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Robert L. Smith

Temperature, salinity, and dissolved oxygen concentration measured in an estuary were analyzed to determine if the effects of coastal upwelling could be observed and used to effectively monitor the degree of upwelling.

Hydrographic data collected weekly at a point four miles from the entrance of Yaquina Bay (Buoy 15) were analyzed for their applicability as indicators of coastal upwelling. Only data collected during the known upwelling season off Oregon of May through October were considered. Low temperature, low dissolved oxygen concentration, and high salinity occurred when the wind was strongly from the north--conditions expected during times of active upwelling.

A regression analysis was performed to establish the relationship between water temperature and wind velocity averaged over a three day period. The two were significantly related. Various weighting schemes were applied to the wind observations to obtain an average

wind which would provide the best correlation between wind and temperature. A wind averaged over four days and weighted heaviest during the third 24 hour period prior to the temperature observation resulted in the best correlation.

A prediction model was formulated to allow for the prediction of water temperature 24 hours in advance based upon the known wind field during times of active upwelling.

Comparisons of temperature and salinity from five miles off the coast with that in the estuary established that the upwelled water entering the estuary on the flood tide originated from a depth of about 20 meters at three-five miles off the coast.

Measuring the temperature, salinity, and oxygen concentration of the bottom water near the mouth of an estuary does provide an effective, reliable, and simple method of monitoring the stage of upwelling occurring outside the estuary.

Monitoring Coastal Upwelling by Measuring Its Effects Within An Estuary

by

Robert Hathaway Bourke

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APPROVED:

Redacted for Privacy

Assistant Professor of Oceanography
In Charge of Major

Redacted for Privacy

Chairman of Department of Oceanography

Redacted for Privacy

Dean of Graduate School

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MONITORING COASTAL UPWELLING BY MEASURING ITS EFFECTS WITHIN AN ESTUARY

INTRODUCTION

Review of Upwelling

Upwelling may be defined as the ascending movement of subsurface water into the surface layer in response to the offshore transport of surface water. It is a phenomena known to occur off the Oregon coast during the summer months and has been studied extensively by several authors. The chemical properties of upwelling were discussed by Park, Pattullo, and Wyatt (1962); its effect on nutrients (Matson, 1964) and plankton distribution (Cross, 1964; Hebard, 1966) have been investigated. Smith (1964) developed a model for coastal upwelling, and Collins (1964) discussed the effects of upwelling on the permanent oceanic front off the Oregon coast. The offshore transport during the early stages of upwelling has been computed by Smith, Pattullo, and Lane (1966). At this time coastal upwelling is being investigated by the use of self recording current meters and thermographs as a continuing research effort by the Department of Oceanography at Oregon State University.

Ekman's classic paper of 1905 (Ekman, 1905) provided the basis for the physical explanation of upwelling and the effects of wind stress on the sea surface. His results provide for a net transport of water due to the wind stress with the transport directed 90 degrees to the right (left) of the wind direction in the Northern Hemisphere (Southern Hemisphere). The northerly winds, which predominate during the summer months off the Oregon coast, transport water offshore and necessitate a rise of deeper water near the coast. This water generally comes from depths not exceeding 200 meters (Sverdrup et al., 1942).

Indicators

Because the upwelling process brings subsurface water into the surface layer, anomalies will normally result in the distribution of physical and chemical properties. These anomalies can be used as indicators of upwelling (Park, Pattullo, and Wyatt, 1962). Upwelled water is generally identified by its colder temperature, low oxygen content, and higher salinity when compared to the surrounding water or when compared to the same waters in times when upwelling is not active. Other indicators of upwelled water would be increased alkalinity, inorganic phosphate, and hydrogen ion concentration.

Purpose of Study

Although coastal upwelling has been rather extensively studied, few investigations have been made of the effects of upwelling on estuaries. Pearson and Holt (1960) have reported their findings of low oxygen concentration values in Grays Harbor, Washington. They conclusively proved that the low dissolved oxygen concentrations, which were originally attributed to industrial pollution, were actually a consequence of oxygen-poor upwelled water entering on the flood tide. The effect of upwelling on the biological population, notably zooplankton, within an estuary was observed by Frolander (1964). He related the distribution of several species of zooplankton found in Yaquina Bay, Oregon, to various temperature and salinity zones. The population of the several species fluctuated as the environment changed. Although tidal variations were largely responsible for these fluctuations, the changes in temperature and salinity caused by the variability in the strength of upwelling were large enough to exert a strong influence on the population.

However, a detailed study of the physical and chemical effects of coastal upwelling on an estuary has not been undertaken. It is the purpose of this paper to investigate or determine for the Yaquina estuary:

1) if coastal upwelling can be adequately observed and monitored within an estuary,
2) assuming upwelling can be monitored within an estuary, the correlation between wind velocity and water temperature in order to obtain a prediction equation for water temperature,

3) the length of the upwelling "season," i. e., its onset in spring and cessation in fall,

4) the mean values of temperature, salinity, and dissolved oxygen concentration that can be expected for each month of the "season."

In order to establish part one, which is the heart of the thesis, it will be necessary to establish that a relationship exists between estuarine water and oceanic water. It will be shown, in fact, that the water in the bay sampled at high tide is coastal oceanic water, uninfluenced by estuarine processes. Furthermore, it will be shown that within the estuary the usual indicators of upwelling respond to the winds in the same manner as has been established for known coastal upwelling regions.

ESTUARIES

Definition

An estuary as defined by Pritchard (1952) is "a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea salt." This broad definition lends to subdivision of estuaries into several types based on various factors. Pritchard classified estuaries into two major types based on fresh water addition and evaporation. The "negative" estuary is one in which evaporation exceeds precipitation. A "positive" estuary exists when the fresh water input exceeds the evaporation. Pritchard further classified estuaries according to their geomorphology. The Yaquina estuary is classified as a "coastal plain" estuary. These are drowned river valleys and are generally positive although they may change to negative if stream flow is decreased or diverted, or evaporation increases. All Oregon estuaries may be classified as positive coastal plain estuaries.

Classification

Pritchard (1955) has subdivided positive coastal plain estuaries into four types, A, B, C, and D, based upon the observed circulation patterns and salinity distribution. Using this classification system, Burt and McAlister (1959) have identified the major Oregon estuaries including the Yaquina estuary based upon the measured salinity difference between surface and bottom water at high tide at the point where the water is half salt and half fresh.

The Type A estuary is a two layered or stratified estuary in which the salinity difference from surface to bottom is $20^{o}/oo$ or greater. This type of estuary requires a low tidal range, a large depth to width ratio, and a high river runoff. This estuarine system is not found in Oregon although the Umpqua estuary approaches it during extended periods of high runoff.

The Type B estuary is one that is partly mixed with a salinity difference ranging from $4^{o}/oo$ to $19^{o}/oo$. The partly mixed estuary is very common in Oregon and is usually present during times of high river runoff.

The Type D or well mixed estuary has a salinity difference of $3^{o}/oo$ or less. High tidal ranges to provide energy for mixing, low river runoff, and wide shallow topography are conditions which create the well mixed estuary. In Oregon many of the estuaries are of this type and change to Type B only during the time of the spring runoff.

Pritchard's Type C estuary is not found in Oregon (Burt and McAlister, 1959).

The Yaquina Estuary

Due to the relatively high tidal range in Yaquina Bay of about 5.5 feet, the low river runoff, and the small depth to width ratio of the estuary, a well developed two layered system seldom, if ever, exists. In the winter and spring when runoff is high, the estuary generally becomes partly mixed (Type B). Throughout the summer months and into the fall (the period covered by this report) the estuary was always well mixed (Type D). At high tide the salinity difference rarely exceeded $1^{o}/oo$ and generally ranged from $0.0^{o}/oo$ to $0.3^{o}/oo$.

According to a survey made by the U. S. Coast and Geodetic Survey in September and October of 1955 when the estuary was well mixed, tidal current velocities near the entrance were found to be in excess of two knots (Kulm and Byrne, 1966). At all depths the maximum ebb current velocity was slightly greater than that of the flood. At Buoy 15, approximately four miles upstream from the entrance, tidal current velocities were reduced to about one knot.

Yaquina Bay (Figure 1), is a body of water about 4.5 square miles in area with a major channel, two large tidal flats, and numerous sloughs. The channel is dredged to a depth of 26 feet from the bar at the entrance to the turning basin opposite McLean Point. From this point upstream to Toledo the channel depth is maintained at 12 feet.

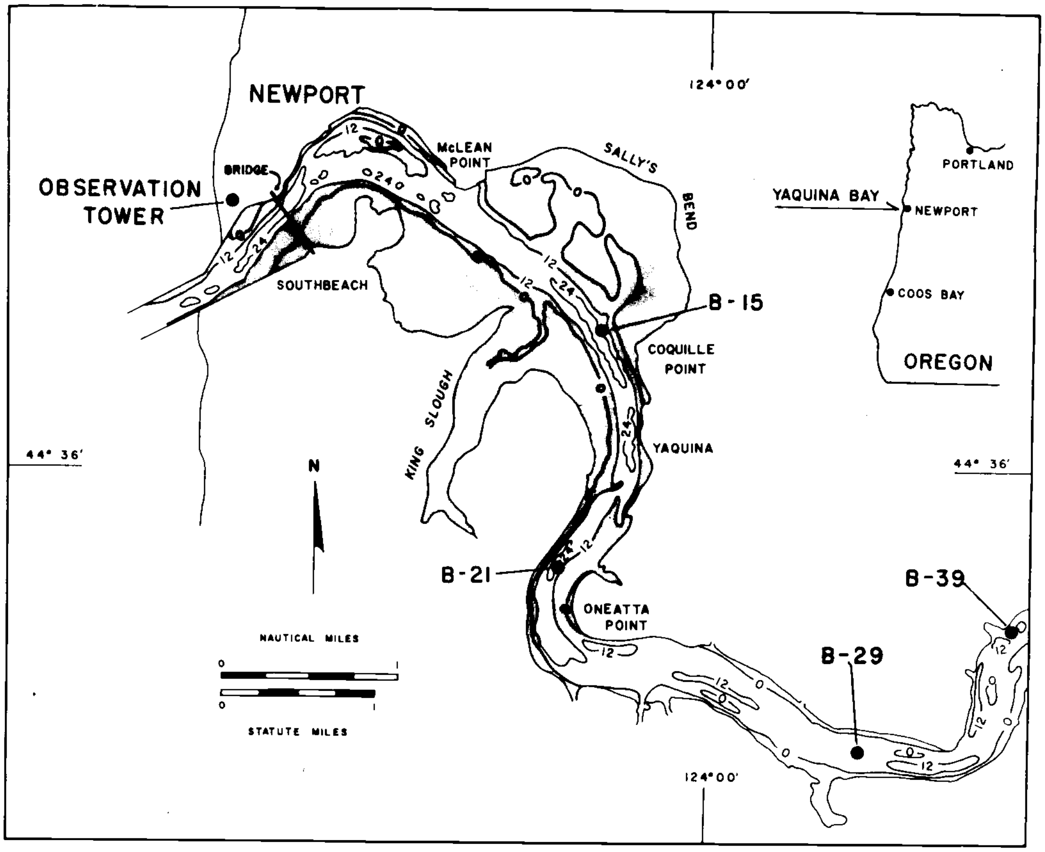


Figure 1. Bathymetry of Yaquina Bay. Indicated also are the sampling stations at Buoys 15, 21, 29 and 39.

