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OBSERVATIONS ON TRANSPARENCY IN THE
SOUTHWESTERN SECTION OF THE
NORTH ATLANTIC OCEAN

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The present measurements were undertaken to extend our knowledge
of the transparency of ocean waters to areas to the south of the
Bermuda region and to the east of the Caribbean region beyond
the limits of earlier investigations (Oster and Clarke, 1935; Clarke,
1938 and 1939). The measurements were made from the research
vessel "Atlantis"* between January 19, 1941 and March 7, 1941 on
Cruise No. 111 which extended from Bermuda to the northeast coast
of South America and back to New York. The positions of all sta-
tions where observations were made are indicated in Figure 50.

It was desired not only to determine what variations existed in the
average transparency of the different areas of the sea traversed,
but also to ascertain whether any changes in the rate of the penetra-
tion of daylight occurred with depth down to levels of 50 meters or
more. Another object of the investigation was to learn how closely
simple Secchi Disc determinations agreed with the transparency
values obtained from the more elaborate Photronic cell photometer.
Since Secchi disc measurements require only a few minutes, they
might be used to supplement the more time-consuming photometer
measurements if good agreement were found.

PROCEDURE

At every station a standard series of measurements was made by
comparing the readings of two photometers, one of which was mounted
on deck and the other lowered into the sea. Each photometer con-
tained a Weston Photronic cell, the spectral sensitivity of which ex-

*Contribution No. 306.
*The measurements at sea were carried out by Mr. A. H. Woodcock and
the calculations and graphs were prepared by Mr. D. F. Bumpus, of the Woods
Hole Oceanographic Institution.
Figure 50. Location of stations where observations were made. Figures give the average value of the extinction coefficient, $k$, (Column 7, Table I) for range from 2 meters to greatest depth at which observation could be made (Column 6, Table I).

hibits a maximum at 5800A and drops off to 10% of the maximum at 7080A and at 3420A. A diffusing disc of opal glass was placed over each photometer but no color filter was used. In general, the same procedure was followed as in the earlier investigations of the author. All measurements were made between 10:45 a.m. and 2:45 p.m. E.S.T. At the same time that these precise determinations were
being carried out with the Photronic cells, a rough visual measure of transparency was made by lowering a Secchi disc (white disc 20 cm. in diameter) into the water and noting the depth at which it disappeared.

The 27 series of measurements with the Photronic cell photometers are summarized in Table I. In each case the range in depth over which the series extended is indicated (Column 6). The first determination was made as near the surface as circumstances permitted (usually at 2 meters) and succeeding readings were taken ordinarily at 6, 10, 15, 20, 25 and 30 meters and thereafter at every ten meters to the greatest depth at which the instrument would respond. The value of the extinction coefficient,* \( k \), for the entire range of depth indicated for each series is given in Column 7. For the sake of uniformity, the value of the extinction coefficient down to 50 meters only has also been worked out and is presented in Column 8. Although certain differences exist in some cases between these values and the extinction coefficients for the entire range in depth, the variance is slight and the same general picture of the regional distribution of transparency is obtained from either set of data.

**TRANSPARENCY CURVES**

A large number of the transparency observations on this cruise were made under very unfavorable weather conditions and consequently considerable irregularity appeared among the individual measurements of each series. Nevertheless the trend of the measurements is consistent in most cases, as may be observed from the sample set of curves presented in Fig. 51. From the straightness of these semilogarithmic plots and from the curves for all the other series of measurements, it is learned that there was no important change in transparency with depth at any station. In other words, the water tended to be optically homogeneous in each case down to the depth to which the series extended.

