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LIGHT PENETRATION IN THE CARIBBEAN SEA AND IN THE GULF OF MEXICO

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The growing interest in the intensity of light beneath the surface of the ocean from both the physical and the biological points of view has resulted in further efforts to obtain reliable measurements under widely differing conditions and in a variety of locations. For the most part, however, these measurements have been made in northern waters and have been confined largely to coastal regions. There has resulted a paucity of precise observations in the tropical parts of the ocean. The work of Grein (1913–14) in the Mediterranean produced highly irregular results (cf. Atkins, 1932). Certain visual observations have been made by Beebe (1934) off Bermuda, and a small number of measurements were undertaken by Stephenson (1934) from a submarine off California. The work of Hulburt (1932) was confined to measurements of the absorption coefficients of samples of sea water brought into the laboratory.

To extend our knowledge of light penetration to the more southern parts of the North Atlantic, our photometric apparatus was placed aboard the research vessel "Atlantis" at the outset of her cruise to the Caribbean and the Gulf of Mexico during the winter of 1936–37. Measurements were carried out at every suitable opportunity, but because of the press of other work and the frequent occurrence of stormy weather, a much smaller number of series was completed than was hoped. The observations presented
below are therefore not to be regarded in any sense as a complete survey, but represent a first step in filling a serious gap in our knowledge of light conditions in tropical and sub-tropical waters.

The deck and sea photometers employing Westinghouse Photox Cells described by Powell and Clarke (1936) were used for this investigation. The spectral sensitivity of these cells exhibits a maximum at 5500Å and drops off to 10% of the maximum at 4650Å and 6250Å. This relatively broad sensitivity admits of the criticism that the value obtained for the

![Figure 26. Map showing the locations of stations where light penetration measurements were made. The "Series Number" of each set of observations appears beside the circle representing the station.](image)

transparency of the water is a composite of the transmissive exponents of a large number of wave lengths, the relative intensities of which may differ with depth. However, since the logarithmic plots of measurements made in homogeneous bodies of water are remarkably straight, any such discrepancies must be of negligible proportion. It would appear that, in these cases at least, the most effective radiation at all depths centers about the same part of the spectrum.

The spectral band to which the present photometers are sensitive is essentially the same as that measured by the "green-sensitive" combination of filters and photoelectric cells employed by Oster and Clarke (1935). The spectral sensitivity of the Photox cells corresponds so closely to that of the human eye that we may refer to the light measured as the visible
part of the total solar radiation. Furthermore, since approximately the same spectral sensitivity appears to characterize the photosensitive organs of marine animals generally (Clarke, 1936a), the reduction of light indicated by our instruments as they are lowered into the sea is presumably the same as that perceived by a fish or other animal sinking a corresponding distance in the water.

![Graph showing the relationship between depth and irradiation expressed as a percentage of the light just over the surface (logarithmic scale). Series numbers indicated at end of each curve.](image)

**Figure 27.** Relation between depth and irradiation expressed as a percentage of the light just over the surface (logarithmic scale). Series numbers indicated at end of each curve.

<table>
<thead>
<tr>
<th>Series</th>
<th>Locality</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Date</th>
<th>Time (E.S.T.)</th>
<th>Sky*</th>
<th>Sea</th>
<th>Wind†</th>
</tr>
</thead>
<tbody>
<tr>
<td>435</td>
<td>Antilles Current</td>
<td>24°00′N</td>
<td>59°03′W</td>
<td>Jan. 4, 1937</td>
<td>09:50–10:44</td>
<td>be</td>
<td>moderate 3-4</td>
<td></td>
</tr>
<tr>
<td>436</td>
<td>No. Equatorial Current</td>
<td>12°04′</td>
<td>60°29′</td>
<td>Jan. 12, 1937</td>
<td>10:55–11:45</td>
<td>o</td>
<td>rough 4-5</td>
<td></td>
</tr>
<tr>
<td>437</td>
<td>Caribbean Sea</td>
<td>15°20′</td>
<td>67°10′</td>
<td>Jan. 26, 1937</td>
<td>10:00–10:42</td>
<td>be</td>
<td>moderate 4-5</td>
<td></td>
</tr>
</tbody>
</table>

* U. S. Weather Bureau symbols. † Wind force on Beaufort Scale.

The same procedure was followed and the same precautions observed in making these light penetration measurements as has been described previously. I am indebted to Mr. Alfred Woodcock for carrying out the observations at sea and to Mr. David Bonnet for assistance in preparing the figures.

The location of each series of measurements is shown in Fig. 26. Series 435 was made in the Antilles Current at a distance of about 900 miles SE of Bermuda. Series 436 was located in the Northern Equatorial Current just East of the Lesser Antilles. Series 437 and 438 were made respectively
in the center of the Caribbean Sea and in the Cayman Sea* just West of Jamaica. Series 439 to 442 were made in the Gulf of Mexico East of the Mississippi Delta at different distances from shore.