Source: Kulm and Byrne, 1966.

DATA COLLECTION

Procedure

Since early in 1960 hydrographic and biological sampling have been undertaken on a weekly basis at selected stations in Yaquina Bay and River (Frolander, 1960-1967). The sampling has been performed from a small boat by students in biological oceanography at Oregon State University. Sampling has been done primarily at four mid-channel stations -- Buoys 15, 21, 29, and 39; occasionally stations were made off the Marine Science Center (Buoys 8 or 9) and under the Yaquina Bay bridge. Figure 1 shows the location of the sampling stations and the approximate water depth at each station.

Surface samples were collected for salinity and dissolved oxygen determination; surface temperatures were determined using a bucket thermometer. To obtain bottom samples a Nansen bottle with one reversing thermometer was lowered to within a meter of the bottom. Upon retrieving the cast, the temperature was read and the samples were drawn for salinity and dissolved oxygen analyses. The oxygen samples were then immediately "pickled" with manganous sulphate reagent and alkaline iodide solution. The concentrated sulphuric acid was not added until several hours later when the oxygen analysis was performed at the Oceanography

Building on the Oregon State University campus in Corvallis, using the modified Winkler method (Strickland and Parsons, 1965).

The salinity of the water was measured by personnel at the Marine Science Center in Newport, using an inductive salinometer. Prior to January 1963, salinity was determined by titration with silver nitrate.

Upon completion of the hydrographic sampling phase at each station, plankton samples were collected by towing two Clark-Bumpus samplers utilizing number 6 and 12 mesh nets and then towing a half-meter net. All tows were generally upstream at bottom, mid-depth and surface levels. No attempt will be made in this paper to correlate the physical and biological oceanographic data.

DATA ANALYSIS

Hydrographic Data

As indicated in the previous section, temperature, salinity, and dissolved oxygen concentration were measured weekly throughout the year at four stations in the Yaquina estuary. Upwelling off the Oregon coast is known to occur during the summer months. A perusal of the data led to the conclusion that only data from the months of May through October were necessary in order to encompass the upwelling season. Measurements were made at the surface and about one meter from the bottom at each station. In order to observe the oceanic effects within the estuary only the bottom measurements were evaluated. This minimized the external influences of heating by solar radiation and dilution by river runoff and precipitation. Although the effects of dilution were small for most of the six month periods under consideration, the effects of heating could be quite noticeable. For example, at high water the surface temperature at Buoy 15 was usually about one degree centigrade warmer than the bottom water; at low tide this difference could amount to four degrees.

Because the water depth in the estuary was so shallow at low tide (five to six meters at Buoys 15 and 21; two to three meters at Buoys 29 and 39), the water was subject to extreme fluctuations in temperature and salinity between high and low tide. At Buoy 15, for instance, the water temperature would increase from 8 to 9° C at high tide to 13-14° C at low tide. Salinity changes between high and low tide were about 2°/oo near the estuary entrance and about 4°/oo above Buoy 29. It was obvious, therefore, that only measurements made at high tide would lead to a valid interpretation of oceanic conditions.

Tidal Analysis

Because no attempt was made to synchronize the time of sampling with the tides, it was necessary to determine which observations were made during periods of high tide. Establishing that an observation was taken during the time of high water proved to be somewhat subjective. The time of each observation was compared with the predicted time of high tide from the Tide Tables of the U. S. Coast and Geodetic Survey (U. S. C. and G. S., 1960-1967). The predicted high water time used was that computed for the town of Yaquina, this being the closest point to Buoy 15. Neal (1966) in a paper on tidal currents in Yaquina Bay, stated that the predicted times were generally good, although nearly all were earlier than the observed tide by 30 minutes or less. In August 1963 at Buoy 15 and in September 1966 at Buoy 21 observations were made every hour for a period of 27 and 24 hours, respectively. The observed temperature and salinity were plotted and the predicted time of the tide indicated (Figures 2 and 3). In each case the predicted high tide occurred earlier than the observed high tide in concurrence with Neal's conclusions. Based on the temperature curve the duration of the high tide was approximately three hours; this was the length of time that the temperature remained at a minimum. In order to include as many observations as possible, the high tide "window," or duration time, was determined to be one-half hour prior to the time of the predicted high tide and two hours after it; observations falling within this two and one-half hour window were included, all others were rejected as not being truly representative of oceanic conditions as discussed previously.

Upon examining the data using the above criterion, it soon became evident that only at Buoy 15 were there enough high tide observations to warrant a statistical analysis of upwelling conditions. At each of the other three stations up river, only two or three observations out of a total of 17-20 for each six month period fell within the high tide "window;" all others were made at low or trans-tidal conditions.

Wind Analysis

As coastal upwelling is intrinsically dependent upon wind velocity in both magnitude and direction, wind data was required to

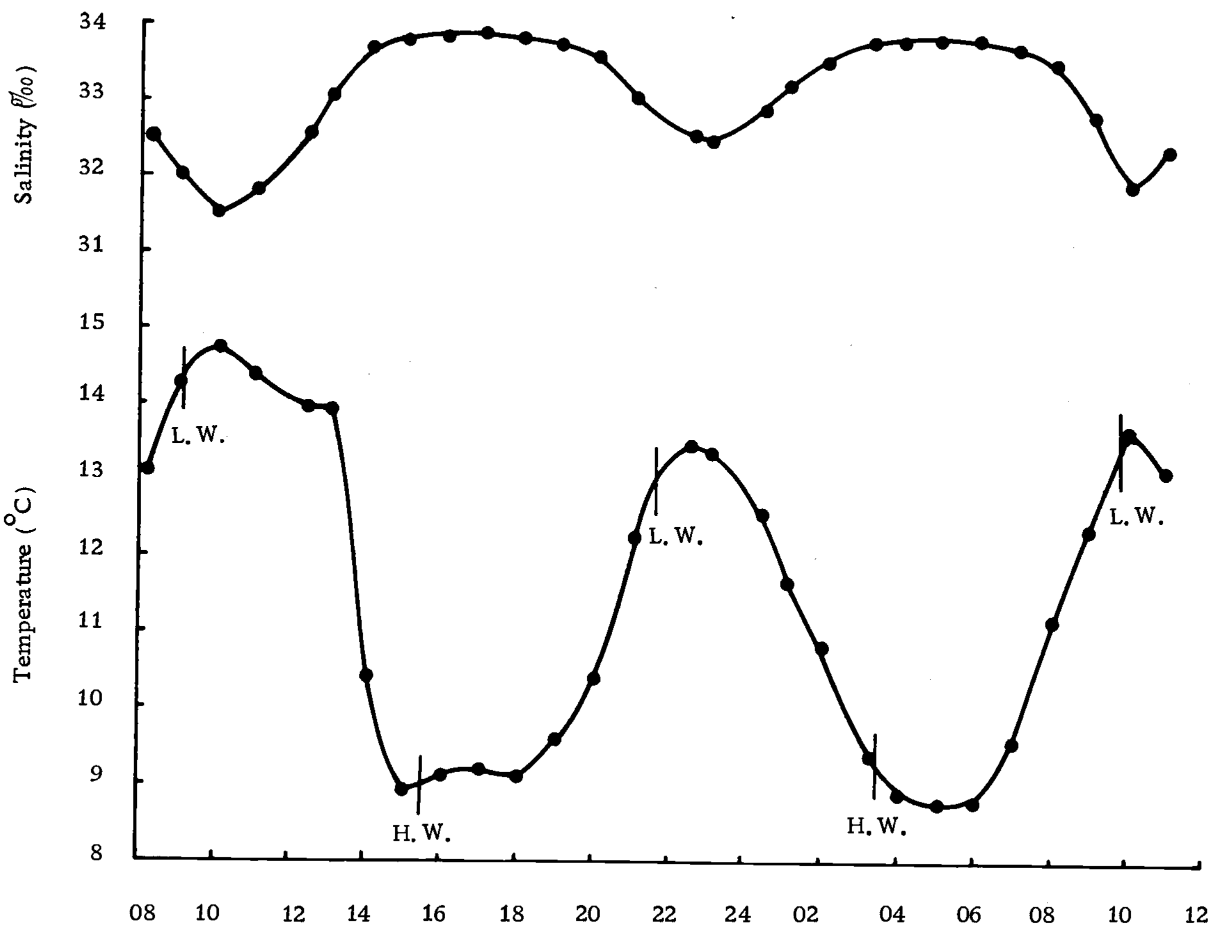


Figure 2. Temperature and salinity of Buoy 15 measured over 27 hour period, 9-10 August 1963. Times of predicted high and low water are indicated.

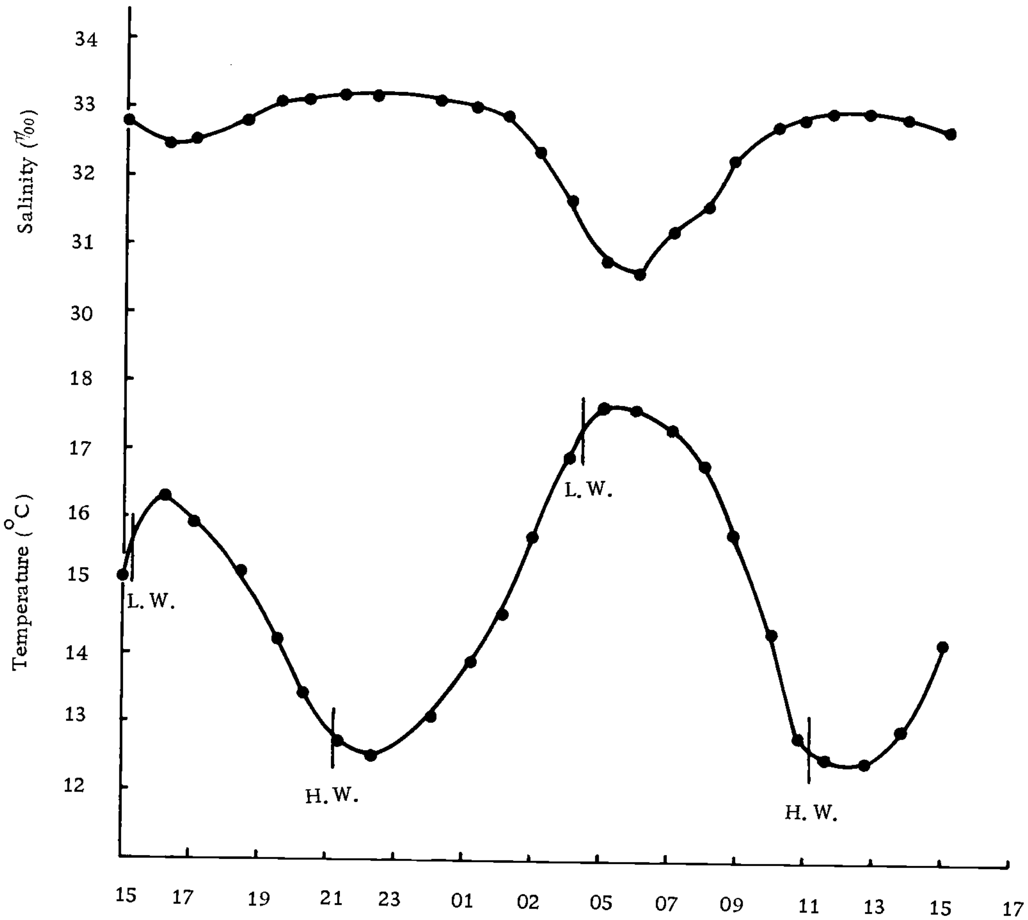


Figure 3. Temperature and salinity at Buoy 21 measured over 24 hour period, 11-12 September 1966. Times of predicted high and low water are indicated.

correlate the temperature, salinity and dissolved oxygen data at Buoy 15 in the estuary with upwelling off the coast. Local wind observations are recorded every four hours by Coast Guard personnel at the observation tower near the entrance to Yaquina Bay. The Coast Guard Station at Newport maintains only a three year backlog of wind records; therefore, wind data was readily available only for the years 1965, 1966, and 1967 (U. S. Coast Guard Station, 1965-1967). Wind speed and direction are continuously indicated on meters in the tower. Observations recorded in the log book should be an average of the conditions over the four-hour period. However, due to the inexperience of the observers, the recorded values may, in fact, be instantaneous values existing only at the time they were logged in. It was thought that because the wind velocity was to be averaged over a three or four day period (18 to 24 observations) that this possible error would be negligible.

