TRANSPORT OF THE FLORIDA CURRENT OFF HABANA

BY

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INTRODUCTION

This report is an analysis of four *Atlantis* sections across the Florida Current in the locality between Key West and Habana. In particular the volume transport of the current is calculated from the mass distribution observed on these four sections. The assumptions for the calculations are critically discussed, making use of records of sea level at Key West.

The first section, 4 March 1934 (stations 2003–2008), was made during Cruise 25 under the leadership of Dr. A. E. Parr (*Bulletin Hydrographique pour l'année 1934,* pp. 45, 111). The second section, 19–20 February (stations 2343–2347), and third section, 12–13 April 1935 (stations 2434–2438), were made during Cruise 41 by Dr. Parr and by Mr. Y. H. Olsen respectively (*Bulletin Hydrographique pour l'année 1935,* pp. 51, 100, 102). The fourth section, 24–25 March 1938 (stations 3006–3012), was made during Cruise 74 by Mr. Alfred H. Woodcock.

This region of the Straits of Florida had been investigated during February–May 1887 by Pillsbury (1887, 1890), who carried out extensive current measurements down to 130 fathoms from the *Blake* at anchor. A section of temperature by means of reversing thermometers and of salinity was made from the *Bache* in March 1914 (Bigelow, 1915).[2] Wüst (1924) attempted a dynamic calculation from the *Bache* material, but found the observations insufficient. *Dana* stations 1224–1229 were made in this region in February 1922,

[1] Contribution No. 303.

[2] In May 1878 the temperature at a number of points between surface and bottom for five stations on this section of the Straits had been determined from the *Blake* (Agassiz, 1888, Fig. 157). Within a few years of the same time another temperature section from the *Blake* was made farther west, approximately along the 84th meridian, but the date is not stated (Lindenkohl, 1895, Diagram No. 4).

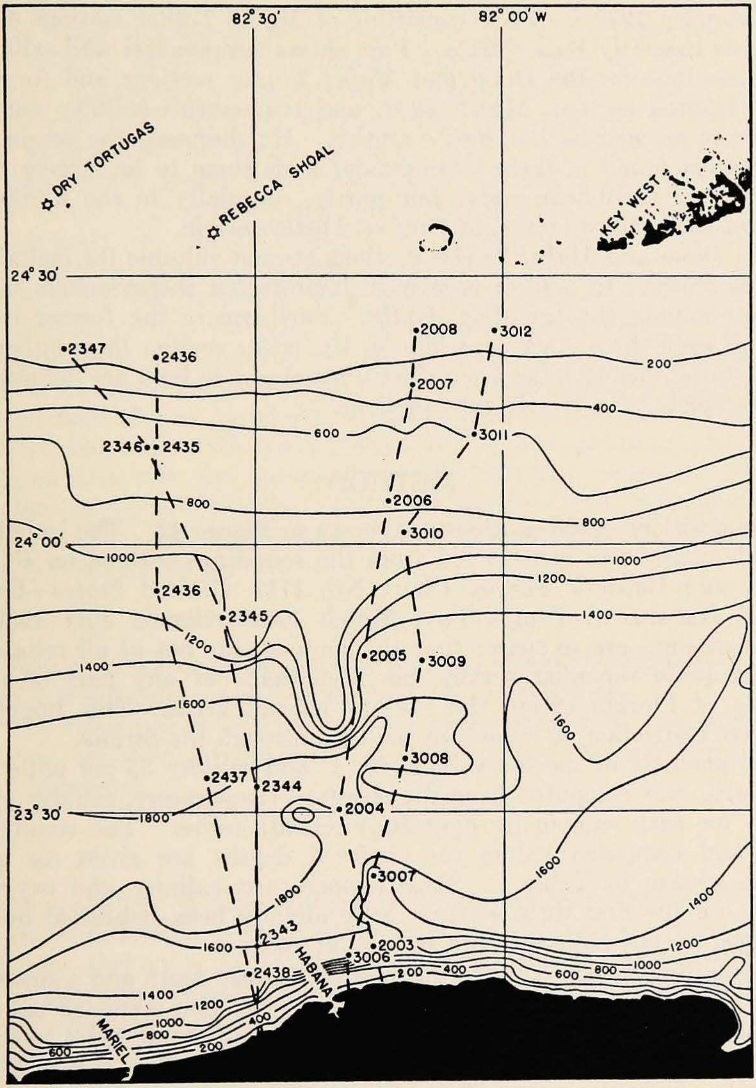

Figure 42. Station positions for the four *Atlantis* sections near Habana in the Straits of Florida. Isobaths are shown for each 200 meters.

three of them forming a section across the Straits (Schmidt, 1929).[3] In February 1932 a section consisting of *Mabel Taylor* stations 401–406 was made by Parr (1935). Parr shows temperature and salinity cross-sections for the *Dana* and *Mabel Taylor* sections and for the first *Atlantis* section, March 1934, and temperature-salinity curves for these as well as the *Bache* section. He discusses the origin of the waters found in these sections and finds them to be largely unadulterated Caribbean water but partly, especially in the northern part of the surface layers, of Gulf of Mexico origin.

The *Dana* and *Mabel Taylor* sections are not suitable for inclusion in this study. In neither case were unprotected thermometers used in determining the sampling depths. Furthermore the former consists of only three stations, while on the latter section the southernmost station lies 12 miles from the Cuban shore, so both are definitely less complete than the *Atlantis* sections.

METHOD

The positions of the stations are shown in Figure 42. The isobaths on this chart were constructed from the soundings entered on U. S. Coast and Geodetic Survey Chart No. 1113 (United States—Gulf Coast, Habana to Tampa Bay, March 1933, reissued July 1938). The soundings are so sparse that the contours are not at all reliable. No adequate sounding survey has been made of any part of the Straits of Florida except the shallow coastal areas. This imposes a severe restriction on studies of the flow through the Straits.

The anomaly of specific volume (0° C and salinity 35 per mille as standard) was computed from the observed temperature, salinity and depth for each sample by Sverdrup's (1933) tables. The complete data and computed values for observed depths are given for the fourth section in Table I. Since temperature, salinity and oxygen values for the first three sections have already been published these sections are not repeated here in tabular form.

Anomaly of specific volume was plotted against depth and a smooth curve drawn for each station. The depths of chosen standard values of anomaly of specific volume were determined from these curves and then entered on the cross-sections, and finally the isopleths of anomaly of specific volume were drawn, giving Figures 43–46. Few of the stations reach near the bottom, so considerable uncertainty was involved in extrapolating the isopleths to the walls of the Straits.

