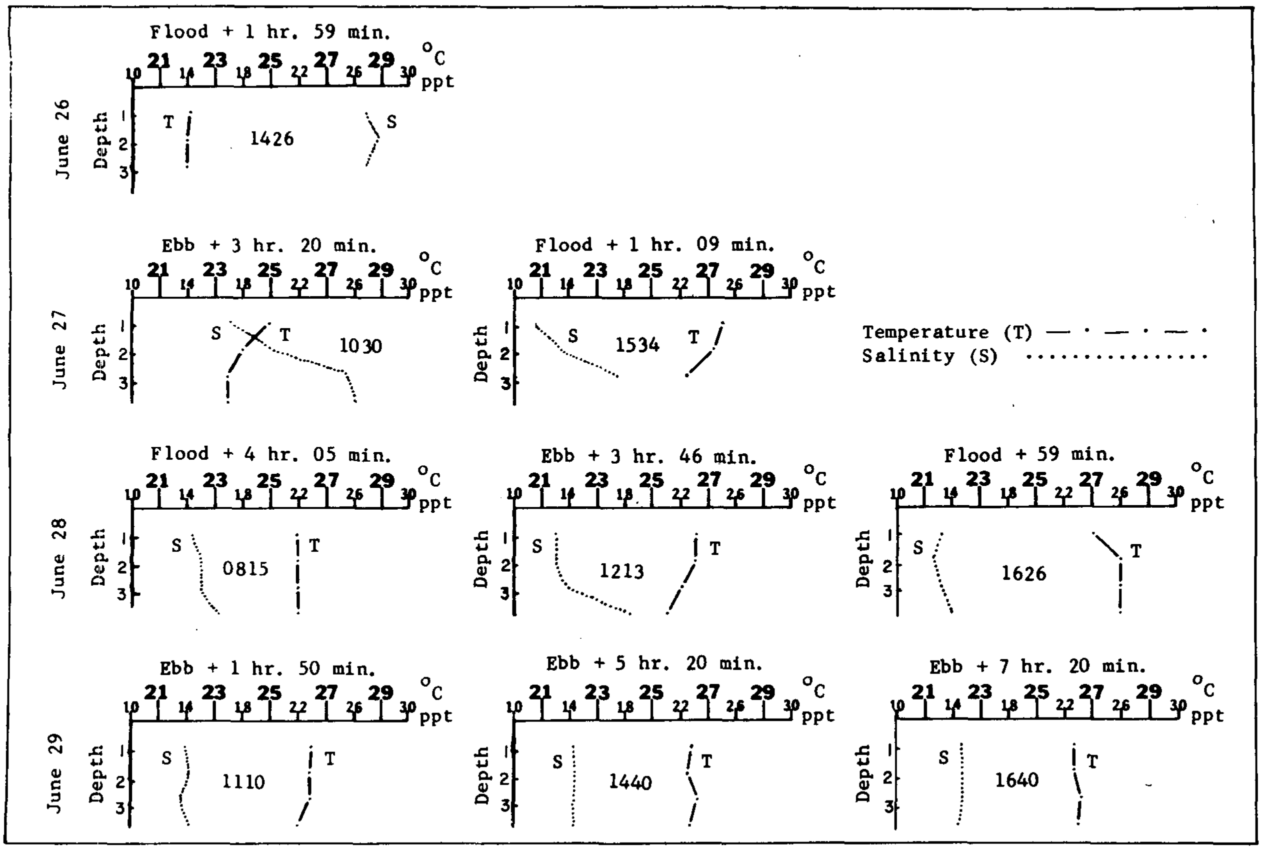

FIG. 6. Vertical profiles of temperature and salinity for Station 5 (26–29 June 1973). Tidal states correspond to Station 3a current meter records and heights are reported in meters.

temperature, and that a return to southerly winds tended to purge the region of this same oceanic influence.