The wind speed recorded for 1965 and part of 1966 were measured in units of the Beaufort scale. After September 1, 1966, all wind speed values were recorded in knots. The conversion of Beaufort wind data to knots allows a four to five knot variability to enter for wind speeds greater than 12 knots. Accordingly, the central or mid-value was used. For example, if the wind speed were recorded as five on the Beaufort scale, which encompasses a range from 17 to 21 knots, a value of 19 knots was used. This was thought to have not biased the data in either direction.

After all the wind speed observations had been converted to knots, the north-south and east-west components of the wind were computed for each observation.

Dissolved Oxygen

The concentration of dissolved oxygen measured at Buoy 15 was analyzed to determine its use as an indicator of upwelling. In order to limit the variability of dissolved oxygen concentration due to changes in temperature and salinity, the percent saturation of oxygen was computed. It is determined from the ratio of the observed oxygen concentration to the solubility of oxygen in the water sample. The solubility of oxygen is a function of the water temperature and salinity. The solubility was computed from tables derived by Carpenter (1966) and further modified by Gilbert et. al. (1968). Temperatures and salinities were those of the bottom water of Buoy 15. The percent saturation values were then plotted for each observation. Many extremely high and erratic percentages (140-160%) were noted and felt to be unrealistic; further investigation indicated that the saturation values prior to July 1966 were suspect due to questionable analytical techniques. Prior to July 1966 the time period between adding the manganous sulphate reagent and alkaline iodide solution and adding the sulphuric acid was quite variable and excessively long -- from seven to thirty days. It is probable that the oxygen content in the samples was increased during the time between pickling and titrating. Since July 1966, however, the samples have been analyzed for dissolved oxygen content within just a few hours after having been drawn from the Nansen bottle. Since this procedure yields more reliable results, only oxygen samples taken since July 1966 will be considered in this report.

Summary

In order to see the effects of upwelling in the Yaquina estuary temperature and salinity measurements of the bottom water at Buoy 15 were plotted for each observation that occurred at high tide during the months of May through October. The results for the years 1965 through 1967 are presented in Figure 4. Percent saturation of oxygen is included for 1966 and 1967. The rise and fall in temperature is well correlated with the fluctuations in oxygen saturation. Salinity minima are correlated with temperature and saturation maxima to a remarkable degree. These fluctuations of oceanic water conditions within the estuary indicate that the characteristic effects of upwelling can be observed in an estuary. Temperature and oxygen saturation seem to be more sensitive to changes in the degree of upwelling than salinity as indicated by the magnitude of their fluctuations. Because the dissolved oxygen data

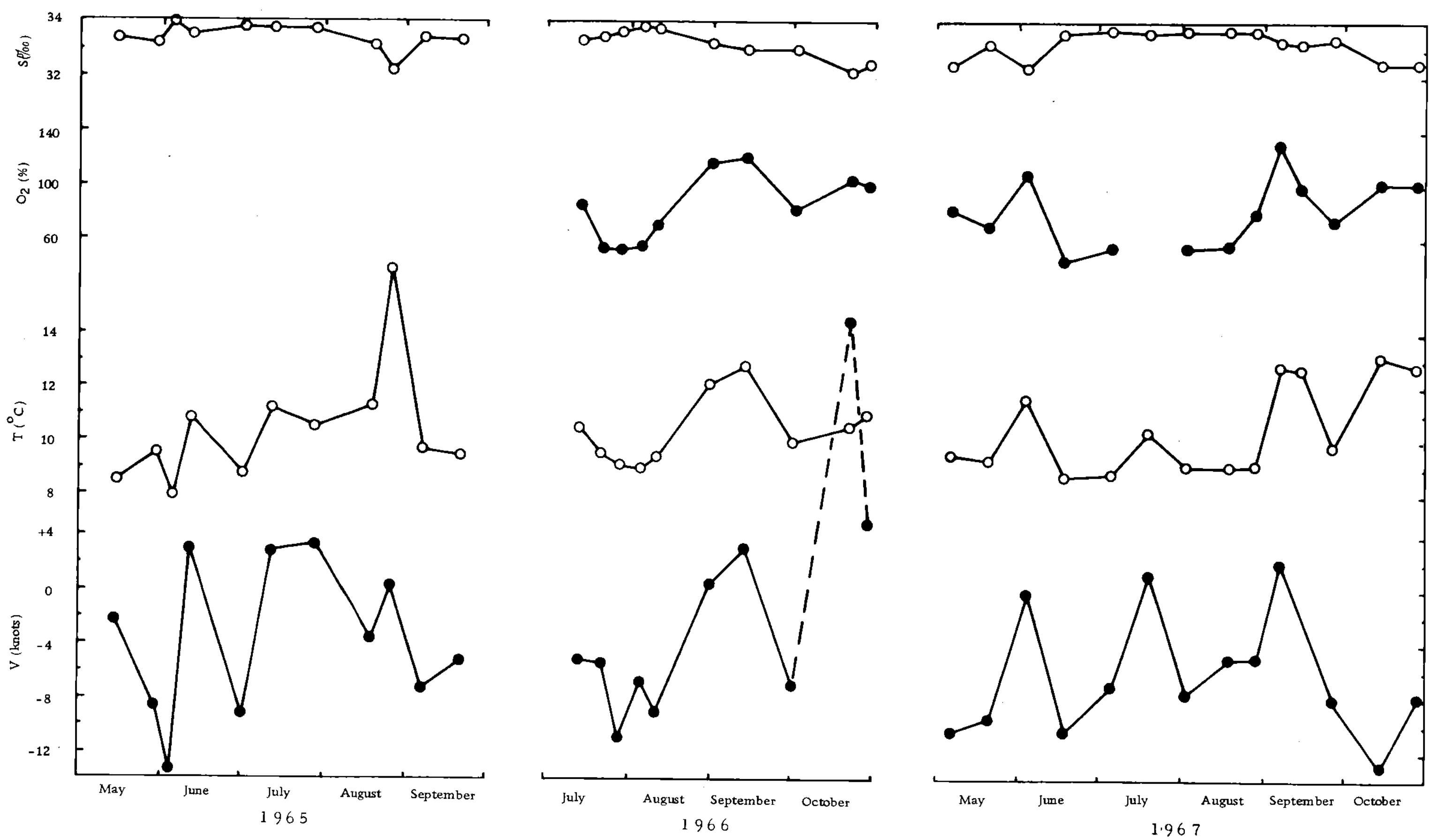


Figure 4. Plot of temperature, salinity, percent oxygen saturation, and north-south component of wind velocity measured at Buoy 15 during the summer months 1965-1967.

was so limited, temperature has been used as the primary indicator of upwelling.

STATISTICAL ANALYSIS

General Considerations

In his study of upwelling off Oregon, Smith (1964, p. 73) concluded that "coastal upwelling --- is clearly associated with a northerly wind stress." However, there are only indirect and approximate methods for obtaining values of wind stress. It also was felt preferable to do the statistical analysis in directly measurable quantities. Therefore, wind velocity instead of wind stress is used in this study.

As the intensity and duration of the northerly component of the wind increases, the volume of upwelled water increases causing the temperature and oxygen concentration of the water in the upwelled region to further decrease and the salinity to increase. To further establish that the fluctuations of temperature, salinity, and oxygen in the estuary were the result of upwelling, wind observations were evaluated to determine the correlation between the observed wind and the water temperature measured at Buoy 15. If the water temperature were responding to the wind induced upwelling, then clearly one could expect the water temperature to decrease with increasing wind speed from the north. To this end a regression analysis was performed on the temperature and wind data. A perfect or near perfect correlation of wind velocity and water temperature is not expected. Other factors may also influence the temperature of the water such as local heating, cloud cover, rainfall and evaporation and mixing.

Components of the Wind

Upwelling associated with Ekman type transport of surface waters off Oregon is primarily a function of the "v" component of the wind, i. e., a wind from the north. Surface waters may also be transported offshore with subsequent upwelling by a wind from the east (Hidaka, 1954).

Because wind observations were recorded every four hours, it was necessary to establish an average wind velocity over a given period of time for each temperature observation. Panshin (1967) has shown that fluctuations in sea level are related to upwelling and that these fluctuations are best correlated when the wind has been blowing from a favorable direction for a period of about three days. Therefore, as a first attempt, an average wind value was calculated by averaging the wind observations for the day the temperature measurement was made plus the wind observations from the two preceding days. Averaging was done for both the north-south and east-west components of the wind.

During the summer months the wind is generally out of the north or northwest. Easterly and westerly winds are not frequent and are of small velocity when present. As expected, the magnitude of the averaged east-west component was quite small. A regression of "u", the east-west component, versus bottom temperature at Buoy 15 showed wide scatter indicating almost no temperature dependence on an east-west wind. Since the scatter was so great and the magnitude of the east-west component so small compared to the north-south component, it was decided to eliminate the "u" component of the wind from any further consideration.

The north-south component of the wind averaged over three days was also plotted against temperature. Here the dependence of temperature on wind velocity was quite good. This three day average wind was also plotted on Figure 4. A comparison of the temperature and wind graphs clearly shows the two are related. Cooler temperatures are associated with strong winds from the north -- a condition expected during the upwelling season. Warmer temperatures result when the wind is from the south or is calm.

Regression Procedure

To test the dependency of the temperature on the velocity of the north-south wind component, a regression analysis was performed. The wind observations were averaged for a period of three days. The scatter in the plot of temperature versus wind velocity (Figure 5) produced a horn shaped figure.