[3] The temperature and salinity cross-section is shown by Nielsen (1925, Fig. 2). See also Jacobsen (1929).

Smooth salinity-depth curves were constructed for each station, from which the depths of 36.4 and 36.6 per mille were determined and entered on the cross-sections. On this basis the areas of the salinity maximum are indicated in Figures 43–46. These may be correct in their broadest features, but the sampling in the upper 300 meters was too coarse to define clearly the thin layer of high salinity, which occurs near the depth of maximum stability.

In order to integrate the hydrostatic equation the station curves of anomaly of specific volume were extended where necessary to 1200 meters, or to the bottom at shallower stations, by use of the isopleths on the cross-sections. Likewise smooth curves of anomaly of specific volume versus depth have been drawn for both walls of each section. By integrating along these curves, using depth in meters to represent pressure in decibars, the anomaly of geopotential above 1200 db was found for the intersections of each station vertical and of the walls with the standard isopleths of anomaly of specific volume and with the sea surface. The resulting values for the sea surface at the northernmost station and at the Cuban shore are given in Table II. The acceleration potential (Montgomery, 1937; Montgomery and Spilhaus, 1941),

$$\Upsilon = \Phi_a + \delta p$$

(where Φ_a is anomaly of geopotential, δ is anomaly of specific volume and p is pressure), was found for all the intersections.

The volume transport through an area bounded by two successive station verticals (or the wall and adjacent station) was found from the expression

$$\Delta V = \frac{\Delta\Upsilon \Delta z}{f}.$$

Here Δz is the average distance between the two isopleths, f is the Coriolis parameter computed for the mid-latitude of each pair of stations, and $\Delta\Upsilon$ is the average, for the two isopleths, of the difference in acceleration potential between the two verticals. The sums for each complete layer and for each section are given in Table III. The transport through the small area lying north of the northernmost station was neglected in each case.

As a check, the total transport for each section was also computed directly from the expression

$$V = \frac{1}{f}\left[\int_{\text{right}} \Phi_a \, dz \quad - \quad \int_{\text{left}} \Phi_a \, dz\right]$$

TABLE I—*Atlantis* Habana Section, 24–25 March 1938

Station	*Depth* (*meters*)	t °C	S ‰	σ_t $g\ l^{-1}$	δ $cl\ ton^{-1}$
3006, 24 III 38	1	26.03	35.79	23.64	427
1715–1820	24	25.97	35.90	23.74	418
23° 14′ N, 82° 19′ W	47	25.90	35.91	23.77	416
Depth 1463–1372 meters	94	25.60	36.00	23.94	402
Wind force 3	141	23.85	36.58	24.90	312
	188	20.92	36.74	25.86	222
	282	17.77	36.45	26.46	168
	376	14.29	35.84	26.79	138
	470	11.21	35.35	27.03	115
	564	9.09	35.07	27.175	102
	752	6.59	34.87	27.39	81
	938*	5.38	34.90	27.575	64
	1128	4.59	34.94	27.70	53
3007, 24 III 38	1	26.01	35.91	23.74	417
1935–2140	44	25.96	35.91	23.75	418
23° 23′ N, 82° 16′ W	82	25.71	36.00	23.905	405
Depth 1710 meters†	119	23.61	35.97	24.51	348
Wind force 3	157	19.91	35.93	25.52	253
	233	18.29	36.47	26.34	178
	308	14.66	35.97	26.81	134
	383*	12.77	35.62	26.94	123
	446	11.12	35.35	27.05	113
	572	8.11	34.96	27.24	95
	699	6.51	34.87	27.40	79.5
	825*	5.53	34.87	27.53	67
	1099*	4.34	34.97	27.75	47
3008, 24–25 III 38	1	25.90	35.93	23.79	412
2255–0105	38	25.92	35.93	23.78	415
23° 36′ N, 82° 12′ W	66	24.25	36.00	24.35	361.5
Depth 1701 meters	89	21.25	35.95	25.16	285
Wind force 2	114	19.62	35.93	25.59	245
	165	18.60	36.38	26.20	189
	216	16.20	36.13	26.59	153
	267*	14.51	35.86	26.76	138
	302	13.15	35.66	26.89	126
	371	10.72	35.28	27.06	110
	440	9.18	35.07	27.16	101
	509*	8.05	34.96	27.25	92.5
	640*	6.31	34.88	27.44	75

TABLE I—*Cont.*

Station	*Depth* (*meters*)	t °C	S ‰	σ_t $g\ l^{-1}$	δ $cl\ ton^{-1}$
3009, 25 III 38	1	24.99	36.06	24.16	377
0245–0358	49	21.42	36.36	25.44	257
23° 47′ N, 82° 10′ W	97	19.72	36.35	25.88	217
Depth 1508 meters	144	17.35	36.29	26.44	165
Wind force 2	191	15.34	36.04	26.71	140
	286	11.64	35.44	27.015	113
	381	8.59	35.01	27.215	94
	476*	7.28	34.90	27.32	84
	570	6.36	34.88	27.43	75
	779	5.05	34.92	27.625	57
	987	4.59	34.94	27.70	51
	1196*	4.26	34.96	27.74	49
	1389*	4.14	34.99	27.785	46
3010, 25 III 38	1	24.77	36.04	24.21	372
0530–0620	25	23.58	36.33	24.79	318
24° 01.5′ N, 82° 12′ W	50	20.95	36.33	25.54	247.5
Depth 878 meters	100	18.73	36.36	26.15	191
Wind force 1	150	15.88	36.08	26.615	148
	199	13.53	35.71	26.85	127
	298	10.19	35.21	27.11	103
	397*	8.09	34.96	27.245	91
	495	6.84	34.87	27.36	81
	594	5.98	35.01‡	27.59	59.5
	793*	.06	34.90	27.61	59
3011, 25 III 38	1	24.55	36.10	24.33	361
0830–0915	25	23.51	36.31	24.79	318
24° 12.5′ N, 82° 03.5′ W	50	20.77	36.36	25.62	240
Depth 539 meters	100	17.15	36.27	26.47	161
Wind force 2	149	14.65	35.91	26.77	133
	198	12.70	35.61	26.94	118
	297	10.47	35.28	27.10	104
	395*	9.18	35.08	27.17	99
	493	7.81	34.94	27.28	89
3012, 25 III 38	1	24.33	36.27	24.52	343
1030–1055	25	21.32	36.38	25.47	253
24° 24′ N, 82° 01′ W	50	19.80	36.31	25.83	220
Depth 161 meters	75	18.50	36.36	26.21	185
Wind force 2	100	15.62	36.08	26.67	141.5
	150	11.57	35.41	27.01	109.5

* Depth determined with unprotected reversing thermometer.