### TABLE I

**COMPARISON OF AVERAGE VALUES OF THE TRANSMISSIVE EXPONENT, \( k \),** for the **"GREEN" COMPONENT OF DAYLIGHT FOR THE DEPTH RANGES INDICATED**

<table>
<thead>
<tr>
<th>Series</th>
<th>Station</th>
<th>Locality</th>
<th>Ranges (meters)</th>
<th>( k )</th>
<th>Total Range (meters)</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>307</td>
<td>2243</td>
<td>Sargasso Sea, N of Bermuda</td>
<td>—</td>
<td>—</td>
<td>5-92</td>
<td>.050</td>
</tr>
<tr>
<td>311</td>
<td>2245</td>
<td>Gulf Stream, N of Bermuda</td>
<td>2-10</td>
<td>.082</td>
<td>5-136</td>
<td>.049</td>
</tr>
<tr>
<td>415</td>
<td>2484</td>
<td>Gulf Stream, S of Grand Banks</td>
<td>10-95</td>
<td>.057</td>
<td>2-95</td>
<td>.059</td>
</tr>
<tr>
<td>435</td>
<td>2726</td>
<td>Antilles Current</td>
<td>2-20</td>
<td>.068</td>
<td>2-121</td>
<td>.049</td>
</tr>
<tr>
<td>436</td>
<td>2748</td>
<td>Northern Equatorial Current</td>
<td>14-141</td>
<td>.045</td>
<td>2-141</td>
<td>.048</td>
</tr>
<tr>
<td>437</td>
<td>2803</td>
<td>Caribbean Sea</td>
<td>20-130</td>
<td>.058</td>
<td>2-130</td>
<td>.042</td>
</tr>
<tr>
<td>438</td>
<td>—</td>
<td>Cayman Sea, W of Jamaica</td>
<td>95-185</td>
<td>.045</td>
<td>2-185</td>
<td>.042</td>
</tr>
<tr>
<td>439</td>
<td>—</td>
<td>Gulf of Mexico, E of Mississippi Delta</td>
<td>2-25</td>
<td>.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>440</td>
<td>—</td>
<td>Gulf of Mexico, E of Mississippi Delta</td>
<td>2-20</td>
<td>.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>441</td>
<td>—</td>
<td>Gulf of Mexico, E of Mississippi Delta</td>
<td>2-6</td>
<td>.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>442</td>
<td>—</td>
<td>Gulf of Mexico, E of Mississippi Delta</td>
<td>2-95</td>
<td>.054</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* In the equation \( I/I_0 = e^{-kL} \) where \( L \) is the thickness of the water layer (in meters) in which the intensity is reduced from \( I_0 \) to \( I \).

† Approximate.

The transparency of the water at the station in the Antilles Current (Series 435) and at the station in the Northern Equatorial Current (Series 436) was found to be uniform over the ranges measured, as is attested by the straightness of the logarithmic plots (Fig. 27), although the upper strata tended to be somewhat less transparent than the deeper layers (Table I). The water in these areas is known to be highly homogeneous from a hydrographic point of view (Iselin, 1936; Parr, 1937), and at the time of the present observations the temperature change from the surface to a depth of 150 m. was only about 4° C. Since the average values of the transmissive exponents for these series \((k = .049 \text{ and } .048 \text{ respectively})\) are so nearly the same, we may conclude that there was practically no difference in transparency at these two localities.

* Name proposed by Parr (1937) to designate the body of water between the Gulf of Mexico and the Caribbean Sea proper (see Fig. 26).
The observations in the Caribbean Sea (Series 437) unfortunately occurred during unfavorable weather conditions with the result that the measurements are rather widely scattered. However, a straight line con-
necting the value at 20 m. with that at 130 m. appears to form a satisfactory average curve for the whole series below 20 m. The slope of this curve gives a value of $k = .058$. Although individual measurements above 20 m. were unreliable, the transparency was evidently considerably reduced in the upper stratum. The temperature at the surface was 26.0° C. and at 150 m. was 19.8° C. at this station.
Since the measurements at the station in the Cayman Sea (Series 438) were made under favorable conditions, and since the values obtained are so consistent, we may place considerable reliance upon them. The series extended to a greater depth (185 m.) than has ever been reached previously with photoelectric or rectifier cell photometers. The curve for this series (Fig. 28) shows that the water at this locality was extremely uniform in transparency as would be expected from the hydrography (Parr, 1937). From 95 m. to 185 m. the value of the transmissive exponent was found to be $k = 0.038$. This water is therefore the most transparent (in respect to the "green" component of daylight) ever reported (cf. Oster and Clarke, 1935) and approaches the clearness of distilled water (for which $k = 0.024$ at wave length 5400Å according to Sawyer, 1931). If we assume that the optical properties of the water at this station are the same as those of the Sargasso water off Bermuda, which is similar hydrographically, we may conclude that the "blue" component of daylight penetrates even more effectively than the "green" in this locality and therefore, that "blue" light is of measurable intensity at an even greater depth.