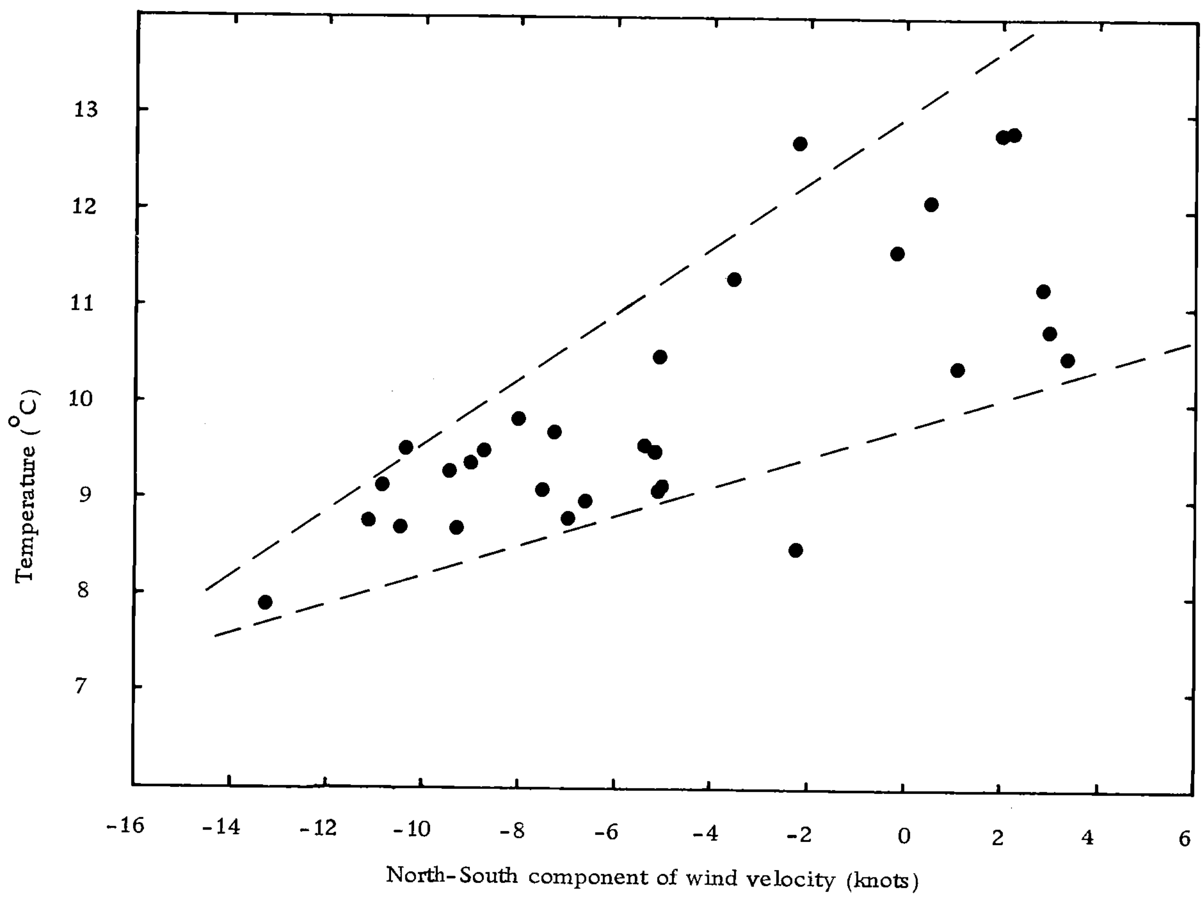


Figure 5. Graph of water temperature at Buoy 15 versus north-south component of wind velocity. The wind velocity is a simple average over a three day period. Note that the scatter is approximately horn-shaped.

The regression analysis of temperature on wind velocity was calculated as follows:

a) A linear model was assumed of the form

$$y = \alpha + \beta\, A(v) + \epsilon \tag{1}$$

where y is the observed temperature, A(v) is the averaged wind velocity, and ϵ is the error from the regression model.

b) The estimated regression of temperature on wind velocity is

$$\tilde{y} = \tilde{\alpha} + \tilde{\beta}\, A(v) \tag{2}$$

where the "tilde" symbol indicates that this term is the estimate of the corresponding term in equation (1).

c) $\tilde{\alpha}$ and $\tilde{\beta}$ were determined by the method of least squares.

d) The error term, e, is the difference between the observed and estimated temperatures, i. e.,

$$e = y - \tilde{y} \tag{3}$$

e) One of the assumptions implicit in regression analysis is that the variance of the error term be the same for every observation,

$$\mathrm{Var}\ (\epsilon) = \sigma^2 . \tag{4}$$

From Figure 5 it is obvious that the errors do not have a common variance, but are dependent upon the wind velocity,

$$\mathrm{Var}\ (\epsilon) = \sigma^2(v) . \tag{5}$$

If equation (1) is normalized by dividing each term by the standard deviation of the error, $\sigma(v)$, then the assumption that all the errors have a common variance can be achieved. This is seen as follows:

let $$z = \frac{y}{\sigma(v)} = \frac{\alpha + \beta\ A(v) + \epsilon}{\sigma(v)} \tag{6}$$

or $$z = \alpha r + \beta s + \eta \tag{7}$$

where $r = \frac{1}{\sigma(v)}$, $s = \frac{A(v)}{\sigma(v)}$, and $\eta = \frac{\epsilon}{\sigma(v)}$;

then, $\text{Var}(\eta) = \text{Var}\ \frac{\epsilon}{\sigma(v)} = \frac{1}{\sigma^2(v)}\ \text{Var}\ \epsilon$;

but from equation (5) $\text{Var}\ \epsilon = \sigma^2(v)$

therefore, $\text{Var}(\eta) = \frac{\sigma^2(v)}{\sigma^2(v)} = 1$

f) $\sigma(v)$, is then, the standard deviation of the un-normalized errors and may be determined from a regression of the absolute value of the error term (equation (3)) on wind velocity. This regression may be estimated by

$$\hat{\sigma}(v) = \hat{\delta} + \hat{\gamma}\ A(v) \tag{8}$$

where $\hat{\delta}$ and $\hat{\gamma}$ are determined by least squares analysis.

g) Lastly, a least squares analysis is performed on the fitted equation

$$\hat{z} = \hat{\alpha} r + \hat{\beta} s \tag{9}$$

where $\hat{z} = \hat{y}/\hat{\sigma}(v)$ (10)

and is the normalized estimate of the regression of temperature on wind velocity.

Weighted Wind Averages

To determine if the correlation between temperature and wind velocity could be improved, weighted averages of the wind observations were used. Twenty-four observations (six observations per day) of the wind were considered sufficient to describe the wind regime prior to the time the temperature observation was made. The 24 observations were grouped by days (a day being the 24 hours prior to the temperature measurement and not a calendar day) and weighted according to the schemes listed in Table I.

Table I
Weighting Schemes Attempted

First 24 hours prior to temperature measurement	Second 24 hour period	Third 24 hour period	Fourth 24 hour period
1	1	1	1
1	2	2	1
1	2	3	2
1	1	2	2
1	1	2	3
2	2	1	1
2	1	1	1
1	2	1	1
1	1	2	1
1	1	1	2
1	3	2	1

The regression procedure described in steps (a) through (g) was repeated for each average wind velocity obtained by varying the weighting factors. The weighted average, A(v), which produced the lowest variance from the estimated regression line, $\hat{\sigma}^2$, would provide the best correlation between temperature and wind velocity.

Results of Weighting

The results of this analysis were somewhat surprising. It was initially thought that the first and second 24 hour periods would have to be weighted more heavily than the later 24 hour periods. However, minimum variance occurred whenever the third day preceding the temperature measurement was weighted the heaviest of the four days. The smallest variance occurred when the weighting scheme was 1, 2, 3 for the first three preceding days and 3, 3, 3, 2, 2, 1 for the last six observations of the fourth day. The weighting scheme 1, 1, 2, 1 was the next best one; its variance was only 0.4% greater than the former scheme. Weighting the first day produced the largest variance, increasing it by about 40.0%. Various combinations of weighting schemes wherein the second, third, and fourth days were weighted concurrently produced moderate variances differing only by about 3 to 12%. The variance of the non-weighted uniform weighting scheme (1, 1, 1, 1) was only 12% larger than the best scheme.

The following tables are presented to clarify the results.

Table II
Weighting Schemes Indicating the Importance of Weighting the Third Day Preceding the Temperature Observation

First Day	Second Day	Third Day	Fourth Day	Variance
2	1	1	1	1.849
1	2	1	1	1.639
1	1	2	1	1.330
1	1	1	2	1.578
1	1	1	1	1.487

Table III
Weighting Schemes Wherein the First Two Days Preceding the Temperature Observation are Weighted Heavier

First Day	Second Day	Third Day	Fourth Day	Variance
2	1	1	1	1.849
2	2	1	1	1.771

Table IV
Weighting Schemes Indicating the Relative Unimportance of the Fourth Day

First Day	Second Day	Third Day	Fourth Day	Variance
1	1	2	1	1.330
1	1	2	2	1.441
1	1	2	3	1.511
1	1	1	2	1.578

Table V
Various Combinations of Weighting Schemes

First Day	Second Day	Third Day	Fourth Day	Variance
(a) 1	1	2	1	1.330
(b) 1	2	3	2	1.365
(c) 1	1	2	2	1.441
(d) 1	1	1	1	1.487
(e) 1	2	2	1	1.490

Table II shows that the third day back from the time of the temperature observation is the most important period. Table III shows the fallacy of weighting the first two days preceding the temperature observation. Table IV shows the relative unimportance of the fourth day. Table V presents various combinations of weighting schemes most of which result in small variances. Scheme (d) indicates that the uniform weighting scheme, though not having the lowest variance, has the advantage of being simple and direct and yet quite acceptable.

From the above it can be concluded that a weighted average produces less variance in temperature than a non-weighted uniform average although the improvement in accuracy is not appreciably larger and may be compensated by the ease with which the latter may be computed. Weighting the third day produces the best results. Weighting the first two days produces the largest deviations indicating that the water temperature is dependent upon the wind conditions generated over a three to four day period.

Assuming that the simple non-weighted wind average describes the wind regime with sufficient accuracy, the results of the regression analysis are as follows:

$$\tilde{y} = \tilde{\alpha} + \tilde{\beta}\, A(v) = 11.110 + 0.223\, A(v)$$

$$\hat{\sigma}(x) = \hat{\delta} + \hat{\gamma}\, A(v) = 0.861 + 0.048\, A(v)$$

$$\hat{z} = \hat{\alpha} r + \hat{\beta} s = 11.100 + 0.221\, A(v)$$

with an estimated variance $\hat{\sigma}^2 = 1.487$.