† At this position Chart No. 1113 shows sounding of 710 fathoms or 1300 meters.

‡ Looks very doubtful on $\sigma_t - S$ diagram, so this observation has been omitted from consideration.

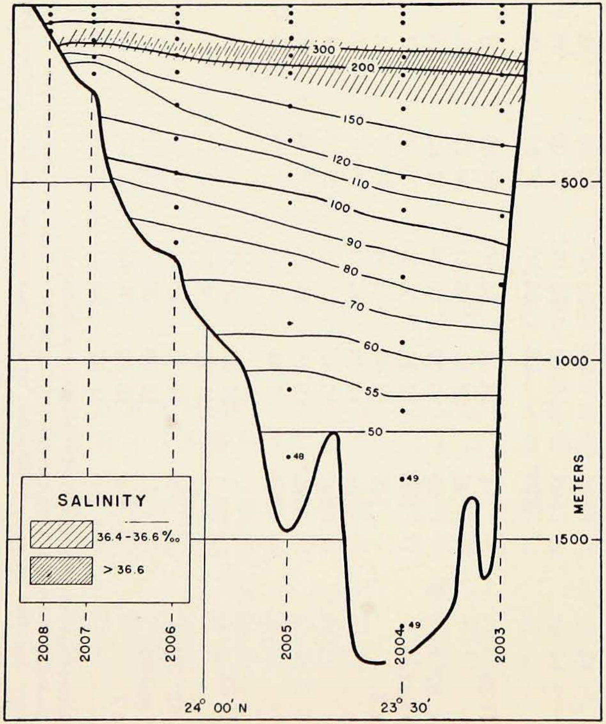

Figure 43. *Atlantis* Habana section on 4 March 1934 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

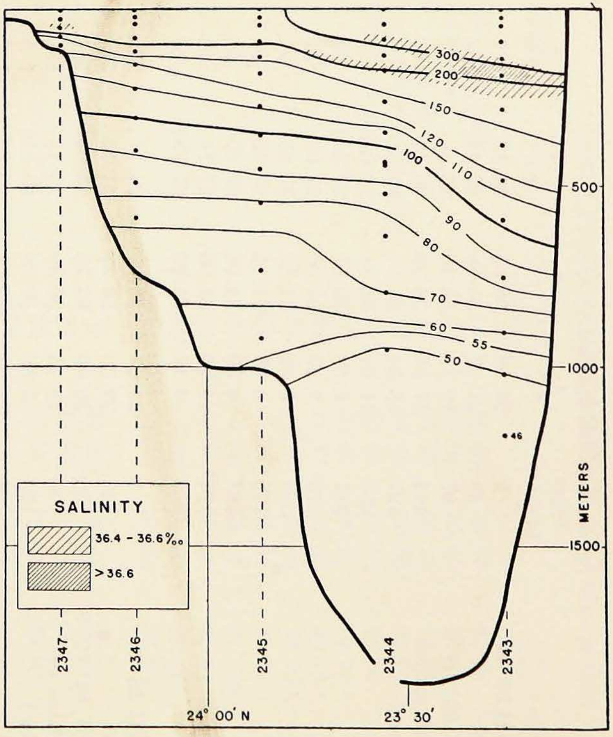

Figure 44. *Atlantis* Habana section on 19–20 February 1935 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

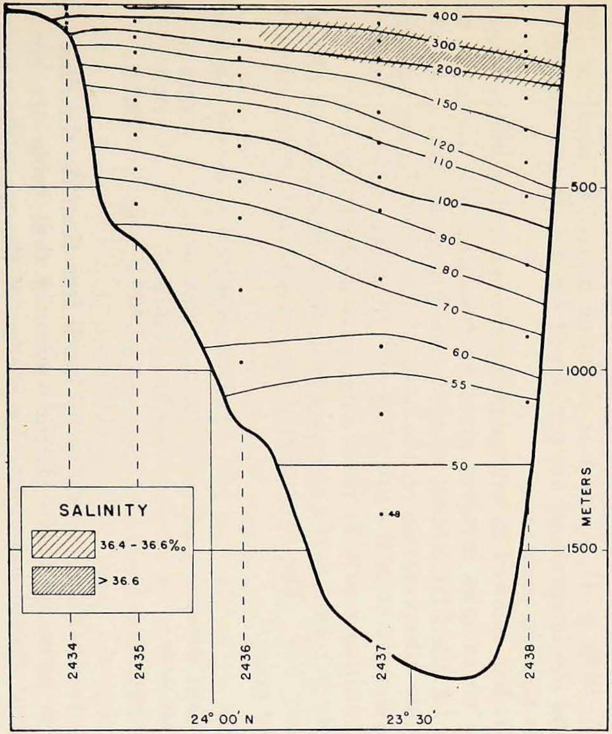

Figure 45. *Atlantis* Habana section on 12–13 April 1935 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

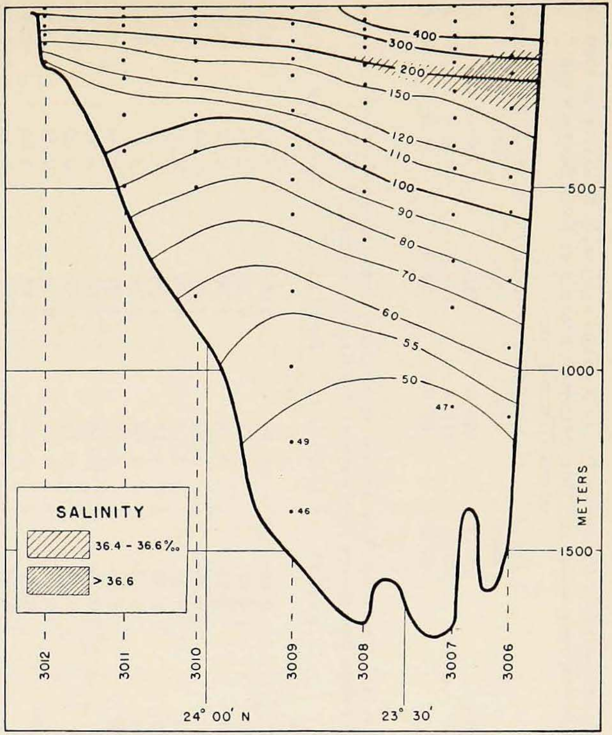

Figure 46. *Atlantis* Habana section on 24–25 March 1938 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