Of the individual series of measurements Series 534, made February 21, 1941 at Station 4121 (about 750 miles Southeast of Bermuda), is of particular interest because of the extremely great transparency it represents. The average value of the extinction coefficient over the range 2 to 133 meters was \( k = 0.037 \) and individual segments of the curve give an even lower value. The Secchi Disc depth was 41 meters at this station. The lowest value obtained previously with a photometer of similar, though not identical, spectral sensitivity was \( k = 0.042 \)

*Extinction coefficient \( = k \) in the equation \( \frac{I}{I_0} = e^{-kL} \) where the light is reduced from \( I_0 \) to \( I \) by a stratum \( L \) meters thick.
<table>
<thead>
<tr>
<th>Series Number</th>
<th>Atlantis Station</th>
<th>Position</th>
<th>Date</th>
<th>Depth Range for Series</th>
<th>Extinction coefficient, k (for range 2-50 m.)</th>
<th>Max. depth of visibility of Secchi Disc</th>
<th>% surface light at Secchi Disc depth</th>
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<tbody>
<tr>
<td>530</td>
<td>4108</td>
<td>33° 51' N 67° 37' W</td>
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<td>0.068</td>
<td>19 m.</td>
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<td>0.038</td>
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Figure 51. Sample set of curves showing percentage of light incident on the surface which reaches the depths indicated (semi-logarithmic plot). Series number appears at end of each curve. For complete data see Table I.
for the range 2 to 185 meters \( (k = .038 \) for the range 95–185 meters) in the Cayman Sea, west of Jamaica (Clarke, 1938, p. 90). In the present investigation average values for the extinction coefficient which were almost as low as in Series 534 were obtained at three other stations (See Fig. 50). The greatest value for the Secchi Disc determination was at Station 4155 (about 130 miles northeast of Puerto Rico) where the disc was seen at 47 meters. On this occasion, calm weather allowed the disc to sink without departing appreciably from the vertical and made possible an unusually precise determination with the Photronic photometer (Series 548, \( k = .036 \) for range 2–50 meters). The greatest previous depth for the visibility of the Secchi Disc of which I am aware is 40 meters for Crater Lake, Oregon (Hasler, 1938).

REGIONAL DISTRIBUTION OF TRANSPARENCY

The observations made across the North Equatorial Current from Latitude 29° N. to Latitude 14° N. between Longitude 51° W. and 53° W. yielded low values for the average extinction coefficient, all of which fell between \( k = .037 \) and .047. Similarly, low values, ranging from .038 to .049, were obtained for measurements made from a point about 200 miles off Antigua northwestward in the water of the Antilles Current to a point about 360 miles southwest of Bermuda. We may therefore conclude that this region lying south of Bermuda and north and west of the Antilles is one of very high and relatively uniform transparency. In fact, the values obtained represent the clearest ocean water known.

Farther to the south the transparency is somewhat reduced and at the southernmost station in the Guiana Current about 100 miles off the coast of Guiana the extinction coefficient rose to \( k = .13 \). At this point and at the next station to the northwest the clearness of the water was distinctly less than at the stations farther offshore.

At the stations immediately southeast of Bermuda and at those northwest of the Island and toward New York, water of intermediate transparency was encountered. The values of the extinction coefficient ranged from \( k = .058 \) to .077 in this region. These values and those for the larger area to the south agree well with the few measurements carried out during earlier investigations near these regions.

COMPARISON WITH SECCHI DISC MEASUREMENTS

The Secchi Disc measurements (Table I, Column 9) may be compared graphically with the values for the extinction coefficients for
the depth range of 2 to 50 meters as determined by the Photronic cell photometers in Fig. 52. It is seen that the majority of measurements fall between $k = 0.040$ and 0.050 and that these are accompanied by Secchi Disc values lying between 30 meters and 40 meters. Higher extinction coefficients are correlated with lower Secchi Disc values. However, the scatter in the correlation is considerable and it is de-

![Figure 52. Correlation chart of the Secchi disc determinations and the extinction coefficients from the Photronic photometer measurements for range 2 to 50 meters. Curve of the equation $k = 1.7/D$ has been superimposed.](image)

sirable to ascertain whether the lack of agreement is due primarily to the relative crudity of the Secchi Disc measurement or to some other cause.