Confidence Interval

In addition to fitting a line through the data points, as described in the previous section, a 95 percent confidence interval on the regression line was determined as follows:

a) From equations (9) and (10)

$$\hat{z} = \frac{\hat{y}}{\hat{\sigma}(v)} = \hat{\alpha}\, r + \hat{\beta}\, s$$

b) The variance of $\hat{z}$ is

$$\mathrm{Var}\,(\hat{z}) = \frac{\mathrm{Var}\,\hat{\alpha} + A^2(v)\ \mathrm{Var}\,\hat{\beta} + 2\,A(v)\ \mathrm{Cov}\,(\hat{\alpha},\hat{\beta})}{\hat{\sigma}(v)^2} \qquad (11)$$

c) Note that

$$\frac{\hat{z} - E(z)}{\sqrt{\mathrm{Var}\,(\hat{z})}} \quad \text{is a t distribution}$$

d) Then

$$\left|\hat{z} - E(z)\right| \leq t_{.025(n-2)}\sqrt{\mathrm{Var}(\hat{z})} =$$

$$t_{.025(n-2)}\sqrt{\frac{\mathrm{Var}\ \hat{\alpha} + A^2(v)\ \mathrm{Var}\,\hat{\beta} + 2A(v)\ \mathrm{Cov}\,(\hat{\alpha},\hat{\beta})}{\hat{\sigma}(v)^2}} \qquad (12)$$

e) If the substitution indicated by equation (10) is made

$$\left|\hat{y} - E(y)\right| \leq t_{.025(n-2)}\sqrt{\mathrm{Var}\,\hat{\alpha} + A^2(v)\ \mathrm{Var}\,\hat{\beta} + 2\,A(v)\ \mathrm{Cov}\,(\hat{\alpha},\hat{\beta})} \qquad (13)$$

which can be rewritten as

$$E(y) - t_{.025(n-2)}\sqrt{\mathrm{Var}\,\hat{\alpha} + A^2(v)\ \mathrm{Var}\,\hat{\beta} + 2A(v)\ \mathrm{Cov}\,(\hat{\alpha},\hat{\beta})} \leq \hat{y} \leq$$

$$E(y) + t_{.025(n-2)}\sqrt{\mathrm{Var}\,\hat{\alpha} + A^2(v)\ \mathrm{Var}\,\hat{\beta} + 2A(v)\ \mathrm{Cov}\,(\hat{\alpha},\hat{\beta})} \qquad (14)$$

Prediction Limits

To be able to predict the water temperature from a knowledge of the past wind requires a set of prediction limits about the regression line. Because the water temperature is a function of the wind velocity averaged over four days, a prediction 24 hours in advance of the last wind observation appeared to be optimum. Therefore, a new four day average of the wind was determined wherein the first six observations were set equal to zero to represent the 24 hour prediction period. A regression analysis was run to determine the best wind average using the same procedure as described previously. Table VI lists the weighting schemes attempted and the resultant variances.

Table VI

Weighting Schemes for Prediction With Resultant Variance. Note the first day weights are zero to account for the 24 hour prediction period.

First Day	Second Day	Third Day	Fourth Day	Variance
0	1	3	2	1.471
0	2	2	1	1.534
0	1	2	1	1.541
0	1	1	1	1.546
0	3	2	1	1.588

Here, as before, when the third day is weighted heavier than the others, minimum variance results. Because of the simplicity of the uniform weighting scheme (0, 1, 1, 1) and the fact that its variance is only 4.0% greater than the uniform weighting scheme when the first six observations are included, the prediction limits were determined from the regression line based on this wind average.

The prediction limits were obtained following the procedure discussed in Draper and Smith (1966).

a) Let y^* be the predicted temperature and

$$z^* = y^* / \hat{\sigma}_{(v)} . \tag{15}$$

b) Note that $z^* - \hat{z}$ has zero expectation and variance

$$\begin{aligned}
\mathrm{Var}\,(z^* - \hat{z}) &= \hat{\sigma}^2 + r^2 \,\mathrm{Var}\,\hat{\alpha} + s^2\,\mathrm{Var}\hat{\beta} + 2rs\,\mathrm{Cov}(\hat{\alpha}, \hat{\beta}) \\
&= \hat{\sigma}^2 + \frac{\mathrm{Var}\,\hat{\alpha} + A^2_{(v)}\mathrm{Var}\,\hat{\beta} + 2A_{(v)}\,\mathrm{Cov}\,(\hat{\alpha}, \hat{\beta})}{\hat{\sigma}^2_{(v)}} \\
&= \hat{\sigma}^2 + \frac{\mathrm{Var}\,\hat{\alpha} + A^2_{(v)}\,\mathrm{Var}\,\hat{\beta} + 2A_{(v)}\,\mathrm{Cov}\,(\hat{\alpha}, \hat{\beta})}{\left[\hat{\delta} + \hat{\gamma} A_{(v)}\right]^2} .
\end{aligned} \tag{16}$$

c) Also since $\dfrac{z^* - \hat{z}}{\sqrt{\mathrm{Var}(z^* - \hat{z})}}$ is a t distribution with (n-2) degrees of freedom

d) then,

$$\hat{z} - t_{.025\,(n-2)} \sqrt{\mathrm{Var}(z^* - \hat{z})} \le z^* \le \hat{z} + t_{.025(n-2)} \sqrt{\mathrm{Var}(z^* - \hat{z})} . \tag{17}$$

e) Making the substitutions indicated by equations (10) and (15)

$$\hat{y} - t_{.025(n-2)}\, \hat{\sigma}_{(v)} \sqrt{\mathrm{Var}(z^* - \hat{z})} \le y^* \le \hat{y} + t_{.025(n-2)}\, \hat{\sigma}_{(v)} \sqrt{\mathrm{Var}\; z^* - z} \tag{18}$$

or,

$$\hat{y} - t_{.025(n-2)} \sqrt{Q} \leq y^{*} \leq \hat{y} + t_{.025(n-2)} \sqrt{Q} \tag{19}$$

where $Q = \hat{\sigma}^2 \; \hat{\sigma}_{(v)}^{\;2} + \text{Var}\,\hat{\alpha} + A^2_{(v)} \,\text{Var}\,\hat{\beta} + 2A_{(v)}\,\text{Cov}(\hat{\alpha}, \hat{\beta})$.

The results of the regression analysis using the prediction model are summarized as follows:

$$\tilde{y} = \tilde{\alpha} + \tilde{\beta}\, A_{(v)} = 10.880 + 0.194\, A_{(v)}$$

$$\hat{\sigma}(v) = \hat{\delta} + \hat{\gamma}\, A_{(v)} = 0.845 + 0.042\, A_{(v)}$$

$$\hat{z} = \hat{\alpha}\, r + \hat{\beta}\, s = 10.784 + 0.178\, A_{(v)}$$

with an estimated variance $\hat{\sigma}^2 = 1.546$

The estimates of the variance and covariance terms for the confidence and prediction limits were computed from the following equations:

$$\widehat{\text{Var}\;\hat{\alpha}} = \hat{\sigma}^2 \frac{\sum_{i=1}^{n} s_i^2}{\left(\sum_{i=1}^{n} r_i^2\right)\left(\sum_{i=1}^{n} s_i^2\right) - \left(\sum_{i=1}^{n} r_i s_i\right)^2} = 0.065$$

$$\widehat{\text{Var}\;\hat{\beta}} = \hat{\sigma}^2 \frac{\sum_{i=1}^{n} r_i^2}{\left(\sum_{i=1}^{n} r_i^2\right)\left(\sum_{i=1}^{n} s_i^2\right) - \left(\sum_{i=1}^{n} r_i s_i\right)^2} = 0.001$$

$$\widehat{\text{Cov}\;(\hat{\alpha}, \hat{\beta})} = \hat{\sigma}^2 \frac{\left(-\sum_{i=1}^{n} r_i s_i\right)}{\left(\sum_{i=1}^{n} r_i^2\right)\left(\sum_{i=1}^{n} s_i^2\right) - \left(\sum_{i=1}^{n} r_i s_i\right)^2} = 0.006$$

Discussion

The regression of temperature on wind velocity is shown in Figure 6 along with the 95 percent confidence interval about the regression line and the prediction limits for determining the water temperature when the wind field is known. From this figure and Figure 4 it is apparent that the wind and temperature are reasonably well correlated when the wind is blowing strongly out of the north, i. e., the temperature decreases as the wind speed of a northerly wind increases. Temperature, salinity, and oxygen saturation values are also typical of the subsurface oceanic waters which are brought to the surface near the coast during upwelling. Thus it can be concluded that the fluctuations in temperature, salinity, and oxygen saturation measured in the estuary are directly related to upwelling off the coast. Further, the correlation of temperature and wind velocity is best when the velocity of the wind is averaged over the four days prior to the time of the temperature observation.

When the wind speed drops to less than three knots or shifts direction and blows from the south, the temperature dependency upon the wind velocity is not good. Coastal upwelling may subside or even cease and the water entering on the flood tide then becomes warmer and less saline which is more typical of the surface oceanic water outside the upwelling region. Since this water remains on the

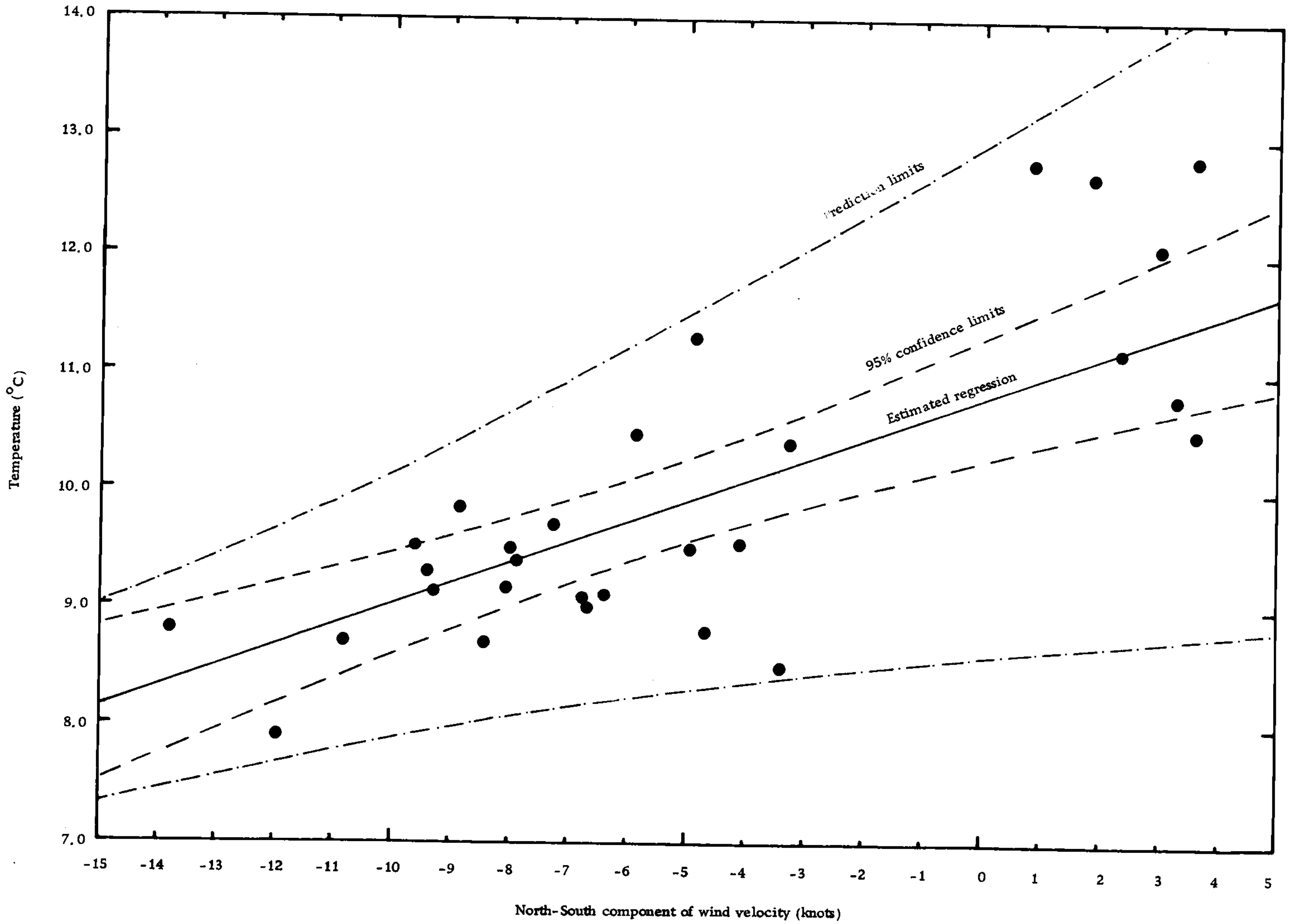


Figure 6. Regression analysis of temperature on wind velocity. Wind average determined by 0, 1, 1, 1 weighting scheme.