TABLE II—ANOMALY OF GEOPOTENTIAL, IN KILERGS PER GRAM, RELATIVE TO 1200 DB OF THE SEA SURFACE AT THE NORTHERNMOST STATION OF EACH SECTION AND AT THE CUBAN SHORE

Date	*4 III 34*	*19–20 II 35*	*12–13 IV 35*	*24–25 III 38*	*Means*
Station No.	*2008*	*2347*	*2434*	*3012*	
Northern station	122.9	104.9	112.0	108.6	112.1
Cuban shore	170.4	172.4	172.5	170.6	171.5
Difference	47.5	67.5	60.5	62.0	59.4

TABLE III—EASTWARD TRANSPORTS, IN MILLION CUBIC METERS PER SECOND, BETWEEN SUCCESSIVE ISOPLETHS OF ANOMALY OF SPECIFIC VOLUME

δ *cl ton*$^{-1}$	*4 III 34*	*19–20 II 35*	*12–13 IV 35*	*24–25 III 38*	*Means*
>400	0.00	0.00	2.34	4.97	1.83
300–400	7.67	9.35	6.37	3.81	6.80
200–300	3.78	6.24	4.80	4.61	4.86
150–200	5.76	4.83	4.38	3.94	4.73
120–150	3.38	3.74	4.00	3.59	3.68
110–120	1.40	1.39	1.28	1.31	1.34
100–110	1.54	1.63	2.38	1.11	1.66
90–100	1.09	1.42	1.67	0.98	1.29
80–90	0.70	0.86	1.05	0.82	0.86
70–80	0.41	0.75	0.63	0.60	0.60
60–70	0.21	0.12	0.10	0.44	0.22
55–60	0.07	−0.07	−0.01	−0.04	−0.01
50–55	0.02	0.02	0.00	−0.13	−0.02
Sums	26.0	30.3	29.0	26.0	27.8

(Jakhelln, 1936, p. 4), where z is elevation above the depth of 1200 meters and the integrations are performed for the walls. The agreement was good in each case.

The freedom allowed in extrapolating the mass distribution where there are no samples involves great uncertainty. For instance, the isopleths for the first section as shown in Figure 43 appear to give a reasonable interpretation on the basis of the observations, and give a total transport of $26.0 \cdot 10^6$ m^{3}sec^{-1}. However, another interpretation, appearing nearly as reasonable, gave $29.2 \cdot 10^6$ m^{3}sec^{-1}. The uncertainty in regard to the anomaly of dynamic height above 1200 db is relatively less. The two calculations for the first section give, in kilergs per gram:

	First calculation	*Second calculation*
Northern station	121.8	122.9
Cuban shore	171.8	170.4
Difference	50.0	47.5

Since the two calculations differ by much less than do the different sections as given in Table II, the values in that table are not in serious error due to incomplete knowledge of the mass distribution.

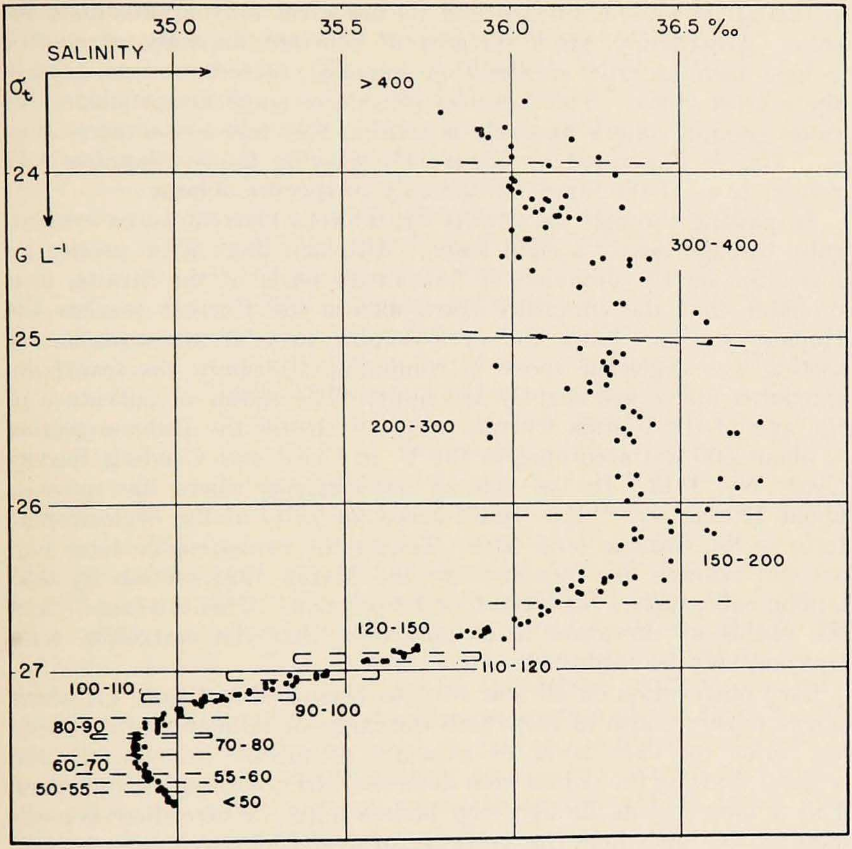

Figure 47. σ_t-Salinity correlations for all observations on the four *Atlantis* Habana sections, indicating also the anomaly of specific volume in centiliters per ton.

The base level of 1200 db was chosen rather than a deeper one because almost no observations below it were obtained.

Integration of curves of anomaly of specific volume versus pressure for the walls in order to obtain the anomaly of geopotential at points along the walls of course involves the questionable assumption that the horizontal pressure gradient vanishes at the walls.

When first suggested it was supposed that the acceleration potential would be computed for σ_t-surfaces, since these are usually best suited for isentropic analysis (Montgomery, 1937). The anomaly of specific volume is not entirely constant over a σ_t-surface (cf. Montgomery, 1938a, pp. 20–22), so $\Phi_a + \delta p$ is not strictly an acceleration potential for such a surface and its use gives only approximate results. Accordingly, since surfaces of constant anomaly of specific volume have an exact acceleration potential, these have been used in the present study. This however introduces some inconvenience because specific volume anomaly is considerably less conservative than σ_t. This is illustrated by Figure 47, showing the overlapping with respect to σ_t of the layers of anomaly of specific volume.