The region east of the Mississippi Delta was unfortunately the only part of the Gulf of Mexico where there was opportunity to make light penetration measurements. The four series of observations here were made in increasing depths of water and show how the effect of the muddy Mississippi water diminishes at increasing distances from shore (Fig. 29). The water in Series 439, where the depth was 25 m., was quite homogeneous and gave an average transmissive exponent of $k = 0.22$. This water was therefore approximately as turbid as Vineyard Sound or Provincetown Harbor (cf. Clarke, 1936b). In Series 440 (depth 63 m.) we see that a distinct change in transparency occurred at 20 m. Above 20 m. the water was only slightly more transparent than at the previous station but below 20 m. the value of the transmissive exponent was reduced to one half ($k = 0.10$).

The measurements composing Series 441 were made under conditions causing the ship to drift more than usual. The values obtained down to 40 m. appear sufficiently consistent to be reliable but below 40 m. the points are seen to scatter widely. At these greater depths the wire supporting the submarine photometers departed by as much as 60° from the vertical, making a precise determination of the depth of each observation difficult. Incorrect estimation of depth due to wire angle is a dangerous source of error in all deep readings and should be carefully guarded against. In this case the last measurement of the series was made with the photometer actually resting on the bottom. As a result the depth could be independently and accurately determined by means of the ship's fathometer and was found to be 81 m. A straight line has been drawn on the plot (Fig. 29) from the value obtained at this depth to the value found at 38 m. This (dashed) line may serve as an approximation for the illumina-
tion below 40 m. The complete curve shows that the water in the upper six meters was still highly turbid \((k = 0.16)\). A transition layer occurred from 6 to 24 m. \((k = 0.088)\). Below 24 m. the water was considerably more transparent \((k = 0.058)\) than at the previous station.

Series 442 was made in 656 m. of water and under much more favorable weather conditions. A comparison with the other measurements in this region (Fig. 29) reveals a further great increase in transparency at this point. There is no evidence of relatively opaque water near the surface. However, a slight change of slope occurs at 95 m. (Fig. 28) giving transmissive exponents of \(k = 0.054\) and \(k = 0.039\) respectively for the curve above and below 95 m. Since the water at this station was almost as clear as that at the station in the Cayman Sea (Series 438), it appears that the effect of the muddy water from the Mississippi does not extend far in this
direction from the Delta. At this point of observation, only some seventy miles from the nearest mouth of the river, the water had a transparency practically equal to the clearest ocean water known. The explanation of this apparent paradox lies in the fact the water debouching from the Mississippi is carried almost entirely to the west (Parr, 1935, Fig. 10). In speaking of the influence of the Mississippi and the other northern drainages, Parr says (loc. cit. p. 62): "This freshening influence, however, stays confined to the bank and does not seem to affect the surface layer over the deeper waters at all, even where the bank is quite narrow as at the mouth of the Mississippi itself. It will be noticed from our map of surface salinities that the freshening influence spreads westward and has very little effect to the east of the Mississippi Delta." Our measurements of transparency support these conclusions.

For the purposes of comparison three previous measurements made in Sargasso water (Series 307, 311, and 415) have been included in Table I and the curve of Series 415 has been added to Fig. 28. These observations taken together with the deep-water series reported in the present paper provide a general picture of transparency for a large part of the western North Atlantic in which oceanic water of high salinity exists. It is seen that the transparency throughout this whole region is extremely high and quite uniform. A gradual, though slight, decrease in transparency does occur from the Cayman Sea (Series 438) to a point in the Gulf Stream, south of the Grand Banks (Series 415), as is revealed by the increasing values of the average transmissive exponents (Table I and Fig. 28). However, the ratio of the highest average value of the exponent to the lowest is only .059 (Series 415)/.042 (Series 438) = 1.4. The extreme change over the whole length of the area (over 2000 miles) is accordingly only 40% in contrast to changes of 600% (for the corresponding "green" component of daylight) found by Clarke (1936b) in passing off-shore from Woods Hole toward Bermuda. Since in the latter case measurements in the turbid coastal waters are included, the two situations are not really comparable. However, most of the investigations of light penetration made heretofore—such as those of Poole and Atkins, Pettersson, and Utterback—have given a picture of great variability. The present observations are the first in which opportunity has arisen to study the transparency of a considerable oceanic area and, in this case, show a wide and uniform distribution of extremely clear water.
SUMMARY

Measurements of light penetration using Photox rectifier cells were made at 8 stations in the Caribbean Sea region and in the Gulf of Mexico. At the stations in shallow water east of the Mississippi Delta, considerable turbidity was encountered in the surface layers. But at the offshore station in the Gulf and at all the other stations the water was found to be highly uniform and extremely transparent. The value of the transmissive exponent from 95 to 185 m. at the station in the Cayman Sea west of Jamaica was \( k = 0.038 \), indicating the presence of the clearest ocean water ever measured.

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