surface during periods when upwelling is relaxed and is not continually being renewed with subsurface water, as is the case when upwelling is active, the temperature of the water may be influenced by many local processes which are not directly related to the winds, such as local heating, evaporation and precipitation, mixing with other waters, and mixing with river water. Predicting the temperature under these conditions is a doubtful process as the prediction limits are based upon a temperature-wind relationship under strong upwelling conditions when local heating effects are minimized.

OTHER OBSERVATIONS

Origin of Upwelled Water

It is interesting to speculate on the origin of the bottom water at Buoy 15. Assuming that this water is upwelled coastal water that has been swept in with the flood tide, then one should expect its temperature and salinity characteristics to be similar to that of the oceanic water just off the coast at Newport. Two sources of near shore data are available for comparison: (1) Station NH-5 (5 miles off the coast at Newport) which was sampled regularly on hydrographic cruises from the research vessels ACONA and YAQUINA of Oregon State University (O. S. U. Dept. of Oceanography, 1960-1967); and (2), the shore station at Otter Rock which was sampled weekly from 1961 to 1963 (O. S. U. Dept. of Oceanography, 1962-1963, 1965).

T-S diagrams from data at Station NH-5 were plotted whenever the date of the station corresponded closely to the date an observation was made at Buoy 15. These diagrams are presented in Figure 7. On each diagram are also the corresponding T-S of the bottom water at Buoy 15 and the T-S of the surface water measured at Otter Rock. It is hypothesized that the offshore water beyond the estuary entrance would enter the estuary on the flood tide. The sigma-t of this coastal water, as indicated on Figure 7, is high -- greater than 26.0 for all depths below ten meters. Collins (1964)

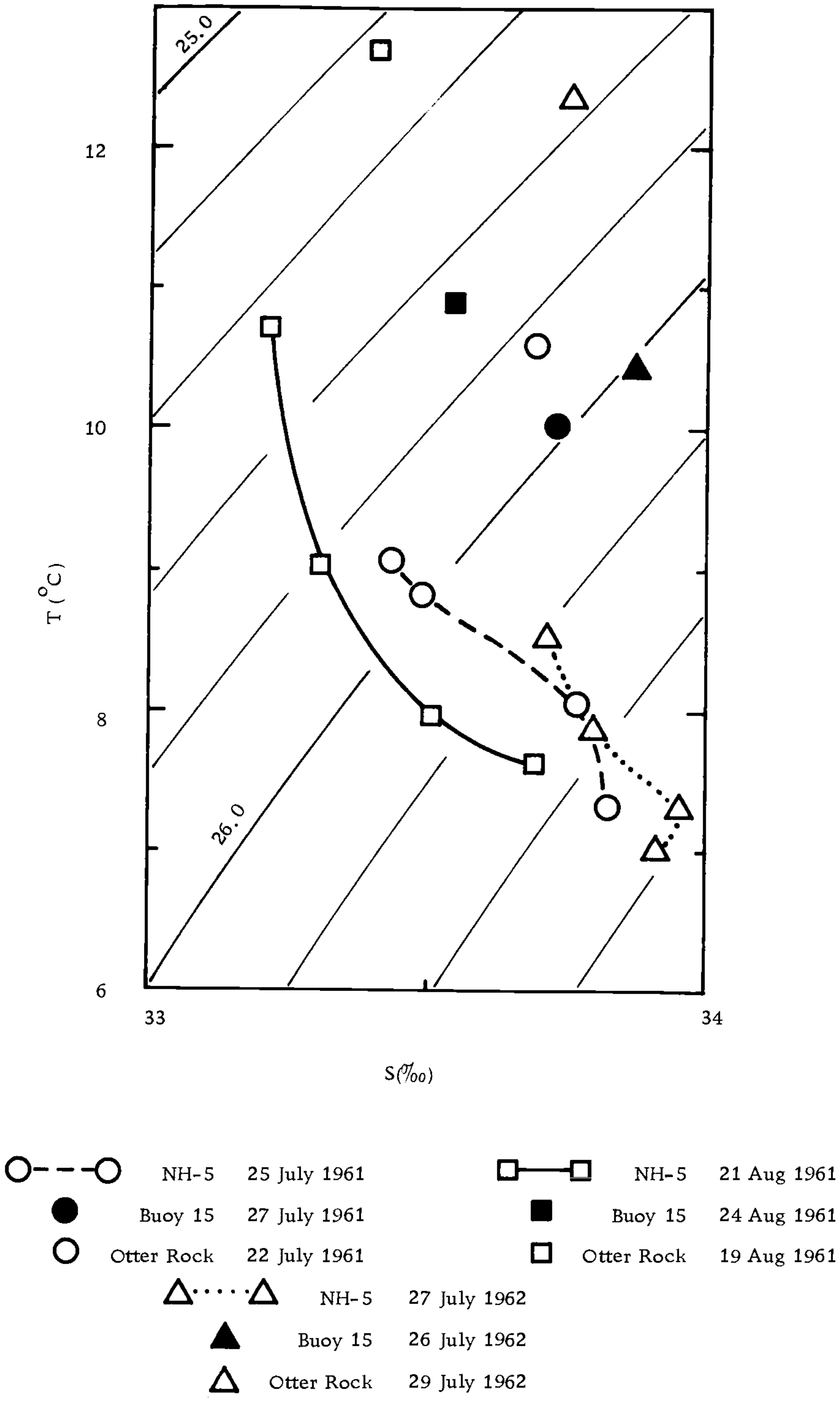
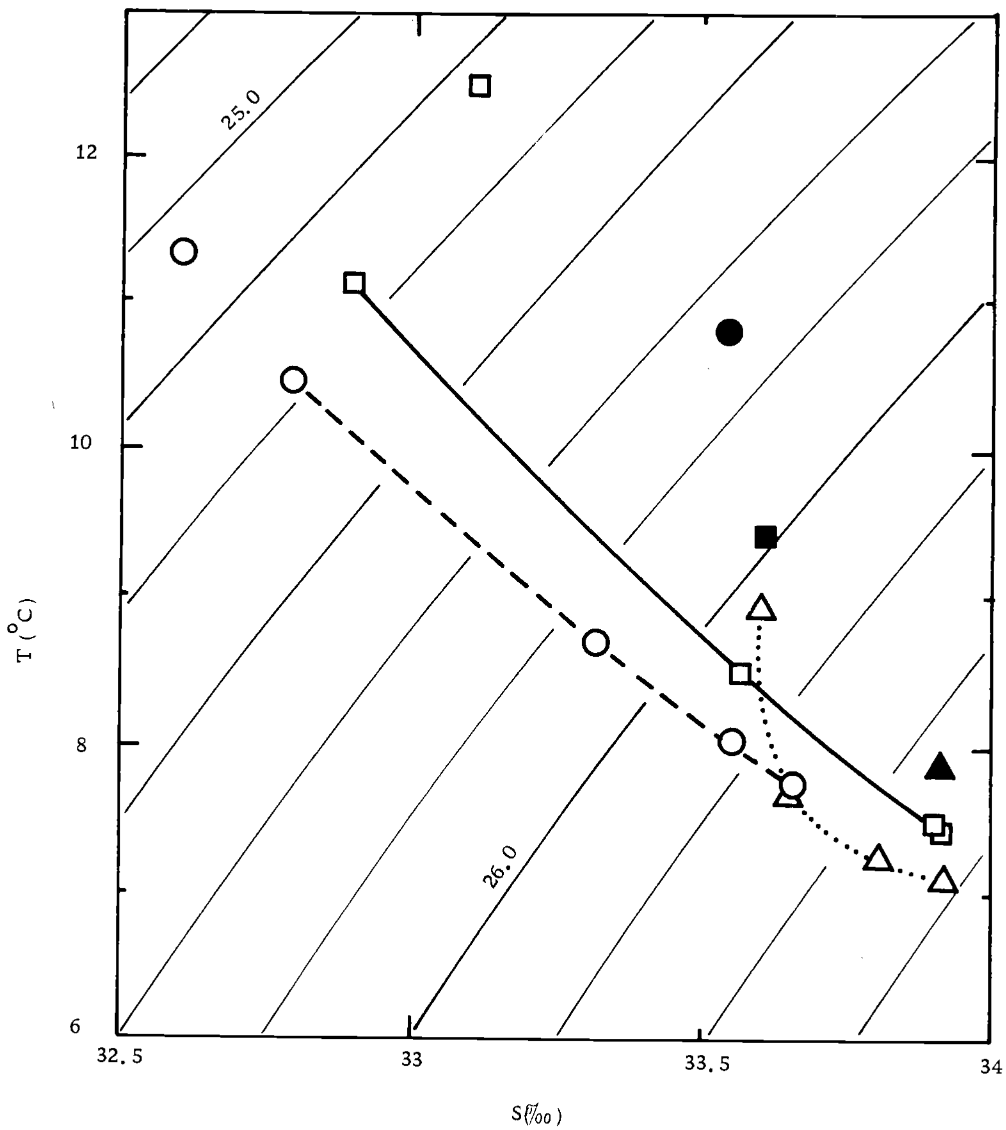


Figure 7a. T-S diagrams for NH-5, Buoy 15, and Otter Rock. Depths sampled at NH-5 are 0, 10, 20, and 30 meters.



O- - -O NH-5	4 Sept 1962		□——□ NH-5	16 July 1963
● Buoy 15	8 Sept 1962		■ Buoy 15	19 July 1963
O Otter Rock	2 Sept 1962		□ Otter Rock	13 July 1963
△· · · · △ NH-5	8 June 1965			
▲ Buoy 15	4 June 1965			

Figure 7b. T-S diagrams for NH-5, Buoy 15, and Otter Rock. Depths sampled at NH-5 are 0, 10, 20, and 30 meters.