In passing through the Straits the Florida Current turns cyclonically through nearly a right angle. Although there is no precise information on the direction of flow in all parts of the Straits, it is probable that the curvature starts before the Current reaches the Habana section. Since the cyclostrophic term in the equation of motion was neglected above in computing transport, the transports tabulated above are slightly too large. The radius of curvature of the axis of the Florida Current where it crosses the Habana section is about 500 km according to the U. S. Coast and Geodetic Survey Chart No. 1113. In the axis of the Current, where the speed is about 120 cm sec^{-1}, this would make the ratio of the cyclostrophic term to the Coriolis term 0.04. Taking the cyclostrophic term into account reduces the transport for the March 1934 section by 0.35 million cubic meters per second, or 1.3 per cent. This is so small, and the radius of curvature is so uncertain, that the correction term may suitably be neglected.

Each observation on all four sections is entered in Figure 47, which therefore serves also to show both the range of salinity and the average value for each layer of anomaly of specific volume. In the original drawing the points were differentiated according to the layers. This is indicated in the figure by broken lines. Where there is overlapping, two lines indicate the range of overlapping.

DISCUSSION

Pressure gradient at the bottom

The transport calculations were carried out on the assumption that there is no cross-stream horizontal pressure gradient at the bottom. It was at the Miami section of the Straits of Florida that Wüst (1924, p. 37) obtained his famous agreement between Pillsbury's current measurements and the density distribution deduced from *Blake* and *Bache* observations. His calculation of velocity distribution from density distribution was based on the absence of horizontal pressure gradient at the depth of the temperature minimum[4] in the

[4] Subsequent observations have not confirmed the existence of this temperature minimum. The temperature higher than 9° near the bottom as shown by Wüst therefore seems in error by several degrees.

central portion of the section, and at the bottom on the sides where the temperature minimum is lacking. Since the temperature minimum is shown less than 200 meters from the bottom, this gives evidence that the gradient is quite small at the bottom itself. In addition to this evidence and to the general fact that currents tend to be weak in deep water there are several considerations which indicate that the bottom gradient is small at the Habana section.

(1) *Bottom friction.* Any cross-stream pressure gradients which may arise at the bottom are automatically reduced by friction. This can be quite effective because the sources of currents and pressure gradients are to be found almost exclusively in the surface layers. For instance, in the deep central part of any section of the Straits of Florida a pressure gradient may arise due to some temporary cause. Bottom friction prevents complete development of a current to balance this pressure gradient, with the result that water flows from higher to lower pressure. Due to the confinement of the Straits a relatively small cross-stream transport of this sort is effective in reducing the gradient. It is unlikely that the cause of the gradient can be of both long duration and considerable magnitude, so bottom friction keeps the gradient small except for brief sporadic periods.

The "walls" of the Straits may be considered from the point of view of any layer bounded above and below by surfaces of constant potential density. This is largely an independent unit as far as frictional forces are concerned. In the central part of the layer the water is flowing through the section as part of the Florida Current, and the cross-stream pressure gradient is closely adjusted to this flow. Due to lateral friction (if not to other causes) the velocity gradually reduces to zero on approaching the wall at either side. Also in this manner adjustment of the pressure gradient takes place if possible, so that it tends to decrease toward zero at the walls.

(2) *Threshold.* The dense water of the lower layers found in the Habana section of the Straits cannot pass through the shallower sections further downstream. The threshold depth of the Straits is not well determined, but may be estimated very roughly as 800 meters. The threshold lies near Miami and the maximum σ_t observed in four sections from this vicinity are given in Table IV.

TABLE IV—Maximum Values of σ_t Observed on Four Miami Sections

Section	*Station*	*Depth (meters)*	*Temp °C*	*Salinity °/oo*	σ_t $g\ l^{-1}$
Bache 19–20 III 14 (Bigelow, 1915, p. 58)	10203	800	6.16	34.85	27.43
Atlantis 17–23 IV 37 (Parr, 1937, Figure 3)	2855	600	6.00	34.90	27.50
Atlantis 27–28 III 38 (unpublished)	3016	579	7.45	34.91	27.305
Atlantis 22–23 V 39 (unpublished)	3506	729	6.06	34.88	27.475

From these values it may be concluded that very little water denser than $\sigma_t = 27.50$ g l^{-1} passes through the Straits. According to Figure 47 this coincides with an anomaly of specific volume of 70 cl ton^{-1} at the Habana section, so that the transport of the layers below this must be very small. The computed transports as given in Table III agree fairly well with this conclusion, showing that the assumption of no cross-stream pressure gradient at the bottom has led to only a slight inconsistency in this respect.

(3) *Current observations.* In Table V are given the surface currents measured from the *Blake* on the Habana section during parts

TABLE V—PILLSBURY'S MEASUREMENTS OF CURRENT AT 3½ FATHOMS BELOW THE SEA SURFACE ON THE HABANA SECTION, FEBRUARY–MAY 1887

Station	*Miles south of Rebecca Shoal Light (24° 35′ N, 82° 35′ W)*	*Current strength (knots)*	*Current direction**	*East component cm sec⁻¹*	$\frac{d\Phi}{dx}$ *cm sec⁻²*
1	18	0.32†	——	16	0.0010
2	34½	0.96	SE x E½E	43	0.0026
3	50½	2.20	E ¼ S	113	0.0066
3½	59	1.77	E ¾ S	90	0.0052
4	67	2.35	E x N	119	0.0069
4½	75½	1.13	NE x E½E	51	0.0029
5	84	0.87	NE ½ N	29	0.0017

* From the small table on page 176 of Pillsbury's paper.
† East component.

of the months February–May 1887, taken from Pillsbury's (1887, Illustration No. 38, Fig. 1) graphical summary. The east component has been computed and in the last column is given the gradient of geopotential at the sea surface along the section,

$$\frac{d\Phi}{dx} = fv.$$

Here v is the east component of the current, and for each station the appropriate latitude has been used in computing the Coriolis parameter. The values of gradient in Table V have been integrated to give the geopotential of the sea surface along the section, represented by the continuous curve in Figure 48.