3. Conclusions

It appears that the sequence and relationship of the wind and temperature data reported during the June study for the three inlet stations before and after the constant temperature period may be explained by and provide additional evidence and documentation of wind-induced oceanic upwelling along the northern North Carolina coast. This has previously been reported by Wells and Gray (1960), Carter *et al.* (1966) and Boicourt (1973), and has been predominately attributed to southerly winds inducing the Ekman transport of surface waters away from the coast with the subsequent replacement by colder, more saline bottom waters. By similar rationale, the constant temperature period could be attributed to downwelling of surface waters in conjunction with northeasterly winds, which may in turn account for the vertical homogeneity observed.

In light of the results of this study and the conclusions just drawn, the events at the inlet may be explained as follows:

1) In time interval A the winds were all southerly. The minimum temperatures observed were for the deeper shelf waters brought nearer the surface by wind-induced upwelling and moved through the inlet on a flood tide; the maximum temperatures observed were for the sound waters moved through the inlet on an ebb tide.

2) In time interval B the winds were northeasterly. Here, almost immediately and coincidentally with wind reversal from southeasterly to northeasterly on 24 June the regularity of the temperature fluctuations was interrupted. The forcing mechanism for upwelling ceased, that for downwelling was initiated and the baroclinic readjustment of density surfaces was begun. By midday on 25 June (the beginning of time interval C) the warmer oceanic surface waters had been moved into position opposite the inlet.

3) In time interval C the winds continued northeasterly and moved sound waters away from the inlet and further back into the sound in advance of the warmer downwelled homogeneous oceanic waters passing through it on a flood. In addition, because the orientation of Oregon Inlet is along the major axis of the prevailing winds (NE–SW), the northeasterly winds set up a pressure gradient through the inlet which induced longer floods. In this particular study,

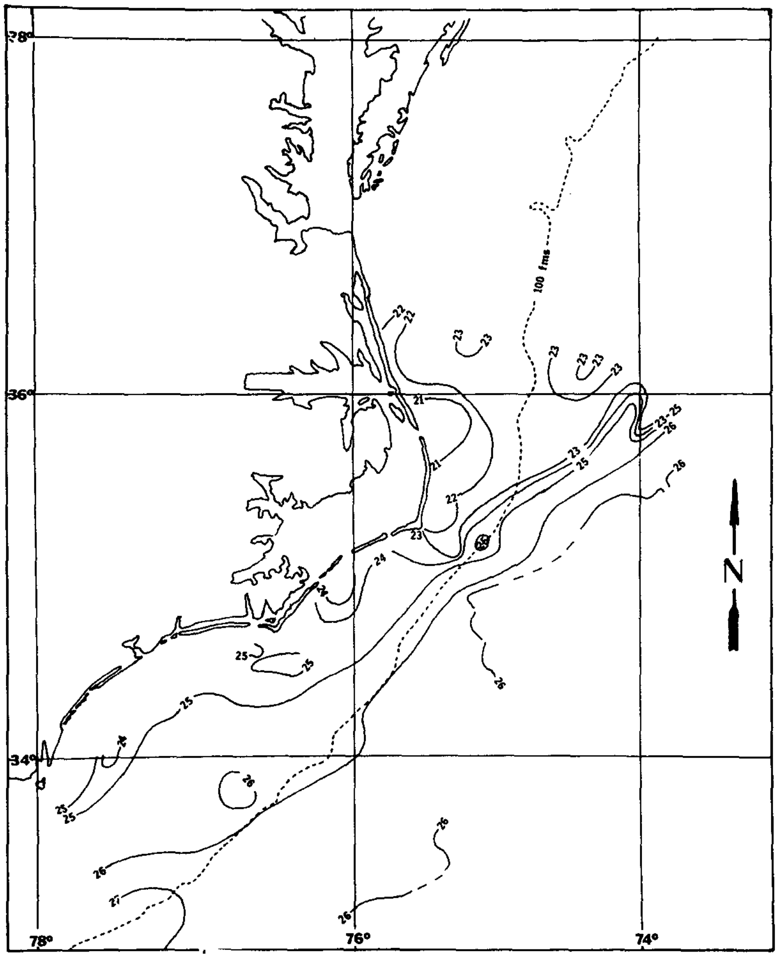

FIG. 7. ART (Airborne Radiation Thermometer) isotherm chart for 24 and 25 June 1973 showing surface temperatures (°C) of the ocean waters off the North Carolina coast.