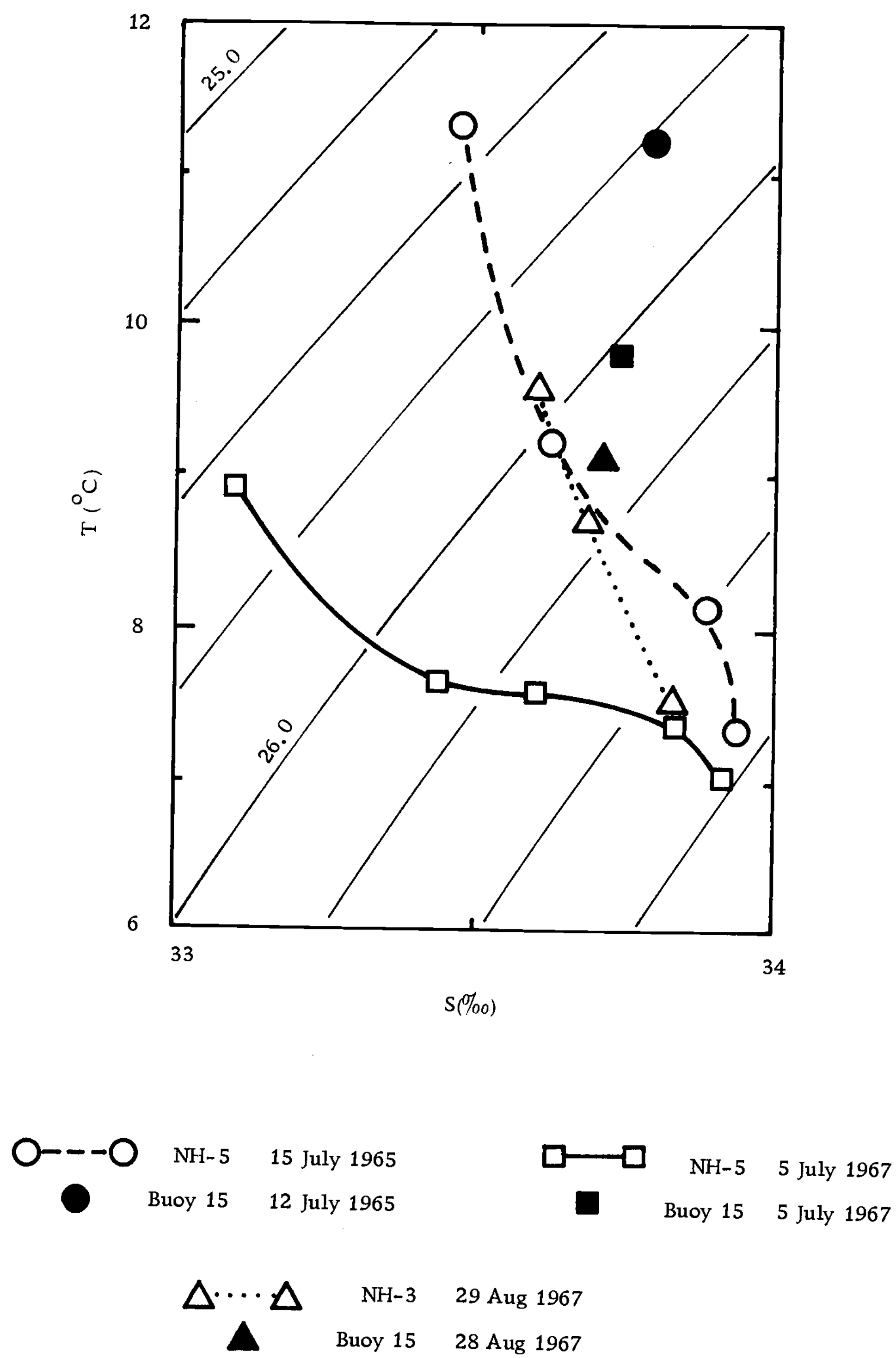


Figure 7c. T-S diagrams for NH-5, Buoy 15, and Otter Rock. Depths sampled at NH-5 are 0, 10, 20, and 30 meters.

has shown that the 26.0 sigma-t isopycnal delineates the permanent pycnocline, and that during times of active upwelling intersects the surface between five and 15 miles offshore. The sigma-t of the bottom water at Buoy 15 measured at high tide is also remarkably high. The salinity of this estuarine water is nearly the same as that of the offshore oceanic water, while its temperature is one to two degrees higher. Because the water at Buoy 15 displays such high salinity and density characteristics, it would appear that this water is not measurably influenced by mixing, by river runoff, or by other estuarine processes. Therefore, one can only assume that the bottom water measured at high tide at Buoy 15 is upwelled oceanic water which has been modified only by warming with no apparent mixing processes altering the salinity.

The plot of surface temperatures and salinities measured off the rocks at the Otter Rock shore station and corresponding temperatures and salinities at Buoy 15 is shown in Figure 8. The data at Otter Rock is less representative of oceanic conditions than that at Buoy 15 as this surface water is warmer and more dilute. This is also seen on Figure 7 if the Otter Rock data is compared with that at Buoy 15. It would seem that measurements made in Yaquina Bay near the mouth of the estuary would provide more accurate information of offshore oceanic conditions than measurements made off

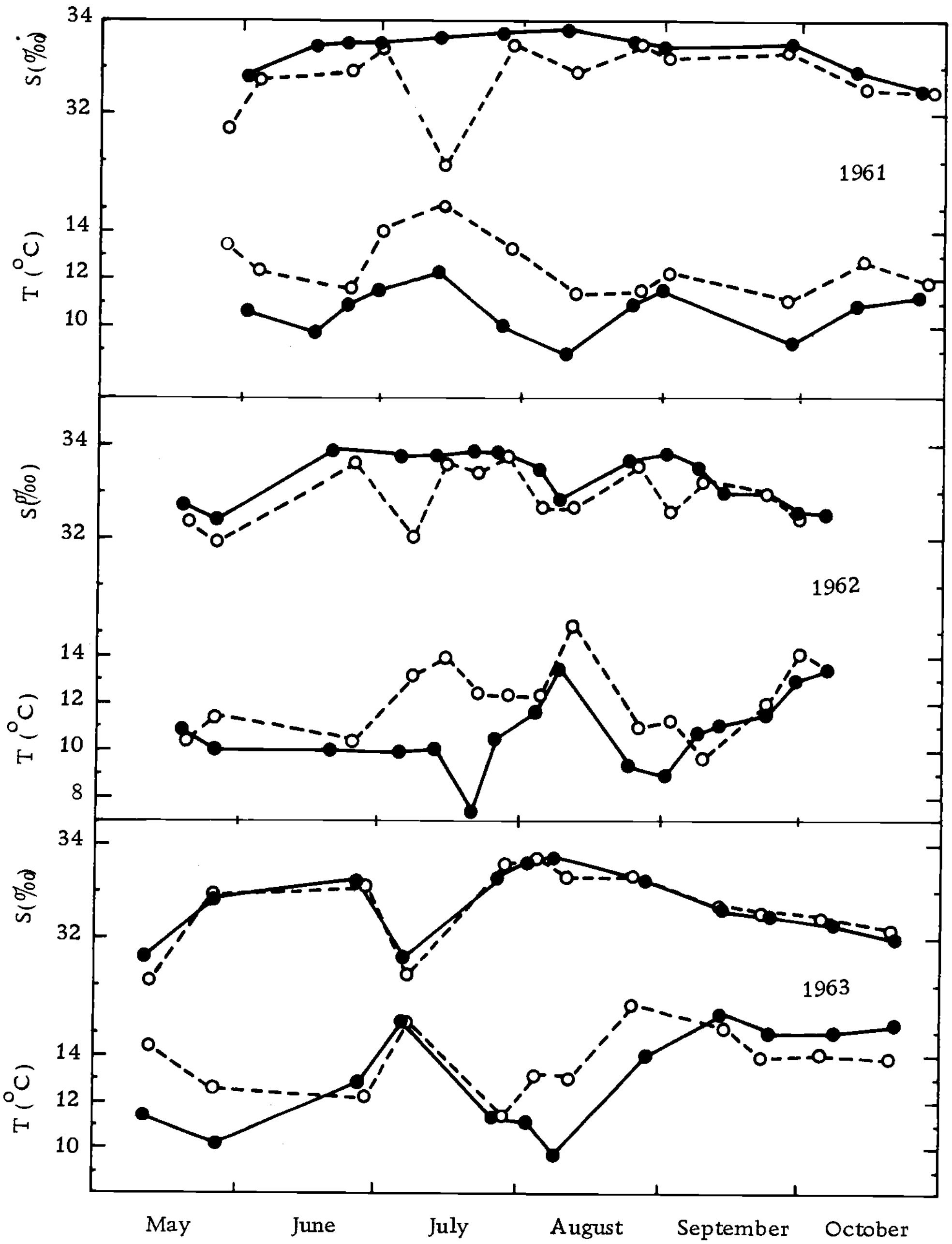


Figure 8. Temperature and salinity comparisons at Otter Rock and Buoy 15 for 1961-1963. Buoy 15 indicated by solid line; Otter Rock by dashed line.

the rocks or along the beach as is done at the various shore stations.

Upwelling Cycles

Temperatures and salinities measured at Buoy 15 during periods of high tide were averaged by month over the eight year period, 1960-1967. The results are graphically shown in Figure 9. Inspection of Figure 9 and Figure 4 leads to the conclusion that the upwelling seasons off the Oregon coast is generally established by June and remains in progress throughout the summer until the month of September. The exact time of onset and cessation is variable from year to year, but generally upwelling commences by late May - early June and ceases by late September. July and August are the months of greatest upwelling. Temperatures and salinities are at a minimum and maximum, respectively, during these months.