The same figure shows the geopotential of the sea surface as computed for each station of the four *Atlantis* sections. The form of the curve based on current measurement agrees well with an imaginary average of the four curves based on density distribution and on the assumption of no cross-stream horizontal pressure gradient at the bottom. In magnitude, the curve from current measurements is 52 kilergs g^{-1} higher at the Cuban shore than at the northern end, whereas the differences between the Cuban shore and the northernmost stations of the *Atlantis* sections range between 47.5 and 67.5 kilergs g^{-1} (Table II).

This comparison cannot lead to definite conclusions because the two types of measurements were made at different times. The height difference from current measurements falls within the range of values from the four *Atlantis* sections, but is 7 kilergs g^{-1} less than the average of the latter. This indicates that the assumption of no cross-stream horizontal pressure gradient at the bottom is not consistently in large error, but that perhaps there is a tendency for

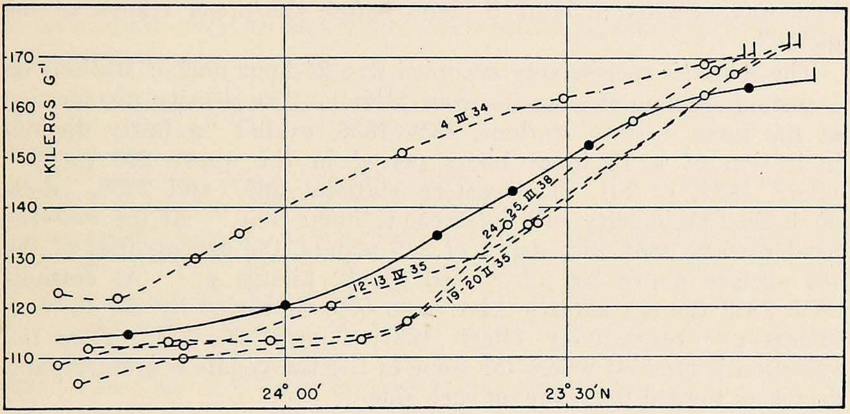

Figure 48. Profiles of sea surface at Habana section of the Straits of Florida. Solid line computed from *Blake* current measurements during February–May 1887. Broken lines computed from the mass distributions on the *Atlantis* sections, the ordinate being anomaly of geopotential above 1200 db. Vertical exaggeration about 10^5.

pressure at the bottom to decrease horizontally toward the right of the stream.

Tidal effects

Each of the four sections required about 16 hours to complete. The question arises as to what effect this lack of simultaneity may have on the observed mass distribution.

The tides and tidal currents in the Straits of Florida are of the mixed diurnal and semidiurnal type. The mean semidiurnal range of tide at Habana is 27 cm and the time of high water, 8^h 36^m after the moon's transit, is practically simultaneous with high water on the south side of the Florida Keys (Sombrero Key Light, American Shoal Light, Sand Key Light), where the mean range is 40 to 49 cm

(Coast and Geodetic Survey, 1940). It is reasonable to assume that the tide is similar all across the intervening strait. Since the range of tide is not identical on the two sides, however, there is necessarily a tidal variation in the cross-stream horizontal pressure gradient at the surface. The speed at the axis of the Florida Current also undergoes a tidal variation of amplitude about 14 cm sec^{-1}. To quote Pillsbury (1890, p. 608), "the maximum [flow] in the Straits of Florida is . . . 2 hours and 15 minutes after mean low water at the southern Atlantic ports of the United States." He further states that "off Cape Florida [Miami], there is but one prominent maximum each day, usually arriving 9 hours before the upper transit of the moon."

The *Atlantis* successively occupied five 24-hour anchor stations on a section crossing the Straits from Miami. The density distribution at the three western stations, 2854–2856, exhibit "a fairly distinct indication of a 12 lunar hours period in the upper 200 meters" (Parr, 1937, p. 20). The eastern stations, 2857 and 2858, "show no distinct periodicity with reference to lunar time." At the westernmost station, 2854 with depth of 375 meters, the geopotential of the sea surface above 300 db varied by 12 kilergs g^{-1}. At stations 2855–2858 the sea surface relative to 600 db varied by 30, 15, 6, 6 kilergs g^{-1} respectively (Parr, 1937, Figures 20, 21). Thus the variation is greatest where the slope of the isopycnals is greatest, and decreases toward the shore on each side.

Presumably similar conditions prevail at the Habana section. At the walls there may be little tidal or other short-period variation of density, so the calculated height of the sea surface at left and right shores and calculated total transport are not much affected. For these quantities, therefore, it is perhaps not significant that the density distribution was not measured simultaneously over the whole section. This conclusion is not substantiated by Parr's (1937, Table IV) values for every third lunar hour of the transport through the Miami section, which do vary. But this may easily be a fictitious variation, because (1) his sections for each third lunar hour are compositely formed from the anchor stations, (2) just as in the case of the Habana sections the observations do not completely determine the density distribution along the bottom, (3) he has not assumed the absence of horizontal pressure gradients at the bottom, which anyway is more doubtful at the constricted Miami section, and (4) his values do not include the considerable transport outside the two end stations.

If the tidal variations of density in the deep water and along the walls are actually small, then the variations in horizontal pressure gradient at the surface must extend to the bottom. It is therefore probable that appreciable horizontal pressure gradients occur periodically at the bottom, but their average value may be expected to be small for reasons already stated. If so, they do not affect the calculation of total transport.

On the other hand there is a tidal lateral shift of the density distribution, producing large density variations at any point in the region of strong current. Hence the computed height of the sea surface at a station distant from the shore depends to large extent on the hour at which the station is occupied, and the computed transports of individual isosteric layers are presumably affected to a considerable degree.

Normal total transport through the Habana section of the Straits of Florida in March

By extrapolating his vertical velocity profiles downward from 130 fathoms, Pillsbury (1887, p. 179) obtained $103 \cdot 10^9$ tons per hour as the transport through the Habana section, which is equivalent[5] to about $28 \cdot 10^6$ m^3 sec^{-1}. A recalculation by Wüst (1924, p. 42) of the same measurements gave $24.15 \cdot 10^6$ m^3 sec^{-1}.

For comparison some estimated transports through other sections may be quoted. Wüst found for the Miami section $24.96 \cdot 10^6$ m^3 sec^{-1} based on the *Blake* current measurements and $25.55 \cdot 10^6$ m^3 sec^{-1} based on the density distribution deduced from *Blake* and *Bache* observations. For the same section Parr's (1937, p. 47) calculation from *Atlantis* anchor stations gives the transport as "somewhat more than" $30 \cdot 10^6$ m^3 sec^{-1}. From *Atlantis* stations made in 1933 and 1934 Parr computed 31.92 and 33.92 million cubic meters per second as the transport through the Yucatan Sea.