Measurements with the Secchi Disc can ordinarily be repeated with a variation of less than one meter but during the present cruise unfavorable weather conditions were encountered at a large number of the stations. The large size of the waves and the irregularity of the light reflected from the surface interfered seriously with the determinations. (The use of a tube passing beneath the surface through which the investigator may observe the disc is indicated for
future work.) Furthermore, the drift of the ship was such that in many cases the cord supporting the disc acquired an angle of 30° or more to the vertical. Although the vertical depth of the disc could be calculated (if the cord be assumed to have been straight), as is always done in the case of the Photronic photometer, this procedure would not give a correct value for the limit of visibility since the path of the light *from the disc to the observer's eye* follows the angle of the supporting cord. In view of this complication it did not seem worth while to attempt a correction for the angle of stray and the values given are the total length of cord from the surface to the disc.

Errors of measurement may therefore account for a part, or all, of the irregularities in the correlation of the Secchi Disc measurements and the extinction coefficients. Another possible explanation, which must be borne in mind, is the fact that in two cases in which the actual amount of light reaching a certain depth is identical (as measured by the Photronic cell photometer), the relative parts played by the processes of *scattering* and true *absorption* may be very different. In the situation in which scattering is greater, the light from the Secchi Disc would be more highly diffused and hence the disc would be less easily recognized from the surface. Such a condition has been reported for lakes (Sauberer, 1939). In the case of the ocean, this possibility, that there may be important differences in the relative roles of scattering and absorption from place to place in addition to the already recognized variation in the "total" rate of light extinction should be carefully tested in as many situations as possible.

The relation between the value of $k$, the extinction coefficient, as determined by a photometer and $D$, the depth for the limit of visibility of the Secchi Disc was found by Poole and Atkins (1929) on the basis of their measurements off Plymouth, England, in water of lower transparency ($k = 0.088$ to $0.203$) to be described roughly by the equation $k = 1.7/D$. A curve expressing this relationship has been drawn on the correlation graph (Fig. 52). It is seen that this curve agrees remarkably well with the average position of the points. If the two observations represented by points within parentheses are rejected as probably in error because of their wide divergence, then the remaining points fall satisfactorily within a band of moderate width, the axis of which is described by the above equation.

The magnitude of the illumination at the depth at which the Secchi Disc is just visible is of interest and has been determined from the curves of light penetration at each station. This may be given as
percentage of light incident at the surface as experience has shown (cf. Poole and Atkins, 1929) that differences in the value of daylight may be neglected if measurements are made near the middle of the day (as was the case in this investigation). The percentage of the light at the surface which existed at the depth obtained for the Secchi Disc appears in Column 10 of Table I. It is observed that the illumination varies from 8.0% to 26% (omitting the two questionable observations) with an average of 15.2%. These values agree very closely with those of Poole and Atkins (1929) who reported a variation for his set of 14 series of measurements from 9.6% to 22.6% with an average of 15.8%. This range in the percentage illumination and the width of the band in the correlation graph (Fig. 3) are a measure of the extent to which the photometric and the visual methods of transparency measurement agree. Further work is called for to determine how much of the discrepancy is due to error of measurement, and how much to differences in the optical properties of the water.

SUMMARY

1. Twenty-seven series of light penetration measurements were made with Photronic cell photometers to depths as great as 133 meters in the southwestern section of the North Atlantic Ocean.

2. The water exhibited no important change in transparency with depth. A minimum average value for the extinction coefficient of \( k = 0.037 \) and a maximum depth for the Secchi Disc of \( D = 47 \) meters were observed.

3. The region south of Bermuda and north and west of the Antilles was found to contain the clearest ocean water known and to be relatively homogeneous in respect to transparency. Off the coast of Guiana a sharp drop in transparency was encountered. To the southeast and to the northwest of Bermuda, the water is very clear but less so than farther to the south.

4. A comparison of the Photronic photometer measurements with the Secchi disc determinations shows in general good agreement with the relation, \( k = 1.7/D \), reported by Poole and Atkins. At the depth of disappearance of the disc the illumination averaged 15% of the light incident at the surface. Individual variations suggest the possibility that important changes in the relative effects of scattering and absorption may occur in ocean waters.
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