As seen from Figure 4, upwelling is not a continuous feature throughout the season. Once the upwelling season has begun, it appears to cease and recommence about two or three times during the period of June through September. The duration and intensity of each period of upwelling may vary considerably, average periods of upwelling being approximately one month. Durations were as short as two weeks and as long as two months. The intensity of each upwelling cycle is dependent on the duration and magnitude of the wind. Non-upwelling periods of long duration may cause the estuarine

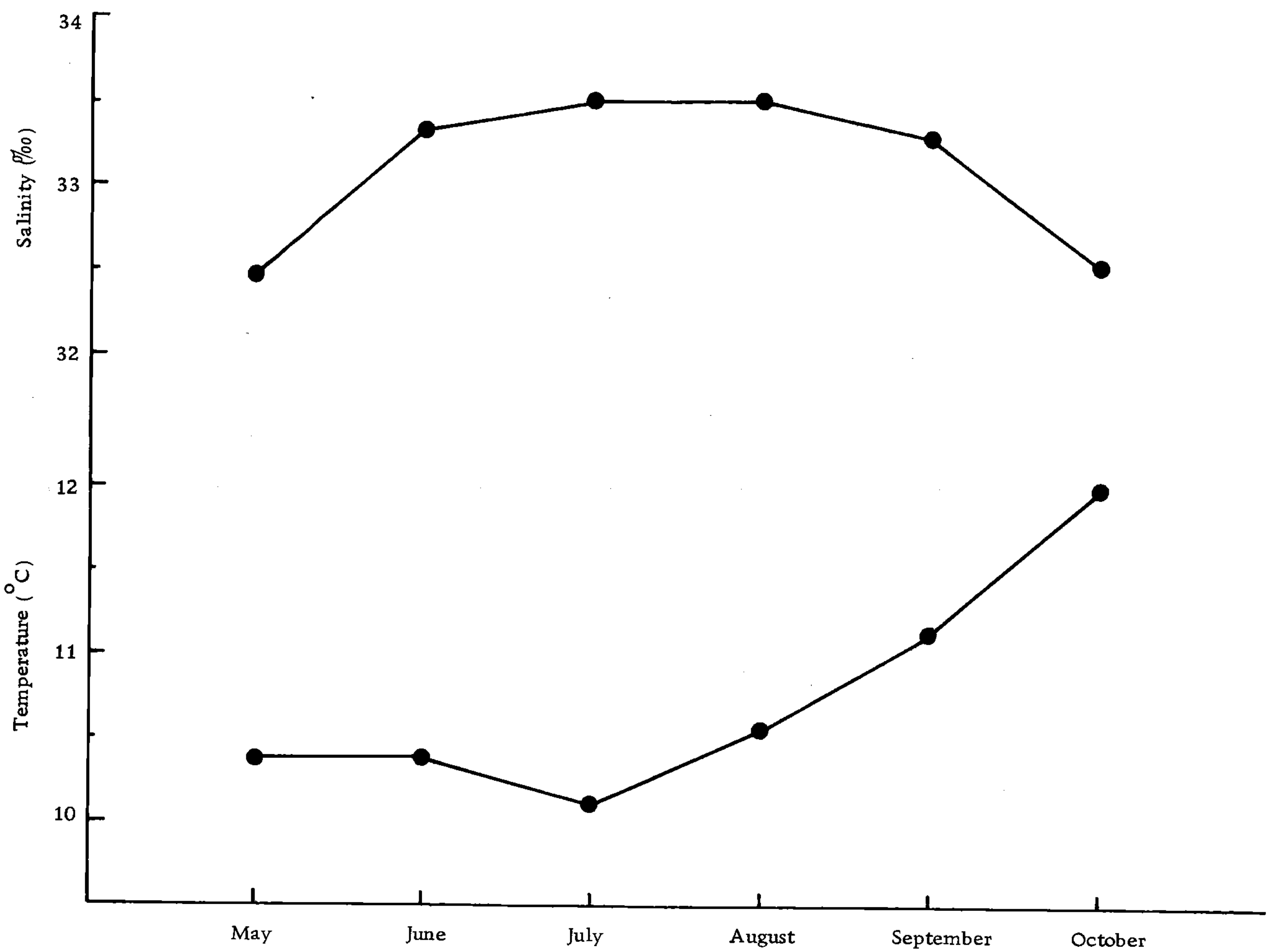


Figure 9. Average monthly temperature and salinity for period 1960-1967.

waters to warm up appreciably.

SUMMARY AND CONCLUSIONS

Upwelling occuring off the Oregon coast was studied to determine if its effects of low water temperature, low oxygen saturation, and high salinity could be noticed in an estuary. The dependence of the temperature of the water within the estuary on the wind velocity was also investigated. These studies lead to the conclusion that coastal upwelling can effectively be monitored in the quiet waters of an estuary. If a continuous reading thermistor and conductivity meter were placed in an estuary, one could cheaply, safely, and easily monitor the progress of upwelling of the ocean waters off the coast. This could prove to be an important asset to biologists and fishermen. They could be forewarned of periods when the normally cool, salty water would become warmer and fresher or vice versa. These changes in the water properties would, of course, cause much of the aquatic population to migrate to more hospitable locations. Marine biologists at aquariums should be able to better regulate the temperature and salinity of the intake water to their tanks.

The prediction limits of Figure 6 allow one to predict the water temperature in Yaquina Bay 24 hours in advance based on a knowledge of the past wind. For an average wind velocity greater than ten knots it is possible to predict the water temperature at high tide to an accuracy of $\pm 1^{\circ}$ C. Such forecasting, it must be remembered, is only accurate during the upwelling season when the correlation of wind velocity and temperature is good. Similar models could also be developed for other localities. The prediction limits should be adjusted to meet the conditions of each location.

Although only the correlation of water temperature and wind velocity has been attempted, it is probable that any other quasi-conservative property such as salinity, percent oxygen saturation, or preformed phosphate would also be highly correlated with wind velocity during the upwelling season. For each of these indicators the "time constant" of the system may be such that the best correlation with wind velocity may result when the wind is averaged for a period of time either longer or shorter than the four days required for temperature.

Other schemes are possible to monitor coastal upwelling. One could correlate the velocities of the winds and currents and establish a model to predict upwelling. The correlation of sea level measurements and wind stress has been shown by Panshin (1967) to lead to an effective method for monitoring upwelling. However, this is not a simple or direct method as the sea level data must be filtered to remove the fluctuations of sea level caused by changes in the tides and barometric pressure. Future investigations should be made to determine which model provides the most accurate results.

Assuming the various methods all result in comparable accuracy, the simplicity and reliability of direct temperature and salinity measurements would probably lead one to use this method to monitor coastal upwelling.

BIBLIOGRAPHY

Burt, Wayne V. and W. Bruce McAlister. 1959. Recent studies in the hydrography of Oregon estuaries. Research Briefs of the Fish Commission of Oregon 7:14-27.

Carpenter, J. H. 1966. New measurements of oxygen solubility in pure and natural water. Limnology and Oceanography 11:264-277.

Collins, Curtis A. 1964. Structure and kinematics of the permanent oceanic front off the Oregon coast. Master's thesis. Corvallis, Oregon State University. 53 numb. leaves.

Cross, Ford A. 1964. Seasonal and geographical distribution of pelagic copepods in Oregon coastal waters. Master's thesis. Corvallis, Oregon State University. 73 numb. leaves.

Draper, Norman R. and Harry Smith. 1966. Applied regression analysis. New York, Wiley. 407 p.

Ekman, V. Walfrid. 1905. On the influence of the earth's rotation on ocean currents. Arkiv för Matematik, Astronomi och Fysik 2(11):1-52.

Frolander, Herbert F. 1960-1967. Unpublished hydrographic data from Yaquina Bay. Corvallis, Oregon State University, Department of Oceanography.

__________. 1964. Biological and chemical features of tidal estuaries. Water Pollution Control Federation, Journal 36: 1037-1048.

Gilbert, William, Walter Pawley and Kilho Park. 1968. Carpenter's oxygen solubility tables and nomograph for seawater as a function of temperature and salinity. Corvallis, Oregon State University, Department of Oceanography. 139 p. (Data Report no. 29, reference 68-3)

Hebard, James F. 1966. Distribution of euphausiacea and copepoda off Oregon in relation to oceanographic conditions. Ph. D. thesis. Corvallis, Oregon State University. 89 numb. leaves.

Hidaka, Koji. 1954. A contribution to the theory of upwelling and coastal currents. Transactions of the American Geophysical Union 35:431-444.

Kulm, LaVerne D. and John V. Byrne. 1966. Sedimentary response to hydrography in an Oregon estuary. Marine Geology 4:85-118.

Matson, Adrian. 1964. Dissolved silicate in waters offshore Oregon and in four adjacent rivers. Master's thesis. Corvallis, Oregon State University. 98 numb. leaves.

Neal, Victor T. 1966. Tidal currents in Yaquina Bay. Northwest Science 40:68-74.

Oregon State University, Department of Oceanography. 1960-1967. Hydrographic data from Oregon waters, June 1960-1967. Corvallis, Oregon. 6 vols.

Oregon State University, Department of Oceanography. 1962-1963. Surface temperature and salinity observations at shore stations on the Oregon coast. Corvallis, Oregon. 2 vols. (Data Report no. 8, 11, reference 62-11, 63-27)

Oregon State University, Department of Oceanography. 1965. Surface temperature and salinity observations at Pacific Northwest shore stations for 1963 and 1964. Corvallis, Oregon. 18 p. (Data Report no. 21, reference 65-20)

Panshin, Daniel A. 1967. Sea level, winds, and upwelling along the Oregon coast. Master's thesis. Corvallis, Oregon State University. 71 numb. leaves.

Park, Kilho, June G. Pattullo and Bruce Wyatt. 1962. Chemical properties as indicators of upwelling along the Oregon coast. Limnology and Oceanography 7:435-437.

Pearson, Erman A. and George A. Holt. 1960. Water quality and upwelling at Grays Harbor entrance. Limnology and Oceanography 5:48-56.

Pritchard, D. W. 1952. Estuarine hydrography. Advances in Geophysics 1:243-280.

Pritchard, D. W. 1955. Estuarine circulation patterns. Proceedings of the American Society of Civil Engineers 81(717):1-11.

Smith, Robert L. 1964. An investigation of upwelling along the Oregon coast. Ph. D. thesis. Corvallis, Oregon State University. 83 numb. leaves.

Smith, Robert L., June G. Pattullo and Robert K. Lane. 1966. An investigation of the early stage of upwelling along the Oregon coast. Journal of Geophysical Research 71:1135-1140.

Strickland, J. D. H. and T. R. Parsons. 1965. A manual of sea water analysis. 2d ed. Ottawa. 203 p. (Fisheries Research Board of Canada. Bulletin 125)

Sverdrup, H. V., Martin W. Johnson and Richard H. Fleming. 1942. The oceans: their physics, chemistry, and general biology. Englewood Cliffs, New Jersey, Prentice-Hall. 1087 p.

U. S. Coast and Geodetic Survey. 1960-1967. Tide tables: high and low water predictions, west coast of North and South America, including the Hawaiian Islands. Washington, D. C. 8 vols.

U. S. Coast Guard Station. 1965-1967. Unpublished data from station log books from May through October, 1965-1967. Newport, Oregon. 18 vols.

APPENDIX

APPENDIX I

List of Symbols

$A(v)$	Weighted average of north-south component of wind velocity
e	Absolute error between observed temperature and estimated un-normalized temperature
r	Normalization constant, $1/\sigma(v)$
s	Normalized north-south wind average
u	East-west component of wind velocity
v	North-south component of wind velocity
y	Observed temperature
$\tilde{y}$	Un-normalized estimate of observed temperature
$\hat{y}$	Estimate of observed temperature based on normalized regression analysis
y^*	Predicted temperature
z	Observed temperature normalized by dividing by the standard deviation of the error from the regression model
$\hat{z}$	Estimated normalized temperature
z^*	Predicted normalized temperature
α, β	Regression coefficients
$\tilde{\alpha}, \tilde{\beta}$	Estimate from un-normalized regression analysis
$\hat{\alpha}, \hat{\beta}$	Estimate from normalized regression analysis
ϵ	True error from regression model
η	Error from normalized regression model

$\sigma_{(v)}$ Standard deviation of error from regression model

$\hat{\sigma}_{(v)}$ Estimate of standard deviation of error from regression model

$\hat{\sigma}^2$ Estimate of variance of error from normalized regression model