The values in Table III for the four *Atlantis* sections range from 26 to slightly over 30 million cubic meters per second. The fact that the two sections in March show lower values than the sections in February and April is probably not significant in regard to the annual variation of transport; in other words it should not be interpreted as indicating a minimum of transport in March. The four sections, all from nearly the same time of year, are probably sufficient to yield a significant estimate of the normal transport at this time. For no reason is it likely that these values differ consistently from normal by large amounts. In view of the scattering of the four values and of the possible error in the mass distribution as deduced

[5] Assuming the ton to be 2240 pounds.

TABLE VI—Departures from Normal in Centimeters of Daily Sea Level at Key West Reduced to Sea Level Pressure of 30.02 Inches (Normal Sea Level Is the Average for 1913–1939, Being Staff Reading of 4.95 Feet; Zero on Staff Is 13.06 Feet Below Bench Mark 29)

	III 34	*II 35*	*IV 35*	*III 38*
1	− 2.8	+ 8.1	− 1.6	− 3.6
2	− 2.3	+ 7.8	− 5.8	− 0.2
3	− 4.3	+ 6.5	− 4.0	− 3.6
4	− 7.5	+ 5.2	− 4.5	− 6.7
5	−12.1	+ 6.2	− 1.4	− 6.7
6	−10.7	+ 3.5	− 2.5	− 5.6
7	− 7.0	+ 2.7	− 1.9	− 7.0
8	− 7.5	+ 4.8	− 5.9	− 3.3
9	− 8.4	+ 4.1	− 3.0	− 2.6
10	− 9.2	− 2.5	− 3.0	− 5.9
11	− 9.7	− 1.3	− 1.8	− 6.7
12	− 8.1	− 3.7	+ 1.1	− 5.4
13	− 2.0	− 1.7	+ 3.1	− 5.2
14	− 5.1	− 5.6	+ 1.3	− 2.5
15	− 5.0	− 8.4	+ 3.8	− 5.0
16	− 1.8	− 9.6	+ 2.2	− 6.3
17	− 2.7	−13.7	+ 4.4	− 8.8
18	− 6.0	−17.8	+ 2.9	− 9.8
19	−12.3	−14.8	+ 4.2	− 6.9
20	−13.3	−11.9	− 0.7	− 5.4
21	−10.3	−10.5	− 3.7	− 4.7
22	− 7.2	− 4.5	− 2.3	− 1.8
23	− 7.1	− 4.6	− 1.7	− 1.8
24	− 5.3	− 8.2	+ 0.9	− 5.1
25	− 0.1	− 8.4	+ 0.4	− 5.8
26	+ 1.4	− 5.6	+ 1.5	− 3.6
27	+ 1.2	−10.7	+ 2.1	− 5.1
28	− 7.3	−11.8	+ 3.0	− 3.5
29	− 9.5		+ 0.4	+ 0.4
30	− 9.7		− 2.8	− 1.4
31	− 7.4			− 4.2
Means	− 6.4	− 3.8	− 0.5	− 4.6

from the observations it seems best to state the conclusion as follows: It is highly probable that the normal total transport through the Habana section of the Straits of Florida in March is a value lying between 26 and 30 million cubic meters per second.

The individual values obtained deviate from normal due to (1) actual departures of the transport from normal, (2) error in determining the mass distribution, (3) effect of tide on the mass distribution, and (4) presence throughout the tidal cycle of cross-stream horizontal pressure gradients at the bottom and of a deviation of the current from complete geostrophic flow.

Comparison with tidal station at Key West

Dietrich (1937, Abb. 15), Montgomery (1938b, pp. 166–169) and La Fond (1939, pp. 18–19) have found for specific localities a fair agreement between monthly or weekly sea level at tidal stations and fluctuations in sea level as computed from the vertical density distribution at nearby oceanographic stations. Good opportunity for such a comparison is offered by the northern station of each of the Habana sections, which lie near the primary tidal station at Key West.

The Director of the Coast and Geodetic Survey has kindly supplied the daily sums of the hourly heights of tide at this station for the months of the four sections. These have been converted to departures from the normal staff reading of 4.95 feet (Montgomery, 1941, Table I). To these departures were added the departures from normal of atmospheric pressure expressed in terms of a water barometer (departure in centimeters of water is 34.532 times the departure in inches of mercury), Table VI giving the resulting values. The pressure used was the average for hours 0800 and 2000, 75th meridian time, which were supplied by the Chief of the Weather Bureau. In regard to whether the tide is largely eliminated by this procedure, Marmer (1931, p. 51) says "it is sufficient to derive daily sea-level as the average of the 24 hourly heights of the tide of the civil day."

Table VII gives a comparison of computed sea level for the northern

TABLE VII—Comparative Values of Sea Level in Centimeters

Date		*4 III 34*	*20 II 35*	*12 IV 35*	*25 III 38*	*Range*
Northern station		+11.0	− 7.4	−0.1	−3.6	18.4
Key West	*day*	− 7.5	−11.9	+1.1	−5.8	13.0
	7 days	− 6.7	−11.1	+0.2	−3.8	11.3
	month	− 6.7	− 3.9	−0.9	−4.7	5.8

station, from Table II, with sea level at Key West for the appropriate day and for the seven days centered on the appropriate day, from Table VI. Mean sea level for the calendar month also is reproduced (Montgomery, 1941, Table I).

Monthly sea level at Key West shows no agreement with computed sea level at the northern station, while the daily and weekly values, which differ only slightly from each other, perhaps do show slight agreement with the northern station. The greatest disagreement is for the first section; compared with the averages of the other three it differs from the daily value at Key West by 14.4 cm. No extreme weather conditions prevailed when any of the sections were made.

Some of the discrepancy may be due to an actual difference in sea level between Key West and the northern station of the section. Evidence that sea level at Key West is perhaps not representative of conditions in the offshore water is to be found in the marked variations in the fall of sea level from Key West to Miami, individual monthly values ranging from — 3.1 cm to 11.9 cm (Montgomery, 1941).