northeast winds induced floods that averaged 7 h in length and ebbs that averaged 5 h 43 min in length, whereas southerly winds, both preceding and following the constant temperature period, induced floods averaging 5 h 43 min in length and ebbs averaging 7 h 45 min in length. Clearly, this means that northeast winds favor the accumulation of oceanic waters in Pamlico Sound. Indeed, an earlier study (U.S. Army Engineers District, Wilmington, 1968) with comparable wind conditions suggests that the total inflow could approach 1.8 times the outflow over a complete tidal cycle. Consequently, for the present study, it is clear that the same oceanic water moved back and forth through the inlet in response to the tides during this time span (interval C) and because the sound water had been moved away from the inlet, very little mixing of the ocean water with the warmer sound waters was achieved.

4) In time interval D the winds returned to southerly once again. This in turn transported the warm oceanic waters away from the shore and allowed the warmer and less saline sound waters to return to the vicinity of the inlet, thereby enhancing the mixing of sound and oceanic waters on subsequent floods. Once again upwelling commenced, there was a baroclinic readjustment of the density surfaces and colder oceanic waters began to pass through the inlet on subsequent floods.

5) In time interval E the winds continued southerly. The colder upwelled shelf waters were being moved through the inlet on floods and the warmer sound waters were being moved through the inlet on ebbs, as in interval A. However, this was interrupted on late 30 June and early 1 July, apparently due to a brief period of northeasterly winds that momentarily initiated another baroclinic readjustment. This in turn was followed by a similar interruption on late 1 July and early 2 July that cannot be so readily explained, since the winds continued to prevail from the southeast.

Also the lowest flood temperatures recorded during southerly winds both preceding and following the constant temperature period (i.e., on 23 June and 1 July) followed within 24 h of the longest periods of high southerly winds observed during time intervals A and E, and the range of extremes in the fluctuations of water temperatures in time interval E were greater than in time interval A due, undoubtedly, to the advent of spring tides on 30 June.

It is not known from this study whether a constant temperature period similar to the one observed is a common event at Oregon Inlet in conjunction with the apparent downwelling induced by northeast winds. No other events like this have been reported in the literature or were observed during the period of this study. During a later study period (February 1974), however though there was almost no incidence of northeasterly winds, northerly and northwesterly winds (which should particularly favor downwelling) were observed to produce longer floods and shorter ebbs at the inlet (Singer and Knowles, 1975), and a thermographic record suggests that the water flowing in and out of the inlet may also have been predominately oceanic in origin. However, no vertical profiles of temperature and salinity were made during this period to either verify or disprove such a tendency.

Finally, one particularly important and unexpected conclusion that can be drawn from this research is that temperature, salinity and current velocity records in and near a barrier island inlet can be used to explain much about the exchange and mixing processes on the adjacent continental shelf, especially when there are large differences in temperature and salinity between the sound and shelf waters.

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The Observed Winter Circulation of Lake Ontario

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ABSTRACT

Observations of Lake Ontario's monthly mean properties during the winter of 1972–73 suggest that currents and temperatures are nearly constant with depth and that the lake-wide mean circulation pattern consists of either one counterclockwise or two counterrotating gyres.

1. Introduction

Lake Ontario's winter circulation had not been observed prior to 1972. In both previous whole-lake studies [Harrington (1895) via surface drift bottles; Casey *et al.* (1966) via moored current meters] harsh weather and lake ice discouraged the extension of observations past autumn. However, there were predictions of the lake's winter currents.

Since the hydraulic circulation (from inflow–outflow) is always small, and thermally driven flow in nearly isothermal water must be small, winter currents should be wind driven. Both Rao and Murty (1970) and