On the other hand if there is little difference in sea level between Key West and the northern station, and if the density distributions for the four sections were correctly extrapolated to the northern wall and their tidal variation and horizontal pressure gradients at the wall are negligible, there must be a non-tidal variation in elevation of the 1200-db surface. Although such pressure variations in deep water have not heretofore been noted, it is conceivable that they should exist, especially in the partially enclosed Central American seas, where the circulation and density distribution is controlled by the variable trade wind system.

Fluctuations in transport of the Florida Current

The computed transport for each of the four sections was given in Table III. Due to the uncertainties already discussed the significance of the fluctuations is questionable, although their magnitude is quite as one might expect.

If the computed fluctuations are essentially real, there is value in comparing them with the computed sea level difference across the Straits, as in Table VIII. The agreement between sea level differ-

TABLE VIII—TRANSPORT OF THE FLORIDA CURRENT IN MILLION CUBIC METERS PER SECOND IN RELATION TO THE COMPUTED SEA LEVEL DIFFERENCE ACROSS THE STRAITS (FROM TABLES 2 AND 3)

Date	*4 III 34*	*19–20 II 35*	*12–13 IV 35*	*24-25 III 38*
Sea level difference, kilergs g^{-1}	47.5	67.5	60.5	62.0
Total transport	26.0	30.3	29.0	26.0
Transport above δ = 200 cl ton^{-1}	11.4	15.6	13.5	13.4
Transport above δ = 300 cl ton^{-1}	7.7	9.4	8.7	8.8

ence and total transport is poor. The sea level difference is however seen to be closely correlated with the transport of water having

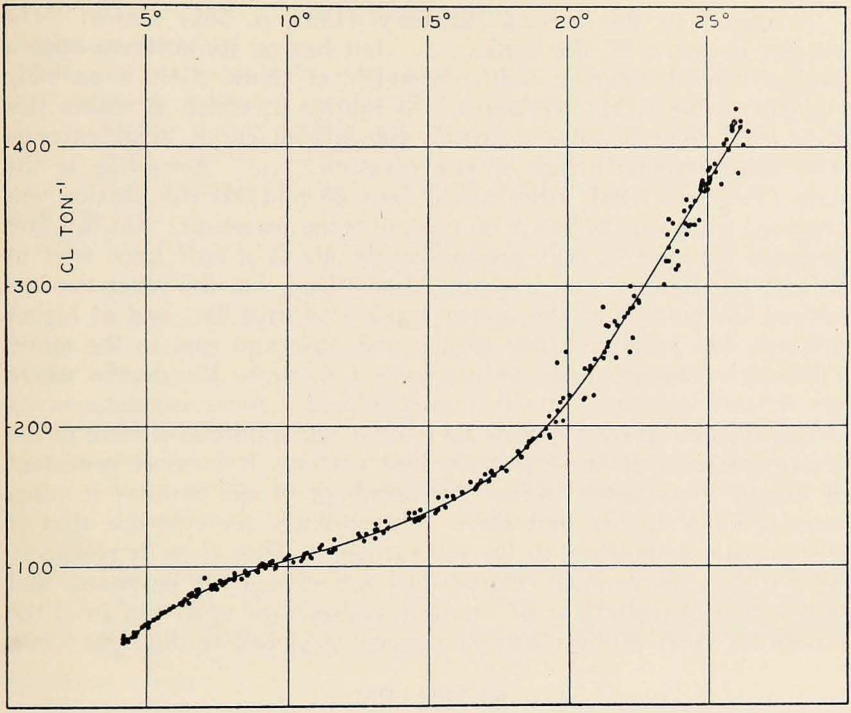

Figure 49. Correlation of temperature with anomaly of specific volume for all observations on the four *Atlantis* Habana sections.

anomaly of specific volume greater than 300 cl ton^{-1} (warmer than about 23° C) or greater than 200 cl ton^{-1} (warmer than about 19.2° C, see Figure 49). This suggests that fluctuations in the transport of warm water through the Straits might be measured with a pair of tidal stations placed on opposite sides and in good exposures. Perhaps the pair of stations now operating further downstream, at Miami and Cat Cay, will prove to serve this purpose at that section.

The deep counter current on the left of the Florida Current

On all the four sections except the first the deeper isopleths of anomaly of specific volume dip downward toward the northern wall (Figures 43–46), indicating a counter current. The calculations showed negative velocities extending up to anomaly of specific volume 70 cl ton^{-1} or 600 meters on the second section, up to 80 cl ton^{-1} or 500 meters on the third section, and up to 200 cl ton^{-1} or 80 meters on the fourth section.

In regard to this section Pillsbury (1890, p. 551) states: "The current does not fill the banks . . . , but has on its northern edge a neutral zone of varying width, in which, at times, there is an eddy current setting to the westward. At Station 1, which is within this zone and about 3 miles from the 100-fathom curve, tidal currents were always found except on one occasion, . . ." According to the data (Pillsbury, 1887, Illustrations Nos. 35 and 36) this station was occupied for about 24 hours on each of three occasions. On the first occasion the current was predominantly about a half knot west at 65 and 130 fathoms and irregular above that. On the other two occasions the current at the deeper levels was irregular, and at higher levels it was predominantly west in one case and east in the other. Pillsbury's measurements do not extend down to the depths where the *Atlantis* sections indicate a predominant counter current.

The counter current appears therefore to be a normal feature of the Habana section of the Straits in late winter. It is most persistent at depths immediately below the threshold of the Straits; it often extends much higher, but there is apparently no evidence that it ever reaches completely to the sea surface. Thus there is reason to believe that the counter current does not extend far eastward, and that it is a characteristic of the deep embayment upstream from the threshold, where also the Florida Current is closest to the right bank.

SUMMARY

A total of four hydrographic sections crossing the Straits of Florida near Habana were executed from the *Atlantis* during the winter months of 1934, 1935 and 1938. From the observed mass distribution the water transport in various layers (defined by surfaces of constant anomaly of specific volume) has been computed by use of the acceleration potential (Table III). The computed total transport varies for the four sections from 26.0 to 30.3 million cubic meters per second, and the conclusion was drawn that probably the normal transport in March is a value lying between these extremes. The assumptions and various sources of error involved in the calculation have been discussed.

The four values of sea level computed for the northern end of the sections show no appreciable correlation with sea level observed at the nearby tidal station at Key West.

The computed difference of sea level across the Straits shows little correlation with the computed total transport, but good correlation with the computed transport of the lighter surface water.

A counter current in the deep water on the left of the Florida Current appears to be a characteristic of this part of the Straits.

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